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Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment

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ABSTRACT

A nationwide saline-aquifer CO_2 storage capacity assessment has been carried out in Japan in two missions: In Mission 1, candidate saline aquifers were classified in terms of the type of geological structure and the amount of data available. Storage capacity for the entire country was then estimated based upon oil and gas exploration data (146 billion tons of CO_2). The areas considered in the Mission were located mostly offshore and far from large CO_2 emission sources. Mission 2 involved storage capacity estimation in 27 areas in the vicinity of large CO_2 emission sources. These areas had been excluded in the Mission 1 capacity assessments. With national-scale geological survey results, a preliminary assessment was performed, and promising sedimentary basins were selected for more detailed examination. To date the overall storage capacity is still under discussion in Mission 2, whereas a systematic way of evaluating data quality and quantity is proposed, and comparative studies on the storage capacity estimation is in progress.

1. Introduction

Tanaka et al. (1995) performed a nationwide CO_2 storage capacity assessment of deep saline aquifers in Japan. The assessment was carried out based on oil and gas exploration data available at that time. Storage capacity was estimated, assuming that all the injected CO_2 would dissolve in the *in situ* aqueous phase. It was also recognized that most high-potential areas were offshore and distant from the existing large CO_2 emission sources. This source/sink mismatch creates an economic challenge for future CO_2 storage.

Oil and gas reservoirs distributed around Japan are the relevant locations for consideration for CO_2 storage because of their proven geological seal that has trapped hydrocarbons over a geological timescale. However, deep saline aquifers are much more common in Japan's geological settings and are the first alternatives (Takahashi et al., 2008). Though they can exhibit large storage capacity, their characteristics have not been investigated as extensively as oil/gas reservoirs. Therefore, the Research Institute of Innovative Technology for the Earth (RITE) and the Engineering Advancement Association of Japan (ENAA) jointly initiated a new nationwide storage capacity assessment project for Japan in 2005. The Ministry of Economy, Trade and Industry (METI) funded this project. The methodology for estimating storage capacity was revised based on experience with ongoing CO_2 storage projects as in Nagaoka, Japan.

The project was divided into two missions:

Mission 1 was a re-evaluation of the storage capacity assessments that had been performed previously by Tanaka et al. (1995). The candidate saline aquifers were first classified into categories for storage capacity assessment in terms of the type of geological structure present and the amount of data available. CO_2 storage capacities were then estimated using a revised calculation methodology based on the original data set together with those newly acquired between 1993 and 2005. As a result, storage capacity for the entire country amounted to a total of 146 billion tons of CO_2. Since the assessment was performed based on data from oil and gas exploration wells and seismic surveys, the areas considered were mostly offshore and far away from large CO_2 emission sources.

Mission 2 involves storage capacity estimation for areas near large CO_2 emission sources that had not been included in Mission 1. Several promising sedimentary basins have been chosen for detailed study by a preliminary assessment based on an exam-

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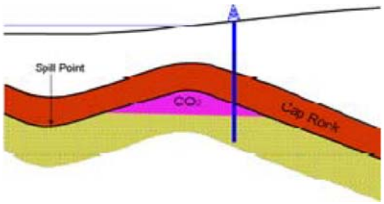
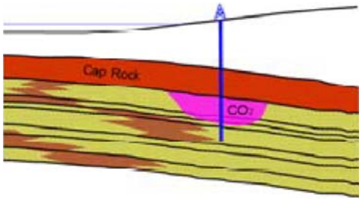
Table 1
Classification of deep saline aquifers for CO_2 storage.

Geological data		Category A (storage in an anticlinal structure)	Category B (storage in a geological structure with a stratigraphic trapping etc.)
Existing oil/gas field	Well and seismic exploration data abundant	A1 3.5Gt-CO_2	B1 27.5Gt-CO_2
Exploratory well and seismic survey	Well and seismic exploration data available	A2 5.2Gt-CO	
Basic seismic exploration	Seismic exploration data available, but no well data	A3 21.4Gt-CO_2	B2 88.5Gt-CO_2
Concept of storage			
Sub totals		30.1Gt-CO_2	116.0Gt-CO_2
Totals		146.1 Gt-CO_2	

After RITE (2006).

The definition for each storage category in Table 1 is summarized, as follows: Category A: Aquifers in the structural traps including depleted oil and gas reservoirs. This storage category is sub-divided into three subcategories:

A1: Petroleum reservoirs and their neighbouring aquifers in oil and gas fields.
A2: Aquifers in the drilled structural traps where exploratory wells were drilled by the government.
A3: Aquifers in the undrilled structural traps where seismic data for petroleum exploration were acquired by the government.

Category B: Aquifers in the offshore sedimentary basins where the water depth is less than 200 m, and are onshore dissolved gas fields.

B1: Aquifers in monoclinal structures and/or heterogeneous aquifers without trapping structures comprising three onshore natural gas fields with gas dissolved in formation water, Minami-Kanto, Niigata and Miyazaki.
B2: Aquifers in monoclinal structures and/or heterogeneous aquifer without trapping structures in the continental shelf where regional seismic data were acquired by the government.

ination of nationwide-scale geological information. As a result, geological structures suitable for CO_2 storage have been identified and characterized for each selected area, and regional scale storage capacity has been calculated using the same method as in the Mission 1 (capacity ranging from 10 million to 4.2 billion tons of CO_2 in different areas). Besides estimating capacity itself in Mission 2, uncertainties in the estimated storage capacities have been examined by comparative evaluation of the storage capacities among the regions considered (Ogawa et al., 2008). Numerical simulation studies for the inferred geological structure at the various specific areas have been carried out, and a Monte Carlo simulation tool has been developed that takes into account the effects of uncertainties in the various key parameter values. Guidelines for surveying and estimating storage capacity have also been developed in the programme (Nakanishi et al., 2008).

Based upon the results obtained by Takahashi et al. (2008) in Mission 1, this paper describes the methodology applied in the CO_2 storage capacity assessment in Mission 2, with an overview of the whole project. Storage categories in terms of the geological structures and amount of data in Mission 1 is reviewed to classify saline aquifers first. An equation used to estimate the storage potential is then described. Important parameters used in the equation are explained. The paper also examines the accuracy of storage capacity estimates based on the data currently available.

2. Categories of aquifers

Initially, saline aquifers under consideration were first classified into two broad groups (Categories A and B) based on their geological structures (Table 1).

Category A represents a closed anticline system, suitable for structural CO_2 trapping. This category can be subdivided into three sub-categories depending on the quantity of the data available. Category A1 includes fully developed and well-understood oil and gas fields with abundant subsurface geological data. Category A2 includes areas where results from both exploratory drilling and seismic surveys are available. Category A3 includes areas where only seismic survey data are available. On the other hand, Category B represents CO_2 storage in other geological structures, and can be subdivided into two sub-groups. Category B1 includes three dissolved-in-water type natural gas fields for which substantial subsurface measurements are available. Category B2 includes 16 large offshore areas from 1000 km^2 to 50,000 km^2 in size with field information largely restricted to seismic surveys (Takahashi et al., 2008).

3. Equation used to calculate CO_2 storage capacity

3.1. Calculation of CO_2 storage capacity

To calculate the CO_2 storage capacity of a deep saline aquifer, the following equation may be used:

$$CO_2 \text{ storage capacity (mass)} = \frac{S_f \times A \times h \times \phi \times S_g \times \rho}{B_g CO_2} \quad (1)$$

where A, h and ϕ are aquifer area, effective aquifer thickness and porosity respectively, so that the product $(A \times h \times \phi)$ represents the total pore volume within the aquifer volume under consideration. S_g is the supercritical CO_2 gas-phase volume fraction in the injected CO_2 plume. ρ is CO_2 density at standard conditions (=1.976 kg/m^3), and $B_g CO_2$ is the CO_2 volume factor, which depends on local pressure and aquifer temperature. Therefore, the term $(\rho/B_g CO_2)$ represents the in situ density of pure CO_2 at the local pressure and temperature. S_f represents a “storage factor”, the ratio of immiscible CO_2 plume volume to total pore volume,

Table 2
Comparisons of storage efficiency factors.

	Efficiency*	Comments*
Australia	19 %	Geodisc, Bradshaw et al., 2004
Japan	*12.5 %*	*S_f x S_g $\simeq$ E (DOE) or Cc (CSLF)*
Alberta	$\simeq$ 9 %	Bachu & Adams, 2003 (Dissolution)
USA	1 — 4 %	DOE Atlas, 2008 (Monte Carlo Simulation)
Norway offshore	$\simeq$ 4.4 %	Joule II, 1996

*Note: After Thibeau and Mucha (2007).

which incorporates the combined effects of trap heterogeneity, CO_2 buoyancy and displacement efficiency and so on. In the calculation, the entire aquifer below a depth of 800 m is considered. At this depth, it is assumed that CO_2 can be maintained at supercritical conditions and that injected CO_2 may be contained for extended periods of time through a combination of different trapping mechanisms.

It may be noted that the parameter S_f is similar to C_c: the "capacity coefficient" introduced in CSLF (Carbon Sequestration Leadership Forum) 2007 (also, see Bachu et al., 2007) or to E: the "storage efficiency factor" used in US DOE (2007). Although it is site specific and difficult to estimate an appropriate value of S_f for the nationwide assessment, S_f is assumed 0.50 for "Category A" because such structures have limited areal extent in which CO_2 buoyancy effects could dominate. For Category B, $S_f = 0.25$ to account for probable heterogeneity effects in aquifer systems with relatively large areal extent. The assumed values of S_f will be further discussed in the following section. From a time-lapse CO_2 well logging in an onshore aquifer, Xue et al. (2006) estimated the saturation of supercritical CO_2 to be 40–50%. In the present study, it is assumed optimistically that $S_g = 0.5$.

3.2. Discussion on the storage factor

In Mission 1, storage capacity was estimated in small areas where there were abundant oil/gas exploration data and sometimes history matching simulation results. In other words, the quality of storage capacity estimation was almost as good as in the EOR case. In Mission 2, since there were very few data available, a tentative, rough, and maybe very optimistic value of S_f (25%) was assumed.

In their research, Thibeau and Mucha (2007) reviewed and compared the storage efficiency factors among different researchers, and showed that there was a large scatter in storage efficiency factors (Table 2). It may be seen that the factor varies from 1 to 4% in the DOE case where Monte Carlo simulation was performed, up to 19% in the Geodisc Study in Australia where theoretical maximum pore volumes were considered. In the current study, S_f and S_g are respectively assumed 0.25 and 0.5, giving their product to be 0.125 (12.5%) for Category B. This value may be on the optimistic side in the world scale storage capacity estimation.

It may also be noted that the effective aquifer thickness h includes an implicit factor that accounts for the sand/clay ratio within a layer. The ratio is assumed to vary depending on the sedimentation history; gravelly and sandy particles are transported shorter distance, giving higher sand fraction, while clayey particles are delivered longer distance, giving higher clay fraction. In the sedimentary basins assessed, the ratio typically varies from 20 to 40%. For Category B, this means the factor corresponding to US DOE's storage efficiency factor (E) may be calculated as $S_f \times S_g \times$ this ratio: the value is in the order of 2.5–5%, which may be a more reasonable estimate.

At any rate, it is very important that the parameter values used in calculations be clearly documented, so that improved estimates may be made in the future as new insights and field information become available.

4. Re-evaluation of the previous assessment (Mission 1)

Mission 1 re-evaluated the results of the previous storage capacity assessment by Tanaka et al. (1995); the Mission 1 results are discussed in detail by Takahashi et al. (2008), and briefly summarized below.

Table 1 summarizes the results of the re-evaluation based on the both the original data set and more recent data, using the proposed calculation method. A total of 146 Gt-CO_2 of storage capacity (30 Gt-CO_2 in Category A and 116 Gt-CO_2 in Category B) was estimated. Fig. 1 shows the locations for which storage capacities were appraised, together with other pertinent information. In the area shaded grey, the water depth is less than 1000 m, and the coloured bar shows the aquifer thickness in the areas where the water depth is less than 200 m. Because the Mission 1 assessment was performed based on data from oil and gas exploration wells and seismic surveys, the areas considered are mainly offshore, at a considerable distance from the coastline as well as from existing large-scale CO_2 emission sources, which are generally located along the coast.

5. Storage capacity estimation of the regions near CO_2 emission sources (Mission 2)

5.1. Area selection and preliminary assessment

Mission 2 is to examine the possibility of CO_2 aquifer storage near CO_2 emission sources so that the transport cost in the overall carbon-capture-and-storage chain is minimized. As can be seen in Fig. 2, promising areas near CO_2 emission sources were first examined, ensuring that a combination of "aquifer" and "cap rock" formations are available at depths below 800 m to form a CO_2 reservoir. A total of 27 candidate aquifers were chosen for the examination, including four close to large CO_2 emission sources (Tokyo Bay, Ise Bay, the Osaka Bay area and northern Kyushu). The other 23 areas are listed in Table 3. Suitability for CO_2 storage was then examined at each aquifer, based on the results of national-scale geological surveys. Promising aquifers identified are indicated with the circles (likely) and triangles (possible), whereas those not promising are indicated with crosses (not likely) and minuses (not known) in the table. For example, there is a fairly large CO_2 emission source in the Seto Inland Sea, but Pre-Tertiary basement rocks

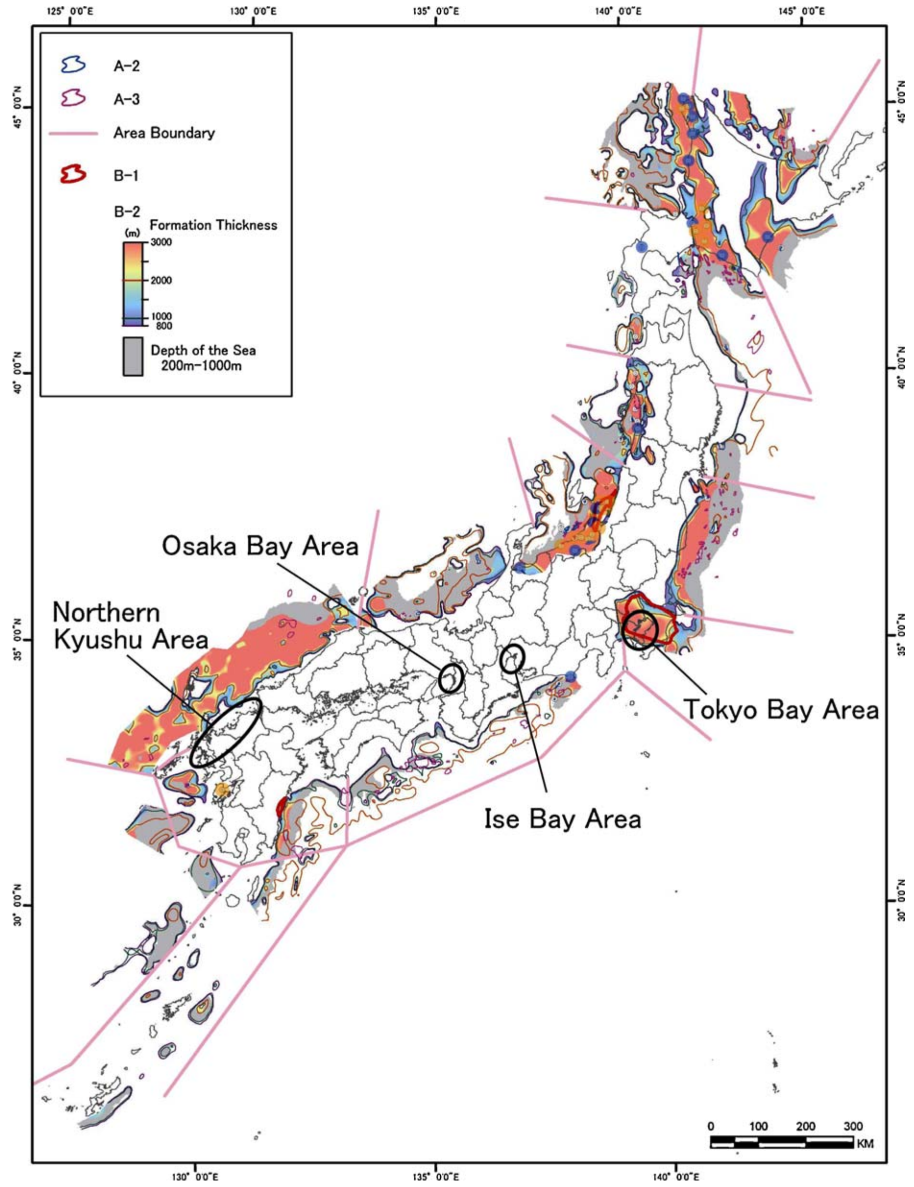


Fig. 1. Locations of aquifers and geophysical prospecting lines.

at shallow depths prevent CO_2 from being stored in a supercritical condition in the aquifer.

5.2. Storage capacity estimation at selected areas

After the preliminary suitability assessment, fourteen study areas were selected for more detailed investigation (the four large emission areas mentioned previously plus ten areas shaded in yellow in Table 3). Existing geological data such as survey data, gravity data and deep well data were collected and examined to delineate geological structures suitable for CO_2 storage. Combinations of cap rock and aquifer below a depth of 800 m were identified and "regional-scale" storage capacities were estimated, using Eq. (1). Hashimoto et al. (2008) provides a very good summary of the analysis at the Osaka Bay area. Some results of the Mission 2 assessment are listed in Table 4.

It should be noted that the results shown in Table 4 are still preliminary since an insufficient amount of data makes storage capacity estimation very difficult.

6. Comparative evaluation among areas considered near CO_2 sources

The storage capacities are calculated based upon borehole, seismic and gravity data collected originally for purposes other than geological CO_2 sequestration (e.g., exploratory boreholes, geothermal exploration). Therefore the data quality and quantity of each investigation are different, resulting in a different certainty (accuracy) of estimated storage capacities. It is important to understand what the estimated storage potential really means, since the method of data collection, surveyed depth, and location of the investigation area relative to the storage aquifer in question are all different.

To quantify the accuracy of the estimated aquifer volume (storage structure) and storage/sealing effectiveness and to compare the estimated storage capacities across regions, a practical method of examining rock property data quantitatively and qualitatively is proposed. Table 5 shows the items used for the evaluation questionnaires. They are divided into two groups: questions regarding data quality and quantity;

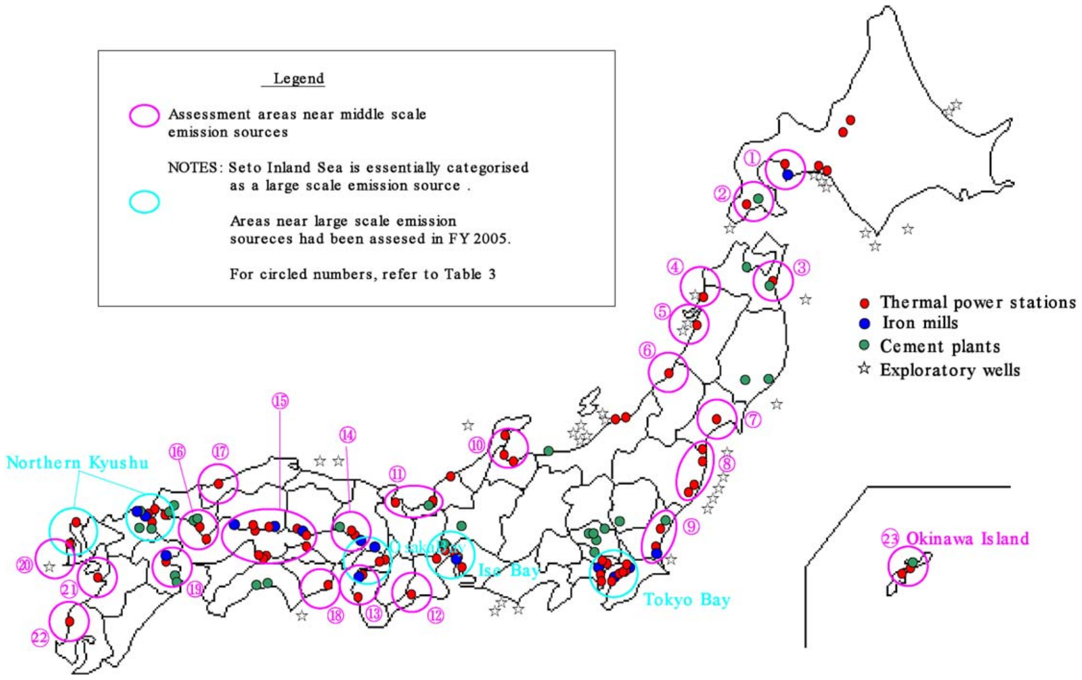


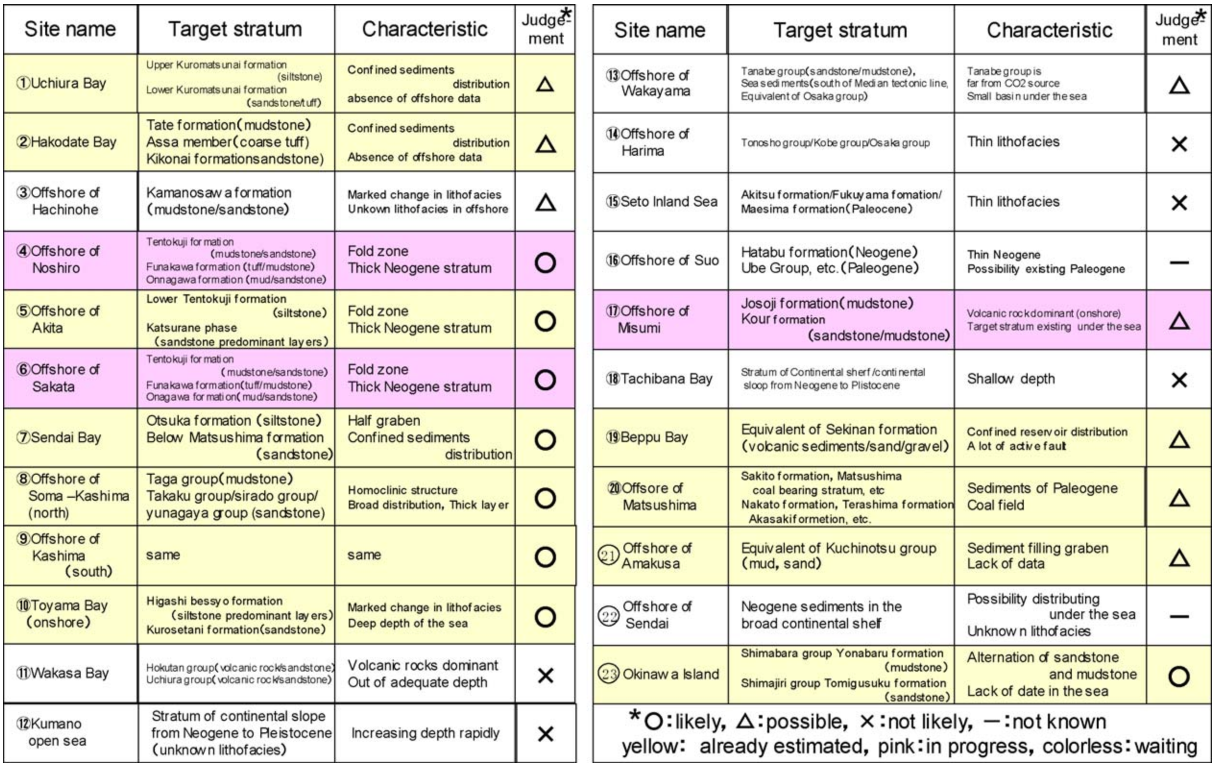
Fig. 2. Storage capacity assessments for areas near large and intermediate emission sources.

and those used to evaluate aquifer volume and storage/sealing effectiveness.

6.1. *Items considered for evaluating data quantity and data quality*

Data required to calculate aquifer volume are derived from reflection seismic exploration, gravity mapping, and borehole investigations. These data are indispensable to understanding the subsurface geological structures. Properly used, they also provide proof of the storage capacity estimation. Property data are rock parameters obtained mainly from borehole explorations. In the questionnaire a full mark of 100 is allocated to the borehole data and the property data respectively, while a full mark of 80 is assigned to the seismic data, and 20 to the gravity data giving the combination of the two forms a full mark of 100. An example of

Table 3
Preliminary evaluations of 23 areas near CO_2 emission sources.



Site name	Target stratum	Characteristic	Judge-ment*
①Uchiura Bay	Upper Kuromatsunai formation (siltstone) Lower Kuromatsunai formation (sandstone/tuff)	Confined sediments distribution absence of offshore data	△
②Hakodate Bay	Tate formation(mudstone) Assa member(coarse tuff) Kikonai formationsandstone)	Confined sediments distribution Absence of offshore data	△
③Offshore of Hachinohe	Kamanosawa formation (mudstone/sandstone)	Marked change in lithofacies Unkown lithofacies in offshore	△
④Offshore of Noshiro	Tentokuji formation (mudstone/sandstone) Funakawa formation (tuff/mudstone) Onnagawa formation (mud/sandstone)	Fold zone Thick Neogene stratum	○
⑤Offshore of Akita	Lower Tentokuji formation (siltstone) Katsurane phase (sandstone predominant layers)	Fold zone Thick Neogene stratum	○
⑥Offshore of Sakata	Tentokuji formation (mudstone/sandstone) Funakawa formation(tuff/mudstone) Onagawa formation(mud/sandstone)	Fold zone Thick Neogene stratum	○
⑦Sendai Bay	Otsuka formation (siltstone) Below Matsushima formation (sandstone)	Half graben Confined sediments distribution	○
⑧Offshore of Soma –Kashima (north)	Taga group(mudstone) Takaku group/sirado group/ yunagaya group (sandstone)	Homoclinic structure Broad distribution, Thick layer	○
⑨Offshore of Kashima (south)	same	same	○
⑩Toyama Bay (onshore)	Higashi bessyo formation (siltstone predominant layers) Kurosetani formation(sandstone)	Marked change in lithofacies Deep depth of the sea	○
⑪Wakasa Bay	Hokutan group(volcanic rock/sandstone) Uchiura group(volcanic rock/sandstone)	Volcanic rocks dominant Out of adequate depth	×
⑫Kumano open sea	Stratum of continental slope from Neogene to Pleistocene (unknown lithofacies)	Increasing depth rapidly	×
⑬Offshore of Wakayama	Tanabe group(sandstone/mudstone), Sea sediments(south of Median tectonic line, Equivalent of Osaka group)	Tanabe group is far from CO2 source Small basin under the sea	△
⑭Offshore of Harima	Tonosho group/Kobe group/Osaka group	Thin lithofacies	×
⑮Seto Inland Sea	Akitsu formation/Fukuyama fomation/ Maesima formation(Paleocene)	Thin lithofacies	×
⑯Offshore of Suo	Hatabu formation(Neogene) Ube Group, etc.(Paleogene)	Thin Neogene Possibility existing Paleogene	—
⑰Offshore of Misumi	Josoji formation(mudstone) Kour formation (sandstone/mudstone)	Volcanic rockdominant (onshore) Target stratum existing under the sea	△
⑱Tachibana Bay	Stratum of Continental sherf /continental sloop from Neogene to Plistocene	Shallow depth	×
⑲Beppu Bay	Equivalent of Sekinan formation (volcanic sediments/sand/gravel)	Confined reservoir distribution A lot of active fault	△
⑳Offsore of Matsushima	Sakito formation, Matsushima coal bearing stratum, etc Nakato formation, Terashima formation Akasakiformetion, etc.	Sediments of Paleogene Coal field	△
㉑Offshore of Amakusa	Equivalent of Kuchinotsu group (mud, sand)	Sediment filling graben Lack of data	△
㉒Offshore of Sendai	Neogene sediments in the broad continental shelf	Possibility distributing under the sea Unknown lithofacies	—
㉓Okinawa Island	Shimabara group Yonabaru formation (mudstone) Shimajiri group Tomigusuku formation (sandstone)	Alternation of sandstone and mudstone Lack of date in the sea	○

*○:likely, △:possible, ×:not likely, —:not known
yellow: already estimated, pink:in progress, colorless:waiting

Table 4
Typical results CO_2 storage capacity assessments (Mission 2).

Site	Location	Detailed classification	A: area (km^2)	h: effective thickness (m)	ϕ: porosity	Ave. reservoir temp. (°C)	Ave. reservoir depth (m)	B_gCO2: volume factor	S_f: storage factor	ρ: CO_2 density	Est'd storage capacity (Gt-CO_2)
Hakodate Bay	Offshore		37	30	0.12	70	1500	0.00397			0.01
Osaka Bay	Offshore		400	600	0.25	60	1400	0.00353			4.2
Offshore Matsushima	Offshore	Sakito-Matsushima coalfield	373	532	0.08	90	2000	0.00371	0.25	0.001976	1.06
		Takashima coalfield	24	462	0.08	80	1800	0.00376			0.06
Okinawa Island	Offshore	Tomigusuku formation	143	98	0.39	45	1200	0.00307			0.44

finer point allocation for assessing the contribution of the borehole location to the capacity estimation is shown in Table 6.

6.2. *Items considered for evaluating estimated storage capacity*

Items concerning storage capacity evaluation are subdivided into two groups: one related to the accuracy of the aquifer volume calculation; the other related to the accuracy of the evaluation of the storage/sealing effectiveness.

6.2.1. *Items related to the accuracy of the aquifer volume estimation*

This section has the items related to geological structures (full mark of 35) and to distributions of facies in seal formation and aquifer rock (full mark of 35), in which the accuracy of three-dimensional expansion of the aquifer volume (storage structure) is evaluated. In addition, questions of whether or not faults exist (full mark of 30) are used to evaluate their locations relative to the storage aquifer. It may be noted, in the evaluation, that higher marks do not necessarily mean better, since the purpose here is to evaluate the accuracy of the storage capacity estimation. This is especially so for the case evaluating faults.

6.2.2. *Items related to accuracy for the evaluation of the storage/sealing effectiveness*

Items related to sealing effectiveness (full mark of 35) and to storage effectiveness (full mark of 35) are used to assess to what extent the property values have been obtained. Furthermore, as a part of effectiveness assessment, questions as to whether or not faults exist (full mark of 30) are used to evaluate their permeability and activity.

Though it is assumed that an aquifer does not include active faults, it is still listed as an evaluation item. It should be noted that storage capacity is estimated as part of the potential investigation and that the evaluation of injectivity is included in the list, but not evaluated here.

The proposed evaluation method uses a determination of the quality and quantity of the investigation data, as well as technical judgment of experienced geologists. It is considered proper, since quality rather than quantity is evaluated in storage capacity estimation. It may be noted that the accuracy of an investigation can be improved by increasing the number of investigations, and that the evaluation result will be improved when the results of a new set of investigations becomes available.

6.3. *Example application (4 aquifers)*

Using the items listed in Table 5, storage capacity estimations for 4 different aquifers (one with onshore and offshore areas) were evaluated for the accuracy of the aquifer volume and of the storage/sealing effectiveness estimation. The results are shown in Table 7. Observations gathered from the results of the evaluations are summarized in the following sections.

6.3.1. *I-Bay*

For the I-Bay, storage capacities were separately estimated for the offshore and the onshore areas. This was done because the data qualities and quantities as well as the locations of the faults relative to the storage aquifers were different in the two areas. In addition, seismic stratigraphy analysis was performed encompassing both areas and the estimation accuracy in the geological structure can be considered high. In the offshore area, however, there are fewer borehole data and more seismic and gravity data than in the onshore area. As a result, estimation accuracy in the structure (aquifer volume) turns out to be similar in both areas, but the storage and sealing effectiveness is evaluated higher in the onshore

Table 5
Items considered and used in the questionnaires to evaluate accuracy of storage capacity estimation.

Items evaluated on available data	Items evaluated on accuracies of aquifer volume and of sealing and storage effectiveness
Borehole data (100)	Accuracy of estimating aquifer volume (100)
Existence of boreholes in aquifer/vicinity	Geological structures (35)
Distribution of boreholes	Planar understanding
Depth of boreholes	In-depth understanding
	Three-dimensional understanding
Reflective seismic exploration data (80)	Distributions of facies in cap rock and aquifer rock (35)
Existence of seismic data in aquifer/vicinity	Verification accuracy of in-depth distribution
Depth of seismic data	Accuracy of horizontal expansion
Method of seismic data acquisition	faults (30)
Survey line in aquifer/on grid	Existence detected faults
Boreholes on survey lines	Accuracy of concluding that there are no faults
	Accuracy of location and distribution determination
Gravity mapping data (20)	Location of faults relative to storage aquifer
Properties of geological formation (100)	Accuracy of estimating sealing and storage capacities (100)
Storage capacity properties	Sealing capacity (35)
Porosity	Permeability
Permeability	Mechanical properties
Sealing capacity properties	Sealing efficiency of layer
Permeability	Storage capacity (35)
Mechanical properties	Porosity
	Ratio of sand to clay (effective thickness)
	Faults (30)
	Existence of detected faults
	Accuracy of concluding that there are no faults
	Hydrological quality of faults
	Fault activity
	Fault type (for reference only. No evaluation made)
	Injectivity (for reference only. No evaluation made)
	Permeability

area, since the borehole data verified the geological structure and rock properties in the onshore area, while they were extrapolated from the onshore area in the offshore area.

6.3.2. *O-Bay*

For the O-Bay, there is a fine seismic network with borehole data to a depth of 1700 m, resulting in a well-defined understanding of the marine clay layers. The geological structure is also well understood to the facies level due to the sedimentary facies analysis. However there are few property data to verify the storage and sealing effectiveness. Therefore the accuracy of the storage and seal effectiveness assessment is evaluated to be somewhere in the middle.

Table 6
Example of questionnaire: borehole location.

1.1	Location of boreholes (quality)
50	Multiple boreholes located to represent aquifer geology well
35	One borehole located to represent the state of aquifer
20	In the aquifer in question, but located at the aquifer boundary

Table 7
Examples of evaluation.

Location		Data available			Accuracy		Remarks
		Borehole	Seismic/ Gravity	Rock Property	Volume	Storage and sealing effectivenes	
A1	I-Bay, onshore	70	62	16	63	59	
A2	I-Bay, offshore	20	86	16	67	39	
B	O-Bay	70	92	32	74	49	
C	H-Bay	0	10	0	27	24	
D	S-Bay	40	56	0	50	24	

6.3.3. *H-Bay*

In the H-Bay, there are no borehole data or seismic data that can be used to estimate the aquifer's geological structure and rock properties. The geological structure can only be estimated using gravity mapping data. Therefore the accuracy of both the aquifer volume and the storage and sealing effectiveness are rated as being low.

6.3.4. *S-Bay*

In the S-Bay, there are borehole data but no property data available for the aquifer. Therefore the estimation accuracy of the geological structure is inferior to that of other aquifers with borehole data. This also gives less rock property data.

6.4. *Example application: 18 aquifers*

To examine the proposed evaluation method, 18 different aquifers were selected, and questionnaires were filled out. Using the items listed in Table 5, storage capacity estimations for the 18 aquifers were evaluated. The results are shown in Fig. 3.

6.4.1. *Evaluation of data quality and quantity*

The evaluated results are shown in 3-dimensional space, with the *X*-axis representing borehole data, and the *Y* axis representing seismic and gravity data, and the *Z* axis representing rock property data. The origin is located in the lower left corner. Moving toward the upper right corner, the evaluation accuracy increases.

It is inferred, in the aquifers with sufficient borehole, seismic and gravity data, that the aquifer structure could be estimated accurately. However the location of the data relative to the aquifers may have to be considered.

For all the aquifers studied, property data are scarce resulting in poor estimation accuracy of the rock property. This is because the referred boreholes were drilled originally as exploratory drilling for oil and gas explorations and not for geological CO_2 sequestration.

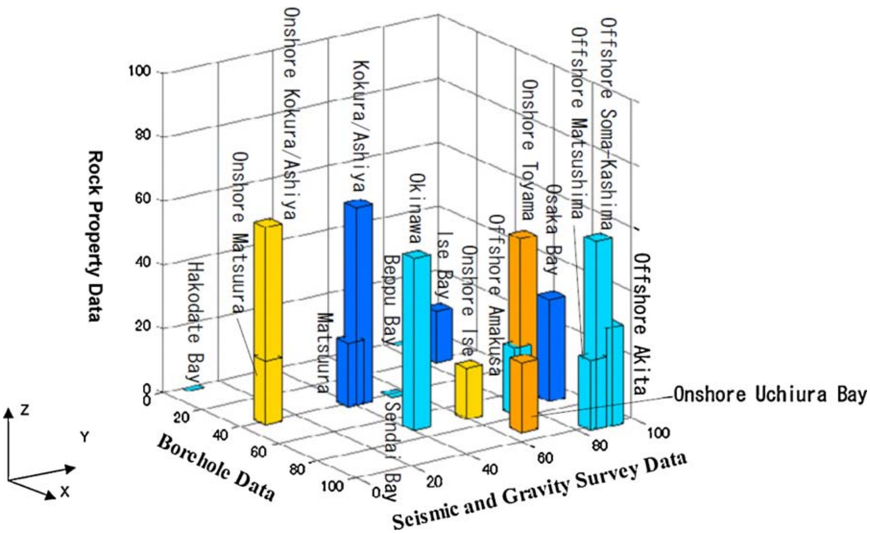


Fig. 3. Evaluated data quality and quantity.

6.4.2. Evaluated accuracies of aquifer volume and storage/sealing effectiveness

For the 18 aquifers investigated, the relationship between the evaluation accuracies in the aquifer volume and the storage/sealing effectiveness is depicted in Fig. 4. Bubbles in the figure represent the preliminary storage capacities of the aquifers evaluated. The following section discusses the evaluation results of this relationship, together with the relationship of the data quality and quantity shown in Fig. 3.

6.5. Discussion

The following observations may be made from Fig. 4:

- Where the aquifer volume is accurately estimated, the tendency is that the sealing/storage effectiveness is also estimated accurately. However there is not a strong positive correlation. Even if a deep borehole exists outside the aquifer, both the aquifer volume and the storage/sealing effectiveness can be estimated accurately, provided the geological structure and facies distribution of the aquifer are well defined from the existing geological information and nearby borehole data. This is not the case when the aquifer volume and its storage/sealing effectiveness are estimated only by extrapolating data from deep boreholes outside the aquifer.

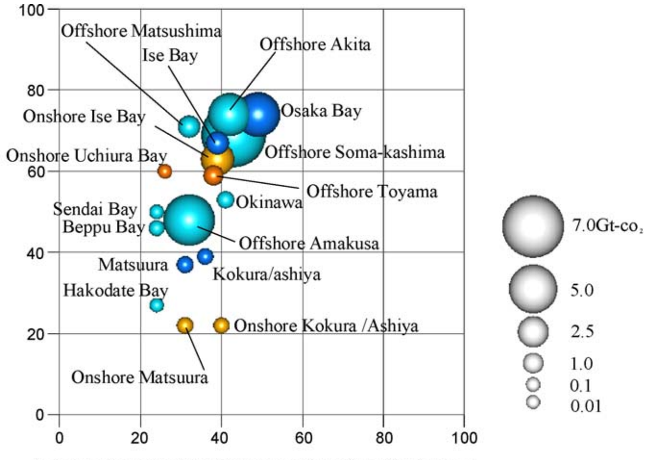


Fig. 4. Evaluated accuracies of aquifer volume and storage and sealing effectiveness.

- For all 18 aquifers studied, the evaluation accuracy of the storage/sealing effectiveness is low due to a lack of rock property data. If the data are obtained, the storage/sealing effectiveness will be estimated more accurately and the evaluation accuracy will increase. This will result in higher correlation between aquifer volume and storage/sealing effectiveness.
- For aquifers with little borehole data, evaluation of aquifer volume and storage/sealing effectiveness is not necessarily assumed to have low accuracy. This is because an evaluation is not based strictly on the quantity of the investigated data, but also on the engineering judgment of experienced geologists. As long as the quality of the engineering judgment is kept high, it is possible to increase the evaluation accuracy of storage capacity estimation.
- As long as the geological data are thoroughly examined and its quality is kept above standard, evaluation of the aquifer volume and the storage and sealing effectiveness using engineering judgment may increase the estimation accuracy. This suggests that the proposed method is appropriate for evaluating estimation accuracy at the present time and that it can be used as a stepping stone for improved evaluation methods for investigations of future site selection of pilot plants as well as actual operation plants.

6.6. Challenges identified for future study

This section discusses under what conditions an evaluation needs to be reassessed or expanded. In the future, the evaluation standard may change, an improvement in the evaluation accuracy of the storage capacity estimation may be needed, or an expansion toward site characterization may need to be accomplished.

6.6.1. Improvement of evaluation accuracy in storage capacity estimation

When is a re-evaluation of storage capacity required? It may be when the data are found insufficient, when the importance of an aquifer increases as a candidate (re-evaluation is necessary for some reasons), when the area that can be investigated expands due to technology development (an investigation method that was not previously possible becomes available, e.g., extra-long borehole drilling becomes possible), or when the investigation cost is improved (same investigation can be performed at lower costs.)

It is however important to evaluate the necessity of an additional investigation. In addition, the storage capacity in Japan has been estimated in Tertiary to Quaternary sedimentary rocks. Compared with the storage aquifers found in other countries, it is expected that the aquifer rocks found in Japan exhibit a lower permeability. This merits further investigation. Furthermore, storage capacity may be estimated more realistically, if injectivity is included in the evaluation.

6.6.2. Expansion of the evaluation toward site characterization

When CCS technology is developed to the stages of field test demonstration, site selection and actual plant operation, information on the targeted sites (economy, distance from the CO_2 emission sources, depth), possibility of hydrocarbon existence (oil and gas exploration and environmentally preserved areas), and other matters (public acceptance, and regulatory measures) have to be supplied in detail. These have not been considered in the current evaluation scheme. They must be added to the evaluation list as well as accounting for the unique geological conditions found in Japan, such as earthquake and volcano activities.

7. Conclusions

A series of nationwide storage capacity assessments for saline aquifers in Japan have been performed. The results may be summarized as follows:

- A total of 146 billion tons of CO_2 storage capacity was estimated based on available oil and gas exploration data in Mission 1 (Takahashi et al., 2008). The CO_2 storage capacities of 14 specific sites located near CO_2 emission sources were estimated, based on available data in Mission 2. These 14 study areas were not included in the previous mission.
- Assessment to date has been carried out on a regional-scale. Due to the inadequacy of the existing data, the probable accuracy of the estimated storage capacities is fairly low. These storage estimates represent “resources”, not “reserves”, in the same sense that they are used in the energy and mining industries. These storage capacity estimates need refinement through additional study and acquisition of new data.
- Further work is needed to improve the estimate of average “storage factor”.
- A method to evaluate the accuracy of the preliminary storage capacity estimation was proposed, in which the accuracy of the storage capacity estimation was compared across aquifers, and the meaning of their differences were studied. Items used for accuracy evaluation and the evaluation procedures were explained. The proposed evaluation method was then applied to actual field cases, and its applicability was examined. Some future measures were proposed.

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