CARBON SEQUESTRATION OPTIONS FOR THE WEST COAST STATES

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP
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Sequestration Options for the West Coast States

Final Report

West Coast Regional Carbon Sequestration Partnership

(WESTCARB)

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Abstract

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of seven partnerships that have been established by the U.S. Department of Energy (DOE) to evaluate carbon capture and sequestration (CCS) technologies best suited for different regions of the country. The West Coast Region comprises Arizona, California, Nevada, Oregon, Washington, Alaska, and British Columbia. Led by the California Energy Commission, WESTCARB is a consortium of about 70 organizations, including state natural resource and environmental protection agencies; national laboratories and universities; private companies working on carbon dioxide (CO_2) capture, transportation, and storage technologies; utilities; oil and gas companies; nonprofit organizations; and policy/governance coordinating organizations. Both terrestrial and geologic sequestration options were evaluated in the Region during the 18-month Phase I project. A centralized Geographic Information System (GIS) database of stationary source, geologic and terrestrial sink data was developed. The GIS layer of source locations was attributed with CO_2 emissions and other data and a spreadsheet was developed to estimate capture costs for the sources in the region. Phase I characterization of regional geological sinks shows that geologic storage opportunities exist in the WESTCARB region in each of the major technology areas: saline formations, oil and gas reservoirs, and coal beds. California offers outstanding sequestration opportunities because of its large capacity and the potential of value-added benefits from enhanced oil recovery (EOR) and enhanced gas recovery. The estimate for storage capacity of saline formations in the ten largest basins in California ranges from about 150 to about 500 Gt of CO_2, the potential CO_2-EOR storage was estimated to be 3.4 Gt, and the cumulative production from gas reservoirs suggests a CO_2 storage capacity of 1.7 Gt. A GIS-based method for source-sink matching was implemented and preliminary marginal cost curves developed, which showed that 20, 40, or 80 Mega tonnes (Mt) of CO_2 per year could be sequestered in California at a cost of $31/tonne (t), $35/t, or $50/t, respectively. Phase I also addressed key issues affecting deployment of CCS technologies, including storage-site monitoring, injection regulations, and health and environmental risks. A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of HSE risk was developed. A web-based, state-by-state compilation of current regulations for injection wells, and permits/contracts for land use changes, was developed, and modeling studies were carried out to assess the application of a number of different geophysical techniques for monitoring geologic sequestration. Public outreach activities resulted in heightened awareness of sequestration among state, community and industry leaders in the Region. Assessment of the changes in carbon stocks in agricultural lands showed that Washington, Oregon and Arizona were CO_2 sources for the period from 1987 to 1997. Over the same period, forest carbon stocks decreased in Washington, but increased in Oregon and Arizona. Results of the terrestrial supply curve analyses showed that afforestation of rangelands and crop lands offer major sequestration opportunities; at a price of $20 per t CO_2, more than 1,233 MMT could be sequestered over 40-years in Washington and more than 1,813 MMT could be sequestered in Oregon.

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1 Executive Summary

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of seven partnerships that have been established by the U.S. Department of Energy (DOE) to evaluate carbon capture and sequestration (CCS) technologies best suited for different regions of the country. The West Coast Region comprises Arizona, California, Nevada, Oregon, Washington, Alaska, and British Columbia. Led by the California Energy Commission, WESTCARB is a consortium of about 70 organizations, including state natural resource and environmental protection agencies; national laboratories and universities; private companies working on carbon dioxide (CO_2) capture, transportation, and storage technologies; utilities; oil and gas companies; nonprofit organizations; and policy/governance coordinating organizations. This report presents results of the 18-month Phase I project, in which both terrestrial and geologic sequestration options were evaluated in the Region.

The 77 major stationary CO_2 sources in the WESTCARB database have a total annual CO_2 emission of 159 Mt. A Geographic Information System (GIS) layer of source locations was developed and attributed with CO_2 emissions and other data, such as ownership, capacity, type of unit, fuels, equipment age, and operating status. A spreadsheet was developed to estimate capture costs based on three key input variables: (1) the flue gas flow rate (in tonnes per hour), (2) the flue gas composition (volume share or weight share of CO_2 in flue gas), and (3) the annual load factor.

Phase I characterization of regional geological sinks shows that geologic storage opportunities exist in the WESTCARB region in each of the major technology areas: saline formations, oil and gas reservoirs, and coal beds. This characterization work focused on sedimentary basins as the initial most-promising targets for geologic sequestration. GIS layers showing sedimentary basins, and oil, gas, and coal fields in those basins, were developed. The GIS layers were attributed with information on the subsurface, including sediment thickness, presence and depth of porous and permeable sandstones, and, where available, reservoir properties.

California offers outstanding sequestration opportunities because of large capacity and the potential for value-added benefits from enhanced oil recovery (EOR) and enhanced gas recovery (EGR). The estimate of the storage capacity of saline formations in the ten largest basins in California ranges from about 150 to about 500 Gt of CO_2, depending on assumptions about the fraction of the formations used and the fraction of the pore volume filled with separate-phase CO_2. Potential CO_2-EOR storage was estimated to be 3.4 Gt, based on a screening of reservoirs using depth, an API gravity cutoff, and cumulative oil produced. The cumulative production from gas reservoirs (screened by depth) suggests a CO_2 storage capacity of 1.7 Gt. In Oregon and Washington, sedimentary basins along the coast offer sequestration opportunities. Of particular interest is the Puget Trough Basin, which contains up to 1,130 m (3,700 ft) of unconsolidated sediments overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. The Puget Trough Basin also contains deep coal formations, which are sequestration targets and may have potential for ECBM. The amount of unmineable coal in the Puget Sound basin was estimated to be over 70 billion tons, with a CO_2 storage potential of 2.8 Gt.

Using source and sink characterization data as input preliminary source-sink matching was carried out to assess regional geologic sequestration opportunities. The straight-line distance based source-sink matching results showed that if all sinks, including Nevada sinks, were considered for sequestration, more than four-fifths of CO_2 sources could be matched with appropriate sinks within 50 km. A more advanced GIS-based least-cost source-sink matching method was applied to analyze sources and sinks in California, which also takes into account the CO_2 storage capacity constraint of the sinks. For most CO_2 sources in California, the transportation costs to the corresponding EOR site are below \$10/t CO_2, less than the assumed \$16/t CO_2 credit for EOR injection. A full sequestration costing analysis, which includes capture cost, transportation cost, and injection cost (or net of EOR credit if matched to an EOR site), was also conducted for CO_2 storage in California. The results of this preliminary full sequestration cost analysis indicates that 20, 40, or 80 Mega tonnes (Mt) of CO_2 per year could be sequestered in California at a cost of \$31/tonne (t), \$35/t, or \$50/t, respectively.

Phase I work addressed key issues affecting deployment of CCS technologies, including storage-site permitting and monitoring, injection regulations, and health and environmental risks.

A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of health, safety, and environmental (HSE) risk was developed based on three fundamental characteristics of a CO_2 sequestration site. Example applications of the framework show that comparative evaluations of prospective sites with limited characterization data can be accomplished based on potential for CO_2 leakage and seepage and related HSE risk.

A web-based, state-by-state compilation of current regulations for injection wells—relevant to geologic sequestration—and required permits/contracts for land use changes—relevant to terrestrial sequestration—was developed. Links to the specific, relevant statutes are provided. An assessment of the current status of regulations showed that the regulatory framework for CO_2 injection in conjunction with EOR is well established, but the framework for injection into saline formations is poorly defined.

As a basis for development of monitoring protocols, modeling studies were carried out to assess the application of a number of different geophysical techniques for monitoring geologic sequestration of CO_2. Time-lapse performance of seismic, gravity, and electromagnetic techniques were considered for a proposed CO_2 sequestration project in the Schrader Bluff field on the North Slope of Alaska. Model results show that both seismic amplitude and seismic amplitude variation with offset could be used to make quantitative estimates of saturation changes, subject to modeling assumptions. Borehole gravity measurements just above the reservoir produced measurable change in the vertical component of gravity that could be used to map lateral distributions of injected CO_2. A preliminary model study for the Rio Vista gas field in California showed that neither gravity nor seismic methods would provide information necessary for monitoring of CO_2 movement because of small changes in reservoir properties.

A spreadsheet for carrying out life cycle assessments for power generation including capture was developed. Major point-source pollutants, in addition to CO_2, were addressed. Results of one example analysis, in which all plants in the Region are retrofit with CO_2 control, and replacement power is split 50/50 between gas turbine combined cycle and coal, the CO_2 and SO_2 emissions are reduced but the NOx and mercury are increased.

In Phase I, the focus of the terrestrial sequestration studies was the development of carbon baselines and supply curves.

In Washington, the baseline studies showed that total carbon stocks in all agricultural land amount to about 6.2 million tons. In CO_2 equivalent terms, total agricultural carbon stocks in 1997 were 22.9 MMTCO_2eq, and the net loss 1987–1997, disregarding non-CO_2 greenhouse gas emissions, was 0.5 MMTCO_2eq. Total forest carbon stocks also diminished, with the rate of loss between 1987–1997 being 62,000 ac per year, equivalent to a gross emission of 187 MMTCO_2e or 12.5 MMTCO_2e/yr between 1987–1997.

Total carbon stocks in all agricultural land in Oregon were estimated at 3.2 million tons. In CO_2 equivalent terms, the net loss for 1987–1997, disregarding non-CO_2 greenhouse gas emissions, was 0.6 MMTCO_2eq, equivalent to an annual source of 0.06 MMTCO_2eq. Forest carbon stocks increased over the same period, resulting in an estimated increase of 23.0 MMTCO_2e/yr. Forest sinks, therefore, potentially can offset as much as 50% of the state's emissions.

Total carbon stocks in all agricultural land types in Arizona were estimated at 1 million tons. In CO_2 equivalent terms, total agricultural carbon stocks in Arizona in 1997 were 3.5 million metric tons CO_2 equivalent (MMTCO_2eq), and the net loss for 1987–1997, disregarding non-CO_2 greenhouse gas emissions, was 0.4 MMTCO_2eq. Forest carbon stocks increased over the period, equivalent to an increase of 9 MMTCO_2e or 0.92 MMTCO_2e/yr between 1987 and 1997.

In all three states, non-CO_2 greenhouse gas emissions from nitrous oxide (N_2O; emitted from agricultural soils after fertilizer application) and methane (CH_4, from livestock and manure management) dwarf the annual CO_2 source from agricultural land conversion.

Results of the terrestrial supply curve analyses showed that afforestation of rangelands and crop lands offer major sequestration opportunities. In Washington, at a price of $20 per t CO_2, almost 289 MMT CO_2 could be sequestered over 20-years. The total amount rises sharply to more than 1,233 MMT CO_2 at 40 years and approximately 3,176 MMT CO_2 at 80 years. In Oregon, at a price of $20, almost 280 MMT CO_2 could be sequestered over 20-years. The total amount rises to more than 1,813 MMT CO_2 at 40 years and approximately 4,203 MMT CO_2 at 80 years.

2 Experimental

2.1 Geologic Source-Sink Characterization: Methodology

2.1.1 Stationary Source Characterization

Working with the Electric Power Research Institute, Nexant assembled data for power plants and major industrial sources. A Geographic Information System (GIS) layer of source locations was developed and attributed with carbon dioxide (CO_2) emissions and other data. The primary sources of information for power generating plants were the Energy Information Agency (EIA) and the U.S. Environmental Protection Agency (EPA). The EIA database contains relevant material about plants and units (*e.g.,* boiler, combustion turbine) Data important to the regional sequestration work includes ownership and location, capacity, type of unit, fuels, equipment age, and operating status. The EIA database has a significant amount of other data, including emission control equipment, which will be examined later to augment the plant and company contacts for our region. The EPA Clean Air Markets organization has a database with emissions, including CO_2. The data is for the plant and lists SO_2 and NO_X as well as CO_2. The plant heat input is also provided. California has a unique database maintained by the California Air Resources Board (CARB). The database contains valuable plant information that will facilitate contacts, and lists pollutant emissions for organics, CO, NO_X, SO_X, and particulates (PM, PM10, and PM2.5). CO_2 is not part of the CARB data.

The sample below, Figure 1, shows the type of data collected for power generation. EPA emission data is colored light blue, and the other plant and unit information is from the EIA database. Additional information is found in Appendix I.

State Company Plant (County)	Unit ID	Generator Nameplate Capacity (megawatts)	Net Summer Capacity (megawatts)	Net Winter Capacity (megawatts)	Unit Type1	Energy Source1 Primary	Year of Commercial Operation	Unit Status1	Further Data Collection
Arizona Electric Pwr Coop		**559.1**	**515**	**515**					
Facility Name	Facility ID (ORISPL)	Year	SO_2 Tons	CO_2 Tons	NO_x Tons	Heat Input (mmBtu)	EPA CLEAN AIR MARKETS DATA		YES
Apache Station	160	2002	5,167.0	3,068,830.5	6,528.4	31,278,625			
Apache Station (Cochise)	GT1	10	10	10	CT	NG	1965	OP	
	GT2	19.8	20	20	GT	DFO	1972	OP	
	GT3	64.9	63	63	GT	DFO	1974	OP	
	ST1	75	72	72	CA	RFO	1965	OP	
	ST2	194.7	175	175	ST	SUB	1979	OP	
	ST3	194.7	175	175	ST	SUB	1979	OP	

Figure 1. Arizona fossil power generation

Only minimal data about emissions at cement and lime facilities was found. Two useful sources of data were the U.S. Geological Survey and the Portland Cement Association, which both list plants and information on location and ownership. CARB has information for the state on plant locations and criteria pollutants similar to the power plant data. The Oregon Department of Environmental Quality (DEQ) has a database for plants via their permitting process. In addition to ownership and plant contact information the DEQ data includes location by latitude and longitude. Estimates of CO_2 emissions from cement and lime plants were made using methods developed by the EPA and EIA, based on cement and lime plant capacity values. The results were sent to the Cement Industry Environmental Consortium for comment. Additional information in found in Appendix I.

Prior to introduction into a pipeline, produced natural gas is typically treated to remove moisture, organic compounds, CO_2, sulfur compounds and other contaminants. While many of the natural gas containments become byproducts and are sold, the reject gas streams may include release of the CO_2 to the atmosphere. Information about natural gas processing was obtained from the Natural Gas Supply Association's Internet site, and the EIA Natural Gas Navigator Internet site. CO_2 emissions data, however, was not available.

Data about refinery operations was obtained from the EPA, EIA, CARB and Oregon DEQ records. The main data elements relevant to the regional sequestration work are the plant capacities and plant location and contact information. Estimates of CO_2 emissions were calculated from information provided by refineries in Canada (Nyboer and Murphy, 2004). In this Canadian study, it was possible to derive a factor for CO_2 emissions based on the plant production capacity of barrels per day. Additional information is found in Appendix I.

2.1.2 Geologic Sink Characterization

WESTCARB has focused on sedimentary basins as the initial most-promising targets for geologic sequestration. Our approach for various states has followed similar steps: first, the extent (area) of the basins is determined and entered into a GIS layer. Second, baseline data are collected and preliminary screening is conducted using such criteria as the presence of porous sediments, depth, and restricted access, resulting in a list of basins for which more detailed data on geologic properties are to be obtained. Priority is given to basins in which there are potential value-added benefits from enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coal bed methane recovery (ECBM). Data from reservoirs in these basins form the bulk of the characterization data. The third step entails evaluating CO_2 storage capacity. The final step integrates the characterization data with source and transportation data to evaluate economics and develop supply curves for regional source/sink options.

In California, the California Geologic Survey identified and catalogued sedimentary basins within California's 11 geomorphic provinces. Selected basins included all large or hydrocarbon-producing basins, as well as numerous smaller basins identified from the 1:750,000 scale geologic map of California (Jennings *et al.*, 1977). Where basins extended offshore, only the onshore portions were considered. This resulted in an inventory of 104 basins, outlines of which were digitized to produce a California sedimentary basin GIS layer. This layer was combined with a California oil and gas field layer to illustrate the distribution of known oil and gas fields. Basins were screened to determine preliminary suitability for potential CO_2 sequestration, with those basins not meeting the screening criteria excluded from further consideration. Screening involved literature searches and analysis of available well logs. Criteria included the presence of significant porous and permeable strata, thick and pervasive seals, and sufficient sediment thickness to provide critical state pressures for CO_2 injection (>800 m—2,625 ft). Accessibility was also considered, with basins overlain by national and state parks and monuments, wilderness areas, Bureau of Indian Affairs-administered lands, and military installations being excluded. Most of the basins excluded for this reason are located in the arid desert valleys of the Basin and Range and Mojave Desert geomorphic provinces. Structural closure or stratigraphic trapping was not considered a prerequisite for saline aquifers at the screening level.

To identify areas of adequate sedimentary fill, depth-to-basement contour maps were prepared for those basins containing sufficient basement penetrations. This included the Sacramento, San Joaquin, and Salinas basins. In some producing basins, where basement well control is limited or absent, basement contour maps were extrapolated from shallower structure maps (Eel River Basin), or published geophysical depth-to-basement maps were used (Los Angeles, Ventura Basins).

To characterize potential saline aquifers and hydrocarbon reservoirs, oil and gas field and reservoir data were assembled for depleted and producing fields. Data was compiled in field level and reservoir-level databases and attributed to the California oil and gas field GIS layer for manipulation and spatial analysis by other WESTCARB participants. Field-level data included information such as location, depth, field area, cumulative production, and depth-to-base of fresh water. Field-level database parameters are shown in Table 1.

Table 1. Sample content of a Field Table database record

Field Code:	**VE024**
Field:	Honor Rancho Oil
Discovery Well Operator:	The Texas Co.
Discovery Well:	Honor Rancho A -1
Section:	6
Township:	4N
Range:	16W
Meridian:	SB
Discovery Date:	8/1/1950
Deepest Well Operator:	So. California Gas Co.
Deepest Well:	Wayside Unit 28
Section:	7
Township:	4N
Range:	16W
Meridian:	SB
Depth (ft.)	11,747
Field Area (ac.)	450
Cum. Oil Prod. (MBO)	31,098
Cum. Gas Prod. (MMCF)	52,992
Base Fresh Water:	1,150

Reservoir-specific parameters for producing, abandoned, or shut-in reservoirs in each field were compiled in the reservoir-level database. These data included reservoir fluid (oil, gas, water), zone status (producing, abandoned, shut-in), average depth, average thickness, producing area, porosity, permeability, initial pressure and temperature, formation water salinity, seal thickness, trap type (structural or stratigraphic), and history of secondary and tertiary recovery efforts. A measure of "fracture intensity" was assigned for most reservoirs to instill a general sense of fracturing and/or faulting. This subjective measure was assigned a value of low, medium, or high, based solely on the number of mapped faults illustrated in published California Department of Conservation, Division of Oil, Gas, and Geothermal Reservoirs (DOGGR) field maps (L = 0–1 fault; M = 2–3 faults; H = 4+ faults). An example of reservoir database parameters is shown in Table 2.

Table 2. Sample content of a Zone Table database record

Field Code:	VE024	Perm. (md):	20
Zone:	Modelo Fm.	Perm. Range Min. (md):	179
Age:	U. Miocene	Perm. Range Max. (md):	
Oil or Gas:	O	Pressure (lb/ft.):	2,962
Date of Discovery:	12/1/1950	Press. Range Min. (lb/ft.):	4,500
Zone Status (P/A/SI):	P	Press. Range Min. (lb/ft.):	190
API Gravity:		Temperature (ºF):	
API Range Min.:	35	Temp. Range Min. (ºF):	
API Range Max.:	39	Temp. Range Max. (ºF):	
GOR:		Salinity (ppm NaCl):	
GOR Range Min.:	220	Sal. Range Min. (ppm NaCl):	11,200
GOR Range Max.:	1,250	Sal. Range Max. (ppm NaCl):	24,800
Sp. Gravity:		TDS (ppm):	20,200
Sp. Gravity Min.:	0.470	TDS Range Min. (ppm):	
Sp. Gravity Max.:	0.765	TDS Range Max. (ppm):	
BTU:	1,066	Seal:	Modelo Fm.
BTU Range Min.:		Seal Thickness (ft.):	
BTU Range Max.:		Seal Thickness Min. (ft.):	5
Cum. Oil (MBO):	29,094	Seal Thickness Max. (ft.):	50
Cum. Gas (MMCF):	47,601	Trap Type:	Stratigraphic
No Pool Breakdown:		Fault Intensity:	L
Depth (ft.):		ERP 1:	Gas Injection
Depth Range Min.:	6,481	ERP 1 Start:	1954
Depth Range Max.:	10,000	ERP 1 Stop:	1956
Thickness (ft.):		ERP 2:	Waterflood
Thickness Range Min. (ft.):	94	ERP 2 Start:	1959
Thickness Range Max. (ft.):	310	ERP 2 Stop:	1966
Producing Area (ac.):	400	ERP 3:	Waterflood
Porosity (%):		ERP 3 Start:	1972
Porosity Range Min. (%):	7	ERP 3 Stop:	1975
Porosity Range Max. (%):	26		

In Nevada, the minimum-basin-depth criterion was taken as 1,000 m (3,300 ft), owing to a generally higher geothermal gradient in the Basin and Range province. The Nevada

Bureau of Mines and Geology (NBMG) developed a GIS-based screening methodology that takes into account the proximity of potential geologic sinks to faults, mineral and geothermal resources, populated areas, other restricted lands, and water resources (Price *et al*., 2005). The NBMG also developed a method, illustrated in Table 3, to interrogate well records for information relevant to geologic sequestration.

Table 3. Information recorded from records of deep wells drilled in Nevada (Hess, 2004)

DEFINITIONS

CO_2 reservoir rock ≡ sandstone, conglomerate, sand, or gravel

Seal rock ≡ shale, mudstone, claystone, mud, clay, halite, gypsum, salt, or nonwelded (possibly clay- or zeolite-altered) ash-flow tuff

NEITHER A CO_2 RESERVOIR ROCK NOR SEAL ≡ limestone, dolomite, fractured volcanic rock, fractured sandstone, quartzite, metamorphic rocks, or granite or other igneous rocks

Data collected from well records, if available, in wells within areas not otherwise excluded for consideration of CO_2

1. Total depth of well.
2. Are there potential CO_2 reservoir rocks in the well below 1 km (3,281 ft) depth? If no, go to next well.
3. Is there a potential seal below 1 km and above that reservoir rock? If no, go to next well.
4. Depth to base of Cenozoic/Tertiary volcanic rocks and alluvium.
5. Depth to base of deepest reservoir rock in pre-Tertiary sedimentary package.
6. How fresh is the water in this deepest reservoir rock? (Total dissolved solids – TDS?)
7. How porous is this deepest reservoir rock?% of porosity?
8. How permeable is this deepest reservoir rock? K in millidarcy?
9. Thickness of the thickest single pre-Tertiary reservoir rock.
10. How fresh is the water in this thickest pre-Tertiary reservoir rock?
11. How porous is this thickest pre-Tertiary reservoir rock?
12. How permeable is this thickest pre-Tertiary reservoir rock?
13. Total thickness of all pre-Tertiary reservoir rocks.
14. Thickness of the thickest single pre-Tertiary seal rock above the deepest reservoir rocks.
15. Total thickness of all pre-Tertiary seal rocks above the deepest reservoir rocks.
16. Depth to base of deepest reservoir rock in Tertiary sedimentary package below 1 km.
17. How fresh is the water in this deepest reservoir rock in Tertiary package?
18. How porous is this deepest reservoir rock in Tertiary package?
19. How permeable is this deepest reservoir rock in Tertiary package?
20. Thickness of the thickest single Tertiary reservoir rock below 1 km.
21. How fresh is the water in this thickest single Tertiary reservoir?
22. How porous is this thickest single Tertiary reservoir?
23. How permeable is this thickest single Tertiary reservoir?
24. Total thickness of all Tertiary reservoir rocks below 1 km.
25. Thickness of thickest single Tertiary seal rock below 1 km.
26. Total thickness of all Tertiary seal rocks below 1 km.
27. Total thickness of all Tertiary seal rocks below 1 km and above shallowest reservoir rock.
28. Thickness of halite beds below 1 km.

FACTORS THAT CAN NOW BE DERIVED FROM THESE NUMBERS

A. Total thickness of potential reservoir rocks = #13 + #24
B. Total thickness of potential seal rocks above the deepest reservoir rock and below 1 km = #15 + #26
C. Reservoir rock to seal rock ratio = #A/#B, ~ sand/shale ratio

In Oregon and Washington, GIS layers were developed that give the location of sedimentary basins. Data on the overall geology of sedimentary basins and the available reservoir properties were assembled. Data from the few available deep wells penetrating the basalt layers in the eastern portions of the states were reviewed to establish the presence of sediments at depths 300 m (1,000 ft) to over 2,700 m (9,000 ft). Information on coal formations as potential sinks was also compiled, including available data on coal rank, percent methane saturation, and sorbtive capacity.

2.2 GIS Database Description

The GIS database for WESTCARB is housed in an Enterprise Geodatabase format using ArcSDE (Spatial Database Engine) from Environmental Systems Research Institute, Inc. (ESRI). This database can be connected directly to any ESRI ArcMap client version 9.0 or greater. The data layers can also be requested from the Utah Automated Geographic Reference Center (AGRC) in a format that can be used in any common GIS software. A complete list of available layers is given in Appendix II. The layers are organized into the main categories of "sedimentary basins," "sources," and "base layers." The sedimentary basin category contains sub-categories of "geologic features" and "supporting data".

An interactive web map has been created to provide access to the data layers via the internet. This interactive map can be viewed at http://atlas.utah.gov/co2wc. In addition to providing a means by which the GIS data layers can be viewed and queried, this interactive map includes tools that let the user perform some basic analysis operations, such as buffering and linear distance measurement.

In addition to the compilation of the partnership database, WESTCARB and AGRC have cooperated with, and will continue to cooperate with, the NATCARB (national carbon) database in the modeling and serving of the nationwide distributed carbon atlas. The data layers are served via ESRI's ArcIMS map services, which are harvested by the NATCARB interactive map portal. Additional information on the structure of the WESTCARB digital database is found in Appendix III.

2.3 Geologic Sequestration Options: Methodology

EPRI led the effort to define cost-effective, environmentally acceptable geologic source-sink options for the region. The Massachusetts Institute of Technology (MIT) performed GIS-based analyses to match sources with sinks in the region, and in California, made an assessment of the potential for sequestration combined with enhanced oil and gas recovery. These analyses used, as input, the data developed in the source-sink characterization work. Sfa Pacific developed a spreadsheet tool for estimating CO_2 capture costs, which were needed in the analyses. MIT also developed computer algorithms (Appendix XIX) needed for least-cost matching of sources and sinks.

Capture cost estimates made using the "*Generic* CO_2 *Capture Retrofit*" spreadsheet prepared by Sfa Pacific were based on three key input variables: (1) the flue gas flow rate (in tonnes per hour), (2) the flue gas composition (volume share or weight share of CO_2 in flue gas), and (3) the annual load factor. The spreadsheet provided estimates of capture cost in terms of both CO_2 captured and CO_2 avoided. CO_2 captured is the amount of CO_2 captured by the absorber and kept out of the atmosphere—assumed to be 90% of the CO_2 in the flue gas. However, since the CO_2 capture process requires energy for purification and compression, the "CO_2 avoided" term subtracts the CO_2 emitted producing this process energy from the total amount of CO_2 captured. The two terms are used differently in CO_2 sequestration analysis. The "CO_2 captured" term is used for calculations involving the amount of CO_2 being handled, such as for pipeline transportation costs, while the "CO_2 avoided" term is used for calculations involving the amount of CO_2 withheld from the atmosphere and therefore eligible for possible CO_2 emissions credits. In order to use the Sfa Pacific capture cost tool with fossil fuel power plants, an assumption was made that the CO_2 capture cost for such plants varied only as a function of fuel type, design capacity, and operating factor. A further assumption was made that power plants would operate at 80% of their designed capacity once the capture facility has been installed. Additional information is found in Appendix XX.

The transportation cost model takes the source-sink matching as *a priori* and estimates the CO_2 pipeline transportation cost at three levels: (1) one source to one sink; (2) many sources to one sink without route-sharing; and (3) many sources to one sink with route-sharing. For the simplest case of one-source-to-one-sink connection, the estimation consists of three steps. First, the pipeline diameter is calculated from the CO_2 flow rate. Second, the least-cost route is selected based on the relative cost factors assigned to various transportation obstacles for both economic and environmental concerns. The identified transportation obstacles include populated places, wetlands, national and state parks, waterways, railroads, and highways. Finally, the base-case pipeline construction cost, additional obstacle-crossing cost, and O&M cost are assigned to estimate the levelized CO_2 transportation cost. The procedures followed in each of these steps are described in Appendix XX.

2.4 Technology Deployment Issues: Methodology

Phase I work addressed key issues affecting deployment of CCS technologies, including storage-site permitting and monitoring, injection regulations, and health and environmental risks. The Action Plan for addressing these key issues in Phase II of the WESTCARB project is found in Appendix XV.

2.4.1 Regulatory Framework

Terralog Technologies worked with state agencies and EPA to compile current regulations for injection wells in the states in the WESTCARB region (see Appendix XIII). Bevilacqua-Knight, Inc., worked with Terralog to develop a web-based, state-by-state compilation, with links to the specific, relevant, statutes. Terralog also worked with various state agencies to compile regulations covering land use changes, which would be relevant to terrestrial forest sequestration activities. More information on the web-based compilation is found in Appendix X.

2.4.2 Health and Environmental Risks

In order to reduce the possibility that geologic CO_2 storage projects will result in health, safety, and environmental (HSE) impacts due to CO_2 leakage and seepage, it is essential that sites be chosen to minimize HSE risk. Lawrence Berkeley National Laboratory (LBNL) developed a spreadsheet-based Screening and Ranking Framework (SRF) for evaluating multiple sites on the basis of their potential for HSE risk due to CO_2 leakage and seepage. The SRF was formulated to evaluate three fundamental characteristics of a geologic CO_2 storage site:

1. Potential for long-term primary containment by the target formation,
2. Potential for secondary containment should the primary formation leak, and
3. Potential of the site to attenuate and/or disperse leaking CO_2 should the primary formation leak and secondary containment fail.

The SRF spreadsheet is designed to provide an independent assessment of each of these three characteristics through an evaluation of the properties of various attributes of the three characteristics. The input required by the SRF is quite general and may rely primarily on expert opinion depending on the degree of characterization and/or published information available for the sites. The assessment made in the framework is based on four classes of information: (1) site characteristics, which are defined by (2) attributes, which are defined by (3) properties, which are defined by (4) values input by the user. Further information on the framework methodology is found in Appendix IX and Appendix XII.

2.4.3 Monitoring and Verification

As a basis for development of monitoring protocols, LBNL studied the application of a number of different geophysical techniques for monitoring geologic sequestration of CO_2. The relative merits of seismic, gravity, and electromagnetic (EM) geophysical techniques were considered. The approach was to carry out numerical simulations of the response of the geophysical methods using site-specific data. Time-lapse performance of seismic, gravity, and EM techniques were considered for a proposed CO_2 sequestration project in the Schrader Bluff field on the North Slope of Alaska. Seismic and gravity responses were simulated for a simplified flow simulation model of the Rio Vista gas field in Sacramento Basin, California. In both cases, rock physics models were used to convert the output of flow simulations to changes in geophysical properties. Thus, for seismic methods, changes in saturation and fluid pressure in the reservoir, brought about by injection of CO_2 , were converted to changes in seismic velocity via the rock physics model. Numerical simulation was then used again to calculate the response of the candidate geophysical method. For example, for seismic methods, numerical simulation was used to calculate the changes in the seismic wavefield. This numerical data was then processed using the same techniques applied to seismic data acquired during geophysical field surveys. Additional information on the numerical modeling methods used in this study can be found in Appendix XIV.

2.4.4 Life Cycle Analysis

Working with EPRI, Nexant prepared a life cycle assessments (LCA) for power generation including capture. Major point-source pollutants, in addition to CO_2, were addressed. The spreadsheet (Appendix VIII) allows the user to select and specify the value of several variables to see how emission estimates are changed. The spreadsheet consists of four parts: Existing Data; Retrofit Estimates; Replacement of Lost Generation Capacity; and Estimates of LCA Emissions Caused by Retrofit Actions.

2.5 Terrestrial Sequestration Baselines and Supply Curves: Methodology

Winrock International worked with the Oregon Department of Forestry, the California Department of Forestry and Fire Protection, the Washington State Department of Natural Resources, and other state and agencies to characterize the terrestrial carbon baseline in the region, and to develop supply curves. The Oregon Department of Forestry was the lead coordinating agency for the work.

2.5.1 Baselines

The objective of the work on carbon baselines was to establish the baseline carbon stocks and changes in stocks for the forest and agricultural sectors during the most recent 10-year period for which data are available (generally the decade of the 1990s). Such baselines can assist in identifying opportunities where carbon removals (sequestration) in each sector might be increased, or carbon emissions decreased, through changes in land use and management.

The same general methodology for determining the agricultural baseline was followed in each state. As with other terrestrial carbon baselines, the areas (hectares) of different land uses and changes in land use are combined with carbon densities (tons of carbon per hectare) of each land use, to yield an estimate of the total emissions and removals of carbon associated with land management and/or conversion of lands over a given time period. Estimates of area and changes in area of agricultural and nonagricultural land use types were derived from the National Resource Inventory (NRI) database. Because of data availability, the period chosen to establish a baseline of changes in land use was 1987 to 1997. The detail of the NRI database made it possible to examine conversion of agricultural lands to other land uses, both at the state and county level of analysis, and for both perennial woody crops (fruit and nut orchards, vineyards, berry crops, etc.) and annual non-woody crops. Carbon densities in each crop type were derived from consultation with local universities and extension agents, crop biomass statistics from the U.S. Department of Agriculture–National Agriculture Statistics Service, consulting the literature, and applying standard methods for biomass carbon estimation.

The baseline for forests is separated into three components. A general forests baseline is presented at the state level for all forestlands, based on U.S. Department of Agriculture (USDA) Forest Service data, detailing change in forest area and change in carbon stocks, but with no attribution to the causes for the change. Using additional data bases, the specific cases of emissions associated with development and with fire are further examined. These components form part of the total detailed in the general forest baseline section and should not be considered separately. Additional information is found in Appendix IV.

2.5.2 Supply Curves

Methodologies developed by Winrock International in its work with Electric Power Research Institute and the California Energy Commission were applied to develop carbon supply curves for the major classes of potential land-use and forest-based activities. The approach involved two steps:

(1) Using standard data from available data sources and available methodologies, estimate the amount of carbon that will be sequestered by a particular change in land use or management practice.
(2) Prepare carbon supply curves for different classes of potential terrestrial projects, including afforestation of cropland, afforestation of rangeland, and changes in management of forestland.

The carbon supply associated with a potential change in land use was estimated through the following steps:

(1) Identify the classes of land uses and the associated changes in management that could lead to significant increase in carbon stocks.
(2) Estimate the area for each potential change in land use.
(3) Estimate the quantities of carbon per unit area that could be sequestered for the change in land use over a given time period.
(4) Estimate the total costs (opportunity, conversion, maintenance, and measuring and monitoring).

(5) Combine the estimated quantities of carbon per unit area with the corresponding area and cost to produce estimates of the total quantity of carbon that can be sequestered for a given range of costs, in $/metric ton C or $/metric ton CO_2.

For rangelands and croplands (lands growing wheat and hay), the potential carbon sequestration was estimated for afforestation using native species. Historical evidence suggests that in many areas, large tracts of forest once stood where grazing and agricultural lands do now. The general approach was to identify and locate existing rangelands and croplands where biophysical conditions could favor forests, estimate carbon accumulation rates for the forest types projected to grow, and assign values to each contributing cost factor. The carbon supply is estimated for three durations—20 years, 40 years, and 80 years of forest growth—to reflect the impact of activity duration on the likely supply and provide an assessment for the near-term and longer-term planning horizons.

For forestlands, potential carbon supply was estimated for three alternatives for 20-year and/or permanent contract periods: (1) allowing timber to age past economic maturity (lengthening rotation time); (2) increasing the riparian buffer zone by an additional 200 ft; and (3) reducing hazardous fuel in forests to reduce catastrophic fires, and subsequently using fuels in biomass power plants. For estimating the costs of allowing timber to age and the costs of enhanced riparian zone management, estimates are based on specific counties for public and private landowners, and then extrapolated to all counties throughout the state. For the fuel reduction alternative, the analysis used a "Suitability for Potential Fuel Reduction" (SPFR) score on forest landscapes where potential exists for significant carbon loss from moderate-to-high-intensity wildland fires. The SPFR scores were created in a GIS using slope, distance to biomass plants, and distance from roads as equal weighted factors in the decision-making process. Suitability scores for potential fuel reduction with highest suitability were assigned to areas with gentle grades of slope close to roads and biomass power plants. Additional information is found in Appendix XXI.

3 Results and Discussion

3.1 Geologic Source-Sink Characterization

3.1.1 WESTCARB CO_2 Emissions

The CO_2 emissions profile for the states in the WESTCARB region (Figure 2) shows that the region accounts for about 11% of the U. S. emissions, based on the 1999 EPA emission inventories from fuel combustion. Within the region, transportation accounts for 53%, utilities 13%, and industry 23%, of the emissions. Emissions from the transportation sector are somewhat higher than the national average while those of the utility sector are lower. California ranks second among all states in CO_2 emissions, with the transportation sector providing around 58% of the total. The large percentage of emissions from mobile sources is one justification for evaluating terrestrial sequestration options. The significant percentage from industrial sources motivates analysis of industrial point sources along with power plants in assessing geologic sequestration options. The largest stationary sources in the region are power plants, oil refineries, and cement plants.

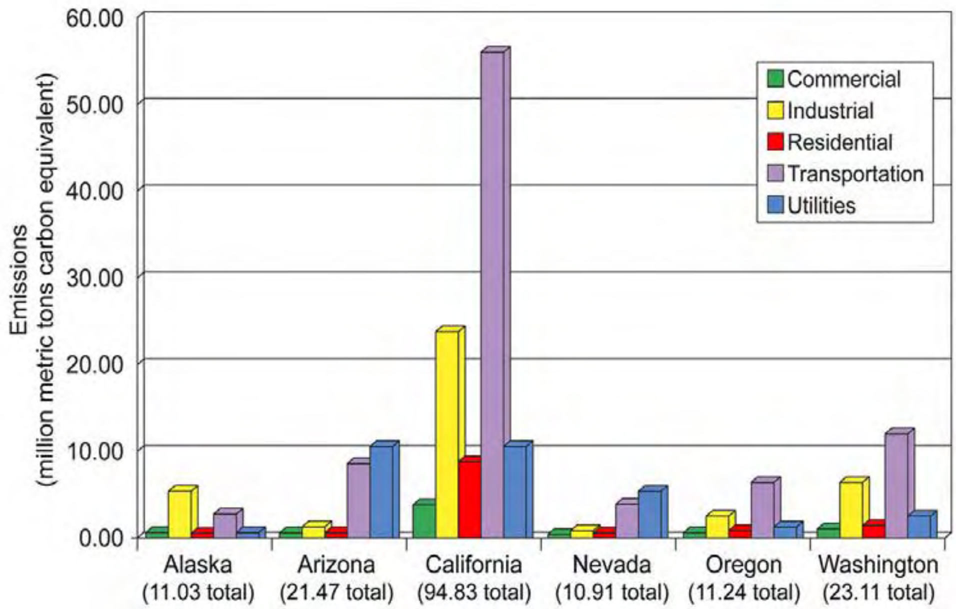

Figure 2. WESTCARB CO_2 emissions profile

The WESTCARB GIS database includes information for 77 facilities from four categories with total annual CO_2 emissions of 159 Mt. Table 4 summarizes the CO_2 emissions from major stationary sources in the WESTCARB region by facility type and by state, respectively. The CO_2 emissions from power plants are actual 2000 CO_2 emissions from eGRID database. As discussed previously, annual CO_2 emissions from cement plants and refineries are estimates based on production capacities. CO_2 emissions for gas processing plants were missing, and so were entered as zero in Table 4. Though not zero, CO_2 emissions from gas processing in WESTCARB is not significant. Power plants are the single largest source of CO_2 emissions, accounting for more than 80 percent of the emissions from the stationary sources in the database. California has the highest annual CO_2 emissions in the region, representing over one-third of the regional total emissions, followed closely by Arizona.

Table 4. CO_2 emissions from stationary sources by facility type and state

State	Power Plants		Cement		Gas Processing[d]		Refineries		Total	
	# of Facilities	CO_2 Emiss (Mt)	# of Facilities	CO_2 Emiss (Mt)	# of Facilities	CO_2 Emiss (Mt)	# of Facilities	CO_2 Emiss (Mt)	# of Facilities	CO_2 Emiss (Mt)
AK	6	2.3	0	0.0	3	0	3	2.6	12	4.9
AZ	7	48.3	2	1.4	0	0	0	0.0	9	49.7
CA	18	36.5	6	6.0	2	0	7	11.3	33	53.8
NV	6	24.8	3[a]	0.0	0	0	0	0.0	9	24.8
OR	3	7.4	2[b]	0.6	0	0	0	0.0	5	8.0
WA	3	12.1	3[c]	0.8	0	0	3	4.4	9	17.3
Total	**29**	**131.3**	**16**	**8.8**	**5**	**0**	**13**	**18.4**	**77**	**158.5**

[a]The WESTCARB database contains no production capacity data for cement in Nevada.

[b]Only one cenment plant in Oregon has production data.

[c]Only two cement plants in Washington have production data.

[d]No production capacity data or CO_2 emission data is avaiable for gas processing facilites.

Locations of the large stationary sources in the WESTCARB states are shown in Figures 3 and 4. Additional information is found in Appendix XX.

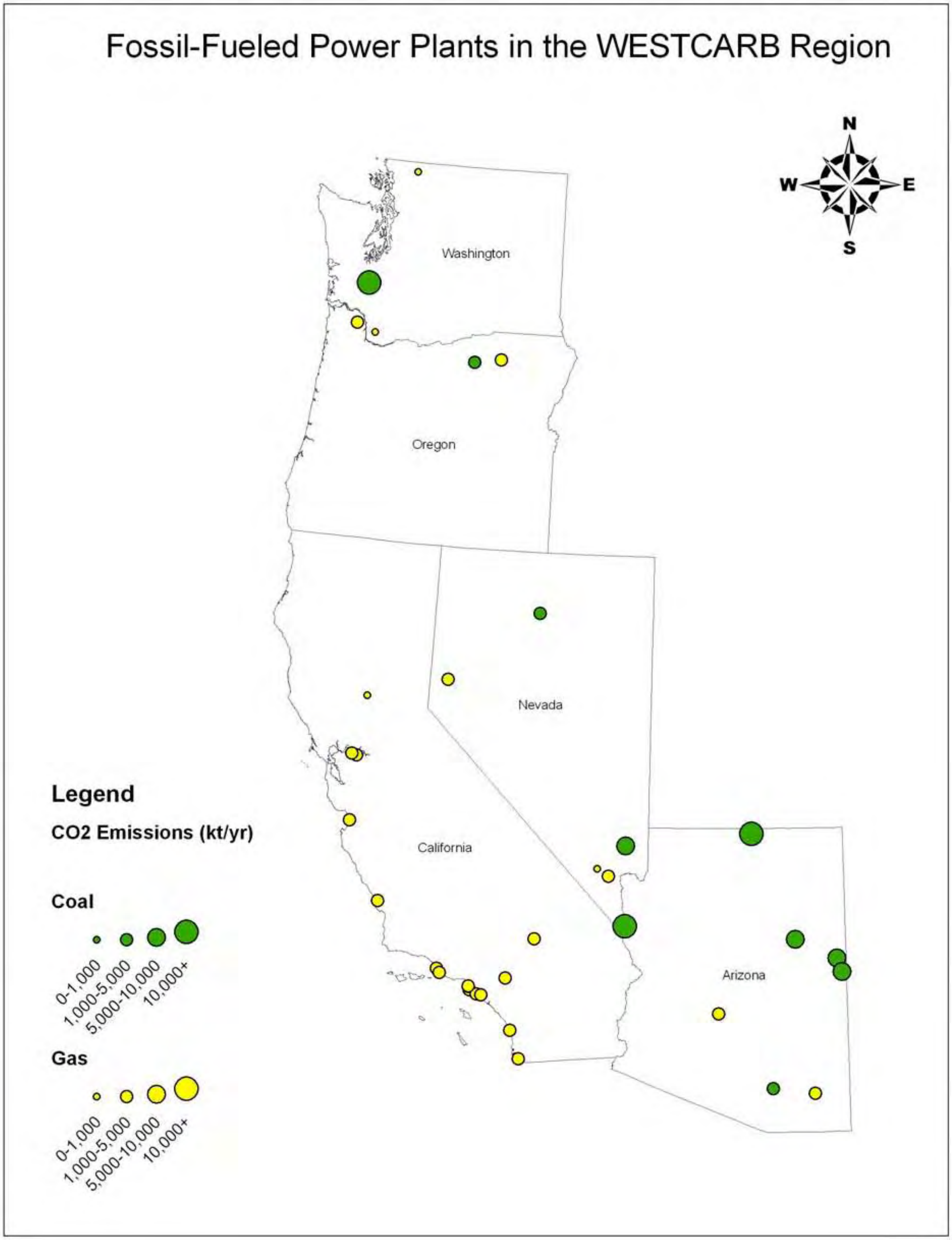

Figure 3. Fossil-fueled power plants in the WESTCARB region

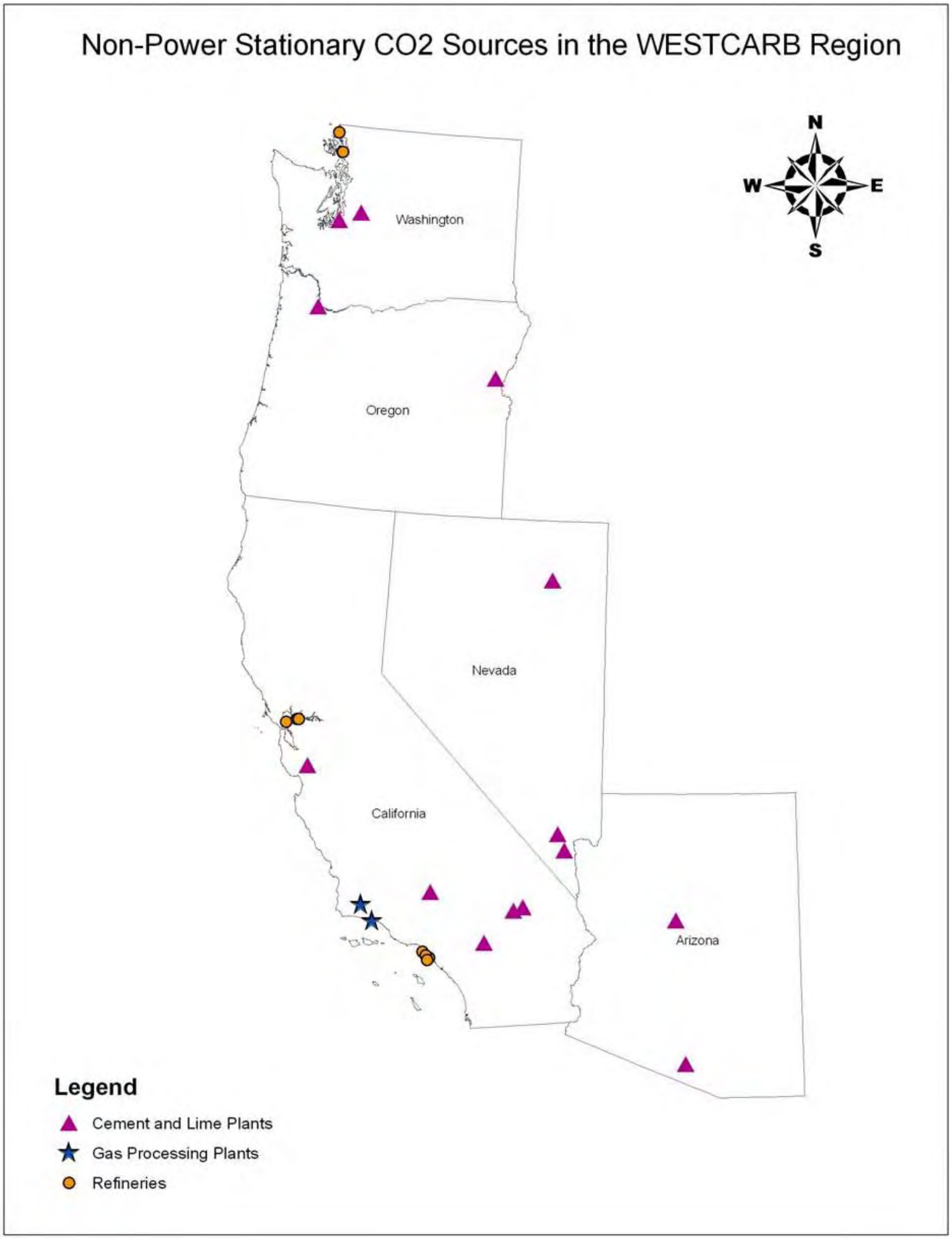

Figure 4. Non-power CO_2 sources in the WESTCARB region

3.1.2 Geologic Sinks

3.1.2.1 California

Sedimentary Basins

Of the 27 basins which met the screening criteria, the most promising are the larger Cenozoic marine basins, including the San Joaquin, Sacramento, Los Angeles, Ventura, and Salinas basins, followed by the smaller Eel River, La Honda, Cuyama, Livermore, and Orinda marine basins. Favorable attributes of these basins include (1) geographic diversity; (2) thick sedimentary fill with multiple porous and permeable aquifers and hydrocarbon reservoirs; (3) thick, laterally persistent marine shale seals; (4) locally abundant geological, petrophysical, and fluid data from oil and gas operations; and (5) numerous abandoned or mature oil and gas fields that might be reactivated for CO_2 sequestration or benefit from CO_2 enhanced recovery operations. Results for the above basins are summarized in the following pages. More detailed discussion of these, as well as other California sedimentary basins, is found in Appendix V.

The Great Valley province is an elongated topographic valley approximately 725 km (450 miles) long lying between the Sierra Nevada and the Coast Ranges, and extending from the Klamath Mountains in the north to the Transverse Ranges in the south. The Great Valley consists of a large depositional basin that has received sediments almost continuously since the late Jurassic and contains, by some estimates, as much as 12,200 m (40,000 ft) of mostly marine, sedimentary rocks (Magoon and Valin, 1995). In the subsurface, the Great Valley is divided into the Sacramento Basin in the north and the San Joaquin Basin to the south, the point of division being the buried Stockton Arch south of the City of Stockton.

The Sacramento Basin is approximately 390 km (240 miles) long and averages about 80 km (50 miles) wide. In its current form, the basin comprises an asymmetric trough with a westerly dipping basement surface ranging from surface exposures in the Sierra foothills to depths estimated to be greater than 6,700 m (22,000 ft). In contrast to the oil-prone San Joaquin Basin, the Sacramento Basin is a natural gas-producing basin. Figure 5 is a generalized cross section from the southern portion of the basin, showing major sandstone units that constitute sequestration targets and shale units that represent regional seals. Formations containing important gas reservoirs include the Winters, Starkey, Mokelumne River, and Domengine. Porosities range from 15 to 35%, and permeabilities range from 10 to 1,700 md (DOG, 1983).

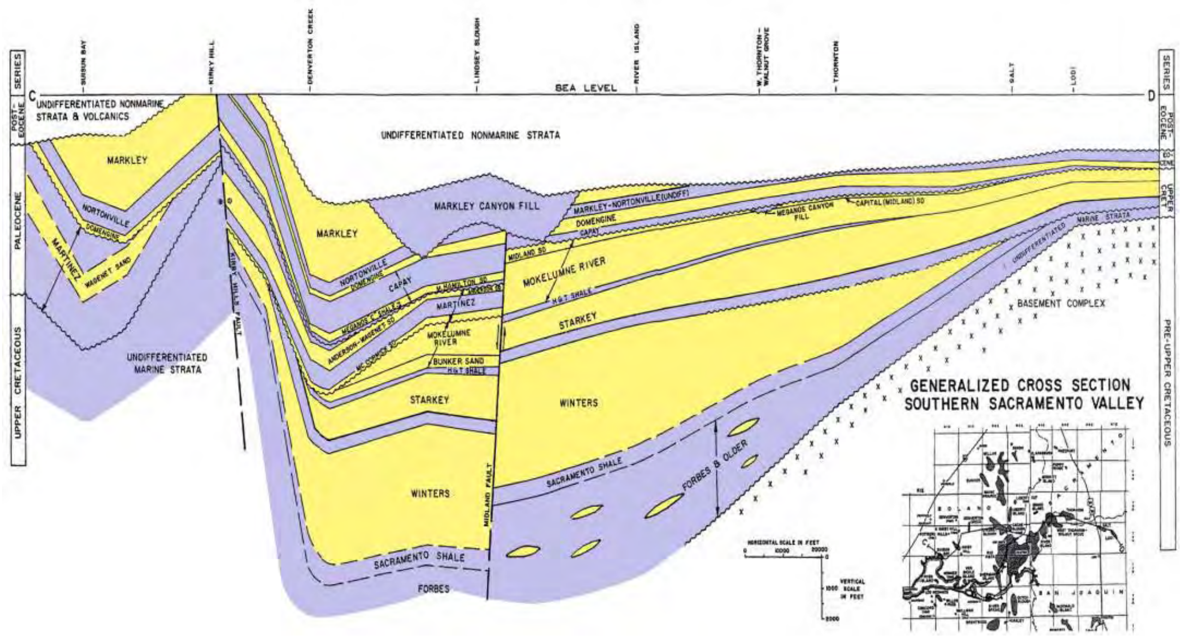

Figure 5. Generalized cross section through the southern Sacramento Valley (adapted from DOG, 1983)

A generalized sandstone isopach map of the Sacramento Basin (Figure 6) reveals good sandstone development paralleling the strike of the basin and ranging from over 300 m (1,000 ft) in Tehama County to nearly 1,220 m (4,000 ft) in Stanislaus County. The southward thickening is largely the result of the post-Cretaceous regional unconformity, which progressively truncates the sand-rich Great Valley Sequence formations to the north, leaving only Forbes and Kione formation sandstones remaining in the northernmost counties.

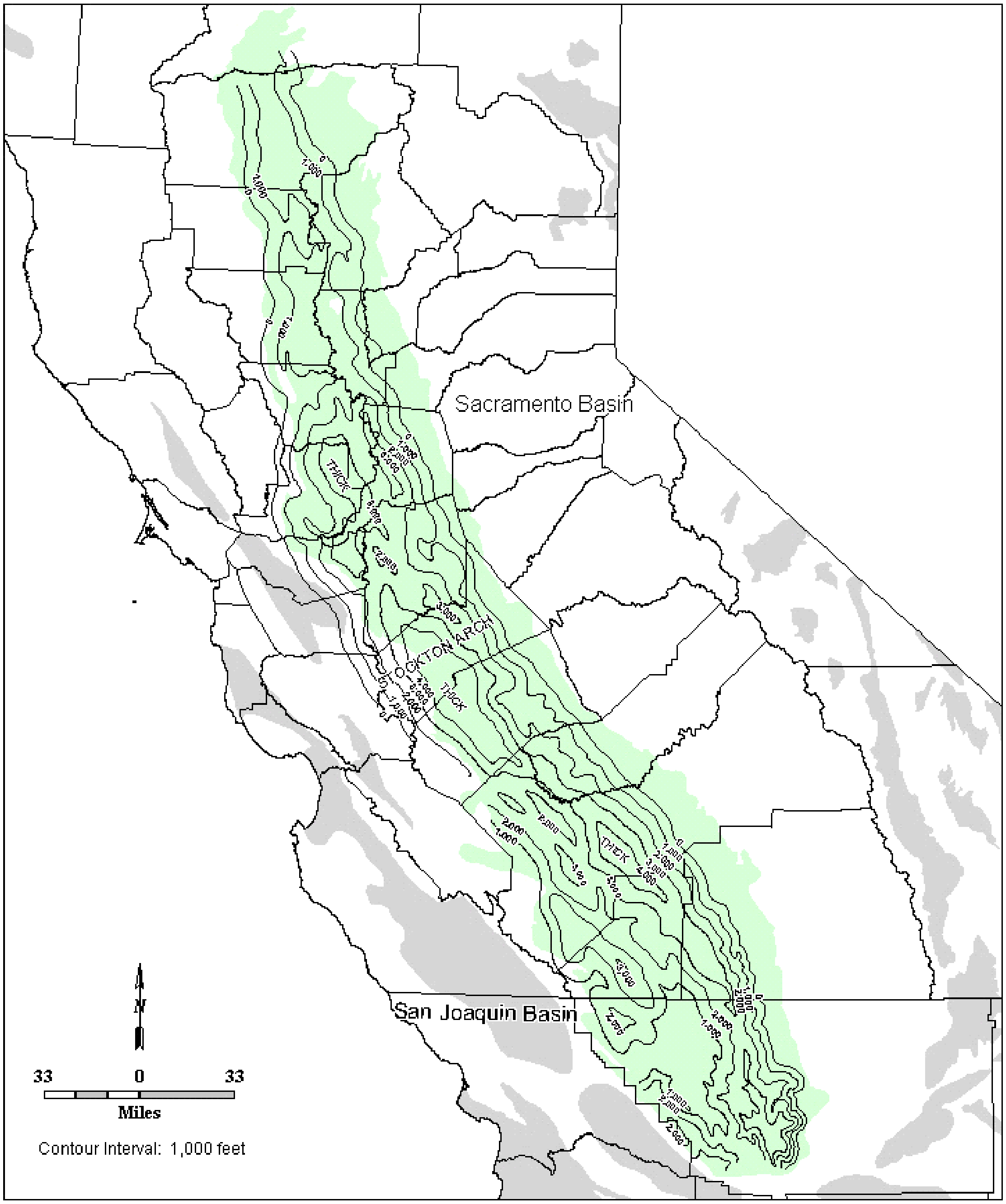

Figure 6. Generalized sandstone isopach map of the Sacramento Basin

The San Joaquin Basin comprises the southern half of the Great Valley province. It extends about 350 km (220 miles) from the Stockton Arch to its southern terminus at the northern Transverse Ranges and averages 80–115 m (50–70 miles) wide. It is bounded on the east by the Sierra Nevada and on the west by the Central Coast Ranges and the San Andreas Fault.

The basin is filled with predominantly marine Cretaceous and Cenozoic clastic sedimentary rocks that attain an aggregate thickness of over 9,150 m (30,000 ft). A generalized cross section in Figure 7 shows sandstone formations that are sequestration targets, and regional shale seals. Important oil producing formations include the Gatchell, Vedder, Jewett, and Pyramid Hill, Temblor, Stevens, Chanac and Santa Margarita, and Etchegoin. Porosities range from 10–40% and permeabilities from 0.2 md to 10,000 md. Porosity and permeability decrease with depth (DOGGR, 1998).

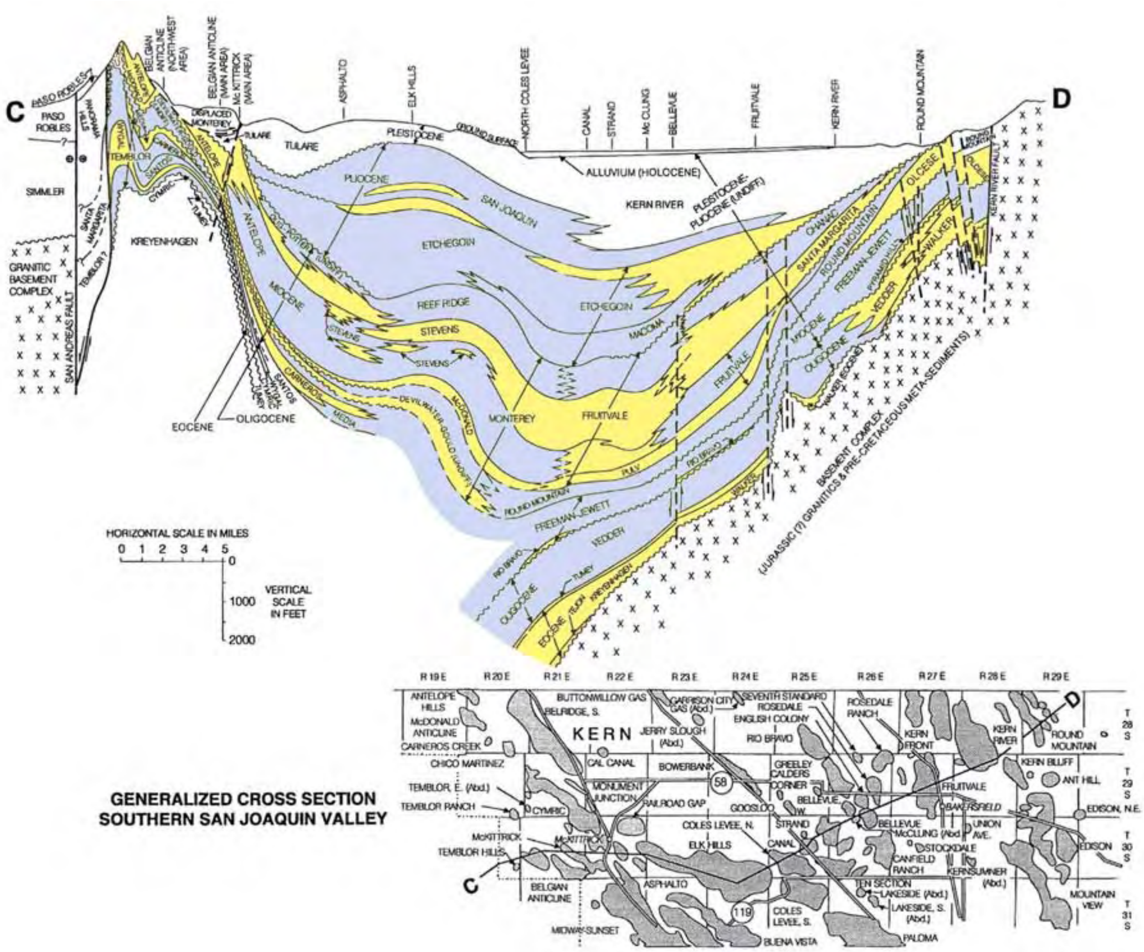

Figure 7. Generalized cross section through southern San Joaquin Valley (adapted from DOGGR, 1998)

A gross sandstone isopach map (Figure 6) shows that sandstone occurs in a trend thickening to over 1,220 m (4,000 ft) parallel to the basin axis. Unlike the Sacramento Basin, the isopach interval includes largely Eocene Gatchell Formation through Pliocene San Joaquin Formation sandstones deposited above the post-Cretaceous unconformity. However, some upper Cretaceous Great Valley Sequence sandstones contribute to the isopach in the northern basin, while lower beds of the Kern River and Tulare formations are included in deeper portion of the southern basin.

The Transverse Ranges are an east-west trending series of mountain ranges and valleys extending about 515 km (320 miles) from Point Arguello eastward to the Mojave Desert. The largest and most important sedimentary basin within these ranges is the Ventura Basin, a complexly folded and faulted Cenozoic marine sedimentary basin. The western two thirds of the basin extends offshore to include the Santa Barbara Channel between the Channel Islands and Santa Ynez Mountains. The onshore portion comprises about 4,079 km^2 (1,575 square miles), including the Santa Clara Valley and Oxnard Plain. The onshore basin is bounded by the Santa Ynez and Santa Monica mountains to the north and south, respectively, and the San Gabriel Fault to the east. The Ventura Basin is the deepest of California's Cenozoic basins, containing more than 17,700 m (58,000 ft) of largely marine sediments. Consequently, the basin includes numerous upper Cretaceous through Pleistocene-age sandstones with sequestration potential, and possibly EOR opportunities. Figure 8 is a generalized cross section of Ventura Basin, which is characterized by major east-west trending thrust faults and tightly folded anticlinal trends that contain the majority of the basin's oil reserves. The Modelo and Pico sandstones are major oil-producing formations with porosities varying from 15 to 35% and permeabilities ranging from 8 md to 6,000 md (DOGGR, 1991). Porosity and permeability decreases with depth.

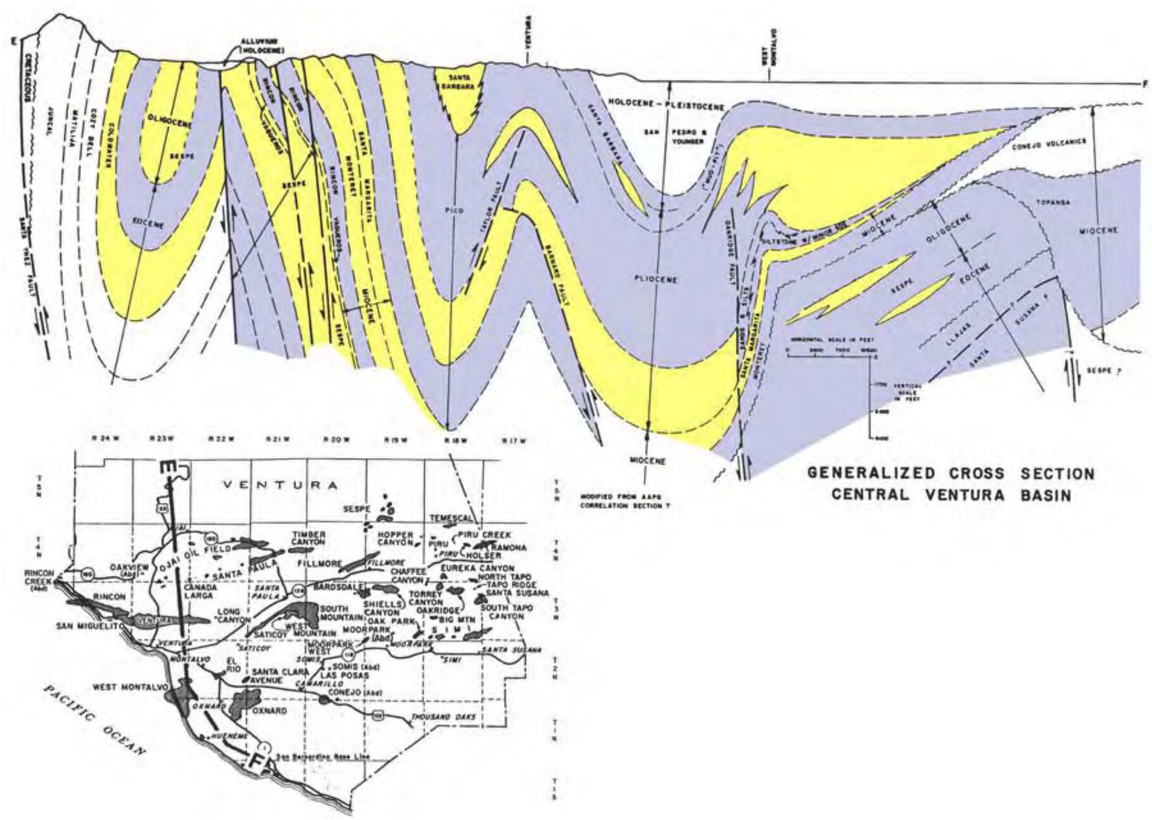

Figure 8. Generalized cross section through the Ventura Basin (adapted from DOGGR, 1991)

A sandstone isopach map for the Ventura Basin reveals three thick east-west trending sandstone zones, each exceeding 1,220 m (4,000 ft) thick, as well as significant sandstone development exceeding 300 m (1,000 ft) throughout most of the basin (Figure 9). In the deeper parts of the basin, sandstones within the isopach interval include primarily Sespe through Pico formation sandstones. Increasing contributions of Cretaceous strata, at the expense of these Eocene through Pliocene deposits, occupy the isopach interval in the shallower basin margins.

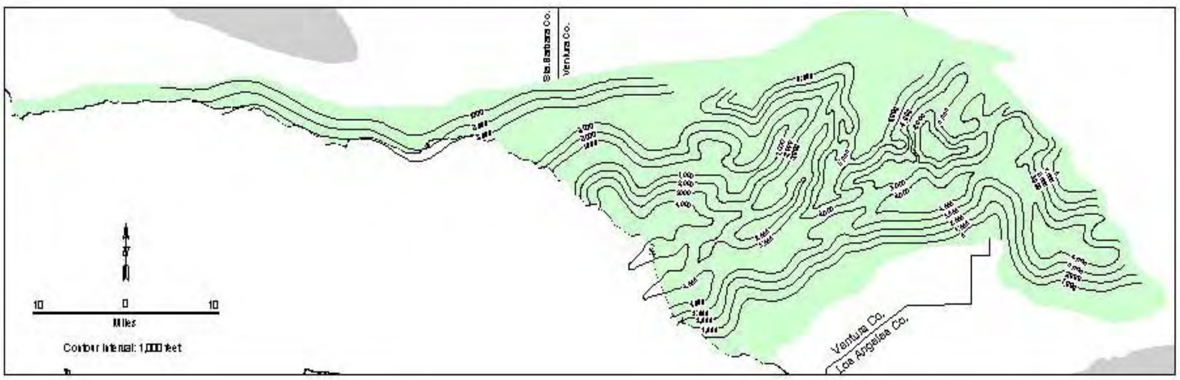

Figure 9. Generalized sandstone isopach map for the Ventura Basin

The Peninsular Ranges are a series of mountain ranges in southwest coastal California characterized by intervening northwest-trending valleys subparallel to faults branching from the San Andreas Fault zone. The Peninsular Ranges are bordered on the north by the Transverse Ranges, on the west by the Channel Islands, and on the east by the Colorado Desert province. The Los Angeles Basin is the largest of the Peninsular Range basins. It is a structurally complex basin located within the San Andreas Transform system at the intersection of the Peninsular Ranges and Transverse Ranges. It covers about 3,890 km^2 (1,500 square miles) and is bordered on the north by the Santa Monica-Hollywood-Raymond Hill Fault Zone and the Santa Monica Mountains; on the northeast by the Sierra Madre Fault and the San Gabriel Mountains; on the east and southeast by the Chino Fault, Santa Ana Mountains, and the San Joaquin Hills; and on the west and southwest by the Palo Verdes Fault. The basin contains a thick section of primarily Miocene and Pliocene sedimentary rocks estimated to be over 8,200 m (27,000 ft) thick. A generalized cross section is shown in Figure 10. The basin is considered the world’s richest in terms of hydrocarbons per unit volume of sedimentary fill and contains three supergiant fields—the Wilmington, Huntington Beach, and Long Beach fields. Major oil-producing formations include the Puente and Repetto sandstones, with porosities ranging from 15 to 35% and permeabilities ranging from 10 to 3,200 md (DOGGR, 1991). Porosity and permeability decrease with depth.

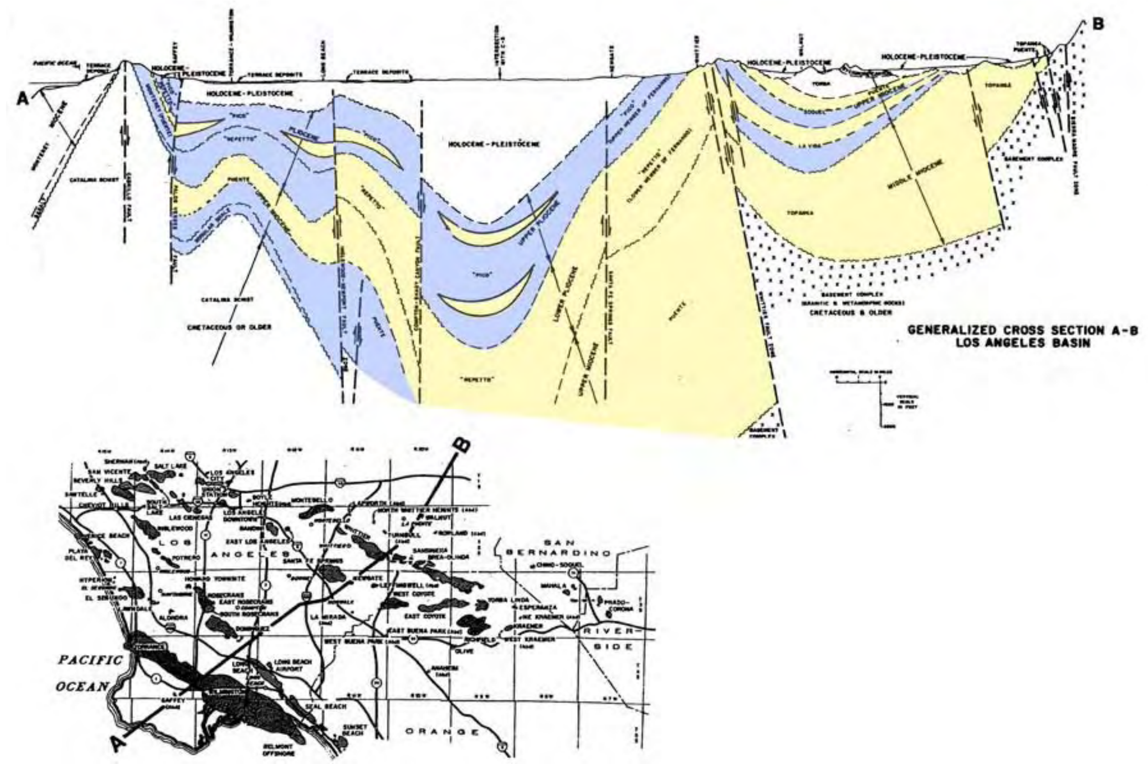

Figure 10. Generalized cross section through the Los Angeles Basin (adapted from DOGGR, 1991)

A sandstone isopach map for the Los Angeles Basin indicates that more than 1,520 m (5,000 ft) of sandstone is present within the isopach interval in the central basin, and that sandstone thickness generally correlates with relative basement depth (Figure 11). The thicker sandstone reflected in the basin center is dominated by Puente, Repetto, and Pico formation sandstones but, in the shallower basin margins, Topanga Formation and older units become locally important in the mapped interval.

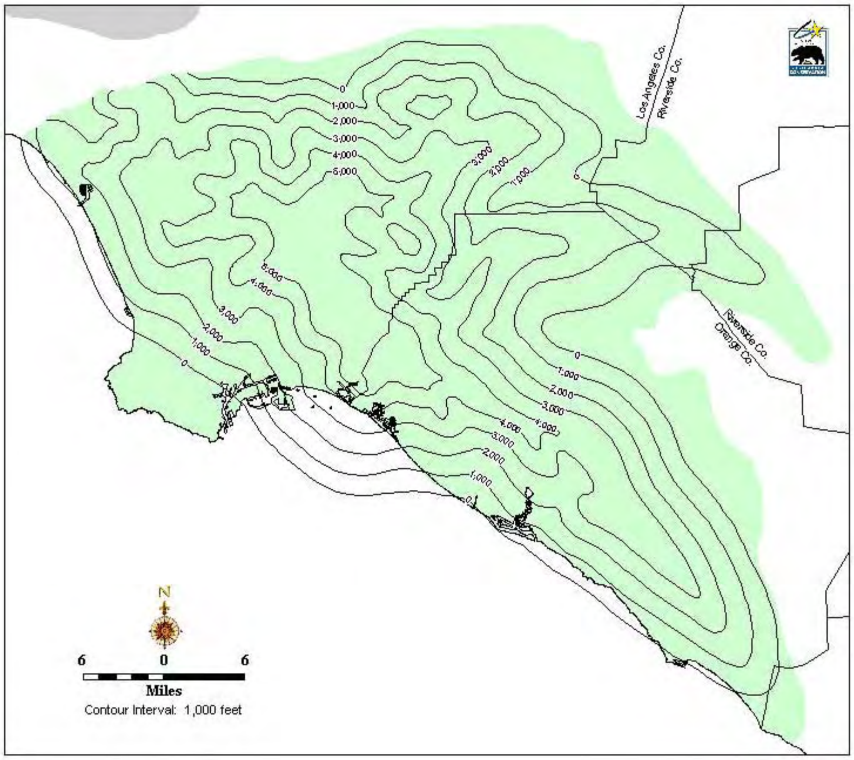

Figure 11. Generalized sandstone isopach map for the Los Angeles Basin

The Eel River, Livermore, Orinda, La Honda, Salinas, and Cuyama marine basins are all found in the Coast Ranges. California's Coast Ranges are composed of a series of northwesterly trending coastal mountain ranges and valleys extending southward from the Oregon state line to the Transverse Ranges in Santa Barbara and Ventura counties. To the east, they are bounded by the Coast Range Thrust, along which older Mesozoic rocks are thrust over Cretaceous rocks of the Great Valley Sequence in the Sacramento and San Joaquin basins.

The Eel River Basin, located in Humboldt County, is the onshore expression of a much larger offshore Cenozoic forearc basin. The onshore portion is expressed as a westerly plunging syncline. While the Freshwater Fault technically bounds the basin on the northeast, its northeast margin is more practically defined by the northeasterly dipping Little Salmon Thrust Fault. To the south, the basin is bounded by the Russ Fault, north of which the upturned beds of the Yager Formation and lower Wildcat Group are exposed. The basin contains more than 3,800 m (12,500 ft) of sedimentary fill, including over 3,350 m (11,000 ft) of dominantly Neogene marine, sandstone, siltstone, and shale resting on sandstones, conglomerates, and shales of the Cretaceous Yager Formation. Sandstones in the Bear River Beds through Rio Dell Formation may provide carbon sequestration opportunities in the deeper parts of the basin, on anticlinal closures and flanking stratigraphic pinch-outs. While individual sandstones are generally thin, a sandstone isopach map reveals a northwesterly trending zone of sandstone in excess of 760 m (2,500 ft) thick paralleling the north flank of the basin (Figure 12). Enclosing siliceous mudstones and shales should provide seals. Porosities of the sandstones range from 12 to 30% and permeabilities range from 1 md to over 300 md (Stanley, 1995b; DOG, 1983).

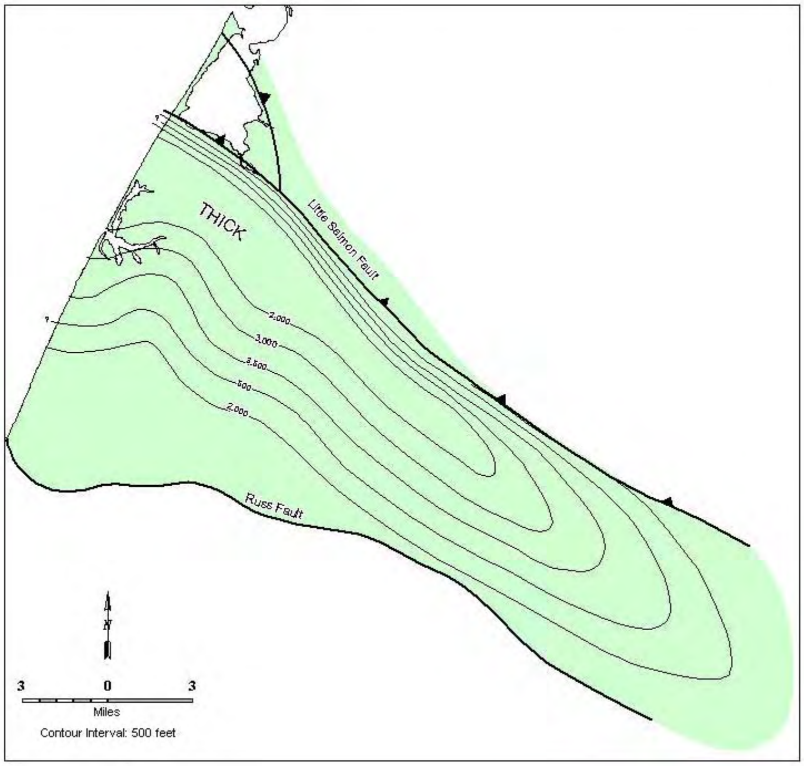

Figure 12. Generalized sandstone isopach map for the Eel River Basin

The Salinas Basin is one of several hydrocarbon-producing Cenozoic marine sedimentary basins west of the San Andreas Fault, including the La Honda Basin to the northwest and the Cuyama basin to the southeast. The basin is a narrow, northwest-trending feature extending almost 225 km (140 miles) from Monterey County southeastward into San Luis Obispo County, and varying in width from less than 16 to 48 km (10 to 30 miles). It is bordered on the east by the San Andreas Fault. To the northeast, the basin narrows where Salinian granitic basement rocks are uplifted and exposed in the Gabilan Range. The western basin margin is defined by the Jolan-Rinconda Fault Zone and uplifted granitic and metasedimentary rocks of the Santa Lucia Range. The structural and lithologic framework of the Salinas Basin consists of a series of tectonic basement blocks assembled during a complex history of subduction and transform motion along plate boundaries.

The Monterey formation sandstones are hydrocarbon producers and are potential sequestration targets in the Salinas Basin. Porosities in the shallow sands range from 15 to 39% with permeabilities of 500 to 8,000 md (DOGGR, 1991). While the Monterey sands in the known oil fields are too shallow for potential sequestration purposes, deeper

Monterey sandstones exist farther west in the deeper basin. A gross sandstone isopach map (Figure 13) shows sandstone developments thickening to over 760 m (2,500 ft) to the southwest towards the basin axis. Underlying poorly known lower-middle Miocene and Cretaceous sandstones may also be present at depth.

The La Honda Basin is located north of the Salinas Basin in Santa Clara and Santa Cruz counties between San Francisco and Monterey Bay. The basin is bounded on the northeast by the San Andreas Fault, on the northwest by granitic rocks of Montara Mountain, on the southwest by the Zayante-Vergeles Fault, and on the west by the San Gregorgio–Hosgri Fault (Stanley, 1995a). The relatively small basin comprises about 930 km^2 (360 mi^2) and represents a small sliver of the larger San Joaquin Basin, which was displaced approximately 298 km (185 miles) by right lateral slip along the San Andreas Fault. It is estimated that as many as 14,600 m (48,000 ft) of Tertiary sedimentary and volcanic strata fill the basin.

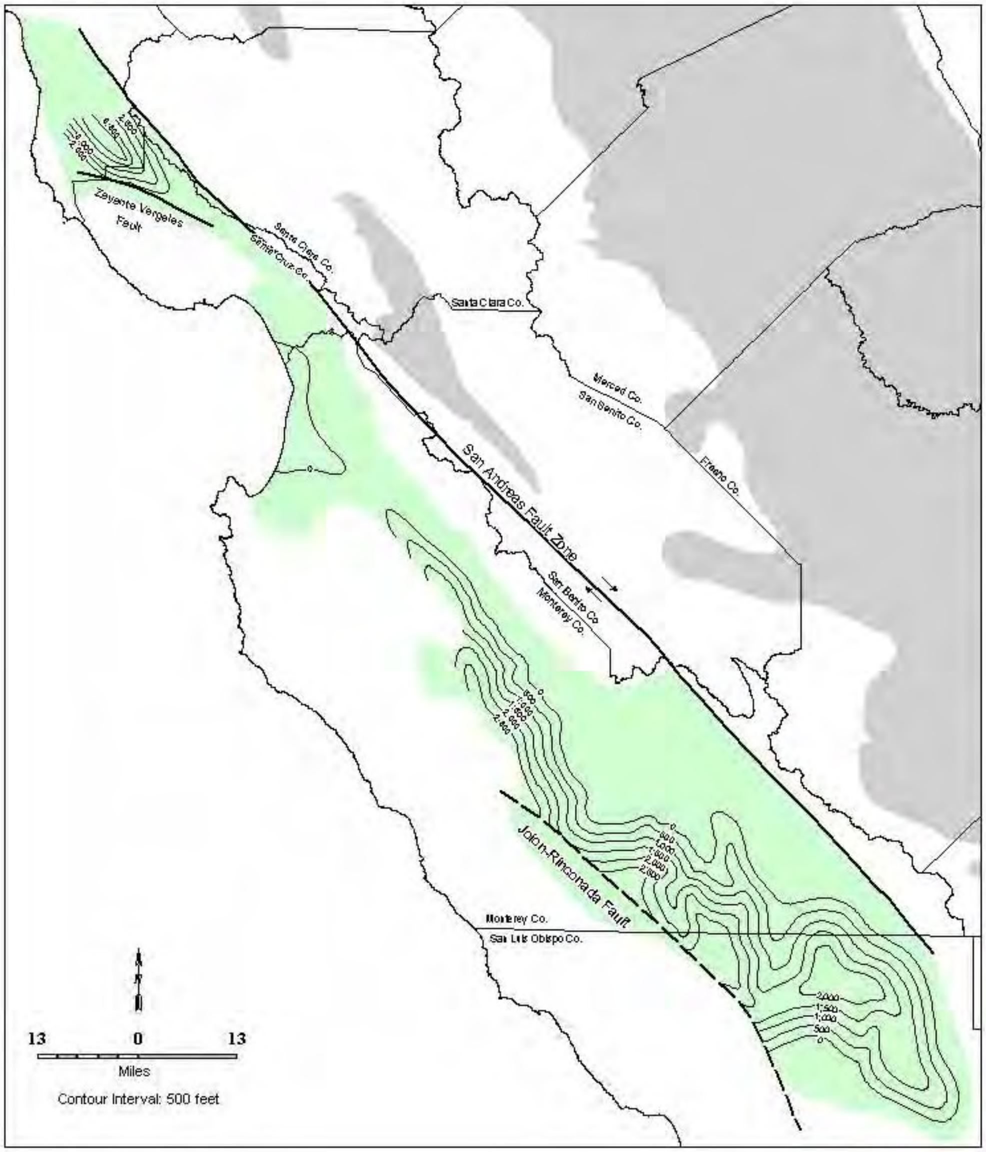

Figure 13. Generalized sandstone isopach map for the Salinas and La Honda Basins

In the eastern basin, the Butano and Locatelli formations are too shallow to be considered for CO_2 sequestration. Westward, towards the basin center, however, sandstone in the Butano and younger formations thickens markedly (Figure 13). The deepest well in the basin, drilled on the Butano Anticline, bottomed in the Butano Formation at 3,370 m (11,053 ft) and encountered more than 1,220 m (4,000 ft) of Butano sandstone within the isopach interval. The Vaqueros through Santa Margarita formations are blanketed by the Santa Cruz Mudstone and Purisima Formation, which can attain thicknesses of 2,700 m (8,900 ft) and 2,400 m (7,900 ft), respectively. Shallow producing sands in the Butano between 550 and 760 m (1,800 and 2,500 ft) deep exhibit porosities between 15 and 35% with permeabilities of 30 to 40 md, but at depth these are expected to be considerably reduced. Shallow Purisima sandstones between 240 and 820 m (800 and 2,700 ft) deep exhibit porosities of 22 to 34% and permeabilities of 1 to 40 md (DOGGR, 1991).

The Cuyama Basin is a relatively small Cenozoic marine basin near the southern end of the Coast Ranges. It extends approximately 105 to 121 km (65 to 75 miles) in a northwest-southeast direction and varies from 13 to 29 km (8 to 18 miles) wide. It is bounded on the northeast by the San Andreas Fault zone and the Temblor Range, which separate it from the San Joaquin Basin. Its southwest margin is structurally complex and consists of at least two early Miocene wrench faults (Russell and La Panza Faults), which separate the basin from the Sierra Madre Range. The northwest end of the basin is indeterminate, but approaches the southeast end of the Salinas Basin. Its southeastern end is defined by a buried normal fault subparallel to the younger Big Pine Fault (Tennyson, 1995). The basin is structurally complex, with extensive normal faulting of the pre-Pliocene section followed by later thrust faulting of the basement through the Pliocene section, burying much of the sedimentary section below complex thrust sheets.

In the north-central portion of the basin, where deep well control exists, a sandstone isopach map (Figure 14) indicates an area of thick sandstone exceeding 1,220 m (4,000 ft) and aligned in a northwest-southeast orientation roughly paralleling the basin axis. Sandstones within the isopach interval include Branch Canyon and Painted Rock sandstones and overlying Santa Margarita sandstones. Porosities of the sandstones range from 19 to 40%, and permeabilities range from 177 to 1,300 md (DOGGR, 1991).

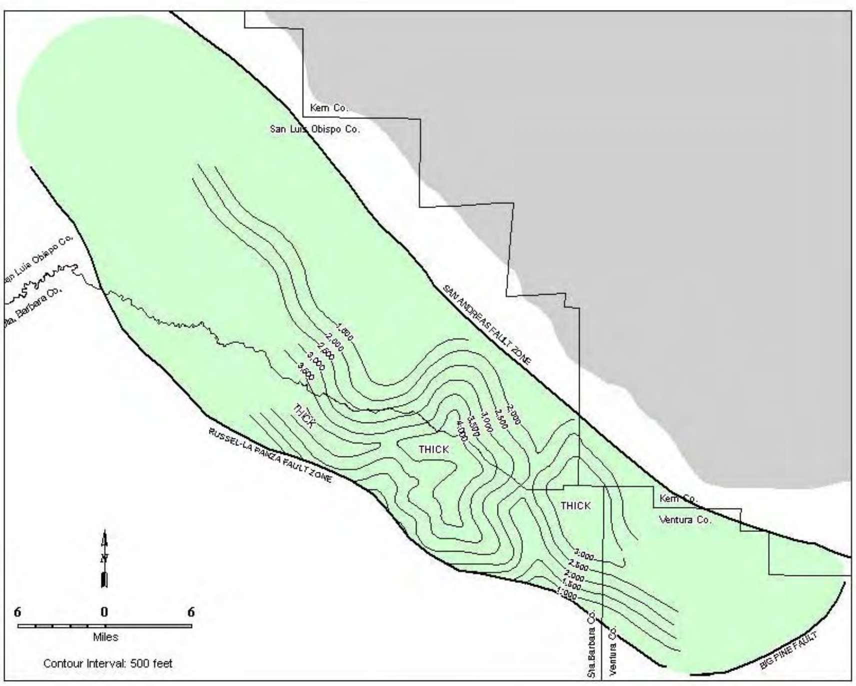

Figure 14. Generalized sandstone isopach map for Cuyama Basin

The Livermore and Orinda basins are part of a related series of deep, linear, Neogene pull-apart basins within the Coast Ranges between San Francisco Bay and the Sacramento Basin. Both basins formed under the influence of extensional stresses after the onset of strike-slip motion along the San Andreas and associated Calaveras and Hayward fault systems during the middle Miocene. The Livermore Basin is approximately 48 km (30 miles) long by 19 km (12 miles) wide. It is bounded on the north and east by Mount Diablo and the Diablo Range, and on the west and southwest by the Calaveras Fault, which separates it from the Orinda Basin. Uplifted Franciscan Complex rocks form its southern end. While the deepest well drilled bottomed at 5,306 m (17,404 ft) in Miocene sediments (Darrow, 1979), outcrop and unpublished geophysical data suggest that the Livermore Basin may be filled with as much as 6,700 m (22,000 ft) of Eocene, Miocene, and Pliocene sediments that have been extensively folded and faulted by later compressional forces caused by motion on the marginal faults.

A gross sandstone isopach map for the basin depicts an area of thicker sand development exceeding 490 m (1,600 ft) in the south central portion of the basin (Figure 15). Given the complex structural configuration of the basin, steep dips, and fault displacements along the basin margins, the isopach interval includes sandstones of the Cretaceous Panoche through Pliocene Orinda formations. Limited data on porosity and permeability yield values of about 25% and 250 md, respectively (DOG, 1983).

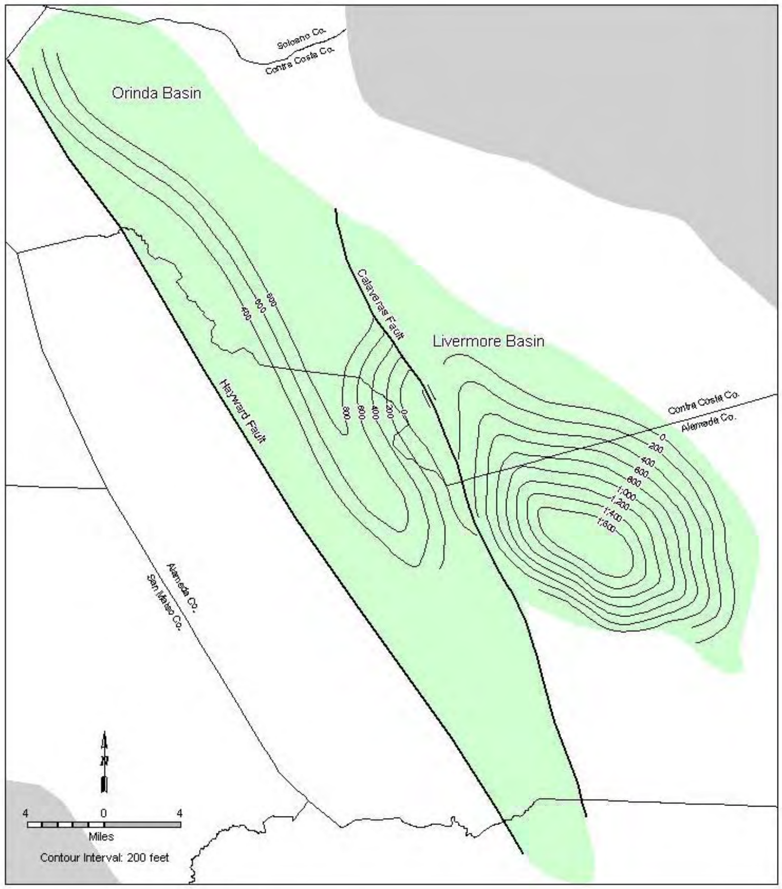

Figure 15. Generalized sandstone isopach map for Livermore and Orinda Basins

The Orinda Basin is a narrow linear basin measuring about 81 km (50 miles) by 11 km (7 miles), bounded on the west by the Hayward Fault and on the east by the Calaveras Fault. Its southern limit is the convergence of the two faults in northern Santa Clara County. Its northern end is taken to San Pablo Bay, past which the Sonoma Basin begins. Limited well control and outcrop data indicates the Orinda Basin contains a sedimentary section very similar to that of the neighboring Livermore Basin. The deepest well bottomed at 3,048 m (9,997 ft) in the abandoned one-well Pinole Point Field near the north end of the basin. Only two other wells exceeded 2,700 m (9,000 ft) with a handful going to 1,500–2,100 m (5,000–7,000 ft). The available well logs were used to construct a sandstone isopach map of logged section, which suggests a longitudinal thickness of at least 240 m (800 ft) extending from near the basin center to San Pablo Bay (Figure 15).

Capacity Assessment

Isopach and depth-to-basement maps were used to estimate the total storage capacity within saline formations in the ten largest sedimentary basins. Table 5 provides the data used to calculate the total available pore volume in the basins. Only a portion of the total pore volume is available for storage. The storage capacity is determined from the mass of CO_2 trapped in the pore space either as a separate phase or dissolved in the pore water.

Table 5. Data used for calculation of pore volume of California basins

Volumetric Data for California Basins			
	Area (sq. miles)+	**Estimated Average Thickness in m (ft)***	**Estimated Average Porosity****
Sacramento-San Joaquin basins	18,550	610 (2,000)	0.25
Los Angeles Basin	1,341	920 (3,000)	0.25
Ventura Basin	1,450	920 (3,000)	0.24
Salton Trough	2,559	610 (2,000)	0.24
Eel River Basin	175	460 (1,500)	0.26
Salinas Basin	1,343	460 (1,250)	0.28
La Honda Basin	268	460 (1,500)	0.25
Livermore Basin	144	240 (800)	0.23
Orinda Basin	296	180 (600)	0.23
Cuyama Basin	582	920 (3,000)	0.27
+Area of basin at depths greater than 800 m (2,625 ft)			
*Average sands (isopachs) thickness for depth window 800–3,050 m (2,625–10,000 ft)			
**Approx. average porosity for all zones in isopachs window			

Many factors affect the percentage of the pore space that could be occupied, including formation heterogeneity, buoyant flow, hydrologic boundary conditions, residual saturation, and other two-phase flow properties. Reservoir modeling studies also suggest that, because of two-phase conditions and diffusion, the pore volume containing dissolved CO_2 will be greater than the pore volume of separate-phase CO_2. Two other factors affecting storage capacity are the density of the in-place CO_2 and the salinity of the pore water. Formation temperature and allowable injection pressures will, in large part, determine the CO_2 density. Salinity of the pore waters is important because CO_2 solubility decreases with increasing salinity.

Figure 16 shows the results of capacity calculations for a range of pore-volume values containing separate-phase and dissolved CO_2. The calculations assumed a single density value of 600 kg/m^3 and a CO_2 dissolved mass fraction of 2.5%. Results show total storage capacity for the 10 basins ranging from about 150 Gt to about 500 Gt. The low end of this range would provide sufficient capacity for storing over 1,000 years of utility and industrial sector emissions at the current emission rates. Table 5 shows that more than half of this capacity is contained in the Sacramento-San Joaquin basins.

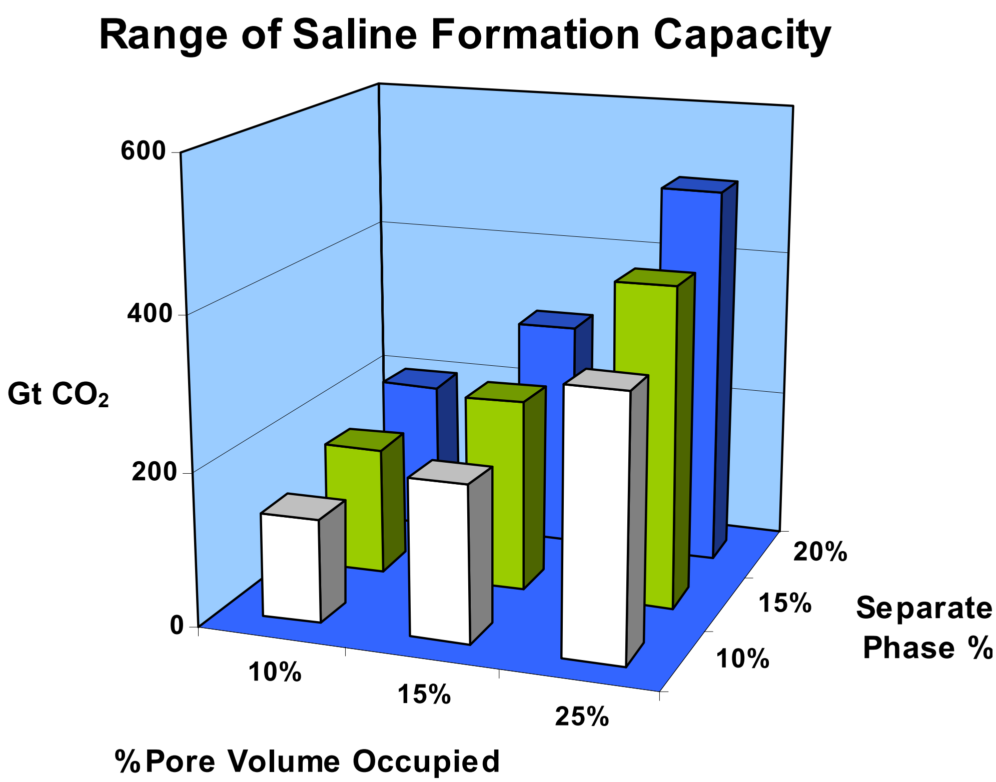

Figure 16. Total sequestration capacity of saline formations in ten largest basins in California

Several of the sedimentary basins, notably the Sacramento, San Joaquin, Los Angeles, and Ventura basins, also contain major oil and gas fields, which will likely be the first targets for geologic sequestration. Estimates for the CO_2 storage capacity of California oil and gas fields were based upon production data using Elewaut *et al*., 1996:

$$Q_{CO2} = (V_{Uoil} + V_{Ugas}) * \rho_{CO_2} / 1{,}000 \quad (1)$$

where Q_{CO2} = CO_2 storage capacity ($MtCO_2$)

V_{Uoil} = underground volume of oil produced (M m^3)

V_{Ugas} = underground volume of gas produced (M m^3), and

ρ_{CO_2} = CO_2 density at the reservoir pressure.

The underground volume of oil and gas was estimated from:

$$V_{Uoil} = V_{oil(st)} * B_o \quad (2)$$

$$V_{Ugas} = V_{gas(st)} * B_g \quad (3)$$

where $V_{oil(st)}$ = Volume of oil at standard conditions (M m^3)

$V_{gas(st)}$ = Volume of gas at standard conditions (M m^3)

B_o = Oil formation volume factor (FVF), and

B_g = Gas formation volume factor (E^{-1}).

A default FVF of 1.2 was applied for oil. The gas expansion factor E was calculated with linear relation: E = 4.8P+93.1, where P is the reservoir pressure in MPa. If the original reservoir pressure value were missing, it was calculated from the average depth of the field, assuming a gradient of 10.5 MPa/km.

An estimate of the CO_2 EOR potential for oil fields was made based on API gravity data and depth. Oil fields at depths greater than 915 m (3,000 ft) and with API gravity more than 25° were classified as fields with miscible CO_2-EOR potential. Fields at depths greater than 915 m (3,000 ft) and with API gravity between 17.5° and 25° were classified as fields with immiscible CO_2-EOR potential. Fields at depths greater than 915 m (3,000 ft) and API gravity less than 17.5° were classified as fields with storage potential but no EOR potential. The attributed GIS database was interrogated using these criteria, yielding 121 fields in California with miscible CO_2 EOR potential and a CO_2 storage capacity of 3.4 Gt. The storage capacity was increased to 3.8 Gt by including the fields in the remaining two categories. Though tiny compared to the total saline formation capacity, the storage capacity associated with potential CO_2 EOR is still equal to over 27 years of current utility and industrial sector emissions.

The capacity of California gas fields, screened by depth, was also estimated using the expression in Equation 1. The result yielded 128 gas fields with a combined storage capacity of 1.8 Gt. Oldenburg *et al*. (2001) have shown that CO_2 can be used to enhance production from depleting gas fields (EGR), though an estimate of the CO_2 EGR potential for California has yet to be done.

3.1.2.2 Oregon and Washington

Sedimentary Basins

In Oregon and Washington, the most promising near-term sedimentary basin targets are found in the Coastal Ranges and Puget-Willamette Lowlands geomorphic provinces, though several interior basins may also be important because of the location of large emission sources (Figure 17). The Coastal Ranges and Puget-Willamette Lowlands provinces are the home of a major Tertiary sedimentary belt of basins that formed in a regional fore-arc environment as the Juan de Fuca plate subducted beneath the North American Plate. These basins, the boundaries of which are uncertain at this time, are characterized by up to 6,100 m (20,000 ft) of Tertiary sedimentary rocks deposited in embayments and shallow seas. Results for these basins are summarized in the following pages. More detailed information on these as well as other basins in Oregon and Washington is found in Appendix VI.

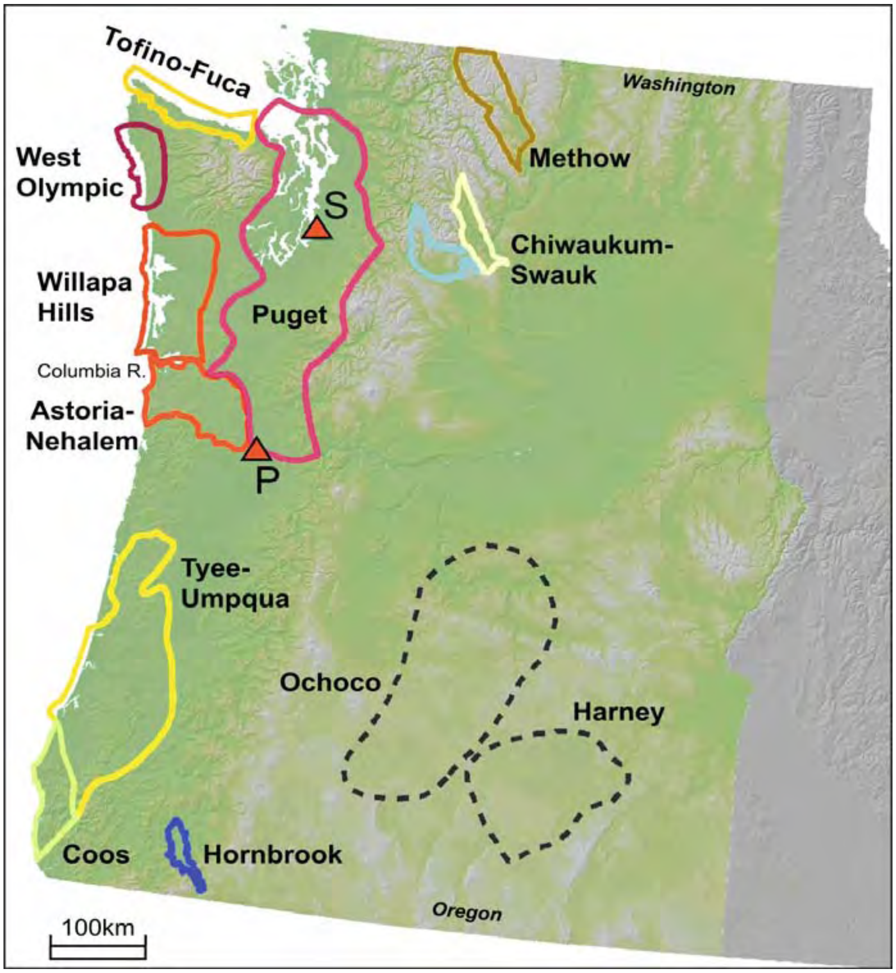

Figure 17. Sedimentary basins in Oregon and Washington. S = Seattle, Wash. P = Portland, Ore.

Three basins are found in the Coastal Ranges of Washington: Tofino-Fuca Basin, Western Olympic Basin, and Willapa Hills Basin. Of these, the Western Olympic and Willapa Hills Basins are the most promising. The Western Olympic Basin is located directly west of the Olympic Mountains in Clallam and northern Jefferson Counties, and extends westwards offshore for at least 40 miles (Wagner and Batatian, 1985). The sedimentary strata have an estimated total thickness of at least 2,700 m (9,000 ft; Figure 18), and the recognized formations are:

- Quinault Formation—Pliocene-Miocene (PLMn), up to 1,500 m (5,000 ft) of nearshore sedimentary rocks (siltstone, sandstone and conglomerate); and

- Hoh Assemblage—lower-mid Eocene, a sequence of marine rocks accreted to the continental margin:
    - Lincoln Creek Formation—Oligocene-Eocene; up to 2,700 m (9,000 ft) of massive sandstones and tuffaceous siltstones;
    - Skookumchuck Formation—mid-upper Eocene, up to 1,100 m (3,500 ft) of interbedded shallow marine and continental facies (arkosic sandstones and siltstone), and coal in upper and lower member; and
    - McIntosh Formation—mid-upper Eocene, up to 1,500 m (5,000 ft) of tuffaceous sedimentary rocks.

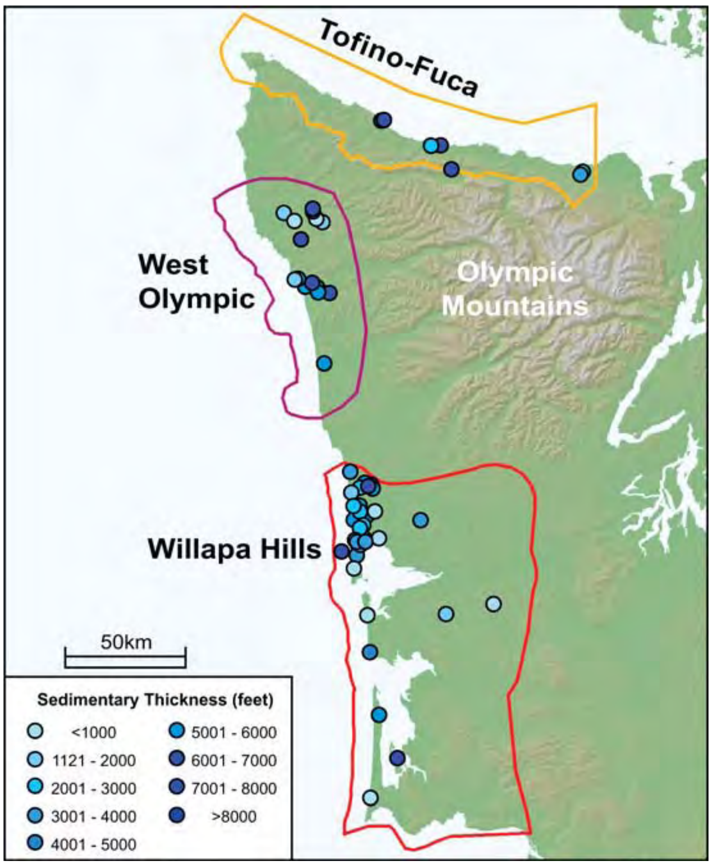

Figure 18. Sediment thickness in basins of Coastal Ranges of Washington

The basin is tectonically active and the sediments are highly deformed; some structural traps are present. The sandstones have porosities of 36–46% and permeabilities of 102 to 917 md.

The Willapa Hills (Grays Harbor) are topographic hills that rise to about 950 m (3,100 ft) above sea level and are situated between the Olympic Mountains to the north and the

Columbia River to the south. The Willapa Hills Basin contains up to 4,600 m (15,000 ft; Figure 18) of late Oligocene to Quaternary strata overlying basement/broken mélange of mid-Miocene to early Oligocene age. Eocene and Oligocene sediments consist predominantly of deep-water siliciclastics, and arkosic sandstones; interbedded volcaniclastic sandstones are contained within thick marine shale sequences.

The recognized geologic formations in the basin above the Crescent Formation are:

- Quinault Formation—Pliocene-Miocene (PLMn), nearshore sedimentary rocks (siltstone, sandstone, and conglomerate);
- Montesano Formation—mid-upper Miocene (Mm(2m)), up to 920 m (3,000 ft) of fluvial, lacustrine, brackish water, and shallow marine sediments;
- Astoria Formation—lower-mid Miocene, Mm(1a), up to 1,100 m (3,500 ft) of marine sedimentary rocks (carbonaceous, fine-grained sandstone);
- Hoh Assemblage—similar sequence to that in the Western Olympic Basin;
- Cowlitz Formation—Eocene (En(c) or Tco), unconformably overlies the Crescent Formation and contains marine/nonmarine siltstone and sandstone; and
- Northcraft Formation—Eocene (Evc(n)), up to 460 m (1,500 ft) of volcaniclastic deposits and lavas.

The Willapa Hills basin is the most promising Coastal Range Basin for hydrocarbon development, and therefore CO_2 storage, because of the deep-water sandstones, thick shales and claystones, and anticlinal traps. Sandstones of the Montesano Formation have porosities of 6.4–32.7% and permeabilities up to 522 md.

The Puget Trough Basin is located in northwestern Washington, and occupies the generally low-lying region east of the Olympic Mountains and west of the Cascade Mountains. The southern extent of the basin is defined by the mergence of the Cascade Range and Coastal Range in Lewis and Cowlitz counties. The basin consists of up to 1,100 m (3,700 ft) of unconsolidated sediments of Pleistocene age overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. The geology of the Puget Trough is complex, and interpretation is made difficult by the large volume of mostly glacially derived, unconsolidated sediments. Faulting and folding is abundant, and many active faults are recognized. The faulting has resulted in the formation of several major sub-basins (Figure 19):

- Everett Sub-basin—bounded to the north and south by the North and South Whidbey Island Fault Zones, respectively, and attains a maximum thickness of between 3,050 and 4,300 m (10,000 and 14,000 ft), of which as much as 1,100 m (3,600 ft) is considered to be unconsolidated sediments (Jones, 1999);
- Seattle Sub-basin—located south of the South Whidbey Island fault, is bounded to the south by the Seattle fault and uplift, and contains up to 4,600 m (15,000 ft) of sedimentary material, of which up to 1,100 m (3,700 ft) is unconsolidated;

- Tacoma Sub-basin—located south of the Narrows Structure, up to 1,800 m (6,000 ft) thick (610 m, or 2,000 ft, of unconsolidated sediments); and
- Chehalis Sub-basin—occupies the southern portion of the Trough, south of the Olympic Gravity Anomaly; the unconsolidated sediment thickness is less than 120 m (400 ft) here.

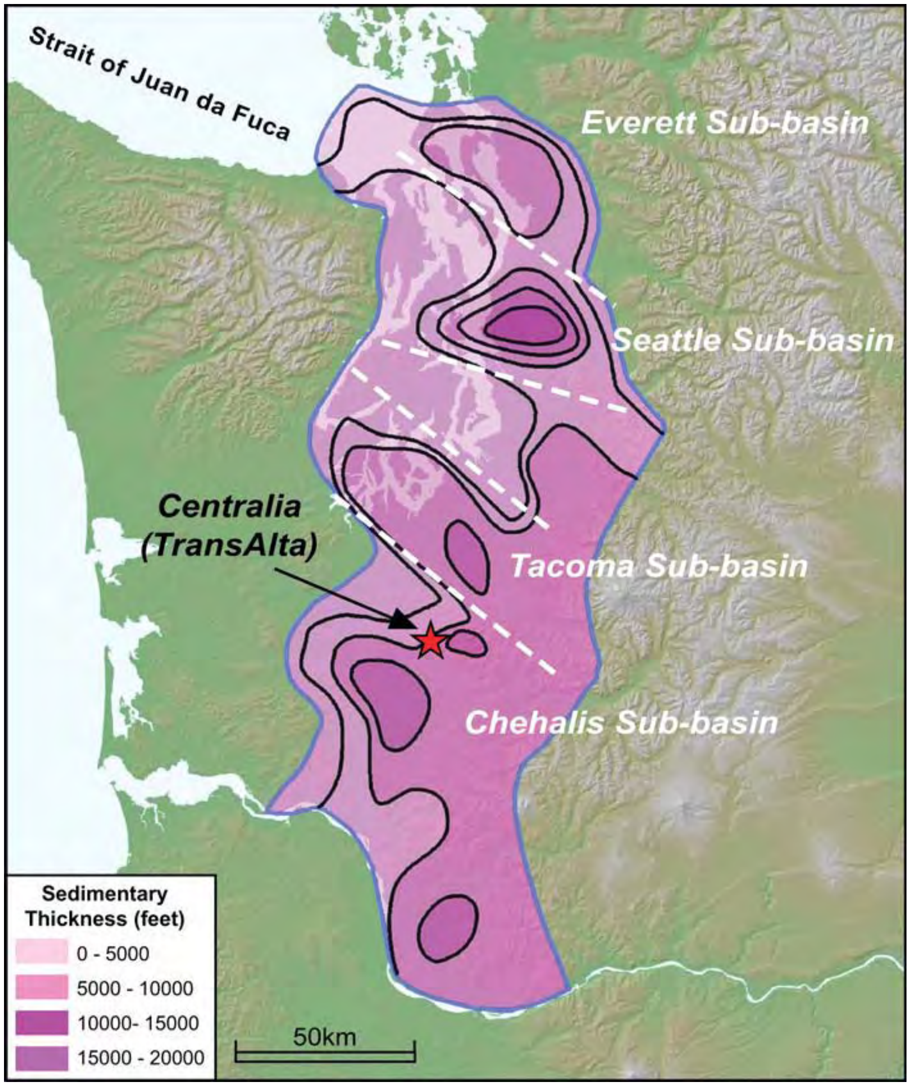

Figure 19. Sedimentary sub-basins in the Puget Trough of Washington. The location of the TransAlta power plant in Centralia, Wash., is noted.

The key sedimentary formations in the Everett-Seattle-Tacoma sub-basins are:

- Blakeley and Blakeley Harbor Formations—Oligocene-Eocene (OEm(b)), marine sedimentary rocks in the northern Puget Sound area of interbedded volcaniclastic sandstone, siltstone, shale, and conglomerate;
- Puget Group—Eocene (Ec(2pg)), continental sedimentary rocks/deposits;
- Renton Formation (Ec(2r))—continental sedimentary rocks/deposits (fine- to medium-grained, massive to cross-bedded arkosic sandstone);
- Tiger Mountain Formation (Ec(2t))—continental sedimentary rocks/deposits; and
- Tukmila Formation (Evc(t)) – volcaniclastic rocks/deposits (sandstone, siltstone, and conglomerate).

The Chehalis Sub-basin occupies the lowland area between the southern extent of Puget Sound in Thurston County, extending into Lewis County and northernmost Cowlitz County. The basin contains up to 4,600 m (15,000 ft) of sedimentary sequence. The key sedimentary formations are:

- Wilkes Formation—Miocene (Mc(w)), continental sedimentary rocks; and
- Hoh Assemblage—lower-mid Eocene, a sequence of marine rocks accreted to the continental margin; includes the Lincoln Creek, Skookumchuck, and McIntosh Formation. Both basal Lincoln Creek Sandstone and Skookumchuck sandstones serve as reservoirs in the Jackson Prairie Gas Storage Field.

Sandstones of the Skookumchuck have porosities of 30–38% and permeabilities of 135 to 3,000 md.

The Puget Trough Basin also contains deep coal formations, which are sequestration targets and may have potential for ECBM. Coals in this region occur within the Puget Group. Figure 20 provides an initial assessment of the subsurface extent of the coal basins, showing deep coals to be present over an area of approximately 2,500 km^2. Coal rank (thermal maturity) is an important factor to consider when assessing coal seams for coalbed methane and for sequestration potential. In general, coal rank increases from northwest to southeast in the Puget region, reflecting greater tectonic deformation and heat associated with Cascade Range uplift. Initial analysis indicates excellent coal seam reservoir properties: 30 m (100 ft) coal thickness (in the Skookumchuck formation), 20-24 G(m^3)/ton (700–850 ft^3/ton) CO_2 sorption capacity, and 5 md permeability. The amount of unmineable coal in the Puget Sound basin was estimated to be over 70 billion tons, with a CO_2 storage potential of 2.8 Gt.

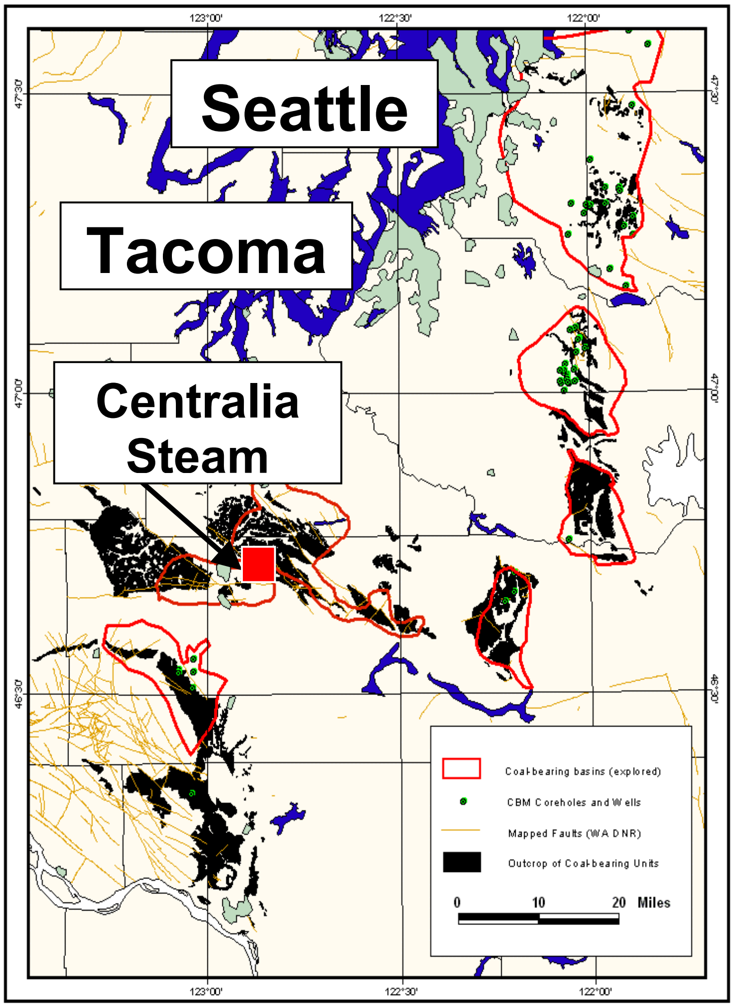

Figure 20. Estimate of extent of coal basins in Puget Trough

In Oregon, there are three main sedimentary basins in the Coastal Ranges province: Astoria-Nehalem, Tyee-Umpqua, and Coos Basins (Figure 21). They extend beneath the Willamette Lowlands, which separate the Coastal Range and the Cascade Mountains. Definition of the exact extent of each of these basins is problematic because of volcanic and sedimentary cover and tectonic deformation.

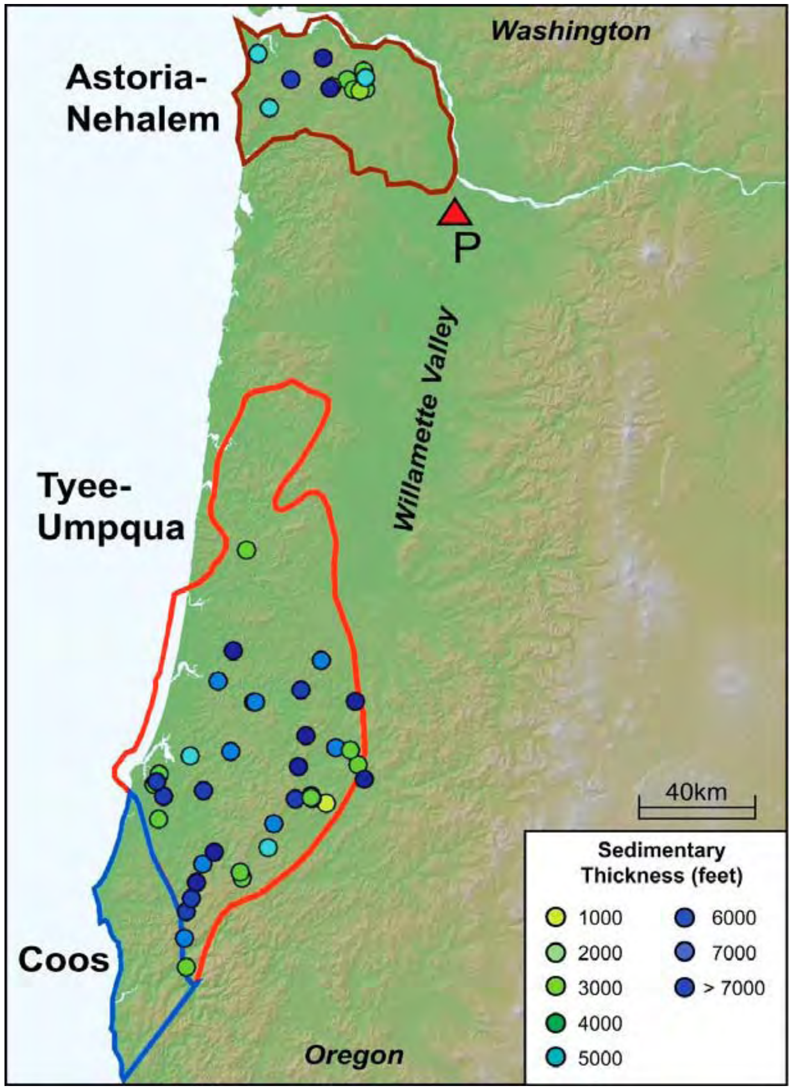

Figure 21. Sedimentary basins and sediment thickness in the Oregon Coastal Ranges. P = Portland, Ore.

The Tyee-Umpqua Basin occupies the southern half of the Coastal Range, extending from a latitude near Salem, beyond Roseburg, to the junction of the Coastal Range with the Klamath Mountains. To the west are the younger basinal sediments of the Coos Basin. The basin consists of more than 6,100 m (20,000 ft) of lower-middle Eocene sedimentary strata preserved in the Coastal Range hills. In fact, the basin contains two superimposed basins with different geologic trends and tectonic histories: the northeast-southwest trending early Eocene Umpqua Basin and the north-south trending Tyee Basin.

The main geologic units identified in the basin are as follows:

- Spencer Formations—lower-mid Eocene, up to 150 m (500 ft) of arkosic sandstone (fluvio-deltaic).

- Bateman Formation—mid-upper Eocene, up to 760 m (2,500 ft) of arkosic sandstone (deltaic) and mudstone.
- Elkton Formation—mid-Eocene, up to 920 m (3,000 ft) of mostly mudstone and minor sandstone.
- Tyee Formation—mid-Eocene, mostly 1,830 m (6,000 ft) of sandstone, deposited in a shallow marine to non-marine deltaic environment (south) to slope and deep marine basinal margin (north). The eastern margin is truncated by younger rocks or covered by younger volcanic rocks; the western margin is a passive sill or a seamount terrane of oceanic crust. Contains several recognized members.
- Umpqua Group—upper Paleocene to lower Eocene, up to 3,050 m (10,000 ft) of mudstone, sandstone, and conglomerate (nonmarine to deep marine origin). Prominent formations recognized in reports include the Camas Valley White Tail Ridge, Tenmile, and Bushnell Rock Formations.

For the massive Tyee sandstones, porosity and permeabilities average 2.76 md, respectively (Ryu and Niem, 1999).

The Coos Basin is located in coastal southwestern Oregon in the Coastal Range Province. The basin extends from the western edge of the Tyee Basin and the Klamath Mountains, and continues offshore. The geology of the basin consists of up to 3,050 m (10,000 ft) of marine sedimentary rocks. The key units are as follows:

- Bastendorff Formation—upper Eocene to lower Oligocene, up to 880 m (2,900 ft) of thinly laminated siltstone and mudstone;
- Coaledo Formation—upper Eocene, up to 1,800 m (6,000 ft) of deltaic sandstones, and prominent coal seams;
- Bateman Formation—mid-Eocene, 300 m (1,000 ft) of sandstone (near-shore, deltaic);
- Tyee Formation—similar strata to those in the Tyee Basin, up to 1,500 m (5,000 ft) thick in the Coos Basin;
- Fluornoy Formation—mid-Eocene, between 300 and 1,500 m (1,000 and 5,000 ft) of sandstone and siltstone sequence;
- Looking Glass Formation—lower Eocene, basal conglomerate and overlying fine-grained sandstone and siltstone sequence (up to 2,100 m—7,000 ft—thick); and
- Roseburg Formation—lower Eocene-upper Paleocene, between 3,050 and 3,700 m (10,000 and 12,000 ft) of rhythmites and submarine basalts.

Sandstones of the Coalcedo and Fluornoy formations have porosities of 18–43% and permeabilities of 4.5 to 1,800 md.

The Astoria-Nehalem Basin is located in northwestern Oregon, in western Columbia and eastern Clatsop counties, about 45 miles northwest of Portland. The basin contains the only economically productive gas field (known as the Mist Gas Field) in Oregon. This field occupies an area of about 13 km^2 (5 mi^2) and was first produced from in 1979. The basin geology is complex because of extensive folding and faulting. Normal and strike-slip faulting is common, with the predominant fault trend being northwest; some significant east-west and northeast-southwest faulting also exists. Faulted anticlines are reportedly the most common trap in the Mist Field. The earliest sedimentary unit is the mid-Eocene Yamhill Formation (siltstones and shales). Although the sedimentary units interfinger with the volcanics, the Yamhill does contain a prominent sandstone member. The Cowlitz Formation overlies the Yamhill Formation, and consists of micaceous, arkosic-basaltic marine sandstone, siltstone, and mudstone. Of key importance is the gas-producing Clark & Wilson (C&W) sandstone, which is overlain by a thick shale unit. The C&W sandstones have porosities up to 39% and permeabilities from 1 to 1,400 md. A sequence of marine sedimentary units overlies the Cowlitz Formation and consists of thickly to thinly bedded tuffaceous mudstone, siltstone, and sandstone. Key units include the Spencer, Keasey, Pittsburg Bluff, and Astoria Formations (all mid-upper Eocene).

There are several interior basins in Washington and Oregon that contain sedimentary deposits. Very little is known about the geology and properties of the rocks in these basins, but they could be potentially important for sequestration because of the proximity to power plants. These basins include the Methow, Chiwaukum, Ochoco, and Hornbrook. The Methow Basin contains approximately 4,000 m (13,000 ft) of sedimentary rocks, including several massive sandstones in the Winthrop Formation. The Chiwaukum Basin contains about 5,800 m (19,000 ft) of continental sedimentary sequences. The Ochoco Basin contains more than 1,500 m (5,000 ft) of fluvio-deltaic sandstones and conglomerates, and the Hornbrook Basin contains about 1,200 m (4,000 ft) of sediments. Hornbrook Formation sandstones have porosities of 6.3–18.6% and permeabilities up to 1.2 md.

3.1.2.3 Nevada

In Nevada, ongoing crustal extension is responsible for the current basin-and-range topography. Essentially every mountain range is bounded on one or both sides by a fault that has been active in Quaternary time. Sediments that have filled the basins between the mountains could provide sequestration targets, but there is generally a paucity of information on the structure and properties of these basin-filling sediments. Figure 22 shows the basins in which fill is greater than 1 km (0.6 mi), based on interpretation of gravity data, with no distinction based on rock type or structure. If all potential screening criteria are applied, the basins with the largest areas of potential for CO_2 sequestration by injection into saline aquifers are Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County. Each contains 30 km^2 (12 mi^2) or more area. The Nevada Bureau of Mines and Geology (NBMG) has no records of deep (>1,000 m, or >3,300 ft) wells in any of these areas.

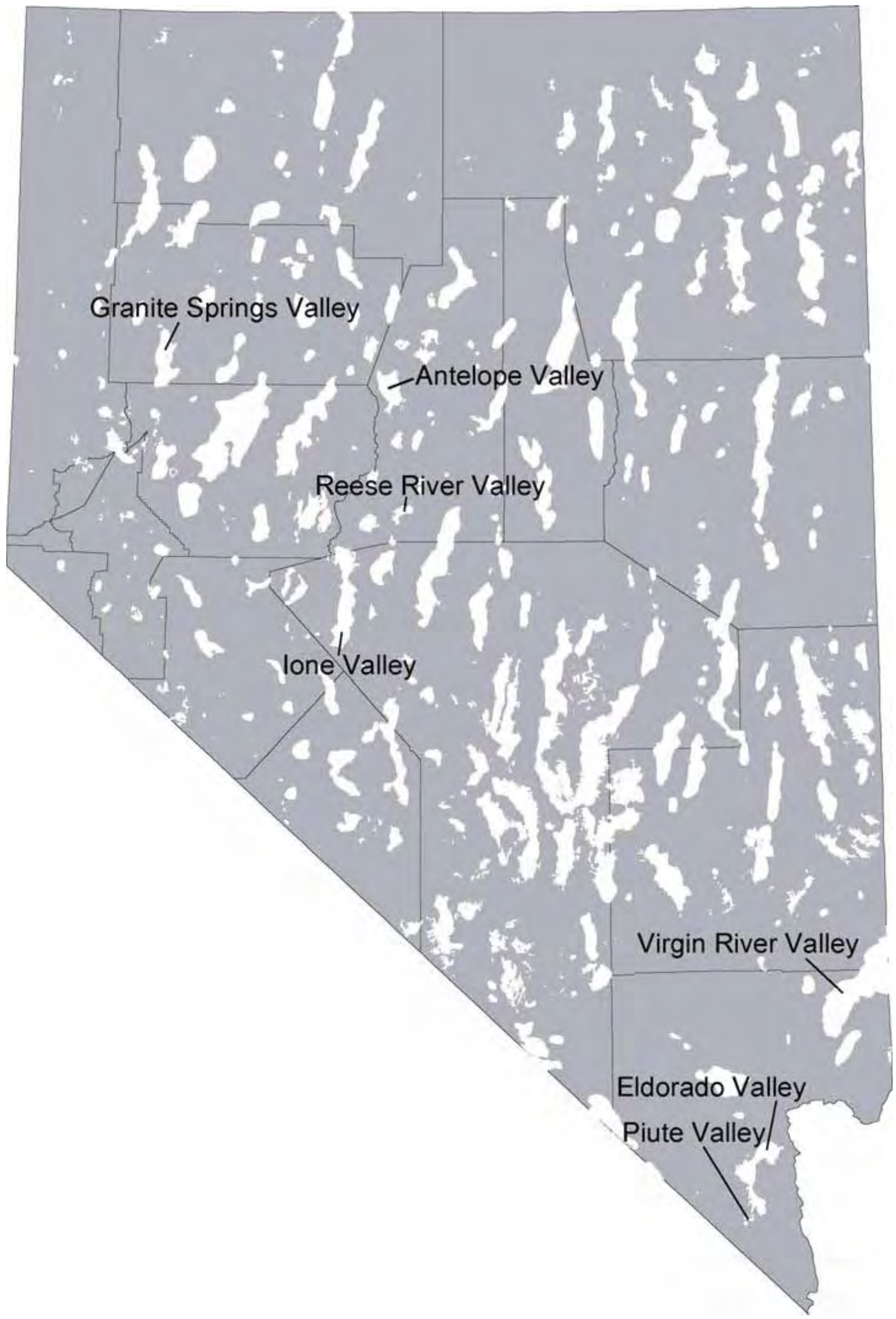

Figure 22. Nevada basins with fill thickness greater than 1 km

The NBMG constructed a conceptual model of oil and potential CO_2 reservoirs and seals in Nevada (Figure 23). NBMG states that oil occurs in two broad types of reservoirs in Nevada: fractured and permeable Paleozoic sedimentary rocks (mostly limestones but locally also sandstones), and fractured Tertiary ash-flow tuffs. They conclude that permeable, unfractured sandstones may occur in the Paleozoic section and in the Tertiary valley-fill sequences in the basins. Seals for the oil reservoirs and, hence, potential CO_2 sequestration sites include Paleozoic marine shales, Tertiary lacustrine shales, and the nonwelded clay- or zeolite-altered upper zones of ash-flow tuffs. NBMG concludes that the best seals appear to be above the Paleozoic-Tertiary unconformity.

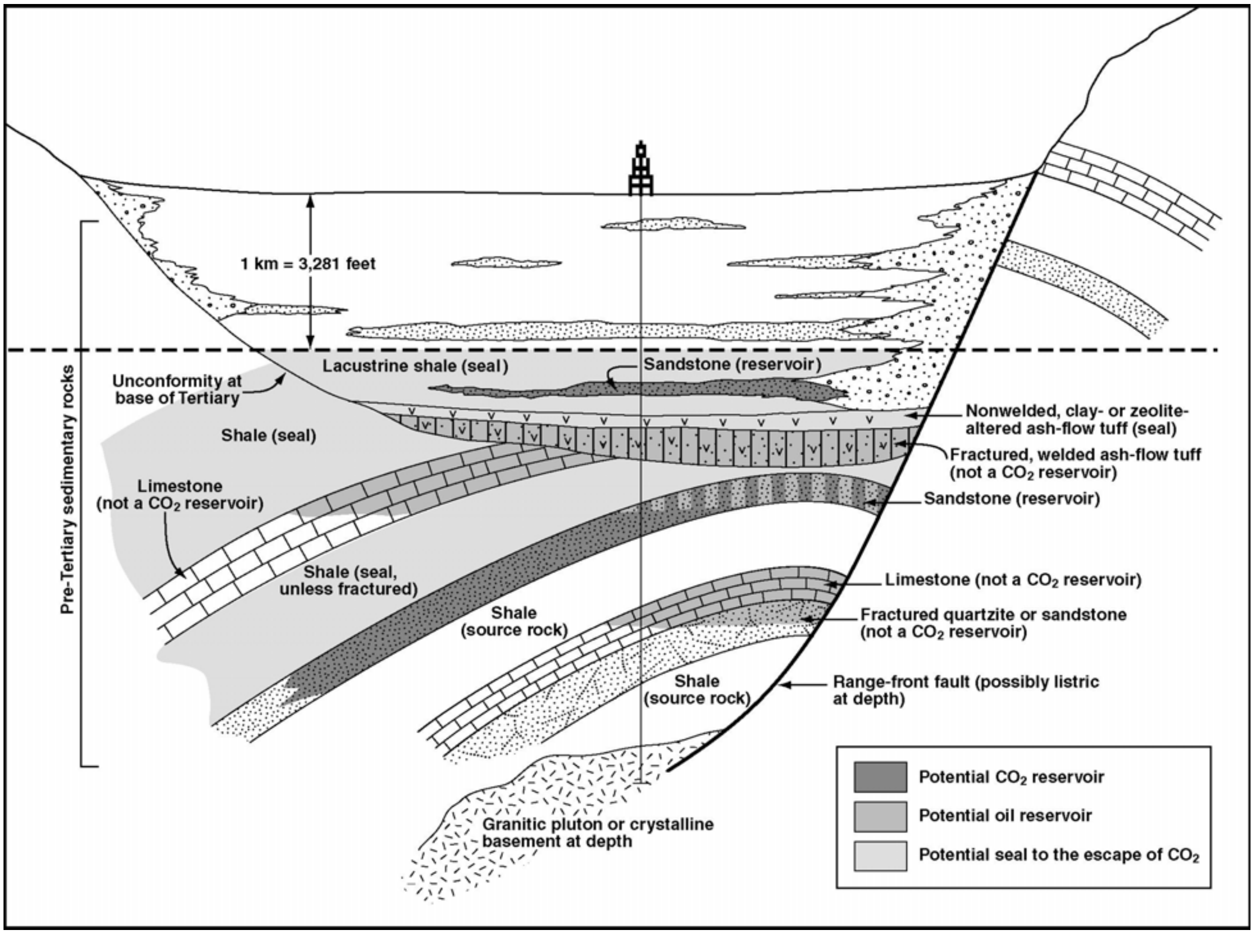

Figure 23. Conceptual model of oil reservoirs and saline formations in Nevada

Additional information on the NBMG assessment of Nevada is found in Appendix VII.

3.2 Geologic Sequestration Options

After identifying the CO_2 sources and candidate sinks, the study then evaluated the CO_2 sequestration potential in the WESTCARB region by analyzing the matching between sources and sinks. Figure 24 shows the distribution of CO_2 sources and sinks that were considered in the source-sink matching analysis. After limiting to CO_2 sources in the contiguous-U.S. part of the WESTCARB region and excluding sources without CO_2 emission data, a total of 58 CO_2 sources were studied in the source-sink matching analysis. These 58 CO_2 sources include 10 coal-fired power plants, 27 gas-fired power plants, 11 cement plants and 10 refineries, with an annual amount of 184 Mt CO_2 to be sequestrated[1].

As a preliminary analysis, the study performed a straight-line distance based matching for the entire contiguous-U.S. part of the WESTCARB region, connecting each source to its closest sink in terms of straight-line distance. In this preliminary exercise, neither the optimal pipeline path nor the sink's storage capacity constraints were considered. The straight-line distance matching analysis was performed for each of the three different groups of eligible sinks and a combination of them altogether (see Tables 6 and 7). Given that the WESTCARB server lacked sufficient data to evaluate the CO_2 sequestration potential for Nevada, the matching exercises were performed under two scenarios: with and without Nevada saline aquifers. Tables 6 and 7 summarize the matching results under the two scenarios in terms of annual CO_2 storage capacity by marginal straight-line distance. If EOR sites were the only sinks used for sequestration, about one-third of the CO_2 sources (by volume) could be matched with a sink that is less than 50 km (30 mi) away while about one half of the sources could be matched with a sink that is less than 250 km (155 mi) away. If all sink types, including Nevada sinks, were considered for sequestration, however, more than four-fifths of CO_2 sources could be matched with appropriate sinks within 50 km (30 mi). However, there are still some sources that cannot be matched to any sinks that is within 250 km (155 mi) from the sources.

[1] The annual amount of CO_2 to be sequestrated differs to the 159 Mt annual emissions reported previously. The 184 Mt $CO_2$was estimated under the following three assumptions: (1) an 80% operation capacity for power plants, (2) full production capacity for non-power stationary CO_2 sources, and (3) a capture efficiency of 90% for all sources.

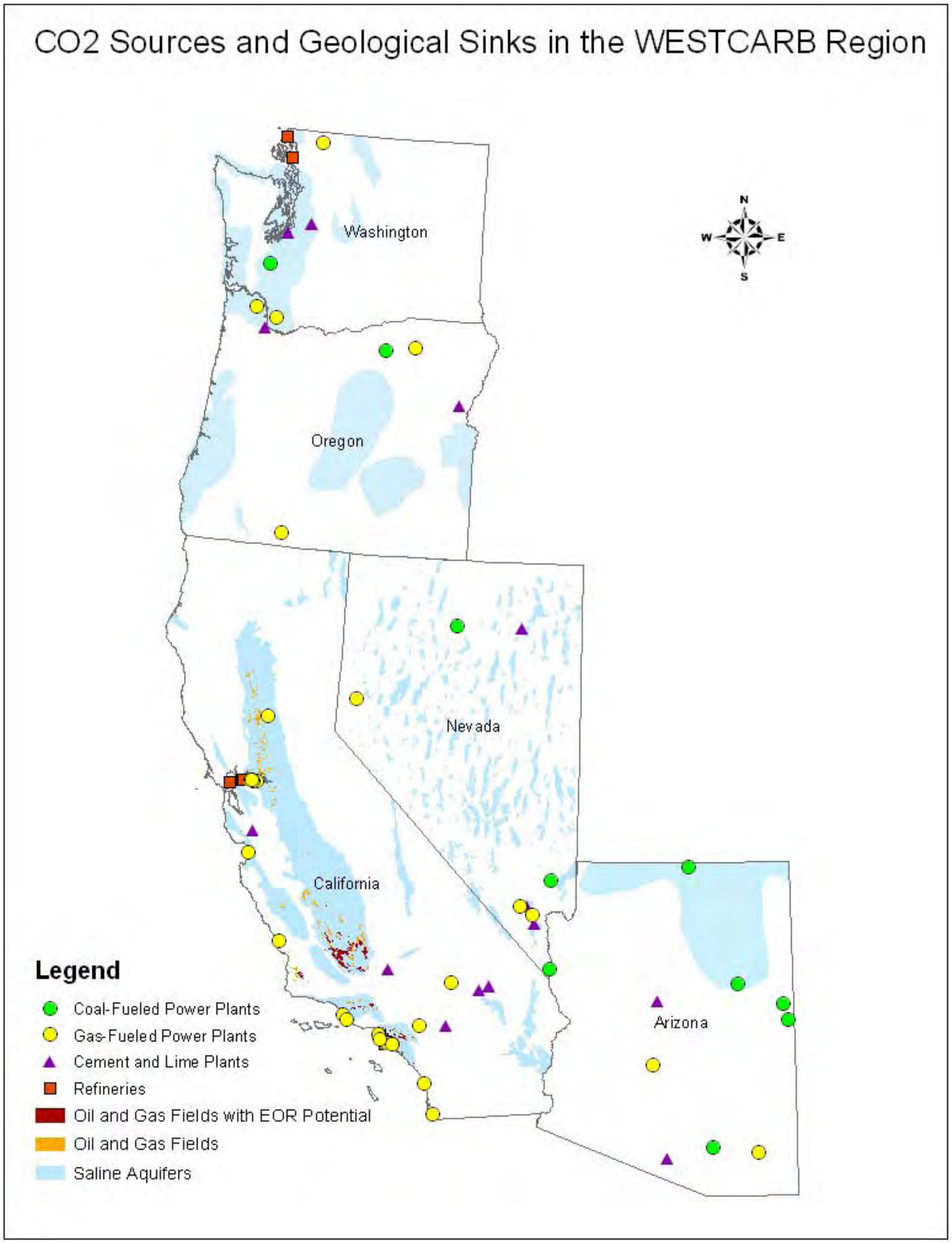

Figure 24. CO_2 sources and sinks in the WESTCARB region

Table 6. CO_2 storage capacity (Mt/yr) by marginal straight-line distance to nearest sink (Nevada aquifers included)

Sink Type	Straight-Line Distance to Nearest Sinks		
	50 km or less	100 km or less	250 km or less
Oil & Gas Fields with EOR Potential	59	64	86
Oil & Gas Fields	76	77	88
Aquifers in WC Region	154	174	176
All Sinks	154	174	176

Note:
The annual CO_2 storage rate was 184 Mt.

Table 7. CO_2 storage rate (Mt/yr) by marginal straight-line distance to nearest sinks (Nevada aquifers excluded)

Sink Type	Straight-Line Distance to Nearest Sinks		
	50 km or less	100 km or less	250 km or less
Oil & Gas Fields with EOR Potential	59	64	86
Oil & Gas Fields	76	77	88
Aquifers in WC Region Excluding Navada	139	168	176
All Sinks	139	168	176

Note:
The annual CO_2 storage rate was 184 Mt.

This study further presented a GIS-based method of matching sources and sinks considering the optimal pipeline route selection and sink's capacity constraint. The pipeline construction costs vary considerably according to local terrains, number of crossings (waterway, railway, highway), and the traversing of populated places, wetlands, and national or state parks. In order to account for such obstacles, the locations and characteristics of these obstacles were loaded into the spatial database and were used to construct a single aggregate transportation obstacle layer. In contrast to the distance-based matching analysis, this least-cost matching analysis links each CO_2 source to a least-cost geological sink based on the sum of the transportation costs associated with the least-cost path and the injection cost subject to the sink's capacity constraint. An iterative algorithm was used to approximate an optimal system solution. Due to the limited availability of detailed sink data for the WESTCARB region, this least-cost matching analysis was only performed for California where the sink data set is relatively rich.

The least-cost source-sink matching analysis for California was conducted in two stages. In the first stage, only 35 EOR sites with storage capacity over 20 Mt[2] were included as candidate sinks, which results in an overall storage capacity of 3.2 Gt. The amount of

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[2] Most of the CO_2 sources will emit more than 20 Mt CO_2 over the 25-year project lifetime.

CO_2 that needs to be sequestrated from the 31 CO_2 sources in California over 25 years was estimated to be 2.1 Gt. The cost calculation assumed a credit of \$16/t CO_2 for EOR injection and omitted the injection cost. With the assumption of a constant CO_2 credit, the optimization algorithm only considers minimizing the overall transportation of the network system. Figure 25 shows the marginal per-tonne CO_2 transportation cost by annual CO_2 storage rate in oil fields with EOR potential. As the CO_2 storage capacity in the EOR sinks was larger than the 25-year CO_2 flow, all the sources were connected to their corresponding least-cost EOR sinks. The transportation costs for most of the sources are below \$10/t CO_2 except for a few outliers.

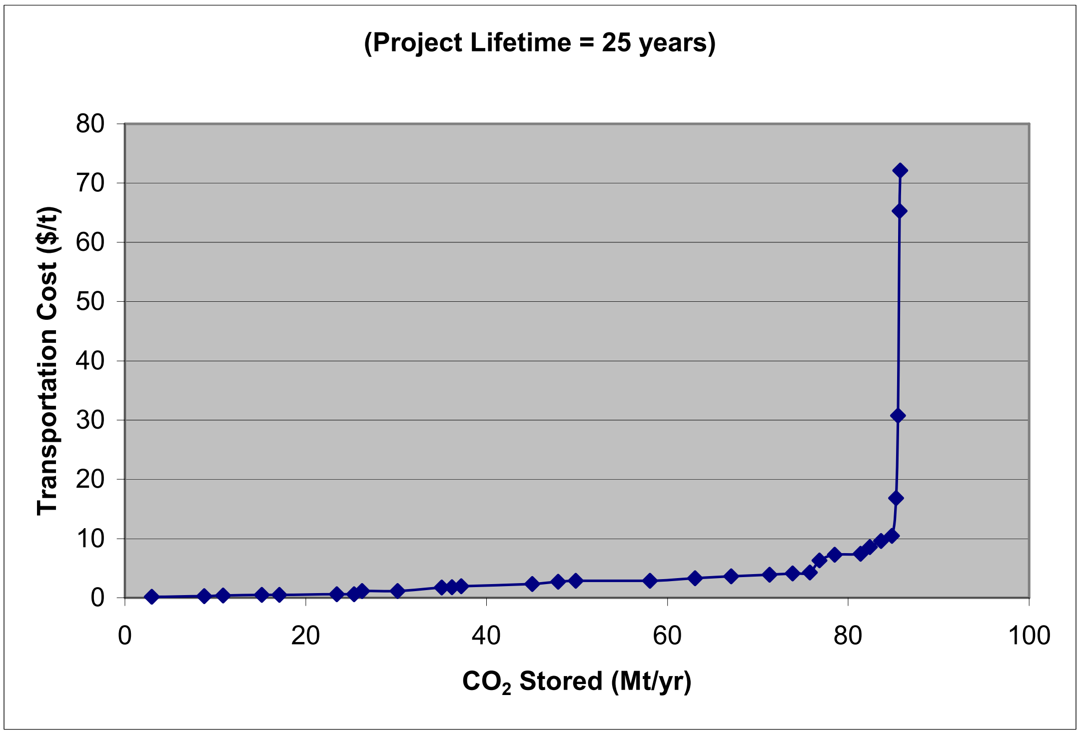

Figure 25. Marginal transportation cost by annual CO_2 storage rate in oil fields with EOR potential, California

Only four sources had transportation costs to the closest EOR site greater than the credit value of \$16/t CO_2. For the second stage of least-cost source-sink matching analysis for California, a new round of source-sink matching was applied to these four sources with the same algorithm as before, but using the oil and gas fields without EOR potential and saline aquifers suitable for CO_2 storage in California as the sink layer instead. A final check was run to conduct a full-cost comparison to decide whether they should be matched to EOR or non-EOR sinks. Except for the source with transportation to EOR site of \$16.8/t CO_2 that remained to be connected to its EOR destination, the other three sources were reassigned to saline aquifers instead because of the lower full costs.

Figure 26 shows the marginal full sequestration cost by annual CO_2 storage rate. For sources matched with EOR sites, the full cost estimate included costs for capture and transportation, net of an EOR credit. For sources matched with non-EOR hydrocarbon fields or aquifers, the full cost estimate included costs for capture, transportation, and injection. The results of the full cost sequestration analysis in California indicate that 20, 40, or 80 Mt of CO_2 per year could be sequestered in California at a cost of \$31/t, \$35/t, or \$50/t, respectively.

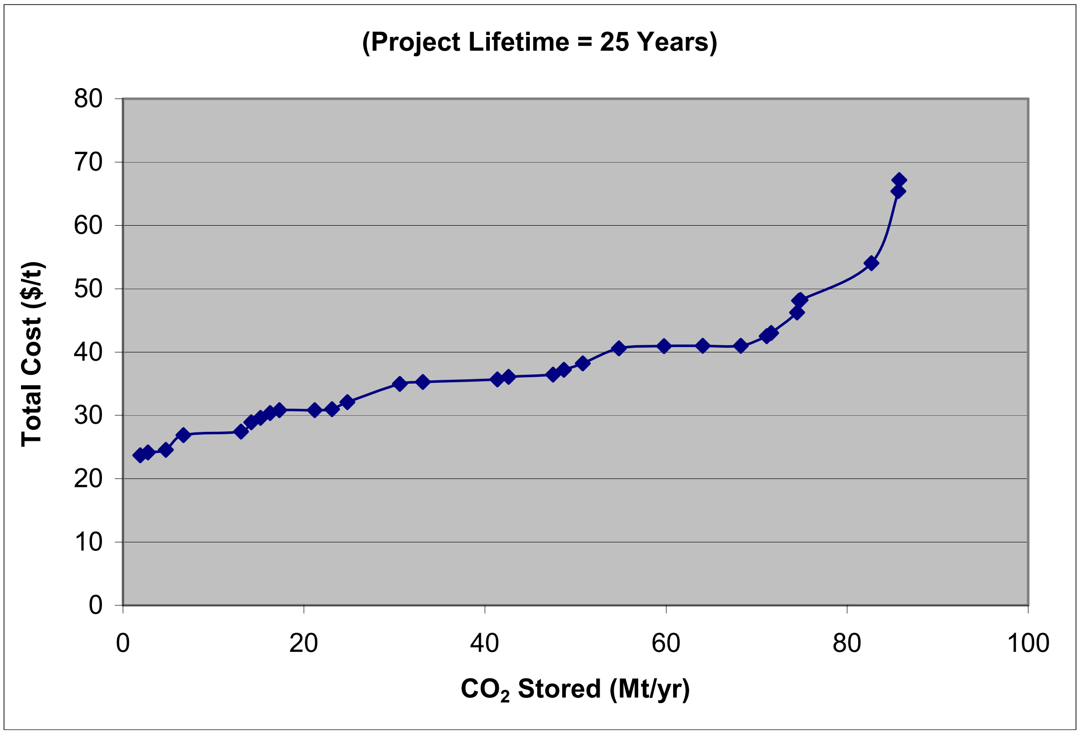

Figure 26. Marginal total cost by annual CO_2 storage rate, California

3.3 Selection of Phase II Pilots

3.3.1 Three-Step Decision Support Method

WESTCARB developed a consensus-based, three-step decision support method for evaluating potential geologic sequestration projects. A WESTCARB committee applied the method to rank the finalists for geologic pilots to be conducted during the WESTCARB Phase II project. The method involved a three step process:

Step 1: Establishing Evaluation Criteria and Scoring Guidelines

The method's first step produced consensus among evaluators on the major categories or criteria and the specific attributes or subcriteria by which candidate projects would be assessed. Scoring guidelines were then developed for each subcriterion.

Step 2: Assigning Weighting Factors to Criteria and Subcriteria

The second step produced consensus among evaluators on the relative importance of criteria and subcriteria. A commercial decision support software package (ExpertChoice) was used to develop the mathematical weighting factors based on a series of pair-wise comparisons among criteria and among subcriteria for each criterion.

Step 3: Scoring Candidate Pilot Projects

The third step produced consensus among evaluators on the score assigned to each candidate project for each subcriterion. The ExpertChoice software multiplied the criterion scores by the weighting factors to calculate composite scores for each project. The projects were then ranked by order of their score.

3.3.2 Application for Phase II Pilot Project Selection

In the case of our Phase II pilot evaluations, consensus on the major criteria, subcriteria, and scoring guidelines was achieved by circulating a “strawman” list and sharing comments and suggestions via e-mail until a mutually agreed upon set was established. The strawman list drew from basic geologic requirements for successful sequestration, pilot project experience (both generally and sequestration-specific, including Frio), and initial reservoir-scale decision analysis criteria developed by several WESTCARB partners. Some subcriteria were derived from cost-share and related requirements in DOE’s Phase II Request For Proposals. Table 8 shows the resulting scoring guidelines, organized by major criteria and subcriteria.

Evaluators then met in-person to conduct the joint exercise in assigning weighting factors for the 5 criteria and 22 total subcriteria and scoring of the 5 finalist projects. The group of 6 evaluators found it could readily discuss and agree upon the relative importance of weighting factors and the project scores (as opposed to strong differences of opinion requiring individual voting). The evaluators were satisfied with the decision support method, finding it workable and objective. They also found the ExpertChoice software to be a handy tool for tabulating and graphically displaying results. The two projects with the highest scores—a combined enhanced gas recovery and saline formation injection project and a saline formation injection project near a major coal-fired power plant—were selected for inclusion in the WESTCARB Phase II proposal. The Action Plan for implementing these pilots during the Phase II WESTCARB project is found in Appendix XXII.

Table 8. WESTCARB Phase II geologic pilot scoring guidelines

MAJOR CRITERIA	Subcriteria	Scoring Guidelines
Partner Commitment	Amount of cost share	No cost share (0.0)
		Less than 10% cost share (0.2)
		10-20% cost share (0.5)
		20% cost share (0.8)
		Greater than 20% cost share (1.0)
	Site selected	No location selected (0.0)
		Suitable location selected but no specific site selected (0.25)
		Location and site(s) selected (0.5)
		Site(s) characterized (0.75)
		Injection well(s) selected (1.0)
	Level of executive interest	No or unknown executive interest (0.0)
		Letter of support under development (0.25)
		Letter of support from senior management (0.5)
		Extensive interest and letter of support from senior manager (with no specific cost share commitment) (0.75)
		Extensive interest and letter of support from management specifying cost share commitment (1.0)
	Commitment of internal staff resources	No or unknown commitment of internal staff resources (0.0)
		Low commitment of internal staff resources (0.25)
		Moderate commitment of internal staff resources (0.5)
		High commitment of internal staff resources (0.8)
		Committed and named internal resources (1.0)
	Degree of interest and awareness of climate change issues	No interest/awareness (0.0)
		Low degree of interest/awareness (0.33)
		Moderate degree of interest/awareness (0.66)
		High degree of interest/awareness (1.0)
	Unique technology (relative to other pilots)	Other sequestration pilots in same field/application or formation (0.0)
		"Typical" EOR or injection to saline formation, but first in reservoir (0.5)
		First-of-a-kind demo of new technology (1.0)
Geological	Extent of pre-existing site	No characterization (0.0)

MAJOR CRITERIA	Subcriteria	Scoring Guidelines
Characteristics	characterization	Partially characterized (0.4)
		Partially characterized with continued characterization under way (0.6)
		Fully characterized (0.8)
		Fully characterized with available well log data (1.0)
	Suitability of storage formation (confidence in permeability, no abandoned wells, etc.)	Unsuitable (0.0)
		Unknown but plausible suitability (0.25)
		High confidence in reasonable suitability, or limited information suggesting good suitability (0.5)
		Expectation of excellent suitability (0.75)
		High confidence in excellent suitability (1.0)
	Presence of adequate caprock (confidence in permanence)	No caprock (0.0)
		Unknown caprock (0.2)
		Fractured caprock (0.5)
		Adequate caprock (1.0)
	Depth between 1000 and 1500 m (deep enough for supercritical storage, but not too deep so that drilling costs are excessive)	No (0.0)
		Deeper than 1500 m (0.5)
		Yes (1.0)
	Potentially representative of large sink	Relatively unrepresentative or unknown (0.2)
		Very representative of a modest sink; near, but not beneath, major point sources (0.4)
		Moderately representative of one of the region's major sinks or very representative of a modest sink; underlying or near major point sources (0.6)
		Very representative of one of the region's major sinks; near, but not beneath, major point sources (0.8)
		Very representative of one of the region's major sinks; underlying major point sources (1.0)
Regulatory Climate	Clear regulatory authority	No (0.0)
		Partially (0.5)
		Yes (1.0)
	Regulators' experience with deep underground injection in relevant formations	No experience (0.0)
		Minimal or unknown level of experience (0.33)
		Moderate level of experience (0.66)
		Extensive experience (1.0)
	Regulators' experience with Class V or Class I permits	No experience (0.0)
		Minimal or unknown level of experience (0.33)

MAJOR CRITERIA	Subcriteria	Scoring Guidelines
		Moderate level of experience (0.66)
		Extensive experience (1.0)
	Regulators' interest in project	No interest (0)
		Low or unknown interest (0.33)
		Moderate interest (0.66)
		High interest (1.0)
Community Involvement and Concern	Size of local population	Urban (0.0)
		Suburban/vacation area (0.33)
		Rural towns and ranches/timber (0.66)
		Remote (1.0)
	Pre-existing favorable opinion about (or proximity to) injection operations	Strongly negative (0.0)
		Moderately negative (0.25)
		No opinion/neutral (0.5)
		Moderately favorable (0.75)
		Strongly favorable (1.0)
	Extent of active "NIMBY-type" community based organizations	Very well organized, very active organizations (0.0)
		Very active organizations (0.2)
		Moderately active organizations (0.4)
		No organizations (1.0)
	Presence of local educational institutions (respected community members who might corroborate sequestration value)	Elementary or K-12 only (0)
		Community college (0.5)
		One or more universities (0.8)
		Major research university (1.0)
Future Benefits	Prospect for economic opportunity (*e.g.*, EOR or EGR)	Low (0.0)
		Medium (0.5)
		High (1.0)
	Likelihood of using site for future integrated pilot and/or large-scale storage project	Unlikely (0.0)
		Moderately likely (0.5)
		Very likely (0.75)
		Very likely; underlying major point source (1.0)
	Local interest in sequestration associated job growth	No interest (0)
		Low interest (0.33)
		Moderate interest (0.66)
		High interest (1.0)

3.4 Technology Deployment Issues

3.4.1 Regulatory Framework

3.4.1.1 Geologic Sequestration

Injection of CO_2 into geologic formations requires an Underground Injection Control (UIC) permit from EPA. The UIC Program was established under the provisions of the Safe Drinking Water Act of 1974 to protect underground sources of useable water. Under this program, five classifications of wells were established:

- Class I – wells used to inject liquid hazardous wastes, industrial non-hazardous liquid, and municipal wastewater beneath the lowermost drinking-water reservoir;
- Class II – wells used to dispose of fluids associated with the production of oil and natural gas, enhanced oil recovery, and storage of liquid hydrocarbon;
- Class III – wells used to inject fluids for the extraction of minerals;
- Class IV – wells used to dispose of hazardous or radioactive wastes into or above drinking water. EPA has banned the use of these Class IV wells; and
- Class V – wells not included in the other classes used to generally inject non-hazardous fluid into or above drinking water.

EPA has delegated primary regulatory authority to state agencies that have demonstrated an ability to implement UIC programs that meet EPA requirements. These states are referred to as "primacy states". In states that have not received primacy status, the responsible permitting agency is EPA.

The regulations on CO_2 injection wells are currently in flux. Regulations are best defined for injection into oil reservoirs where the CO_2 will be used for EOR. In this case, injection wells would be classified as Class II by all 6 western states in WESTCARB. The agencies responsible for permitting such wells, and the specific relevant regulations, are summarized in Table 9.

Table 9. Federal and state EOR permit requirements. (See the Appendix of Appendix XIII for an explanation of acronyms.)

STATE	REGULATING AGENCY	WELL/PERMIT TYPE	REGULATIONS CITED
Alaska	EPA OGCC share primacy w/EPA	Class IIR	40CFR144-148 20AAC25; 31 AK O&G Consvr. Act Ch31.05
Arizona	EPA no primacy w/state OGCC	Class II 2nd jurisdiction	40CFR144-148 12AAC7; ARS 27-516

	DEQ	Aquifer Protection Permit	ARS 49-241; 18AAC,Ch9
California	EPA DOGGR share primacy w/EPA	Class II	40CFR144-148 14CCR Div2, Ch2, 4; Public Resources Code 30262
Nevada	DEP DOM BLM	Class II (Interagency Cooperation between 3 agencies)	NAC445A.810 to 445A.925 NAC Ch522; NRS 445A.470 43CFR Ch2 Part3160
Oregon	DEQ DOGAMI	Class II Interagency cooperation	40CFR144-148; 44OAR340-044-0005 and Appendix A OAR Ch.632 Div. 10; ORS 520
Washington	Dept. of Ecology DNR	Class II (joint control)	40CFR144-148; WAC173-218 78.52 RCW

Currently, the regulatory framework for saline formation CO_2 injection wells is not well defined (see Appendix XIII for further discussion).

Regulations for CO_2 injection into coal beds for enhanced coal-bed methane (ECBM) recovery vary among the three WESTCARB states (Alaska, Arizona, and Washington) that have sizable deposits. Washington (primacy status) has permitted one Class II injection well for ECBM. Since ECBM deals with hydrocarbon recovery, it appears that CO_2 injection for ECBM would lead to a Class II classification. Storage of CO_2 in ECBM produces a significant amount of water during the initial injection phase, and the disposal of the water produced may require a National Pollutant Discharge and Elimination System permit (Veil, 2002). Additional information is found in Appendix XIII.

3.4.1.2 Terrestrial Sequestration

Both Federal and State agencies will require permits for any land-use changes or disturbances associated with forest terrestrial sequestration activities. The regulating agency and applicable statutes varies depending on land ownership. Table 10 provides a summary for Arizona; data for other WESTCARB states is found in Appendix XIII.

Table 10. Potential Arizona permits/contracts for land-use changes or disturbances. (See the Appendix of Appendix XIII for an explanation of acronyms.)

<table>
<tr><th colspan="2">TYPE OF LAND</th><th>REGULATING AGENCY</th><th>REGULATIONS CITED</th></tr>
<tr><td colspan="2">State land</td><td>State Land Dept.
Dept. of Fish & Wildlife
DEQ (Water Quality)
U.S. Fish and Game</td><td>ARS Title 37-102 and 37-622
ARS Title 17 Ch3
AAC Title 18 Ch9
50CFR17</td></tr>
<tr><td rowspan="4">Federal land</td><td>USDA</td><td>USDA
Dept. of Fish and Game
U.S. Fish and Game</td><td>36CFR Ch1 part 1
ARS Title 17 Ch3
50CFR17</td></tr>
<tr><td>USDI – National Parks</td><td>Not allowed</td><td></td></tr>
<tr><td>USDI – BLM</td><td>BLM
Dept. of Fish and Game
U.S. Fish and Game</td><td>43CFR part 5000-5510
ARS Title 17 Ch3
50CFR17</td></tr>
<tr><td>USDI – Tribal land</td><td>USDI
BLM
Local tribunal</td><td>25CFR part1 and 163
All BLM regulations
HR3826 (Tribal Forest Protection Act); local tribunal laws</td></tr>
<tr><td rowspan="2">Private land</td><td>Forest land</td><td>Same as State land</td><td>State land regulations</td></tr>
<tr><td>Ranch land</td><td>County/city planning
DEQ (Water Quality)
Dept. of Fish and Game
U.S. Fish and Game</td><td>Various county/city zoning codes
AAC Title 18 Ch9
ARS Title 17 Ch3
50CFR17</td></tr>
</table>

3.4.2 Health and Environmental Risks

A demonstration of the SRF approach described in section 2.3.2 is provided by comparison of two potential CO_2 storage sites in California: the Rio Vista Gas Field and the Ventura Oil Field.

The Rio Vista Gas Field is located in the delta region of the Sacramento-San Joaquin Rivers in the Sacramento Basin of California, approximately 75 km (47 mi) northeast of San Francisco. Published materials and expert's knowledge of the geology of the area was used to fill in values in the SRF spreadsheet and arrive at overall attribute assessments and certainties for the Rio Vista Gas Field. As shown in the Summary worksheet in Figure 27, the high attribute score displayed by the SRF spreadsheet reflects the very effective primary containment expected at Rio Vista. Secondary containment is not expected, as sealing formations above the Nortonville shale are largely absent; however, the attenuation potential is excellent at Rio Vista due largely to steady winds and flat topography. As shown in the figure, confidence in the attribute assessments is quite high for subsurface and surface characteristics at Rio Vista because of the long history of gas production at the site. The high score and certainty at this site suggest that Rio Vista Gas Field is a good candidate for geologic CO_2 storage.

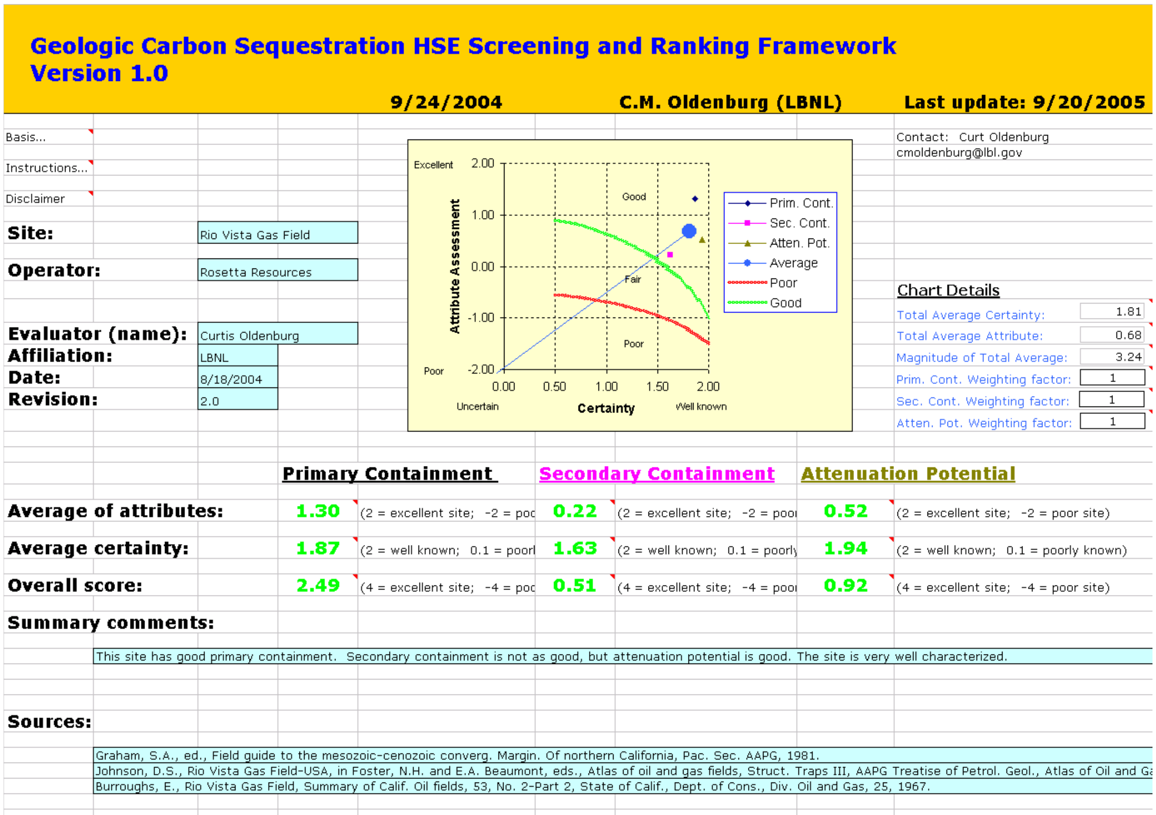

Figure 27. Summary graphic showing the attribute assessment (*y*-axis) and uncertainty (*x*-axis) of the three fundamental characteristics along with qualitative regions of poor, fair, and good HSE risk for the Rio Vista Gas Field

The Ventura Oil Field taps reservoirs in young folds and fault traps of marine sediments in the tectonically active coastal area northwest of Ventura, California. As shown in Figure 28, the Ventura Oil Field comes out worse on average than the Rio Vista Gas Field (Figure 27). The very significant oil accumulations at Ventura indicate that good traps exist, but the evidence of widespread oil and tar seepage along with the lack of significant natural gas accumulation suggest that pathways to the surface also exist. As for secondary containment, some of the oil reservoirs in the area are quite shallow, suggesting that secondary containment may occur but there is a high degree of uncertainty, especially in light of the abundant seepage. As for attenuation potential, the Ventura area is highly dissected with steep canyons that do not promote dispersion of seeping CO_2. There is also considerable population and agriculture to the southeast, which could be exposed to seeping CO_2. Therefore, attenuation potential is also judged worse at Ventura than at Rio Vista.

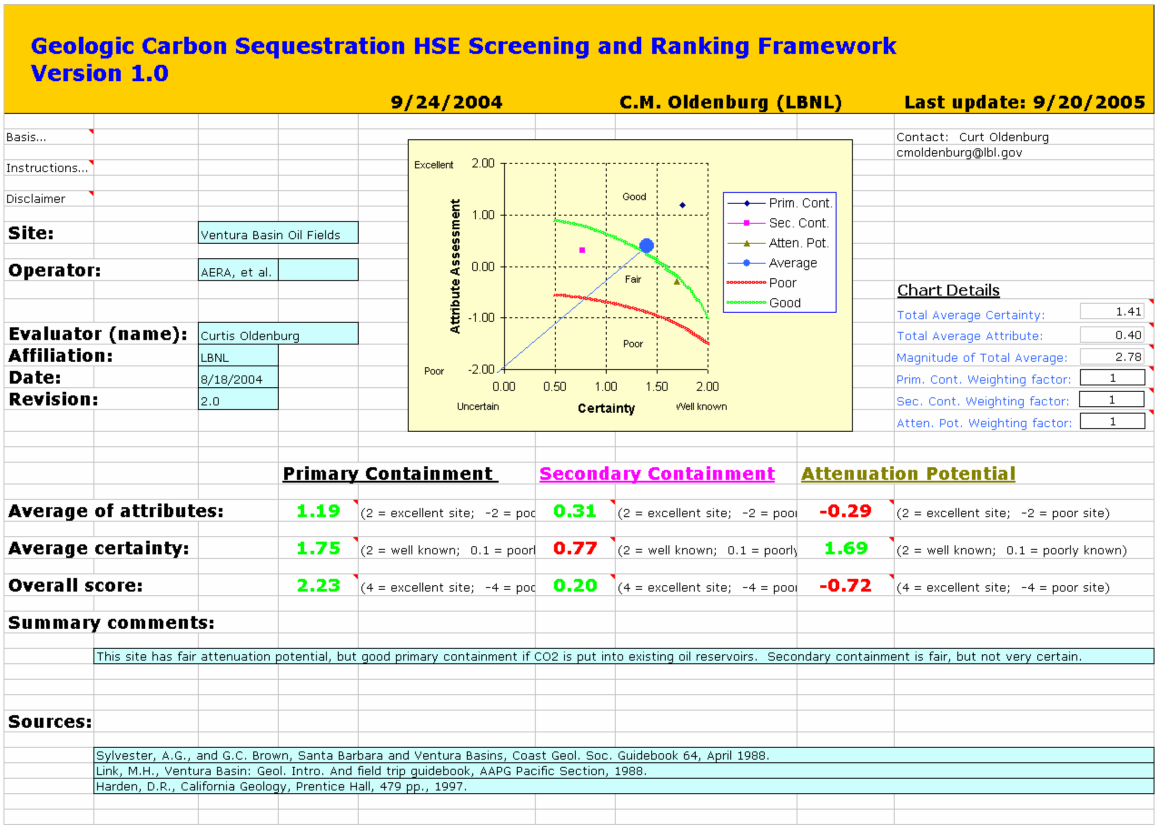

Figure 28. Summary worksheet showing the attribute assessment (*y*-axis) and uncertainty (*x*-axis) of the three fundamental characteristics for the Ventura Oil Field

Additional results and further discussion of the SRF approach are found in Appendix XII.

3.4.3 Monitoring and Verification

The time-lapse performance of seismic, gravity, and EM techniques were considered for the Schrader Bluff, Alaska, model. This model represented the most difficult end member of a complex spectrum of possible sequestration scenarios because of thin injection intervals with multiple fluid components (oil, hydrocarbon gas, brine, and CO_2). The spatial variations in the changes in the vertical component of gravity as well as the vertical gradient of the vertical component of gravity directly correlate with the spatial variations in the net density changes within the reservoir. Although the magnitude of the signals measured on the surface is in the noise level of the field survey, borehole measurements just above the reservoir do produce measurable change in the vertical component of gravity that could be used to map lateral distributions of injected CO_2. The difference in both the borehole gravity response and the vertical gravity gradient measured in vertical profiles within boreholes clearly identifies the position of the reservoir. As shown in Figure 29, there is a clear change in seismic amplitude associated with the reservoir caused by the changes in water and CO_2 saturation (S_w and S_{CO2}, respectively). To produce the figure, the pressure response was sorted to common-depth-point (CDP) gathers, normal move-out corrected, and stacked to produce the sections for model years 2005 and 2020. The red line is a constant time horizon within the reservoir for reference. The 30 m (98 ft) reservoir interval is not uniform and is comprised of 5 m (16 ft) thick substrata, each of which has reflection coefficients at their top and base that vary with S_{CO2}. These sub-strata are all below the seismic tuning thickness, which produces a seismic response without a clear top and base reflector. There is a significant increase in S_{CO2} to the right of CDP 8412.5, producing the large change in the stacked sections shown in figure.

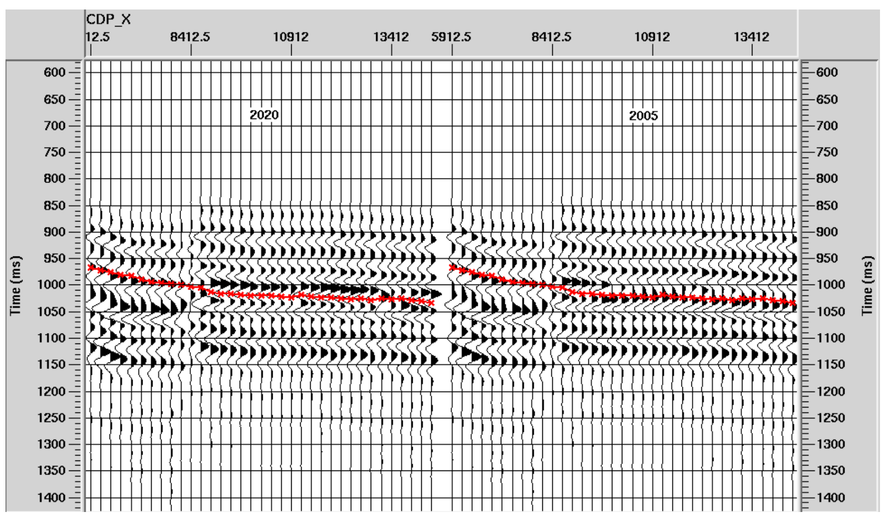

Figure 29. Stacked section for model years 2005 and 2020

In addition, modeling results show that there is a change in the seismic amplitude variation with offset (AVO). Both seismic amplitude and AVO can be exploited to make quantitative estimates of saturation changes. There is a direct one-to-one correspondence with the change in S_w and the change in the electric field amplitude. While this signal level is low, it can be measured given the signal-to-noise ratio of the data. While this represents a potential low-cost monitoring technique, it is best suited for CO_2-brine systems where there is a one-to-one correlation between the change in water saturation and the change in CO_2 saturation (since $S_w + S_{CO2} = 1$). In petroleum reservoirs such as Schrader Bluff, the presence of hydrocarbons as additional fluids eliminates the one-to-one correlation between changes in S_w and changes in S_{CO2}.

The seismic and gravity responses were simulated for a simplified flow simulation model of the Rio Vista gas field in the Sacramento Basin of California. Models were used to calculate anticipated contrasts in seismic velocity, density, and impedance in gassaturated rock when CO_2 is introduced. Numerical simulations were performed to evaluate whether a CO_2-CH_4 front can be monitored using seismic and/or gravity. For the model parameters used in this study, the changes in reservoir properties are very small and neither gravity nor seismic methods would provide information necessary for monitoring of CO_2 movement.

Additional information on both the Schrader Bluff and Rio Vista monitoring studies is found in Appendix XIV.

3.4.4 Life Cycle Analyses

Spreadsheets described in Section 2.3.4 were used to assess the impact on emissions of retrofitting current power generating plants in WESTCARB. Results are shown in Tables 11 and 12. Table 11 shows the existing, retrofit, and change in emissions for WESTCARB states, and for the Region. Table 12 presents the same type of comparison for fuel types. The results reflect key assumptions made on the proportion of gas and coal used for replacement power. It is interesting to note that, for the Regional case where all plants are retrofit with CO_2 control, and replacement power is split 50/50 between gas turbine combined cycle (GTCC) and coal, the CO_2 and SO_2 emissions are reduced but the NOx and mercury are increased. This is due to the criteria set for the retrofits, which are thought to be reasonable, but certainly have a range of alternative conditions.

Table 11. Report example for the states and the region

		Alaska			Arizona		
		Existing	Retrofit	Delta Emissions1	Existing	Retrofit	Delta Emissions2
NET GENERATION CAPACITY MWe		905	726		7,977	6,166	
GROSS GENERATION CAPACITY, MWe		933	798		8,406	6,932	
PLANT CAPACITY FACTOR		0.42	0.42		0.63	0.63	
ANNUAL GENERATION MWh		3,353,621	2,687,518		44,187,217	37,607,268	
PLANT HEAT RATE, Btu/kWh		10,671	13,315		11,327	13,309	
INSTALLED CONTROL EQUIPMENT							
SO2 CONTROL, % OF GEN. CAPACITY		0.00%	0.00%		77.41%	77.41%	
NOx CONTROL, % OF GEN. CAPACITY		0.00%	0.00%		89.34%	89.34%	
PRIMARY FUEL		Portions Below	Portions Below		Portions Below	Portions Below	
COAL		0.06	0.06		0.92	0.92	
OIL		0.10	0.10		0.00	0.00	
NATURAL GAS		0.84	0.84		0.08	0.08	
SO2 EMISSION	Tons Per Year	2,712	1,117	(1,600)	71,316	3,605	(65,530)
NOX EMISSION	Tons Per Year	7,477	7,477	90	93,877	93,877	4,460
MERCURY	Lb Per Year	13	13	-	1,432	1,432	113
CO2 EMISSION	Tons Per Year	2,288,594	228,859	(1,667,000)	49,146,500	4,914,650	(38,603,800)
SOLID WASTE	Tons Per Year	na	na	na	na	na	na

1. Assumes all replacement power is supplied by GTCC units.
2. Assumes 50% of replacement power is supplied by GTCC units and 50% by coal units.

		California			Nevada		
		Existing	Retrofit	Delta Emissions1	Existing	Retrofit	Delta Emissions2
NET GENERATION CAPACITY MWe		18,713	15,035		4,604	3,592	
GROSS GENERATION CAPACITY, MWe		19,274	16,522		4,825	4,016	
PLANT CAPACITY FACTOR		0.38	0.38		0.66	0.66	
ANNUAL GENERATION MWh		62,564,201	50,267,597		26,607,155	20,644,562	
PLANT HEAT RATE, Btu/kWh		10,456	13,014		10,253	13,214	
INSTALLED CONTROL EQUIPMENT							
SO2 CONTROL, % OF GEN. CAPACITY		0.00%	0.00%		19.08%	19.08%	
NOx CONTROL, % OF GEN. CAPACITY		100.00%	100.00%		45.22%	45.22%	
PRIMARY FUEL		Portions Below	Portions Below		Portions Below	Portions Below	
COAL		-	-		0.71	0.71	
OIL		0.00	0.00		0.00	0.00	
NATURAL GAS		1.00	1.00		0.29	0.29	
SO2 EMISSION	Tons Per Year	312	156	(160)	53,100	2,715	(48,400)
NOX EMISSION	Tons Per Year	19,891	19,891	1,720	46,883	46,883	4,050
MERCURY	Lb Per Year	-	-	-	366	366	103
CO2 EMISSION	Tons Per Year	38,598,164	3,859,816	(27,488,200)	24,766,010	2,476,601	(17,174,900)
SOLID WASTE	Tons Per Year	na	na	na	na	na	na

		Oregon			Washington		
		Existing	Retrofit	Delta Emissions1	Existing	Retrofit	Delta Emissions2
NET GENERATION CAPACITY MWe		1,768	1,399		1,954	1,513	
GROSS GENERATION CAPACITY, MWe		1,838	1,551		2,056	1,699	
PLANT CAPACITY FACTOR		0.70	0.70		0.73	0.73	
ANNUAL GENERATION MWh		10,844,263	8,566,558		12,422,893	9,618,277	
PLANT HEAT RATE, Btu/kWh		8,908	11,276		10,493	13,553	
INSTALLED CONTROL EQUIPMENT							
SO2 CONTROL, % OF GEN. CAPACITY		0.00%	0.00%		0.00%	0.00%	
NOx CONTROL, % OF GEN. CAPACITY		100.00%	100.00%		25.27%	25.27%	
PRIMARY FUEL		Portions Below	Portions Below		Portions Below	Portions Below	
COAL		0.35	0.35		0.83	0.83	
OIL		0.00	0.00		0.01	0.01	
NATURAL GAS		0.65	0.65		0.16	0.16	
SO2 EMISSION	Tons Per Year	14,461	762	(13,700)	83,777	4,269	(78,580)
NOX EMISSION	Tons Per Year	13,298	13,298	320	20,638	20,638	1,890
MERCURY	Lb Per Year	165	165	-	578	578	48
CO2 EMISSION	Tons Per Year	7,398,759	739,876	(5,315,900)	12,102,561	1,210,256	(8,502,100)
SOLID WASTE	Tons Per Year	na	na	na	na	na	na

		WESTCARB		
		Existing	Retrofit	Delta Emissions2
NET GENERATION CAPACITY MWe		35,921	28,432	
GROSS GENERATION CAPACITY, MWe		37,332	31,519	
PLANT CAPACITY FACTOR		0.51	0.51	
ANNUAL GENERATION MWh		159,979,349	129,391,779	
PLANT HEAT RATE, Btu/kWh		10,565	13,063	
INSTALLED CONTROL EQUIPMENT				
SO2 CONTROL, % OF GEN. CAPACITY		19.64%	19.64%	
NOx CONTROL, % OF GEN. CAPACITY		84.03%	84.03%	
PRIMARY FUEL		Portions Below	Portions Below	
COAL		0.46	0.46	
OIL		0.00	0.00	
NATURAL GAS		0.54	0.54	
SO2 EMISSION	Tons Per Year	225,678	12,623	(202,950)
NOX EMISSION	Tons Per Year	202,063	202,063	20,640
MERCURY	Lb Per Year	2,554	2,554	525
CO2 EMISSION	Tons Per Year	134,300,588	13,430,059	(94,779,500)
SOLID WASTE	Tons Per Year	na	na	na

Table 12. Report example for types of fuel

		Coal			Natural Gas		
		Existing	Retrofit	Delta Emissions3	Existing	Retrofit	Delta Emissions4
NET GENERATION CAPACITY MWe		11,709	8,956		24,606	19,770	
GROSS GENERATION CAPACITY, MWe		12,412	10,132		25,345	21,726	
PLANT CAPACITY FACTOR		0.73	0.73		0.39	0.39	
ANNUAL GENERATION MWh		74,539,530	57,014,080		84,014,545	72,105,348	
PLANT HEAT RATE, Btu/kWh		11,136	14,559		10,340	12,235	
INSTALLED CONTROL EQUIPMENT							
SO2 CONTROL, % OF GEN. CAPACITY		56.04%	56.04%		0.00%	0.00%	
NOx CONTROL, % OF GEN. CAPACITY		66.54%	66.54%		93.05%	93.05%	
PRIMARY FUEL		Coal	Coal		Natural Gas	Natural Gas	
COAL		Not Applicable	Not Applicable		Not Applicable	Not Applicable	
OIL		Not Applicable	Not Applicable		Not Applicable	Not Applicable	
NATURAL GAS		Not Applicable	Not Applicable		Not Applicable	Not Applicable	
SO2 EMISSION	Tons Per Year	222,709	11,135	(200,010)	847	423	(420)
NOX EMISSION	Tons Per Year	155,693	155,693	21,180	44,783	44,783	1,660
MERCURY	Lb Per Year	2,554	2,554	601	-	-	-
CO2 EMISSION	Tons Per Year	83,351,430	8,335,143	(55,477,300)	52,171,849	5,217,185	(39,932,900)
SOLID WASTE	Tons Per Year	na	na	na	na	na	na

3. Assumes all replacement power is supplied by coal units.
4. Assumes all replacement power is supplied by GTCC units.

		Oil		
		Existing	Retrofit	Delta Emissions4
NET GENERATION CAPACITY MWe		193	155	
GROSS GENERATION CAPACITY, MWe		199	170	
PLANT CAPACITY FACTOR		0.20	0.20	
ANNUAL GENERATION MWh		339,034	272,351	
PLANT HEAT RATE, Btu/kWh		12,644	15,740	
INSTALLED CONTROL EQUIPMENT				
SO2 CONTROL, % OF GEN. CAPACITY		0.00%	0.00%	
NOx CONTROL, % OF GEN. CAPACITY		0.00%	0.00%	
PRIMARY FUEL		Oil	Oil	
COAL		Not Applicable	Not Applicable	
OIL		Not Applicable	Not Applicable	
NATURAL GAS		Not Applicable	Not Applicable	
SO2 EMISSION	Tons Per Year	2,130	1,065	(1,060)
NOX EMISSION	Tons Per Year	1,726	1,726	10
MERCURY	Lb Per Year	-	-	-
CO2 EMISSION	Tons Per Year	342,195	34,219	(268,700)
SOLID WASTE	Tons Per Year	na	na	na

The above is one example of a possible application of the spreadsheet model; many others are possible by varying the input parameters. Additional information on the LCA analyses is found in Appendix XI.

3.5 Public Outreach

One of the WESTCARB's six primary goals is to promote public participation and education. The objective of Phase I Task 3, Implement Public Outreach, is to engage stakeholders and the public in an open dialogue on carbon sequestration technologies through multi-stakeholder public meetings, presentations at technical and policy-oriented conferences, and web and print media.

Three Phase I deliverable are associated with Task 3, Implement Public Outreach, and are summarized below: (1) education materials, (2) a summary of the multi-stakeholder public meeting, and (3) a Phase II action plan.

3.5.1 Public Outreach Education Materials

During Phase I, WESTCARB established a partnership website, http://www.westcarb.org, and produced numerous communications materials, including a fact sheet and meeting flyer, technical reports and papers, posters, news releases, and various PowerPoint presentations. WESTCARB also established web access to some of its GIS-based maps of CO_2 emission sources, geologic formations suitable for CO_2 storage, and terrestrial carbon storage baselines and supply curves for various timeframes.

All of these communication materials contribute to overall education on climate change issues, the potential role of carbon sequestration technology in mitigating adverse impacts, and WESTCARB's role in advancing our understanding of carbon sequestration opportunities. Within this body of materials, however, were several documents and web pages specifically developed as tutorials on these topics intended for general audiences. Appendix XVI contains a selection of those WESTCARB-produced tutorials.

3.5.2 Public Meeting Summary

WESTCARB held a "public forum" in Portland, Oregon, on October 27, 2004, targeted to public and private sector professionals, researchers, community leaders, and conservation/environmental groups. The half-day forum featured presentations in two panel sessions interspersed with Q&A time. The first panel addressed climate change science, its regional implications, technology/policy response options, and emerging initiatives in Oregon and Washington. This outstanding panel was composed of internationally known scientists and economists, senior representatives in state government, and a power company program manager. Their talks provided context for the second panel, comprised of WESTCARB members, who offered an overview of geologic and terrestrial sequestration and the DOE and WESTCARB programs.

About 55 people attended the forum, exceeding our expectations and nearly filling the room to capacity. About half were from WESTCARB member organizations, and half from our non-member target audience. Audience questions ranged from clarifying queries on basic climatic understanding to knowledgeable comments on current research. No contentious debate took place.

Preparations for the meeting involved audience segmentation, communication channel analysis, and crafting of direct mail and media outreach activities to reach target audiences (see Appendix XVII). Pre-meeting publicity included mailing a professional-looking flyer to more than 1000 people matching our target audience profile, and preparing news releases for local media, all of which are also included in Appendix XVII.

3.5.3 Public Outreach Strategy (Action Plan) for Phase II

WESTCARB plans to continue its successful Phase I public outreach activities (*i.e.*, web communications, handouts and mailing materials, presentations at key conferences and annual Partnership meetings, news releases to media) in Phase II, and to expand their scope to accommodate new information from the geologic and terrestrial sequestration pilot projects as well as continued characterization of the region. Planned activities are summarized in Appendix XVIII.

WESTCARB will hold general public meetings on an approximately annual basis (modeled after our successful 2004 public forum in Portland, Oregon) and pilot-project-specific public meetings on an as-needed basis. Meeting locations, even for the former, could coincide with pilot locations, or they may be held in major metropolitan areas or capital cities of the various WESTCARB states (to broaden exposure and facilitate education of the public and affiliated professionals). WESTCARB's annual business meetings will almost certainly be held in major metropolitan areas to reduce travel time and expense.

For each pilot project, and in conjunction with planning for environmental review and permitting, members of WESTCARB's Public Outreach Committee will meet with technical and public affairs representatives from the pilot host organization(s) to develop public outreach objectives, strategies, roles and responsibilities, activities, and points of contact for the project. Such plans will seek to gain stakeholder "buy in" for the project, and knowledge of local communities and any relevant histories or sensitivities will be key to successful outreach planning.

Communication activities are expected to include development of straightforward summaries of each pilot project's goals/rationale, activities, timetable, possible impacts, associated safety precautions, and benefits (in both broad terms and to the local community). These materials will be disseminated to residents, elected and safety officials, clergy, chambers of commerce, union stewards, civic group leaders, publishers of local media, employees of the pilot host, landowners, educators, and other stakeholders and concerned parties. We also expect that speaking engagements and exhibition opportunities at local venues will figure prominently in the outreach plans.

Opinion leaders will be identified and engaged in dialogue early in the process—through face-to-face meetings wherever possible. Such sessions will be designed not just to inform, but also to find areas of mutual interest (*e.g.*, expansion of local job opportunities), and to assure that community concerns are clearly understood by pilot project planners. Where advisable, WESTCARB and the pilot host organizations may engage locally trusted "key stakeholder communication facilitators" to assure effective dialogue with community leaders and/or participate in negotiations regarding permit terms and conditions.

Our planned terrestrial pilot projects involve an added challenge: they are "decentralized," and involve a suite of voluntary activities on multiple lands owned by multiple types of entities with varying objectives. Accordingly, WESTCARB plans to engage industry associations to help prepare and disseminate project materials to the forest products industry and private commercial forest owners.

WESTCARB will aggregate and report pilot project activities to the California Climate Action Registry (CCAR) and The Climate Trust in Oregon. CCAR will use the pilot projects to "road test" the forest protocols it has developed for afforestation and conservation and may use the fuel treatment pilot activities to facilitate development of new protocols for fire management. Although the ultimate aim of the pilot projects is to register certified marketable emission reductions with CCAR and The Climate Trust, WESTCARB is generally seeking to demonstrate that the applicable forest protocols are practical and functionally effective. Validation by CCAR and The Climate Trust provides public visibility for project activities and responds to the concerns and interests of a broad range of stakeholders.

To obtain an objective assessment of its public outreach activities (and to guide their refinement), WESTCARB will support independent university researchers conducting interviews and surveys to measure public perception of carbon sequestration in communities near Rio Vista, CA (*i.e.*, with a local geologic pilot) vs. similar "control" communities without pilot projects, and the effectiveness of outreach materials (or endorsements by others) in educating the public, addressing their concerns, and influencing their opinion.

Finally, WESTCARB will continue to coordinate its outreach activities with other Regional Partnerships through the Outreach Working Group and select joint activities.

3.6 Terrestrial Sequestration

3.6.1 Baselines

3.6.1.1 Washington

General Forestlands Baseline

Forest area and carbon stocks were derived from U.S. Forest Service (USFS) published data for the period 1987 to 1997. An extrapolation was made for the period 1997 to 2003 using recently completed USFS inventory data. Between 1987 and 2003 forest area in Washington decreased by 0.9 million acres. Rates of loss between 1987–1997 were 62,000 ac per year, and slowed to 49,000 ac/yr between 1997 and 2003 (Table 13). This is equivalent to a gross emission of 187 MMTCO_2e or 12.5 MMTCO_2e/yr between 1987–1997, and 10.1 MMTCO_2e/yr between 1997 and 2003.

Table 13. Gross change in forest* area and forest carbon stocks in Washington

	1987	1997	2003	Annual Change 1987–1997	Annual Change 1997–2003
Area (million ac)	22.5	21.9	21.6	-0.062	-0.049
Carbon stock (MMTCO_2e)	3,091	2,965	2,904	-12.6	-10.1

*Includes all forests, federal and non-federal

The values presented here are gross emissions and will be reduced when consideration of the storage in dead wood and wood products pools are included. However, the emissions from forests are undoubtedly a significant proportion of the total emissions for the State of Washington, estimated to be 101 MMTCO_2e in the year 1995.

Baseline for Development on Forest Lands

The baseline for emissions from development was created using land use data from the National Resources Inventory of the USDA and carbon data derived from the USFS Forest Inventory and Analysis Database (FIA). Due to data availability, the period chosen was 1987 to 1997. Due to data limitations the analysis is limited to non-federal forests and to the gross CO_2 emissions from aboveground live tree biomass on conversion of non-federal forestland to developed land uses. As the focus is on non-federal lands the analyses should only be used to explore decisions on private lands.
Between 1987 and 1997, 246,000 acres of non-federal forest were converted to development. Large losses were concentrated in the coastal regions.

For gross carbon emissions, two scenarios were considered. Under Scenario 1, all tree biomass in the converted area was immediately emitted as CO_2. Under Scenario 2 for developed areas of less than 10 acres, it was assumed that 50% of the carbon was retained in the form of residual trees. Under Scenario 1, an estimated 70.3 MMTCO_2e were emitted for the 10-year period due to development. Under Scenario 2, 65.4 MMTCO_2e were emitted. Development was concentrated in the Puget Sound region where the major city of Seattle is located (Table 14). In this region 60% of the emissions under scenario 1, or 56% of the emissions under scenario 2 occurred, despite the fact that the region represents only 16% of the area of the state.

Table 14. Region-level summary of loss in area and carbon emissions between 1987 and 1997 due to development on non-federal forests. Scenario 2 is more conservative assuming that trees are not clearcut during small-scale development.

	Area lost (ac)	Carbon emissions ($MMTCO_2e$) Scenario 1	Scenario 2
Puget Sound	138,500	42.3	39.4
Olympic	53,800	16.4	15.3
southwest	30,000	8.2	7.5
central	20,100	2.9	2.7
Inland Empire	3,300	0.6	0.6
TOTAL	245,700	70.3	65.4

The emissions from development on non-federal lands of 6.5–7.3 $MMTCO_2e$/yr represent between 52 and 55% of the total gross emissions from the forest sector (12.6 $MMTCO_2e$/yr between 1987 and 1997). Compared to total emissions for the state as a whole, 101 $MMTCO_2e$/yr for the year 1995 (Kerstetter, 1999), emissions from deforestation on non-federal land represent more than 5% of the total in the state.

Baseline Effect of Fire on Forest Lands

Emissions from fire were examined through overlaying the wildfire database for Washington (point data and an estimate of aerial extent) on Advanced Very High Resolution Radiometer (AVHRR) satellite imagery showing change in NDVI (normalized differential vegetation index). (NDVI measures 'greenness' of landscapes, greenness decreases immediately after fire.) This process determined the location, size and estimated intensity (based on degree of change in the NDVI) of fires between 1990 and 1996[3]. Carbon values were applied to these areas burned using data from the USDA FIA and proportional emissions from the detailed baseline fire analysis for California.

The analysis considered all forests and rangelands in Arizona, federal and non-federal. Across the six years analyzed, a total area of 70,800 hectares (0.175 million acres) of fire was recorded. This is equivalent to an average 11,800 hectares per year (29,200 ac/yr) for the period studied. Emissions totaling 1.07 $MMTCO_2e$ were estimated to have occurred from fire during the analysis period. On an averaged annual basis this is equal to 0.18 $MMTCO_2e$/yr.

Thirty-three percent of the burned area and 87% of the emissions were in forest rather than rangeland. No one year dominated fire incidence. Fifty-five percent of area burned and 44% of the emissions were from private land. Fires covered a greater extent and

[3] 1994 was excluded due to poor image quality.

caused more emissions in the north and northeast of the state. Incidence was low in the southeast and northwest.

Compared to total emissions for the state as a whole, 101 $MMTCO_2e$/yr for the year 1995, the average annual emissions from fire of 0.18 MMTCO2e represented more than 0.2% of the total in the state. However, data limitations led to the exclusion of fires from 1994. Unfortunately 1994 was a year with a total area burned that was five times greater than the average annual burn between 1970 and 2003. The inclusion of 1994 would have significantly raised the average annual emissions due to fire.

Baseline for Agricultural Lands

Agricultural land in Washington amounts to almost 15% of the total land area. The state lost agricultural land area from 1987–1997 through conversion to other land uses, in particular to urban development/transportation and the retiring of agricultural land from cultivation. In some counties, the area of woody cropland increased, but these increases were more than offset by decreases in non-woody cropland. Accompanying these losses in area were losses in standing carbon stocks on agricultural land, so that conversion of agricultural land to other uses was responsible for a net annual emission of CO_2 to the atmosphere of 0.05 $MMTCO_2eq$/yr (Table 15).

Table 15. Summary of agricultural land area and changes in area, carbon stocks and changes in stocks for Washington 1987–1997

Parameter	Units	Results
Proportion of agricultural land to total land	%	14.6
Change in agricultural land area, 1987–1997	Hectares (%)	-234,486 (8%)
Change in woody cropland area		+43,828 (37%)
Change in non-woody cropland area		-278,314 (9.9%)
Total carbon stocks in agricultural land, 1997	$MMTCO_2e$	22.9
Change in carbon stocks in agricultural land,	$MMTCO_2e$	-0.5
Estimated net annual source (emissions) from agricultural lands, disregarding non-CO_2 greenhouse gas emissions	$MMTCO_2e$	-0.05
From woody cropland		+0.1
From non-woody cropland		-0.15
Estimated net annual source from non-CO_2 greenhouse gas emissions, 1995	$MMTCO_2e$	-3.54

Emissions of CO_2 from agricultural land conversion, while the primary focus of this report due to data availability, represent only a portion of the total greenhouse gas emissions attributable to the agricultural sector. The primary non-CO_2 greenhouse gas associated with agricultural activities, emitted from agricultural soils especially after fertilizer application, is nitrous oxide (N_2O), with approximately 296 times the global warming potential of CO_2. Examination of data from Washington indicated that greenhouse gas emissions from N_2O in the agricultural sector dwarf the annual CO_2 source from agricultural land conversion: CO_2 emissions from land conversion represented about 1.4% of the total CO_2 and non-CO_2 greenhouse gas emissions attributable to the agricultural sector.

Additional information is found in Appendix IV.

3.6.1.2 Oregon

General Forest Baselines

Forest area and carbon stocks were derived from USFS published data for the period 1987–1997. An extrapolation was made from 1997 to 2003 using recently completed USFS inventory data. Between 1987 and 2003, there was an estimated increase in forest area in Oregon of 2.1 million acres or 94,000 acres per year between 1987 and 1997 and 175,000 ac/yr between 1997 and 2003 (Table 16). This is equivalent to an estimated increase of 431 $MMTCO_2e$ between 1987 and 2003 or 23.0 $MMTCO_2e$/yr between 1987 and 1997, and 34.4 $MMTCO_2e$/yr between 1997 and 2003.

Table 16. Gross change in forest* area and forest carbon stocks in Oregon

	1987	1997	2003	Annual Change 1987–1997	Annual Change 1997–2003
Area (million ac)	28.7	29.7	30.8	0.094	0.175
Carbon stock ($MMTCO_2e$)	3,327	3,557	3,763	23.0	34.4

*Includes all forests, federal and non-federal

The total emissions for Oregon (excluding forests) for the year 2000 were estimated as 67.7 $MMTCO_2e$ (from Governor's Advisory Group on Global Warming). Forest sinks, therefore, potentially can offset as much as 50% of the state's emissions.

Baseline Effect of Development on Forest Lands

The baseline for emissions from development on non-federal lands was estimated using land use data from the National Resources Inventory of the USDA and carbon data derived from the USFS FIA for the period 1987 to 1997. Due to data limitations the analysis is limited non-federal lands and to the gross CO_2 emissions from aboveground live tree biomass on conversion of non-federal forestland to developed land uses. As the focus is on non-federal lands the analyses should only be used to explore decisions on private lands. Between 1987 and 1997, 69,000 acres of non-federal forest were converted to development. This is equal to 6,900 acres per year. Large losses were concentrated in the coastal regions.

For gross carbon emissions, two scenarios were considered. Under Scenario 1, all tree biomass in the converted area was immediately emitted as CO_2. Under Scenario 2 for developed areas of less than 10 acres, it was assumed that 50% of the carbon was retained in the form of residual trees. Under Scenario 1, an estimated 15.4 $MMTCO_2e$ were emitted due to development or 1.54 $MMTCO_2e$/yr. Under Scenario 2, 13.9 $MMTCO_2e$ were emitted or 1.39 $MMTCO_2e$/yr. Development was concentrated in the northwest region of the state where the major city of Portland is located (Table 17). In this region 56% of the emissions under scenario 1, or 58% of the emissions under scenario 2 occurred, despite the fact that the region represents only 9% of the area of the state.

Table 17. Region-level summary of loss in area and carbon emissions between 1987 and 1997 due to development on non-federal forests. Scenario 2 is more conservative assuming that trees are not clearcut during small-scale development.

Region	Area lost (ac)	Carbon emissions ($MMTCO_2e$) Scenario 1	Scenario 2
northwest	35,000	8.6	8.1
west central	14,200	3.2	2.6
southwest	15,400	3.1	2.8
central	4,100	0.51	0.46
Blue Mtns.	200	0.02	0.02
TOTAL	68,900	15.4	13.9

The emissions from development on non-federal lands of 1.39–1.54 $MMTCO_2e$/yr represent about 2.3% of the total gross emissions for the state of 63 $MMTCO_2e$/yr in 1995 (from Governor's Advisory Group on Global Warming). Oregon's forests have a net sequestration of 22 $MMTCO_2e$/yr between 1987 and 1997 (see Table 16), after accounting for the emissions from development of about 1.4 $MMTCO_2e$/yr.

Baseline Effect of Fire on Forest Lands

The emissions from fire were examined through overlaying the wildfire database for Oregon on AVHRR satellite imagery showing change in NDVI. This process determined the location, size and intensity of fires between 1990 and 1996[4]. Carbon values were

[4] 1994 was excluded due to poor image quality.

applied to these fires using data from the USFS FIA and proportional emissions from the detailed baseline fire analysis for northern California.

The analysis considered all forests and rangelands in Arizona, federal and non-federal. Across the six years analyzed, fires with a total area of 328,000 hectares (0.81 million acres) were recorded. This is equivalent to an average 54,700 hectares per year (135,100 ac/yr) for the period studied. Emissions totaling 25.0 $MMTCO_2e$ were estimated to have occurred from fire during the 6-year period. On an average annual basis this is equal to 1.03 $MMTCO_2e$/yr.

Forty-eight percent of the burned area and 83% of the emissions were in forest rather than rangeland. Fire incidence varied by year with high emissions in 1996 and low impact in 1993 and 1995. Seventy-nine percent of area burned and 83% of the emissions were from Federally owned land, 18% of the area burned and 13% of the emissions were from private land. Emissions from fire occurred throughout the state but were markedly lower in the northwest.

The emissions from fire of 1.03 $MMTCO_2e$/yr during the 6-year period represented about 1.6% of the total gross emissions for the state of 63 $MMTCO_2e$/yr in 1995 (from Governor's Advisory Group on Global Warming).

Baseline for Agricultural lands

Agricultural land area in Oregon amounts to about 6% of the total land area. The state lost agricultural land area from 1987–1997 through conversion to other land uses, in particular to urban development/transportation and the retiring of agricultural land from cultivation. In some counties, the area of woody cropland actually increased, but these increases were more than offset by decreases in non-woody cropland. Accompanying these losses in area were losses in standing carbon stocks on agricultural land, so that conversion of agricultural land to other uses was responsible for a net annual source (emission) of CO_2 to the atmosphere. Losses of agricultural carbon stocks over the period 1987–1997 period estimated at 160,000 tons. The estimated net annual source from Oregon agricultural lands was 0.06 $MMTCO_2eq$ (Table 18).

Table 18. Summary of agricultural land area and changes in area, carbon stocks and changes in stocks for Oregon 1987–1997

Parameter	Units	Oregon
Proportion of agricultural land of total land	%	5.9
Change in agricultural land area, 1987–1997	Hectares (%)	-75,833 (4.8%)
Change in woody cropland area		-2301 (4.1%)
Change in non-woody cropland area		-73,532 (4.8%)
Total carbon stocks in agricultural land, 1997	$MMTCO_2e$	11.6
Change in carbon stocks in agricultural land,	$MMTCO_2e$	-0.6
Estimated net annual source (emissions) from agricultural lands, disregarding non-CO_2 greenhouse gas emissions	$MMTCO_2e$	-0.06
From woody cropland		-0.02
From non-woody cropland		-0.04
Estimated net annual source from non-CO_2 greenhouse gas emissions, 1995	$MMTCO_2e$	-3.8

Examination of data from Oregon indicated that greenhouse gas emissions from N_2O and CH_4 in the agricultural sector dwarf the annual CO_2 source from agricultural land conversion: CO_2 emissions from land conversion represented about 1% of the total CO_2 and non-CO_2 greenhouse gas emissions attributable to the agricultural sector.

Additional information is found in Appendix IV.

3.6.1.3 Arizona

General Forestlands Baseline

Between 1987 and 1997 there is an estimated increase in forest area in Arizona of 0.5 million acres or a mean of 54,000 ac per year (Table 19). This is equivalent to an increase of 9 $MMTCO_2e$ or 0.92 $MMTCO_2e$/yr between 1987 and 1997.

Table 19. Gross change in forest* area and forest carbon stocks in Arizona

	1987	1997	Annual Change 1987–1997
Area (million ac)	19.4	19.9	0.054
Carbon stock ($MMTCO_2e$)	1,229	1,238	0.92

*Includes all forests, federal and non-federal

This sequestration compares with the estimated sequestration in soil and forests reported by the Arizona Climate Change Advisory Group of 6.7 $MMTCO_2e$ in the year 2000. The estimate here is clearly substantially lower. However, some of this divergence can be accounted for by the inclusion of soil carbon sequestration in the Climate Change Advisory Group analysis. In addition, there is some uncertainty on whether the carbon is artificially inflated due to a USFS change in forest definition from 10% cover to 5% cover in the study period.

The Advisory Group further estimated the gross emissions for Arizona (excluding sinks) for the year 2000 as 99 $MMTCO_2e$. Sinks, therefore, potentially can offset as much as 7% of the state's emissions.

Baseline Effect of Development on Forest Lands

The baseline for emissions from development was created using land use data from the National Resources Inventory of the USDA and carbon data derived from the USFS FIA for the period 1987 to 1997. Due to data limitations the analysis is limited non-federal lands and to the gross CO_2 emissions from aboveground live tree biomass on conversion of non-federal forestland to developed land uses. As the focus is on non-federal lands the analyses should only be used to explore decisions on private lands.

Between 1987 and 1997 3,499 acres of non-federal forest were converted to development. All of this area was located in the north of the state. This is equal to just 350 ac per year. For gross carbon emissions two scenarios were considered. Under Scenario 1, all tree biomass in the converted area was immediately emitted as CO_2. Under Scenario 2 for developed areas of less than 10 acres, it was assumed that 50% of the carbon was retained in the form of residual trees. Under Scenario 1, an estimated 152,000 t CO_2e were emitted due to development or 15,200 t CO_2e/yr. Under Scenario 2, 145,000 t CO_2e were emitted or 14,500 t CO_2e/yr (Table 20).

Table 20. Region-level summary of loss in area and carbon emissions between 1987 and 1997 due to development on non-federal forests. Scenario 2 is more conservative assuming that trees are not clearcut during small-scale development.

	Area lost (ac)	Carbon emissions ($MMTCO_2e$)	
		Scenario 1	Scenario 2
southern	0	0	0
northern	3,500	0.152	0.145

These emissions compare with the estimated gross sequestration from non-federal forests in Arizona of 0.92 $MMTCO_2e$/yr between 1987 and 1997 (see Table 19) and gross emissions for the state of 99 $MMTCO_2e$/yr (from Arizona Climate Change Advisory Group). Emissions from deforestation therefore represent a fraction of a percent of the total emissions in the state.

Baseline Effect of Fire on Forest Lands

The emissions from fire were examined through overlaying the wildfire database for Arizona on AVHRR satellite imagery showing change in NDVI. This process determined the location, size and intensity of fires between 1990 and 1996. Carbon values were applied to these fires using data from the FIA and proportional emissions from the detailed baseline fire analysis for California. The analysis considered all forests and rangelands in Arizona, federal and non-federal.

Across the seven years analyzed fires with a total area of 437,700 hectares (1.08 million acres) were recorded. This is equivalent to 62,500 ha/yr or 154,000 acres/yr. Emissions totaling 904,000 tons of carbon or 3.3 $MMTCO_2e$ were estimated to have occurred from fire during the analysis period. This is equivalent to an emission of 0.47 $MMTCO_2e$/yr.

Eighty-five percent of the burned area was on rangelands but 42% of the emissions were from the 15% of burned area that was forest. Fire incidence varied by year with high emissions in 1993 to 1996 (> 168,000 t C) and low emissions between 1991 and 1992 (< 23,000 t C). Fires occurred throughout Arizona during the study period and there was no apparent geographical relationship between either area burned or carbon emissions from fire and geographic location.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 $MMTCO_2e$/yr between 1987 and 1997 (see above) and gross emissions for the state of 99 $MMTCO_2e$/yr (from Arizona Climate Change Advisory Group). During the analysis period, emissions from fire therefore represented almost 0.5% of the total emissions in the state.

Baseline for Agricultural Lands

Agricultural land area in Arizona amounts to about 1.5% of the total land area. The state lost agricultural land area during 1987–1997 through conversion to other land uses, in particular to urban development/transportation and the retiring of agricultural land from cultivation. In some counties, the area of woody cropland actually increased, but these increases were more than offset by decreases in non-woody cropland. Accompanying these losses in area were losses in standing carbon stocks on agricultural land, so that conversion of agricultural land to other uses was responsible for a net annual source (emission) of CO_2 to the atmosphere. Losses of agricultural carbon stocks over the 1987–1997 analysis period were estimated at 99,000 tons. The estimated net annual source from Arizona agricultural lands was 0.04 $MMTCO_2eq$ (Table 21).

Table 21. Summary of agricultural land area and changes in area, carbon stocks and changes in stocks for Arizona 1987–1997

Parameter	Units	Arizona
Proportion of agricultural land of total land	%	1.5
Change in agricultural land area, 1987–1997	Hectares (%)	-30,759 (6.6%)
Change in woody cropland area		+687 (2.3%)
Change in non-woody cropland area		-31,446 (7.2%)
Total carbon stocks in agricultural land, 1997	$MMTCO_2e$	3.5
Change in carbon stocks in agricultural land,	$MMTCO_2e$	-0.4
Estimated net annual source (emissions) from agricultural lands, disregarding non-CO_2 greenhouse gas emissions	$MMTCO_2e$	-0.04
From woody cropland		-0.02
From non-woody cropland		-0.02
Estimated net annual source from non-CO_2 greenhouse gas emissions, 2000	$MMTCO_2e$	4.2

Examination of data from Arizona indicated that greenhouse gas emissions from N_2O and CH_4 in the agricultural sector dwarf the annual CO_2 source from agricultural land conversion: CO_2 emissions from land conversion represented less than 1% of the total CO_2 and non-CO_2 greenhouse gas emissions attributable to the agricultural sector.

3.6.2 Supply Curves

3.6.2.1 Washington

The state of Washington's lands are classified into three main groups for the analyses: forests, rangelands, and agricultural lands. Forests (about 20.2 million acres) include conifers, hardwoods, and mixed classes; rangelands (about 11.7 million acres) include a variety of non-woody and woody ecosystems; and agricultural lands (about 9.6 million acres) include a wide range of non-woody crops such as wheat and hay and woody crops such as vineyards and orchards.

For rangelands and croplands (lands growing wheat and hay), the potential carbon sequestration was estimated for afforestation using native species. Historical evidence suggests that in many areas, large tracts of forest may have once stood where grazing and agricultural lands now do. The general approach was to identify and locate existing rangelands and croplands where biophysical conditions could favor forests, estimate rates of carbon accumulation for the forest types projected to grow, and assign values to each contributing cost factor. The carbon supply is estimated for three time durations: 20 years, 40 years and 80 years of forest growth, to reflect the impact of activity duration on the likely supply and to provide an assessment for the near-term and longer-term planning horizons.

For forestlands, potential carbon supply was estimated for three alternatives for 20-year and/or permanent contract periods: (1) allowing timber to age past economic maturity (lengthening rotation time); (2) increasing the riparian buffer zone by an additional 200 feet; and (3) hazardous fuel reduction in forests to reduce catastrophic fires, and subsequent use of fuels in biomass power plants. For estimating the costs of allowing timber to age and the costs of enhanced riparian zone management, estimates are based on specific counties for public and private landowners, and then extrapolated to all counties throughout the state. For the fuel reduction alternative, the analysis used a "Suitability for Potential Fuel Reduction" (SPFR) score on forest landscapes where potential exists for significant carbon loss from moderate to high intensity wildland fires. The SPFR scores were created in a GIS using slope, distance to biomass plants, and distance from roads as equal weighted factors in the decision-making process.

Table 22 summarizes the amount of carbon and the area available for afforestation of range and crop lands at three commonly used price points: ≤ \$2.40/t CO_2 (\$8.81/t C), ≤ \$10.00/t CO_2 (\$36.67/t C), and ≤\$20.00/t CO_2 (\$73.33/t C). At a price of \$2.40/t CO_2, no carbon could be sequestered by afforesting rangelands and croplands at 20 and 40 years but the amount reaches about 1,399 MMT CO_2 at 80 years (Table 22). If prices per t CO_2 rose to \$20 it is possible to convert more productive range and crop lands with higher opportunity costs and sequestering almost 289 MMT CO_2 carbon even with a 20-year time duration, and the total amount rises sharply to more than 1,233 MMT CO_2 at 40 years and approximately 3,176 MMT CO_2 at 80 years (Table 22). Converting this total amount at 40 years to an approximate annual rate results in about 31 MMT CO_2/yr.

Although Washington has substantial areas of forests, the cost of carbon sequestration from changing forest management practices is relatively high and the quantity of carbon that could be sequestered is relatively small. All of the carbon available at prices of less that \$10/t CO_2 for extending rotations by 5 years is located on non-federal public lands; only when prices reach between \$10-20/t CO_2 do private lands generate potential carbon credits. If all of the private and non-federal public land nearing the economically optimal rotation period (1.46 million acres) were contracted to increase rotation ages by up to 15 years, 61.6 MMT CO_2 could be sequestered for average costs of \$37/t CO_2.

The potential area of mature forests where the riparian buffer zone could be increased by an additional 200 feet was estimated at 34,9000 acres. The additional carbon that could be stored on these lands if the forests were conserved is 2.2 MMT CO_2 at an average cost of \$33.3/t CO_2.

Table 22. Summary of the quantity of carbon (million metric tons CO_2 [MMT CO_2]) and area (million acres) available at selected price points (\$/t CO_2) for afforestation of existing rangelands and croplands over 20-year, 40-year, and 80-year durations.

Activity	Quantity of C—MMT CO_2			Area available—million acres		
	20 years	40 years	80 years	20 years	40 years	80 years
Rangelands-Afforestation						
≤\$2.40	0.0	0.0	1,399	0.0	0.0	3.1
≤\$10.00	0.0	877.9	2,153	0.0	4.3	6.2
≤\$20.00	279.4	1,178	2,450	4.2	8.8	8.9
Croplands-Afforestation						
≤\$2.40	0.0	0.0	14.4	0.0	0.0	0.0
≤\$10.00	0.0	0.0	140.5	0.0	0.3	0.3
≤\$20.00	9.8	54.9	725.9	0.1	1.4	5.5

From the forest hazardous fuel reduction analysis, the area of Washington forests with historically low-severity and mixed-severity (HLS-HMS) fire regimes is estimated to be 3.3 million acres. A commonly used potential hazardous fuels treatment is "Cut-Skid-Chip-Haul" (CSCH), a treatment in which hazardous fuel is harvested in the woods, bunched and skidded to a landing, chipped into a chip van, and hauled to a biomass energy facility for electricity and/or heat generation. The area of forestlands with HLS-HMS fire regimes in the state to which this treatment could be applied is approximately 1.2 million acres. Two removal scenarios were analyzed: hazardous fuel reduction (HFR) removal of 4 bone dry tons (BDT)/acre on these lands would yield 5 million BDT biomass fuel for use in energy facilities, while removal of 8 BDT/acre would yield 10 million BDT. Total estimated costs and potential revenue from these removals was analyzed. During moderate to intense fires, 10-70% of the biomass stock burns and is emitted as CO_2. A preliminary analysis suggested that considering the differences in CO_2 emissions between high-, medium- and low-intensity fires, HFR treatments that reduced fire intensity would avoid sufficient emissions to be able to cover, at commonly used prices for carbon of \$2.40/t CO_2 and \$10/t CO_2, the subsidies needed to pay for CSCH, adding support to the argument for qualifying fuel reduction activities as carbon offset projects.

Additional information is found in Appendix XXI.

3.5.2.2 Oregon

The state of Oregon's lands are classified into three main groups: forests, rangelands, and agricultural lands. Forests (about 26.1 million acres) include conifers, hardwoods, and mixed classes; rangelands (about 27 million acres) include a variety of non-woody and woody ecosystems; and agricultural lands (about 6.4 million acres) include a wide range of non-woody crops such as wheat and hay and woody crops such as vineyards and orchards.

For rangelands and croplands (lands growing wheat and hay), the potential carbon sequestration was estimated for afforestation using native species with no subsequent harvesting (*i.e.,* for restoration). Historical evidence suggests that in many areas, large tracts of forest may have once stood where grazing and agricultural lands now do. The general approach was to identify and locate existing rangelands and croplands where biophysical conditions could favor forests, estimate rates of carbon accumulation for the forest types projected to grow, and assign values to each contributing cost factor. The carbon supply is estimated for three time durations: 20 years, 40 years and 80 years of forest growth, to reflect the impact of activity duration on the likely supply and to provide an assessment for the near–term and longer-term planning horizons.

For forestlands, potential carbon supply was estimated for three alternatives: (1) allowing timber to age past economic maturity (lengthening rotation time); (2) increasing the riparian buffer zone by an additional 200 feet; and (3) hazardous fuel reduction in forests to reduce catastrophic fires, and subsequent use of fuels in biomass power plants. For estimating the costs of allowing timber to age and the costs of enhanced riparian zone management, estimates are based on specific counties for public and private landowners, and then extrapolated to all counties throughout the state. For the fuel reduction alternative, the analysis used an SPFR score on forest landscapes where potential exists for significant carbon loss from wildfires. Suitability scores for potential fuel reduction with highest suitability were assigned to areas with gentle grades of slope that are close to roads and biomass power plants.

Table 23 summarizes the amount of carbon and the area available for afforestation of rangelands and croplands at three price points: ≤ \$2.40/t CO_2 (\$8.81/t C), ≤ \$10.00/t CO_2 (\$36.67/t C), and ≤\$20.00/t CO_2 (\$73.33/t C). At a price of ≤ \$2.40/t CO_2, the no carbon can be sequestered after 20 years by afforesting rangelands and croplands, but after 80 years about 732 MMT CO_2 could be sequestered on rangelands (Table 23). If prices per t

CO_2 rose to $20 it is possible to convert more productive range and crop lands with higher opportunity costs and sequestering almost 280 MMT CO_2 carbon even with a 20-year time duration, and the total amount rises sharply to more than 1,813 MMT CO_2 at 40 years and approximately 4,203 MMT CO_2 at 80 years (Table 23). Converting this total amount at 40 years to an approximate annual rate results in about 45 MMT CO_2/yr.

Although Oregon has substantial areas of forests, the cost of carbon sequestration from changing forest management practices is relatively high and the quantity of carbon that could be sequestered is relatively small. If all of the private and non-federal public land nearing the economically optimal rotation period (790 thousand acres) were contracted to increase rotation ages up to 15 years, 35.6 MMT CO_2 could be sequestered for average costs of $37/t CO_2.

The potential area of mature forests where the riparian buffer zone could be increased by an additional 200 feet was estimated at 20,700 acres. The additional carbon that could be stored on these lands if the forests were conserved is 1.25 MMT CO_2 at an average cost of $40/t CO_2.

Table 23. Summary of the quantity of carbon (million metric tons CO_2 [MMT CO_2]) and area (million acres) available at selected price points for afforestation on existing rangelands and croplands of Oregon over 20-year, 40-year, and 80-year durations.

	Quantity of C—MMT CO_2			Area available—million acres		
Activity	**20 years**	**40 years**	**80 years**	**20 years**	**40 years**	**80 years**
Rangelands-Afforestation						
≤$2.40	0.0	0.489	732.2	0.0	0.001	1.4
≤$10.00	0.195	337.3	2,156	0.001	1.42	12.3
≤$20.00	117.7	1,336	2,827	1.40	15.6	19.1
Croplands-Afforestation						
≤$2.40	0.0	0.0	0.0	0.0	0.0	0.0
≤$10.00	0.279	457.2	997.9	0.002	1.91	1.93
≤$20.00	162.0	477.2	1,376	1.91	2.15	5.06

From the forest hazardous fuel reduction analysis, the area of Oregon forests with historically low and mixed severity fire regimes, yet mapped today as containing high quantities of hazardous fuel, is estimated to be 10.3million acres. The area of forestlands with historically low and mixed severity fire regimes in the state to which CSCH could be applied is approximately 2.9 million acres. Two removal scenarios were analyzed: HFR removal of 4 BDT/acre on these lands would yield 12 million BDT biomass fuel for use in energy facilities, while removal of 8 BDT/acre would yield 23 million BDT. Total estimated costs and potential revenue from these removals was analyzed. During moderate to intense fires, 10-70% of the biomass stock burns and is emitted as CO_2. A preliminary analysis suggested that considering the differences in CO_2 emissions between high-, medium- and low-intensity fires, HFR treatments that reduced fire intensity would avoid sufficient emissions to be able to cover, at commonly used prices for carbon of \$2.40/t CO_2 and \$10/t CO_2, the subsidies needed to pay for CSCH, adding support to the argument for qualifying fuel reduction activities as carbon offset projects.

Additional information is found in Appendix XXI.

4 Conclusions

Both terrestrial and geologic sequestration options were evaluated in the WESTCARB Region during the 18-month Phase I project. A centralized GIS database of stationary source, geologic and terrestrial sink data was developed. The GIS layer of source locations was attributed with CO_2 emissions and other data and a spreadsheet was developed to estimate capture costs for the sources in the region. Phase I characterization of regional geological sinks shows that geologic storage opportunities exist in the WESTCARB region in each of the major technology areas: saline formations, oil and gas reservoirs, and coal beds. California offers outstanding sequestration opportunities because of its large capacity and the potential of value-added benefits from enhanced oil recovery (EOR) and enhanced gas recovery (EGR). The estimate for storage capacity of saline formations in the ten largest basins in California ranges from about 150 to about 500 Gt of CO_2, the potential CO_2-EOR storage was estimated to be 3.4 Gt, and the cumulative production from gas reservoirs suggests a CO_2 storage capacity of 1.7 Gt. . More detailed characterization and further refinement of capacity estimates will be carried out in Phase II. A GIS-based method for source-sink matching was implemented and preliminary marginal cost curves developed, which showed that 20, 40, 80 Mt of CO_2 per year could be sequestered in California at a cost of \$31/t, \$35/t, or \$50t, respectively. Additional work on marginal costs for geologic sequestration in WESTCARB will be carried out in Phase II. Phase I also addressed key issues affecting deployment of CCS technologies, including storage-site monitoring, injection regulations, and health and environmental risks. A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of HSE risk was developed. A web-based, state-by-state compilation of current regulations for injection wells, and permits/contracts for land use changes, was developed, and modeling studies were carried out to assess the application of a number of different geophysical techniques for monitoring geologic sequestration. Public outreach activities resulted in heightened awareness of sequestration among state, community and industry leaders in the Region. Assessment of the changes in carbon stocks in agricultural lands showed that Washington, Oregon and Arizona were CO_2 sources for the period from 1987 to 1997. Over the same period, forest carbon stocks decreased in Washington, but increased in Oregon and Arizona. Results of the terrestrial supply curve analyses showed that afforestation of rangelands and crop lands offer major sequestration opportunities; at a price of \$20 per t CO_2, more than 1,233 MMT could be sequestered over 40-years in Washington and more than 1,813 MMT could be sequestered in Oregon.

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Appendixes

The following appendixes are the paper (*i.e.*, not digital) deliverables for DOE contract number DE-FC26-03NT41984, “West Coast Regional Carbon Sequestration Partnership Phase I”. Digital copies of most deliverables are included on a CD-ROM packaged with this report.

Information on each appendix is outlined in Table 24. Because each appendix is an individual deliverable, the page numbering for each appendix begins anew for each document.

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PLEASE NOTE THAT THE APPENDICES ARE NOT AVAILABLE FROM THE CALIFORNIA ENERGY COMMISSION’S PIER PROGRAM'S WEBSITE.

Most appendices will be published separately by the PIER Program in the near future.

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