Site geomechanics analysis of CO_2 geological sequestration

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Abstract: Carbon dioxide (CO_2) sequestration offers an attractive opportunity to reduce the greenhouse gas (GHG) emission on our planet. Geological sequestration into deep saline aquifers is widely regarded as a reasonable option for long-term disposal of captured GHG mainly including CO_2 from the hydrocarbon-powered plant point sources in the future. However, CO_2 geological sequestration may change the geomechanical conditions of the disposal site and these geomechanical changes near the fault zones may induce an additional deformation, especially around the location of faults. Thus, the site geomechanical assessment process is prerequisite for such complicated geo-engineering projects. In this paper, we firstly construct a reservior model to consider effects of the geomechanical conditions induced by the injected CO_2 plume on fault activity. Then, both quantitative and qualitative geomechanical analyses for the geo-sequestration site around the faults under different geological conditions are discussed. Finally, based on the proposed assessment flowchart, the potential disposal sites are identified for the islands of Japan.

Résumé: La séquestration d'anhydride carbonique (CO_2) donne une occasion attrayante de réduire l'émission de gaz de effet de serre sur notre planète. La séquestration géologique dans les couches aquifères salines est largement considérée comme une option raisonnable pour la depotoir à long terme du CO_2 capturé des centrales à charbon à l'avenir. Cependant, la séquestration géologique de CO_2 peut changer géologique et les états mécaniques de la décharge et de ces changements près des zones faillées peuvent induire une déformation additionnelle. Ainsi, le processus géologique et mécanique de l'emplacement d'évaluation est préalable à de tels projets compliqués de geo-technologie. En cet article, nous construisons premièrement un modèle de reservior pour considérer des faillées des conditions géologiques et mécaniques induites par la plume injectée de CO_2 sur l'activité de faillées. Puis, des analyses géologiques et mécaniques quantitatives et qualitatives pour l'emplacement de geo-séquestration autour des défauts dans différentes conditions géologiques sont discutées. En conclusion, basé sur l'organigramme proposé d'évaluation, le depotoir potentielles sont identifiées autour des îles du Japon.

Keywords: climate change, discontinuities, finite element, injection, pore pressure, site investigation.

INTRODUCTION

As a global strategy to combat greenhouse effect, many kinds of possibilities to reduce CO_2 emission into the atmosphere have been widely studied since 1980s. CO_2 geological sequestration (geo-sequestration) is being proposed as one of the most attractive and feasible options for this purpose. The idea was based on experiences gained in EOR (enhancing oil recovery) practice in the petroleum industry. The conceptual framework and method for CO_2 geo-sequestration were presented in some early papers by Koide, Tazaki & Noguchi (1992); van der Meer (1992); Koide, Tazaki & Noguchi (1993); Omerod (1993); van der Meer (1993); Gunter, Perkins & McCann (1993); Hendriks & Blok (1993); Holloway & Savage (1993); Bachu, Gunter & Perkins (1994); Bergman & Winter (1995); Weir, White & Kissling (1995); and van der Meer (1996).

Although the technical feasibility of CO_2 geo-sequestration has been proven by some successful experiences in numerous underground natural gas storage projects, EOR schemes, and the commercial practice in Sleipner, the mechanical stability of sequestration sites has not been thoroughly studied yet. Especially, Japan Islands Arc is located in a tectonically active region with density distributed and frequent faults. The effects of these faults on mechanical stability of CO_2 sequestration sites must be evaluated with respect to the potential for induced seismicity and leakage associated with seismic events. In recent years, many studies have focused on assessing important aspects of regional formations that may be suitable for sequestration (Tanaka, Koide & Sasagawa 1995; Gunter, Bachu & Law 1996; Liu, Huang & Chakma 1998; Hattenbach, Wilson & Brown 1998; Li, Wu & Li 2002, 2004; Li & Wu 2005).

In this article, a geo-sequestration site model is firstly simplified and a two-dimensional (2-D) finite element simulator is constructed to do an analysis of injected CO_2 influence on mechanical behaviours of a fault. The shear stress change, pore pressure effect and local safety factor have been discussed. Then, an assessment flowchart is proposed for an exact site analysis of CO_2 geo-sequestration. Finally, we are attempting to identify some potential sequestration sites with relatively high mechanical stability based on the distribution of active faults.

SITE GEOLOGICAL MODEL

Geological model

A conceptual sketch of CO_2 geo-sequestration system in deep reservoirs (saline aquifers, depleted oil and gas formations, depleted coal bed, and et. al) is depicted in Figure 1. By simplifying the complicated geo-sequestration system into a representative and idealized plane strain model, Figure 2 shows the 2-D cross section of the present pilot model of a CO_2 geo-sequestration system. The sequestration system is consisted of four rock layer formations and the size is 2,000 meters laterally and 4,000 meters vertically. A CO_2 injection well over 1,200 meters deep is considered in the analysis. The final status (named as plume or bubble) of injected CO_2 has a thickness of H and extended width of X. A normal fault with a dip angle of α degrees is embedded in the overlying rock formation, the bottom end of which has a distance of W meters from the centre of the CO_2 plume (See Figure 2). The physical properties of rock layer formations are listed in Table 1.

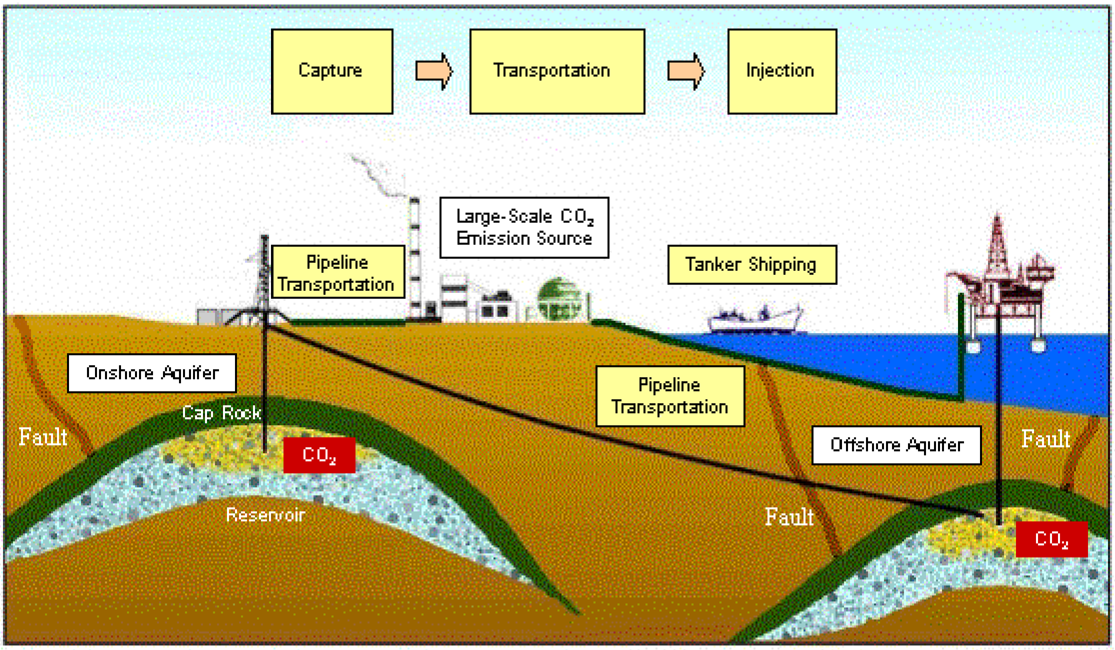


Figure 1. A modified conceptual drawing of CO_2 geo-sequestration (Soure: RITE)

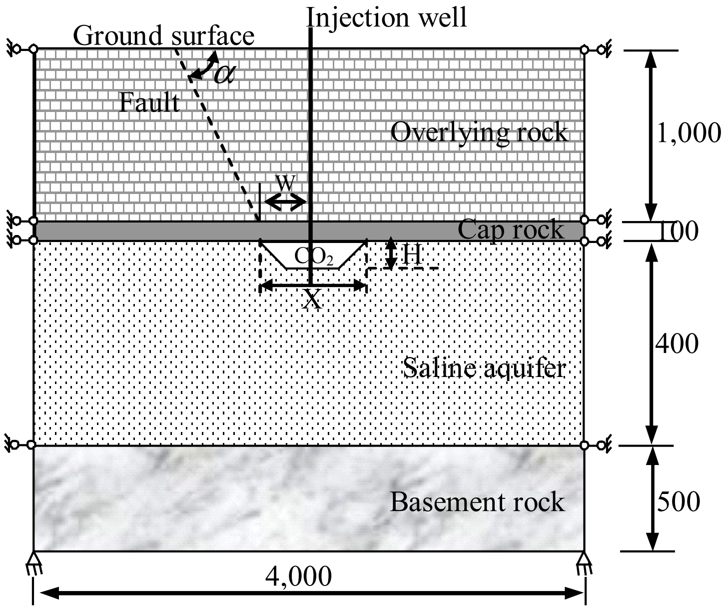


Figure 2. Profile of simplified geological model (Not-to-scale / Unit: m)

Table 1. Physical properties

Parameter	Basement rock	Saline aquifer	Cap rock	Overlying rock
Young's modulus (Pa)	$1.0x10^{10}$	$2.0x10^{9}$	$2.0x10^{9}$	$2.0x10^{9}$
Poisson's ratio (-)	0.25	0.25	0.25	0.25
Saturated density (kg/m^3)	2,600	1,900	1,900	1,900
Permeability (m/s)	$1.0x10^{-11}$	$1.0x10^{-6}$	$1.0x10^{-11}$	$1.0x10^{-7}$

Fault model

In a finite element analysis, modelling of status developments of a fault can be treated as a contact problem. Herein, a classical spring model is adopted to consider mechanical changes of a fault. Two flexible joint springs are used to devote to the simulation of normal and tangential mechanical behaviours of a fault. This proposed fault modelling can be depicted in the plot of Figure 3. The same normal stiffness $2.0x10^7$ N/m and shear stiffness $1.0x10^7$ N/m of the fault surfaces are chosen to use in the analysis (Li, Wu & Li 2002).

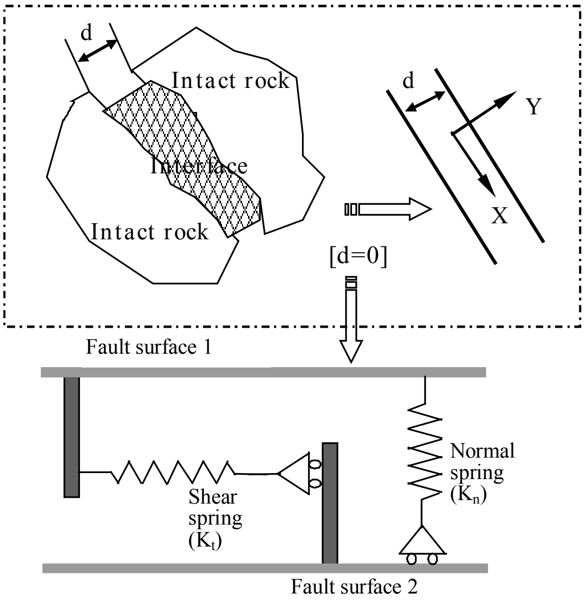


Figure 3. Fault modelling and local coordinates

CO$_2$ plume

Due to the density difference between aqueous formation water and CO$_2$, the supercritical CO$_2$ will eventually float toward the bottom of the cap rock layer. This density driven flow finally results in the birth of buoyancy of CO$_2$ plume at the bottom of the confining cap rock layer. During the analysis, the buoyancy is applied around the injection well and along the bottom of the cap rock layer as the distributed forces. Further description about the buoyancy pressure of CO$_2$ plume can be found in Li, Wu & Li 2002.

NUMERICAL SIMULATION AND RESULTS DISCUSSION

To inject CO$_2$ into a deep aquifer means an increase in pore pressure, which possibly results in fracturing or faulting in the surrounding strata and finally leads to the leakage of CO$_2$ from the storage aquifer. Site safety assessment and selection need a deep understanding of post-injection behaviours. In this section, two fault cases are evaluated. Fault cases are listed in Table 2. Firstly, the shear stress change on the fault due to the buoyant pressure is evaluated with and without consideration of pore pressure. Then, the local safety factor is considered as a measure to evaluate the mechanical stability of the faults.

Table 2. Two fault cases

Fault case	*W* (m)	*H* (m)
I	250	100
II	500	100

Shear stress change on fault due to buoyancy

Figure 4 shows the variation of the shear stress change of the fault under the same dip angle, 45 degrees but with or without consideration of the pore water pressure in the strata. After considering the pore water pressure, the absolute value of the shear stress change accordingly increases but it is not smooth along the fault surfaces and behaves an abrupt change at the deep bottom end of the fault. This abrupt situation may be interpreted as the block effect of the cap rock on the CO_2 induced buoyancy transfer. It results in the small difference of mechanical changes at the bottom end of the fault. The gravity effect serves on an important role to bring local extrema around 700 meters. In Figure 4, w/oPor and wPor denote the case is evaluated without or with consideration of the pore water pressure. Some further and detailed analyses can be found in Li, Wu & Li (2002, 2004) and Li & Wu (2005).

Local safety factor

As we have known, the Mohr-Coulomb failure criterion is often applied in geotechnical engineering analysis. In our research, we consider the safety factor used in the practical engineering from another viewpoint. A value close to the failure level, as shown in Figure 5, is adopted as the local safety factor, F_s, and it is used to evaluate the stability of the faults without considering the effects of pore water pressure. Figure 6 presents the local safety factor of the faults, Case I and Case II, which are analyzed according to three different dip angles, 30 degrees, 45 degrees and 60 degrees. From Figure 6, the following two trends can be observed: when a fault is being far away from the disposal zone, the value of the safety factor will increase; the high-dip fault easily gets the high value of the safety factor. This is an important and easy-to-apply factor to evaluate the obvious influence of CO_2 sequestration on the geomechanical site system.

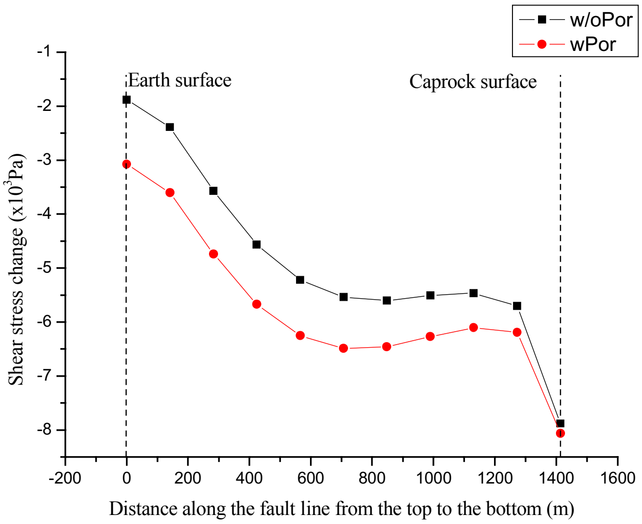
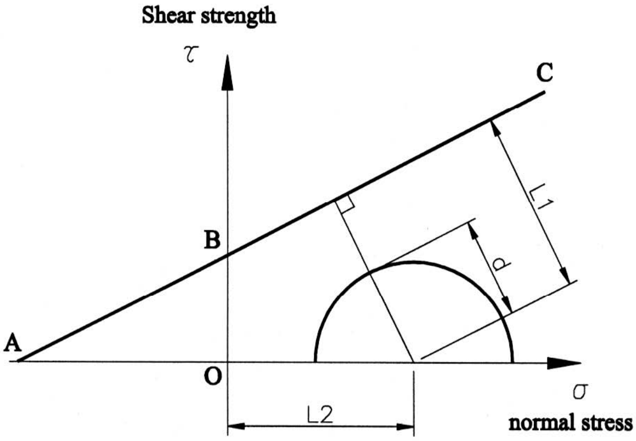


Figure 4. Shear stress change of fault Case I under the same dip angle, 45 degrees



$$F_s = \frac{\min(L1, L2)}{d}$$

Figure 5. Definition of local safety factor

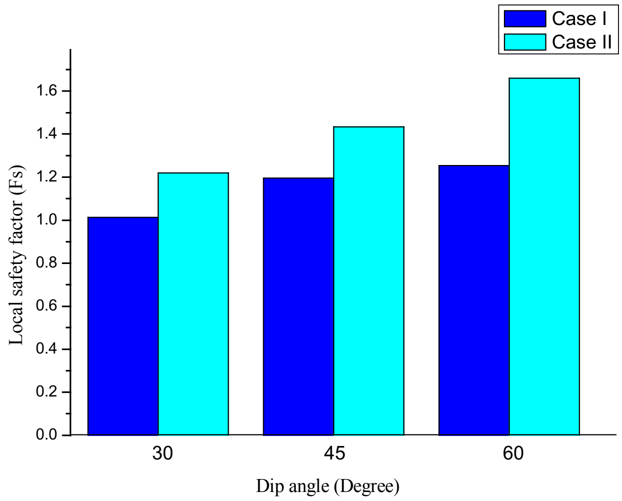


Figure 6. Local safety factor of two fault cases with three different dip angles

ASSESSMENT FLOWCHART AND POTENTIAL SITE EVALUATION

As an important evaluation factor, the local safety factor is emphasized to consider the shear stress along fault surfaces. In order to consider the full thermo-hydro-mecho-chemical (THMC) behaviours of the fault and the whole site stability, our proposed assessment flowchart is illustrated in Figure 7 for the CO_2 geo-sequestration system.

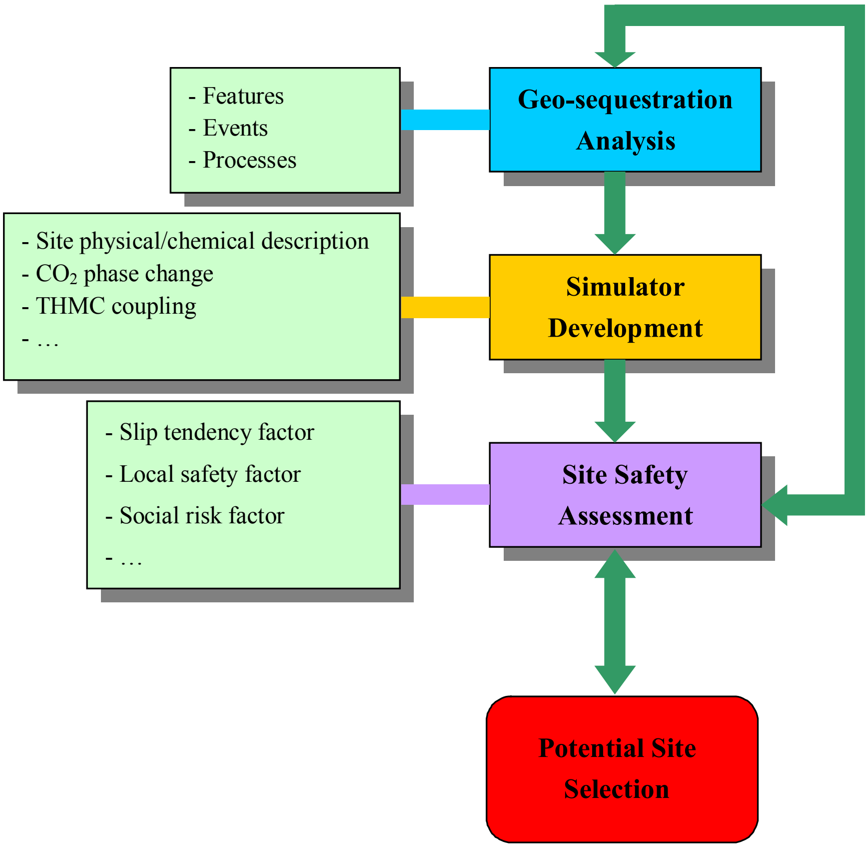


Figure 7. Site assessment flowchart

The general idea of CO_2 geologic sequestration is to inject and dispose the GHG (usually, in a supercritical state) in deep permeable formations that are confined by impermeable (or low permeable) cap rocks so that the GHGs can be almost completely isolated from the atmosphere for a very long period. In Japan, saline aquifers in sedimentary basins have the largest storage capacity and most extensive distribution, as suggested by Tanaka et al. (1995). In a general way, a geologic structure that has confined connate over-pressured water for a geologic period can potentially trap a reasonable volume of CO_2 as long as the cap rock maintains its hydraulic integrity. The damage of the hydraulic integrity may result from the combining effects of such factors as injection pressure and buoyant pressure that may modify the mechanical conditions of the strata.

As the simulations revealed, the buoyant pressure may exert a certain significant influence on the stability of the fault close to CO_2 plume. With this in mind, one may reasonably expect that the sites with relatively sparsely distributed faults are preferred as promising sequestration sites. Another condition is that the sites should be enough stable to tolerate the injection pressure and buoyant pressure that tend to decrease the stability.

The sites with sparse faults can be found based on fault distribution data (Figure 8). Exactly, there are plenty of areas with sparse faults, including the eastern and south-western Hokkaido, the Pacific coastal areas of the east Japan, Japan sea coastal areas of the west Japan, and Kyushu (GSJ 1996). Theoretically, the mechanical stability of a site is governed by weak discontinuities, i.e. primary faults. The stability of a fault can be evaluated by its shear strength and the stresses exerted on it. However, the quantitative measurements of the quantities are not realistic, so in general the stability of the sites is difficult to directly evaluate. Herein, we think that geologic phenomena such as active faults and shallow earthquakes may be reliable indicators of the site stability. Figure 9 shows the distribution of the active faults (Active Fault Research Society, 1991).

Figure 10 shows the location of the 113 fossil fuel fired power plants in operation and under construction, and some of the major potential storage sites, by synthesizing fuel resource map of Japan and location map of thermal power plants (METI 2001; Safety and Environment Center for Petroleum Development 1994; Japan Natural Gas Association 1992). The four categories of the storage sites are classified based on each site's geologic structural features.

- Category I: oil and gas reservoirs and neighboring aquifers
- Category II: aquifers in anticlinal structures
- Category III: aquifers in monoclinal structures on land
- Category IV: aquifers in monoclinal structures offshore

The storage sites of categories II, III and IV are indicated in Figure 10. The economically promising storage sites may be selected from the sedimentary basins on the land or offshore of four main islands of Japan.

The combination of the above information on faults and active faults leads to a map that indicates the sedimentary basins with sparse faults and active faults, therefore relatively higher stability (Figure 11). In Figure 11, the locations of the stable and mobile sedimentary areas are traced out. The areas are bounded by coastlines, 1000m sedimentary isopaches and 500m sea depth isograms, based on Fuel Resources Map of Japan (GSJ 1992) with a scale of 1:5,000,000. It can be seen that although Japan is situated at tectonically active zone, there are still plenty of mechanically stable areas on land and off shore.

Figure 8. Distribution of on-land faults

CONCLUDING REMARKS

In this paper, a typical geo-sequestration site is considered and the shear stress change, dip angle effect and local safety factor have been discussed under numerical analyses. Then, an assessment flowchart is proposed for an exact site analysis of CO_2 geo-sequestration. Some major concerns, which are conducted to investigate and develop site selection criteria and operational constraints for potential disposal areas, are put forward, especially near fault zones of seismic concerns in Japan. Finally, we are attempting to identify some potential sequestration sites, mainly mechanically stable sedimentary basins, with relatively high mechanical stability based on the historic data of faults and active faults.

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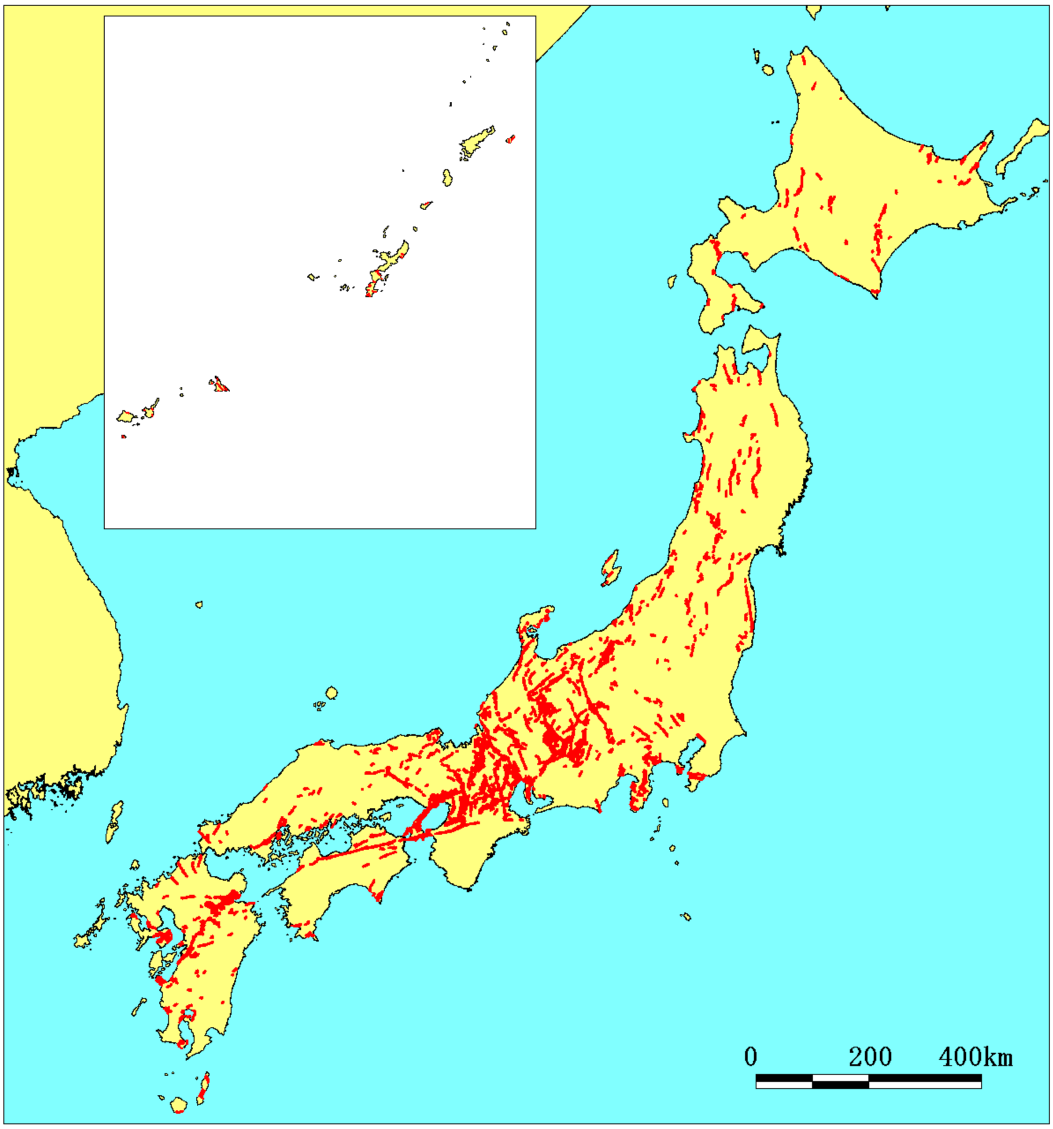

Figure 9. Distribution of on-land active faults

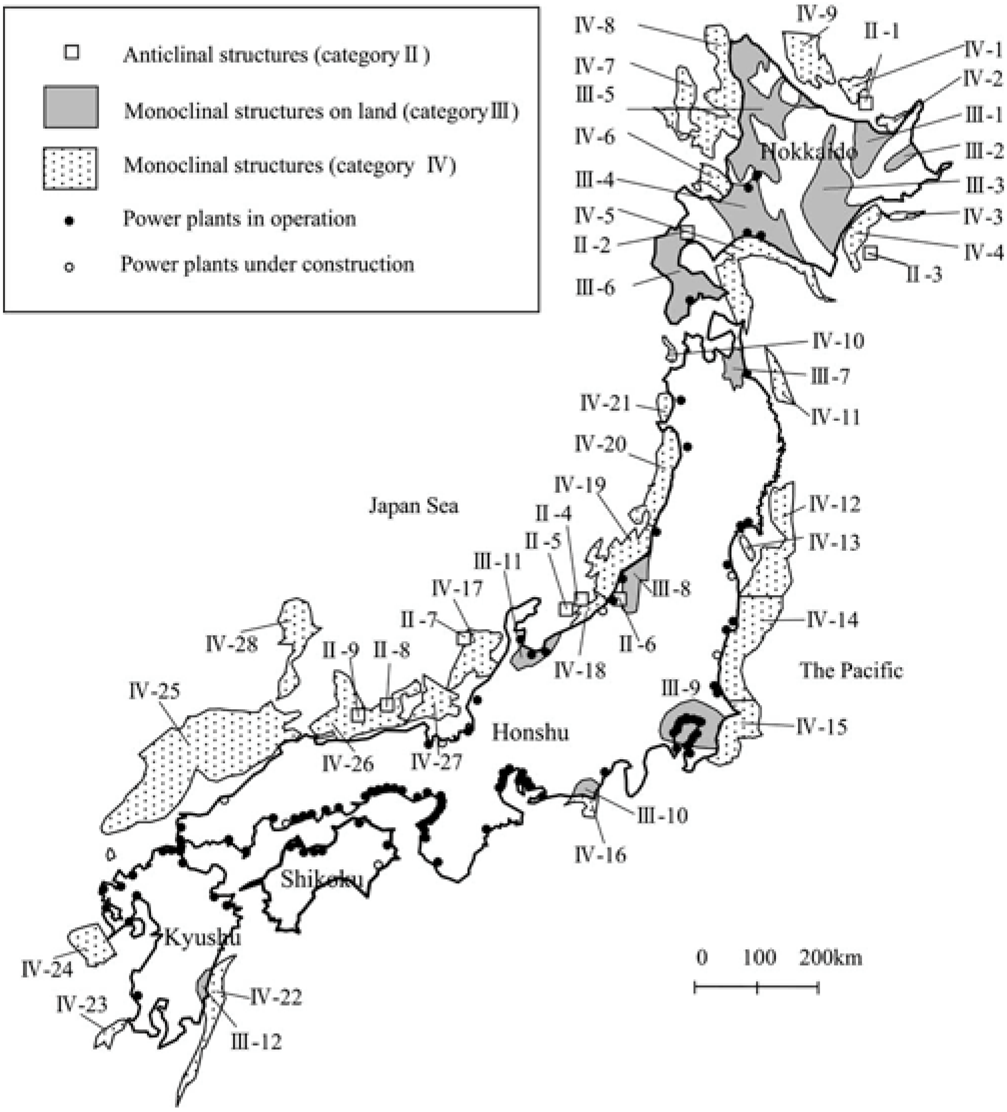

Figure 10. Location map of fossil fuel fired power plants and potential storage sites

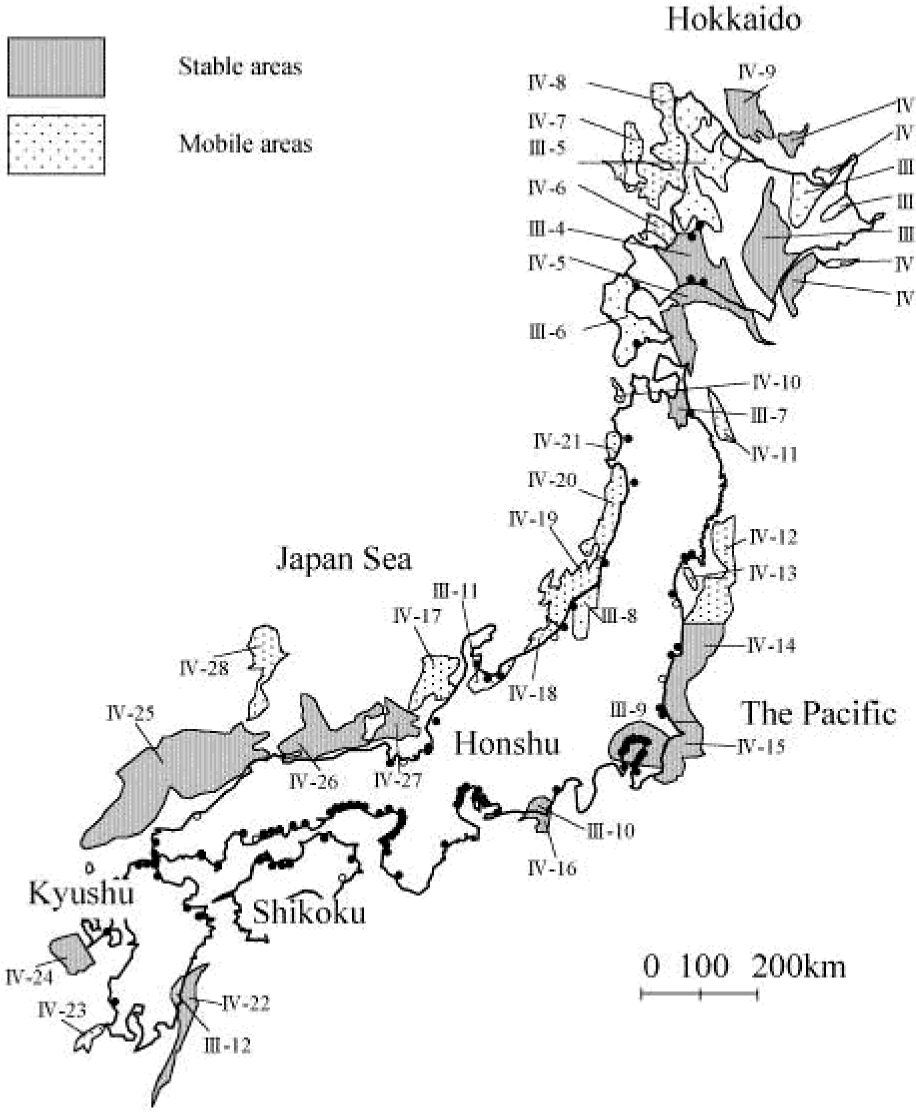

Figure 11. A map shows the locations of stable and mobile sedimentary areas of Japan

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