Geological Carbon Dioxide Storage Technology Research Association

Practical Guidance for Geological CO_2 Storage

Phase 02

Site selection

Chapter 2. Selection of Storage Sites
Table of contents

2.1 Introduction

Selecting a storage site is the first phase of the CO_2 geological storage project described in the basic plan and involves selecting qualified sites that satisfy the CO_2 injection rate and injection volume requirements specified in the plan. As sufficient geological information is not always available at this phase, the evaluation of storage capacity, safety, and economical efficiency involves significant uncertainty. Therefore, several qualified sites must be chosen in the storage site selection process. Note that any uncertainties due to lack of geological information will be addressed in the next characterization phase.

2.2 Procedures for storage site selection

The storage site selection process first involves a regional geological evaluation. The purpose of this evaluation is to select sites that are suitable for the amount of CO_2 emissions isolated from the target emission source on the basis of publicly available reference materials and geological survey data. The ongoing CO_2 geological storage projects in the US, Canada, and Norway have an annual CO_2 injection volume of approx. one million tons and a planned project duration of 20 to 30 years. In addition, a storage site in the vicinity of the emission source is desirable from an economic standpoint of the project as it costs less to transport the CO_2.

Fig. 2.2-1 is a conceptual diagram showing the ideas and procedures involved in the qualified site selection process of the geological storage project (NETL, 2017). First, several potential sub-regions are screened on the basis of existing reference material (primarily geological information), taking into account their distance from the emission source; then, several selected areas are chosen from the screened regions.

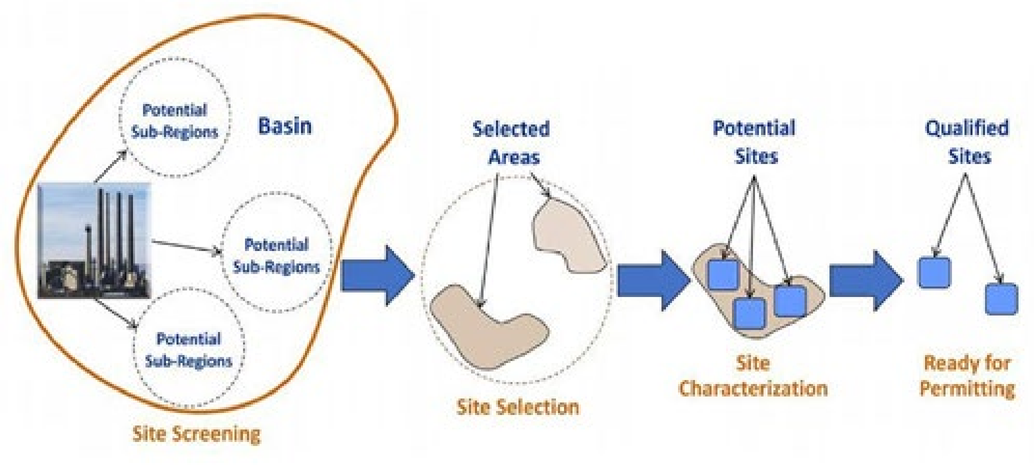


Fig. 2.2-1 Conceptual diagram of the CO_2 injection site selection process (NETL, 2017)

Next, several potential sites deemed worthy of additional site-specific investigations are identified from among all selected areas. Finally, additional data on the potential sites is obtained where necessary, and qualified sites suitable for the geological storage project are determined.

An international standard (ISO 27914: 2017) was established for qualified site selection in 2017. Although this international standard serves as a guideline for qualified site selection, the specific criteria for the selection process must reflect the geological characteristics of the country or region of interest. The criteria for qualified site selection include items such as geologic setting; storage capacity, injectivity; faults, earthquake activity; CO_2 plume size, CO_2 monitoring; and abandoned well distribution.

2.2.1 Regional geological evaluation

(1) Significance of sedimentary basins in CO_2 geological storage

Sedimentary basins vary greatly in size; some can cover several hundred square kilometers with a sedimentary thickness exceeding 1,000 m. Furthermore, oil fields and natural gas fields are formed when certain conditions are met. Typically, in the formation of oil and natural gas deposits, the source rock needs be formed (production and preservation of organic matter) and matured (buried in thick sediments), and the generated/migrated carbohydrates need to be accumulated and preserved by trapping. Of these conditions, the geological condition of trapping (including reservoirs and the seal layer) also applies to CO_2 geological storage. In that respect, sedimentary basins with a distribution of oil and natural gas fields are advantageous.

(2) Properties of sedimentary basins

Sedimentary basins with a sedimentary thickness of 1,000 meter or more make up approximately 70% of Earth's crust, and there are said to be about 600 of them in the world (Fig. 2.2.1-1). Many of these sedimentary basins are located in or around continental plates (some of them formed by collision between continental plates), distributed across the central eastern part of North America and northern Eurasia. On the other hand, although sedimentary basins that are formed through the subduction of marine plates beneath continental plates tend to be smaller in area, they primarily develop in East and Southeast Asia. As these regions feature mobile belts and frequently experience natural earthquakes, geologically young sediments develop in them. This makes the porosity of the reservoir larger, thereby making these regions more suitable for geological storage. Furthermore, back-arc basins that are formed in the inner side of arcs through subduction (e.g., Akita-Niigata Sedimentary Basin in Japan, Sumatra-Java Sedimentary Basin in Indonesia) have oil and gas deposits based on good quality source rock, making them ideal for geological storage.

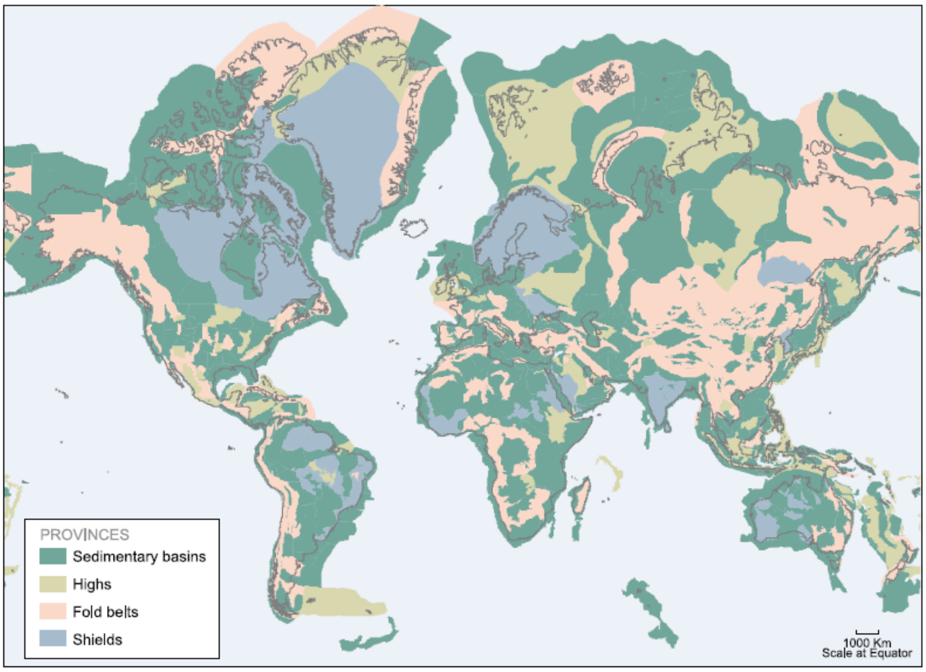


Fig. 2.2.1-1 Distribution map of the world's major sedimentary basins (IPCC, 2005)

(3) Information and types of evaluation needed for regional geological evaluation

In the initial phase of site selection, regional geological conditions and other factors are evaluated in order to identify areas within the sedimentary basin that have favorable conditions for CO_2 storage. Some CO_2 geological storage guidelines refer to this evaluation process as screening. In this phase, it is desirable to utilize existing regional geological survey reports and other related material that are available in the country or region for efficiency and economic reasons. In cases where seismic exploration and well data is available for the area surrounding an oil and natural gas exploration zone, the available geological information tends to be accurate and cover a wide area. Geological information generally includes diagrams showing the stratigraphy, the subsurface structure of each horizon structure, variations in horizon thickness, etc.

The specific procedures of the regional geological evaluation are described below with reference to public information on the Decatur Project (CO_2 injection size: 5 million tons) conducted in Illinois, USA.

(i) Analyzing the stratigraphy (Fig. 2.2.1-2)

A combination of the reservoir and seal layer are selected on the basis of the rock quality, geological age, and thickness of each horizon. If oil and gas exploration has been conducted in the area of interest, physical property data such as the reservoir porosity and permeability may be available as well.

(ii) Analyzing the thickness and extent (Fig. 2.2.1-3)

The thickness variation and horizontal extent of the reservoir and seal layer are analyzed on the basis of a regional isopach map. As seismic exploration and well data are available for areas surrounding the oil and gas exploration zones, isopach maps and other diagrams tend to be more accurate. Depending on the horizontal variations in reservoir thickness, it may be possible to present the possibility of stratigraphic traps such as pinch out traps. If possible, the lithofacies variation should also be considered when evaluating the suitability of the reservoir and seal layer. Furthermore, the CO_2 storage amount should be estimated in this step.

(iii) Analyzing the depth and structure (Fig. 2.2.1-4)

The suitability of a potential storage site is evaluated in terms of depth and structure on the basis of a regional geological section that integrates the structural map of a particular horizon (reservoir upper limit/seal layer lower limit) with existing geological information. From a storage efficiency and safety perspective, a depth that enables a supercritical state where a relatively high density of injected CO_2 can be maintained (generally a depth of 800 m or more) is desirable. Since the physical properties (porosity and permeability) of the reservoir decrease at greater depths, which leads to a decrease in storage capacity and increase in injection costs, there are certain depth restrictions.

A supercritical state with a high CO_2 density is ideal for storage efficiency. Moreover, a depth that requires less cost is desirable from the perspective of the power necessary for injection. Assuming the conditions needed to create supercritical CO_2 (temperature: 31°C, pressure: 7.3MPa), the appropriate reservoir depth would be 800 m or more. The reservoir pressure is hydrostatic pressure at typical target depths, and the depth required to create a supercritical state depends on the underground temperature. The average geothermal gradient of a sedimentary basins is about 1.5 to 5°C/100 m, but the geothermal gradient may be lower than 1°C/100 m in sedimentary basins containing geologically young sediments. On the other hand, the geothermal gradient can reach 10°C/100 m in volcanic and geothermal fields.

In and around Japan, the geothermal gradient tends to be higher in the green tuff region and back-arc basins and lower in the forearc basins on the Pacific side. Temperature information obtained in a deep chute is necessary to obtain the geothermal gradient. In Japan, the Geological Survey of Japan published the “1: 3,000,000 Geothermal Gradient Map of Japan” in 1999, which was based on temperature data collected at 1,937 wells deeper than 300 m. In addition, the Geological Survey of Japan published a CD-ROM (DGM P–5) titled “Geothermal Gradient and Heat Flow Data in and around Japan” in 2004 that included various numbers and geological maps.

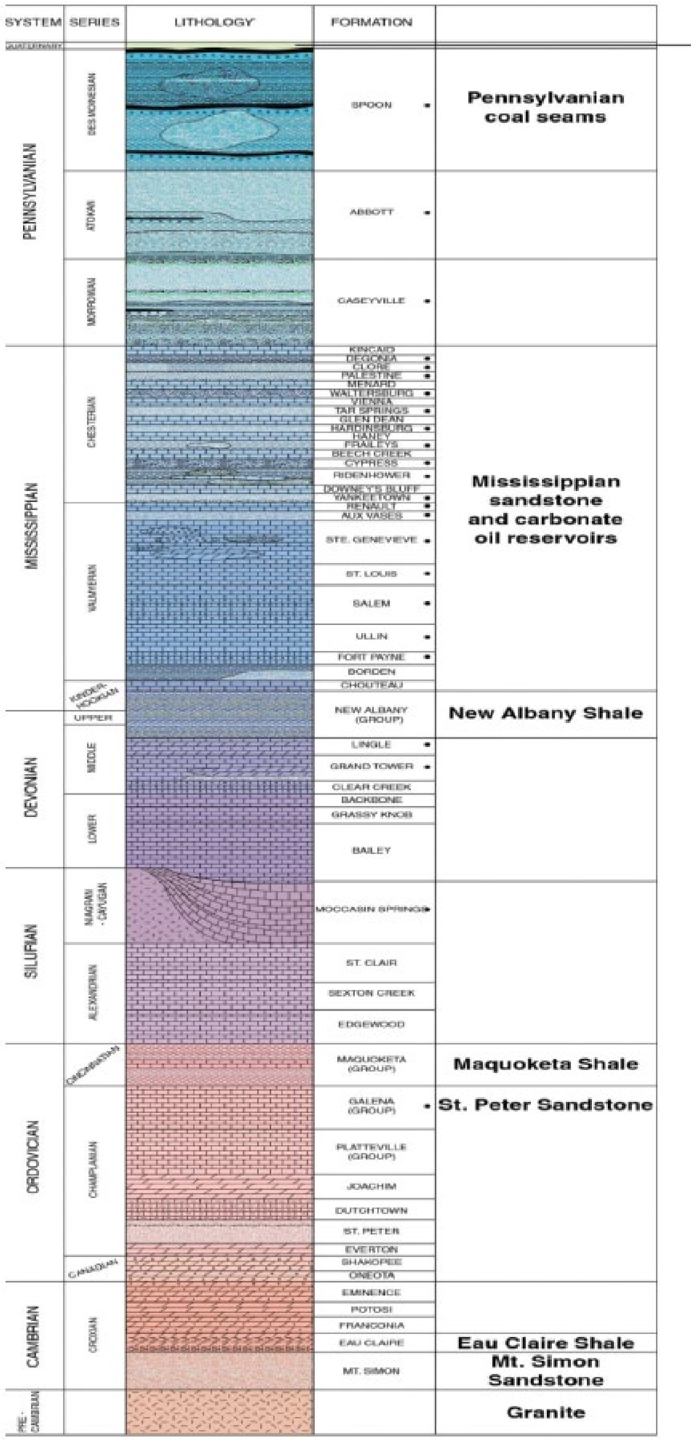


Fig. 2.2.1-2 Example of a stratigraphic chart (Illinois Basin) (NETL/DOE, 2013)

Per the right column, Mt. Simon Sandstone (bottom of the chart) was chosen as the reservoir and Claire Shale above that was chosen as the seal layer.

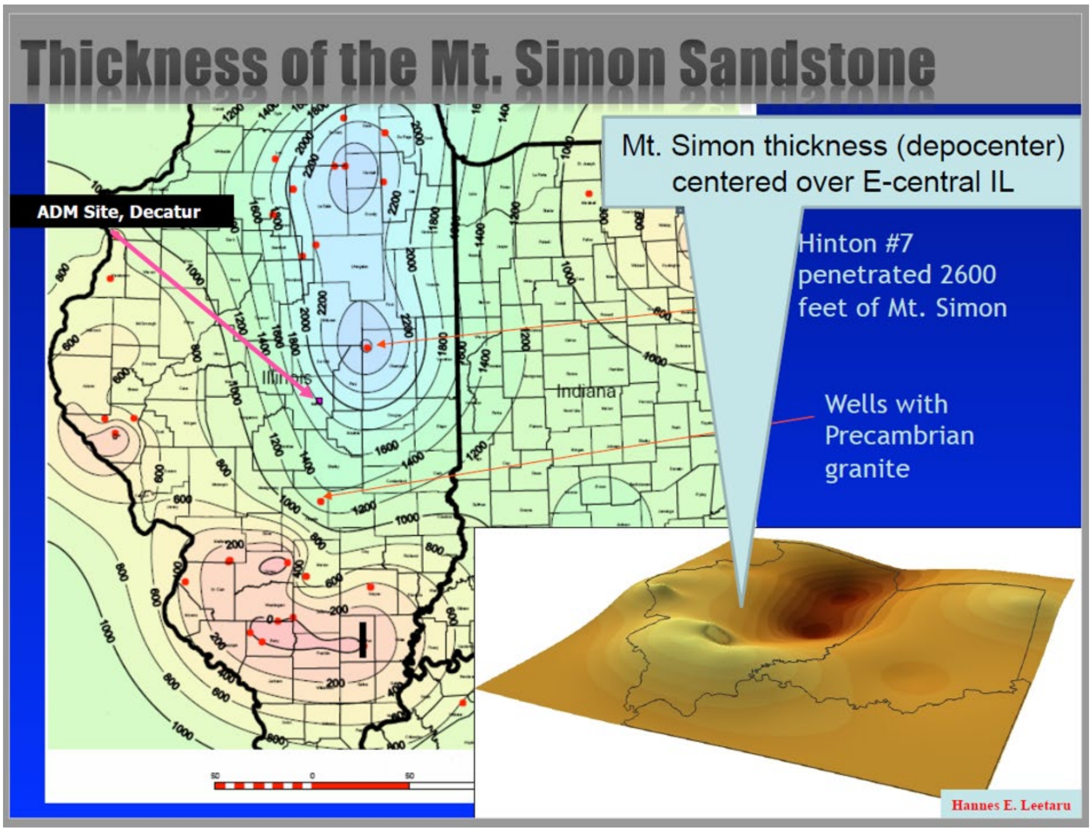


Fig. 2.2.1-3 Example of an isopach map (McBride et al., 2013)

The elevated sedimentary area on the southwest side (buried hills shown circled in blue) was excluded owing to lack of sandstone bed thickness, and the thick area on the north side was determined as suitable for storage.

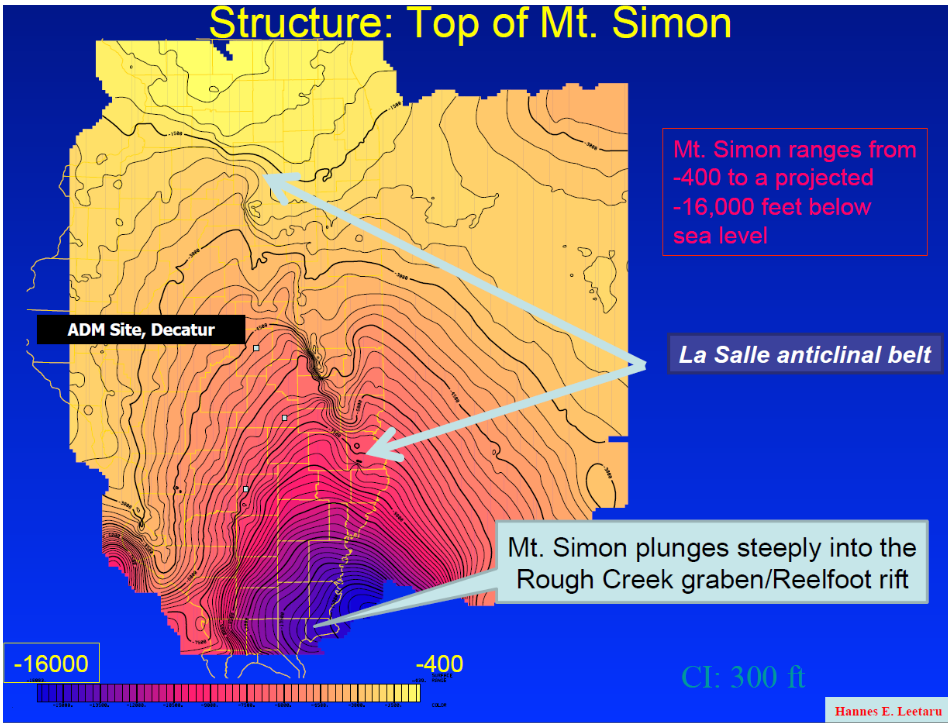


Fig. 2.2.1-4 Example of structural map (McBride et al., 2013)

There are small and mid-sized structural traps located in the area around the Decatur site that are not shown in the map.

(iv) Analysis of trapping, etc.

In the geological structure analysis above, trapping structures and the positional relationship with faults are considered in addition to depth. Even if a trapping structure is not present in the vicinity of the emission source, a given site may be selected for storage if the injected CO_2 flows down a gentle inclination and is eventually stopped by a distant trapping structure. However, sites close to large faults should be avoided to reduce risk of CO_2 leakage and induced earthquakes.

(4) Collection of reference material necessary for regional geological evaluation

The most fundamental reference material in any regional geological evaluation is the regional geological information provided by a public geological research organization, such as the National Institute of Advanced Industrial Science and Technology (AIST) of Japan (Fig. 2.2.1-5). Geological resource exploration reports may also be used. The "Domestic Oil and Gas Basic Survey" conducted by the Japanese government provides detailed geological information, including the results of seismic exploration and survey of exploration wells (Fig. 2.2.1-6). More recently, there have been cases where regional data is published for the purpose of evaluating the CO_2 geological storage capacity.

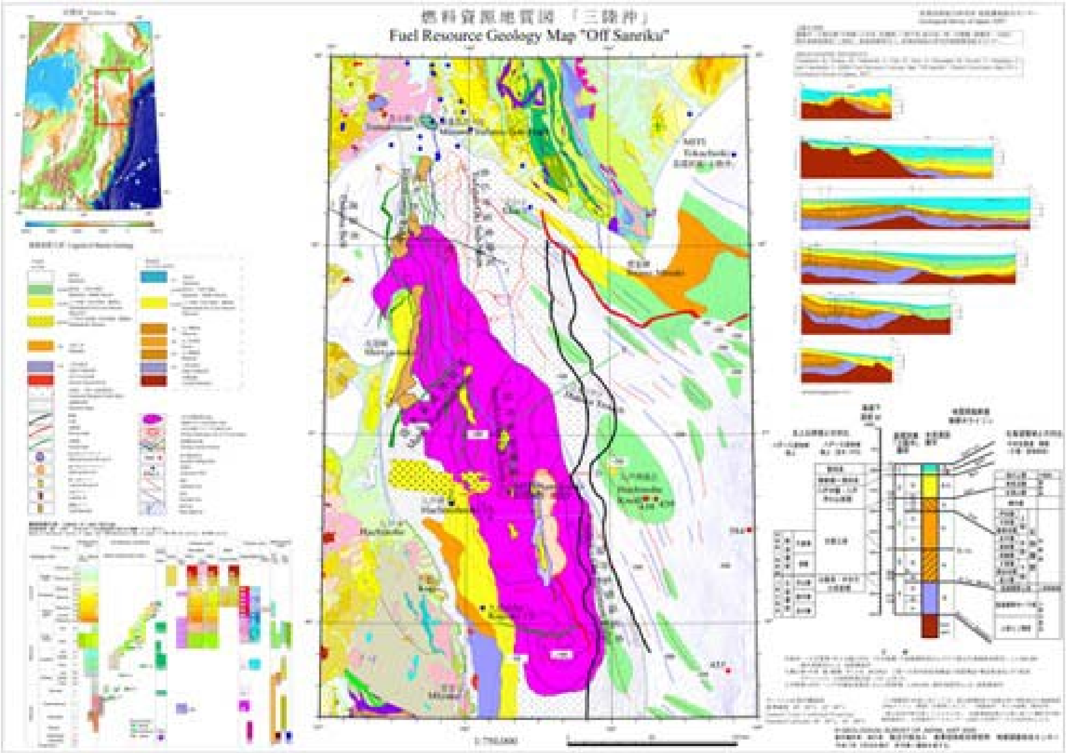


Fig. 2.2.1-5 Fuel Resources Map of Japan,Off Sanriku (AIST, 2005)

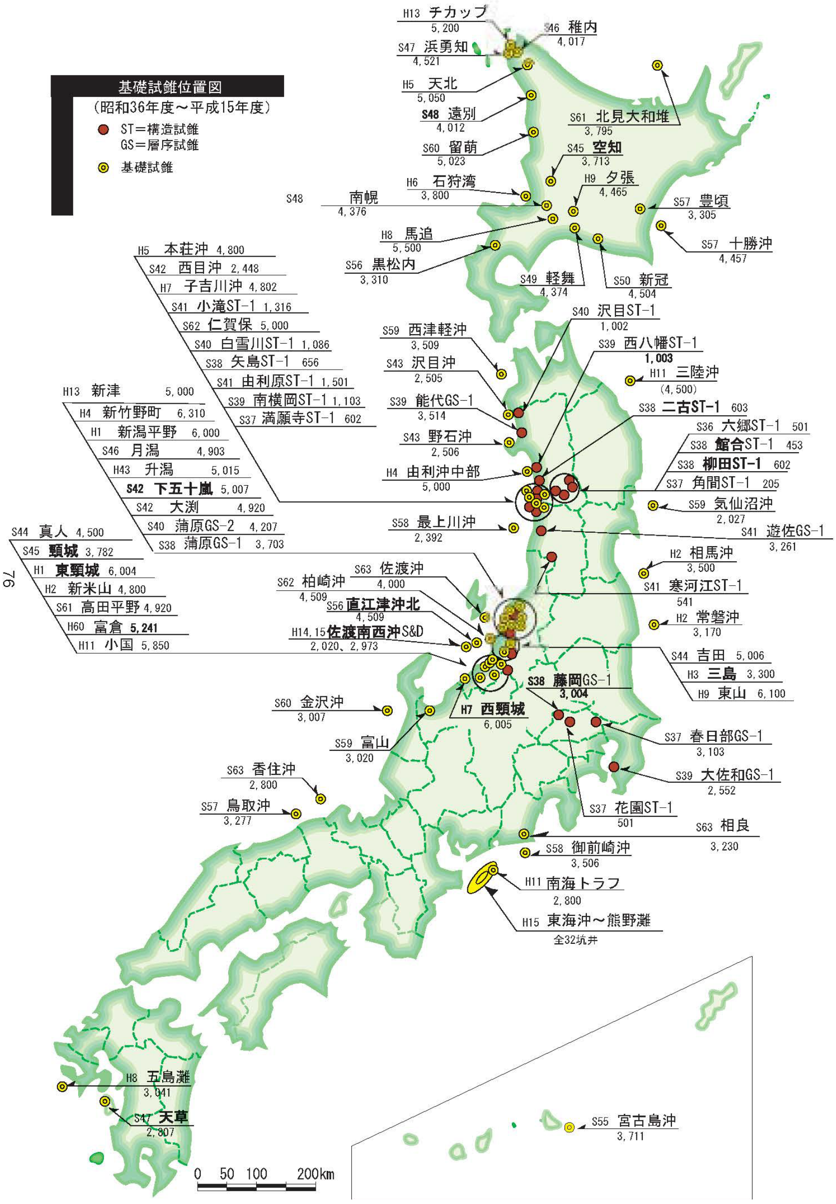
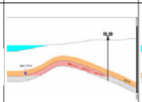
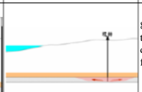


Fig. 2.2.1-6 Sites where basic boring was conducted (before 2003)（JOCMEC, 2004）

(i) Examples of Japanese regional evaluation on CO_2 geological storage capacity

RITE conducted the Survey of Storage Capacity in Japan and Survey of Viability of CO_2 Geological Storage Near Emission Sources from 1993 to 2008, which involved evaluating the CO_2 geological storage capacity of coastal sedimentary basins, and later published the results.

Using the basic survey data provided by the government, these surveys targeted all horizons with storage potential (generally excluding bedrocks). They categorized the horizons by the presence/absence of structural trapping and quality/quantity of geological data, estimating that up to 146.1 billion tons of potential storage capacity was available (Fig. 2.2.1-7).

Data		Category A	Category B	Accuracy	Scale
gas and oil field	well and seismic data available	A1	B1	H	M to S
Drilling	limited well and seismic data	A2		H	M
geophysical exploration	No well data and limited seismic data	A3	B2	M	H
schematic diagram		Physical Trapping	Physical/ Residual Trapping	Period: 1000 year Target: sediment	
Type				800 m or deeper, shallower than 4000m depth (200m. 500m, 1,000m) fault type	
Storage Potential		Moderate	Large	depend on data amount and quality	

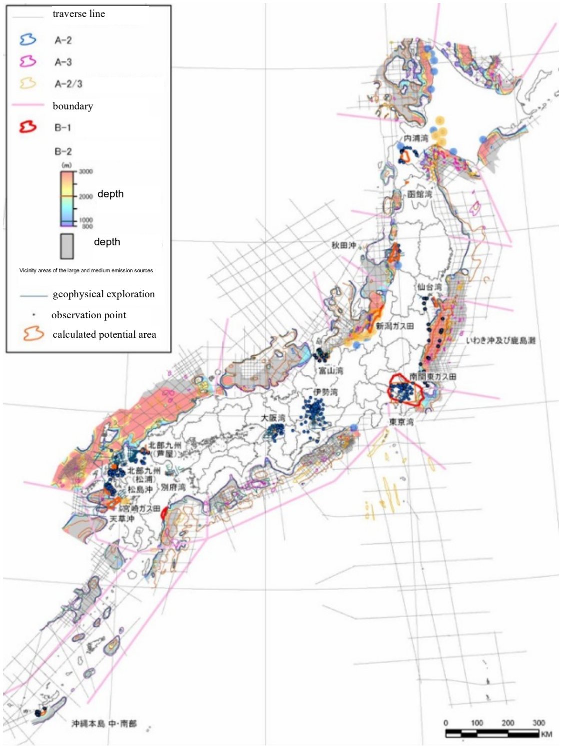


Fig. 2.2.1-7 Categorization according to the estimation of Japan's CO_2 storage capacity (RITE, 2006) CO_2 saturation is assumed to be 50%. The storage capacity was estimated to be A1 = 3.49 billion tons, A2 = 5.2 billion tons, A3 = 21.4 billion tons, B2 = 88.48 billion tons, and B3 = 27.53 billion tons (146.1 billion tons in total).

Later, the Survey of Viability of CO_2 Geological Storage Near Emission Sources analyzed the storage potential on an emission source basis and presented an estimation of storage capacity. The areas reviewed included Osaka Bay, Ise Bay, northern Kyushu, and Tokyo Bay, which are located close to areas with a concentration of large-sized emission sources, as well as 23 other regions that are located close to medium-sized emission sources (Fig. 2.2.1-8).

Such regional geological evaluations aim to evaluate the storage potential of all back-arc and forearc sedimentary basins located in and around the Japanese archipelago. For a specific project plan, the optimal area must be selected with consideration to the emission source location and other factors.

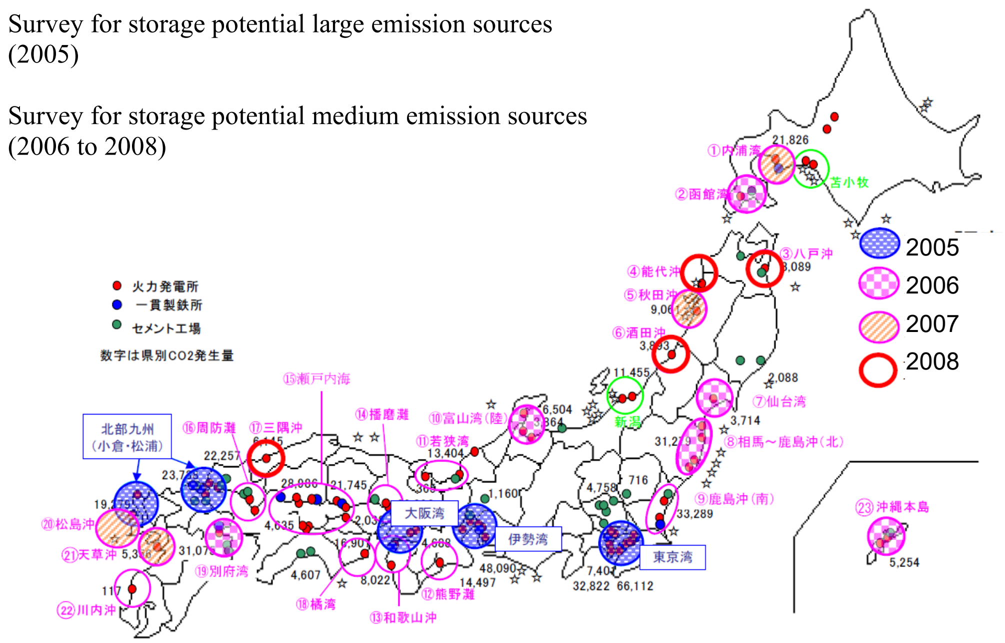


Fig. 2.2.1-8 Vicinity areas of the large and medium emission sources that were surveyed for storage potential (RITE, 2009)

(ii) Examples of overseas regional geological evaluations

a) US and Canada

In the US and Canada, oil companies are required by law to submit to the government and publish some of the geological data obtained through oil and gas field development. This data is utilized in regional evaluations conducted prior to the selection of CO_2 geological storage sites. The land and waters of the US feature many sedimentary basins as well as large oil and natural gas deposits, making it a country with high CO_2 geological storage potential (Fig. 2.2.1-9).

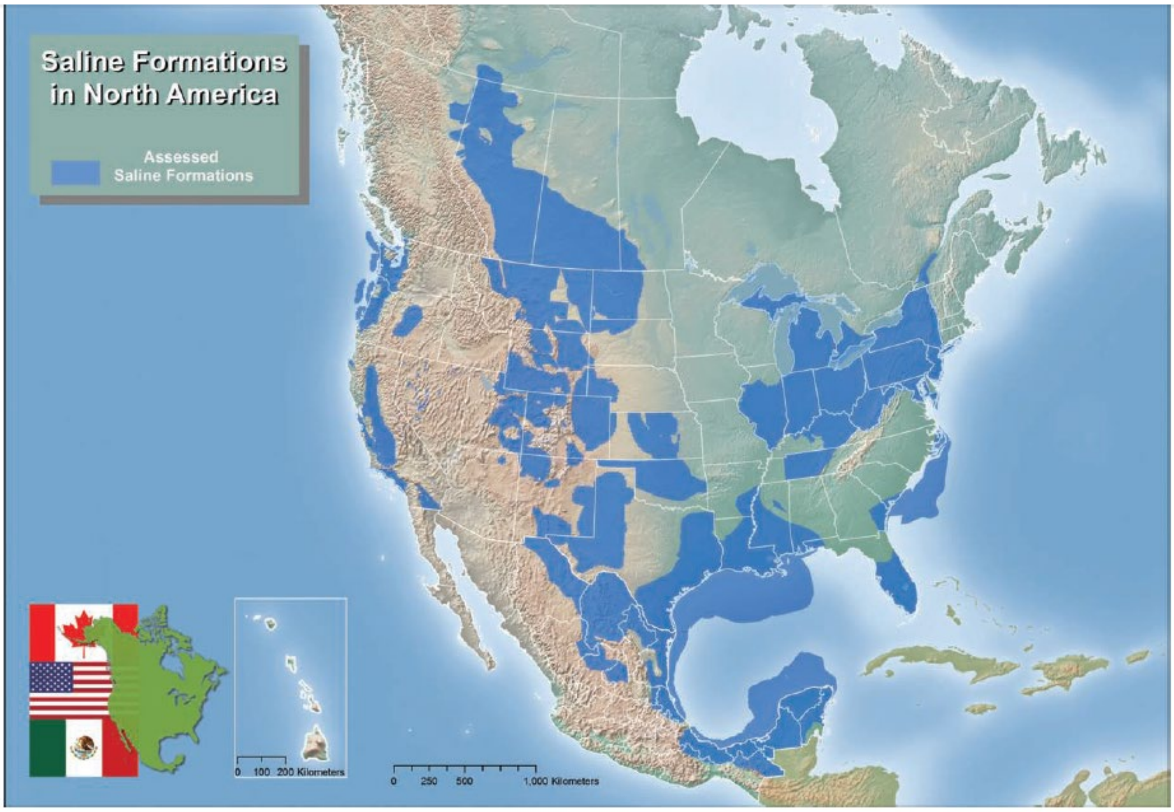


Fig. 2.2.1-9 Development of deep saline formations in North America (Atlas Partnership (NACAP), 2012)

In order to support the development of CCUS technology, the US Department of Energy (DOE) divided the country (including parts of Canada) into 7 regions and has carried out the Regional Carbon Sequestration Partnerships (RCSP) initiative since 2003. The RCSP initiative consists of 3 phases: evaluation of the CO_2 geological storage potential of the area of interest (Phase 1), small-sized verification experiment (Phase 2), and verification experiment involving the injection of one million tons of CO_2 into a deep saline formation or oil reservoir (Phase 3).

Planning for the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative, a successor project of the RCSP initiative, began in 2016. Funded by the public and private sectors, the project aims to achieve CO_2 storage on a commercial scale, i.e., more than 50 million tons (Fig. 2.2.1-10).

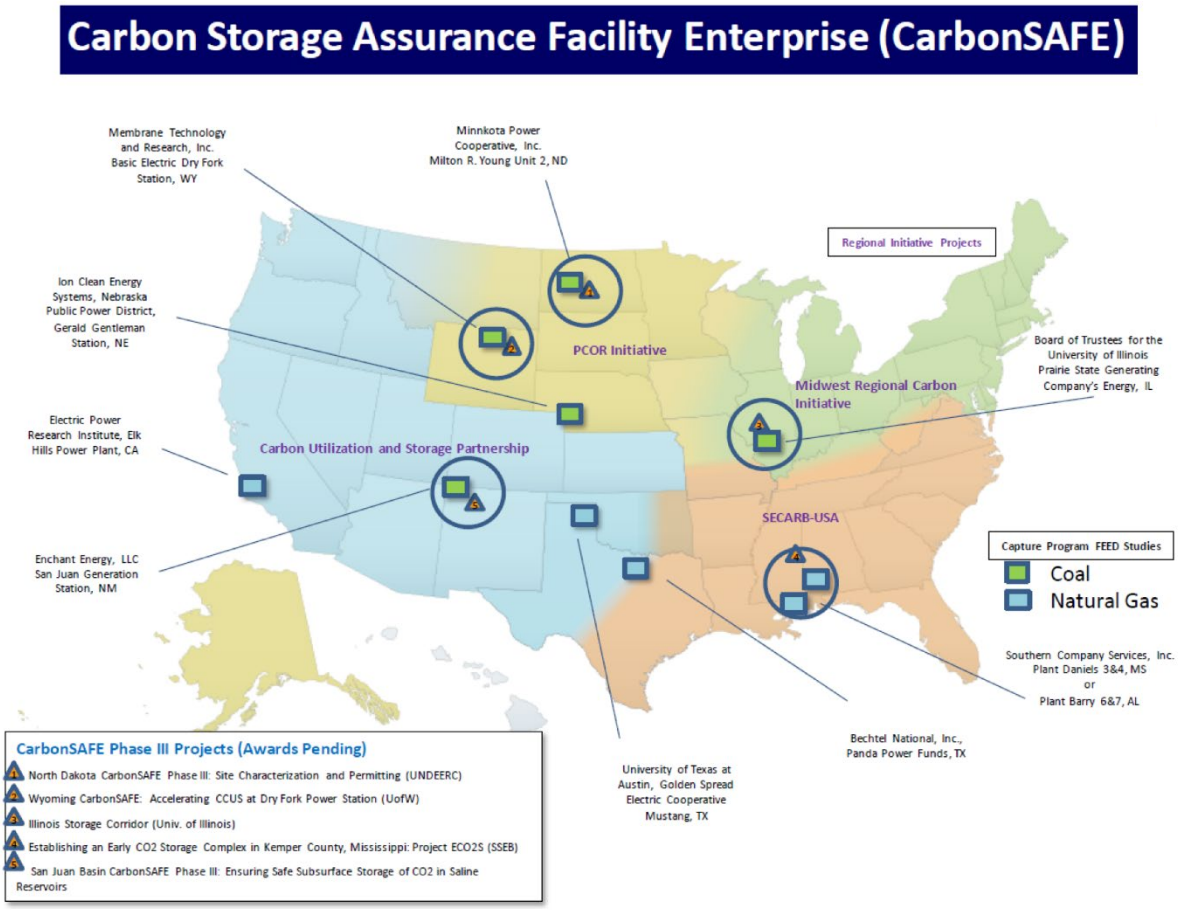


Fig. 2.2.1-10 Distribution of the CarbonSAFE project (Quillinan, 2019)

The CarbonSAFE project has published the evaluation results of CO_2 geological storage potential in America's land and waters. Particularly noteworthy is the CO_2 storage potential evaluation being carried out on the continental shelf. Currently, commercial development of oil and natural gas is only permitted in 6 percent of federal waters on an area basis, including parts of western and central Gulf of Mexico. However, in its new 5-year plan from 2019 to 2024, the US Bureau of Ocean Energy Management (BOEM) permitted the drilling for oil and gas in almost all federal waters (approx. 90% on an area basis), including the eastern Gulf of Mexico (offshore Florida), the Gulf of California, the offshore Atlantic (where exploration ceased in the early 1980s and no oil or gas is currently produced), and the Arctic, with the aim of promoting the utilization of domestic energy resources. Furthermore, efforts are being made to evaluate the CO_2 geological storage potential of the continental shelf of the US and Canada, and the results have been published (Fig. 2.2.1-11). If marine drilling is carried out on a wider scale in federal waters, this may greatly accelerate subsea CO_2 geological storage (not to mention geological storage projects in general) as the eastern Gulf of Mexico, the California continental shelf, and the Atlantic continental shelf, among others, are all located close to large-scale emission sources.

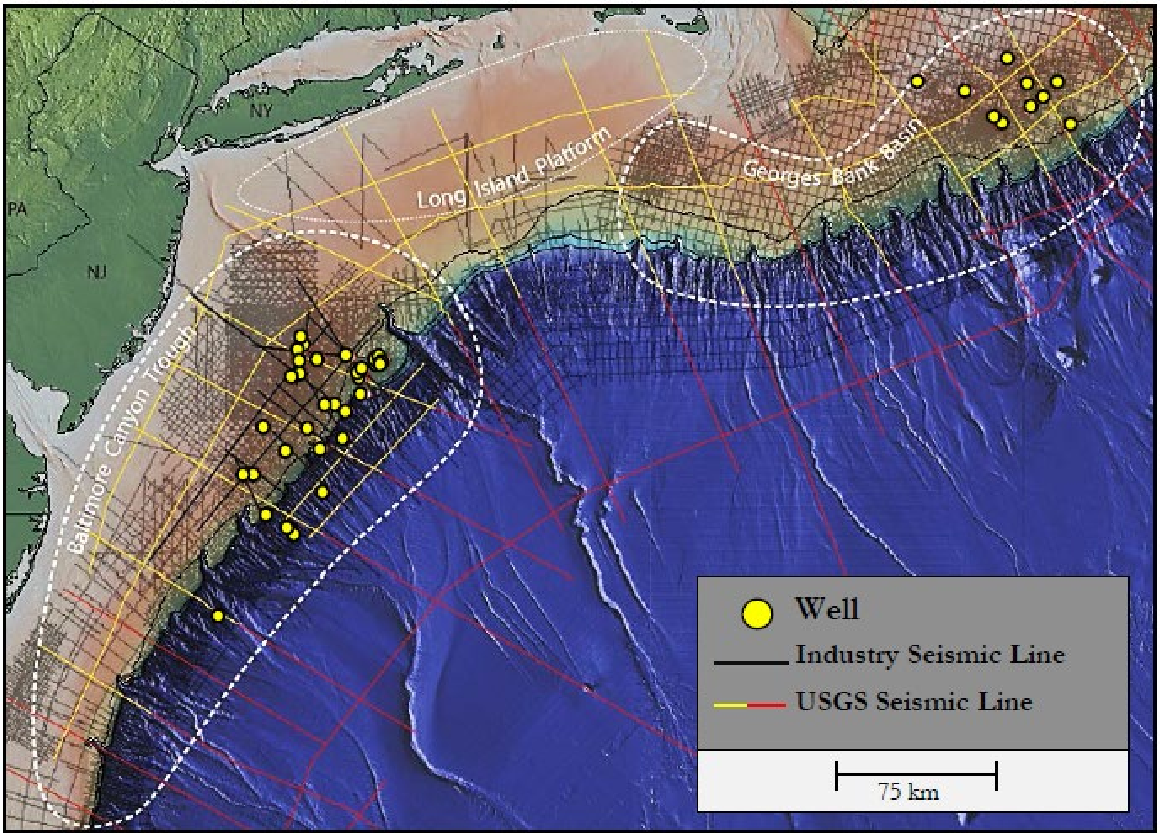


Fig. 2.2.1-11 Well and seismic exploration data used in the regional evaluation of CO_2 storage potential in the central Atlantic continental shelf (Gupta, 2017)

b) Australia

In Australia, all oil development-related data must be stored, and companies must submit such data to the government. Geoscience Australia, an organization that handles the data and advises the government on geological and topographical matters, plays a central role in publishing regional (size of a sedimentary basin) stratigraphic reports and oil-related geological evaluation reports. These regional reports provide highly accurate geological information that can be very useful in the selection of CO_2 storage sites. Fig. 2.2.1-12 shows the storage potential (ranking) of sedimentary basins located in Australia's land and waters; with the total storage potential estimated to be 417.0 billion tons (Langford et al., 2013).

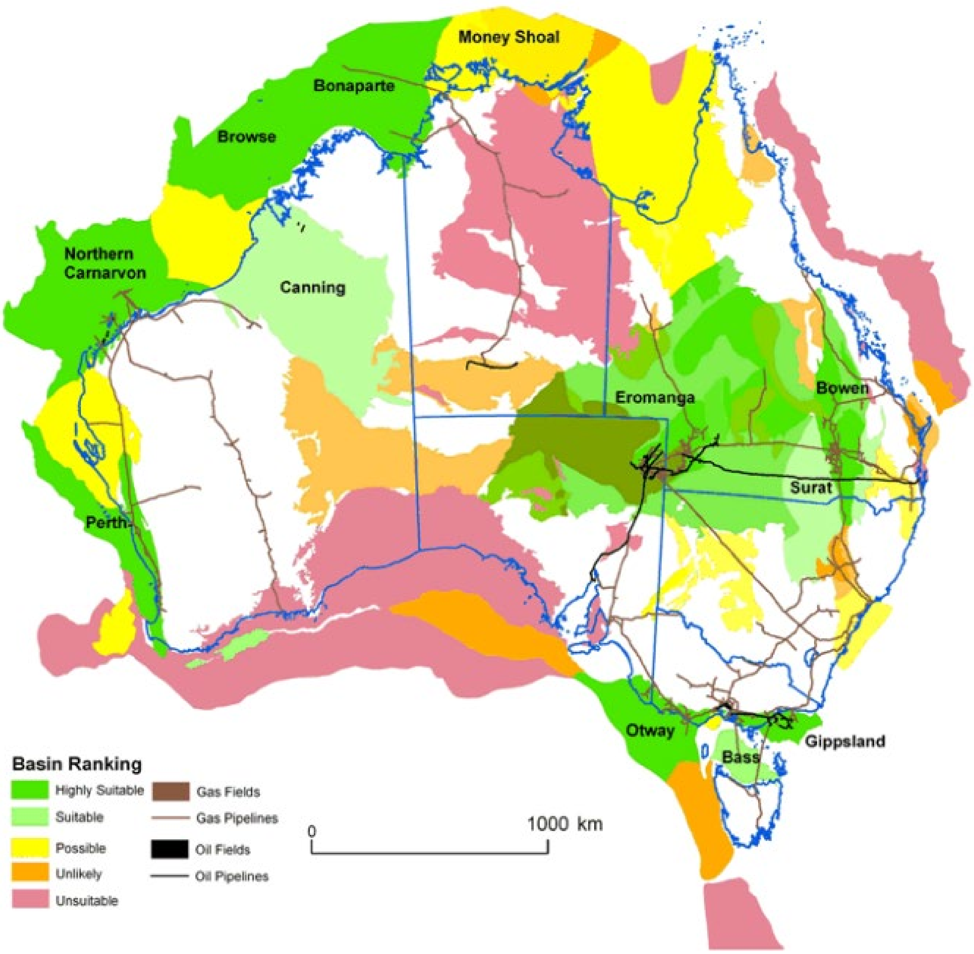


Fig. 2.2.1-12 CO_2 storage potential (ranking) of Australia's sedimentary basins
(Carbon Storage Taskforce, 2009)

The Browse Basin, Gippsland Basin, Petrel Basin, and Vlaming Sub-basin are listed as highly suitable sedimentary basins. A huge amount of data has been collected through oil and natural gas exploration and development in these sedimentary basins. This suggests that CO_2 storage site selection is conducted efficiently in Australia.

< Example of regional evaluation on the Vlaming Sub-basin (Borissova et al., 2015) >

Geoscience Australia conducted a comprehensive regional evaluation on the Vlaming Sub-basin. Located off the Perth coast in Western Australia, the Vlaming Sub-basin is the center of the Mesozoic sediments within the South Perth Basin (Fig. 2.2.1-13). The sub-basin covers an area of approx. 23,000 km^2, with sediments reaching up to 14 km. As it is close to the Perth region, which is an industrial area with large CO_2 emissions, numerous sites have been recognized as suitable candidates for CO_2 geological storage. The combination of the early Cretaceous Gage Sandstone (reservoir) and upper South Perth Shale (seal layer) is the most promising reservoir-seal layer pair for CO_2 storage in the South Perth Basin, with a maximum storage potential of 110 million tons. The regional evaluation by Geoscience Australia focused on reservoir unconformity, seal layer integrity, and storage capacity.

- Reservoir and seal layer properties

Understanding the porosity, permeability, and spatial distribution of such features in a reservoir is essential for estimating its storage capacity. As a candidate for combination with the seal layer, the lower Cretaceous Gage Sandstone (Gage Lowstand Fan) was targeted (Fig. 2.2.1-14). Understanding the variations in the Lowstand Fan (LSF) sedimentary environment through the analysis result of the seismic exploration made it possible to determine reservoir unconformity (Fig. 2.2.1-15). Similarly, the evaluation estimated the physical properties of the South Perth Shale (seal layer) through paleogeographic analysis based on the seismic exploration results and obtained lithologic distribution information about the seal layer (Fig. 2.2.1-16).

- Seal layer integrity

The evaluation showed that the upper seal layer is sufficiently effective for most of the Gage reservoir. Furthermore, evaluations were made on the reactivation of faults and signs of oil/gas, as well as analyzing the impact of CO_2 injection on fault safety. This analysis suggested that if the Gage reservoir covers the lower reservoir unit (Charlotte Shale) across a wide area of the Vlaming Sub-basin, the injected CO_2 may flow into the lower reservoir unit in the absence of the South Perth Shale sandwiched in between the Gage reservoir and lower reservoir unit. In this way, the seal layer integrity was evaluated from various angles (Fig. 2.2.1-17).

- Evaluation of storage capacity and desirable area

The evaluation demonstrated that the Lowstand Fan (LSF) of the Gage reservoir has favorable reservoir properties and that the upper South Perth Shale exhibits favorable sealing capacity. The storage capacity of the entire Gage Sandstone was estimated to be 126 million tons (P90), 493 million tons (P50), and 1.36 billion tons (P10). As described above, the regional evaluation (including geological modeling) determined the area potentially suitable for CO_2 geological storage by examining the reservoir quality and thickness, seal layer quality and integrity, and possible flow paths of the injected CO_2, among many other aspects, using existing information (Fig. 2.2.1-18).

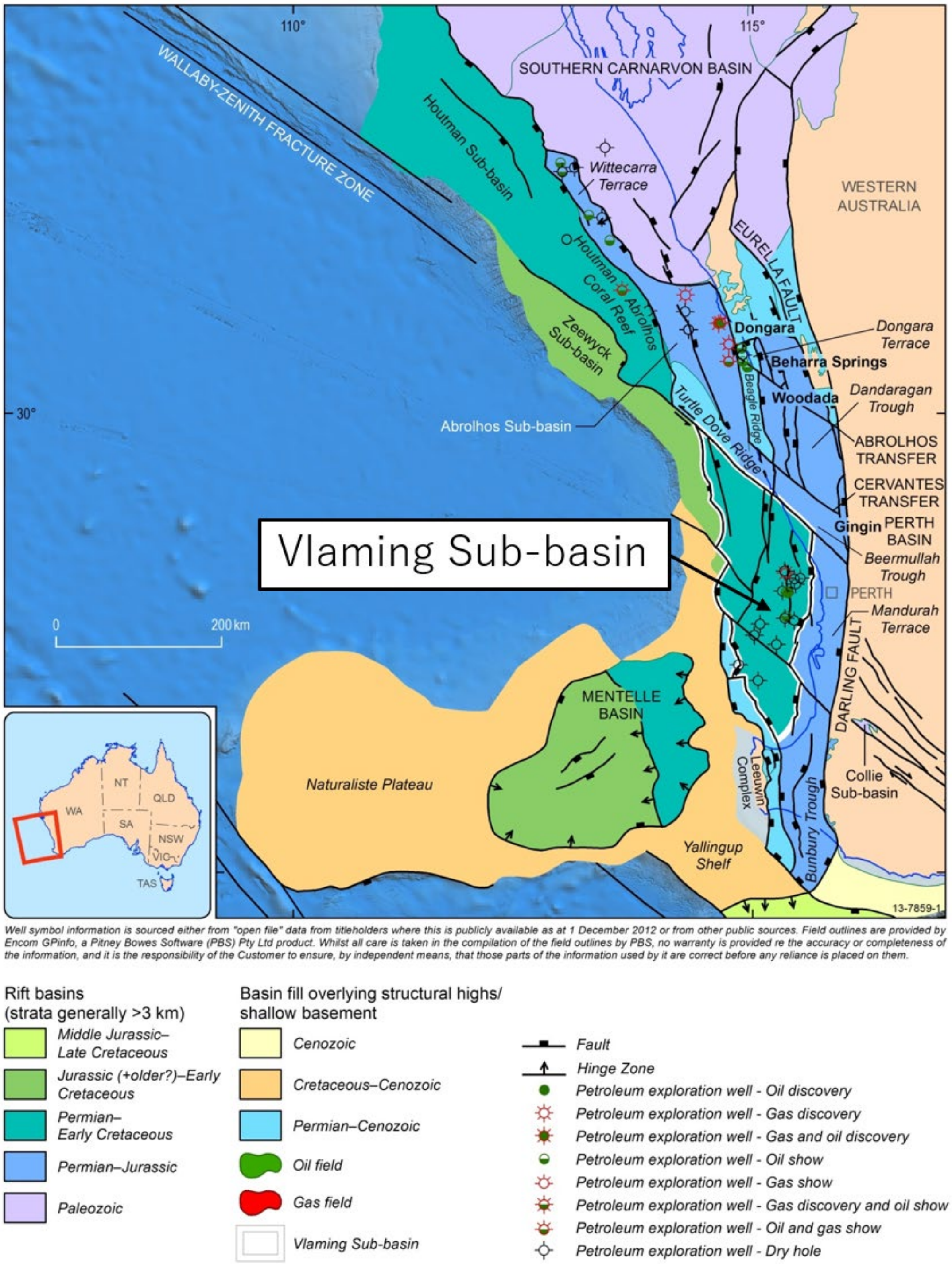


Fig. 2.2.1-13 Location of the Vlaming Sub-basin (Borissova et al., 2015)

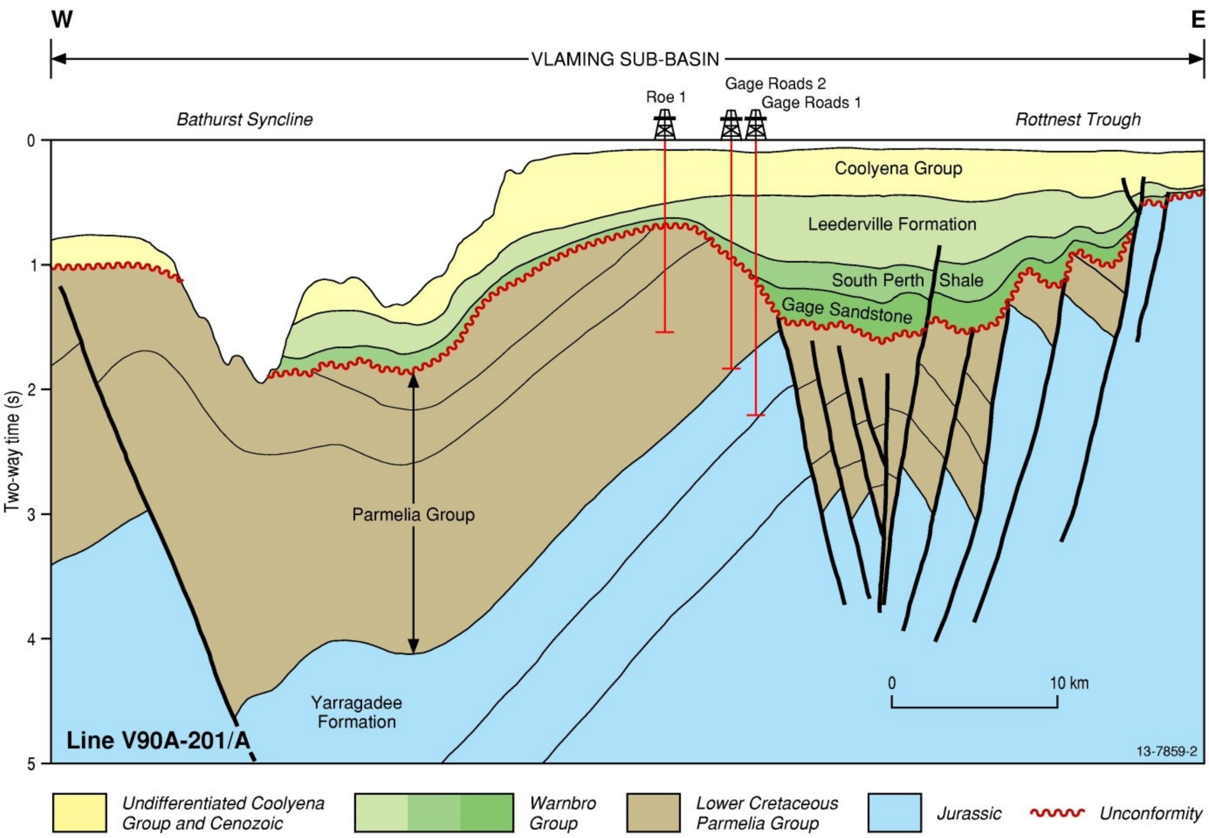


Fig. 2.2.1-14 Vlaming Sub-basin (Borissova et al., 2015)

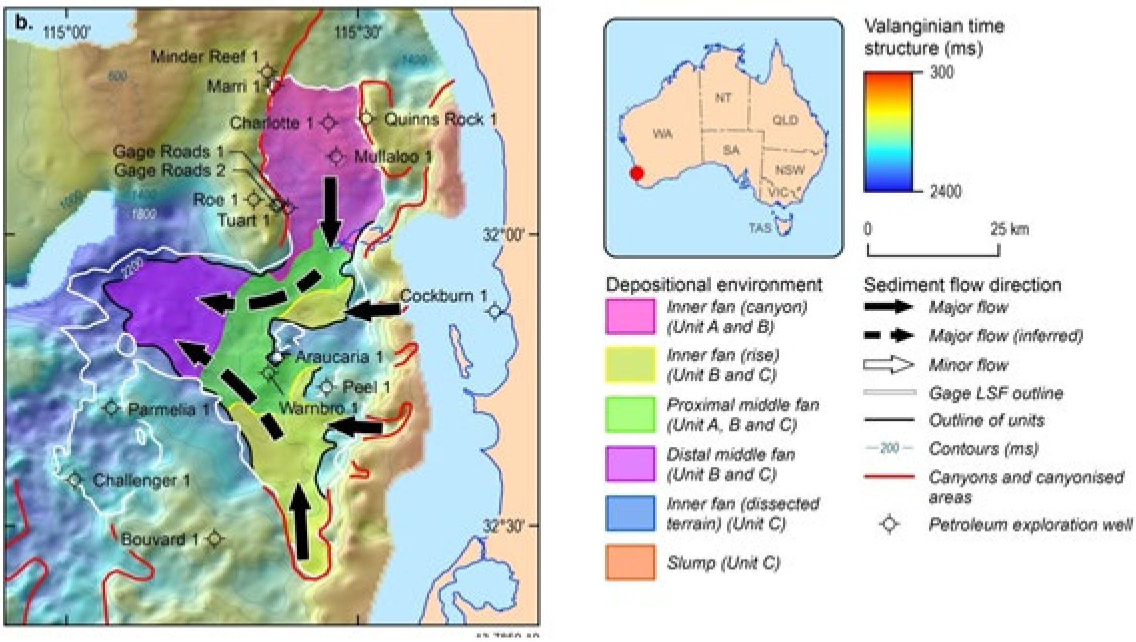


Fig. 2.2.1-15 Sedimentary environment of the Gage Low Stand Fan as indicated by the sediment flow direction to Units A, B, and C and changes in sedimentary facies by time slice (Borissova et al., 2015)

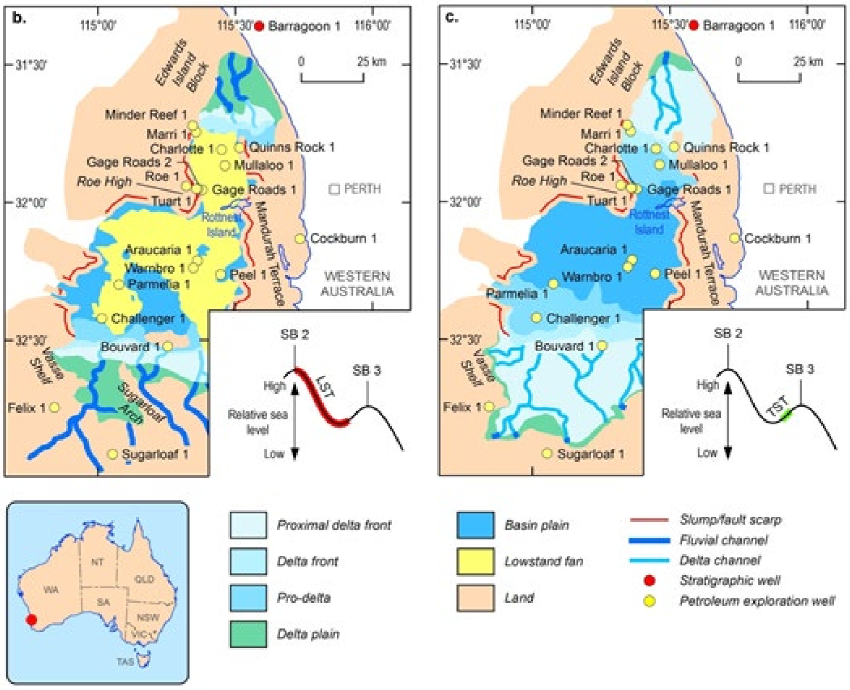


Fig. 2.2.1-16　Location of sequence and sediments system of the reservoir (Gage sandstone) and seal (South Perth Shale）, modified after Borissova et al.(2015)

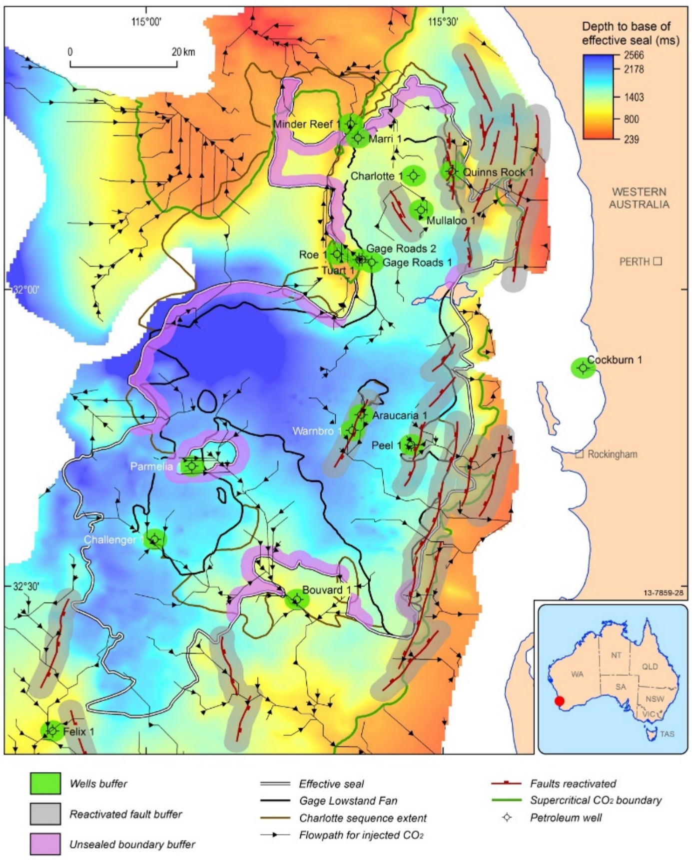


Fig. 2.2.1-17 Evaluation diagram of seal layer-related constraints such as fault reactivation, seal layer disappearance, and existing wells (Borissova et al., 2015)

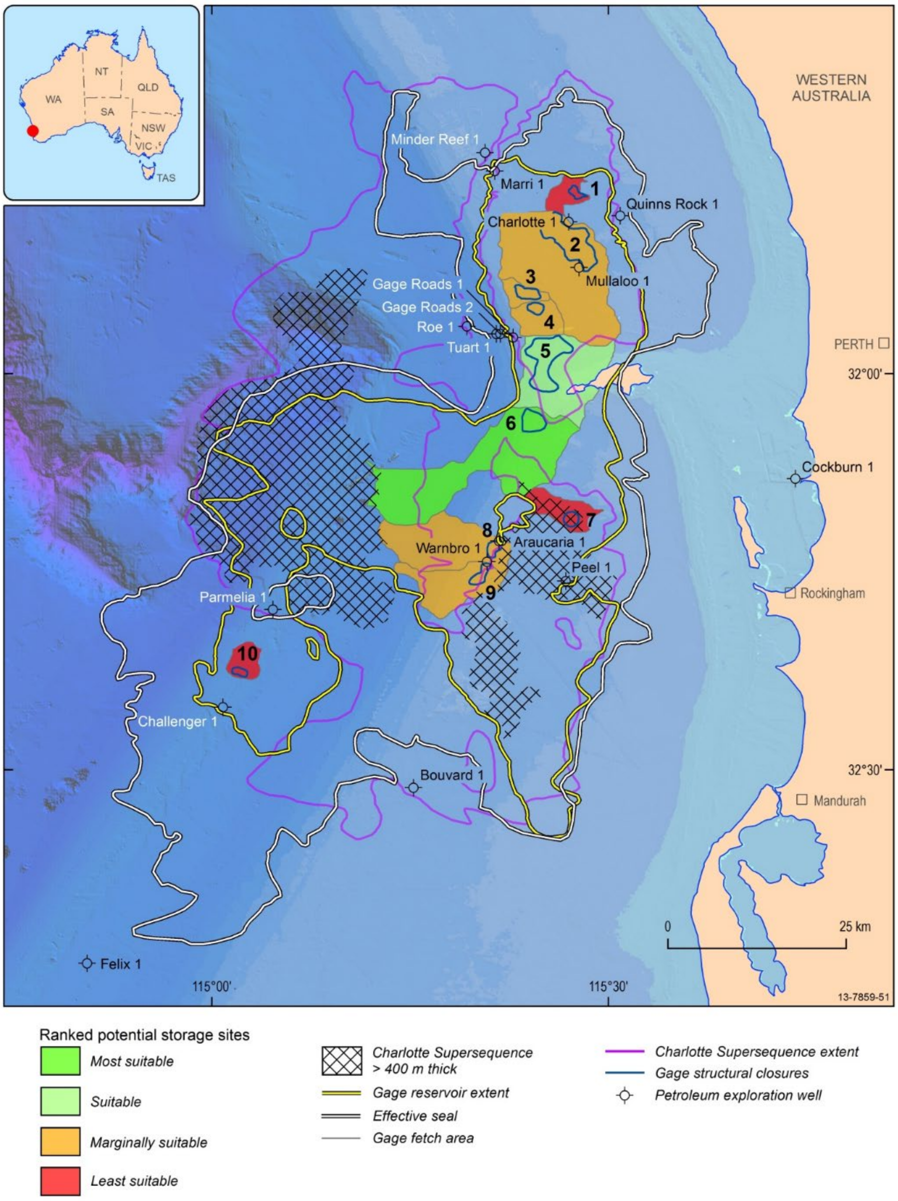


Fig. 2.2.1-18 Suitable storage sites in the Vlaming Sub-basin as per suitability evaluation based on geological modeling and CO_2 flow path analysis (Borissova et al., 2015)

c) Southeast Asian countries

In Southeast Asia, it is not common for government agencies to publish regional geological reports on entire sedimentary basins or similar terrains. Most geological reports on sedimentary basins are issued and sold by a handful of oil consulting firms. Although the reviewed area and contents differ by firm, most of these reports provide an overview of the stratigraphy and tectonics of a given sedimentary basin, stratigraphy and structure of existing oil wells, and other related aspects. They serve as a vital source of information in the selection of CO_2 storage sites, providing an overview of the region of interest.

In Indonesia, the government manages most of the data held by domestic oil companies such as Pertamina as well as foreign oil companies. Patra Nusa Data (PND), a lower branch of the Directorate General of Oil and Gas, Ministry of Energy and Mineral Resources (MIGAS), is responsible for managing the information, which can be purchased freely from the PND. However, the data management system is not always reliable and can be difficult to use; data is not registered or cannot be found even if registered, or data that did exist in the past is lost or not found, etc. For example, although seismic exploration data is mostly purchased in the form of post-stack data in a SEG-Y format, there are cases where raw data can be purchased for reprocessing. As a rule, such data cannot be taken outside the country, but this may be permitted through negotiation or an agreement with the PND.

In Thailand and Vietnam, data can be purchased or viewed for a fee but cannot be taken outside the country.

Malaysia does not offer a system for purchasing data freely. Normally, when exploring for oil or natural gas in a mining area that is publicly known, data on the mining area can be viewed in Petronas' data room.

2.2.2 Site selection process

This process involves choosing a site selection region (potential region), determining potential sites within the region, identifying qualified sites that meet the CO_2 storage site requirements, and, finally, selecting one or more sites from among them. The site selection requirements are as follows: presence of a reservoir capable of CO_2 injection and storage, presence of a seal layer that prevents the CO_2 from migrating upward, and presence of a geological structure that enables long-term geological storage of CO_2.

The site selection process requires the following types of information:

- Diagrams
    - Structural map
    - Isopach map (reservoir, seal layer)
    - Lithologic map or paleoenvironmental map (reservoir, seal layer)
    - Topographical map/bathymetric map
- Seismic exploration record
    - 2D exploration data (3D exploration data if possible)
- Well data
    - Mud logging
    - Geophysical logging (gamma ray logging, resistivity logging, sonic logging, density logging,

neutron logging, and, if possible, borehole imaging logging, nuclear magnetic resonance logging, and formation pressure/permeability logging (MDT))

- Drilling records (e.g., leak off test)
- Core analysis (porosity, permeability, and, if possible, relative permeability and threshold pressure)

● For regions close to oil or gas fields
  - Well test records (output test, production test, step rate test, etc.)
  - Hydrocarbon output records, reservoir pressure variation data

The types of data listed above are used in the site selection process after compiling, input into geographic information systems, formatting, or, especially in the case of seismic exploration records, processing and analysis using the latest technology.

Table 2.2.2-1 Data required and used for site selection

Type of data		Expected information	Usage for CCS
Production records for oil & gas		Production history	Reservoir characteristics
Well	Drilling records	Wellbore condition	Reference for drilling injection wells
	Well logging	Lithofacies	Identification of reservoirs and seals
		Formation characteristics (Porosity, Permeability, and so on)	Storage potential estimation
		Sonic velocity	Seismic data processing
		Formation pressure and temperature	CO_2 solubility, injection pressure
	Leak-off test	Formation fracture pressure	Upper limit of injection pressure
	Production test	Permeability	Injectivity
	Injection test	Permeability	Injectivity, injection pressure
Lab. exam.	Mineral analysis of core sample	Mineral assemblage	Chemical Reactivity with CO_2
	Core porosity	Reservoir porosity	Potential storage volume
	Core permeability	Reservoir permeability	Storage potential
	Core capillary pressure	Reservoir capillary pressure	Maximum gas saturation
	Core threshold pressure	Seal threshold pressure	Upper limit of injection pressure
	Formation water analysis	Chemical composition	CO_2 solubility, solution reactivity
Geophysical survey	Seismic survey	Geological structure, formation physical property	Trap evaluation (type, mechanism, and so on)
			Reservoir, seal extent

(1) Geological evaluation items for site selection

(i) Presence of reservoir-seal layer pair

A reservoir must have a seal layer that has developed above it. Given the potential for uncertainties in reservoir properties and seal layer defects, it is desirable to have 2 or more of such pairs.

a) Reservoir

Potential reservoirs are selected on the basis of oil and natural gas regional evaluations and CO_2 storage capacity survey reports, as well as diagrams such as stratigraphic charts that document lithology, formation thickness, and other features. If an oil or gas field is located nearby, production formation information (especially basic physical properties such as porosity and permeability) can be used for the reservoir evaluation. A porosity of at least 10% and permeability of at least several md are desirable. If there are fields that are currently producing or used to produce oil or gas, the production history and production records taken there would be very helpful in the evaluation of reservoir capacity. If such oil or gas fields do not exist, the results gained from outcrop observation of horizon lithofacies or physical properties measurement of outcrop samples conducted in the vicinity may be useful.

Although the required reservoir thickness depends on the injection volume and reservoir properties, it generally needs to be at least several tens of meters on a gross basis and 10 m on a net basis. The net reservoir thickness cannot be measured unless a well has been drilled.

As for reservoir extent, the bigger the better. In addition, a reservoir with minimal lithofacies variations, anisotropy, and unconformity is desirable. Caution is needed in cases where reservoir compartmentalization has been confirmed in existing oil or gas fields. In general, continental aeolian deposits, estuary sediments in large rivers, sediments in extensive continental shelves, and submarine fan sediments have favorable storage properties and cover a large area. If regional isopach maps are available, they can be used as is. Even if an isopach map is unavailable, the evaluation can be conducted by studying seismic exploration data if available.

If data on the formation water filling the reservoir can be obtained, it can be used to conduct additional geochemical analysis on, for example, solubility trapping. CO_2 solubility trapping is advantageous under low salinity conditions (Mito et al., 2008). CO_2 mineralization through geochemical reaction is more advantageous when there are more components such as Ca and Mg that can precipitate the CO_2 as carbonate minerals. Canada's Quest project has confirmed that injectivity declines if salt precipitates into the pore space through the dry-out effect associated with CO_2 injection under high salinity conditions.

b) Seal layer

Formations that can physically seal the CO_2 serve as the seal layer. Such formations include pelitic formations located above and covering the reservoir. Lithofacies that typically exhibit superior sealing capacity are evaporite and pelite. In particular, evaporites have excellent features that make them ideal as a seal layer. Ubiquitous evaporites include halite and gypsum.

With CO_2 geological storage, multiple trapping mechanisms enable safe storage over a long period of time. These trapping mechanisms can be categorized into the following: structural traps, stratigraphic traps, solubility traps, residual-gas traps, and mineral traps. Whichever trap is available, the seal layer must be located above the reservoir. The necessary seal layer properties include the following: sealing capacity, seal form, and seal integrity (IEAGHG, 2011).

b-1) Sealing capacity

Since the injected CO_2 has a lower density than formation water, it migrates to the upper part of the reservoir. The seal layer is a formation that covers the reservoir from above, preventing the CO_2 from migrating upwards owing to buoyancy and enabling storage in the reservoir immediately beneath the seal layer or the CO_2 immediately beneath the seal layer to gradually migrate sideways. Sealing capacity refers to the seal layer's ability to prevent the CO_2 in the reservoir below from entering the seal layer owing to buoyancy and keeping the CO_2 in the reservoir. Sealing is achieved through the seal layer's motive force, i.e., capillary pressure. Therefore, the physical properties required for sealing are low permeability and high capillary pressure.

Threshold pressure expresses a seal layer's sealing capacity based on capillary pressure in numerical terms. However, regarding oil and gas fields, the threshold is not measured using actual seal layer samples in most cases, which makes it difficult to obtain the threshold pressure from existing material. Therefore, another method may be adopted to indirectly estimate threshold pressure in the site selection phase. This method involves estimating threshold pressure on the basis of correlation with general physical property data, such as the seal layer's porosity and permeability. Yet other methods have been proposed in the oil industry, such as estimating threshold pressure from nuclear magnetic resonance logging results and estimating sealing capacity on the basis of the oil or gas column height measured in a nearby oil or gas field in the same seal layer horizon as the potential site. The threshold value obtained in this way is used to determine the maximum size of a CO_2 column that the seal layer is capable of containing.

b-2) Seal layer form

Seal layer form refers to the structural position, thickness, and area of the seal layer. These can be estimated from seismic exploration, core samples, well drilling, and local geological characteristics.

- Seal layer thickness

Theoretically, the seal layer thickness is irrelevant as long as a threshold pressure exceeding the buoyancy of the CO_2 injected in the reservoir located immediately below is maintained. However, the seal layer needs some thickness for the following reasons:

- it reduces the risk of pinch out of the seal layer, and
- it reduces the risk of CO_2 leakage even if a small-sized fracture occurs.

Some sectors in the oil and natural gas industry define the thickness required for oil and gas seal layers as 50 m or more for pelites and 10 m or more for evaporites, with 30 m or more being considered the optimal thickness (Warren, 2007).

- Seal layer extent

The seal layer must have a planar area that completely covers the CO_2 plume (extent of CO_2 distribution underground), i.e., the extent to which the injected CO_2 migrates (expands) over time within the reservoir. Regional evaluation of the seal layer extent involves selecting a first candidate (and second and third candidates if favorable geological conditions are met) on the basis of stratigraphic information and evaluating the target formation's physical properties and thickness as a seal layer. The extent is evaluated along with the thickness variation using an isopach map, and the sedimentary environment is also an important evaluation factor in this respect. Evaporite is favorable in terms of seal layer integrity owing to its petrophysical properties, such as threshold pressure and ductility, and because it generally develops over a large area. As for pelite, its lithology, capillary pressure, petrophysical properties, thickness, and area vary greatly owing to factors such as sedimentary environment and diagenesis. As described later, examination of the sedimentary environment or paleoenvironment is especially vital when evaluating extent-related aspects. In addition, seismic exploration records if available can be used to estimate the area through tracking the seal horizon.

Evaporite, which exhibits excellent seal layer capacity, is chemically formed on sea or lake beds by the frequent supply and active evaporation of seawater or freshwater to and in closed environments where seawater is not freely exchanged with a lake or ocean under high temperature/dry conditions. Evaporite is only found in about 25% of the earth's surface and/or underground in continental areas. Pelite is sedimentary rock formed from minute detritus, organic matter, and other substances, including types such as mudstone, shale, and siltstone depending on the constituent particles. In addition, pelites are categorized depending on the minerals they include (e.g., calcareous, siliceous, tuffaceous). Pelite accumulates in almost all sedimentary environments on earth and undoubtedly develops in all sedimentary basins on earth, but features such as form, thickness, and extent vary significantly depending on the sedimentary environment.

b-3) Seal layer integrity

Seal layer integrity refers to the seal layer's mechanical stability with respect to the increase in reservoir pressure due to CO_2 injection and changes in stress exerted on the seal layer. The development of fractures that allow fluid permeation is a very relevant issue when it comes to seal layer s for CO_2 storage, as this may lead to the formation of new fractures or the reactivation of faults that existed in the past. seal layer integrity is related to seal lithology, existing faults, and underground stress, among other factors.

In terms of lithology, ductility, compressibility, and fragility are related to fracture development. Assuming that evaporites and organic shale exhibit the highest ductility and compressibility and thus are unlikely to cause fracture formation in ductile rock, then ductile formations would have relatively low strength, which would make them desirable from an integrity perspective. Fig. 2.2.2-1 shows the relative ductility/compressibility and strength/seismic velocity by lithology. Integrity increases toward the upper left of the diagram. As ductility/compressibility are in reverse proportion to the seismic velocity of a given rock type, this characteristic enables evaluation of seal layer integrity based on seismic exploration data and physical logging data.

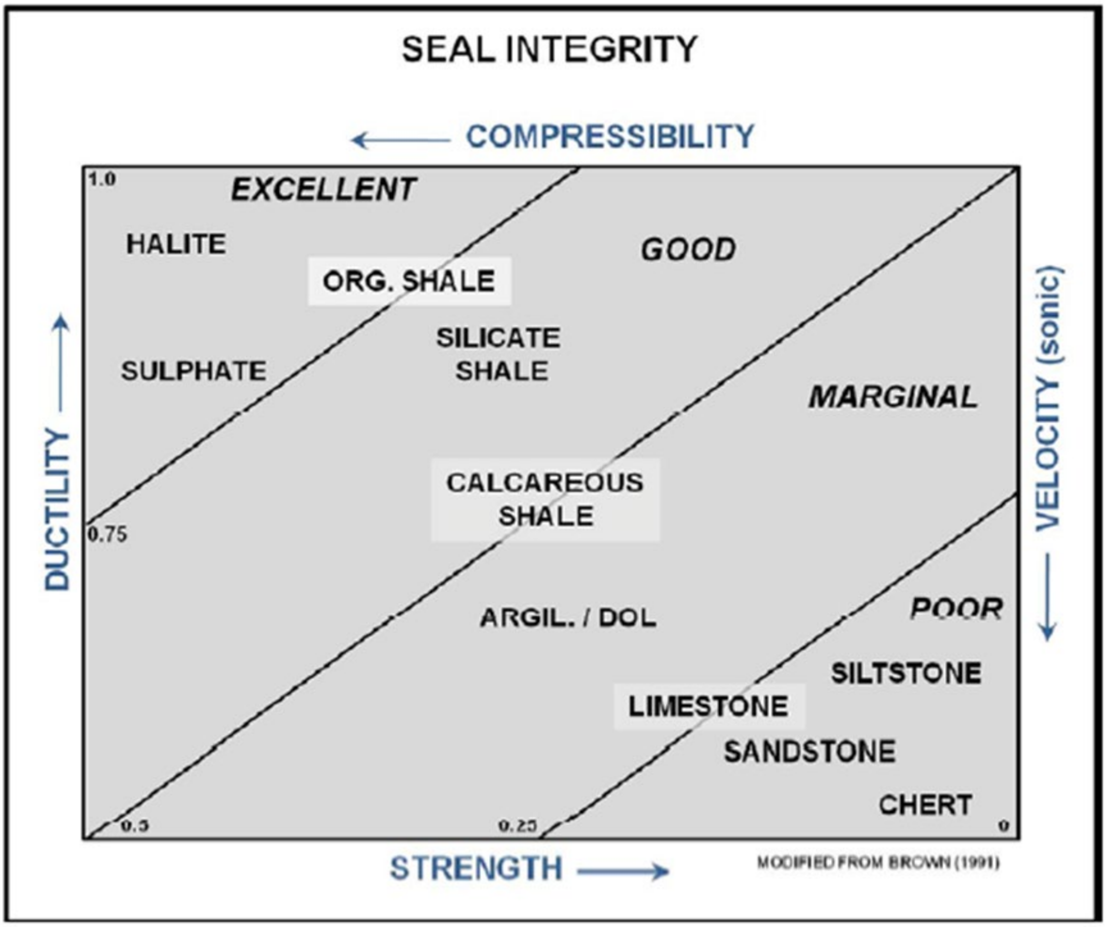


Fig. 2.2.2-1 Schematic diagram illustrating the relative relationship between ductility/compressibility and strength/seismic velocity by lithology (IEAGHG, 2011)

(ii) Sedimentological method for reservoir and seal evaluation

One of the important aspects of a reservoir and seal is horizontal extent, or horizontal variation. It is difficult to estimate these when sufficient existing data is lacking, but in order to reduce the risk of reservoir and/or seal pinch-out, it is important to estimate the horizontal extent through studying the sedimentary environment.

One way is to estimate the sedimentary environment and lithofacies distribution and evaluate the reservoir and seal through sequence stratigraphy based on existing well data and seismic exploration data. This method involves identifying a depositional sequence (which is a package of strata created by a single cycle of marine transgression and regression) on the basis of seismic exploration data, core samples, physical logging data, and the like. After identifying the depositional sequence, the lithofacies distribution of sand strata, mud strata, and other strata in the depositional sequence is estimated from the well data, which makes it possible to determine whether the rock is suitable as a reservoir or seal.

(iii) Storage capacity

The CO_2 injected underground is stored in the pore space of porous sandstone. Therefore, storage capacity is evaluated on the basis of the pore space volume of the stratum in question. Such strata are also known as saline aquifers because prior to CO_2 injection, they are filled with fossil saltwater resulting from sandstone deposition. Once CO_2 injection starts, some of the fossil saltwater in the pore space gets pushed away by the CO_2. The storage capacity depends greatly on how much of the pore space can be occupied by CO_2 and how much fossil saltwater is pushed away. Fig. 2.2.2-2 is a conceptual diagram illustrating how CO_2 injected into a reservoir expands from a well.

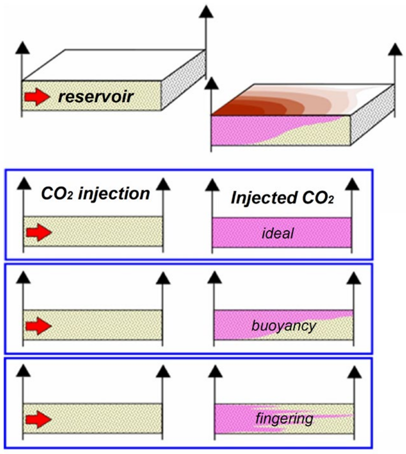


Fig. 2.2.2-2 Conceptual diagram illustrating the behavior of CO_2 injected underground (RITE)

Ideally, the CO_2 should be able to migrate into all gaps in the reservoir and occupy it in a uniform manner. However, as CO_2 has a lower density than fossil saltwater, the buoyancy generated owing to the density difference causes the CO_2 to accumulate in the upper area in the process of its migration from the well. Furthermore, unconformity in the reservoir may cause fingering whereby the CO_2 selectively flows through areas that are easy to pass. These phenomena lead to a decline in sweep efficiency during CO_2 storage and pose uncertainties to storage capacity evaluation.

CO_2 storage capacity evaluation can roughly be categorized into 2 types: static evaluation and dynamic evaluation. Dynamic evaluation involves estimating the storage capacity on the basis of the site's geological model and CO_2 behavior simulation. Static evaluation is also known as the volumetric method and is often employed in storage capacity evaluation.

a) Volumetric method

On the basis of the volume of reservoir pore space, the storage capacity can be evaluated through the formula below. Japan's total storage capacity has been estimated to be 146 billion tons.

In the nationwide evaluation of storage capacity conducted by RITE from 2005 to 2008, the storage capacity was calculated through Formula 2.2.2-1 below.

Geological storage capacity = $Sf \times A \times h \times \varphi \times Sg/BgCO_2 \times \rho_o$ (Formula 2.2.2-1)

Sf	: Storage coefficient
A	: Area (area of potential storage space)
h	: Effective thickness
φ	: Porosity
Sg	: CO_2 saturation
$BgCO_2$	: CO_2 volume coefficient (approx. 0.003 m^3/m^3)
ρ_o	: CO_2 density (1.976 kg/m^3 Standard state: 0°C, 1 atm)

Total area (A), effective thickness (h), and porosity (φ) are items that relate to the total volume of available pore space. CO_2 saturation (Sg) indicates the CO_2 occupation rate after the formation water has been pushed away. CO_2 volume coefficient ($BgCO_2$) and CO_2 density (ρ) relate to the volume and weight of the CO_2 on and under the ground. Storage coefficient (Sf) indicates how much of the total pore space volume is occupied by the injected CO_2 (RITE 2006).

In the formula above, the storage coefficient Sf and CO_2 saturation Sg are essential in evaluating storage capacity, and the product of the 2 is also known as the storage rate coefficient. As shown in Table 2, the storage rate coefficient varies significantly depending on the geological conditions of a given country or region. Japan's storage rate, which is slightly higher than that of other countries and regions, was determined with reference to the storage coefficient Sf and CO_2 saturation Sg obtained in a small-scale CO_2 injection test (injection volume: approx. 10,000 tons) conducted at the Nagaoka site. It should be noted that the storage rate coefficients indicated in Table 2.2.2-2 are only representative values and depend greatly on the geological conditions of individual sites, including reservoir size, reservoir unconformity, and basic physical properties of the reservoir (porosity, permeability). Since determination of the reservoir's basic physical properties in the site selection process is based on the amount of available information (e.g., seismic exploration and well drilling data), storage capacity evaluation always involves a degree of uncertainty. Such uncertainties are considered in oil and gas reserves evaluation; but as CO_2 geological storage projects involve fewer exploration wells than oil or gas field projects owing to financial and safety reasons, storage capacity evaluation is considered to entail more uncertainty.

Table 2.2.2-2 Comparison of storage coefficients for several countries and regions (Ogawa, 2011)

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

Reference: Recommended by the US Department of Energy (DOE, 2013)

These are the criteria for determining whether the volumetric method is desirable when evaluating the

CO_2 storage capacity of deep saline formations in the site selection phase.

G_{CO2} = At × hg × φ_{tot} × ρ × E (Formula 2.2.2-2)

G_{CO2}	: Estimated mass of CO_2 storage capacity of saline formation
At	: Area for calculating CO_2 storage capacity
hg	: Gross thickness of saline formation at A
φtot	: Average porosity of entire saline formation at thickness hg
ρ	: CO_2 density measured under reservoir pressure and temperature conditions
E	: CO_2 storage efficiency coefficient reflecting proportion of total pore space volume filled by or in contact with CO_2

Although Formula 2.2.2-2 is based on the same idea as Formula 2.2.2-1, "BgCO_2 × ρ" in Formula 2.2.2-1, which expresses volume change due to surface and underground conditions and CO_2 density, is expressed as "ρ" in Formula 2.2.2-2. In addition, Formula 2.2.2-2 includes the expression "E: CO_2 storage efficiency coefficient" instead of "Sf: storage coefficient" and "Sg: CO_2 saturation" in Formula 2.2.2-1. This is similar to the concept of sweep efficiency (i.e., ratio of the volume of the sections that are in contact with the injected fluid to the total pore space volume of the reservoir), covering the ratio of net to gross area, ratio of net to gross thickness, and ratio of effective porosity to total porosity (Formula 2.2.2-3).

E = (An/At) × (h_n/h_g) × (φe/φtot) × Ev × Ed (Formula 2.2.2-3)

An/At	: Net to gross area
h_n/h_g	: Net to gross thickness
φe/φtot	: Effective porosity to total porosity
Ev	: Volume sweep rate: (area sweep rate) × (vertical sweep rate) × (gravity/buoyancy sweep rate)
Ed	: Microscopic displacement efficiency: sweep rate affected by immobile formation water

b) Storage capacity evaluation through CO_2 behavior simulation

In most cases, the volumetric method is employed because the quality and quantity of available data is not always sufficient in the site selection phase. However, if a geological model based on data of sufficient quality and quantity is developed, it is desirable to calculate storage capacity through a simulation. The storage capacity estimated on the basis of reservoir pore space volume is static storage capacity, which is often compared with dynamic storage capacity that is estimated through a CO_2 injection simulation based on a reservoir geological model. The dynamic storage capacity is evaluated by incorporating constraints (e.g., burst pressure of the seal covering the reservoir) in the CO_2 injection simulation, which is considered to increase the reliability of storage capacity evaluation. Although it is logical that incorporation of constraints leads to increased reliability, it must not be forgotten that CO_2 injection simulation involves uncertainties that depend on how well the reservoir model is made or stem from the relative permeability curve, for example. In other words, various measures can be taken to reduce uncertainty in storage capacity evaluation, but uncertainty cannot be eliminated completely. Therefore, uncertainty must be managed as a potential risk in any geological storage project.

(iv) Trapping and structural position

As it is safer if the injected CO_2 migrates to the up dip (i.e., moves in the structurally upper direction of the reservoir) and ultimately gets structurally and stratigraphically trapped, it is desirable to have a structural or stratigraphic trap. In addition, further improvement of CO_2 storage safety can be expected because residual trapping, solubility trapping, and mineralization occur during migration of the injected CO_2 to the structural or stratigraphic trap (the end point). A formation inclination of approx. 10° is considered preferable. It is also worth noting that when CO_2 migrates to the structurally upper part in the reservoir, a longer migration distance and slower migration speed is better in terms of CO_2 solubility, etc.

(v) Faults

a) Leakage and seepage path[1]

In cases where a fault is located within or around the assumed CO_2 plume of the storage site and divides the reservoir and seal, it is essential to conduct leakage/seepage risk evaluation. There have been cases where hot springs and underground water gush out along the faults, and faults can become flow paths for bodies of water underground. On the other hand, regarding oil and natural gas deposits, many examples are known where faults serve as barriers that prevent formation fluids (oil and natural gas) from flowing, which is a phenomenon commonly known as a fault trap. In the exploration phase of oil and natural gas fields, faults can serve as flow paths for formation fluids, directing the fluids to the trap for accumulation, but there are also cases where the oil or natural gas accumulated through the flow path leaks. The following observations have been made regarding the properties of faults, and they may be applicable to CO_2 geological storage.

b) Consideration of induced earthquakes, active faults, and fault reactivation

Regarding induced earthquakes caused by wastewater injection, etc., it has been pointed out that increased gap water pressure in formations may cause or induce fault reactivation (National Research Council, 2013). Some have suggested that this also applies to CO_2 geological storage, but no perceptible earthquakes have been reported at CO_2 injection sites. However, as earthquakes cause much damage to local communities and residents, all faults around potential CO_2 storage sites need to be examined carefully from the viewpoint of social acceptability.

---

[1] Herein, leakage and seepage are defined as follows:
Leakage: CO_2 leaks out from a CO_2 storage system (a geological system consisting of a reservoir-seal pair that forms a trap capable of storing CO_2).
Seepage: CO_2 seeps out from underground through the earth's surface or seabed and into the atmosphere or ocean.

A substantial amount of survey material on active faults has been published in Japan. *Shinpen nihon no katsudanso* [Active faults in Japan: new edition] (Japanese Society for Active Fault Study, 1991) and the *Geological Sheet Map 1:500,000* series (e.g., Sangawa et al., 1984) issued by the Geological Survey of Japan are examples of literature that identifies the active faults or lineaments that may be active faults located in the Japanese archipelago and its surrounding waters. The Headquarters for Earthquake Research Promotion publishes the results of long-term evaluations on major active faults and subduction zone earthquakes, which include information such as earthquake magnitude and the possibility of an earthquake occurring within a certain period (http://www.jishin.go.jp/main/p_hyoka02_danso.htm).

Seismic exploration records serve as valuable data when selecting offshore geological storage sites. This data can be used to determine whether a fault is active or not, which is determined by looking at whether displacement due to the fault has reached the seabed. Furthermore, if seabed survey data is available, seabed topographical data can be used to compare known faults and seabed displacement and thus identify fault reactivation.

The fault reactivation evaluation based on seismic exploration results conducted as part of the CO_2 geological storage site selection process for the Vlaming Sub-basin located off the Perth coast in Western Australia is a helpful example. Faults that were created during lift formation exist in the northern area of the Vlaming Sub-basin (Fig. 2.2.2-3). Multibeam echo sounding results were compared to analyze fault reactivation. The multibeam echo sounding identified 2 lineaments that potentially corresponded to the faults (Fig. 2.2.2-4). The east lineament (F1 in Fig. 2.2.2-4) corresponds to the one-meter cliff located on the seabed just above a reactivated fault created during lift formation. The west lineament (F2 in Fig. 2.2.2-4) has the features of both carbonate rock and a cliff and may also correspond to a reactivated fault (F2 in Fig. 2.2.2-3).

As described above, high resolution regional seabed topography data obtained by sidescan sonars, sub-bottom profilers, multibeam sonars, and other devices can be used to analyze fault reactivation and topographic lineaments on the seabed. Such topographic lineaments are compared with faults identified through seismic exploration, and their relationship with deep structures is examined. This can help evaluate fault reactivation in the CO_2 storage site selection process.

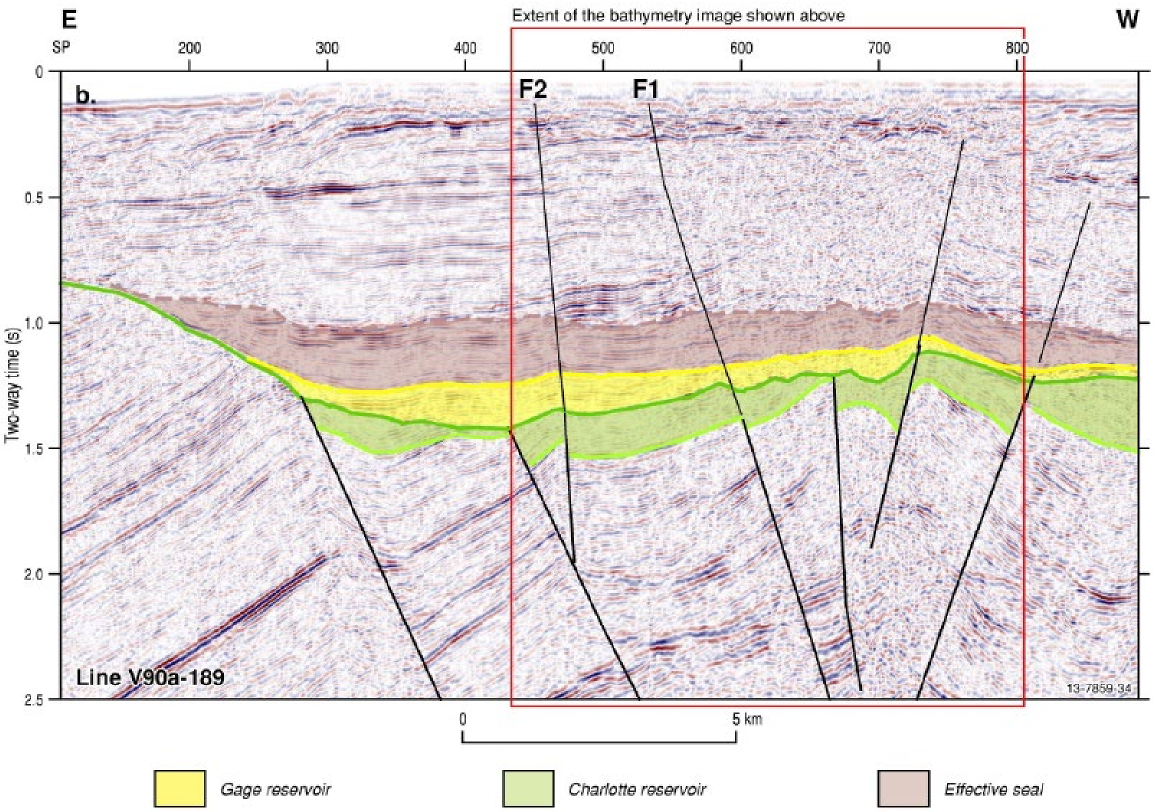


Fig. 2.2.2-3 Seismic exploration results of the Vlaming Sub-basin

The traverse line is shown in Fig. 2.2.2-4 (Borissova, et al., 2015)

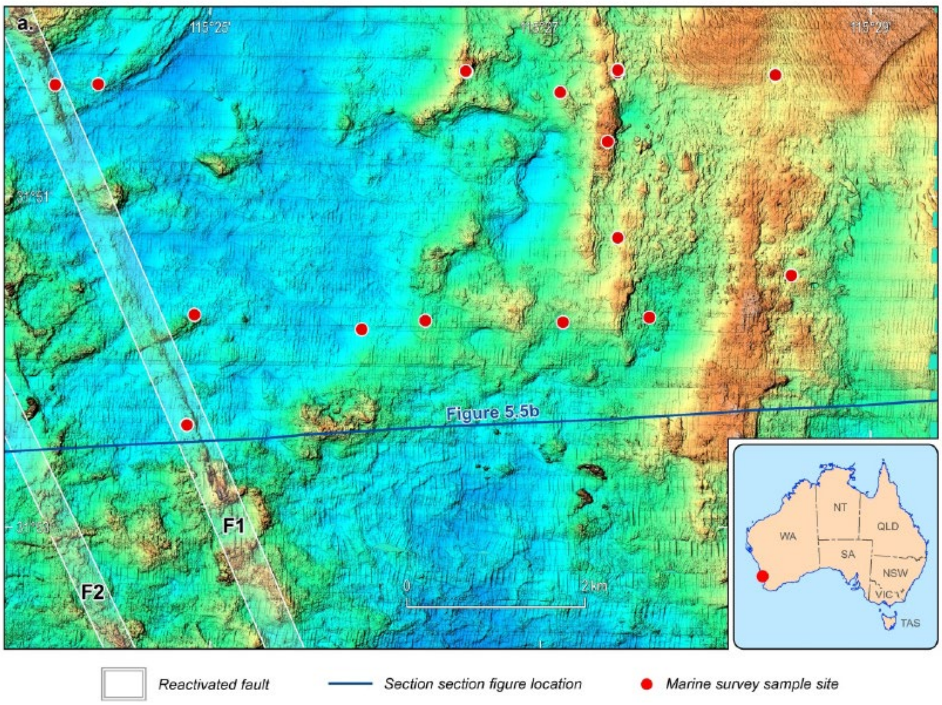


Fig. 2.2.2-4 Multibeam echo sounding results (Borissova, et al., 2015)

This diagram shows the linear cliffs corresponding to F2 and F1 in Fig. 2.2.2-3.

(2) Non-geological evaluation items for site selection

In addition to safety, economic efficiency is an important element in a CO_2 geological storage project and may determine the project's success. Although economic efficiency is closely related to technical aspects, non-geological factors can be just as relevant. Therefore, the aspects below must also be evaluated in site selection.

(i) Distance from emission source

The distance between the storage site and emission source has a significant impact on the CO_2 transportation method and cost. In the case of large-scale CO_2 geological storage projects, the only feasible way to transport the CO_2 is by pipeline or ship (offshore sites, hub and cluster). As for onshore sites, the surface and topographic conditions determine whether a pipeline can be built as well as how much it would cost. On the other hand, with offshore projects, water depth and offshore distance are crucial factors when selecting a suitable site. Generally speaking, tanker transportation is effective for long distances (Fig. 2.2.2-5).

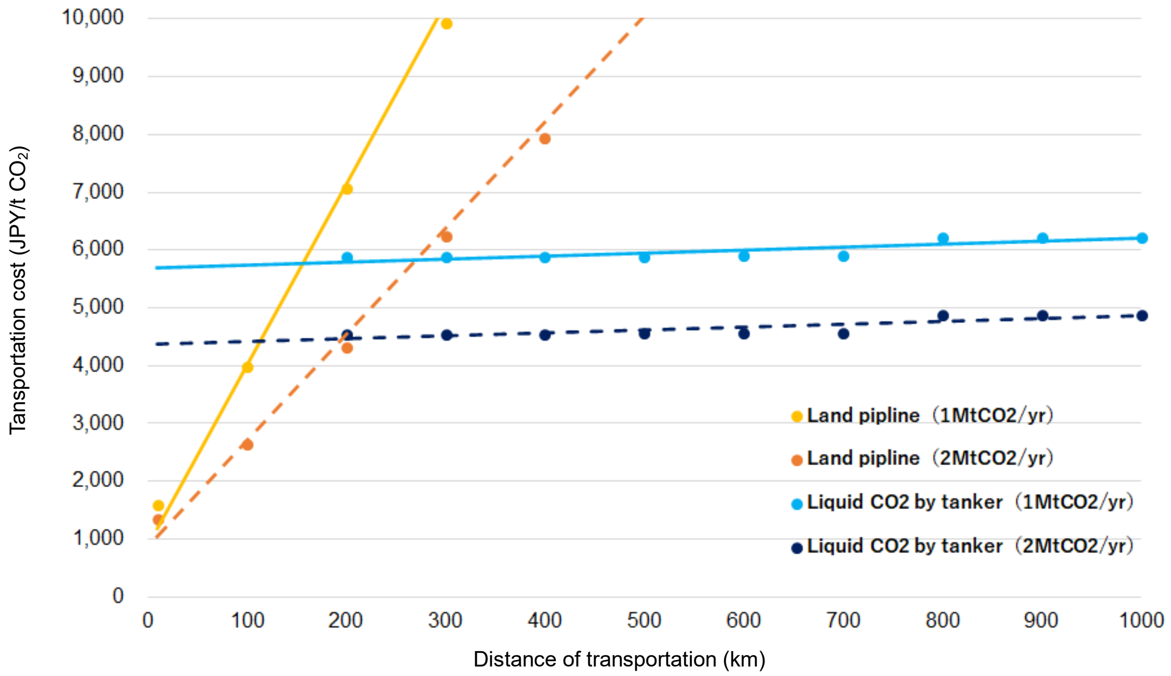


Fig. 2.2.2-5 CO_2 transportation distance and cost (RITE)

(ii) Conditions for storage site location

The ground surface conditions of the storage site must be considered when securing land for well drilling and estimating injection facility construction costs. Information on topographic and ground surface conditions can be obtained from existing topographic maps or the internet. Note that parks, nature reserves, and the like should be avoided. Furthermore, a site needs to be easy to monitor.

For subsea geological storage, the total cost of the CO_2 storage project will vary considerably depending on where the injection facility is constructed. Broadly speaking, the following 3 injection methods may be adopted:

A: Establish the injection well mouth onshore, drill a highly inclined well extending to the subsea storage site, and conduct onshore injection. The facility can be operated in a similar manner as onshore CO_2 storage.

B: Establish the injection facility and injection well mouth on an offshore fixed-foundation or floating platform. An existing platform may be used.

C: Establish the injection well mouth on the seabed, and then inject the CO_2 transported by pipeline or ship from the well mouth on the seabed.

Of the options above, method C is currently employed in deep-water oil and natural gas development projects around the world and seeing a rapid increase in adoption. There are several reasons for this, including that subsea completion techniques have been established, conventional offshore fixed-foundation platforms have reached their limit in terms of profitability for depths exceeding 300 m, and development projects involving offshore fixed-foundation platforms, which require a smaller initial investment, tend to take a longer lead time until production can start.

(iii) Social infrastructure, etc.

As far as possible, the information listed below should be gathered for reference in the site selection process.

- Social acceptability: identification of stakeholders
- Historical background: social, economic, and political history of the region from past to present
- Climate/weather: climate and weather records
- Natural disasters: records of past natural disasters, disaster prevention zones, hazardous areas, etc.
- Local industry: industrial structure
- Social infrastructure: roads (highways, major roads, transport operators), water/sewer, power, and gas infrastructure and supply network
- Demographics: population trend, daytime/night-time population, weekday/holiday population
- Facilities: schools, commercial facilities, hospitals, factories, parks, evacuation sites, etc.

This kind of information is available online. In Japan, local government websites serve as a valuable source of information, while the Japan Meteorological Agency provides detailed weather records on its website. For selecting offshore sites, the websites of the Japan Coast Guard, various marine agencies around the world, and harbors located in the vicinity of the offshore area can be used. Furthermore, Google Map and Google Earth can be useful tools for understanding the topography and locations of various facilities.

(iv) Depleted oil and gas fields

If oil or gas development has been carried out in the site's vicinity, a wide range of existing geological data would be available for use in the geological evaluation process. In addition, it would be advantageous from a cost perspective to reuse depleted oil and gas field facilities if available. When reusing an existing well as an injection well, reusing an existing platform for subsea geological storage, or reusing a pipeline for CO_2 transportation, for example, the facilities must be thoroughly examined to determine whether they are fit for reuse. Furthermore, local communities are more likely to accept the geological storage project if an oil or gas field already exists in the area.

(v) Existing wells

Existing wells and abandoned wells serve as paths for the CO_2 to seep out to the ground or seabed, thereby posing the risk of CO_2 leakage and seepage. In some countries, well positions are indicated in published geological maps. In the case of Japan, published geological maps indicate the extent of oil fields and gas fields and thus serve as a source for making preliminary decisions on existing/abandoned wells. In the US, Canada, and Australia, a variety of oil and natural gas related documents are published and available, as well as documents related to wells for drinking water and waste disposal.

(vi) Laws and regulations

Laws and regulations pertaining to CO_2 geological storage vary by country and region. Australia and Norway have incorporated CO_2 geological storage related laws into their conventional oil and natural gas related laws that have been in force for many years. Therefore, the laws governing both types of underground projects are consistent. On the other hand, many countries lack a clear legal and regulatory framework for CO_2 geological storage, which can cause project uncertainty. For this reason, laws and regulations must be considered when selecting a site.

2.2.3 Potential site ranking

Once each site is evaluated from a geological and non-geological perspective in accordance with the site selection procedures, the goal is to select the potential site(s) suitable for evaluation in the next phase (site characterization). To this end, it is necessary to compare the scores of the sites according to each evaluation item and rank their suitability as storage sites. The potential site ranking process will be described below.

(1) Ranking overview

(i) Reservoir-seal pair

Sites with a reservoir and seal with a larger thickness and extent are ranked higher. Sites with a reservoir with higher porosity and permeability, as well as a seal with greater threshold pressure (which is an indicator of sealing capacity) are ranked higher. The ranking should be based on not only these physical properties but also unconformity in distribution; however, if a detailed examination is not possible, information on the regional sedimentary environment could be helpful in the analysis. In addition, it is better to have multiple reservoir-seal pairs, and the presence of multiple developed seals leads to improved physical properties.

If depleted oil or gas fields are included as candidates, those with the following characteristics are ranked the highest (leaving storage capacity and other factors aside):

- long-term sealing has been demonstrated
- the reservoir form meets or exceeds certain requirements
- the reservoir pressure has declined
- a structural or stratigraphic trap is present

(ii) Storage capacity

In terms of ensuring operational and storage safety, potential sites with ample storage capacity get a higher rank. The quantity and reliability of the data used to calculate storage capacity should be considered.

(iii) Trapping and structural position

Sites in which structural or stratigraphic traps present are ranked higher as it is easier to explain the safety of storage to stakeholders. In particular, sites featuring a gentle inclination are given a higher rank because this structure causes the CO_2 to migrate over a longer distance, thereby enabling residual, solubility, and mineralization traps to function. In terms of depth, sites that cost less to drill and are capable of maintaining the CO_2 in a supercritical state are ranked higher.

(iv) Non-geological factors of the site

Generally, the shorter the distance between the site and emission source, the less it costs to transport the CO_2, which is desirable from an economical standpoint. Additionally, sites are ranked higher if they are situated in a favorable social or natural environment (topography, presence of harbor facilities, and other criteria). Since offshore geological storage tends to be more expensive than onshore storage, the ranking is influenced by the injection facility construction method and CO_2 transportation method too.

Another factor considered in the site ranking process is the presence of other resources that could compete with the storage project. A wide range of geological data may be available if a closed or active oil or gas field is located in the vicinity, which would allow a more accurate and reliable understanding of the reservoir system's form. However, given that existing wells (and abandoned wells) could become potential leakage/seepage paths for CO_2, they have a negative impact on the ranking.

2.2.4 Other points to consider in the site selection process

(1) Site selection in areas where geological data is lacking

There may be cases where there is a desirable area for CO_2 geological storage in the immediate vicinity of an emission source that is considered to be part of a sedimentary basin, but regional evaluation reports do not exist or do not provide the information necessary to select a site, or no deep underground surveys have been conducted that provide information such as sediment thickness. In such cases, a basic survey must be conducted to enable site selection. Simple survey methods to determine sediment thickness include the magnetotelluric (MT) method and array microtremor observation.

(2) Importance points on public engagement

On the social side, public engagement is necessary for facilitating the implementation of CO_2 geological storage projects. One could almost say that public engagement is the key to success for any CO_2 geological storage project. Indeed, there have been CO_2 geological storage projects around the world that were canceled owing primarily to the lack of public engagement. In the site selection phase, there is no need to limit the scope of public engagement activities to a particular area. Once in the site characterization phase, public engagement activities should be started in earnest as soon as possible, involving the local and surrounding communities of the potential site as well as the communities located along the planned CO_2 transportation route. In the public engagement process, it has been reported that many stakeholders seek clear answers for questions such as the following (European CCS Demonstration Project Network, 2012):

- What are the site selection criteria?
- What are the selection procedures?
- Why was this site chosen?

Documents, records, and reference material providing clear explanations about the 3 points above should be prepared/compiled.

(3) Lessons from the RCSP initiative

Although the CO_2 geological storage demonstration projects conducted under the Regional Carbon Sequestration Partnerships (RCSP) initiative in the US saw many achievements and contributed to the accumulation of knowledge, there are some lessons to be learned from the site selection process (NETL, 2017).

- Big Sky Carbon Sequestration Partnership (BSCSP): Importance of evaluating data quality

The BSCSP project was a demonstration project primarily focused on CO_2 geological storage in basaltic rock. One of the potential sites was known as the Kevin Dome Project site. Even though the site had not been developed and there was less existing information on it than other oil and gas field projects sites, the site met the basic requirements in the screening phase. The reservoir was located over 800 m below ground, and a thick anhydrite formation could serve as the seal. Furthermore, the area was not densely populated, and its shallow parts had been explored for oil and natural gas. In the subsequent site selection phase, an analysis of the available data showed that although logging data on wells deeper than the target horizon was obtained, the logging method was outdated and data quality was poor. What is more, the well test results had not been organized properly, and as the target area was close to the Canadian border, the formation names were mixed up and the records of well positions and well closures lacked consistency. Further investigation revealed that some of the well data used in the screening phase was inaccurate. Such inaccuracy (especially that about old wells in Kevin Dome) had a significant impact on the setting of an Area of Review (Aor) as required under UIC Class VI as well as the well restoration costs. Thus, in the site selection phase, it is vitally important to understand the limits of the existing data early on in the site selection process, identify data inaccuracy, and communicate the data limitations to the project manager.

- Plains CO_2 Reduction (PCOR) Partnership: Importance of surface geological surveys

This was a CO2 injection demonstration project conducted in the plains of the Central United States and southern Canada. In cases where it is difficult to make geological estimates about deep underground areas, outcrop data can be used to estimate the regional structure, sedimentary facies, and unconformity. This is a key approach for examining complex reservoirs. In the project, information on the same formation obtained from an outcrop was compared with the core sample; this was then used to improve a 3D geological model. In order to make a comparison with the Bell Creek oil field reservoir under review, an outcrop 25 miles away in Wyoming was surveyed. Even though the Bell Creek oil field reservoir itself is located 4,500 ft below ground, the outcrop observation allowed an understanding of the reservoir's unconformity. The oil field had a huge number of wells, but there was little core data that could be used to examine lithofacies variation. Therefore, a high-resolution 3D geological model based on well information could not be sufficiently developed. However, outcrop observation provided vertical and lateral geological information that was essential for understanding the regional structure and geological unconformity.

The outcrop observation allowed sedimentological comparison of the outcrop and underground core sample, which yielded favorable results. The core sample indicated 3 horizons and 5 lithofacies, while the same 3 horizons and 4 out of the 5 lithofacies were observed in the outcrop. Even though a sufficient number of core samples could not be obtained, the similarity between corresponding surface and underground lithofacies allowed the team to use similar outcrop samples in an indoor test. The data collected from the outcrop helped understand the major spatial-statistical ranges, conversion from porosity to permeability, and rock mechanical diversity as well as identify the reservoir and seal, thereby contributing to the minimization of uncertainty in the 3D geological model development process.

2.3 Subsurface pore space ownership and site exploration permits

2.3.1 Pore space ownership

For the development of resources such as oil, natural gas, and metallic minerals, the mineral rights that define the ownership of the resources deposited underground are clearly stipulated by law. Therefore, such resources cannot be extracted from the ground freely.

In the US and Canada, mineral resources belong to the owner of the land above the resource deposit. Mining companies must conclude a lease agreement with the landowner before launching mining operations.

Some countries and regions have applied the concept of subsurface pore space ownership (which is similar to the concept of mineral rights that applies to mineral resources exploration) to CO_2 geological storage. In the US, only the 3 states of Montana, Wyoming, and North Dakota explicitly present this idea in their laws. Meanwhile in Canada, Alberta has declared that all subsurface pore spaces in the province, except for those located in land owned by the national government, belong to the provincial government (GCCSI, 2012).

2.3.2 Pore space ownership and subsurface exploration rights

In relation to pore space ownership, some countries and regions legally define the right for CO_2 geological storage. In European countries, pore space ownership resides with the national government just like mineral rights; therefore, CO_2 geological storage rights are granted to operators by the national government. In Australia, pore space ownership resides with state governments in land and onshore areas and the federal government in offshore areas, and thus CO_2 geological storage rights are granted by either a state government or the federal government. In the case of the US, landowners also hold ownership of the pore space under their land, so CO_2 geological storage operators need to secure a lease from the landowner to obtain storage rights. As for land and onshore areas, state governments are responsible for leasing storage rights to operators, while the federal government is responsible when an offshore area (i.e., the Outer Continental Shelf) is involved.

Since the extraction of oil, natural gas, and other mineral resources requires a high level of economic efficiency, it is vitally important to conduct exploration in advance to select the optimal extraction site. That is why in many countries a permit is required for resource exploration regardless of whether it involves a scientific survey or prospecting. For instance, the US, Australia, European countries such as the UK and Norway, Japan, South Korea, China, and Russia all require permits for resource exploration. In countries with a bidding system, applicants are generally required to submit documents proving their financial foundation and technical capabilities, and only those deemed capable are granted a permit. The same applies to CO_2 geological storage; most countries have laws defining the conditions operators need to meet in order to obtain a permit for exploration in a given area conducted with the aim of selecting a site that allows long-term, safe geological storage of CO_2.

(1) Current situation by country

(i) US

- US land areas

Operators wishing to conduct exploration for a CO_2 geological storage site on private land must conclude an agreement with (obtain a deed from) the landowner. As for exploration on public land, operators must obtain a permit from the US Bureau of Land Management (BLM) in accordance with the Federal Land Policy and Management Act to carry out CO_2 geological storage activities (Global CCS Institute et al., 2009).

- US sea areas

In the US, the federal government has jurisdiction over the Outer Continental Shelf (OCS), which refers to offshore areas more than 3 nautical miles (5,556 m) from the coastline. State governments have jurisdiction over all sea areas within 3 nautical miles of the coastline, with some exceptions. In Texas and Florida, state government jurisdiction extends over 9 nautical miles (16,668 m) from the coastline, while in Louisiana it covers 3 imperial nautical miles (5,559.5 m).

In accordance with the Outer Continental Shelf Lands Act (OCSLA), the US Department of the Interior's Bureau of Ocean Energy Management (BOEM) and Bureau of Safety and Environmental Enforcement (BSEE) have the powers listed below pertaining to the regulation of mineral resource development in the Outer Continental Shelf:

- grant permission for CO_2-EOR and geological storage in relation to existing oil/gas field leases, and
- grant permission exclusively for geological storage of CO_2 that is generated as a by-product in onshore coal power plants.

No such permits have been issued to date (Godec, 2020).

The oil and gas lease as provided in the OCSLA allows the lease holder to explore and prospect for, develop, and produce oil and natural gas. An oil/gas lease sale is conducted in accordance with a 5-year leasing plan, after which a 5-year lease is granted (10-year lease for deep water). The lease holder is required to submit an exploration plan describing the drilling and exploration method, positions of exploration wells and wildcats, spill prevention measures, and other geological/physical information within 4 years of lease acquisition. The lease holder must also attach an environmental report and a permit issued by the coastal state. These rules governing oil and natural gas exploration in the continental shelf are expected to also apply to exploration for subsea geological storage of CO_2 in the continental shelf.

(ii) Canada (Alberta)

In order to conduct CO_2 geological storage, operators must first conclude a lease or tenure agreement for pore space use with the Government of Alberta Department of Energy. A permit from the Alberta Energy Regulator (AER) is necessary for conducting injection operations. In addition, an evaluation permit must be obtained to conduct site evaluation, injection tests, and reservoir evaluation. Evaluation permits are granted in the form of a lease or tenure agreement, allowing the permit holder to conduct site evaluation work that involves the use of wells (e.g., injection tests for reservoir evaluation). Evaluation permits last for 5 years and cannot be extended (OECD/IEA, 2015).

(iii) EU, CCS Directive

The CCS Directive does not include detailed provisions for exploration permit application. Article 5 addresses exploration permits as follows.

- An exploration permit is required for conducting exploration for potential storage sites.
  - When it is determined that exploration is required to generate the information necessary for selection of storage sites, the exploration cannot take place without an exploration permit.
- Monitoring of injection tests may be included in the exploration permit.
- The granting of exploration permits is governed by the conditions below.

- Permit application shall be open to all entities possessing the necessary capacities. Member states shall ensure that the procedures for the granting of exploration permits are open to all entities possessing the necessary capacities and that the permits are objective, published, and non-discriminatory.
- Exploration permits shall be granted or refused on the basis of objective, published, and fair criteria.
- Exploration permits shall be granted in respect of a limited volume area.

● The duration of a permit is equivalent to the period necessary to carry out the exploration for which it is granted.

- The duration of a permit shall not exceed the period necessary to carry out the exploration for which it is granted. However, member states may extend the validity of the permit where the stipulated duration is insufficient to complete the exploration concerned and where the exploration has been performed in accordance with the permit.

● The holder of an exploration permit has the sole right to conduct exploration.

According to the CCS Directive, "exploration" means the evaluation of potential storage complexes by means of activities intruding into the subsurface such as drilling to obtain geological information about strata in the potential storage complex and, as appropriate, carrying out injection tests in order to characterize the storage site. Furthermore, even though a storage permit from the relevant authorities is necessary to carry out a CO_2 geological storage project, the CCS Directive states that the holder of the exploration permit will be given priority for the granting of a storage permit provided that the exploration is completed.

(iv) UK

In response to the establishment of a common CO_2 geological storage permit regime for EU member states by the CSS Directive, the British government adopted the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 that describe the details of its own permit regime. The UK's CO_2 geological storage permit regime is made up of 4 stages, and a different type of permit is required for existing operators that possess knowledge about the storage site from experience in oil production or other similar activities and new operators that need to select a storage site through subsurface exploration (UK Government, 2010; OECD/IEA, 2015).

- Stage 1 (initial exploration)

New operators that need to select a storage site through a preliminary survey apply for an exploration license pursuant to the Petroleum Act 1998 from the Department of Energy & Climate Change (DECC). Operators that obtain the license are permitted to conduct seismic exploration, gravity surveys, magnetic prospecting, and core sample extraction as well as drilling surveys in depths of up to 350 m.

- Stage 2 (deep drilling surveys and injection tests)

An operator that wishes to conduct demonstration tests, such as injection tests, in addition to the surveys conducted in Stage 1 applies for a storage license from the DECC. The operator is asked to lease the site from the Crown Estate (an organization controlled by Parliament that manages lands held by the British monarchy), and the 2 parties enter into an Agreement for Lease (AfL). An AfL grants the lease holder exclusive options for a limited period, including the option to obtain a storage permit from the DECC.

- Stage 3 (CO_2 storage)

Operators that have decided on a storage site and concluded an AfL for commencing CO_2 storage then apply for a storage permit from the DECC. Operators that already engage in oil production or other similar activities and possess knowledge about the storage site can apply for a storage license without performing a preliminary survey.

- Stage 4 (closure of site and expiration of storage permit)

Operators that have terminated their CO_2 storage project and closed the facility conduct monitoring during the post closure phase, that is the period before long-term responsibility is transferred to the government. Although the Energy Act does not stipulate the specific duration of the post closure phase, it provides 20 years as a general estimate in line with the CSS Directive.

(v) Australia

In Australia, land and sea areas up to 3 nautical miles (5.6 km) from the coast fall under the jurisdiction of states and territories, while sea areas further than 3 nautical miles from the coast up to the end of the continental shelf fall under the jurisdiction of the federal government. The same applies to CO_2 geological storage.

Aiming to develop a rights regime for subsea geological storage of CO_2 in federal waters as well as a rights regime that could allow coordination with the oil industry, Australia amended the Offshore Petroleum Act 2006 in 2008 to establish the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (officially known as the Petroleum Exploration and Recovery, and the Injection and Storage of Greenhouse Gas Substances, in Offshore Areas Act). Through this amendment, the existing acreage release method applied to offshore oil extraction in federal waters was extended to CO_2 geological storage.

- Acreage release

Acreage release is conducted to carry out CO_2 geological storage projects, taking into consideration geological evaluation results and, in particular, compatibility with other enterprises such as oil operations and the impact on existing industrial structures. Once the acreage is released, bidding is held to decide which operator can conduct an evaluation. The bidding for an evaluation permit adopts either a work-bid or cash-bid system. Successful bidders obtain an evaluation permit that gives them the right to evaluate the GHG injection/storage sites in the area.

Application for a CO_2 geological storage evaluation permit begins within 6 months of release of the acreage in the official gazette. After the acreage is released in the official gazette, operators wishing to participate in the bidding must submit an application form to the relevant federal minister by a specific date.

Evaluation permits are valid for 6 years but may be extended by up to 12 months. If as a result of the evaluation the CO_2 geological storage project is officially launched, then the operator applies for an injection license, which is a permit for injecting and storing greenhouse gas at a specific site. If as a result of the evaluation it is judged that the site is suitable for CO_2 geological storage, but CO_2 injection and storage should be conducted in the future, the operator may ask the authorities for a holding lease that gives it the right to apply for a GHG injection and storage permit in the future. The duration of the holding lease is 5 years and can be extended by up to 5 years. Additionally, if it is judged that CO_2 geological storage would impact oil or natural gas operations, a special holding lease can be issued whereby CO_2 injection and storage may be postponed for any length of time. Fig. 2.3.2-1 is a flowchart of the procedure described above (RITE, 2009). Table 2.3.2-1 is a comparative list of the major rights granted in relation to CO_2 geological storage projects and the rights granted for oil production.

Table 2.3.2-1 Main rights to CO_2 geological storage projects and oil production in Australia (RITE, 2009)

	CCS project	E & P project
Exploration permit	Assessment Permit The licenses to explore for GHG storage sites in designated concessions	Exploration Permit The licenses to explore for oil & gas in designated concessions
Retention Lease	Holding Lease (include Special Holding Lease) The licenses to retain the rights to apply for an injection permit, if GHG injection & storage is feasible in the future	Retention Lease The licenses to retain the rights to apply for a production permit if oil & gas production is feasible in the future
Injection /Production permit	Injection License Licenses to permit GHG injection and storage	Production License The licenses to permit oil & gas production

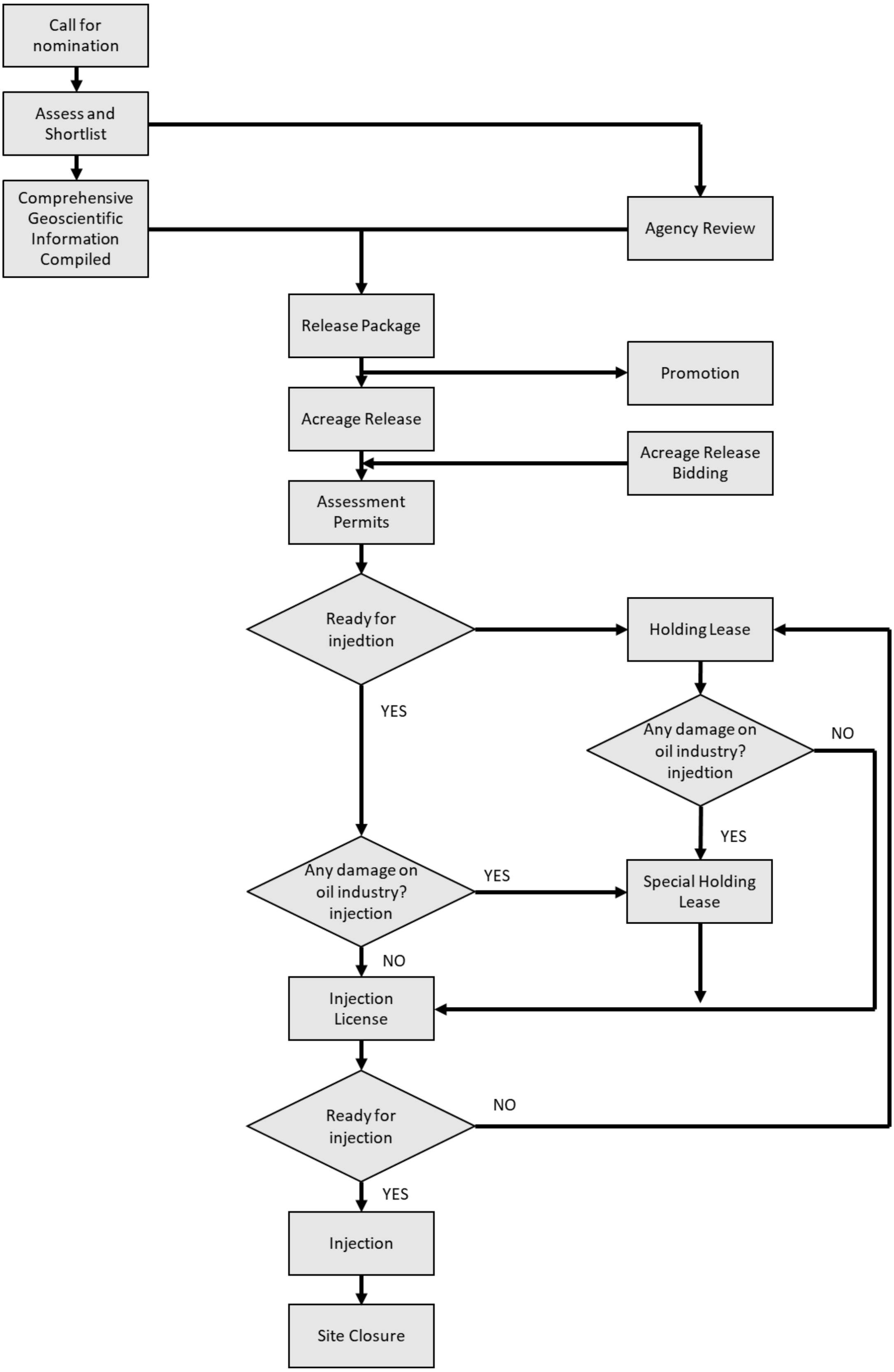


Fig. 2.3.2-1 CCS project permit application flow (RITE, 2009)

(vi) Norway

In Norway, CO_2 geological storage is regulated by the same laws that regulate oil and natural gas projects, namely the Petroleum Act and the Pollution Control Act. A description of the permit regime for CO_2 geological storage is given below (Global CCS Institute, 2012).

- Prospecting permit for site selection: a permit necessary to conduct prospecting issued by the relevant ministry. As a non-exclusive permit it does not come with the preferential right to obtain an exploration permit in the next step.
- Exploration permit for site selection: an exclusive permit granted by the King-in-Council that is valid for up to 10 years.
- Permit for development of storage site: an exclusive permit granted by the King-in-Council. Detailed and broad implementation plans are formulated for the CO_2 geological storage project, including a plan for injection and storage-related development work as well as a management plan. Implementation of an environmental evaluation is another important aspect.
- Storage permit: a permit for commencement of injection.

(vii) Netherlands

Operators must acquire an exploration permit to conduct exploration (primarily exploration drilling) for selecting a CO_2 geological storage site. An exploration plan and documents proving the operator's technical and financial potential must be attached to the application. However, seismic exploration can be conducted without a permit.

A storage permit is required for CO_2 geological storage. If an operator acquires an exploration permit to conduct an exploration/evaluation and on the basis of the exploration/evaluation results determines that the site of interest meets the criteria for a storage site, the operator is given priority to obtain a storage permit (OECD/IEA, 2015).

(viii) Denmark

Operators must acquire an exploration permit from the Minister for Climate and Energy to conduct exploration for selecting a CO_2 geological storage site. This is an exclusive permit valid for 6 years; it may be extended by 2 years and, in exceptional cases, an additional 2 years. Exploration permits are granted through a bidding process (Global CCS Institute, 2012).

(ix) France

Operators must acquire a permit from the Minister for Mining to conduct exploration for selecting a CO_2 storage site. An open bid is held 30 days after the tender is released in the official gazette. Exploration permits are valid for 5 years but can be extended. To participate in the bidding, operators must possess the technical and financial capability to conduct the mandatory work specified by the authorities. An operator that obtains an exploration permit is given the exclusive right to conduct exploration in the area indicated in the permit (Global CCS Institute, 2012).

(2) Japan

Japan does not have a system for establishing mining areas for CO_2 geological storage sites, and lacks laws on rights related to storage project implementation. However, permission is required for subsurface exploration including the selection of CO_2 geological storage sites.

Mining rights (which also apply to oil and natural gas) are stipulated by the Mining Act and include prospecting rights (the right to survey for and confirm the occurrence and amount of minerals, etc.; valid for up to 8 years for oil and natural gas) and digging rights (the right to dig for a registered mineral in a mining area). Up until 2012, mining rights were granted on a first-to-file basis. Furthermore, although some provisions specified the conditions for non-permission, such as when a mining application area overlaps another mining area, no provisions were provided regarding the eligibility of developers as well as the requirements for granting permission. It should also be noted that the Mining Act included no provisions on resource exploration activities (e.g., seismic exploration) that are essential preparatory steps for creating mining rights (prospecting rights, digging rights).

The Mining Act was revised in 2012 to address these issues. New systems were put in place, such as the specified area system and resource exploration regulation system, and the permission criteria for mining rights were revised (Agency for Natural Resources and Energy website). Furthermore, the previous application process based on the first-to-file principle was changed to a system that allows the most suitable entity to receive permission for creating mining rights under appropriate government supervision. The revision not only enabled the government to specify areas, but also allowed operators (Japanese citizens or Japanese corporations) to make proposals about areas with confirmed or potential resource deposits and apply for specified area designation. Developers for areas designated as specified areas are selected through open application, and development is conducted by a suitable developer (specified developer) that is granted mining rights from the Minister of Economy, Trade and Industry. The revised act requires specified developers to be selected on the basis of an examination of financial basis and technical capability as well as other evaluation criteria for specified developer selection (e.g., previous development achievements, feasibility of development plan), ensuring that resource development is conducted in a reasonable manner .

In addition, a new permission system was introduced that requires all individuals or entities intending to conduct seismic exploration, electromagnetic prospecting, or intensive sampling exploration (regardless of the purpose) to obtain permission from the Minister of Economy, Trade and Industry. Under this new system, those who intend to conduct an exploration employing any of the methods below specified by the Mining Act for the development of mineral resources, scientific investigation, or any other purpose must file an application with and obtain permission from the Minister of Economy, Trade and Industry in accordance with Article 100-2 of the Revised Mining Act.

- Seismic method: equivalent to seismic exploration herein.
- Electromagnetic method: generating electromagnetic waves near the seabed to detect changes in the resulting electromagnetic field.
- Intensive sampling exploration method: using a device designed for bottom material collection to

collect bottom material in an intensive manner.

2.4 Site selection in the Quest project

Under the ongoing Quest project in Alberta, Canada, more than one million tons of CO_2 emitted from Shell Canada's Scotford Upgrader (a plant for processing bitumen collected from oil sand) is injected and stored underground each year. Planning began in 2009, and operations began in 2017. In 2009, the operator, Shell Canada drilled 2 exploration wells located within a radius of 16 km of the plant to evaluate the properties of the Basal Cambrian Sands (BCS), which was considered a potential reservoir, as well as the seal. This procedure differed from the normal site selection process, but the company had to gain the information necessary to apply for project funding from the Government of Alberta.

In the site selection process, Shell Canada conducted an evaluation in terms of CO_2 geological storage safety and security. The selection criteria were established referring to the criteria published by the Alberta Research Council that are listed below.

<u>Critical level (mandatory conditions)</u>

- Reservoir-seal pair: appropriate extensive barrier against vertical flowing
- Formation pressure
- Monitorability
- Impact on groundwater

<u>Essential level (key conditions)</u>

- Seismic activity
- Fault and formation breaking strength
- Hydraulic system

<u>Desirable level (requirements)</u>

- Depth
- Is site located in fold belt?
- Diagenesis
- Geothermal gradient
- Formation temperature
- Formation pressure
- Reservoir thickness
- Porosity
- Permeability
- Seal thickness
- Density of existing wells

On the basis of examination of regional geological reports on the reservoir and seal as well as an evaluation based on the selection criteria, Shell Canada concluded that the area around the Scotford Upgrader exhibited favorable conditions for CO_2 geological storage. Accordingly, the company selected 3 areas as candidate storage sites and conducted a comparative analysis (Fig. 2.4-1).

- Candidate A: North of the North Saskatchewan River
- Candidate B: South of the river some 16 km ESE from Scotford
- Candidate C: North of river directly WNW from Scotford

The Basal Cambrian Sands (reservoir) is composed of fine to coarse sandstone with a few thin pelitic layers in between and has a porosity of 17 % and permeability of 1,000 mD. The regional evaluation showed that in the area surrounding Scotford, the coarse sandstone of the base and the fine sandstone at the very top have favorable reservoir properties, characterized by a thickness of 35 to 50 m. As for seals, the following formations are located above the Basal Cambrian Sands: the Middle Cambrian Shale (main seal) of the Middle Cambrian age, Lower Lotsberg Salt and Upper Lotsberg Salt (secondary seals) of the Lower Devonian age, and Prairie Evaporite of the Middle Devonian age (IEAGHG, 2019).

The areas around Scotford other than the 3 candidate sites were excluded in the screening because they completely failed to meet some key criteria. Specifically, the area southwest to Scotford lacked a seal capable of covering a wide area and is located in proximity to industrial and housing infrastructure that hinders measurement, monitoring, and verification (MMV). The areas to the east and north of the 3 sites were considered to entail significantly higher development costs as a pipeline would need to be extended to a more distant potential storage site; these areas were thus excluded in the screening through comprehensive evaluation based on the site selection criteria.

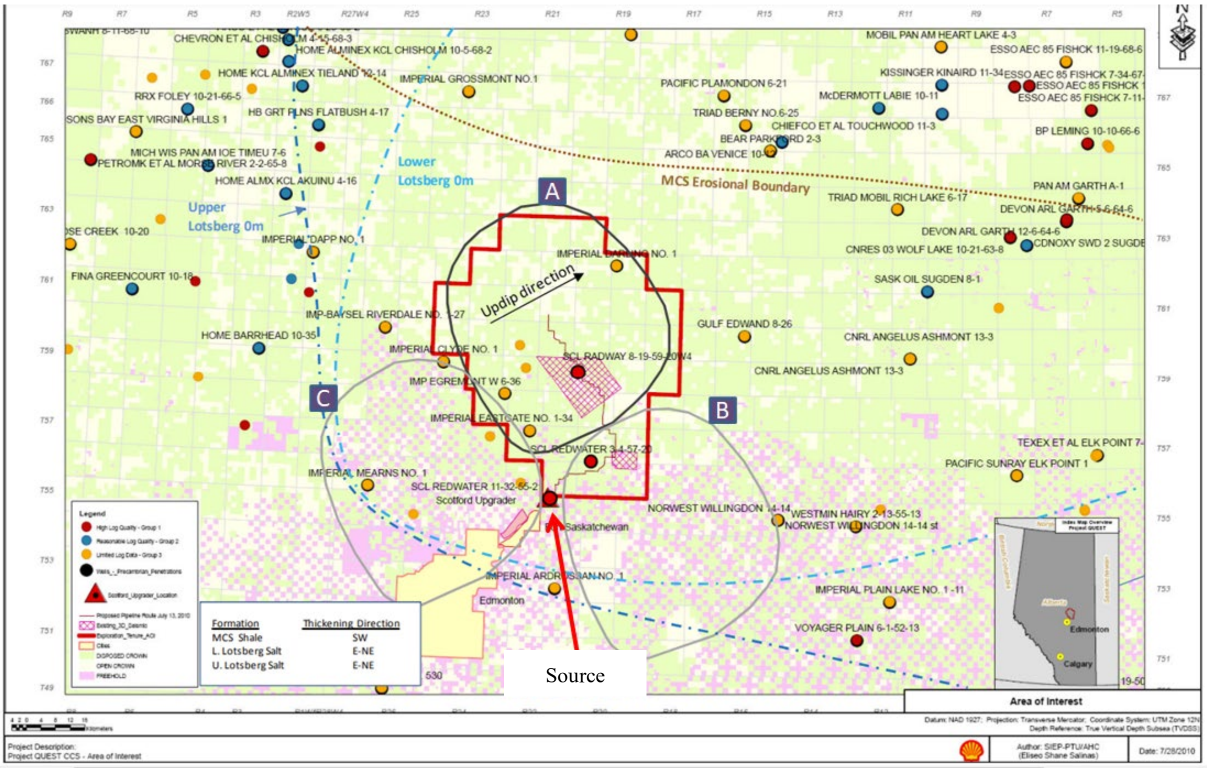


Fig. 2.4-1 3 candidate storage sites selected around the Scotford Upgrader (Candidates A, B, C). The distribution of the main seal is limited to the area south of the MCS Erosional Boundary drawn in the north part, while the distribution limits of the secondary seals are limited to the area northeast of the 2 blue lines drawn from the northwest to southeast part of the map (Shell Canada, 2011, partially modified).

The 3 candidate sites were compared, evaluated, and ranked with respect to the following items:

- Storage capacity
- Injection capacity
- Sealing capacity
- MMV feasibility
- Access to pore space
- Cost
- Developability

On the basis of the information gathered, it was shown that the differences between the 3 sites were most striking in terms of sealing capacity, access to pore space, cost, and developability.

Storage capacity

Candidate A: Roughly the same

Candidate B: Roughly the same

Candidate C: Roughly the same

Injection capacity

Candidate A: Equivalent to Candidate C

Candidate B: The reservoir is divided by a fault that may function as a permeability barrier in the east, but the risk is low.

Candidate C: Equivalent to Candidate A

Sealing capacity

Candidate A: The (Devonian) secondary seals thickly cover the estimated plume over a broad area. Fewer existing wells extend to the reservoir compared to Candidate C.

Candidate B: The distribution of the (Devonian) secondary seals is a smaller compared to Candidate A.

Candidate C: Numerous existing wells extend to the reservoir.

MMV feasibility

Candidate A: Least infrastructure on the surface.

Candidate A: Some infrastructure on the surface.

Candidate C: Has the Redwater oilfield and a lot of infrastructure on the surface. The oilfield's existing wells could be used, and synergies such as joint 3D seismic exploration of the oilfield and CO_2 storage site may be possible.

Access to pore space ownership

(As there was no system for granting the right to use pore space including formation water at the time of site selection, the right to use pore space in national land was considered easier to obtain.)

Candidate A: Includes much national land.

Candidate B: Includes much private land, thus entailing risk of trouble and delays in the development process.

Candidate C: A competitor has a drilling plan.

Cost

Candidate A: Furthest from the emission source, and the pipeline construction cost is higher than the other candidates.

Candidate B: Development and pipeline construction costs are lower than Candidate A.

Candidate C: Development and pipeline construction costs are lower than Candidate A.

Developability

(Considering that the Government of Alberta wishes to achieve 139 Mt/year of CCS by 2050, the potential of enabling this was added as a ranking criteria)

Candidate A: Most suitable for development in the direction of Candidate B, as well as the north and northwest direction.

Candidate B: Can be developed in the direction of Candidate A, as well as the northeast direction.

Candidate C: A new pipeline to Candidate A or B would be necessary for further development.

Of the 3 candidate sites, Candidate A was the furthest from the bitumen upgrader (CO_2 emission source), making it the costliest in terms of pipeline construction costs. However, Candidate A was ranked the highest owing primarily to the favorable properties of the main seal and secondary seals, access to pore space ownership, and developability potential. Accordingly, the area in the red box in Fig. 2.4-1 was selected as the CO_2 storage area for application.

2.5 Conclusion

CO_2 geological storage is a technology with a relatively short history and track record and is yet to be fully established. However, in technological terms it is similar to existing techniques that are used for the exploration, development, and production of oil and natural gas, processes that also involve handling fluids deep underground. Nevertheless, geological conditions can vary significantly, and no 2 regions have identical characteristics. The crucial elements for any CO_2 geological storage project are to inject the planned amount of CO_2 at the planned rate and store the fluid safely over the long term, while also ensuring economic efficiency. Technical issues and technical/non-technical uncertainty cannot be avoided, but the best way to reduce those risks is to appropriately select a suitable site. Therefore, CO_2 geological storage cannot be properly achieved without selecting a suitable site.

This chapter is intended to provide information that could be useful when selecting safe and reliable CO_2 geological storage sites meeting the requirements laid out in the basic plan that specifies the emission source, injection volume, and other basic matters. The selected one or more potential sites are then further evaluated in the site characterization phase, which involves acquiring new geological data, evaluating suitability as a CO_2 geological storage site from a technical standpoint on the basis of detailed geological models and simulations, and factoring in economic efficiency. Ultimately, the most suitable potential site is selected as the storage site.

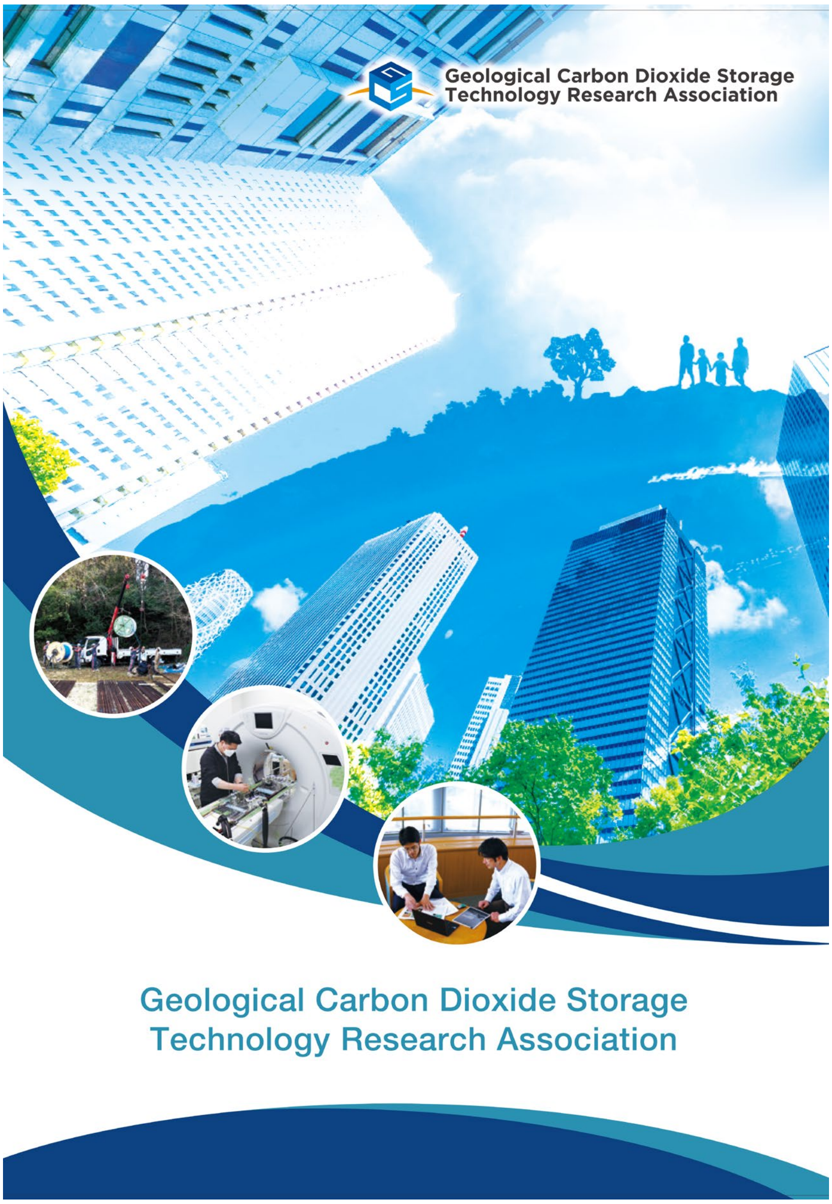
References

1) Agency for Natural Resources and Energy:https://www.enecho.meti.go.jp/category/resources_and_fuel/strategy/mining_act/(2022/3)
2) Atlas Partnership (NACAP) (2012): North American Carbon Storage Atlas- First Edition, NETL/DOE, http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf (2015/11)
3) Borissova, I., Lech, M. E., Jorgensen, D. C., Southby, C., Wang, L., Bernardel, G., Nicholas, W. A., Lescinsky, D. L. and Johnston, S. (2015): An Integrated Study of the CO_2 Storage Potential in the Offshore Vlaming Sub-Basin, Results of the study undertaken as part of the NCIP program, GEOSCIENCE AUSTRALIA RECORD
4) Carbon Storage Taskforce 2009 (2009): National Carbon Mapping and Infrastructure Plan – Australia, Full Report, Department of Resources, Energy and Tourism, Camberra, http://www.parliament.wa.gov.au/parliament/commit.nsf/%28$lookupRelatedDocsByID%29/518FAC2BBA6C246648257C29002DB8E6/$file/NCM_Full_Report.pdf (2015/11)
5) European CCS Demonstration Project Network (2012): Lessons learned from the Jänschwalde project, Summary report, Knowledge Sharing Event Cottbus,May 2012,European CCS Demonstration Project Network, http://hub.globalccsinstitute.com/sites/default/files/publications/77476/lessons-learned-janschwalde-project-summary-report.pdf (2015/11)
6) Global CCS Institute (2012): Property rights in relation to CCS, GCCSI https://www.globalccsinstitute.com/resources/publications-reports-research/property-rights-in-relation-to-ccs/ (2013/10)
7) Global CCS Institute, Baker & McKenzie, WorleyParsons (2009): Strategic analysis of the global status of carbon capture and storage. Report 3: policies and legislation framing carbon capture and storage globally, GCCSI, http://hub.globalccsinstitute.com/publications/strategic-analysis-global-status-carbon-capture-storage-report-3/1-executive-summary (2010/12)
8) Godec, M. (2020): Characterizing Legal and Regulatory Frameworks, SECARB Offshore GoM & GoMCarb Annual Joint Partnership Meeting, New Orleans, Louisiana, March 25-27,2020
9) Gupta, N. (2017): Mid-Atlantic U.S. Offshore Carbon Storage Resource Assessment, Carbon Storage and Oil and Natural Gas Technologies Review Meeting, August 1-3, 2017, NETL/DOE HP, https://www.netl.doe.gov/sites/default/files/2017-12/Gupta-P2-FY17_MidAtlanticProjectTeam_DOE_FINAL.pdf (2018/11)
10) IEA Environmental Projects Ltd. (IEAGHG) (2011): Caprock Systems for CO_2 Geological Storage, IEAGHG
11) IEAGHG (2019): The Shell Quest Carbon Capture and Storage Project", 2019/04, September 2019
12) IPCC (2005): IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de

Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

13) Japan Oil, Gas and Metals National Corporation(2004):2003 Fiscal Year Financial Statements
14) Japanese Assoc. for Petroleum Technology(2013):Oil Mining Handbook、Japanese Assoc. for Petroleum Technology
15) Japanese Society for Active Fault Studies(1991):New Japanese Active Fault-Distribution Map、University of Tokyo Press
16) Langford, R., Borissova, I., Chrinos, A., Henson, P., Heap, A. (2013): Pre-competitive Data Acquisition Program for CO_2 Storage in Australia, Energy Procedia 37(2013) 4968-4974, Elsevier, http://ac.els-cdn.com/S1876610213006528/1-s2.0-S1876610213006528-main.pdf?_tid=9025f4ce-08f1-11e5-a8fa-00000aab0f6b&acdnat=1433227110_6148bf66aced8ee7cf83d09d04282fdc (2015/11)
17) McBride, J. H., Leetaru, H. E., Keach II, R.W., McBride, E. I. (2013):Illinois Basin Basement and Structure, Midwest Geological Sequestration Science Conference, Midwest Geological Sequestration Consortium,
http://www.sequestration.org/resources/PAGOct2013Presentations/04-IL-Basin-Basement-Structure-McBride_PAG_Oct8-2013_FINAL_revised.pdf (2015/8)
18) Mito, S., Xue, Z., Ohsumi, T. (2008):Geochemical Aspects of a Geological Storage of CO2 : A Case Study Based on a Formation Water Analysis at the Nagaoka Pilot-scale CO2 Injection Site (in Japanese with English abstract) , Journal of Geography, 117, 753-767.
19) NETL/DOE (2013): BEST PRACTICES for Site Screening, Site Selection, and Initial Characterization for Storage of Best practice for the storage of CO_2 in saline aquifers in Deep Geologic Formations, 2013 Revised Edition, National Energy Technology Laboratory, Department of Energy
20) NETL/DOE (2017): Best Practices: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects, NETL (National Energy Technology Laboratory, Department of Energy
21) National Institute of Advanced Industrial Science and Technology,Geological Survey of Japan(2005) :Numerical geological map FR-1 Fuel resource geological map "Off Sanriku"
22) National Research Council (2013): Induced Seismicity Potential in Energy Technologies, Washington DC: The National Academies Press, 1-262
23) OECD/IEA (2015): Carbon Capture and Storage: Legal and Regulatory Review-Edition 5. International Energy Agency, Insights Series 2016
24) Ogawa, T., Nakanishi, S., Shidahara, Okumura, T., Hayashi, E. (2011): Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment,, International Journal of Greenhouse Gas Control 5, 318–326
25) Quillinan, S. (2019): Carbon capture, utilization and storage, Joint Minerals Committee, May 16th and 17th, https://www.wyoleg.gov/InterimCommittee/2019/09-201905163-02QuillinanJointMinerals.pdf (2020/8)
26) RITE (2003):Reports on Geological Carbon Dioxide Research

27) RITE (2009):Reports on Geological Carbon Dioxide Research
28) Samukawa,A., Kinugasa,Y., Kakimi,T.,(1984):1 / 500,000 active structure diagram, National Institute of Advanced Industrial Science and Technology,Geological Survey of Japan
29) Shell Canada (2011): Quest Storage Development Plan, October 6, 2011. https://open.alberta.ca/dataset/46ddba1a-7b86-4d7c-b8b6-8fe33a60fada/resource/5555eb2e-6d86-4419-97a3-8d3de7c5b702/download/storagedevelopmentplan.pdf (2012/6)
30) Smith, N., Paul, B., Oguntimehin, A., Gijs E., Guo, R., Reynolds, M, A. Friesen, L., Cano, M,C, O'Brien, S. (2021): Quest CCS facility: Halite Injectivity Damage Remediation in CO_2 Injection Wells,15th International Conference on Greenhouse Gas Control Technologies, GHGT-15th March 2021 Abu Dhabi, UAE
31) UK Government (2010): 2010 No. 2221, ENVIRONMENTAL PROTECTION, The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 http://www.legislation.gov.uk/uksi/2010/2221/pdfs/uksi_20102221_en.pdf(2011/6)
32) Warren, J. K. (2007): Evaporite: Sediments, Resources and Hydrocarbons, Springer,1035p



http://www.co2choryu-kumiai.or.jp/

This document is based on results obtained from a project (JPNP18006) commissioned by the New Energy and Industrial Technology Development Organization (NEDO) and Minister of Economy, Trade and Industry (METI) of Japan.