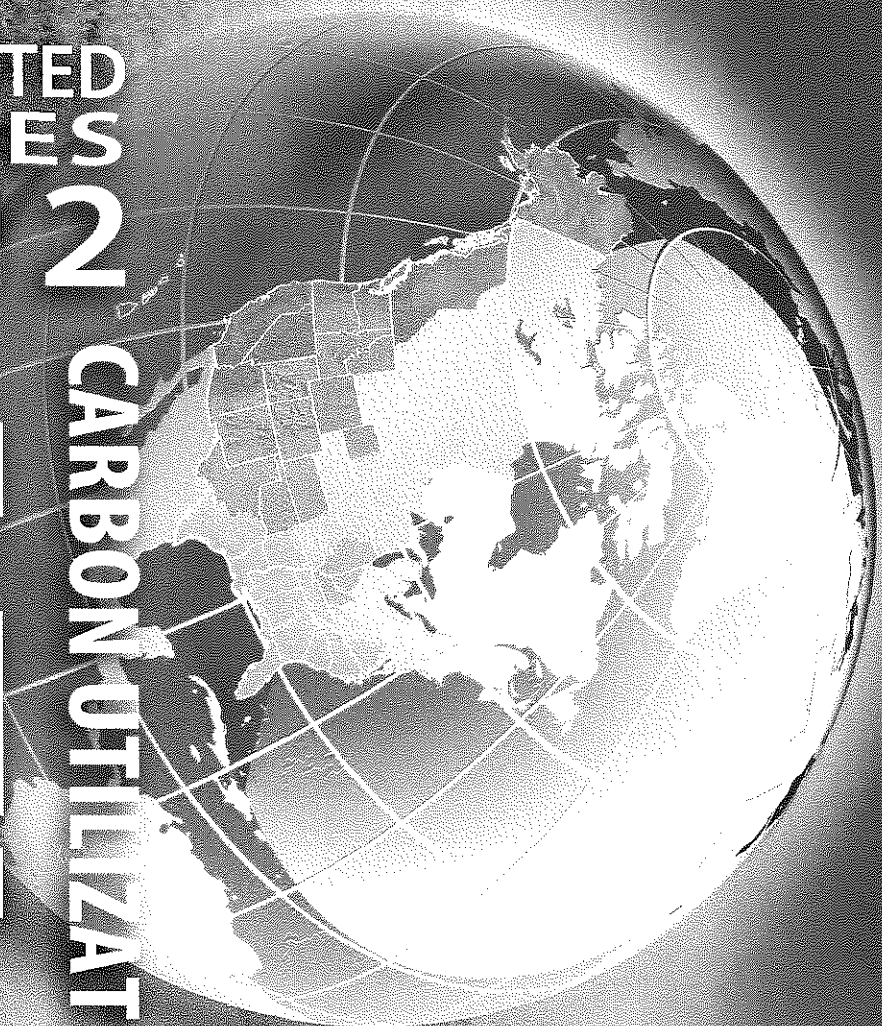
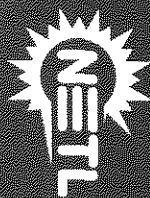




U.S. DEPARTMENT OF
ENERGY

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Fossil Energy

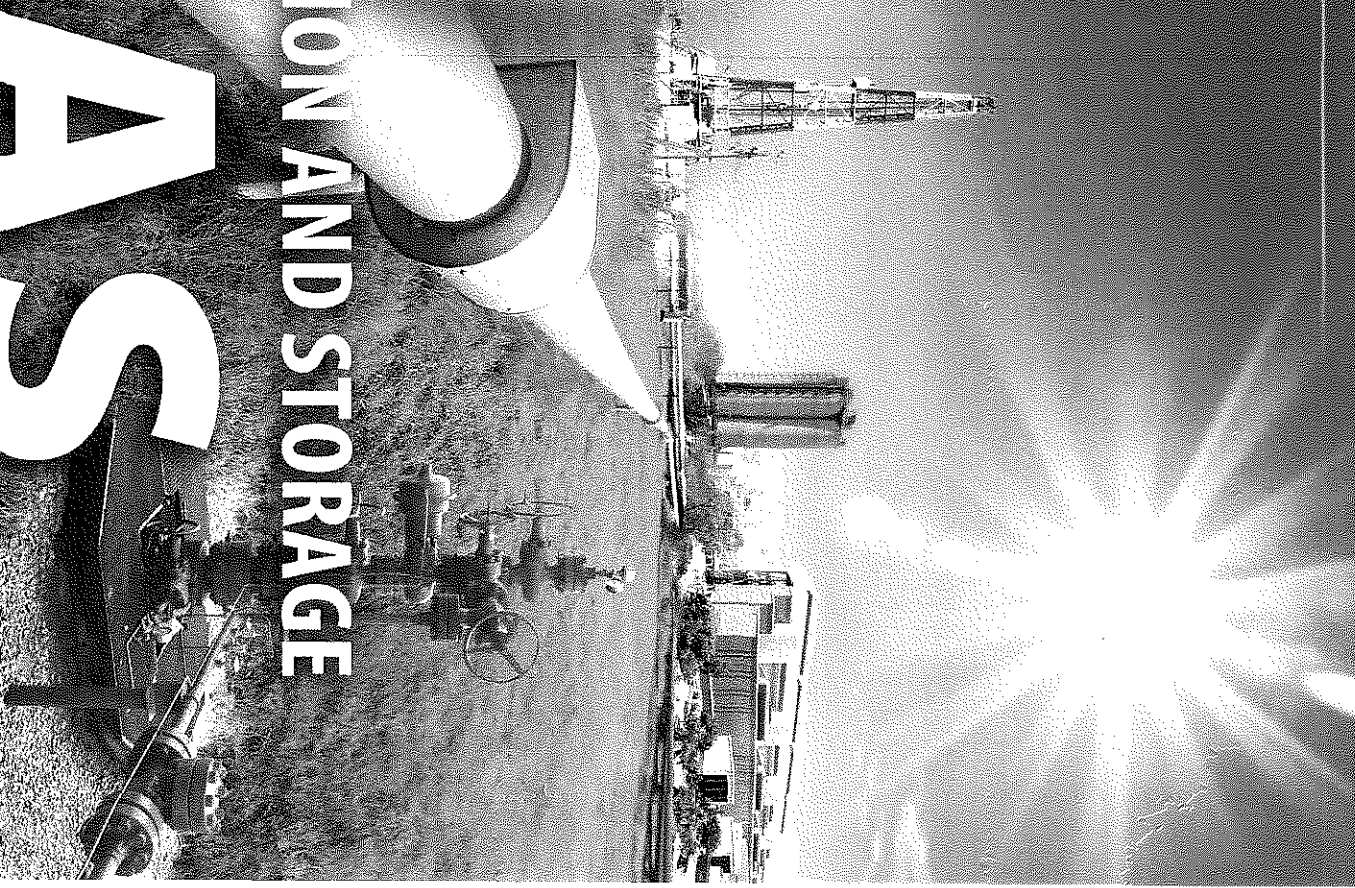


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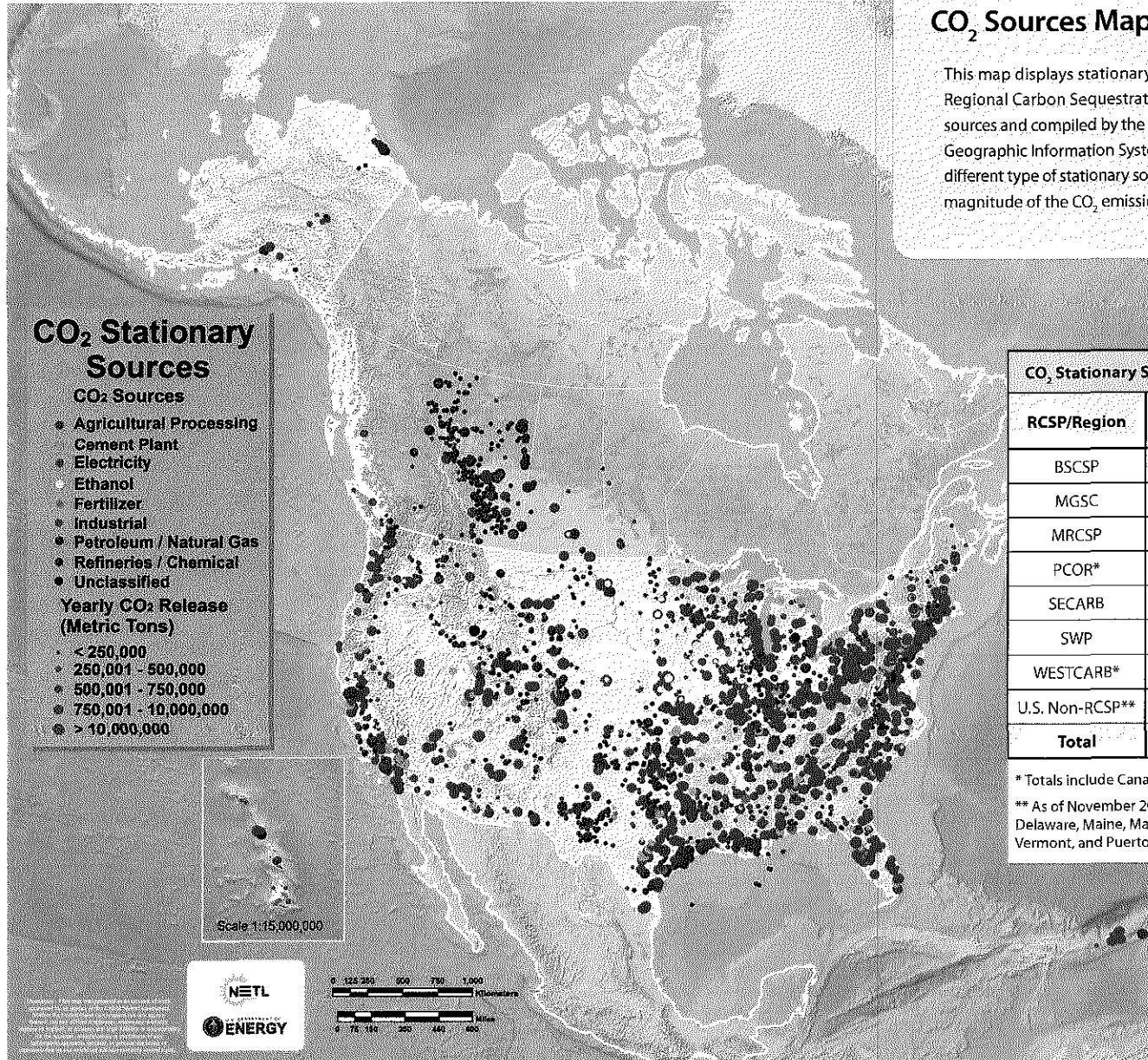
CARBON UTILIZATION AND STORAGE

ATLAS

Fourth Edition



National Perspectives



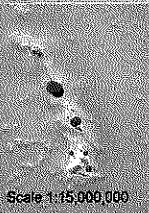
CO₂ Stationary Sources

CO₂ Sources

- Agricultural Processing
- Cement Plant
- Electricity
- Ethanol
- Fertilizer
- Industrial
- Petroleum / Natural Gas
- Refineries / Chemical
- Unclassified

Yearly CO₂ Release (Metric Tons)

- < 250,000
- 250,001 - 500,000
- 500,001 - 750,000
- 750,001 - 10,000,000
- > 10,000,000



CO₂ Sources Map

This map displays stationary source data that were obtained from the Regional Carbon Sequestration Partnerships (RCSPs) and other external sources and compiled by the National Carbon Sequestration Database and Geographic Information System (NATCARB). Each colored dot represents a different type of stationary source with the dot size representing the relative magnitude of the CO₂ emission source (see map legend).

CO ₂ Stationary Source Emission Estimates by RCSP/Region		
RCSP/Region	Number of Sources	CO ₂ Emissions (million metric tons per year)
BSCSP	244	48
MGSC	311	291
MRCSP	443	670
PCOR*	926	517
SECARB	1,003	1,103
SWP	649	333
WESTCARB*	513	268
U.S. Non-RCSP**	156	49
Total	4,245	3,279

* Totals include Canadian sources identified by the RCSP.

** As of November 2012, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico.

CO₂ Sources

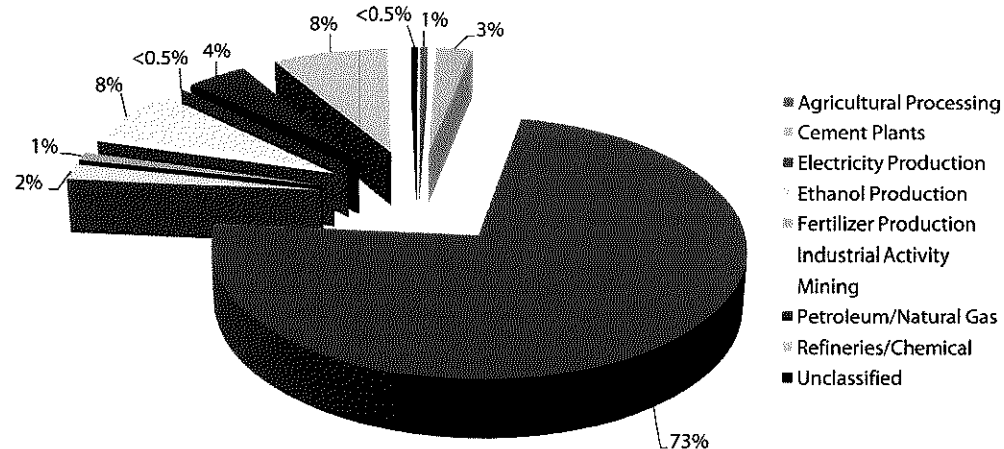
There are two different types of CO₂ sources: natural and anthropogenic (manmade). Natural sources include respiration from animals and plants, volcanic eruptions, forest and grass natural fires, decomposition of biomass material (plants and trees), and naturally occurring sources in geologic formations. Anthropogenic sources result from human activity and include the burning of fossil fuels, cement production and other industrial processes, deforestation, agriculture, and changes in natural land usage. Although CO₂ emissions from natural sources are estimated to be greater than the anthropogenic sources, natural sources are usually in equilibrium with a process known as the global carbon cycle, which involves carbon exchange between the land, ocean, and atmosphere. Increases in anthropogenic emissions throughout the last 200 years have led to an overall increase in the concentration of CO₂ and other greenhouse gases in the atmosphere.

In the United States, DOE's RCSPs have documented the location of 4,245 large stationary CO₂ sources (each emitting more than 100,000 metric tons per year) with total annual emissions of approximately 3,279 million metric tons of CO₂.

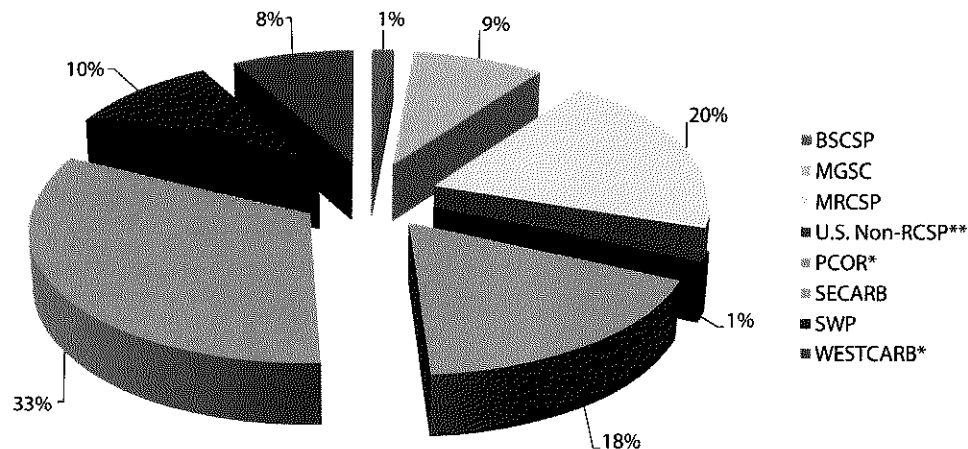
For details on large stationary sources of CO₂ by state, see Appendix D. For more information on the methodologies used to estimate these emissions, please see Appendix A. More detailed information on regional sources can be found in the RCSP section of this Atlas and information on Canadian and Mexican source data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

The number of sources and emissions reported in this Atlas was based on information gathered by the RCSPs and NATCARB as of May 2012.

CO₂ Stationary Source Emissions by Category

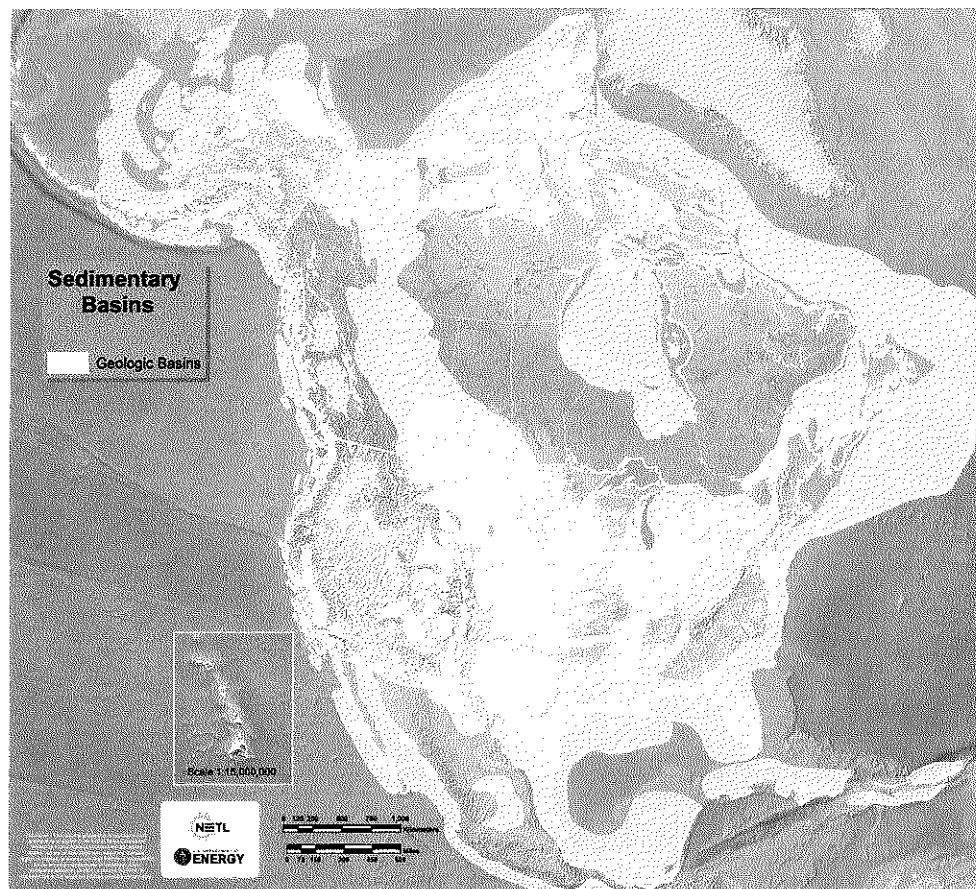


CO₂ Stationary Source Emissions by RCSP



* Includes only Canadian Sources Identified by RCSP

** As of November 2012, "U.S. Non-RCSP" includes Connecticut, Delaware, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, and Puerto Rico



Supercritical (Dense Phase) CO₂

It is common for experts to talk about storing CO₂ in the supercritical (dense phase) condition. In supercritical condition, CO₂ is at a temperature in excess of 31.1 °C and a pressure in excess of 72.9 atm (about 1,057 psi); this temperature and pressure defines the critical point for CO₂. At such temperatures and pressures, the CO₂ has some properties like a gas and some properties like a liquid. In particular, it is dense like a liquid but has viscosity like a gas. The main advantage of storing CO₂ in the supercritical condition is that the required storage volume is substantially less than if the CO₂ were at standard (room) pressure conditions. This reduction in volume is illustrated in the figure at right. The blue numbers show the volume of CO₂ at each depth compared to a volume of 100 at the surface.

Temperature naturally increases with depth in the Earth's crust, as does the pressure of the fluids (brine, oil, or gas) in the rocks. At depths below about 800 meters (about 2,600 feet), in most places on Earth, the natural temperature and fluid pressures are in excess of the critical point of CO₂. This means that CO₂ injected at these temperatures and pressures will be in the supercritical condition. The pressure of CO₂ must be greater than the naturally existing fluid pressure in order to inject the CO₂ into the reservoir. Large temperature differences between the injected CO₂ and the surrounding rock are not recommended; however, the CO₂ will take on the temperature of the surrounding rock as it moves into the reservoir. Hence, even if not injected under supercritical conditions, it will—in most cases—end up in the supercritical condition in the reservoir.

Sedimentary Basins

The Regional Carbon Sequestration Partnerships have identified and examined the location of potential CO₂ injection formations in different sedimentary basins throughout the United States and Canada. These sedimentary basins collected sediments that lithified to become sedimentary rocks. If these sedimentary rocks are porous or fractured, they can be saturated with brine (water with a high total dissolved solids concentration), oil, or gas. If the sedimentary rock is permeable (e.g., many sandstones), it could be a target for CO₂ injection. If it is impermeable (e.g., many shales), it could act as a confining zone to prevent migration of CO₂. Necessary conditions for a CO₂ storage site are the presence of both a reservoir with sufficient injectivity and a seal to prevent migration.

Brine is water that contains appreciable amounts of salts that have either been leached from the surrounding rocks or from seawater that was trapped when the rock was formed. The U.S. Environmental Protection Agency (EPA) has determined that a saline formation used for CO₂ storage must have at least 10,000 parts per million of total dissolved solids—a measure of the amount of salt in water. Most drinking water supply wells contain a few hundred parts per million or less of total dissolved solids.

Oil and gas reservoirs are often saline formations that have traps and seals that allowed oil and gas to accumulate over millions of years. Many oil and gas fields contain stacked formations (different reservoirs over top of each other), which have characteristics, including good porosity, that make for excellent multiple target locations at one geologic storage site.

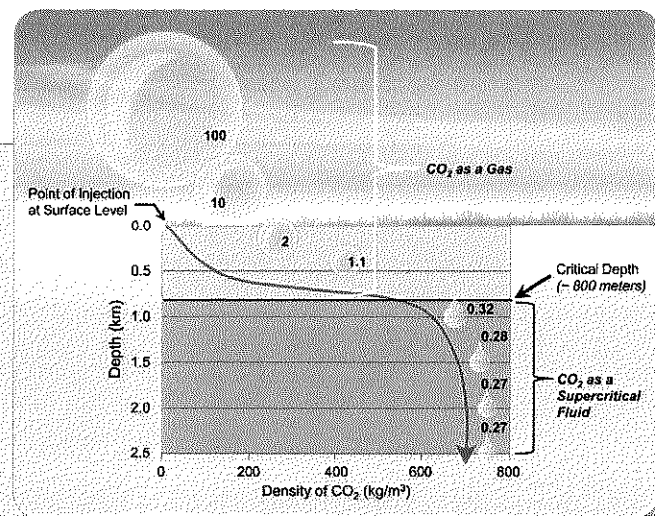


Illustration of pressure effects on CO₂ volume (based upon image from the Cooperative Research Centre for Greenhouse Gas Technologies [CO2CRC]).

Oil and Gas Reservoirs

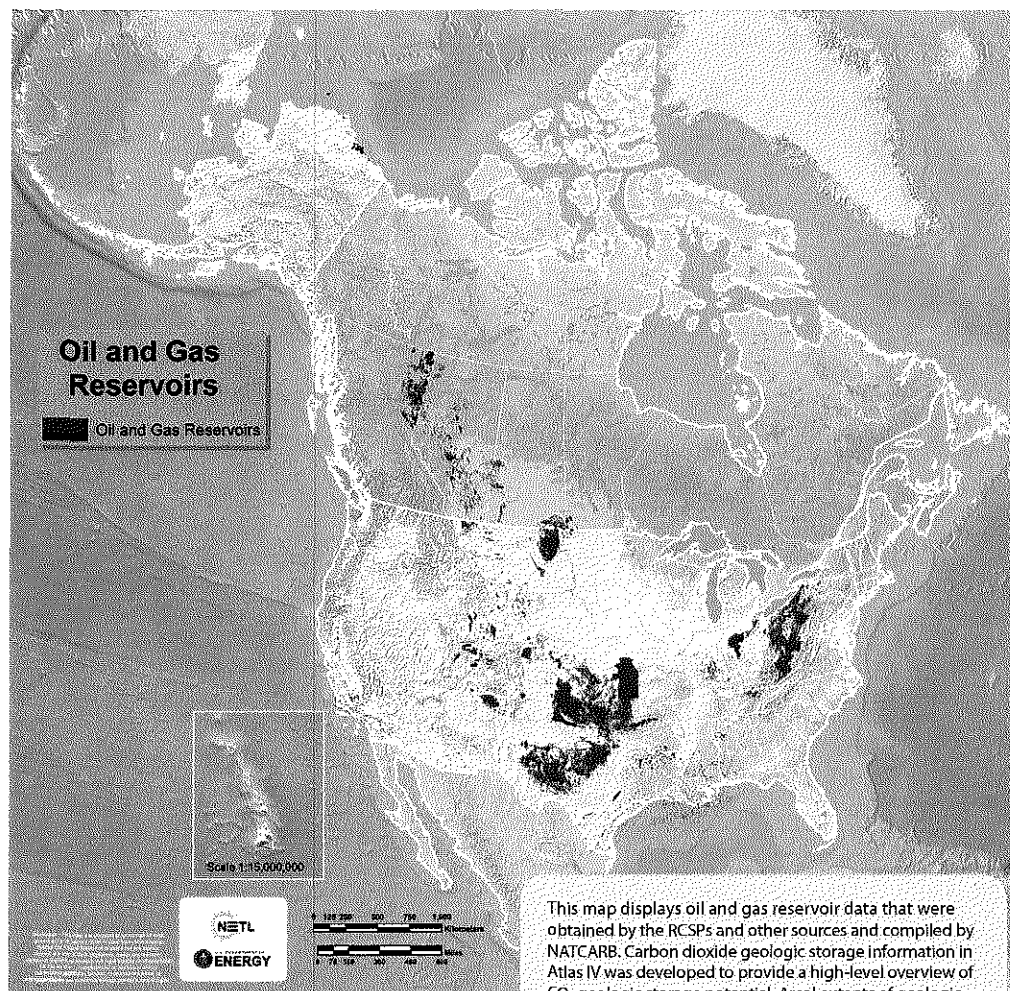
Oil and gas reservoirs are porous rock formations (usually sandstones or carbonates) containing hydrocarbons (crude oil and/or natural gas) that have been physically trapped. There are two main types of physical traps: (1) stratigraphic traps, created when changes have occurred in rock types, and (2) structural traps, in which the rocks have been folded or faulted to create a trapping reservoir. Oil and gas reservoirs are ideal geologic storage sites because they have held hydrocarbons for thousands to millions of years and have conditions suitable for CO₂ storage. Furthermore, their architecture and properties are well known as a result of exploration for and production of these hydrocarbons. In addition, due to the industrialization of these sites, infrastructure exists for CO₂ transportation and storage.

Traditionally, oil can be extracted from a reservoir in three different phases. The primary recovery phase uses the natural pressure in a reservoir to push the oil up. This process usually accounts for 10 to 15 percent of oil recovery. The secondary recovery phase involves the injection of water to increase the reservoir pressure and displace the oil towards producing wells. This process produces an additional 15 to 25 percent of the original oil. Together, these two phases account for the recovery of 25 to 40 percent of the original oil, but approximately two-thirds of the oil remains in the reservoir. Tertiary recovery, or enhanced oil recovery (EOR), is frequently conducted with CO₂ to recover additional original oil. When CO₂ is injected, it raises the reservoir pressure and increases the oil mobility, making it easier for the oil to reach producing wells. This method, called CO₂-EOR, is an attractive option for CO₂ storage because it allows for the recovery and sale of additional oil that would otherwise remain trapped in the reservoir, thus lowering the net cost of CO₂ storage. In North America, CO₂ has been injected into oil reservoirs to increase oil recovery for more than 40 years.

While not all potential mature oil and gas reservoirs in the United States have been examined, DOE's RCSPs have documented the location of approximately 226 billion metric tons of CO₂ storage resource. For details on oil and gas reservoir CO₂ storage resource by state/province, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional oil and gas reservoir storage information can be found in the RCSP section of this Atlas, and information on Canadian oil and gas storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of November 2012.

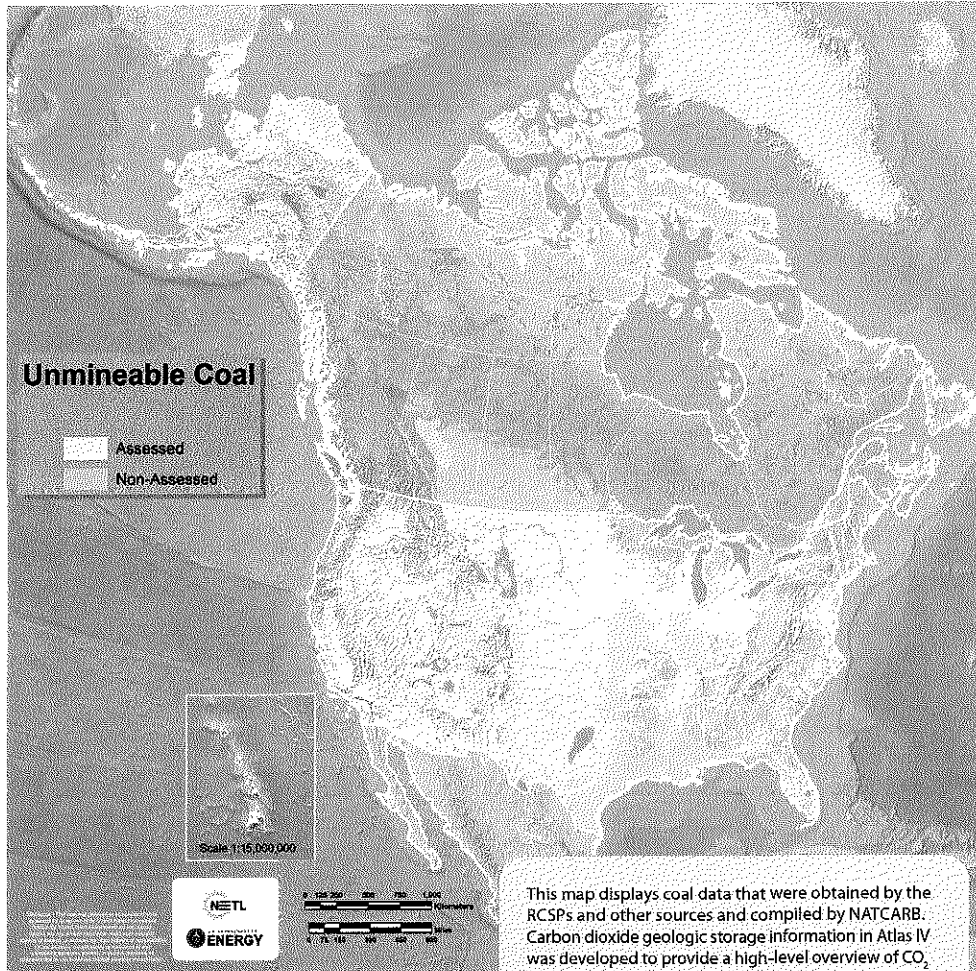
CO ₂ Storage Resource Estimates for Oil and Gas Reservoirs by RCSP		
RCSP	Billion Metric Tons	Billion Tons
BSCSP	1	1
MGSC	1	1
MRCSP	14	15
PCOR	25	28
SECARB	32	35
SWP	149	164
WESTCARB	4	4
Total	226	248



This map displays oil and gas reservoir data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO₂ geologic storage potential. Areal extents of geologic formations and CO₂ resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO₂ emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that oil and gas reservoir data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.



EOR operations in Michigan. (Courtesy of MRCSP)



Skyland coalbed in Kentucky. (Courtesy of MRCSP)

This map displays coal data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO₂ geologic storage potential. Areal extents of geologic formations and CO₂ resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides carbon capture, utilization, and storage (CCUS) project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO₂ emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that coal data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.

Unmineable Coal

Coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined with today's technologies) may have potential for CO₂ storage. Coal preferentially adsorbs CO₂ over methane, which is naturally found in coal seams, at a ratio of 2 to 13 times. This property, known as adsorption trapping, is the basis for CO₂ storage in coal seams. Methane gas is typically recovered from coal seams by dewatering and depressurization, but this can leave significant amounts of methane trapped in the seam. The process of injecting and storing CO₂ in unmineable coal seams to enhance methane recovery is called enhanced coalbed methane (ECBM) recovery. Enhanced coalbed methane recovery parallels CO₂-EOR because it provides an economic benefit from the recovery and sale of the methane gas, which helps to offset the cost of CO₂ storage. However, for CO₂ to be stored in coals, the coal must have sufficient permeability, which controls injectivity. Coal permeability depends on the effective stress and usually decreases with increasing depth. Furthermore, studies have shown that CO₂ injection can impact coal permeability and injectivity.

For CO₂ storage in coals or ECBM recovery, the ideal coal seam must have sufficient permeability and be considered unmineable. Carbon dioxide need not be in the supercritical (dense phase) state for it to be adsorbed by coal, so CO₂ storage in coals can take place at shallower depths (at least 200 meters deep) than storage in oil and gas reservoirs and saline formations (which require at least 800 meters depth). Research to optimize CO₂ storage in coals is ongoing.

While not all unmineable coal has been examined, DOE's RCSPs have documented the location of approximately 56 to 114 billion metric tons of potential CO₂ storage resource in unmineable coal. For details on unmineable CO₂ storage resource by state, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional coal storage information can be found in the RCSP section of this Atlas. Information on Canadian and Mexican coal storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of May 2012.

CO ₂ Storage Resource Estimates for Coal by RCSP				
RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	1	1	1	1
MGSC	2	2	3	3
MRCSP	1	1	1	1
PCOR	7	8	7	8
SECARB	33	36	75	83
SWP	1	1	2	2
WESTCARB	11	12	25	28
Total	56	61	114	126

Saline Formations

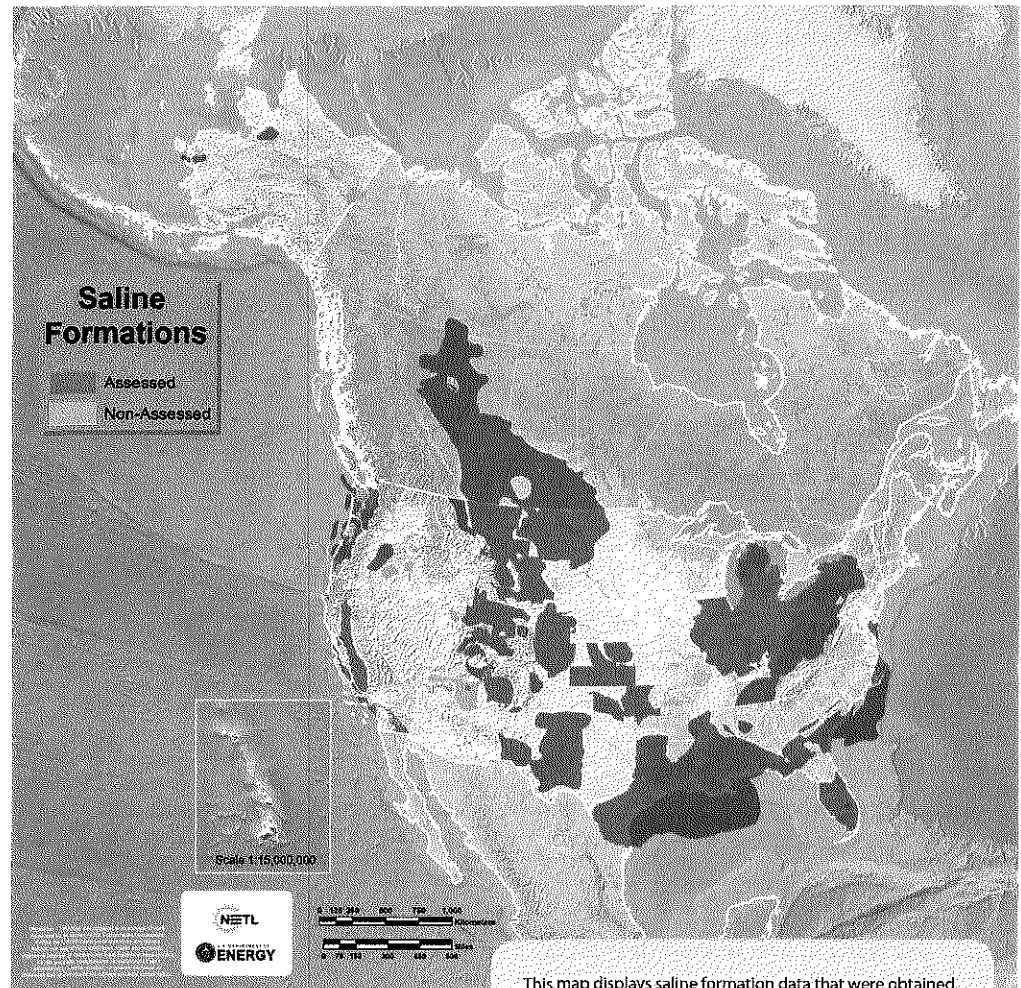
Saline formations are layers of sedimentary porous and permeable rocks saturated with salty water called brine. These formations are fairly widespread throughout North America, occurring in both onshore and offshore sedimentary basins, and they have potential for CO₂ storage. It is important that a regionally extensive confining zone (often referred to as caprock or seal) overlies the porous rock layer. Trapping mechanisms include the CO₂ dissolving in the brine (solubility trapping), reacting chemically with the minerals and fluid to form solid carbonates (mineral trapping), or becoming trapped in the pore space (volumetric trapping).

Saline formations are estimated to have much larger storage potential for CO₂ than oil and gas reservoirs and unmineable coals because they are more extensive and widespread. Much knowledge about some saline formations exists from the exploration and production of oil and gas, and prior oil industry experience, but there are also saline formations about which less is known. Although saline formations have a greater amount of uncertainty than oil and gas reservoirs, they represent an enormous potential for CO₂ storage, and recent project results suggest that they can be used as reliable, long-term storage sites. Saline formation storage lacks the economic incentives of CCUS storage in oil and gas reservoirs or unmineable coal areas; however, they represent a significant future storage resource and can serve as buffer storage for EOR operations.

While not all saline formations in the United States have been examined, DOE's RCSPs have documented an estimated CO₂ storage resource ranging from approximately 2,102 billion metric tons to more than 20,043 billion metric tons of CO₂. For details on saline formation CO₂ storage resource by state, see Appendix D. For more information on the methodologies used to estimate this potential, please see Appendix B. More detailed regional saline formation storage can be found in the RCSP section of this Atlas, and information on Canadian and Mexican saline storage data can be found in the North American Carbon Storage Atlas at www.nacsap.org.

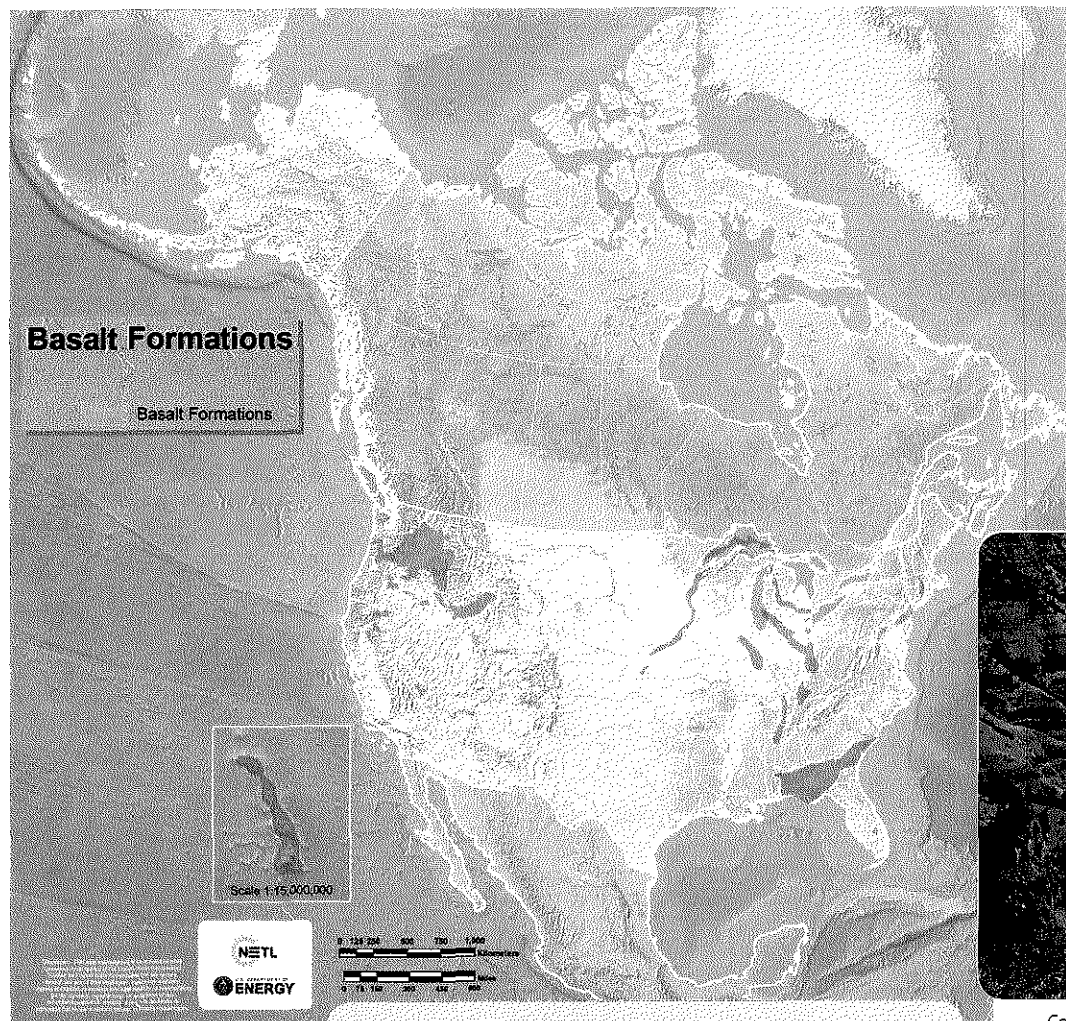
The storage resource estimates reported in this Atlas were based on information gathered by the RCSPs and NATCARB as of May 2012.

CO ₂ Storage Resource Estimates for Saline Formations by RCSP				
RCSP	Low		High	
	Billion Metric Tons	Billion Tons	Billion Metric Tons	Billion Tons
BSCSP	98	108	1,237	1,364
MGSC	11	12	158	174
MRCSP	95	105	123	136
PCOR	174	192	511	563
SECARB	1,376	1,516	14,089	15,530
SWP	266	293	2,801	3,088
WESTCARB	82	90	1,124	1,239
Total	2,102	2,316	20,043	22,094



Surface outcropping of a saline storage formation near Belfry, Montana. (Courtesy of John Talbott, BSCSP)

This map displays saline formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO₂ geologic storage potential. Areal extents of geologic formations and CO₂ resource estimates presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO₂ emissions and is not intended to serve as a substitute for site-specific assessment and testing. Please note that saline formation data resulting in a straight edge in the map above is indicative of an area lacking sufficient data and is subject to future investigation.



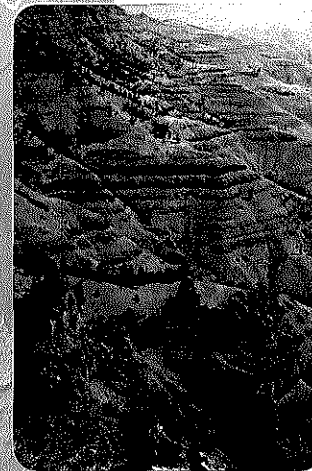
This map displays basalt formation data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO₂ geologic storage potential. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO₂ emissions and is not intended to serve as a substitute for site-specific assessment and testing. Carbon dioxide storage in basalt formations is an area of current research. Before basalt formations can be considered viable storage targets, a number of questions relating to the basic geology, the CO₂ trapping mechanisms and their kinetics, and monitoring and modeling tools need to be addressed. As such, *Atlas IV* presents a map of these potential future storage opportunities, but provides no CO₂ storage resource values for basalt formations.

Basalt Formations

Another potential CO₂ storage option DOE is investigating are geologic formations of solidified lava called basalt formations. The relatively large amount of potential storage resource in basalts, along with their geographic distribution, make them an important formation type for possible CO₂ storage, particularly in the Pacific Northwest and the southeastern United States. These formations have a unique chemical makeup that could potentially convert all of the injected CO₂ to a solid mineral form, thus isolating it permanently from the atmosphere.

The chemistry of basalts potentially allows injected CO₂ to react with magnesium and calcium in the rocks to form the stable carbonate mineral forms of calcite and dolomite. This mineralization process shows promise to be a valuable tool for carbon capture and storage (CCS) since the mineralization process permanently locks carbon in the solid mineral structure. Thus, basalts may offer one of the safest options for long-term isolation of CO₂ from the atmosphere

because of the unique capacity for permanent incorporation of injected CO₂ into carbonates via mineralization. However, more research is needed to understand the time frames and actual chemical inputs and outputs of a basalt CO₂ injection. Some key factors affecting the capacity and injectivity of CO₂ into basalt formations are effective porosity of flow, top layers, and interconnectivity. DOE's current efforts are focused on enhancing and utilizing the mineralization reactions and increasing CO₂ flow within basalt formations.



Columbia River Basalt.



An example of a basalt flow. (Courtesy of Travia McLing, INL)



Basalt outcrop in eastern Washington. (Courtesy of Sarah Koenigsberg)

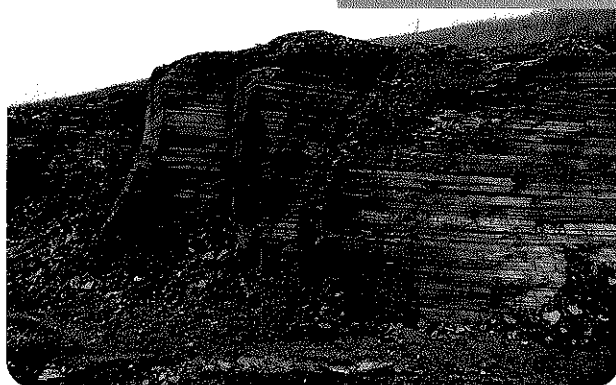
Organic-Rich Shale Basins

Organic-rich shales are another geologic storage option. Shales are formed from silicate minerals, which are degraded into clay particles that accumulate over millions of years. The plate-like structure of these clay particles causes them to accumulate in a flat manner, resulting in vertical rock layers with extremely low permeability. Therefore, shales are most often used in geologic storage as a confining zone or caprock.

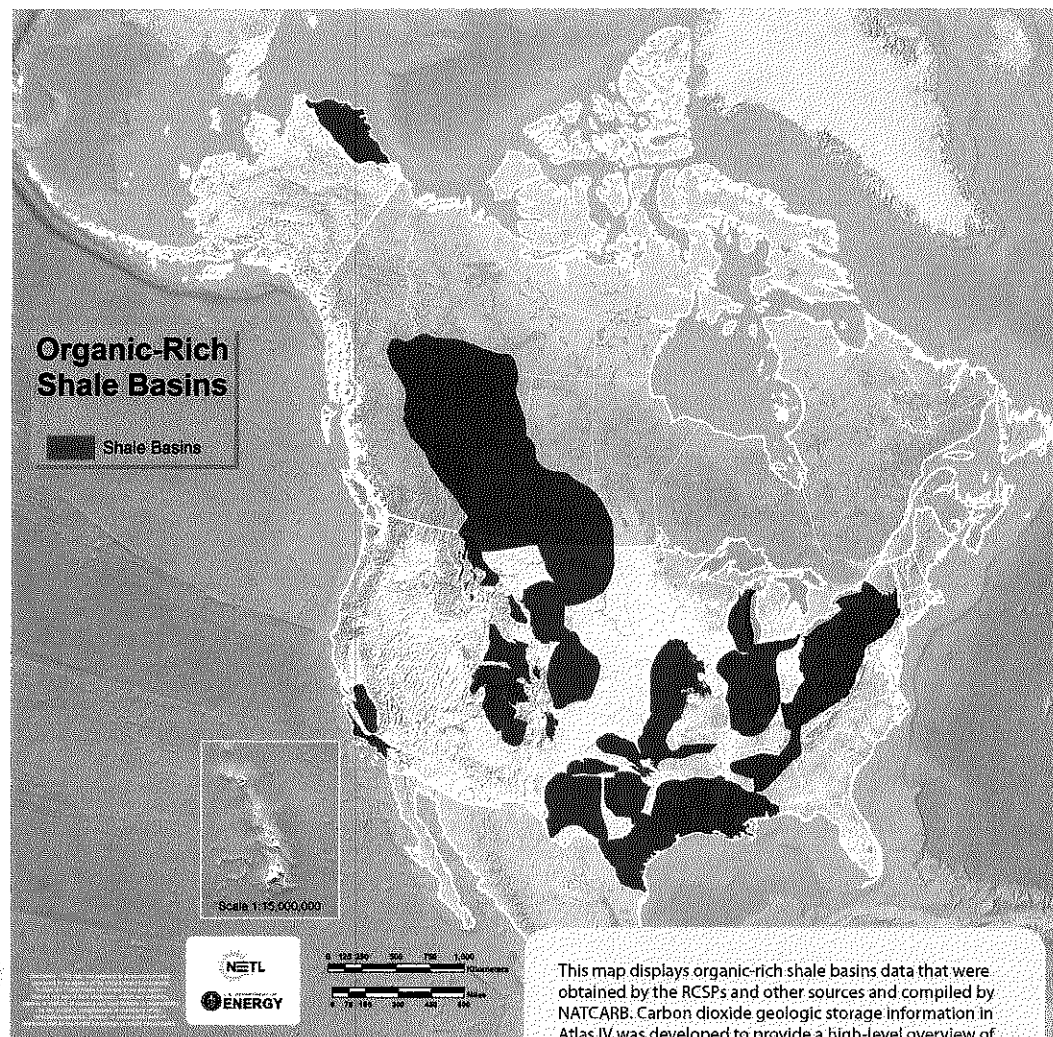
Ongoing efforts are focused on using CO₂ for enhanced gas recovery. Through engineering, the horizontal permeability in shales can be preferentially increased, which makes CO₂ storage feasible. Recent technological advances in horizontal drilling and hydraulic fracturing have increased interest in the energy sector for natural gas production from organic-rich shales. With horizontal drilling and hydraulic fracturing, operators engineer porosity and permeability into organic-rich shales to create flow pathways. These technologies, coupled with the fact that CO₂ is preferentially adsorbed over methane, will improve the feasibility of using CO₂ for enhanced gas recovery (EGR) in much the same way as ECBM recovery. While the additional engineering of the rocks would add to the cost, the potential for hydrocarbon production could potentially offset it.



Geologist examining the base of the Marcellus Shale at an outcrop near Bedford, PA.



New Albany Shale outcrop.
(Courtesy of MGSC)



This map displays organic-rich shale basins data that were obtained by the RCSPs and other sources and compiled by NATCARB. Carbon dioxide geologic storage information in Atlas IV was developed to provide a high-level overview of CO₂ geologic storage potential. Areal extents of geologic formations presented are intended to be used as an initial assessment of potential geologic storage. This information provides CCUS project developers a starting point for further investigation. Furthermore, this information is required to indicate the extent to which CCUS technologies can contribute to the reduction of CO₂ emissions and is not intended to serve as a substitute for site-specific assessment and testing. Carbon dioxide storage in organic-rich shale basins is an area of current research. Before organic-rich shale basins can be considered viable storage targets, a number of questions relating to the basic geology, the CO₂ trapping mechanisms and their kinetics, and monitoring and modelling tools need to be addressed. As such, *Atlas IV* presents a map of these potential future storage opportunities, but provides no CO₂ storage resource values for organic-rich shale basins.

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