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Screening and Selection of CO_2 Storage Sites

Outline

- CO_2 storage assessment scales
- Basin and regional scale screening criteria
- Local and site-scale screening criteria
- Estimation of CO_2 storage capacity

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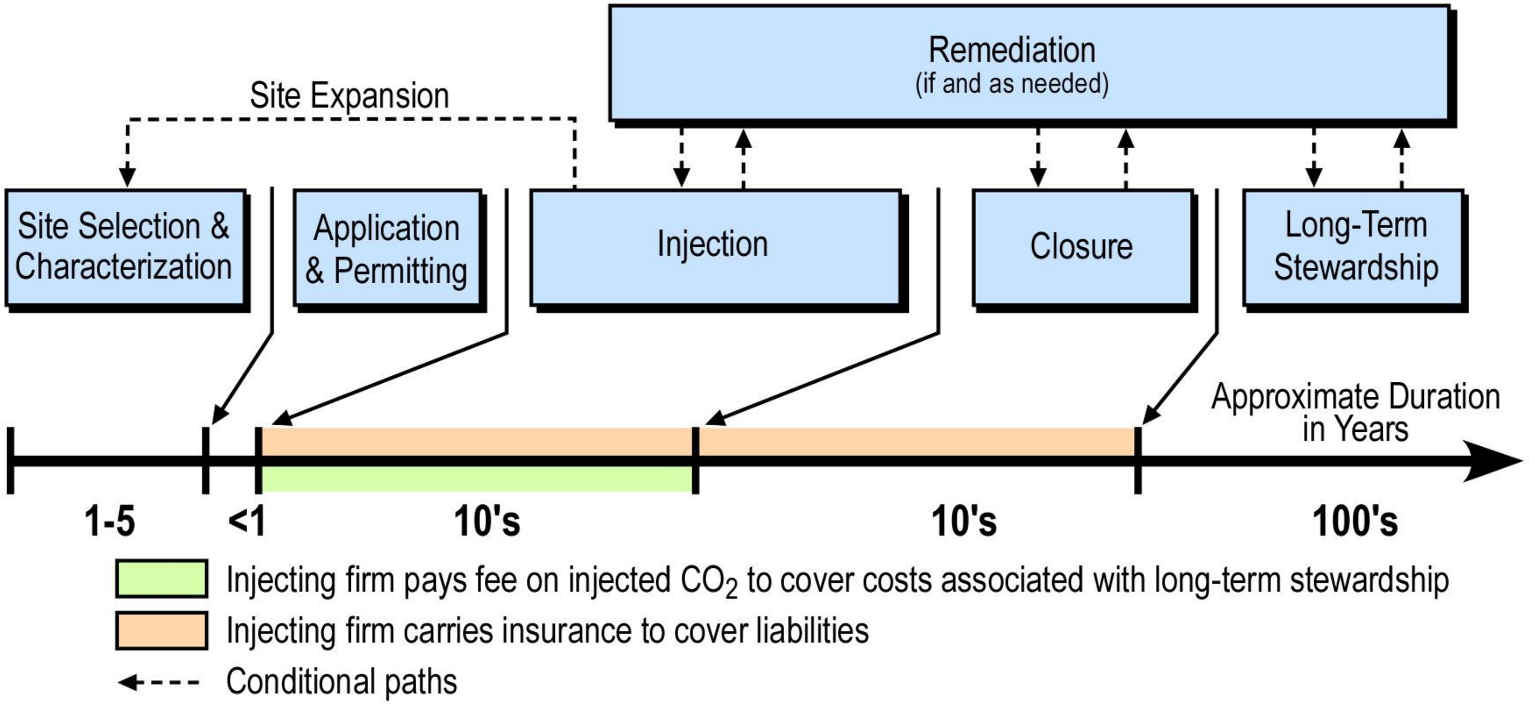
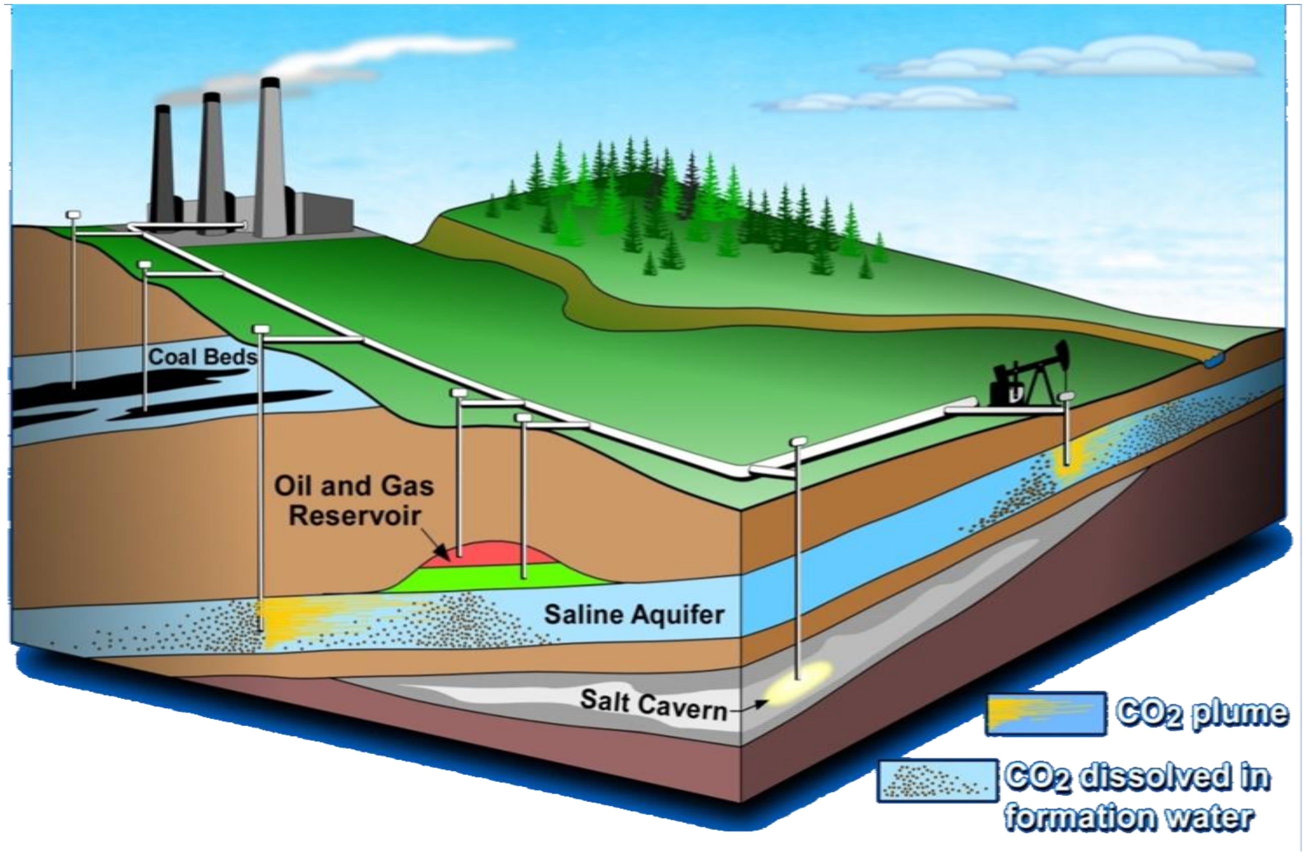
Operational Stages of CO_2 Storage



modified after Rubin et al., 2007

Site characterization is a continuous, iterative process during all operational stages of a CO_2 storage project

Geological Media Suitable for CO_2 Geological Storage



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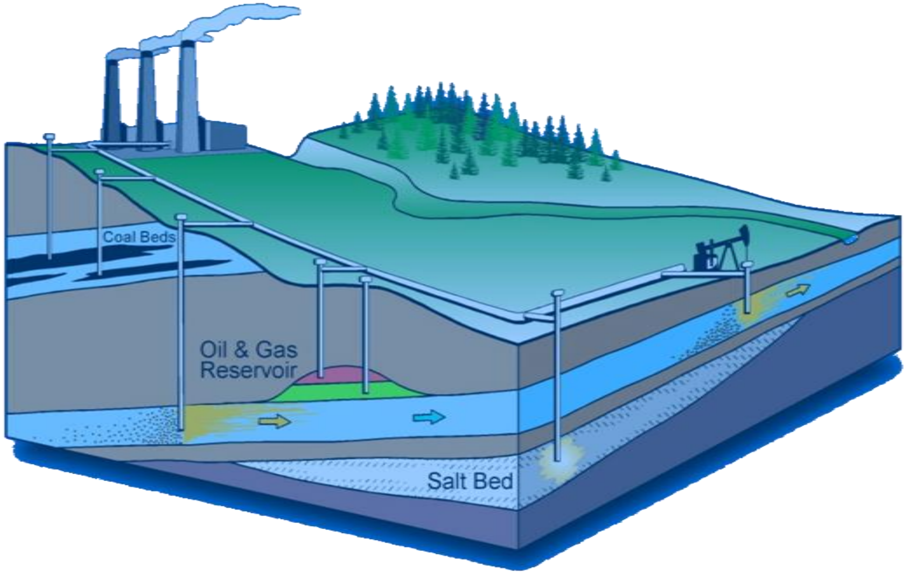
CO_2 Storage Assessment Scales



Basic Principles

- Site selection criteria are the criteria by which a site is assessed, evaluated, judged, and, in the case of multiple possible sites, ranked for final selection and qualification

- Site selection and characterization depend on the scale of the assessment

- Storage safety and security is a common thread throughout all the stages of the operational chain and has to be demonstrated when applying for tenure of the storage unit and permit to operate, during operations, and after cessation of injection to complete site abandonment

- Site characterization represents a collection of types of data and information needed to reach the necessary understanding and confidence that the proposed storage site is safe and acceptable

- Site characterization is a continuous, iterative process during all operational stages of a CO_2 storage project

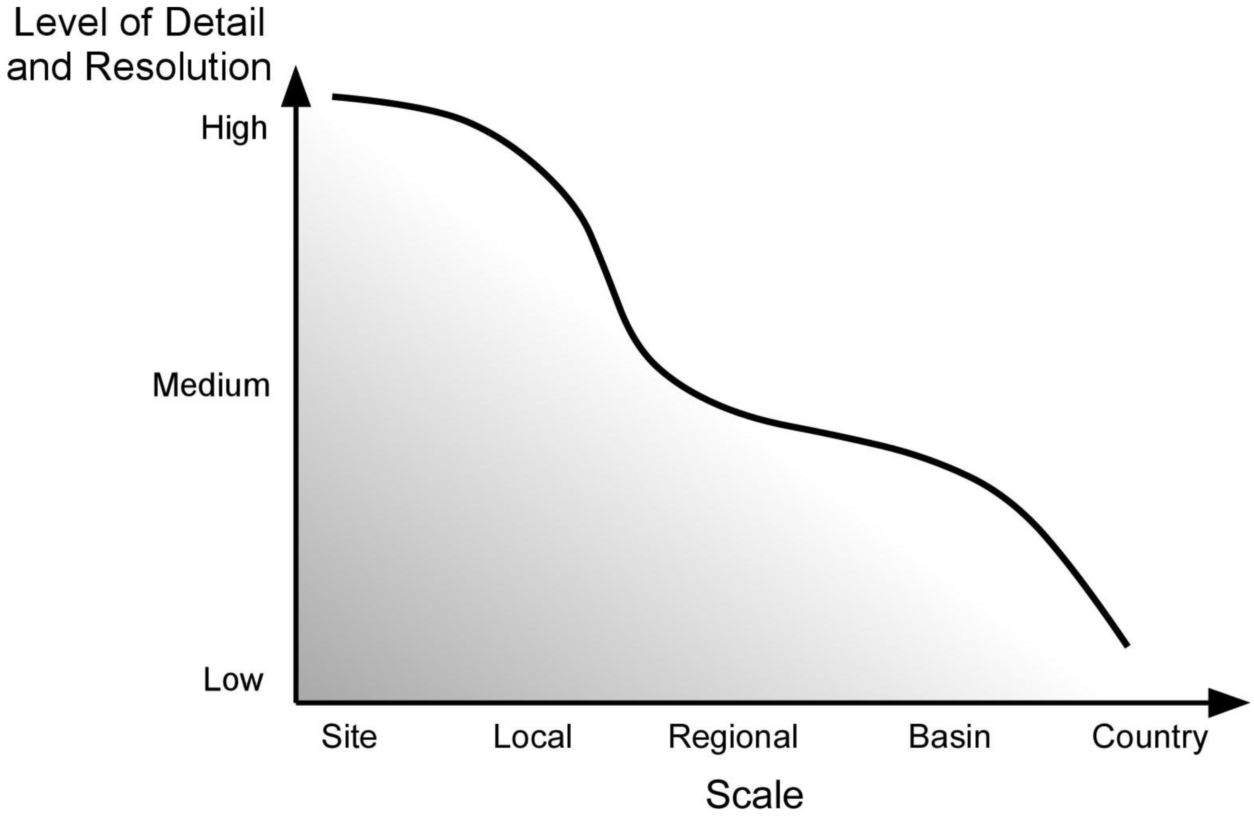
- Monitoring is a key element in site operation and closure, and is likely to be a permitting requirement

Assessment Scales and Resolution

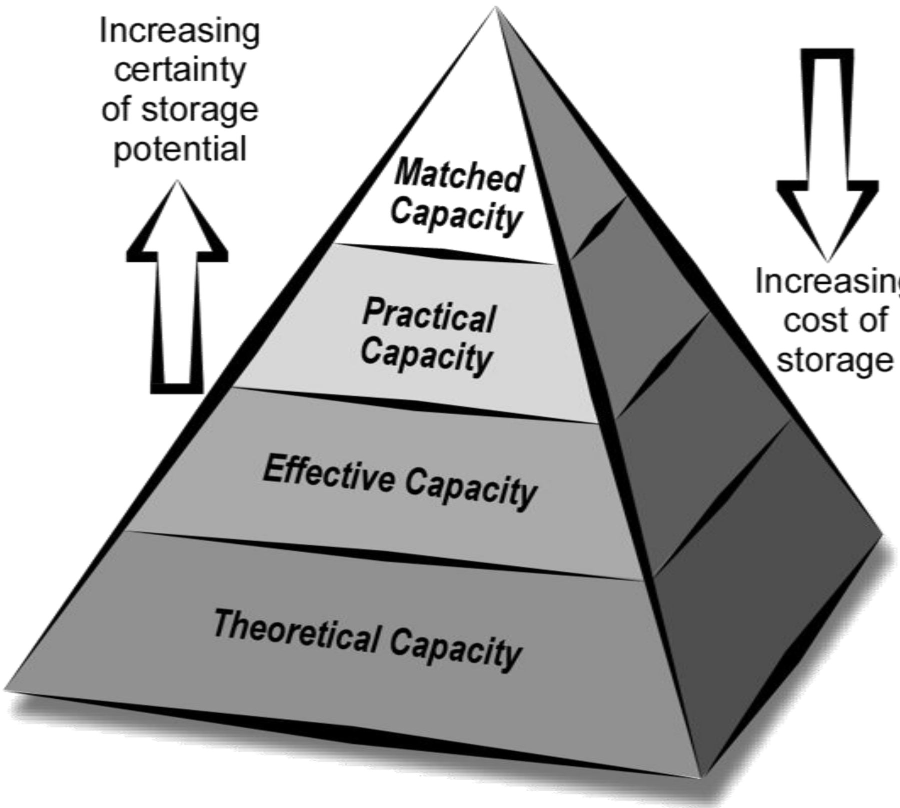
- **Country**: high level, minimal data
- **Basin**: identify and quantify storage potential
- **Regional**: increased level of detail, identify prospects
- **Local**: very detailed, pre-engineering site selection
- **Site**: engineering level for permitting, design and implementation

Note: Depending on the size of a country in relation to its sedimentary basin(s), the order of the top two or three may interchange

Relationship Between Assessment Scale and Level of Detail and Resolution



Techno-Economic Resource-Reserves Pyramid for CO_2 Storage Capacity



Required Characteristics of Geological Media Suitable for Storage of Fluids

- Capacity, to store the intended CO_2 volume
- Injectivity, to receive the CO_2 at the supply rate

In real time, i.e., during the active-injection phase

However, if capacity and/or injectivity are insufficient, some measures can be taken (e.g., use multiple and/or horizontal wells, use several storage sites, store less CO_2)

- Containment, to avoid or minimize CO_2 leakage

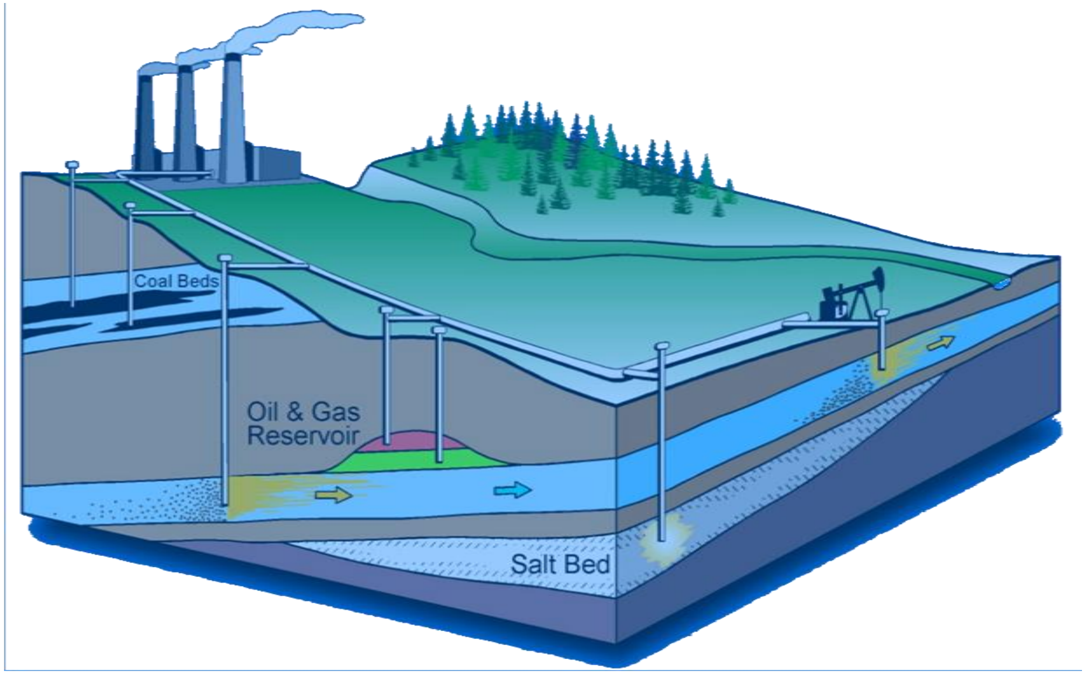
During all phases of a CCS operation

If containment is defective, then the prospective site is disqualified!

Screening and Selection of Sites for CO_2 Storage

- At the basin scale
- At the local scale

Basin and/or Regional Scale Screening

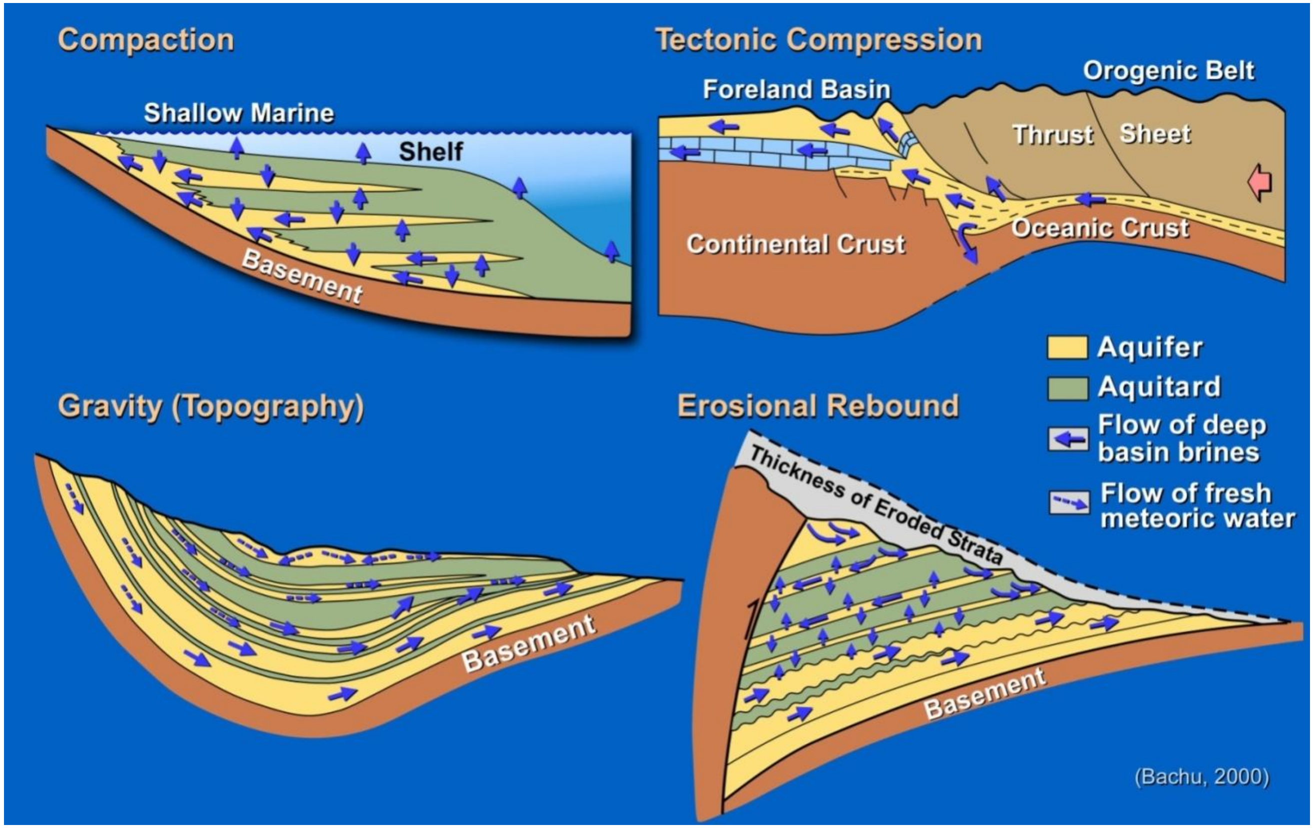


Flow of Formation Waters in Sedimentary Basins

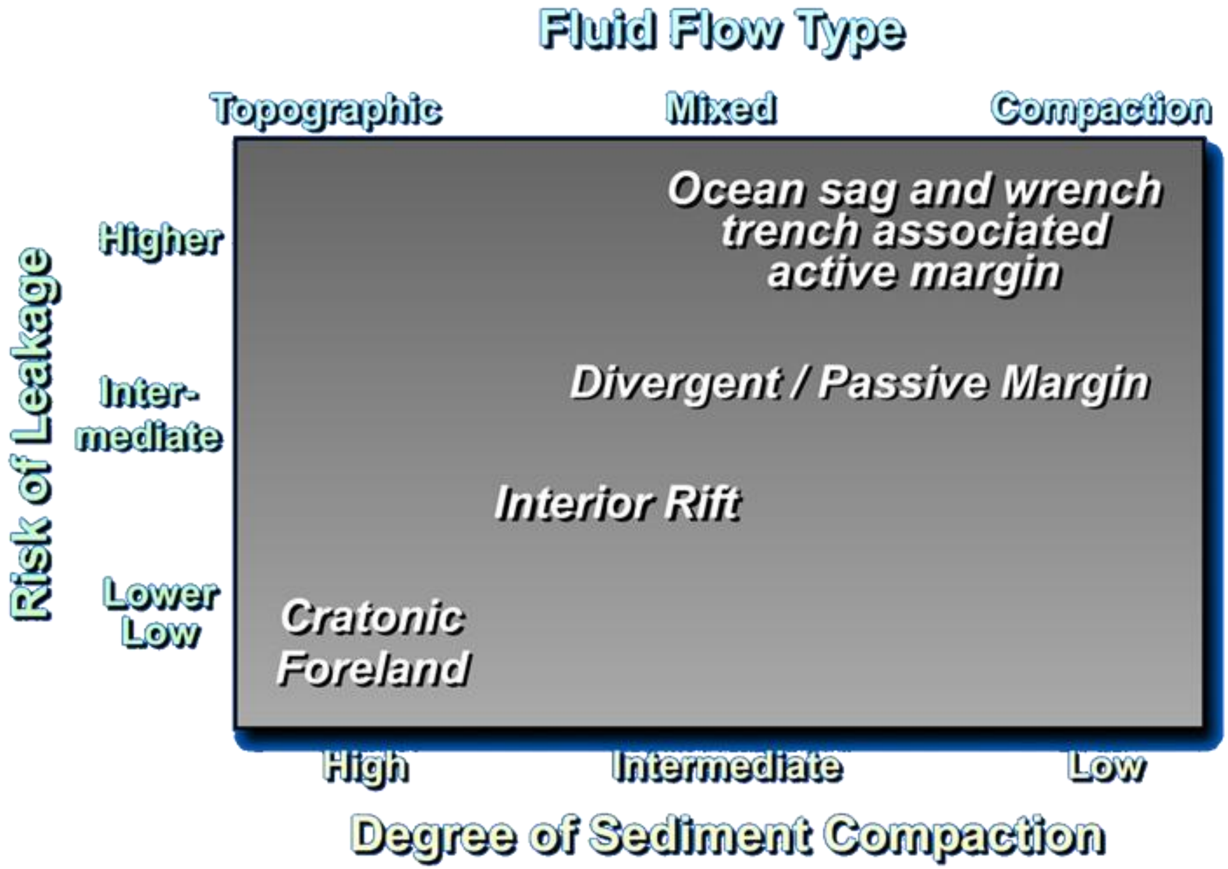
Flow driven by:

- Sediment compaction on marine shelves
- Topography (gravity) in intra-montane, foreland and intra-cratonic basins
- Tectonic compression in orogenic belts
- Erosional and/or glacial rebound
- Hydrocarbon generation and other internal overpressuring processes

Types of Fluid Flow in Sedimentary Basins



Risk of Leakage in Sedimentary Basins



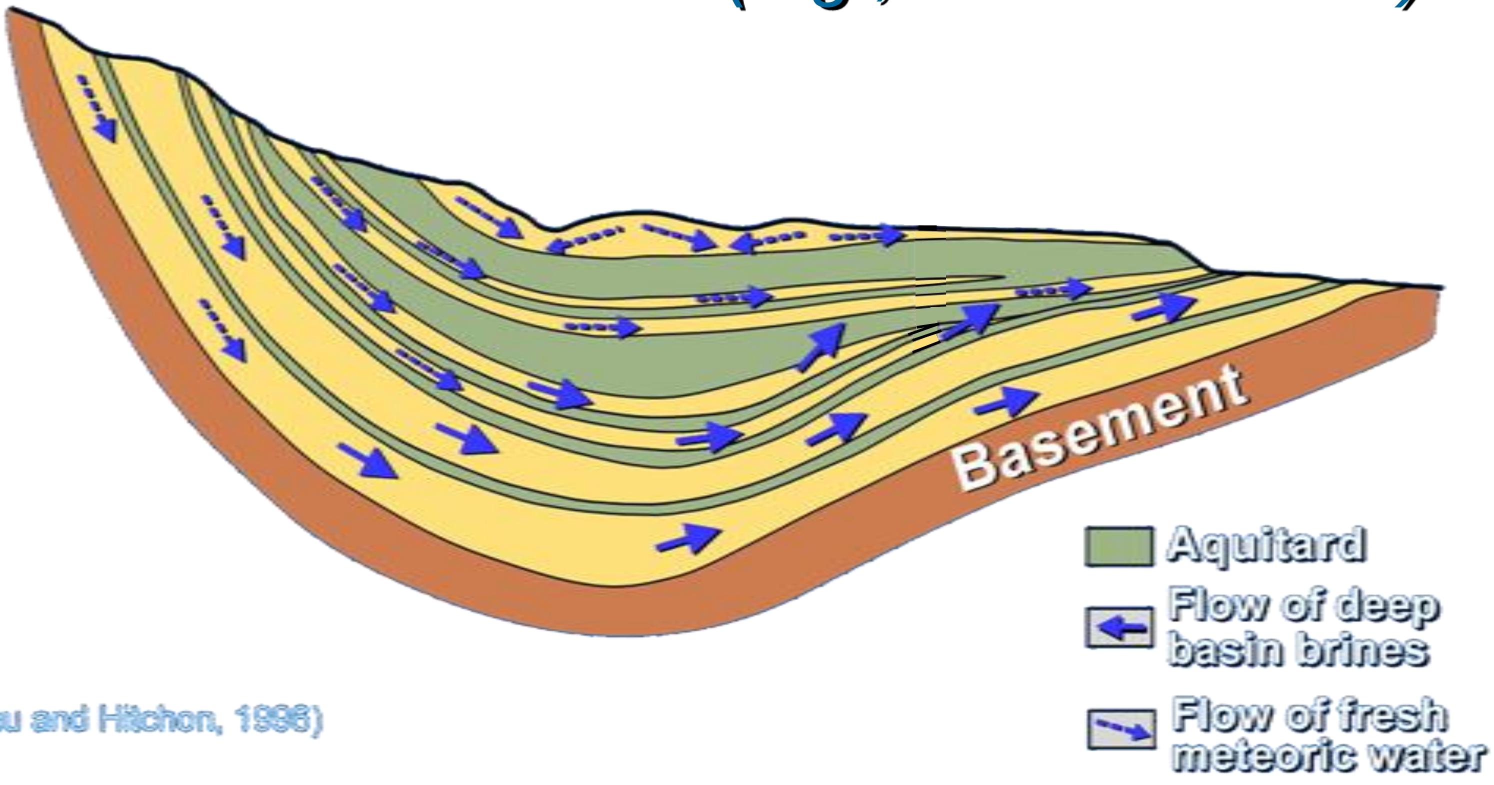
(Hitchon et al., 1999)

Hydrodynamic Characteristics of Geological Media Suitable for CO_2 Storage

- Regional-scale competent sealing units (aquitards or aquicludes, aka caprock)
- Favorable pressure conditions (i.e., not overpressured)
- Favorable flow systems (deep, long travel time)
- Adequate porosity (storage space)
- Adequate permeability (injectivity)

Preferred Flow Systems

Deep, regional scale, driven by topography or erosional rebound (e.g., Williston Basin)



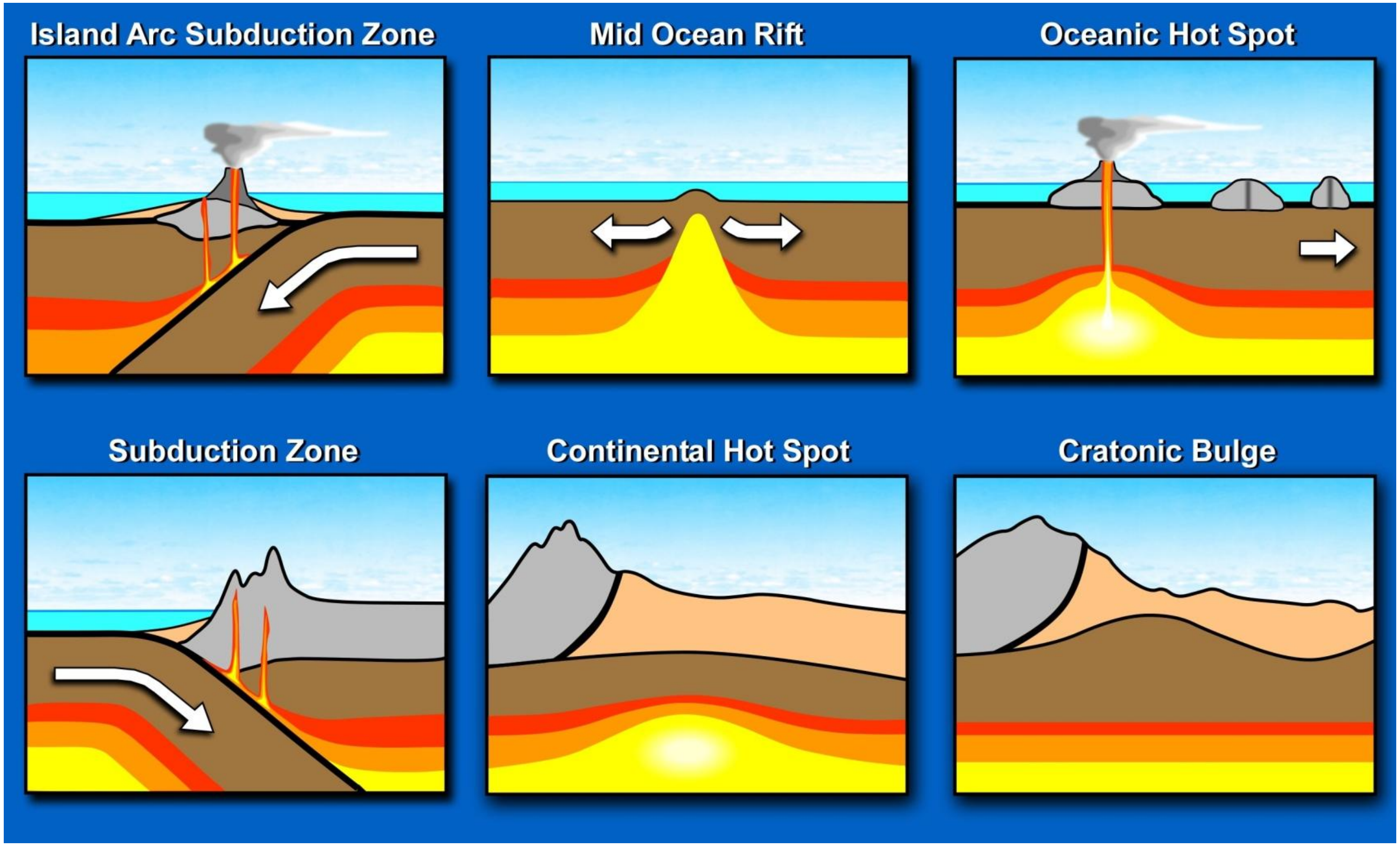
(Bachu and Hitchon, 1996)

Geothermal Regime in Sedimentary Basins

Depends on:

- Basin type, age and tectonism
- Proximity to crustal heat sources
- Basement heat flow
- Thermal conductivity and heat production of rocks
- Temperature at the surface

Plate Tectonics and Earth's Heat Flow



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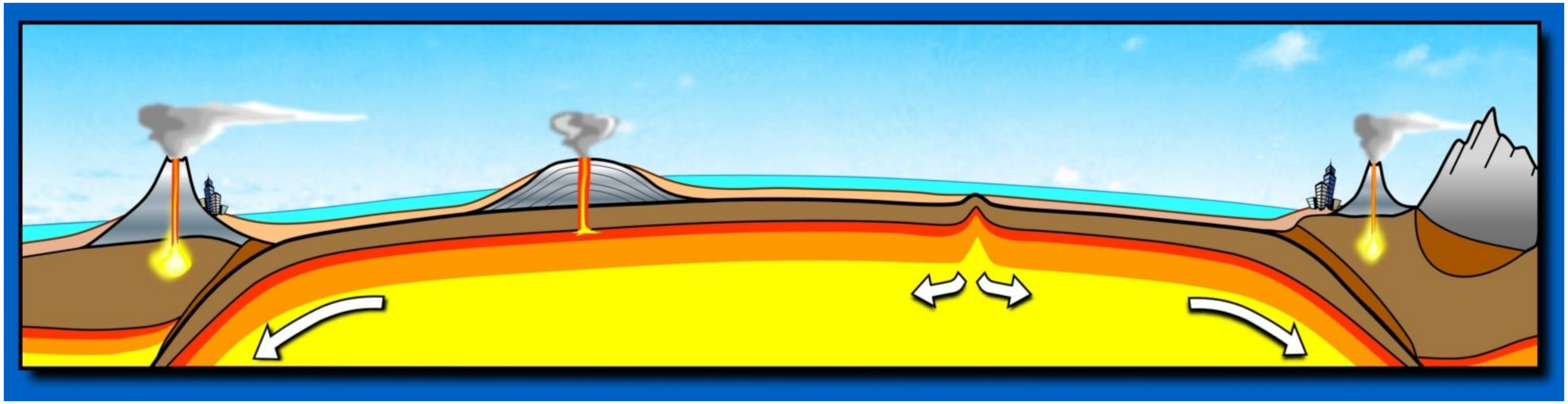
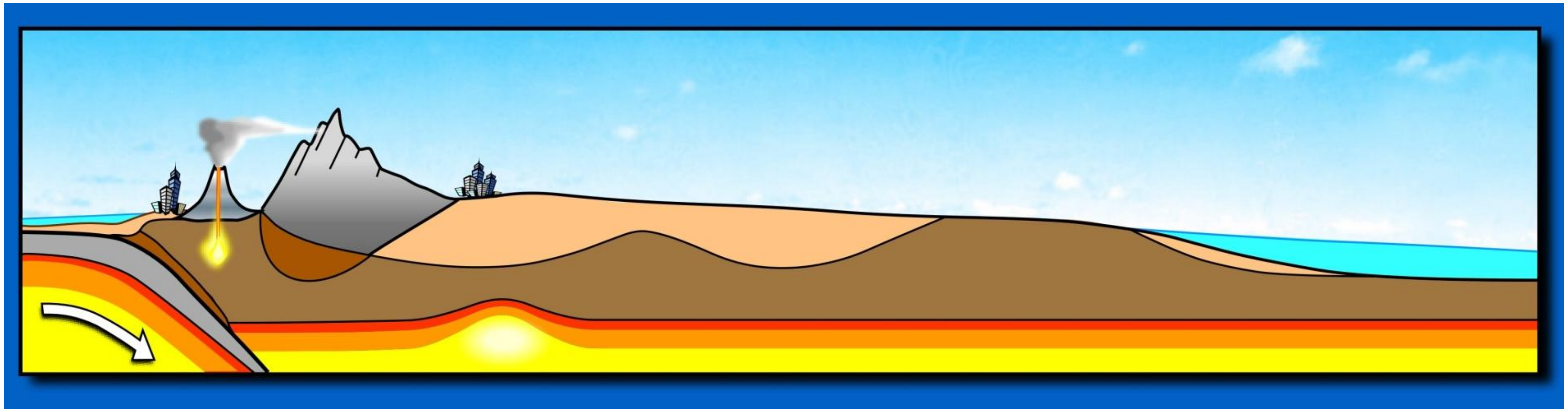
Heat Flow in Pacific and North American Plates

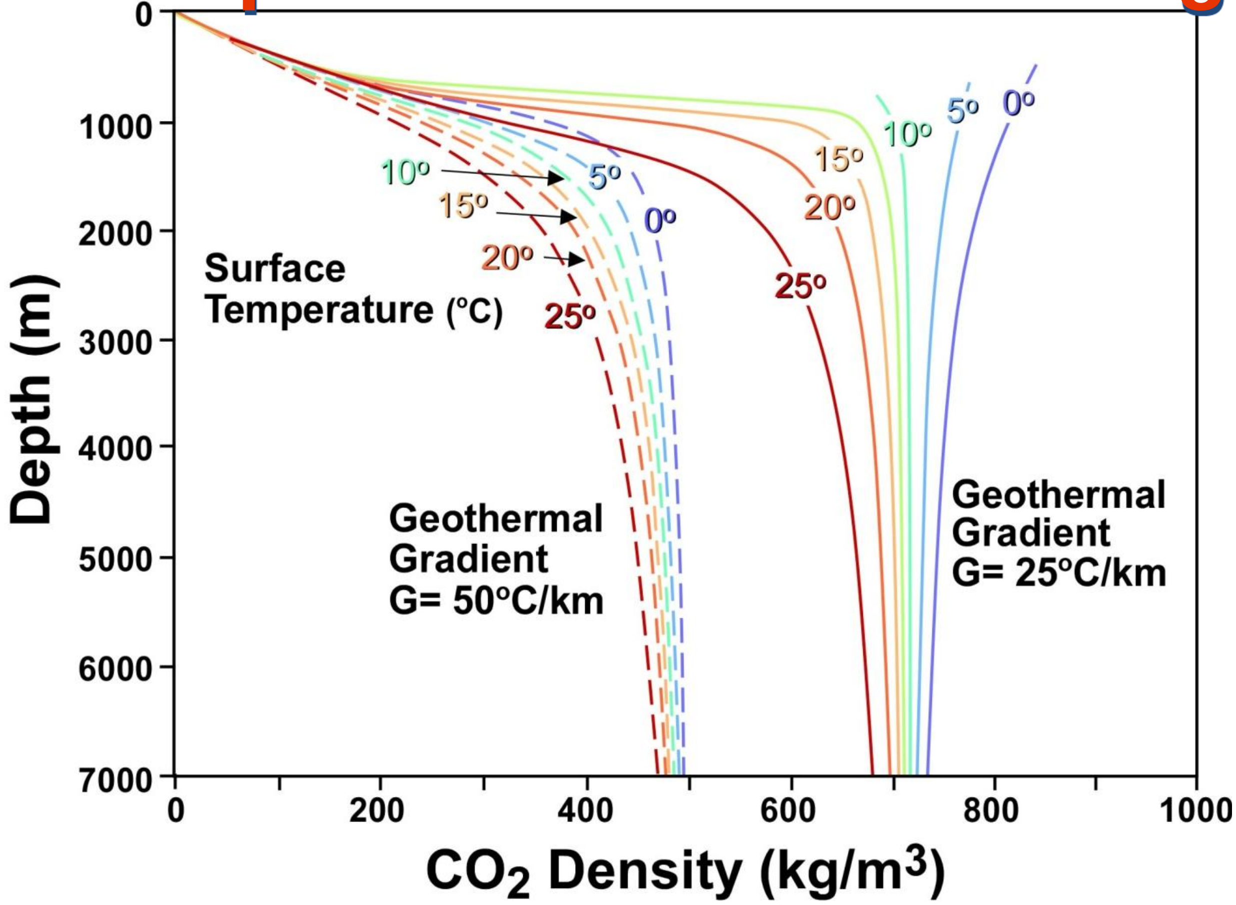




Surface Temperature for Sedimentary Basins

- Marine basins: 3-4 ^oC at the bottom of the sea/ocean
- Continental (sub) Arctic and (sub) Antarctic basins: -2 ^oC below the permafrost
- Continental temperate basins: 4-10 ^oC depending on latitude and altitude
- Continental tropical basins: 10-25 ^oC depending on latitude and altitude

Variation of CO_2 Density with Depth and Geothermal Regime



Sedimentary Basins by Geothermal Regime

Cold basins:

- Low surface temperature and/or geothermal gradients
  - more favorable (higher CO_2 density, at shallower depths)

Warm basins:

- High surface temperature and geothermal gradients
  - less favorable (lower CO_2 density, larger depths needed)

Geothermal Characteristics of Geological Media Suitable for CO_2 Storage

Low temperatures ("Cold Basins"), resulting from:

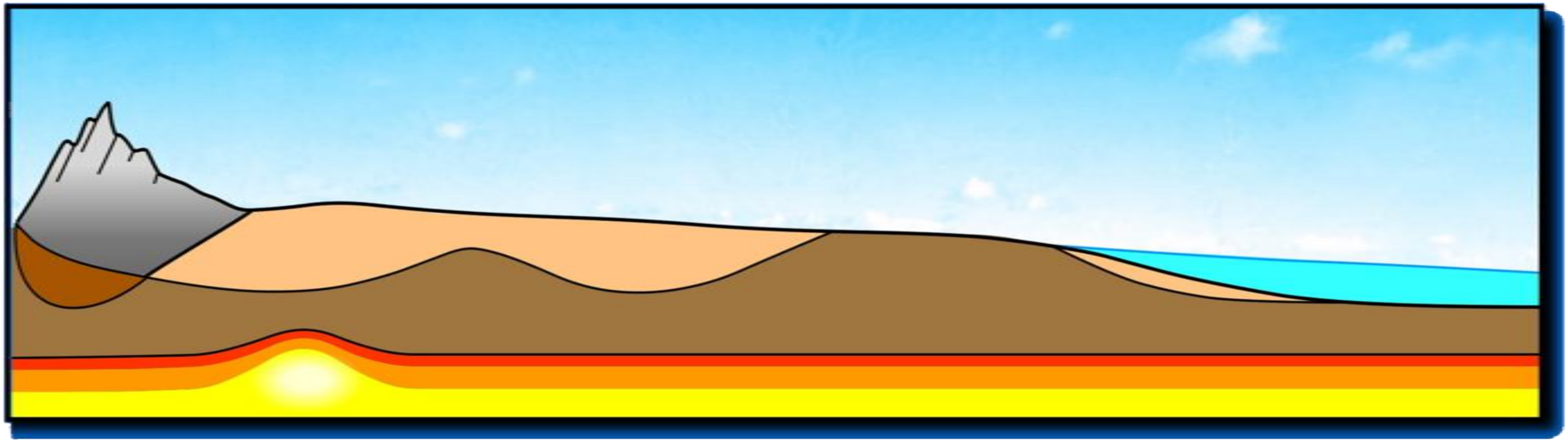
- Low geothermal gradients
- Low surface temperatures

Effects

- Higher density, hence higher storage efficiency
- Less buoyancy, hence smaller driving force for migration and/or leakage

Preferred Sedimentary Basins

Intra-cratonic, foreland and passive-margin basins



Basin Maturity

Defined by fossil-energy potential (oil and gas, coals) and degree of exploration and production

Mature:

- Rich in energy resources, advanced production

Immature:

- Rich in resources, in exploration & early production stage

Poor:

- No or poor in hydrocarbon resources

Industry Maturity and Infrastructure

Developed continental basins:

- Access roads, pipelines, wells (e.g., Texas, Alberta)

Developed marine basins:

- Drilling and production platforms (e.g., North Sea)

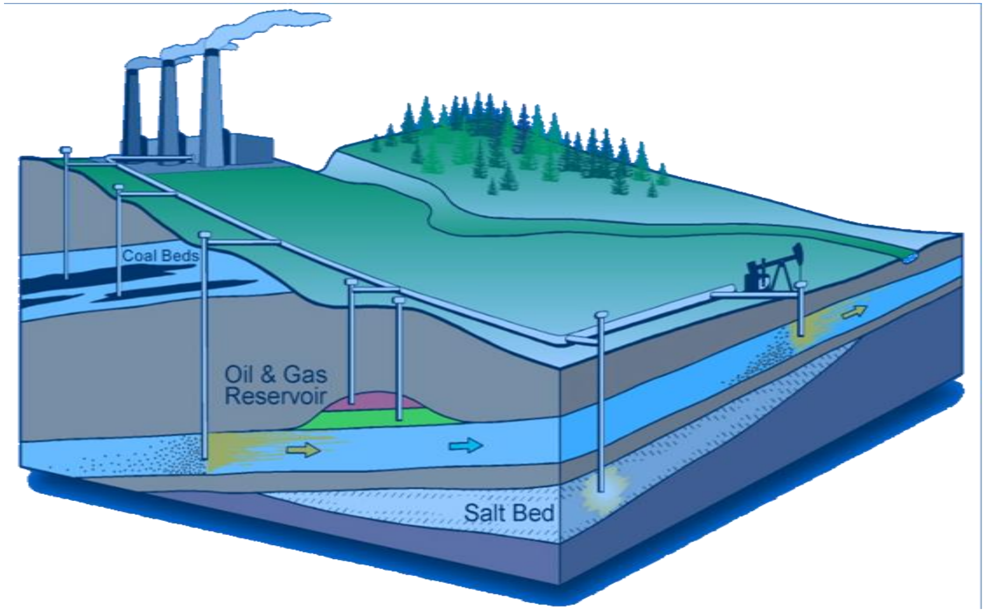
Eliminatory Criteria for Sedimentary Basins

	Criterion	Unsuitable	Suitable
1	Depth	< 1000 m	>1000 m
2	Aquifer-seal pairs	Poor (few, discontinuous)	Intermediate, excellent
3	Pressure regime	Overpressured	Hydrostatic
4	Seismicity	High and very high	Very low to moderate
5	Faulting and fracturing	Extensive	Limited to moderate
6	Hydrogeology	Shallow, short flow systems	Intermediate, regional-scale flow systems
7	Areal size	<2500 km^2	>2500 km^2
8	“Legal accessibility”	Forbidden	Allowed

Desirable Characteristics of Sedimentary Basins

	Criterion	Undesirable	Desirable
1	Within fold belts	Yes	No
2	Significant diagenesis	Present	Absent
3	Geothermal regime	Warm basin	Cold basin
4	Evaporites	Absent	Present
5	Hydrocarbon potential	Absent/small	Medium/giant
6	Industry maturity	Immature	Mature
7	Coal seams	Absent, shallow or very deep	Between 400 m and 800 m depth
8	Coal rank	Lignite/Anthracite	(sub) Bituminous
9	Coal value	Economic	Uneconomic
10	On/offshore	Deep offshore	Onshore, shallow
11	Climate	Harsh	Moderate
12	Accessibility	No or difficult	Good
13	Infrastructure	Absent/undeveloped	Developed
14	CO_2 sources <500 km	Absent	Present

Local and Site-Scale Screening Criteria



Types of Site Selection Criteria

- Sites must pass the basin-scale eliminatory criteria, and should broadly possess basin-scale desirable characteristics
- Sites must pass and/or meet criteria that fall broadly into five categories:
  - Capacity and injectivity
  - Confinement, i.e., safety, security and environmental acceptability
  - Legal and regulatory restrictions
  - Economic
  - Societal (public acceptance)

- The same criteria can be organized into:
  - Eliminatory criteria: sites are eliminated if they don’t meet these criteria
  - Selection criteria: sites are selected if they meet most or the preferred of these criteria, depending on local circumstances

Safety Criteria

- Avoid contamination of energy, mineral and groundwater resources
- Avoid risk to life (vegetation, animal, human)
- Avoid or minimize equity impact
- Avoid, or minimize, leakage for the desired time period

Eliminatory Site Selection Criteria - 1

Sites under consideration should be eliminated if they are:

1. Legally inaccessible (in protected areas)
2. Legally unreachable (right of access cannot be secured)
3. Legally unavailable (e.g., equity interest held by third parties)
4. Physically unavailable (e.g., a hydrocarbon reservoir in production, an aquifer used for geothermal energy or for natural gas storage)
5. Located in high-density population areas – ‘flexible’
6. Potentially affecting other natural, energy and mineral resources and equity

Eliminatory Site Selection Criteria - 2

7. Within the depth of protected groundwater
8. In hydraulic communication or contact with protected groundwater
9. Located at shallow depth (<750-800 m) - debatable!
10. Lacking at least one major, extensive, competent barrier to upward CO_2 migration
11. Located in an area of very high seismicity
12. Located in over-pressured strata
13. Lacking monitoring potential

Site Selection Criteria - 1

Sites under consideration should be selected if they meet as many as possible of the following criteria:

For efficacy of storage:

1. Sufficient capacity and injectivity: they are not independent, injectivity may limit capacity!
2. Sufficient thickness
3. Low temperature
4. Favorable pressure and hydrodynamic regime

Site Selection Criteria - 2

For safety and security of storage:

5. Low number of penetrating wells
6. Presence of multi-layered overlying system of aquifers and aquitards (secondary barriers to upward CO_2 migration)
7. Potential for attenuation of leaked CO_2 near and at surface

Site Selection Criteria - 3

For cost/economics:

8. Accessibility and infrastructure (location, terrain, climate, right of access, avoidance of populated/protected areas)

9. Transportation economics (distance from source, pipelines of shipping facilities, compression and site delivery)

10. Storage economics (site facilities, wells and compression, operational and environmental monitoring)

Additional Site Selection Criteria?

- Depth
- Thickness
- Porosity
- Permeability
- Water salinity

These have been suggested in the past, but they are implicit in (proxies for) the criteria of capacity, injectivity, and protection of groundwater and/or mineral resources

They still can be used as selection criteria, but they are not completely independent and changes in one may affect another

Economic Selection Criteria

- Potential for additional energy production (EOR, EGR, ECBMR)
- Penalty avoidance by meeting regulatory requirements
- Access to surface infrastructure and right of access
- Avoidance of land and subsurface-use conflicts
- Optimization of storage depth to reduce costs of
- drilling and compression

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Critical Site Qualification Criteria

	Criterion	Eliminatory Condition	Acceptable Condition
1	Sealing	Poor, faulted, breached,	Multi-layered system
2	Pressure gradients	>14 kPa/m	< 12 kPa/m
3	Monitoring potential	Absent	Present
4	Affecting groundwater	Yes	No

A site must pass all these criteria to be considered for CO_2 storage

Essential Site Qualification Criteria

	Criterion	Eliminatory Condition	Acceptable Condition
1	Seismicity	High	Moderate and less
2	Faulting and fracturing intensity	Extensive/high	Limited to moderate
3	Flow systems	Short and/or in communication with protected groundwater	Intermediate and regional scale

A site should pass all these criteria to be considered for CO_2 storage, but exceptions can be made

Desirable Site Qualification Criteria - 1

	Criterion	Unfavorable	Favorable
1	Within fold belts	Yes	No
2	Adverse diagenesis	Significant	Low to moderate
3	Geothermal regime	G ≥ 35 ºC/km and/or high T_s	G < 35 ºC/km and low T_s
4	Temperature	< 35 ºC	≥ 35 ºC
5	Pressure	< 7.5 MPa	≥ 7.5 MPa

A site should meet as many as possible of these criteria;
if too few are being met, then maybe it should be rejected

Desirable Site Qualification Criteria - 2

	Criterion	Unfavorable	Favorable
6	Thickness	< 20 m	≥ 20 m
7	Porosity	< 10%	≥ 10%
8	Permeability	< 20 mD	≥ 20 mD
9	Caprock thickness	< 10 m	≥ 10 m
10	Well density	High	Low to moderate

Selection Criteria Specific to Oil and Gas Reservoirs

Should have sufficient capacity without raising reservoir pressure above the initial pressure

Selection Criteria Specific to CO_2 Enhanced Oil Recovery

- Light oil (25 to 48 API)
- Reservoir pressure greater than Minimum Miscibility Pressure (MMP)
- Temperature between 31 C and 121 C (85 F to 250 F)
- Homogeneous reservoir
- Preferably thin net pay (<20 m) for horizontal sweep efficiency (vertical sweep suitable for reef reservoirs)

Selection Criteria Specific to CO_2 Enhanced Coalbed Methane Recovery

- Sufficient permeability (at least several millidarcies, considering also coal swelling and loss of permeability)
- CO_2 in gaseous phase
- Minimal faulting and folding of the coal seam
- Low water saturation
- Thin, unmineable and uneconomic coal seams, deeper than potable groundwater

Additional Selection Criteria Based on Source-Sink Matching

- Volume, rate and purity of the CO_2 stream
- Proximity and right of access
- Infrastructure for capture, delivery and injection
- Injection, and where appropriate, production strategies
- Terrain and right of way
- Proximity to population centres
- Expertise and know-how
- Legal and regulatory framework

Broad Site Characterization - 1

1. 3-D structure of the sedimentary succession from the storage unit to ground surface

2. Geology of the sedimentary succession from the storage unit to ground surface

3. Rock properties (porosity, permeability, relatve-permeability)

4. Mineralogical, chemical and mechanical characteristics of all system components

5. Hydrogeology and geothermics

Broad Site Characterization - 2

7. Planar discontinuities such as faults and fractures
8. Fault and fracture characteristics
9. In-situ conditions of P, T and stress
10. Fluid compositions and PVT behaviour
11. Linear features such as wells
12. Reservoir and wells history

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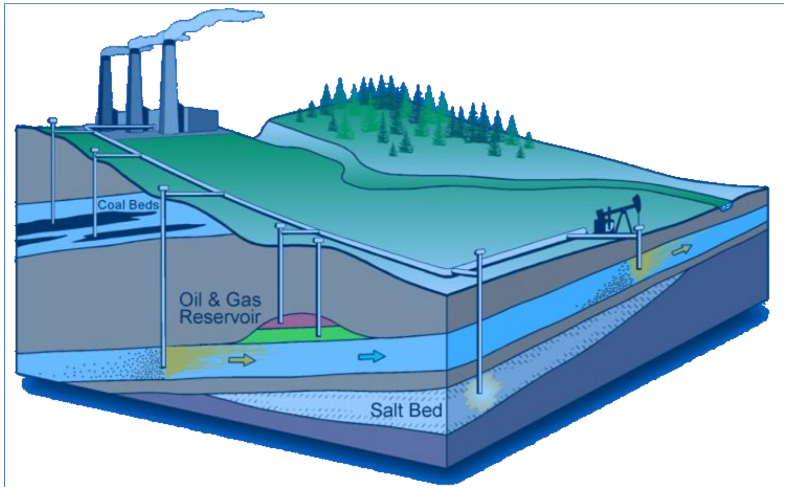
Risks and Hazards of Poor Site Selection and Characterization



Prior to Permitting

Hopefully the permitting agency will identify the poor quality of the site and will reject it, resulting in time and financial loses for the proponent

After Permitting while under Operator's Liability

- Global risk: CO_2 leakage into the atmosphere, with a reduction in "emissions reductions"
- Local risks:
  - Affect/contaminate other resources
  - Affect/contaminate shallow potable groundwater resources, as well as possibly affecting life through poisoning by mobilized heavy metals
  - Affect soils and vegetation, and possibly life at surface

Consequences for the operator/liability holder: financial and economic loss, loss of GHG credits, additional costs for remediation, possible loss of license to store CO_2, public and social effects, delay in transfer of long-term liability to the state designated authority

Storage Risks and Hazards

- Migration and/or leak* of CO_2 out of the storage unit
- Pressure build-up above forecasted and/or approved limits
- Pressure propagation beyond the forecasted and permitted region
- Insufficient capacity and/or injectivity

*Migration is defined as CO_2 lateral movement within the same formation, leakage is defined as CO_2 upwards cross-formational flow

CO_2 Migration and/or Leakage

- May contaminate energy and mineral resources, or untenured pore space (affects equity)
- May affect the quality of potable groundwater if it reaches it
- May affect vegetation and life in the soil and at the soil surface if it reaches there
- May affect life in enclosed spaces with no ventilation or natural dispersion
- Reduces “emission reductions” if it leaks into the atmosphere (affects credits)

Pressure Build-up Above Forecaasted and/or Permitted Limits

- May fracture the storage unit and overlying caprock, leading to leakage
- May open existing fractures, leading to leakage
- May open closed faults, leading to leakage
- May lead to ground heaving beyond acceptable limits, with possible damage to surface infrastructure
- Will lead to farther propagation of pressure changes

Pressure Propagation Beyond the Forecasted/Permitted Region

- May affect energy production operations in the same formation
- Will affect injectivity outside the CO_2-storage licensed area, hence the storage capacity in neighboring leases
- May lead to brine movement (laterally) or leakage (vertically) into shallower aquifers, even into potable groundwater, across fractures, faults, wells or breaches in the caprock

Insufficient Capacity and/or Injectivity

All previous risks (CO_2 migration/leakage) and pressure build-up/propagation lead to limiting storage capacity and/or injectivity. Also, a poorly selected site may not have the required capacity and/or injectivity to start with.

Consequences:

- Mainly economic and financial in the sense that either other site(s) must be found and infrastructure built (pipelines, facilities, wells), or
- CO_2 will have to be released into the atmosphere with as yet undefined consequences in terms of penalties

Risks of Early Failure

The public, which is already skeptical and doesn’t understand and trust the technology, will harden its opposition to CO_2 geological storage

ENGOs will increase the level of their campaign against the production and use of fossil fuels

Politicians will cave in and stop CCS

A hiatus will follow similar to the one experienced by the nuclear power industry after 3 Miles Island, Chernobyl and Fukushima accidents

Concluding Remarks - 1

- CO_2 storage sites should be selected based on the safety and security of storage, their capacity and injectivity, ability to meet regulatory requirements including monitoring, accessibility and economics
- Any assessment of CO_2 storage capacity should carefully consider the processes involved, their spatial and temporal scales, the resolution of the assessment, and the available data and their quality
- Sites should be properly characterized to meet regulatory and stakeholders requirements, particularly in regard to safety and security of storage

Concluding Remarks - 2

- Sites for CO_2 storage should be selected with great care considering possible impacts on equity, the environment and life
- Public safety and resource protection take primacy over CO_2 storage
- CO_2 leakage is unacceptable and plans for monitoring and remediation should be put in place
- The regulatory requirements for permitting, operating, closing and liability transfer of CO_2 storage sites are likely to be more stringent than for any other operations because of the spatial and temporal scales involved, public awareness and public assumption of long term liability

References Regarding Site Selection

1. **Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change.** Bachu. S., Environmental Geology, v. 44, no. 3, p. 277-289, doi: 10.1007/s00254-003-0762-9

2. **Screening and selection criteria, and characterisation for CO_2 geological storage.** Bachu, S. *In:* Developments and Innovation in Carbon Dioxide (CO_2) Capture and Storage Technology, Vol. 2 (M. Maroto-Valer, ed.), Woodhead Energy Series No. 16, Woodhead Publishing Ltd., p. 27-56, 2010.

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