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Final Scientific/Technical Report

Capture and Sequestration of CO_2 at the Boise White Paper Mill

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Abstract

This report documents the efforts taken to develop a preliminary design for the first commercial-scale CO_2 capture and sequestration (CCS) project associated with biomass power integrated into a pulp and paper operation. The Boise Wallula paper mill is located near the township of Wallula in Southeastern Washington State. Infrastructure at the paper mill will be upgraded such that current steam needs and a significant portion of the current mill electric power are supplied from a 100% biomass power source. A new biomass power system will be constructed with an integrated amine-based CO_2 capture plant to capture approximately 550,000 tons of CO_2 per year for geologic sequestration. A customized version of Fluor Corporation's Econamine Plus™ carbon capture technology will be designed to accommodate the specific chemical composition of exhaust gases from the biomass boiler.

Due to the use of biomass for fuel, employing CCS technology represents a unique opportunity to generate a net negative carbon emissions footprint, which on an equivalent emissions reduction basis is 1.8X greater than from equivalent fossil fuel sources (SPATH and MANN, 2004). Furthermore, the proposed project will offset a significant amount of current natural gas use at the mill, equating to an additional 200,000 tons of avoided CO_2 emissions. Hence, the total net emissions avoided through this project equates to 1,100,000 tons of CO_2 per year. Successful execution of this project will provide a clear path forward for similar kinds of emissions reduction that can be replicated at other energy-intensive industrial facilities where the geology is suitable for sequestration.

This project also represents a first opportunity for commercial development of geologic storage of CO_2 in deep flood basalt formations. The Boise paper mill site is host to a Phase II pilot study being carried out under DOE's Regional Carbon Partnership Program. Lessons learned from this pilot study and other separately funded projects studying CO_2 sequestration in basalts will be heavily leveraged in developing a suitable site characterization program and system design for permanent sequestration of captured CO_2. The areal extent, very large thickness, high permeability in portions of the flows, and presence of multiple very low permeability flow interior seals combine to produce a robust sequestration target. Moreover, basalt formations are quite reactive with water-rich supercritical CO_2 and formation water that contains dissolved CO_2 to generate carbonate minerals, providing for long-term assurance of permanent sequestration. Sub-basalt sediments also exist at the site providing alternative or supplemental storage capacity.

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Executive Summary

The overall objective of the Boise White Paper Carbon Capture and Sequestration Project (BCCS Project) is to demonstrate the first commercial-scale CO_2 capture and sequestration (CCS) project associated with the pulp and paper production industry. The Boise White Paper Mill is located near the township of Wallula in Southeastern Washington State. Infrastructure at the paper mill will be upgraded to provide additional steam to support the CO_2 capture plant, and to provide auxiliary electricity to offset current power usage at the plant. A new hog fuel boiler and power generation island will be integrated with an amine-based CO_2 capture plant to capture and compress over 545,000 MT of CO_2 per year. With a primarily bio-based fuel source, employing CCS technology at the Boise White Paper Mill represents a unique opportunity to generate a net negative carbon emissions footprint. The proposed plant upgrades will also offset current natural gas use at the mill, which represents an additional 145,000 tons of CO_2 emissions avoided. Total emissions avoided for the Boise White Paper Mill are expected to be in excess of 1.1 kilotons per year. For the Phase 1 study, Fluor Corporation has designed a customized version of their Econamine Plus™ carbon capture technology for operation with the specialized chemical composition of exhaust gases produced from hog fuel boilers. Integration of the CO_2 capture system with the paper mill operations is planned to minimize operating costs of the capture system.

This project also represents a first opportunity for commercial development of geologic storage of CO_2 in deep flood basalt formations. The Boise White Paper Mill site is host to a Phase 2 pilot study being carried out under DOE's Regional Carbon Partnership Program. Lessons learned from this pilot study and other separately funded projects studying CO_2 sequestration in basalts are being heavily leveraged to develop a suitable site characterization program and system design for permanent sequestration of the 545 kilotons of CO_2 proposed to be captured per year at the plant. The areal extent, very large thickness, high permeability in portions of the flows, and presence of multiple very low permeability flow interior seals combine to produce a robust sequestration target. Moreover, basalt formations are quite reactive with water-rich supercritical CO_2 and formation water that contains dissolved CO_2 to generate carbonate minerals, providing for long-term assurance of permanent sequestration. Sub-basalt sediments also exist at the site providing alternative or supplemental storage capacity.

The proposed amine-based CO_2 capture technology requires a variable steam load based on the total CO_2 capture rate. The Boise White Paper Mill has a high intrinsic steam demand and cannot accommodate the steam demands of the capture system in its present configuration. Therefore, several plant modifications are proposed as part of the overall design process. The primary plant modification involves the installation of a high-capacity, high-efficiency, fluidized bed hog fuel boiler to feed the steam demand of both the capture system and the mill's paper production needs. The new hog fuel boiler is expected to generate 72 tons CO_2/hr. The entire flue gas stream from this new boiler would be routed to the CO_2 capture and compression plant. With a capture efficiency of 90%, 65 tons CO_2/hr would be captured, resulting in a net return of 7 tons/hr to the atmosphere. Assuming continuous operation 350 days/year, this system would result in a capture and injection rate in excess of 545,000 tons/year.

To further enhance the efficiency of the Boise White Paper Mill, a new steam turbine generator will be used to recover energy from the boiler's high pressure steam output as its pressure is lowered for use in other mill operations. The steam turbine generator will have a gross electrical output of 23.7 MW/h, of which, 11.2 MW/h will be returned to the mill to offset usage from the local power grid. The remaining 12.5 MW/h will be used to power the CO_2 capture and compression plant.

A key attribute of this design is its proposed location. The new boiler, steam turbine generator, and CO_2 capture and compression plant would be constructed on undeveloped land owned by Boise adjacent to the existing mill. Steam lines would be built to tie the new boiler into the existing mill infrastructure. This conceptual design will facilitate construction while minimizing impact to mill operations. Phase 2 will be divided into three subcategories: Phase 2a,2b, and 2c. Phase 2a is expected to last 18 months and will be used to perform detailed characterization at the proposed injection site, drill the 12,000 foot deep injection well, and initiate orders for components requiring long lead-times. Phase 2b will have a duration of 3 years and will be the primary construction phase of the project. During this time, the new boiler and steam turbine generator will be installed, the CO_2 capture and compression plant will be built, and infrastructure tiles will be made to the existing paper mill. Additionally, the approximately 5 mile-long, 8 $^5/_8$ inch diameter CO_2 transport pipeline will be constructed between the compression plant and injection well. The final year of this five-year long project will be used to demonstrate operation of the CO_2 capture and compression plant, CO_2 injection, and performance of the monitoring, verification, and accounting program. It is anticipated that over 545,000 tons of CO_2 will be sequestered over this demonstration period, with a total emissions avoidance impact of more than 1.1 MMT tons of CO_2.

Anticipated environmental impacts for the proposed project are primarily positive. The new energy efficient fluidized bed boiler will replace one older 1950s era hog fuel boiler and two natural gas fired boilers at the Boise White Paper Mill. The new boiler can accommodate a wider variety of agricultural waste, enabling greater reuse of material that would otherwise be landfilled. Via the addition of a steam turbine generator, the hog fuel boiler will become a source of green energy that will be used to offset power demands of the CO_2 capture plant and existing mill operations. Additionally, capture and sequestration of CO_2 resulting from burning of biofuels results in a truly negative CO_2 footprint. By replacing the existing steam generating boilers with a new efficient hog fuel boiler tied to a CCS system, annual CO_2 emissions at the plant are expected to decrease by more than 40%. Finally, use of the amine-based capture system will make the plant a better neighbor since an important commercial side benefit is the removal of reduced sulfur compounds currently causing the odors associated with effluents from the mill.

1.0 Introduction

The overall objective of the Boise White Paper Carbon Capture and Sequestration Project (BCCS Project) is to demonstrate the first commercial-scale CO_2 capture and sequestration (CCS) project associated with the pulp and paper production industry. The Boise paper mill is located near the township of Wallula in Southeastern Washington State. Infrastructure at the paper mill will be upgraded to provide additional steam to support the CO_2 capture plant and to provide auxiliary electricity to offset current power usage at the plant. A new hog fuel boiler will be integrated with an amine-based CO_2 capture plant to capture approximately 550,000 MT of CO_2 per year. Due to the majority use of biomass for fuel, employing CCS technology with paper production represents a unique opportunity to generate a net negative carbon emissions footprint, which on an equivalent emissions reduction basis is 1.8X greater (SPATH and MANN, 2004) or 0.98 MMT CO_2 equivalent from fossil fuel sources. The upgrades will also offset current natural gas use at the mill, which represents an additional 145,000 tons of CO_2 emissions avoided. Hence, the total net emissions reduction for this project is just over 1.16 MMT of CO_2 per year. Successful execution of this project will provide a clear path forward for similar kinds of emissions reduction that can be replicated at other paper production plants where the geology is suitable for sequestration. For the Phase 1 study, Fluor Corporation has designed a customized version of their Econamine Plus™ carbon capture technology for operation with the specialized chemical composition of exhaust gases produced from the hog fuel boiler. Integration of the CO_2 capture system with the paper mill operations is planned to minimize operating cost of the capture system.

This project also represents a first opportunity for commercial development of geologic storage of CO_2 in deep flood basalt formations. The Boise paper mill site is host to a Phase 2 pilot study being carried out under DOE's Regional Carbon Partnership Program. Lessons learned from this pilot study and other separately funded projects studying CO_2 sequestration in basalts will be heavily leveraged in developing a suitable site characterization program and system design for permanent sequestration of the 230 kilotons of CO_2 captured per year at the plant. The areal extent, very large thickness, high permeability in portions of the flows, and presence of multiple very low permeability flow interior seals combine to produce a robust sequestration target. Moreover, basalt formations are quite reactive with water-rich supercritical CO_2 and formation water that contains dissolved CO_2 to generate carbonate minerals, providing for long-term assurance of permanent sequestration. Sub-basalt sediments also exist at the site providing alternative or supplemental storage capacity.

The State of Washington where this project is located is one of the United States most progressive states on CO_2 policy and carbon sequestration standards. On May 3, 2007, ESSB 6001 was signed into law which established emissions reductions goals for the State to 25 percent below 1990 levels by 2035. This was followed in July of 2008 with enactment of specific rules in the State's UIC program for permitting commercial-scale geologic sequestration projects. Hence, this project aligns with the State's goals and leadership position on the environment while protecting Washington State businesses and jobs. With a CO_2 emissions rate of 0.04 GT per year, execution of this project alone would represent an emissions reduction of over 3% of WA State's total emissions.

2.0 Boise White Paper Mill Operations

The Boise paper mill is situated approximately 15 miles south of Pasco, Washington adjacent to the Columbia River in a general area that is lightly inhabited and on private property owned by Boise White Paper, L.L.C. in western Walla Walla County, within eastern Washington State (Figure 2.1).

2.1 Boise Paper Mill

The Boise Wallula mill was built in 1958 and now employs approximately 400 people. The average total mill production is 1200 tons per day and includes bleached paper, fine paper, coated paper, and corrugated medium. The facility has five boilers, six pressure headers, several mechanical drive steam turbines, and three paper machines. The boilers include two Kraft recovery boilers (black liquor and supplemental natural gas), one hog fuel boiler (bark, chips, and supplemental natural gas), and two conventional, gas-fired power boilers. The rotary lime kiln burns both natural gas and reclaimed oil. More than one million tons of CO_2 are emitted from the Boise White Paper Mill annually. Approximately 25% of the CO_2 emissions are from fossil fuel sources – primarily natural gas – and the remaining are from wood feed components.

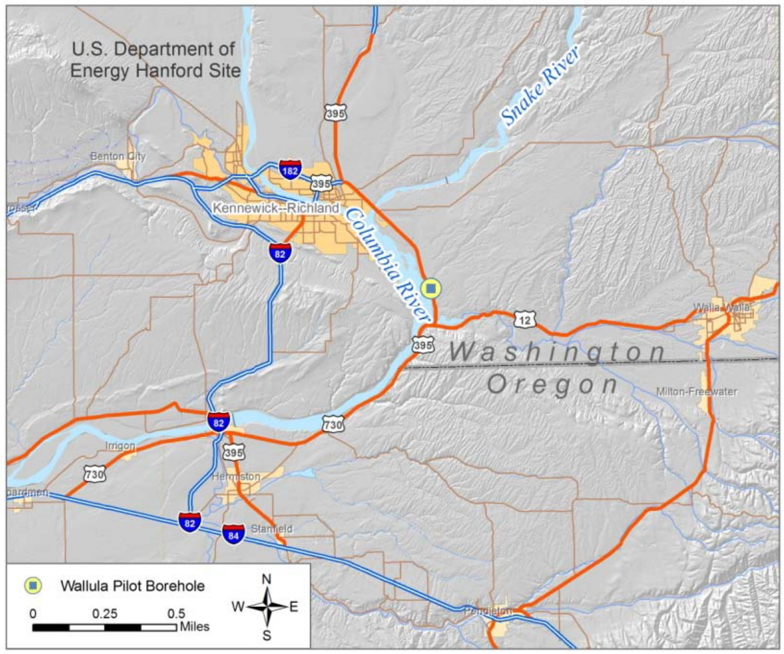

Figure 2.1. Regional Location Map of Boise Paper Mill and Co-located Pilot Test Site of Regional Carbon Partnership Program.

2.2 Regional Setting

Within a general area of approximately 10 miles around the Boise paper mill, irrigated agriculture is the predominant land use. A commercial feedlot operation and refrigerated freight train distribution center are the major industries in the area besides the Boise paper mill. Three townships are within this same radius and include Wallula, population 236, located approximately 2 miles south of the paper mill, and Burbank and Finley, populations 3,461 and 6,427, respectively located approximately 8 miles to the NW. The closest major population centers are the city of Pasco, population 55,246, and Kennewick, population 63,216. Figure 2.2 provides a satellite image of the general area where the project would be located. As will be discussed in greater detail later, the most likely suitable sequestration site area is located to the NE of the paper mill due to more favorable surface and subsurface geological conditions in that area.

Figure 2.2. Satellite image of area surrounding Boise paper mill. White circle is 10 mi radius around the plant. The Columbia River is the major river near the plant site.

3.0 Project Design

The Boise Wallula mill currently emits a total of 1.2 million tons of CO_2 annually. Approximately 25% of the CO_2 emissions are from fossil fuel sources – primarily natural gas – and the remaining are from wood feed components. The plant utilizes a primary recovery boiler (720,000 tons of CO_2 per year), a smaller recovery boiler (150,000 tons/yr), and a bark, or hog-fuel, boiler (350,000 tons/yr).

Based on the CO_2 emissions breakdown, the Phase 1 application was developed with a focus on capturing and sequestering CO_2 from the primary recovery boiler. Here, Fluor's Econamine FG Plus technology was to be integrated into the primary recovery boiler exhaust stack to achieve the target capture rate. The Econamine system was to be powered with an auxiliary natural gas boiler system. The net CO_2 reduction from CCS was determined to be enough, such that revenue from forecasted carbon credits could adequately payback the cost share capital and system operating costs.

However, during the time between the Phase 1 application submission and early stages of project definition, the uncertainty around U.S. carbon legislation timing had grown. After the inconclusive climate change conference in Copenhagen, the prospect of continuing uncertainty in the ability to adequately monetizing CO_2 emission reductions credits was too great to receive Boise management approval to proceed with the project. As a result, the project team worked diligently to identify an alternate project concept that would achieve the DOE project goals, while still producing an economically viable operation, despite the risks in carbon legislation timing. The following sections describe the two primary project design options considered for implementation during Phase 2.

3.1 Plant Design: Scenario 1

The first scenario involves replacing the plant's primary hog fuel boiler, a 1970's vintage Kipper stationary grate hog fuel boiler used for steam supply only, with a much larger and more efficient biomass fuel boiler. A key attribute of this design is its location adjacent to the existing mill, which would facilitate construction while minimizing impact to mill operations. This boiler could supply the current plant steam needs along with the CO_2 capture plant steam, and 15 MW of incremental electrical power for use at the Boise mill site or for external sale. In this configuration only CO_2 emitted from the new biomass boiler would be subsequently captured and sequestered, due to capital cost constraints. A total CO_2 capture rate of 550,000 tons per year is currently targeted for the system. With this configuration operating the CCS system would be strictly tied to carbon tax revenue thresholds. If those thresholds were not yet met the operation would be capable of operating without CCS and using the incremental steam supply to produce an additional 15MW of electric power (30MW total).

The new hog fuel boiler in scenario 1 is expected to generate 72 tons/hr CO_2, all of which would be routed to the CO_2 capture and compression plant. With a capture efficiency of 90%, 65 tons/hr CO_2 would be captured, resulting in a net return of 7 tons/hr to the atmosphere. Assuming continuous operation 350 days/year, scenario 1 would result in a capture and injection rate in excess of 545,000 tons/year.

3.2 Plant Design: Scenario 2

The plant design considered under scenario 2 involves upgrading the plant's primary hog fuel boiler to allow it to burn fuel with higher ash content. Additionally, a smaller hog fuel boiler would be added to the mill to generate steam for the CO_2 capture plant. Under this scenario, the new smaller hog fuel boiler and CO_2 capture plant would be sited on Boise property within the existing mill footprint. The new hog fuel boiler would have approximately 25% less capacity than Boise's existing hog fuel boiler, and would supply steam solely to operate the CO_2 capture plant. A shortcoming of this design is its location within the existing mill, which is already congested. Additionally, this design would only generate up to 7.4 MW/h of auxiliary power for plant use or resale on the power grid.

The existing hog fuel boiler at the Boise White Paper Mill generates 38.3 tons/hr CO_2. The new supplemental hog fuel boiler in this scenario is expected to generate an additional 32.1 tons/hr CO_2. Combined, these two boilers would still not equal the single largest CO_2 emission source at the plant, the #3 Recovery Furnace at 102.3 tons/hr. Only CO_2 from the new supplemental hog fuel boiler would be routed to the CO_2 capture plant. With a capture efficiency of 90%, 28.9 tons/hr CO_2 would be captured, resulting in a net return of 3.2 tons/hr to the atmosphere. Assuming continuous operation 350 days/year, this scenario would result in a capture and injection rate of just less than 250,000 tons/year.

3.3 Proposed Phase 2 Plant Design

Both scenarios considered as part of the Phase 2 application process require significant modification to the existing plant design at the Boise White Paper Plant. A key attribute of scenario 1 is its proposed location. By constructing the plant on undeveloped land adjacent to the existing mill, construction of the entire power island and capture plant could be complete prior to taking the existing hog fuel boiler offline. This scenario would minimize downtime for the paper mill and simplify the construction process. Another advantage of scenario 1 is that it is modeled after a reference plant recently developed within the US. Modeling the plant after an existing design will significantly reduce cost and schedule to the project. Finally, scenario 1 would enable a total annual CO_2 emissions avoidance in excess 1 MMT to be achieved by the project. These attributes, coupled with the inability of scenario 2 to meet the U.S. DOE's emissions reductions goal for the ICCS projects, scenario 1 was selected for comprehensive design analysis and ultimately construction during Phase 2.

3.3.1 Biomass Power Description

The biomass power plant being proposed is of similar size to a reference plant under construction within the US. The reference system is capable of producing a nominal 55.5 MW net of electrical power through the use of a highly efficient bubbling fluidized bed (BFB) boiler, which is ideal for combusting woody biomass materials. The electrical output of the system is a gross nominal 62 MW. The net output takes into account electrical demands required by plant operations, which can vary depending on plant operations and climate conditions. The system incorporates into its design proven and highly efficient control technologies and techniques for the reduction of potential emissions of air pollutants. The primary fuel for the proposed BFB boiler is limited to clean woody biomass, with natural gas, propane, or ultra low sulfur distillate fuel to be utilized only for boiler startup, shutdown and boiler bed stabilization.

The power plant will involve four (4) specific process areas. These process areas include:

- Fuel (i.e., woody biomass) receiving, handling, storage and processing;
- Power Island, including a bubbling fluidized bed boiler and steam turbine /generator;
- Ash (i.e., fly and bottom) handling, storage and shipment; and
- Emergency support equipment.

The bubbling fluidized bed (BFB) boiler used proposed for use is proven to be efficient at combusting clean woody biomass. The clean wood can be untreated wood or untreated wood products including clean untreated lumber, tree stumps (whole or chipped), and tree limbs (whole or chipped) and slash. This also includes, but is not limited to, wood, wood residue, bark, or any derivative fuel or residue thereof, in any form, including but not limited to sawdust, sander dust, wood chips, scraps, slabs, millings, shavings, and processed pallets made from wood or other forest residues.

The maximum design heat input of the propsed boiler while combusting woody biomass at 55% moisture is approximately 758 MMBtu/hr (24-hour average). The moisture content of the fuel affects the heat input of the boiler. A fluid-like mixture of solid fuel (such as sand) is suspended in the BFB boiler's combustion chamber by a turbulent upward air flow. The turbulent mixing provides for greater chemical reaction efficiency in the BFB boiler. The prposed boiler utilizes proven and efficient control devices/techniques to minimize potential emissions of regulated air pollutants. These typically include a fabric filter (baghouse) for particulate emissions control, and dry in-duct sorbent Injection for sulfur dioxide and acid gas control.

3.3.2 Infrastructure Impacts at the Wallula Mill

The new biomass boiler is planned to be installed on undeveloped land adjacent to the Boise White Paper mill. The land is owned by Boise White Paper, LLC and is currently used as a storage facility for mill equipment and pulp bales. Steam, water, and sewer lines are present on the proposed construction site and will allow easy connections for the necessary utilities to and from the new biomass cogeneration plant and the Boise paper manufacturing facility.

The flue gas from the new boiler will be directed to the carbon capture plant, where the CO_2 will be captured and compressed. The new boiler will generate up to 560 kpph of 1,000 psig / 900°F steam. If all of the steam is sent through the back pressure turbine, a total of 35 MW of power would be generated, along with 350 kpph of steam at 250 psig/ 500°F that would offset current mill steam requirements presently supplied by the existing hog-fuel and natural gas boilers. With the CCS system in operation, the net electrical output reduces to 11.2 MW of electric power and the same mill steam supply.

3.3.3 CO_2 Capture Technology

The CO_2 capture plant for the Boise site is centered on the Econamine FG Plus^{SM} (EFG+) technology for the capture of CO_2 from the new BFB boiler. The EFG+ system is designed to capture 90% of the CO_2 contained in the flue gas.

4.0 Site Geology

Southeastern Washington State, and indeed a large portion of the entire Pacific Northwest east of the Cascade Mountain Range belong to the Columbia Plateau Province, which hosts a world-class set of continental flood basalt deposits. The Miocene Columbia River Basalt Group (CRBG) covers over 77,200 mi^2 of portions of eastern Washington, northeastern Oregon and western Idaho (Figure 4.1), with a total estimated volume of more than 53,700 mi^3 (REIDEL et al., 2002). Collectively, over 300 individual CRBG flows have been mapped within the region, with a maximum composite thickness of greater than 5,000 ft within the central portion of the Columbia Basin (Figure 4.2). Brecciated flow tops of the CRBG form regional aquifers, and are targets for sequestration of anthropogenic CO_2 in areas where the basalts contain nonpotable water and are at depths greater than 2400 feet. Conservative estimates of CO_2 storage capacity in the CRBG are approximately 10 to 50 $GtCO_2$ (MCGRAIL et al., 2006). Groundwaters within the Grande Ronde Basalt and below in this region of the Columbia Basin have high pH and contain high concentrations of fluoride that exceed maximum concentration limits (MCL) as specified in the National Primary Drinking Water Regulations (40 CFR 141.62). Exceedance of MCLs listed in 40 CFR 141.62 is the standard adopted in Washington State for permitting geologic sequestration projects under WAC 173-218-115.

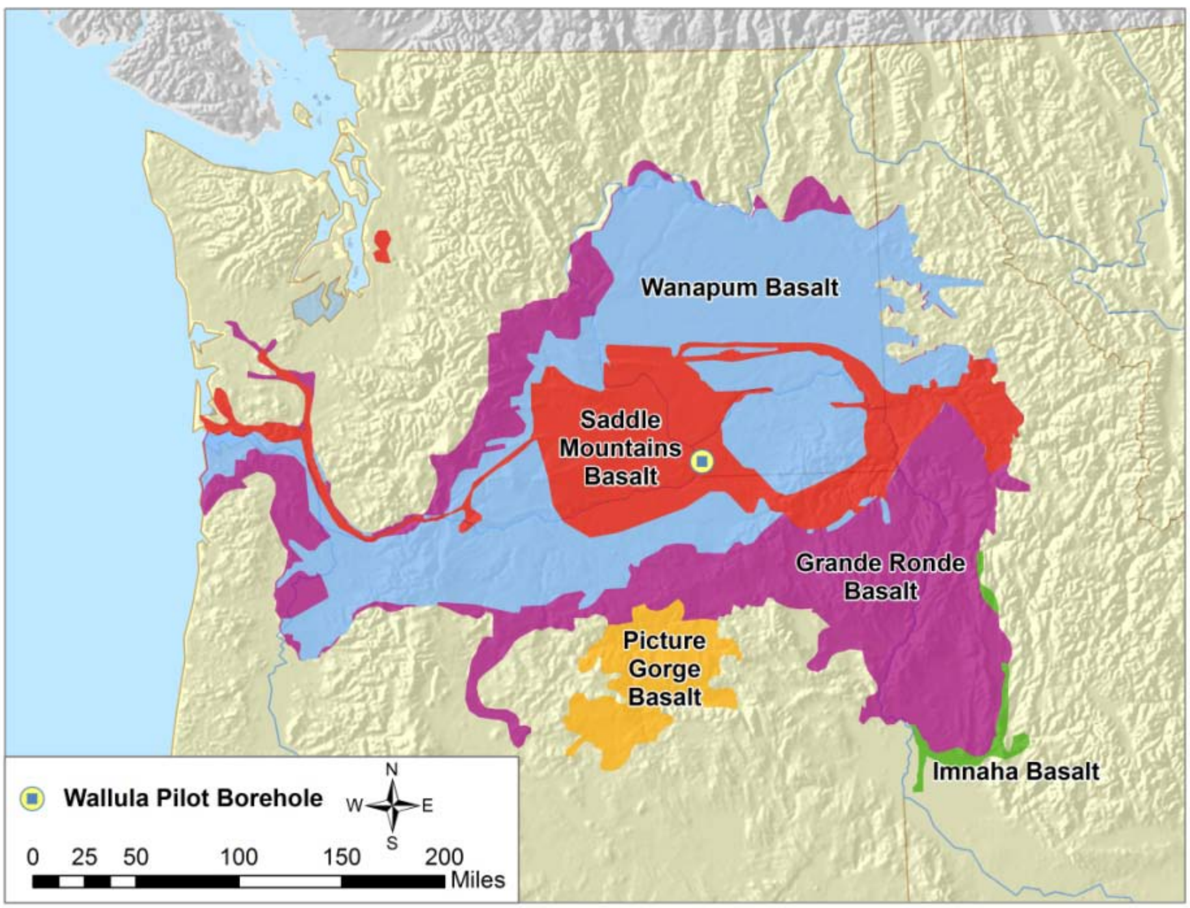

Figure 4.1. Surface Areal Extent of Basalt Formations of the Columbia River Basalt Group (modified from Reidel et al., 2002)

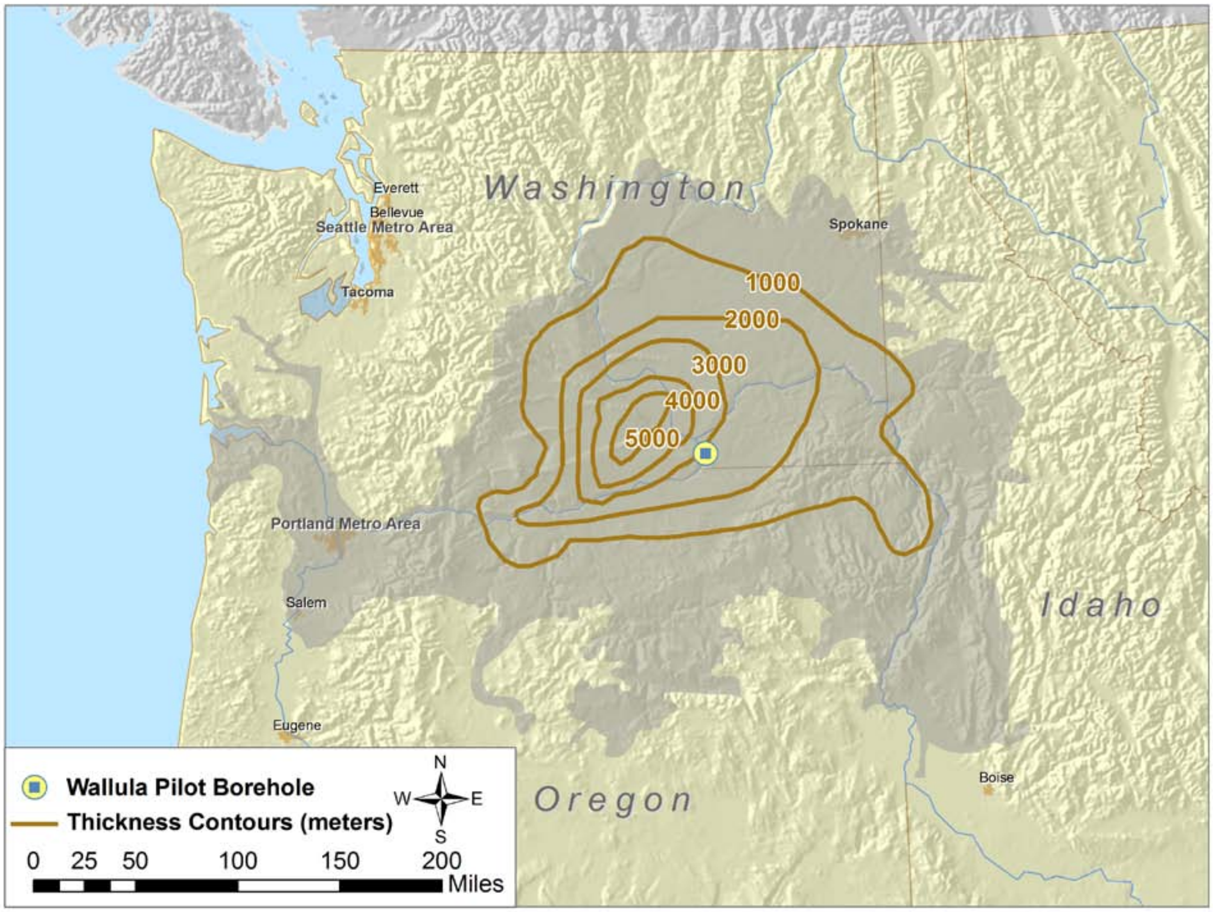

Figure 4.2. Regional Thickness and Structure Map for the Columbia River Basalt Group (modified from Reidel et al., 2002).

Because flood basalt formations exist in other regions of the U.S. (and other countries such as India), where sedimentary basin storage capacity is similarly limited, demonstration of commercial-scale storage in deep flood basalts is of intrinsic importance to meeting global CO_2 emissions targets. However, in addition to the CRBG primary sequestration target, sub-basalt sedimentary rocks form a potential saline formation target in the Columbia Basin. Lower Tertiary sedimentary rocks are widespread beneath the basalt cover and include Eocene fluvial sandstones and coals of the Roslyn Formation, volcanic flows, tuff beds, and arkosic sandstones of the Eocene and Oligocene Naches Formation, and the Oligocene Ohanapecosh, Wenatchee, and Wildcat Creek Formations (Montgomery, 2008) (Figure 4.3). These formations are presently the target of natural gas exploration activities in western and northern parts of the Columbia Basin. The presence of natural gas "shows" and preservation of porosity and permeability in sedimentary rocks penetrated by exploration wells in the Columbia Basin support potential for CO_2 storage in the sub-basalt rocks and sealing properties of the overlying basalt sequences.

4.1 Site Selection Overview

A detailed geological evaluation of the region surrounding the Boise White Paper mill was conducted to identify suitable basalt and deep saline formations (DSF) to meet the objectives of the ICCS demonstration program. New products and understandings developed during this time include a locally constrained extensible 3 D GIS model of the Columbia Basin basalts; a new understanding of the subsurface at the ICCS site, gained by combining outcrop data, updated aeromagnetics, and emerging radon transform velocity modeling techniques for basalts.

	PERIOD/ EPOCH	AGE Ma		STRATIGRAPHIC UNIT	LITHOLOGY
TERTIARY	PLEISTOCENE			Hanford	Unconsolidated glacial flood deposits
	PLIOCENE	3.3		Ringold	Semi-indurated sand and gravel
	MIOCENE	8.5 13.5	Columbia River Basalt Group	Saddle Mountains Basalt	Basalt and tuff
		14.5		Wanapum Basalt	
		15.6		Grande Ronde Basalt	
		17.5		Imnaha Basalt	
	OLIGOCENE	30		Wildcat Creek Wenatchee Ohanapecosh	Rhyolite and basalt flows interbedded with tuff and sandstone
	EOCENE	40		Naches	
		47		Roslyn	Arkosic and tuffaceous sandstone, siltstone, shale, coal, and conglomerate
		48		Teanaway	Basalt flows and tuff
		54		Swauk	Lacustrine black shale,limestone, arkosic sandstone, conglomerate
	PALEOCENE	55		Stuart batholith	Granodiorite and quartz diorite
CRETACEOUS		63 93 138			
JURASSIC		150 205		Ingalls metamorphic rocks	Schist, amphibolite, gneiss, serpentine

Figure 4.3. Stratigraphy of the Columbia Basin. After Montgomery, 2008.

The proposed ICCS sequestration site is located about six miles northeast of the Boise White Paper mill (Figure 4.4). The primary sequestration target is the thick (> 6000 ft) stack of Grande Ronde porous and permeable basalt flow tops that occur below the massive and laterally extensive Umtanum flow (Reidel et al., 1989, Tolan et al., 1989). Targeted permeable flowtop injection zones below the Umtanum are confined by low permeability to impermeable basalt flow interiorsm which commonly comprise 90% of an individual basalt flow thickness (see Figure 4.5). The secondary injection formation target is the underlying, sub-basalt, silici-clastic units within the Roslyn and Swauk Formations. Wireline log data, hydrologic tests and numerical modeling (details provided in Section 5.3) indicate that the Grande Ronde target can easily accept the plant output of 0.8 MMT/yr. However, sub-basalt silici-clastics may provide sufficient reserve capacity to accept the entire plant output should site characterization demonstrate less injectivity in the deep basalt sequences than anticipated.

The Miocene basalts and associated shallow sedimentary interbeds have been mapped and studied for almost a century, primarily in relation to aquifer usage, nuclear repository work at the Hanford Site, and more recently in regard to hydrocarbon exploration (e.g., Bretz, 1917; Waters, 1961; Spane et al., 2003; Reidel 2003; Montgomery, 2008). Aquifer studies have produced a large body of knowledge on storage capacity, injectivity and production, and zonal containment and lateral continuity of both shallow and intermediate-depth basalts. Nuclear repository studies undertaken as part of the Basalt Waste Isolation Project (BWIP) provided detailed, hydrologic characterization information to extended basalt depths (e.g., 5,000 ft). In addition, BWIP studies provided extensive geomechanical properties for basalt flows including: in-situ stresses, minimum threshold fracture pressures, and fracture reopening pressures. This type of geomechanical property information is critical for realistic numerical modeling of CO_2 injection operations and the planning injection programs. Hydrocarbon exploration has greatly increased knowledge of basin configuration, structure, and regional rock properties of sub-basalt sedimentary units that have potential for carbon sequestration.

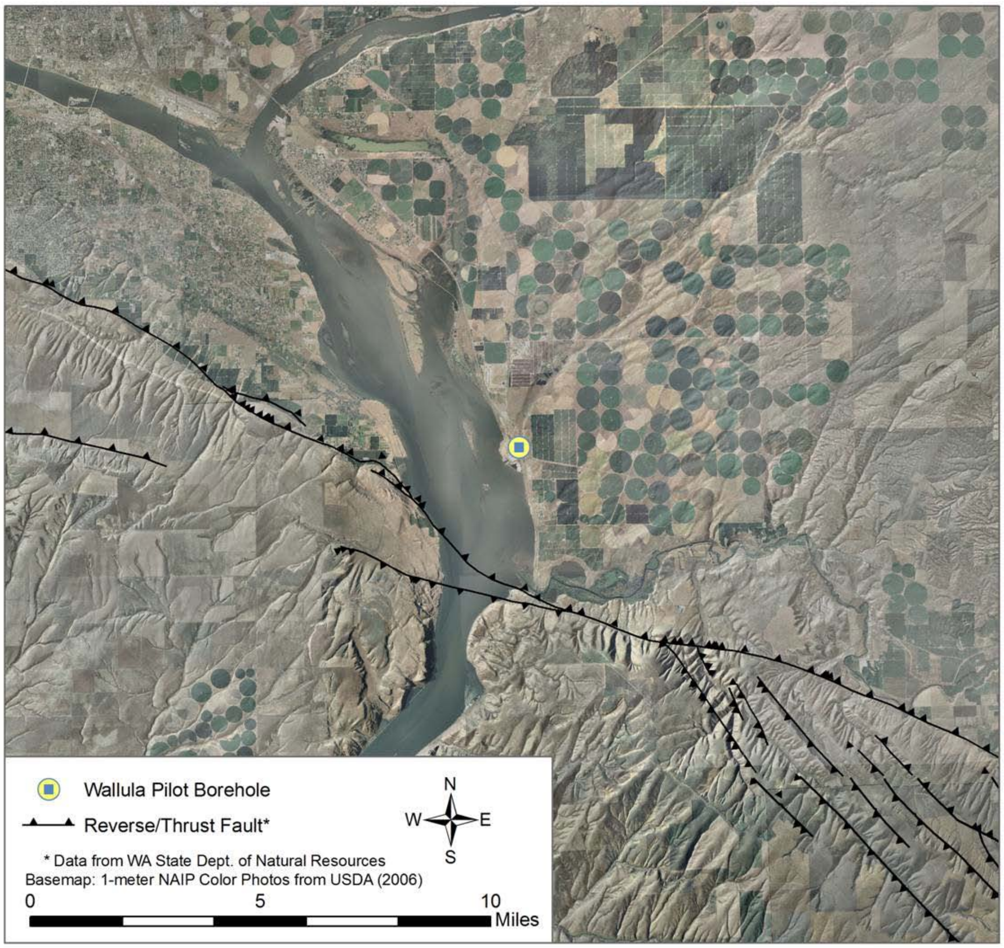

Figure 4.4. Geographic and Geologic Constraints on Location of Boise CO_2 Sequestration Site. The presence of the Columbia River, and Horse Heaven Hills escarpment and faults limit sequestration opportunities south and west of the plant. The proposed sequestration site is about six miles NNE of the Wallula Pilot well.

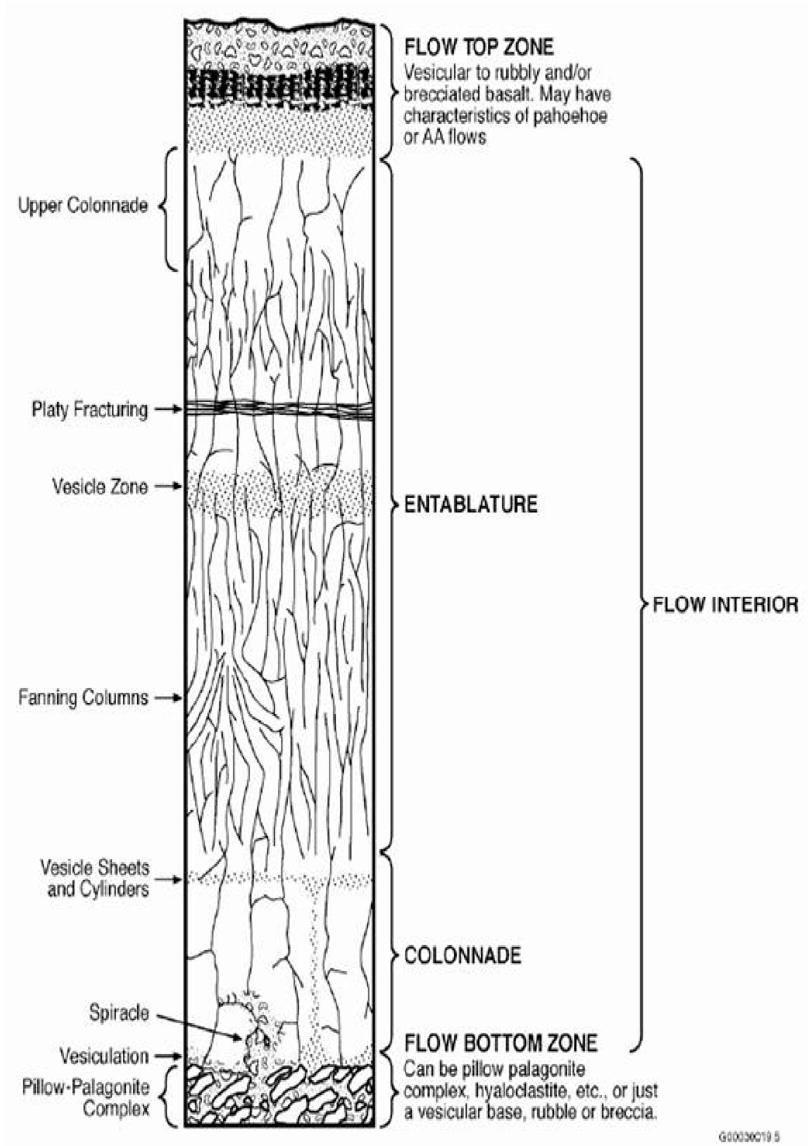

Figure 4.5. Structures of a Single Idealized Flood Basalt Flow. Brecciated flow tops form confined aquifers throughout the region.

Formation water quality generally decreases with depth in the Columbia River basalts, with fluorides and sulfides rendering water-bearing zones of deeper basalt layers non-potable (Gephart, et al. 1979, DOE 1988, Reidel, et al. 2003; Lindsey, et al. 2009). Formation waters below the dense Umtanum Member of the Grand Ronde Formation in the 2009 Wallula Basalt Pilot well are geochemically evolved , relatively dilute sodium-bicarbonate waters with elevated pH (9 to 9.7), fluoride, silica, bicarbonate and sodium. Of particular note, groundwater for sampled basalt flowtop zones below the Umtanum Member at the proposed pilot injection zone has a fluoride concentration levels ranging between 4.98 and 11.9 mg/L. These fluoride concentrations exceed both the secondary and primary drinking water standards of 2.0 and 4.0 mg/L, respectively. The Grande Ronde sequestration target consists of stacked, brecciated flow tops of massive tabular pahoehoe flood basalts below the Umtanum Member of the Grande Ronde (Figure 4.6). Individual CRBG flows typically cover hundreds to a few thousand square miles, and become thicker in the central part of the Columbia River Plateau, particularly in the Pasco Basin (Reidel 2002) located to the immediate northwest of the proposed sequestration site. Outcrop geometries, together with petrography, geochemistry, and lateral extent relationships indicate that the CRBG continental flood basalts formed as continuous, laterally extensive sheets, rather than as compound flows with discontinuous lenticular layers (Hooper; Reidel; Tolan et al, 2009). The massive interiors of more thick and laterally extensive basalt flows may form regional intraformational seals that isolate groundwater within underlying basalt flowtop horizons, and can be reflected by distinct differences in hydrologic heads and hydrochemical/isotopic differences in fluid geochemistry with depth within the basalt formation (Gephart, et al., 1979, DOE 1988, Reidel et al. 2005). The low-permeability, sealing properties of massive flow interiors were demonstrated during direct field tests conducted within deep boreholes on the Hanford Site as part of the BWIP basalt characterization investigation (e.g., Gephart et al., 1979, Eslinger 1986, DOE, 1988), and locally within the Wallula Pilot Borehole (McGrail et al., 2009). The Vantage Horizon at the contact between the Wanapum and Grande Ronde Formations and the Umtanum basalt member within the upper Grande Ronde Basalt, represent secondary regional hydrologic system seals for deeper CO_2 basalt injection horizons. As noted previously, the Umtanum basalt flow is an extremely large, aerially extensive, and thick basalt flow that is recognized regionally across the Columbia Plateau region (e.g., Reidel et al. 1989, Tolan, 1989).

The secondary target is the sub basalt Lower Tertiary Roslyn and Swauk Formations. The closest penetration of the sub-basalt section is in the gas exploratory Shell 1-10 Darcell well, about 15 miles northeast of the proposed sequestration site (Figure 4.7). The Darcell well, drilled by Shell Western E&P Inc. in 1987, reached a depth of 8565 feet below ground surface in metamorphic basement. Total basalt thickness is less than 8000 feet, with about 500 feet of sub-basalt sedimentary strata reported as Paleogene tuff (Lasmanis, 1991) on a local erosional high (Montgomery, 2008). In general, the pre-Miocene sedimentary column in the Columbia Basin is greater than 3000 ft thick (Figure 4.8) (Wilson, et al., 2008). Based on gravity models (William Lingley, personal communication, 2009) and the proximity to the Darcell high, the sedimentary column in the proposed sequestration area is expected to be 1000-2000 feet thick. The lower sedimentary units, the Roslyn and Swauk, have the highest likelihood of being present, based on cross-sections in Wilson et al. (2008). Basin modeling using gravity and aeromagnetic data during the early phase of site characterization could reduce uncertainty on thickness of the sedimentary column prior to drilling. VSP and new PNNL 3C seismic swath technology applied as part of the characterization activities would further enhance imaging and definition of sub-basalt features. In natural gas exploratory wells in Yakima and Grant counties, the Roslyn and Swauk Formations exhibited porosities of 5-20% and permeabilities of 0.25-400 mD (Wilson et al., 2008). Water production was common in tests of these formations. Although deeper parts of the Pasco Basin are expected to have lower porosities and permeabilities because of secondary mineralization/cementation (Gephart et al., 1979, DOE 1988, Montgomery, 2008), the proposed sequestration site east and up dip of the Pasco Basin may be in a more favorable position to retain storage capacity.

Series		Group	Formation	Member	Isotopic Age (m. y.)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
				Ice Harbor Member	8.5	
				Basalt of Goose Island		N
				Basalt of Martindale		R
				Basalt of Basin City		N
				Buford Member		R
	Middle			**Elephant Mountain Member**	10.5	R,T
				Pomona Member	12	R
				Esquatzel Member		N
				Weissenfels Ridge Member		
				Basalt of Slippery Rock		N
				Basalt of Tenmile Creek		N
				Basalt of Lewiston Orchards		N
				Basalt of Cloverland		N
				Asotin Member	13	
				Basalt of Huntzinger		N
				Wilber Creek Member		
				Basalt of Lapwai		N
				Basalt of Wahluke		N
				Umatilla Member	13.5	N
				Basalt of Sillusi		N
				Basalt of Umatilla Member		N
			Wanapum Basalt	**Priest Rapids Member**	14.5	
				Basalt of Lolo		R
				Basalt of Rosalia		R
				Roza Member		T,R
				Shumaker Creek Member		N
				Frenchman Springs Member		
				Basalt of Lyons Ferry		N
				Basalt of Sentinel Gap		N
				Basalt of Sand Hollow	15.3	N
				Basalt of Silver Falls		N,E
				Basalt of Ginkgo		E
				Basalt of Palouse Falls		E
				Eckler Mountain Member		
				Basalt of Dodge		N
				Basalt of Robinette Mountain		N
				Vantage Horizon		
			Grande Ronde Basalt	**Member of Sentinel Bluffs**	15.6	N_2
				Member of Slack Canyon		
				Member of Field Springs		
				Member of Winter Water		
	Lower			**Member of Umtanum**		
			Grande Ronde Basalt / Wanapum Basalt (Pruett...)	**Member of Ortley**		
				Member of Armstrong Canyon		
				Member of Meyer Ridge		R_2
				Member of Grouse Creek		
				Member of Wapshilla Ridge		
				Member of Mt. Horrible		
			Picture Gorge Basalt	**Member of China Creek**		N_1
				Member of Downey Gulch		
				Member of Center Creek		R_1
				Member of Rogersburg		
				Member of Teepee Butte		
				Member of Buckhorn Springs	16.5	
			Imnaha Basalt			R_1
						T
						N_0
					17.5	R_0

Figure 4.6. Stratigraphy of the Columbia River Basalt Group. (From Reidel et al., 2002)

The Eocene Roslyn and Swauk represent secondary target formations and consist of fluvial silici-clastic sediments deposited in a westward draining plain that included peat swamps. Regional paleoenvironments conducive to the generation of natural gas are confirmed by strong flow tests of gas (up to 5 Bcf/day) in exploratory wells north of the Pasco Basin (Wilson et al. 2008). The generation and migration of even minor amounts of thermogenic gas may be sufficient to retain porosity in the more sand prone Roslyn Formation. Because the sub-basalt secondary target formations were deposited in non marine environments (Montgomery, 2008), the contained formation fluids may be brackish or saline. The widespread association of pre-Miocene units with hydrocarbons in the Columbia Basin area is expected to produce non-potable formation fluids.

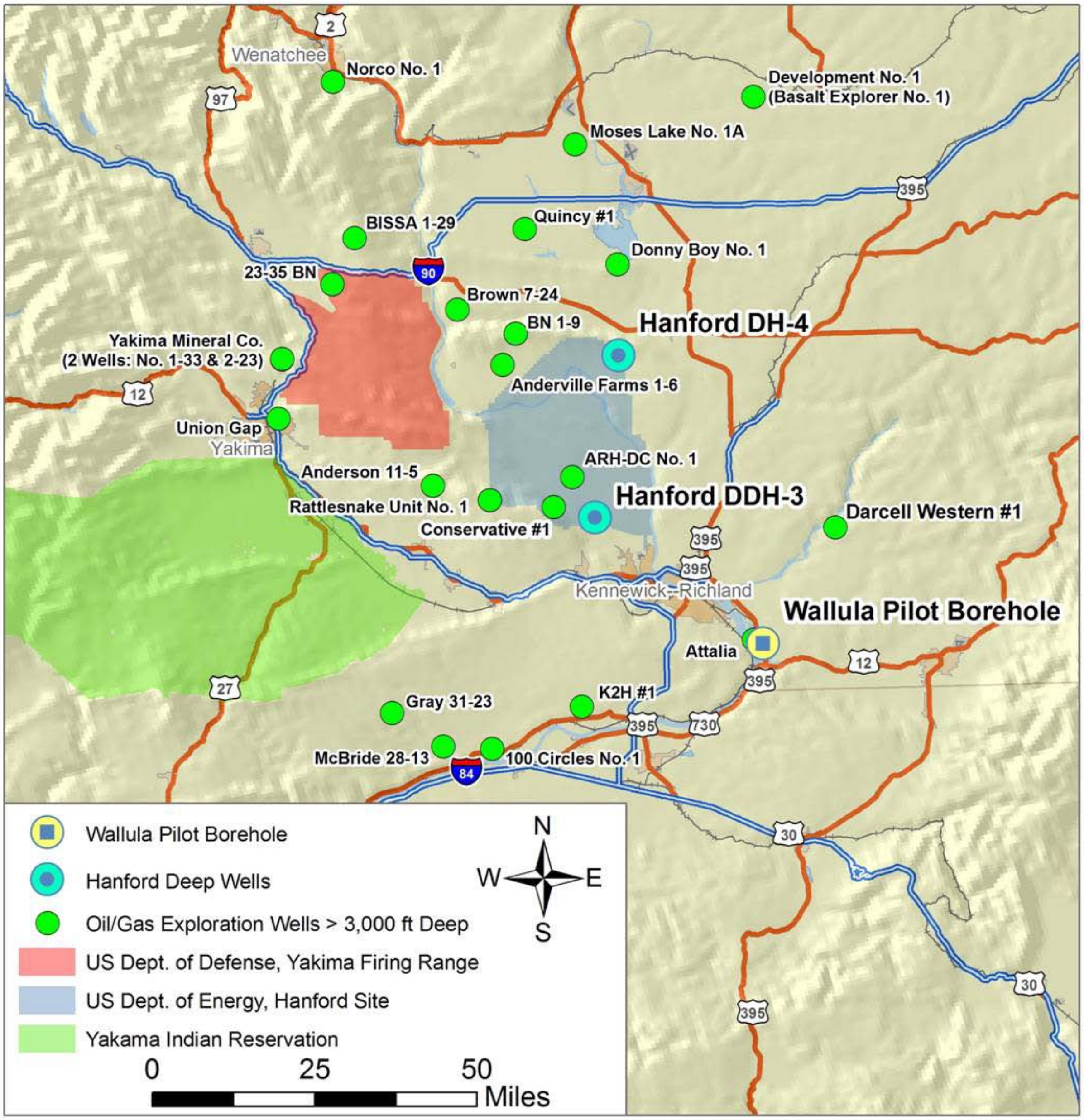

Figure 4.7. Location of the Shell 1-10 Darcell Gas Exploration Well and Other Deep Wells in the Region

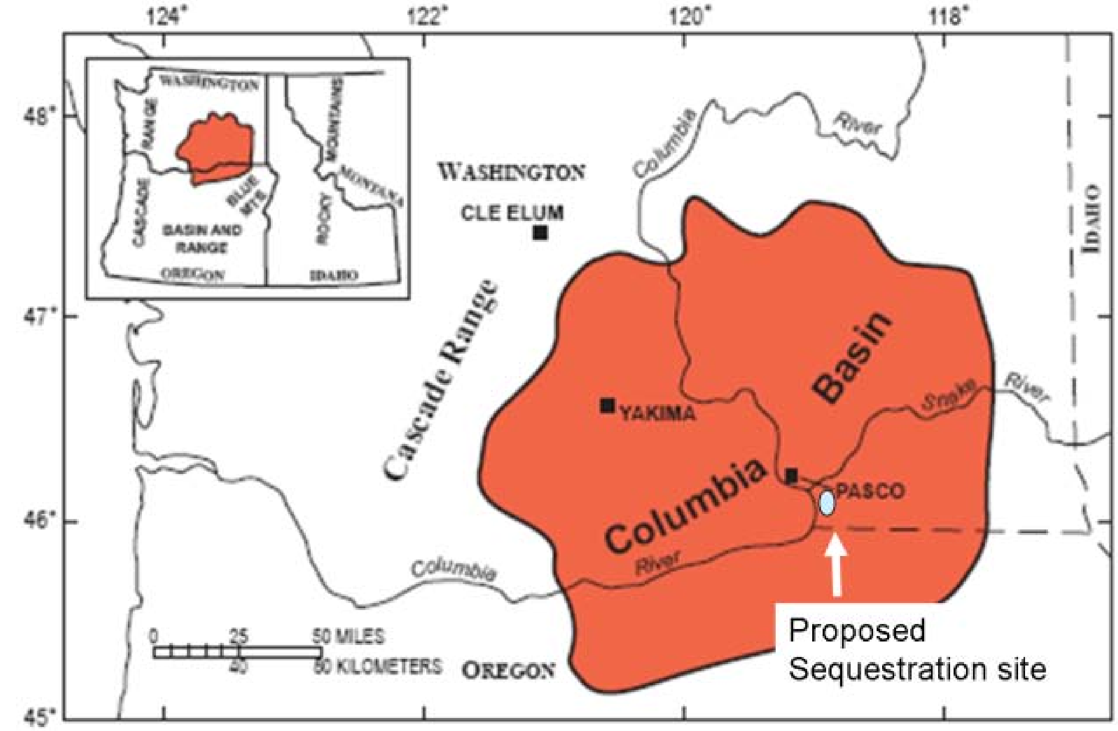

Figure 4.8. Area of the Columbia Basin with Greater than 3000 ft of pre-Miocene Sedimentary Strata. (After Wilson et al., 2008)

The only local penetration of the Umtanum basalt and upper Grande Ronde Formation is the Big Sky Carbon Sequestration partnership basalt pilot well at the Boise White paper mill, which reached a total depth of 4,110 ft. The pilot borehole penetrated to the Wapshilla member within the upper Grand Ronde Formation, and is located a distance of ~five miles from the proposed ICCS injection well site. The location of relatively shallow, water-supply wells within the area of interest is shown in Figure 4.9. The circle around the proposed ICCS well represents a radius of one mile.

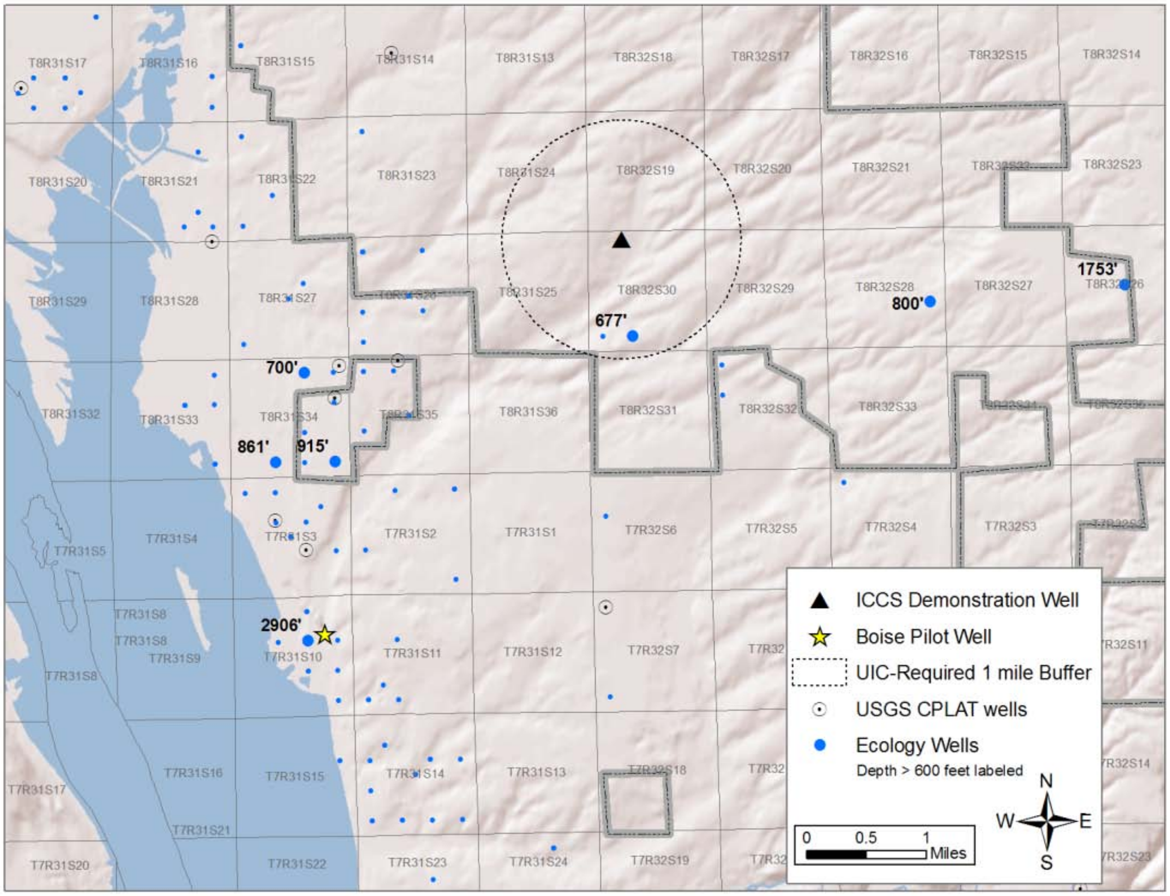

Figure 4.9. All Wells of 600 Feet Depth or Greater Within the Proposed Sequestration Area. Circle around the proposed ICCS demonstration well is one mile radius required in a UIC application for geologic sequestration permit.

4.2 Key Site Geological Structure Information

The portion of the Columbia Basin that contains the proposed sequestration site is bounded on the east by the Palouse Slope, on the west by the Pasco Basin and on the south by the Horse Heaven Hills (Figure 4.10) The Horse Heaven Hills, an elongated anticlinal ridge that is part of the Yakima Fold Belt (REIDEL et al., 1989), forms a prominent escarpment along the west side of the Columbia River, at a distance of approximately three miles from the Boise plant and 8 miles from the proposed ICCS well location . The ridge is bounded on the north by narrow faults that do not exhibit historical movement. An earthquake in 1934 at Milton-Freewater, Oregon located >40 miles to the southeast, may have occurred on an extension of this fault.

As shown in the U.S. Geological Survey (USGS) earthquake hazard map (Figure 4.11), the proposed site has a relatively low hazard ranking. The site lies within an area that has a PGA of 0.150 g with 2 percent probability of exceedance in 50 years. Structural dips interpreted from image based log data in the Wallula Basalt Pilot well are low (2 degrees to the northwest), and are heavily overprinted by stratigraphic dip conditions of the basalt flows. Regionally, structural dip becomes increasingly steep to the west into the Pasco Basin, but flattens to the west and north of the Wallula well, and within the proposed sequestration site (Reidel et al. 2002).

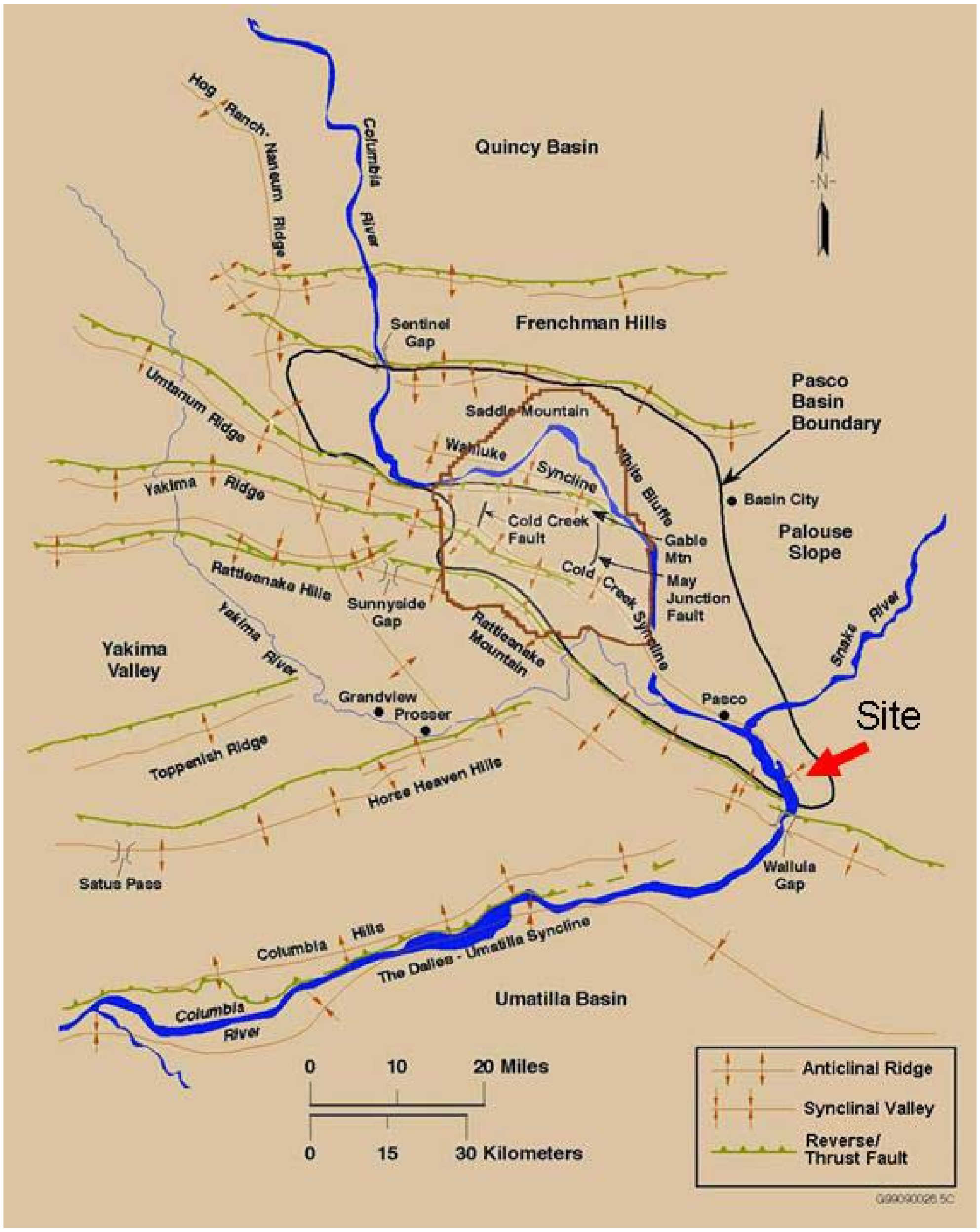

Figure 4.10 Location of Major Regional Tectonic Features (Reidel et al., 2002)

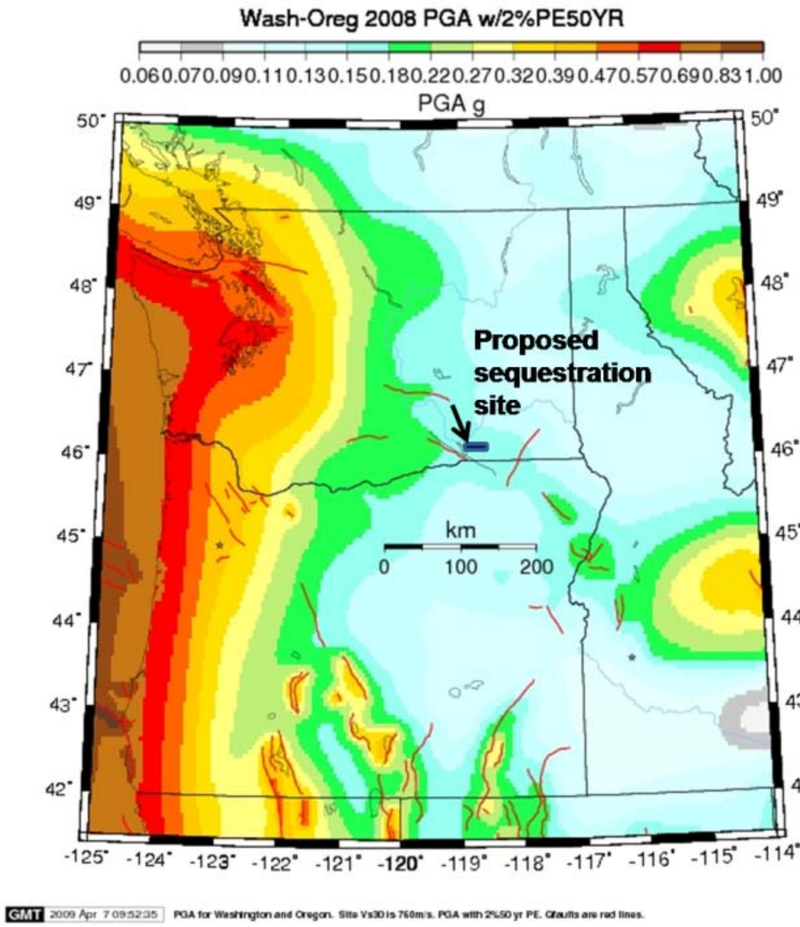

Figure 4.11. USGS earthquake hazard map for the Pacific Northwest. The black rectangle is the proposed sequestration site.

4.3 Geologic Model of the Sequestration Site Subsurface

Battelle was able to access a new digital Columbia Basin basalt geomodel being constructed as part of the Columbia Plateau Regional Aquifer System study conducted cooperatively by the USGS Water Science Centers in Washington, Oregon, and Idaho, and the USGS Office of Groundwater. A sub-volume of the USGS geomodel is shown in Figure 4.12 updated by subsurface data from the Wallula Basalt pilot and the Darcell well. The integration of new state-of the-art subsurface well data to update a robust new digital regional model greatly reduces uncertainty in the subsurface configuration of the basin and in establishing continuity of major individual basalt flows. The geomodel snapshot shows the configuration of selected basalt layers, including the bottom of the Miocene basalts, and the on-lap of basalts onto the Darcell high. This model illustrates the location of the Wallula well and the proposed ICCS sequestration site at the eastern edge of the syndepositional Pasco Basin. Although structural dip increases into the Pasco Basin to the west, structural dip to the east is relatively flat. This lack of significant structural dip will simplify monitoring of the CO_2 plume.

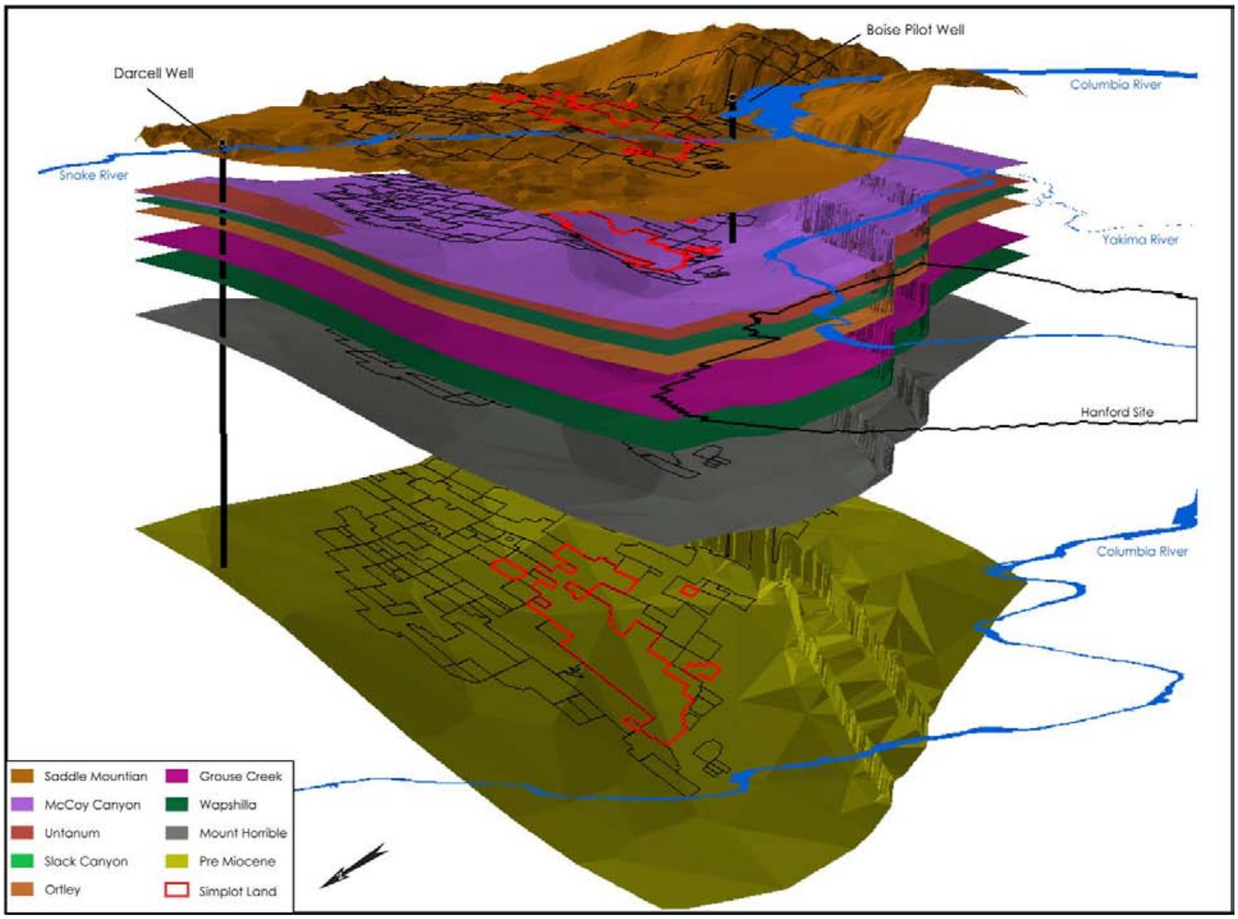

Figure 4.12. Sub-volume of USGS Basalt Geomodel, Updated with Data from the Wallula and Darcell Wells. USGS Data courtesy of Dr. Eric Burns. Note North arrow for orientation. Horse Heaven Hills faults are visible in right center of figure.

The acquisition of the regional USGS GIS grids also facilitated building solid earth models in EarthVision and geocellular models in Petrel.

The steps for building the EarthVision and Petrel models included:

- Import USGS grids for basalt formation contacts as points (Figure 4.13)
- Revise those grids to match the data from Darcell and the Wallula Pilot boreholes
- Determine the dip and location of the major faults and use to create fault surfaces.
- Delete data near the faults from the USGS data set because it "warps" over the faults.
- Build the faulted model of the major formation contacts
- Build intermediate grid surfaces for all of the individual GR flows based on the picks from Darcell and the Wallula Pilot
- Build the model with the GR flow layers (Figure 4.14)
- Transfer all of the input data sets to PETREL and build the model in Petrel.
- Add the seismic data and geophysical log to Petrel

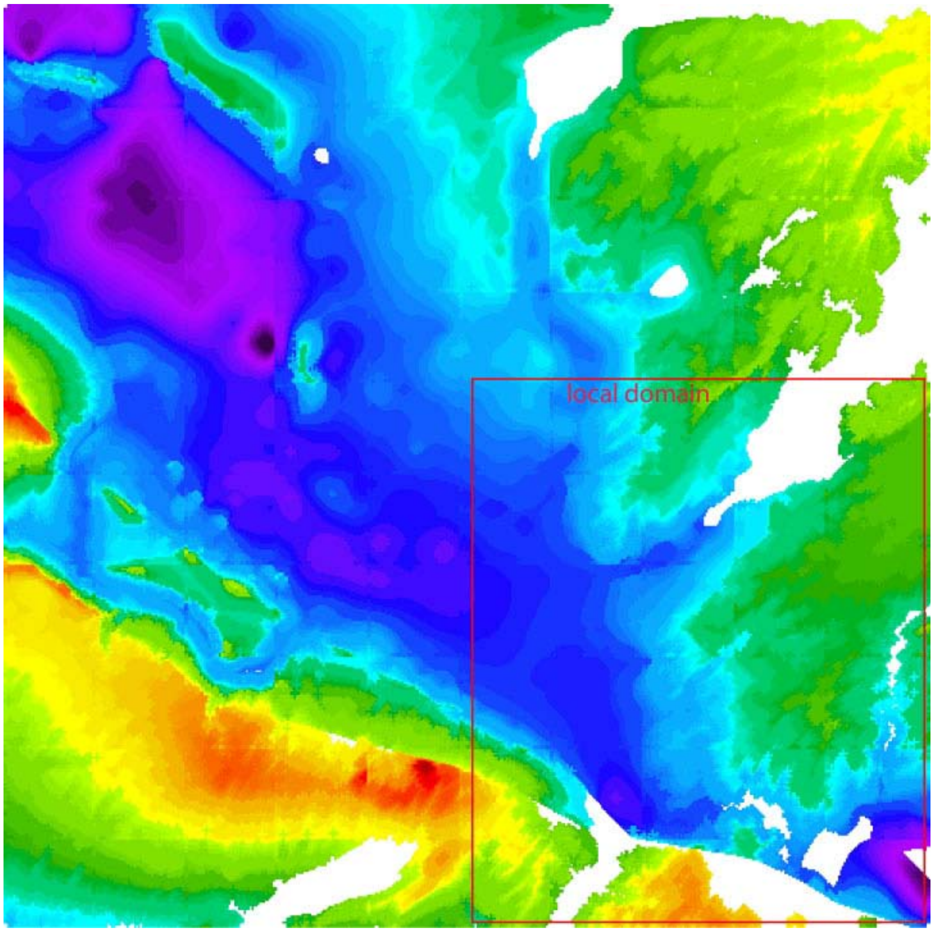

Figure 4.13. Example of Regional USGS Basalt Grids with Wallula sub-volume

Additional sources of data for building improved geologic basalt models include seismic and potential fields including gravity and aeriomagnetics data, The characterization program includes acquisition and processing of state-of-the-art 3C 2D swath seismic technology for onshore continental flood basalts, pioneered by Battelle as part of the Wallula site characterization in 2007 (McGrail et al., 2009). The seismic survey, which utilized advanced multicomponent sensors, two 60,800 pound vibroseis sources and a 5-line receiver swath layout, was the first of its kind to be used on continental flood basalts. The survey was designed to greatly enhance acoustic signal preservation, and to allow the identification and removal of converted wave or other noise that traditionally results in extremely poor seismic images of onshore basalt layers. The successful identification and removal of several modes of shear wave and other energy during the Wallula seismic program resulted in a breakthrough in imaging of these notoriously problematic rocks. Figure 4.15 is the final P-wave image from the processor. With a dominant frequency of about 30 Hz, the data are sufficient to determine there are no large vertical offsets in the subsurface along the seismic line. More importantly, this successful image processing of the basalt sequences suggests that surface seismic imaging may be used for tracking CO_2 migration, something considered all but impossible before this survey was carried out. Subsurface characterization of the ICCS site will include both surface seismic and borehole VSP and will build on the acquisition and processing lessons learned during the Big Sky basalt sequestration pilot.

The new ICCS seismic will be calibrated by wellbore data, including a VSP zero offset and walk-away surveys, and will in turn be used to calibrate more regional gravity and aeromagnetics modeling. These data will then be used to construct and test conceptual models to reduce uncertainty of subsurface geological parameters, reduce risk of project failure, and develop best practices. Currently, on-going seismic processing experiments are being conducted by research geophysicists at the University of Texas. In particular velocity models built with Radon transform techniques delineate erosional features in the shallow subsurface along the Wallula seismic line (Figure 4.16). Such features are common in outcrop and may extend down a few hundred feet from erosional surfaces in the Saddle Mountains Basalt Formation.

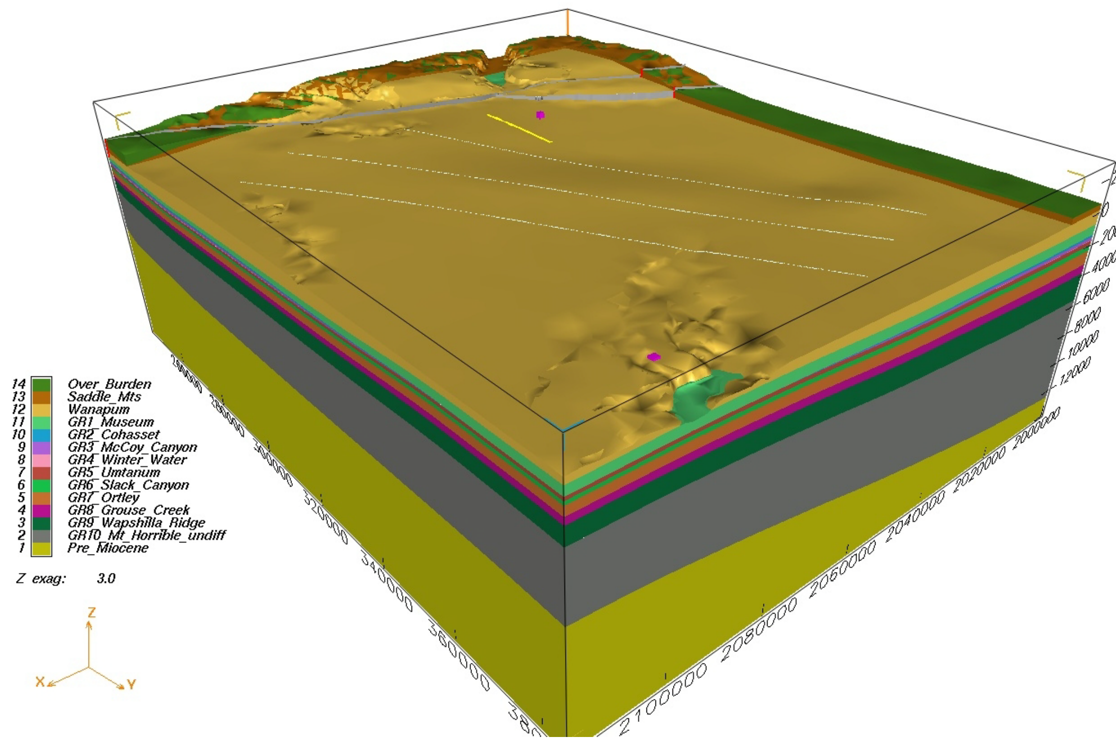

Figure 4.14.Top of Wanapum Member with location of Wallula seismic swath and the 2009 basalt pilot well. Note Wallula Gap in the background, and the Darcell well location in the foreground

The location of the anomaly on the seismic line coincides with an anomaly in reprocessed aeromagnetic potential field data (such features are important to be able to recognize in the subsurface for well planning). Although erosional channels would not be at a deep enough level to breach the Umtanum seal, the orientations of cooling joints could cause drilling difficulties. Figure 4.17 is a diagrammatic representation of the subsurface stratigraphy and the shallow sedimentary interbeds that represent ever increasing time between eruption of flows in the waning phase of flood basalt activity.

New processing versions of publically available aeromagnetic data show anomalies that appear to align with known dikes in outcrop (Figure 4.18). The presence of intrusive dikes may compartmentalize groundwater and subsurface CO_2 injection reservoirs. The distance of these possible dikes, however, is sufficiently far from the proposed ICCS injection well, and is expected to have minor hydrologic impact on subsurface CO_2 flow and transport. 3-D numerical simulation of various injection rates and time periods will be used during detailed site characterization to help predict the influence of these possible dikes on CO_2 plume growth.

In summary, a comprehensive assessment of geologic and hydrologic characteristics of the proposed sequestration site confirms expectations of favorable subsurface properties to support a commercial-scale ICCS project. Thousands of feet of multiple, highly impermeable basalt flow interior sections are expected to provide secure and permanent caprock seals of injected CO_2. While the number of permeable interflow zones is unknown below 4110 ft, expectations based upon regional drilling experience suggests that several additional interflow zones will be encountered that have sufficient permeability to be suitable for CO_2 injection. Furthermore, an additional 1000 ft or more of underlying, sub-basalt sedimentary formations are available for supplemental injection capacity should the basalt sequences prove less favorable than expected. Based on the sum of all the available information, the selected sequestration site appears to be and acceptable and secure candidate for this proposed ICCS project. In the next section, land ownership associated with the proposed sequestration site is discussed.

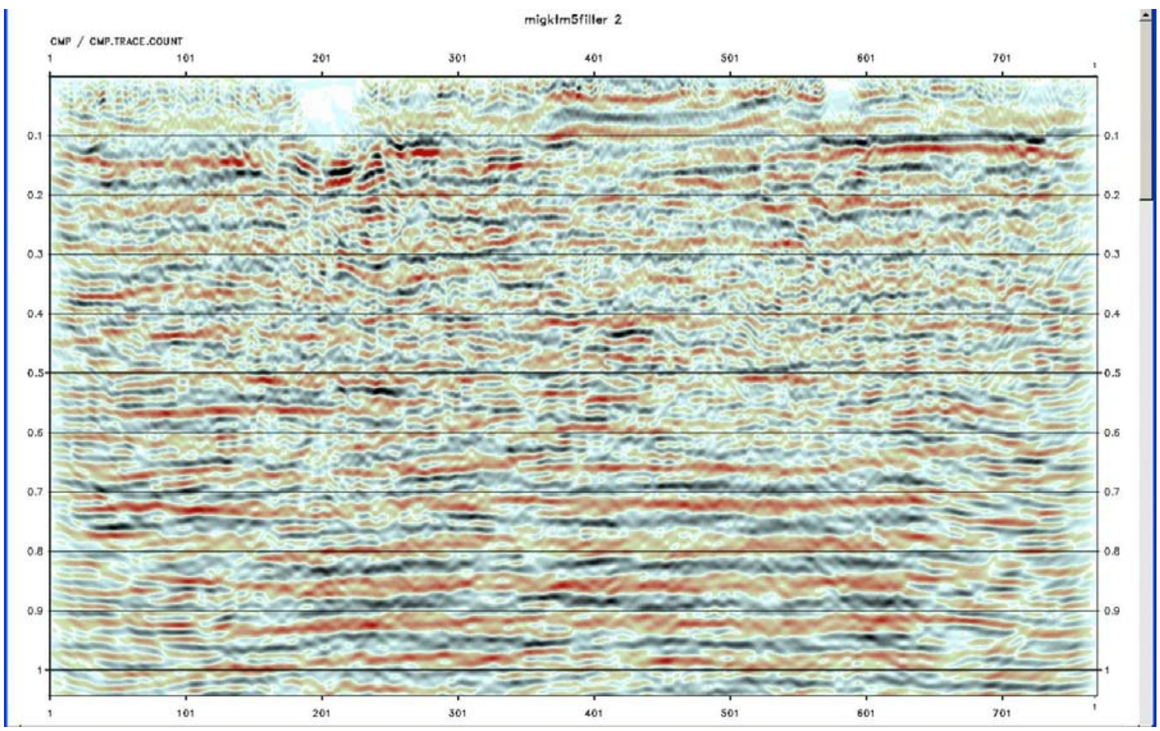

Figure 4.15. Final P-P Image as Processed by CGG Veritas. The dominant frequency is about 30 Hz. There is no evidence of vertical faulting within the deeper basalt units (0.8 s to 1.0 s). On-going velocity-modeling and boutique processing is expected to enhance this image.

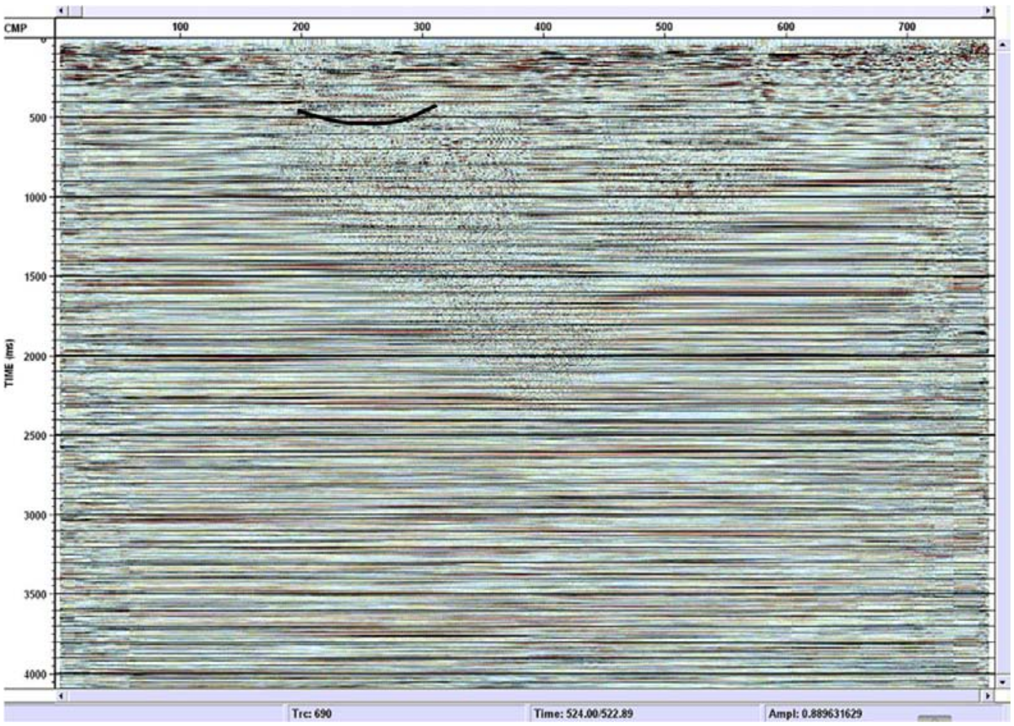

Figure 4.16.Velocity Model Built Using New Radon Transform Techniques. This technique may allow imaging of erosional channels in the shallow subsurface. Channels may have a large "shadow" below them caused by scattering of seismic energy.

4.4 Land Ownership

Figure 4.19 shows landownership in the area surrounding the Boise paper mill. As can be readily seen in the Figure, landownership in the general area is complicated with the exception of certain large areas with contiguous parcels owned by single parties, which are either corporations or private individuals. The area approximately 5 miles NE of the Boise mill is expected to be the principal area of focus for the Phase 1 evaluation. This is because the majority landowner in this area is J.R. Simplot, Inc. J.R. Simplot was contacted by Battelle and Boise staff to determine willingness to consider granting surface access rights as well as subsurface storage rights for CO_2. A Letter of Intent from J.R. Simplot to negotiate those terms and conditions has been obtained. Battelle did not contact the other two companies with parcels to the north of the Simplot parcels because the need to acquire surface and/or subsurface rights for those parcels will not be need based on injection simulations performed during Phase 1 activities.

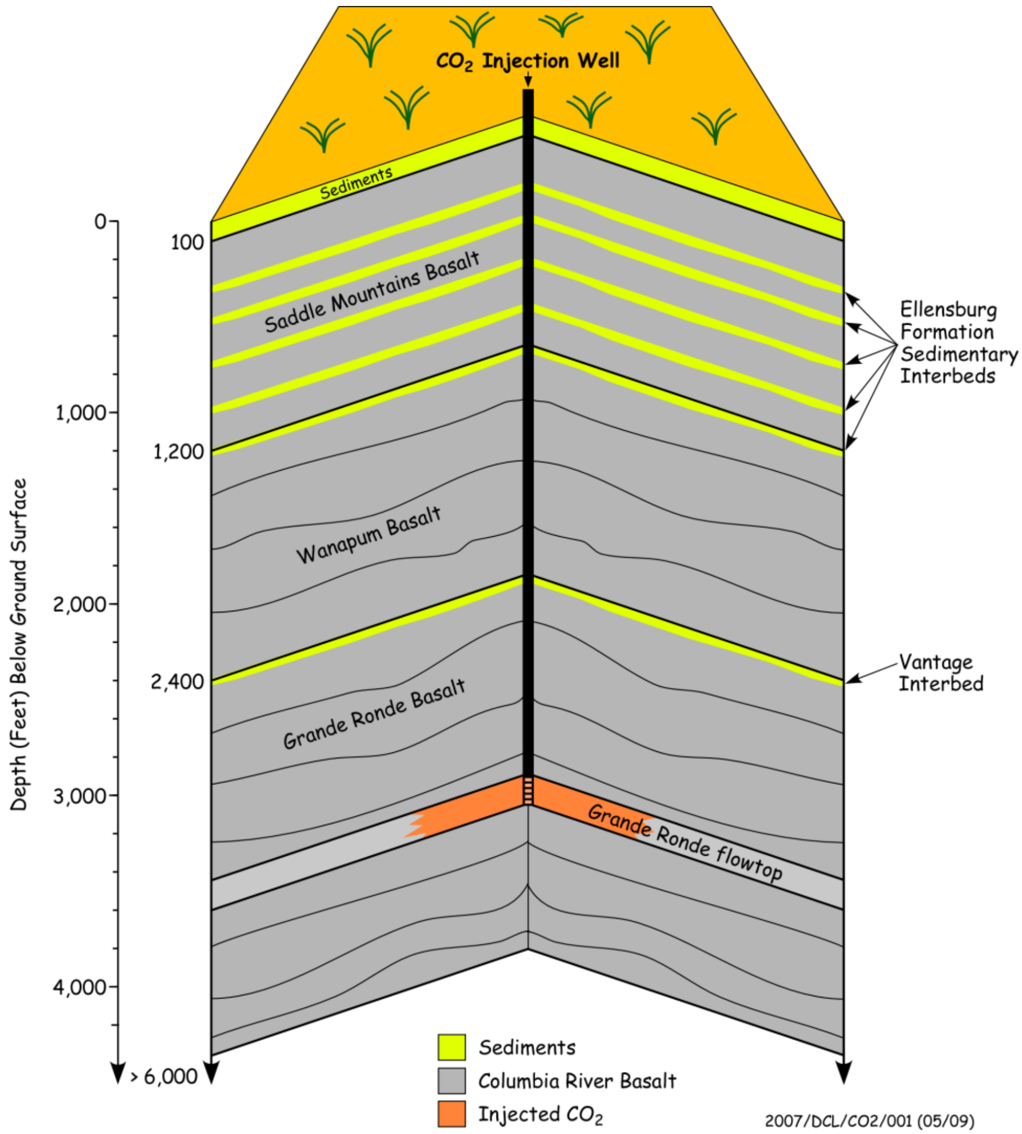

Figure 4.17. Diagrammatic representation of the subsurface stratigraphy and the shallow sedimentary interbeds. Erosional channels form stream valleys and canyons that become filled with basalt flows.

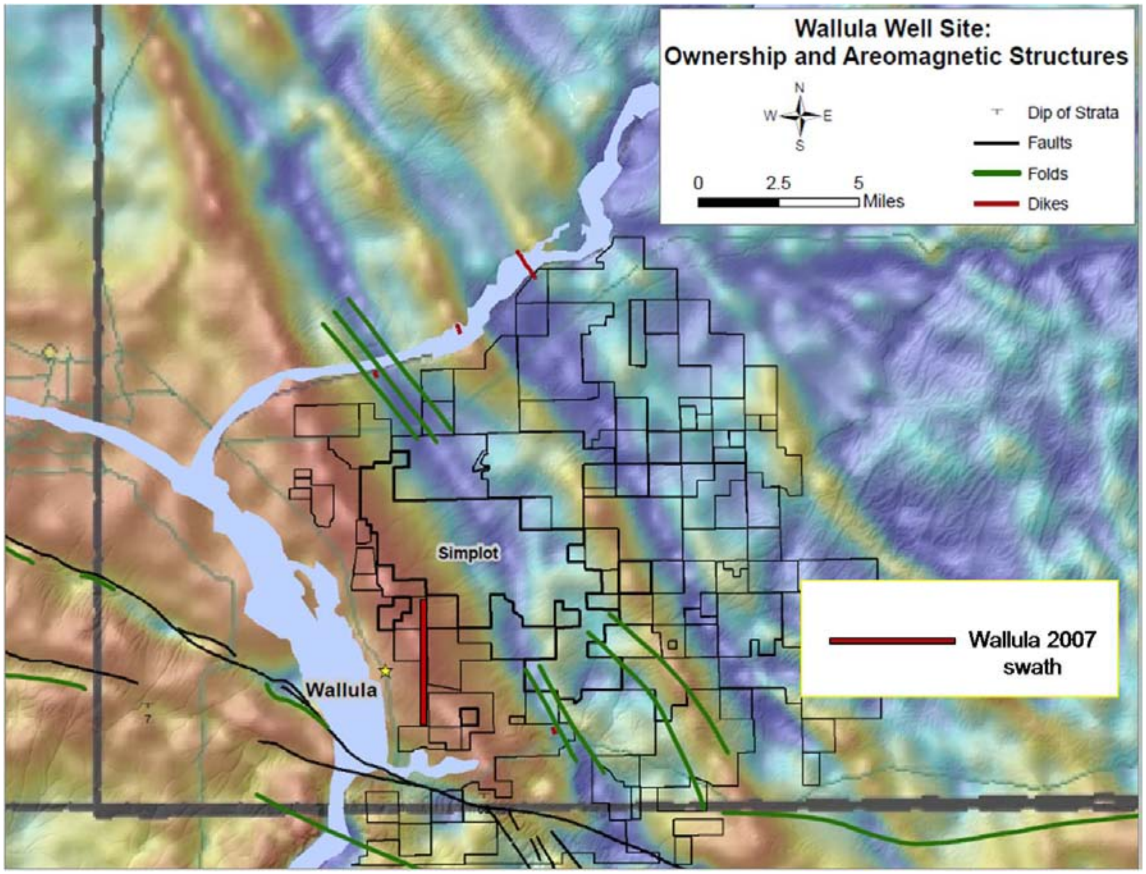

Figure 4.18. Magnetic anomaly map with location of dikes in outcrop (red near rivers) and 2007 Wallula Seismic. The seismic line crosses a pronounced break in the anomaly.

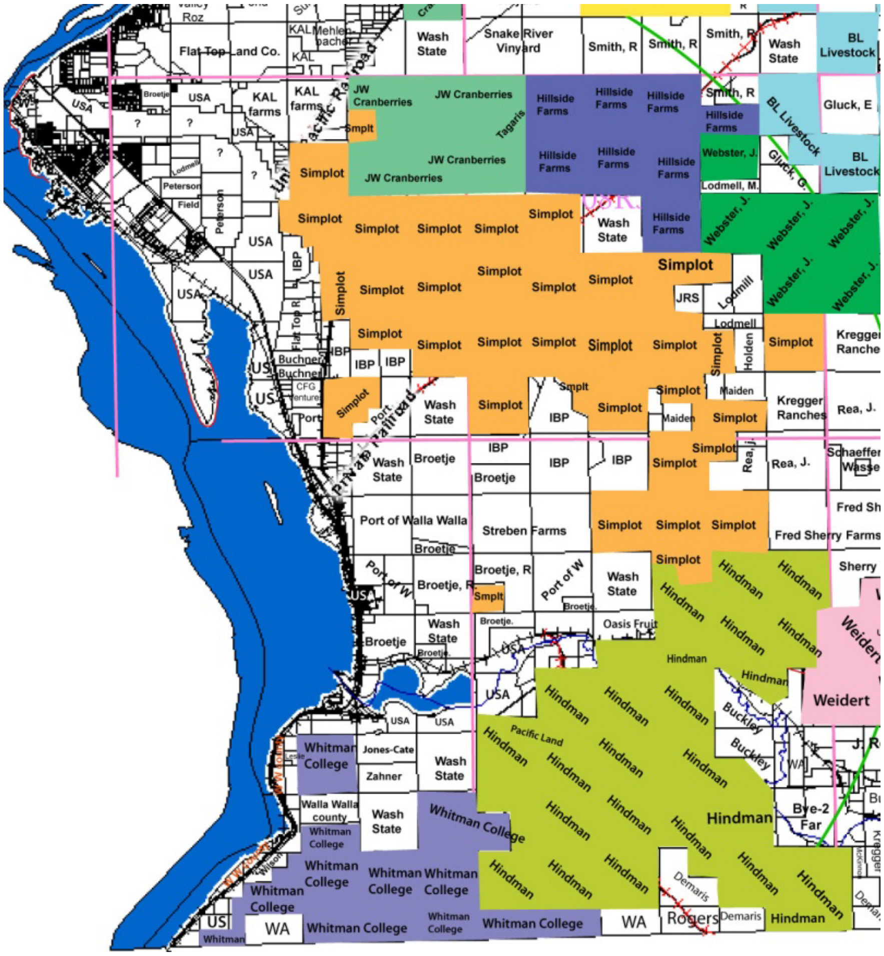

Figure 4.19. Landowners within 15 mile radius of Boise Wallula mill. The approximately 25 mi^2 area 5 miles NE of the mill is the primary area of interest as it involves only 3 commercial landowners and one parcel owned by the State Department of Natural Resources.

5.0 Sequestration System Design

A successful commercial CO_2 sequestration operation within basalts for the Boise White Paper mill facility will require the execution of the detailed site characterization activities discussed previously to resolve only partially-known hydrogeologic properties at the sequestration site. Nevertheless, utilizing the results from the Wallula pilot borehole (which reached a depth of 4,110 ft), data obtained from deep borehole studies on the nearby Hanford Site, and other surrounding regional irrigation, aquifer storage, and natural gas exploration activities in the basin, reasonable assumptions about the hydrogeological conditions have been developed to support a preliminary sequestration system design.

5.1 Pipeline and Wellbore Thermohydraulics

Figure 5.1 shows the planned pipeline route to reach the proposed location on the J.R. Simplot property for the injection well. The proposed ROW follows an abandoned railroad track previously owned by Northern Pacific Railway and now owned by J.R. Simplot. The abandoned railroad track easement will allow direct access from the Boise White Paper Mill to the proposed injection location and provides for a relatively straightforward ROW agreement with J.R. Simplot.

Although analysis of pipeline flow behavior of CO_2 is well established and over 110 million standard cubic meters per day of CO_2 are transported by pipeline in the United States, frequently for distances greater than 100 km, surprisingly little analysis has been done of a fully coupled system linking the compression requirements at an industrial facility capturing CO_2 all the way to pressure requirements at the bottom of the injection well(s) at a sequestration reservoir. To ensure that proper pipeline sizes were selected and appropriate sizes for injection wells were designed, a coupled pipeline-wellbore thermohydraulic analysis was conducted.

A simple, steady state, one-dimensional flow model was used to calculate the pressure drop along a series of segments of the pipeline or well. Pressure changes from frictional loss, gravity head, and acceleration of the flow are included in the model. The CO_2 density is calculated from the pressure and internal energy from the carbon dioxide state equation of Span and Wagner (1996). The carbon dioxide is assumed to be a liquid or supercritical fluid and the calculation stops if two-phase conditions occur. The temperature change of the carbon dioxide from plant to wellhead and from wellhead to injection zone due to heat transfer to and from the surrounding soil and rock was included in the calculation. Bounding summer and winter cases were considered. Temperature of the CO_2 leaving the Boise plant was assumed to be 104°F (40°C).

Two cases were examined for the combined pipeline and injection well at the Wallula site. Case 1 is our reference case with a design basis CO_2 capture rate at the Wallula mill of 500 MMT/yr. Case 2 represents an alternative scenario for installation of higher capacity CO_2 capture system representing 90% of the CO_2 output from the plant of 0.878 MMT/yr. To achieve these flow rates, the resulting injection pressure must be greater than the minimum pressure required to drive the carbon dioxide into the reservoir formation but less than the maximum safe pressure to avoid fracturing. The minimum pressure to provide the required flow rate into the formation was determined by subsurface reservoir modeling for the two following sub-cases: 1) injection in the basalt interflow layers, and 2) injection in sub-basalt sediments only. The maximum safe pressure is specified as 90% of the pressure developed assuming 0.87 psi/ft of depth to the top of the reservoir.

Figure 5.1. Proposed Pipeline Route to Sequestration Site. Total distance is 5 miles.

Calculations using the thermohydraulic model showed that the best well design would support a 4 inch diameter J-55 injection tubing string. A summary of the final design results with this tubing string diameter is provided in Table 3.3. Results of the heat transfer analysis show no significant effect on the injected CO_2 properties in the well, only changing the fluid temperature at the bottom of the well by about a few degrees compared to an adiabatic case. Therefore, well bottom temperatures for only the adiabatic case are shown in Table 3.3.

A 6 5/8 inch pipeline for Case 1 and a 8 5/8 inch pipeline for Case 2 provide sufficient capacity to minimize pressure drop over the 5 miles between the plant and the wellhead. In winter, temperature of the CO_2 reaching the wellhead is predicted to drop a maximum of 31°F (Case 2b). Case 2b also requires the highest pipeline pressure of just over 2100 psig, which was used to specify the pipe wall thickness. Note that for Cases 1a-b, the CO_2 temperature fluctuates slightly above and slightly below the in situ temperature. Hence, the injected CO_2 will be on average at nearly the same temperature as the surrounding rock. For Cases 2a-b, the injected CO_2 is significantly colder than the in situ temperature and will expand somewhat as heat transfer raises the temperature over time after injection stops.

Table 5.1. Summary Results of Thermohydraulic Evaluation

Parameter	Case 1a		Case 1b		Case 2a		Case 2b	
	summer	winter	summer	winter	summer	winter	summer	winter
Plant data								
flow rate (MMt CO_2/year)	0.5		0.878		0.5		0.878	
Pipeline Data								
Pipeline length (miles)	5		5		5		5	
Pipeline diameter (inches)	6 5/8		8 5/8		6 5/8		8 5/8	
Pipeline inside diameter (inches)	6.065		7.981		6.065		7.981	
Pipeline inlet pressure (psig)	1479	1302	1662	1470	1723	1358	2159	1800
Wellhead pressure (psig)	1414	1236	1612	1426	1664	1298	2109	1756
Wellhead temperature (°F) [a]	100	78	102	79	100	72	101	73
Wellbore Data[b]								
Depth to top of injection horizon (ft)	2837		2837		8068		8068	
Max. injection pressure (psi)	2223		2223		6320		6320	
Required injection pressure (psi)	2119		2119		4037		4037	
In situ temperature (°F)	106		106		209		209	
Predicted bottom hole pressure (psi)	2120	2119	2120	2119	4037	4037	4037	4037
Predicted bottom hole temperature (°F) adiabatic	121	93	117	92	144	107	136	103

a) temperatures correspond to a plant delivery temperature of 104 °F and to average winter (33.8 °F) and summer (73.4 °F) surface temperatures observed at Wallula.

b) nominal 4 inch J-55 pipe with inner diameter of 3.476 inches with a roughness factor of $4.6 \times 1^{0-5}$ m.

5.2 Injection Well Design

Design of the injection well for this project is based upon experience gained from permitting the Wallula pilot CO_2 test well drilled at the Boise mill site and on well construction requirements listed for Washington Administrative Code (WAC) WAC-173-160-442 and -444.[1] Cementing protocols will follow recommended Washington State regulations specified for resource protection well construction/completions (WAC-173-160-420, -430, and -450).[2] Conventional circulation will be used to drill to the base of the Saddle Mountains basalt; the remainder of the drilling program is expected to utilize the reverse-flood drilling method using primarily bentonite-based drilling fluid. The casing annulus will be sealed with neat cement and State approved additive accelerants (calcium chloride), using a tremie-pipe delivery system. Figure 5.2 shows the expected well completion design. Protective sand/gravel layers we be installed across each basalt interflow zone (to prevent cement penetration) that is indentified from hydrologic testing as having sufficient permeability to support CO_2 injection. A well screen assembly will be installed in the sub-basalt sediments all the way to the metamorphic basement. This design will support a number of potential injection strategies including simultaneous injection in all targeted injection zones to sequential injection at selected target intervals. Gun perforation of the well casing will be used to provide flow conduits to the target injection zones.

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[1] WAC-173-160-442, *Limitations for Use of Drilling Materials*; WAC-173-160-444, *Standards for Use of Polymers and Additives*.

[2] WAC-173-160-420, *General Construction Requirements for Resource Protection Wells;* WAC-173-160-430, *Minimum Casing Standards;* WAC-173-160-450, *Well Sealing Requirements.*

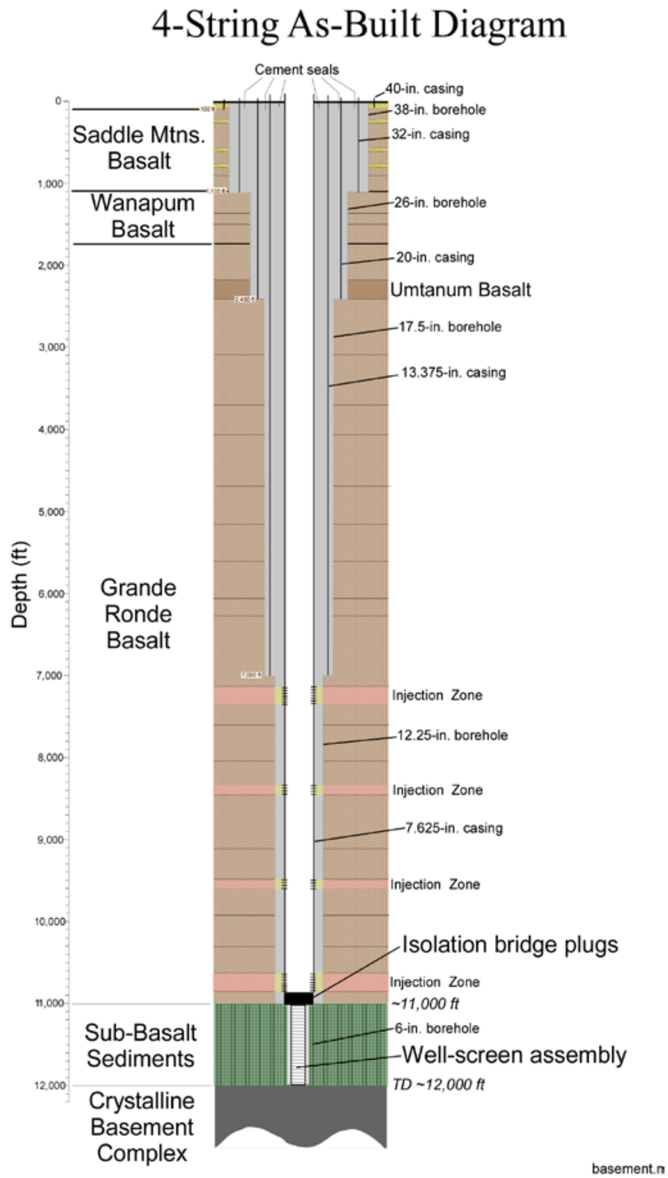

Figure 5.2. Anticipated Injection Well Design for the Wallula ICCS Project

5.3 Fate and Transport Analysis

The principal objective of CO_2 fate and transport analysis is to predict the migration, dissolution, entrapment, chemical reaction, and ultimate disposition of CO_2 in the reservoir formation. Because of the complexity of these processes, these predictive analyses are typically conducted using numerical simulation, which is commonly referred to as reservoir modeling. Numerical simulation calculates migration, dissolution, entrapment, and chemical reaction processes by solving sets of equations that describe the motion of fluids and transport of heat through geologic media. These equations are generally solved for a set of primary variables, equal in number to the number of solved equations, which must be able to completely define the thermodynamic and hydrologic system, through a series of constitutive equations. The sets of flow and transport equations are partial differential equations that cannot be solved directly due to the complex dependence of the secondary variables on the primary unknowns. The equations are thus solved approximately by discretizing space into grids and time into time steps. In general, the greater the resolution of the spatial and temporal discretizations, the more accurate the simulation results. The consequence of increasing discretization resolution is longer execution times. The art of numerical simulation is finding the balance between discretization resolution (i.e., solution accuracy) and execution time.

5.4 Simulation Software Description and General Assumption

Numerical simulations conducted for this proposal were executed using the sequential version of the STOMP-CO2 simulator developed by Battelle. STOMP-CO2 is an operational mode of the collection of STOMP multi-fluid flow and reactive transport simulators with capabilities for modeling the flow and transport of CO_2. All CO_2-capable operational modes of STOMP have reactive transport capabilities through the ECKEChem module (WHITE and MCGRAIL, 2005).

STOMP-CO2 solves three nonlinear hyperbolic partial differential conservation equations: 1) water mass, 2) CO_2 mass, and 3) salt mass. The governing equations are transformed to algebraic form using integral volume spatial discretization on structured orthogonal grids (e.g., Cartesian, cylindrical, curvilinear boundary fitted) and a backward-Euler temporal discretization (i.e., fully implicit). Nonlinearities in the resulting algebraic equations are linearized via multivariate Newton-Raphson iteration; where, the Jacobian matrix is computed using numerical derivatives. Phase transitions are handled using primary variable switching. Details concerning the solved governing equations and numerical solution approaches are reported in the STOMP Theory Guide (WHITE and OOSTROM, 2000). Details concerning use of STOMP-CO2, including input formatting details are reported in the STOMP User's Guide (WHITE and OOSTROM, 2006).

5.5 Site-Specific Assumptions and Methodology

Simulations of CO_2 injection into the Grande Ronde Basalt and underlying sediments at Wallula were based on data from the pilot well and the geologic model described in section 4. The primary sequestration target is the interval between depths of 2837.5 and 9068 ft bgs. The basalts are underlain by Triassic metamorphic basement rock which acts as a seal. The model domain was discretized using a two-dimensional radially symmetric grid with 60 radial nodes and 117 vertical nodes. The computational domain was designed to simulate the radial and vertical migration of the injected CO_2 from a well that is perforated over the entire vertical extent of the target sequestration reservoir. The radial domain extended from the well casing 4.3125 in. (0.12 m) to 16,404.2 ft (5000 m), using a geometrically radially increasing grid spacing with a 3.28-ft (1-m) grid spacing adjacent to the well casing. The grid spacing in the vertical direction corresponded to the alternating permeable interflow zones and impermeable flow interior layers.

The STOMP-CO2 simulator assigns hydrologic properties to grid cells either by specifying a distribution of rock/soil types across the domain and then assigning properties to the specified rock/soil types, or direct specification for every grid cell. For these simulations, the flow tops and flow interiors were specified as zones and were assigned hydraulic properties determined from hydraulic test results. Horizontal hydraulic conductivities were converted to intrinsic permeabilities. Flow tops were assigned a permeability of 14mD, which corresponds to a hydraulic conductivity of 8.2×10^{-6} cm/sec. Flow interiors were assigned a permeability of 0.0001mD, which corresponds to a hydraulic conductivity of 1.0×10^{-12} cm/sec. The sub basalt sedimentary unit permeability varied between 5mD and 20mD. Vertical hydraulic conductivities were assumed to be one order of magnitude lower than the horizontal hydraulic conductivities. Flow tops were assumed to have 10% porosity, flow interiors to have 1% porosity and the sub basalt sediments to have 5% porosity. A summary of the hydraulic properties is shown in Table 5.2.

Unsaturated flow properties of the basalt flows at the Wallula borehole have not been measured and were assumed for each of the materials (White et al. 2006), as listed in Table 5.3. The unsaturated hydraulic properties for the flow tops are similar to those of gravel, whereas the flow interiors were assigned higher air-entry pressure to reflect the smaller pore size inherent for their lower permeability.

Table 5.2. Hydraulic Properties at Wallula

Model Layer Layer	Hydraulic Conductivity (cm/sec)	Intrinsic Permeability (mD)	Porosity (%)
Flow Interior	1.00E-12	0.0001	1
Flow Top	8.20E-06	14	10
Sub-Basalt Sediments	----	5	5

Table 5.3. Brook-Corey Function Parameters

Model Layer Layer	Air Entry Pressure (cm)	λ	Residual Saturation
Flow Interior	154	4.033	0.01
Flow Top	54	4.033	0.01
Sub-Basalt Sediments	154	4.033	0.01

A hydrostatic gradient of 0.435 psi/ft was assumed based on observed formation pressure versus depth measurements exhibited for a deep Hanford Site characterization borehole, RRL-2, as reported in Strait and Spane (1982). Formation temperature was assumed to be 94.59°F at a depth of 2930.5 ft, with a geothermal gradient of –0.02°F/ft, based on observed measurements within the Wallula pilot borehole and regional data. The salinity was assumed to be 10,000 ppm. The upper and lower boundaries of the computational domain were assumed to be impermeable. The outer radial boundary was assumed to be under hydrostatic conditions in equilibrium with the initial conditions. A summary of the initial conditions for the model is provided in Table 5.4.

Table 5.4. Summary of Initial Conditions (assigned to bottom node of computational domain)

Parameter	**Value**
Reservoir Bottom Temperature	207.34°F
Reservoir Temperature Gradient	-0.02 ºF/ft
Aqueous Saturation	1.0
Reservoir Bottom Pressure	3741.78 psi
Reservoir Pressure Gradient	-0.435 psi/ft
Salinity	10,000 ppm

5.6 Simulation Results

Two depth intervals were simulated for each of the two injection period scenarios. The scenarios are summarized in Table 5.5. All simulations continued for a total time of 50 years to allow for CO_2 to redistribute in the reservoir. In addition, for the above scenarios, the sub-basalt sediment permeability was evaluated at values of 5mD, 10mD and 20mD to account for the uncertainty in this parameter.

Plume radii were calculated by integrating the mass of CO_2 over the total numerical grid domain and setting the radius at the radial distance from the injection well where 95% of the CO_2 mass was contained. The 95% cutoff was used to ensure that the reported plume radii represent the bulk of the injected CO_2. Thin high-permeability zones often interpreted from well log data can result in thin layers of CO_2 that advance ahead of the main plume. These thin layers account for a very small fraction of the injected CO_2 and their extent and presence is not often well known for a specific site. Hence, use of the 95% cutoff prevents structures such as these from dominating the plume calculations and giving an unrealistically high spatial resolution interpretation of the plume dimensions that is not justified by the quality of the available reservoir data.

Table 5.5. Summary of Injection Scenarios

Scenario	**Injection Zone**	**Depth Interval, ft bgs**	**Injection Duration, yrs**
LGRSB1	Lower Grande Ronde plus sub-basalts	2837.5 - 9068	1
SB1	Sub-Basalts only	8068 - 9068	1
LGRSB30	Lower Grande Ronde plus sub-basalts	2837.5 - 9068	30
SB30	Sub-Basalts only	8068 - 9068	30

5.6.1 One Year Injection Scenarios

Figure 5.3 shows the calculated mass of CO_2 injected at a rate of 0.878562 MMT/yr into a single well completed in the Lower Grande Ronde plus sub-basalt sediments and Figure 5.4 shows the Injection Pressure at the top and near the bottom of the injection well for the same scenario. Shortly after injection starts, reservoir pressures quickly rise around the well. If at any time the maximum pressure set for the simulation is reached, the CO_2 injection rate is reduced to maintain pressures below that maximum limit. The results of these simulations suggest that assuming conservative properties for reservoir permeability, 0.878562 MMT/yr can be injected into a single well without exceeding the pressure limit. The pressure limit for these simulations was set at 2222.56 psi, the pressure determined to be 90% of the fracture re-opening pressure at the top of the injection zone.

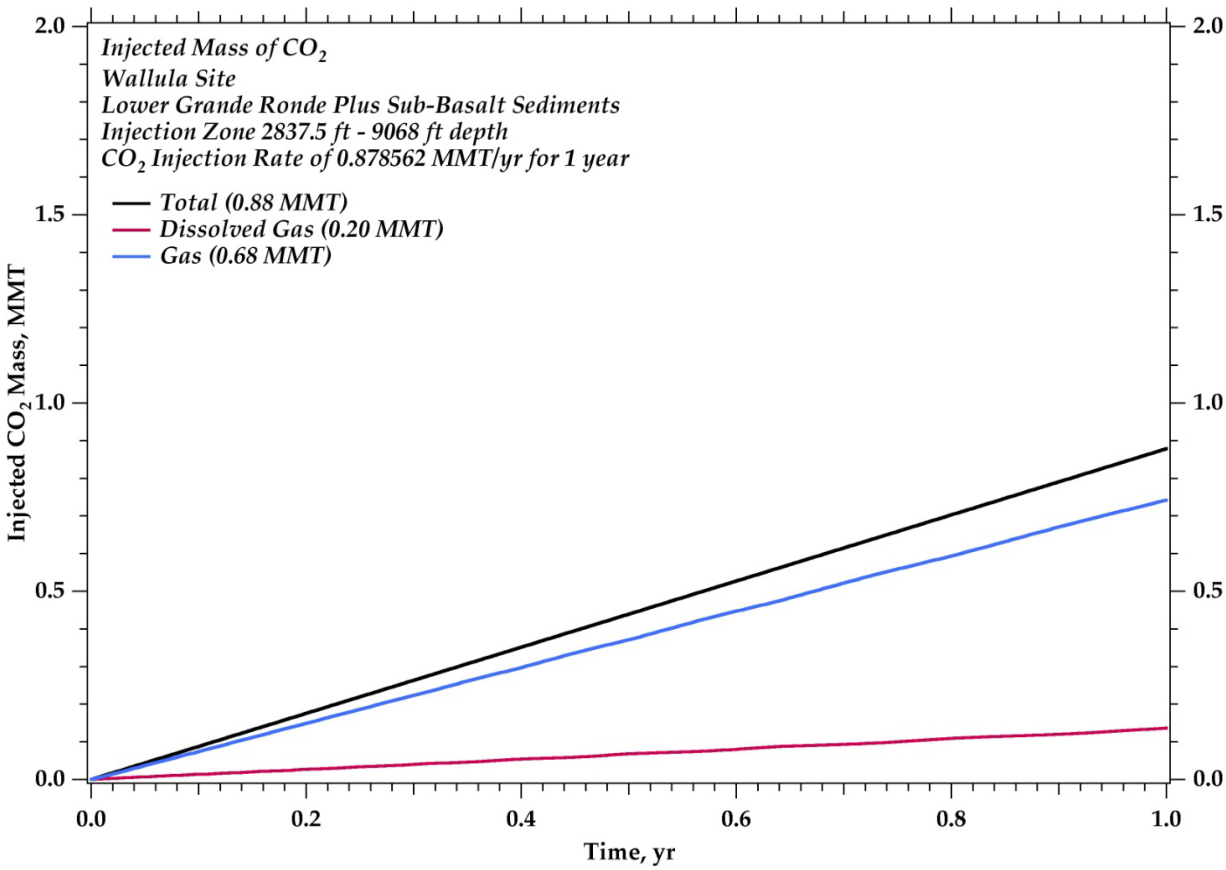

Figure 5.3. Calculated Mass of CO_2 Injected at a Rate of 0.878562 MMT/yr into a Single Well Completed in the Lower Grande Ronde plus Sub-Basalt Sediments

Figure 5.5 and Figure 5.6 show the mass of CO_2 injected and injection pressure for injection into the sub-basalt sediments only. The results of these simulations suggest that even by limiting injection to this zone, 0.878562 MMT/yr can be injected into a single well without exceeding the pressure limit. The pressure limit for these simulations was set at 6319.51 psi, the pressure determined to be 90% of the fracture re-opening pressure at the top of the injection zone.

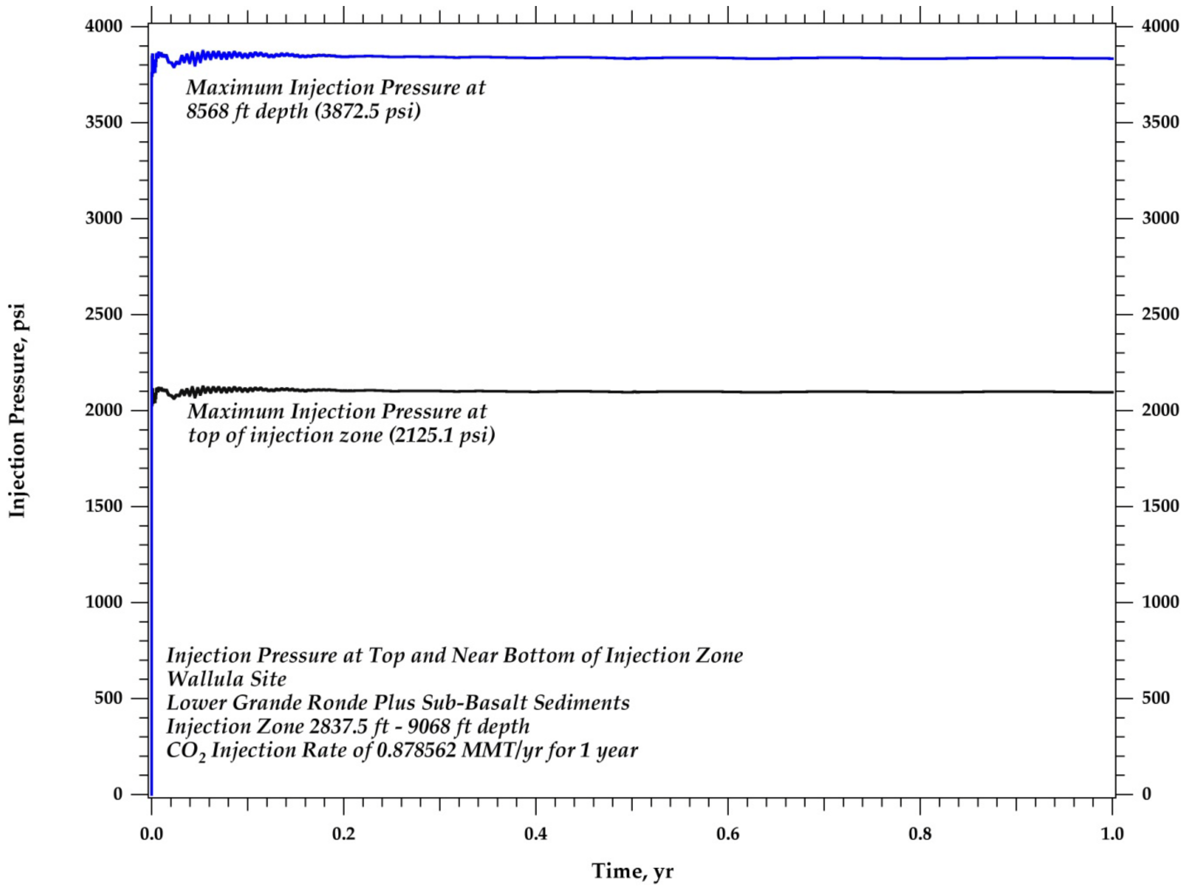

Figure 5.4. Injection Pressure for Scenario of CO_2 Injected at a Rate of 0.878562 MMT/yr into a Single Well Completed in the Lower Grande Ronde plus Sub-Basalt Sediments

To visually understand the development of the pure-phase plume of injected CO_2, a sequence of color-scale profiles of the gas saturation for one year injection is shown in Figure 5.7and and for 30 years injection is shown in Figure 5.8.

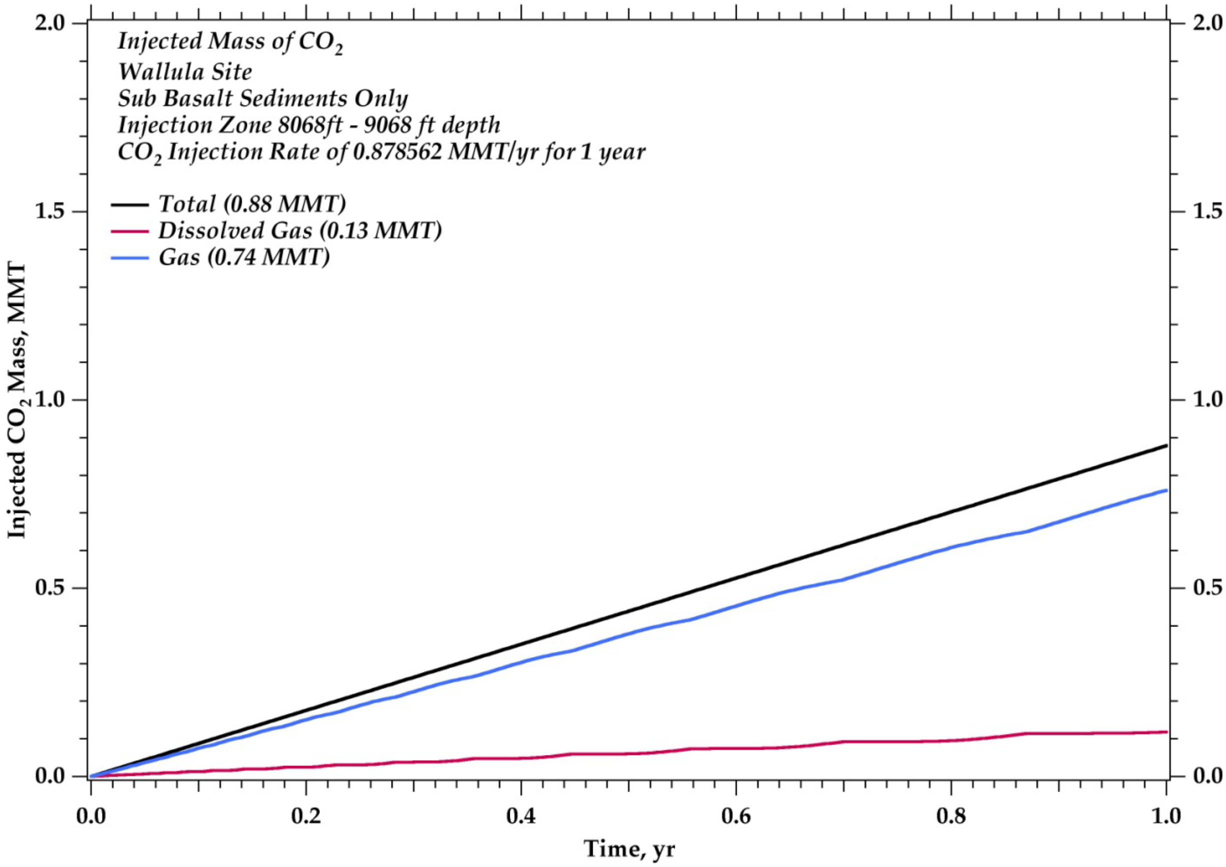

Figure 5.5. Calculated Mass of CO_2 Injected at a Rate of 0.878 562 MMT/yr into a Single Well Completed in the Sub-Basalt Sediments Only

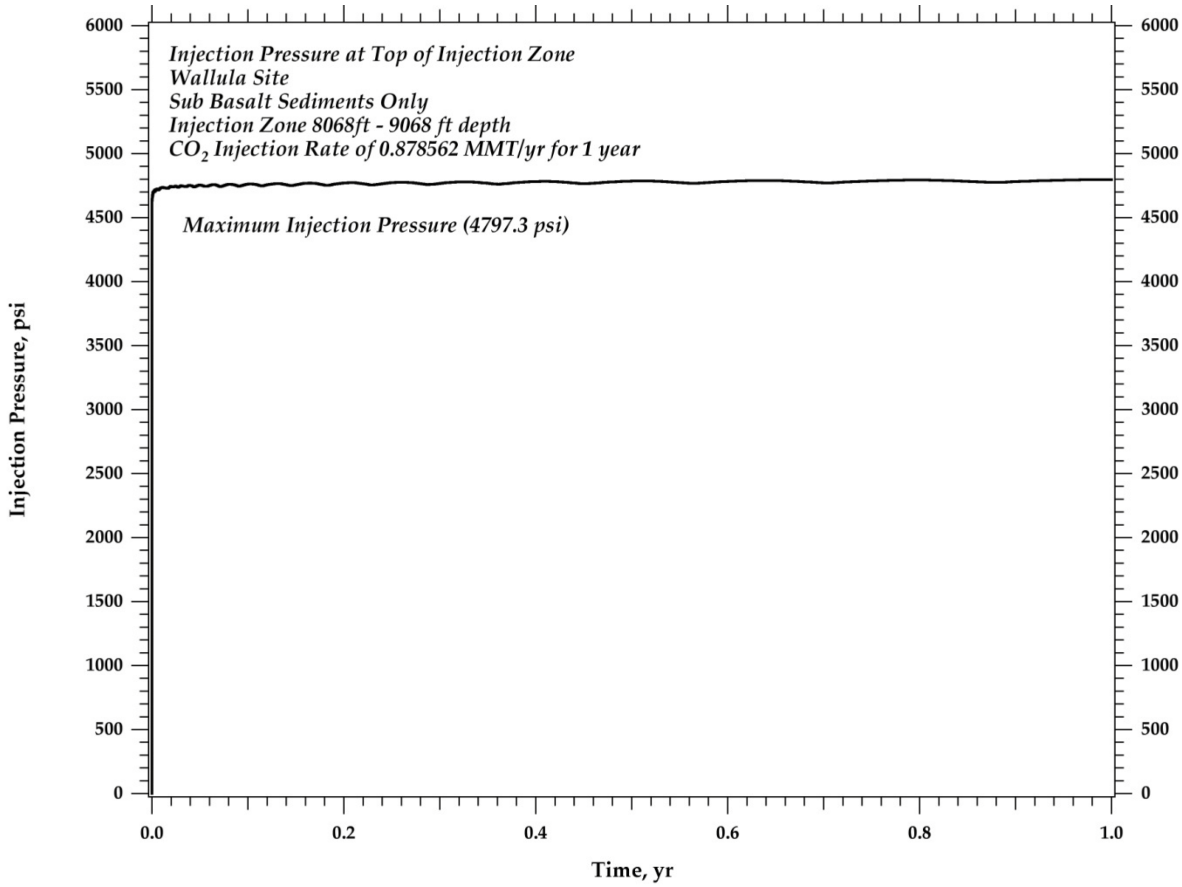

Figure 5.6. Injection Pressure for Scenario of CO_2 Injected at a Rate of 0.878562 MMT/yr into a Single Well Completed in the Sub-Basalt Sediments Only

A plot of the plume diameters defined by 95% of the injected CO_2 mass is shown in Figure 5.9 superimposed on a satellite image of the J.R. Simplot property. The results indicate that the selected site will ensure that injected CO_2 remains within the contiguous borders of the J.R. Simplot owned parcels with certainty for the 1-year Phase 2c operational period and provides sufficient area for continued operation for many years after conclusion of the Phase 2c operations under the ICCS project. Provided market conditions develop by 2015 that would support a commercial CCS business model, the selected site offers opportunity for Boise and its business partners to continue CCS operations into the future.

Based on these modeling results, and the arguments presented previously regarding favorability of other aspects of this sequestration site and overall project concept, the project team strongly believes that the BCCS project should proceed into Phase 2, conduct detailed site characterization, and design and costing analysis to support an informed go/no-go decision to proceed into construction and operations under Phase 2b and 2c. Details on the planned site characterization activities, and sequestration infrastructure necessary to carry out the project are described next.

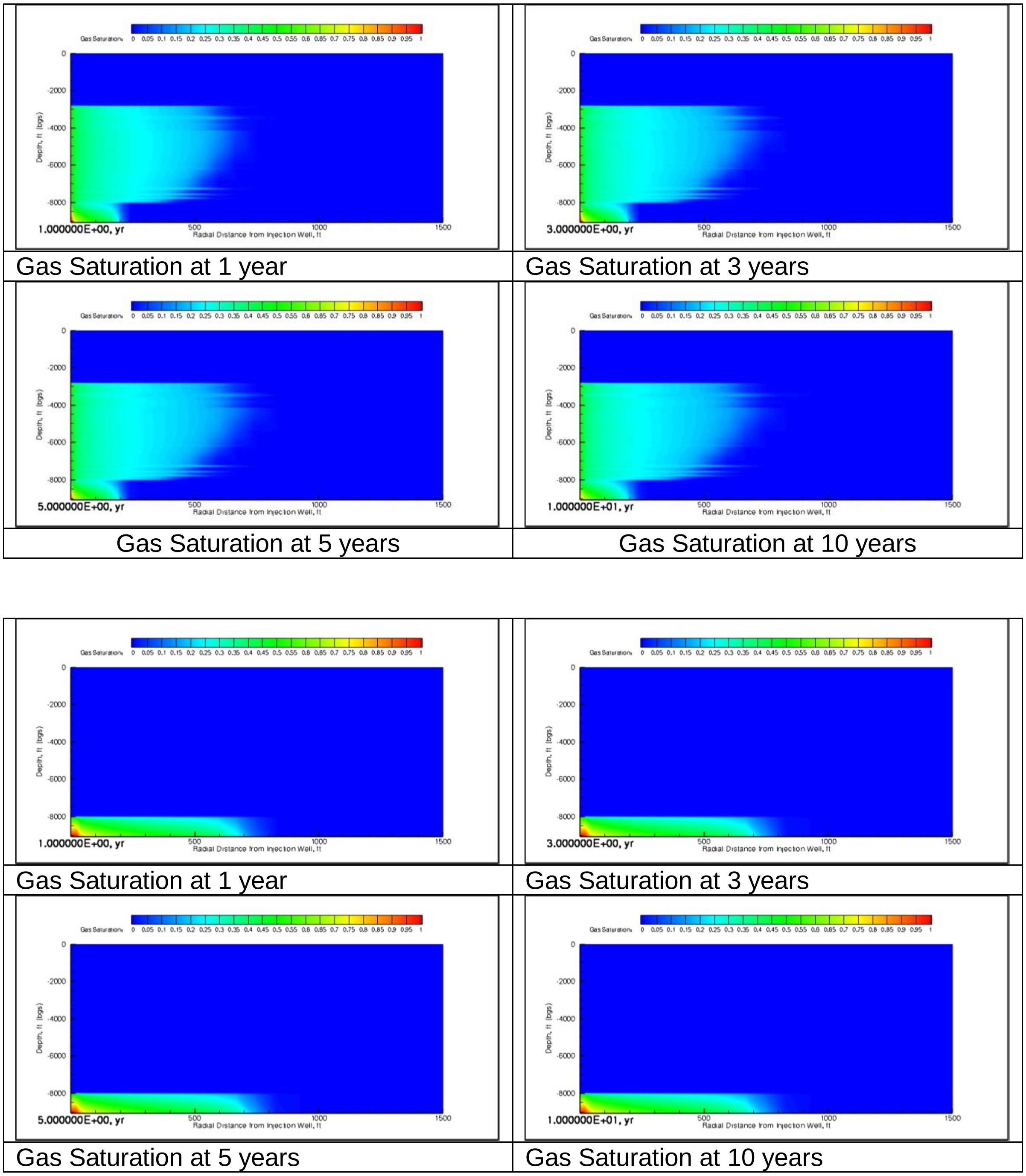

Figure 5.7. One-Year Injection Scenario. Gas-phase saturation profiles at 1, 3, 5, and 10 years for two different injection intervals. The upper set of images show the saturations for one-year injection into both the Lower Grande Ronde and Sub-Basalt sedimentary layers, and the lower set of images show the saturations for one-year injection into the sub-Basalt units only.

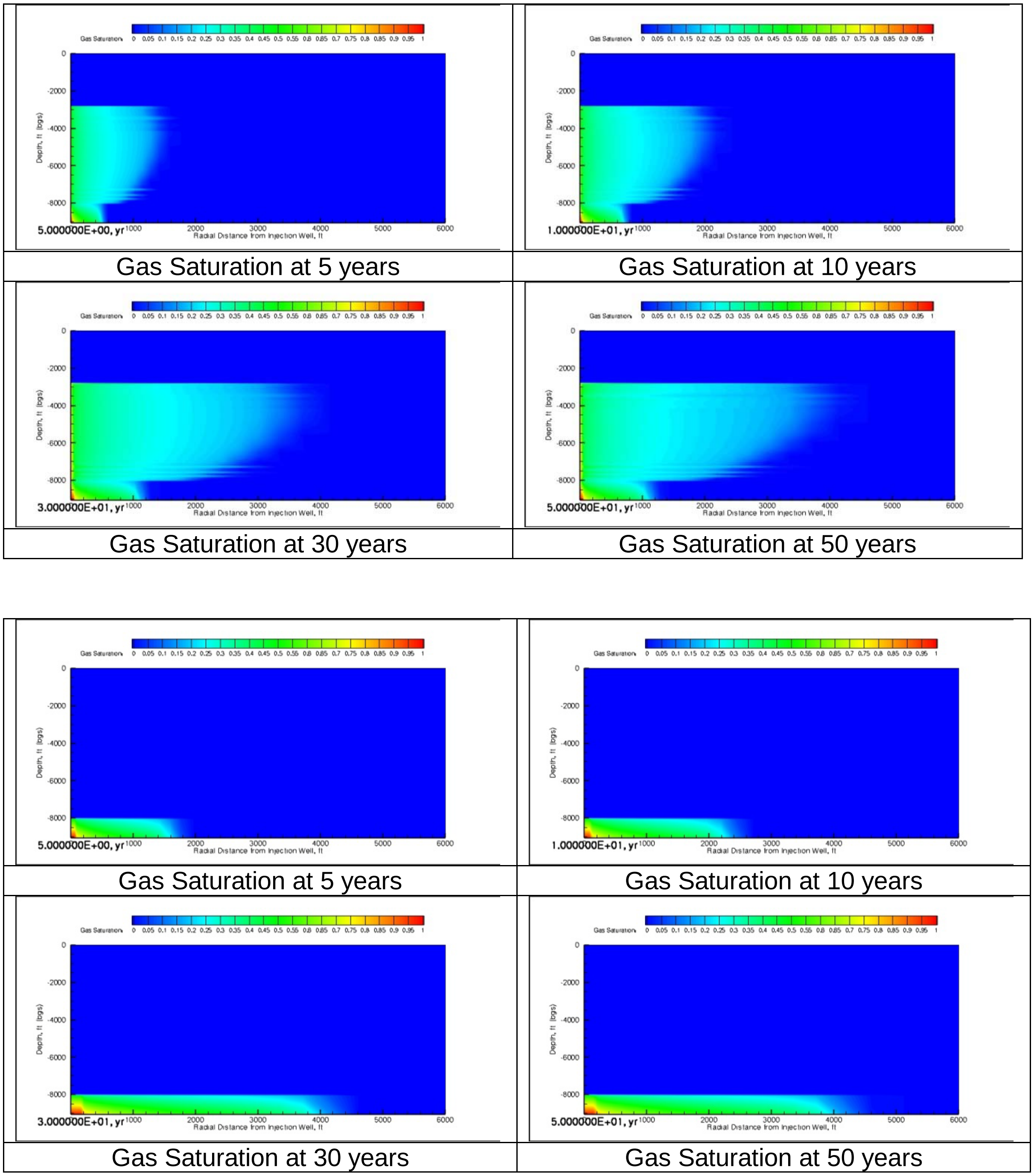

Figure 5.8. Thirty-Year Injection Scenario. Gas-phase saturation profiles at 5, 10, 30, and 50 years for two different injection intervals. The upper set of images show the saturations for 30 years of injection into both the Lower Grande Ronde and Sub-Basalt sedimentary layers, and the lower set of images show the saturations for 30 years of injection into the sub-Basalt units only.

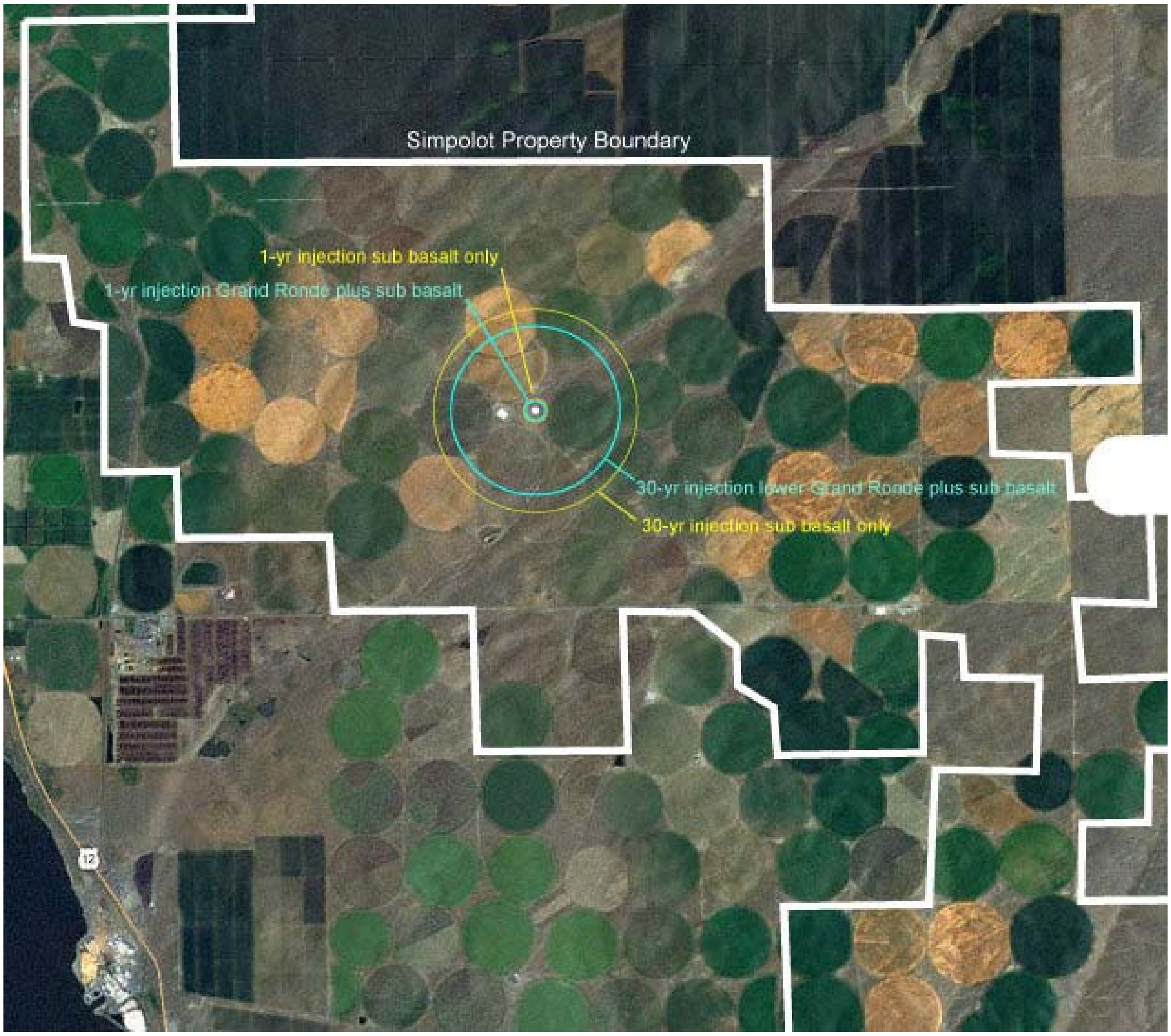

Figure 5.9. Plot of Plume Radii Under both injection Scenarios

6.0 Monitoring, Verification, and Accounting Program

Monitoring is a critically important component of the CO_2 sequestration program for the Wallula ICCS project. It has the following objectives:

- establish pre-injection/baseline conditions to compare with active injection and post-injection measurements;
- ensure and document effective injection well controls, specifically for monitoring the condition of the injection well and measuring injection rates, wellhead, and formation pressures;
- optimize the efficiency of the CO_2 storage;
- track location of CO_2 plume and phase distribution over time;
- detect leaks or seepage early and provide guidance for mitigation methods;
- demonstrate that CO_2 remains contained in the intended storage formations(s) (i.e., for credits/emissions trading/liability reduction);
- verify the quantity of injected CO_2 that has been trapped by various mechanisms;
- provide data to refine/calibrate reservoir models and other monitoring tools; and,
- reassure public that protection of human health and the environment are the highest priorities of the project team.

There is a diverse range of possible monitoring techniques, some invasive to the formation and more expensive, and some less proven, non-invasive and less costly techniques. The MVA Plan developed for this project is a balanced combination of these methods to achieve the objectives of the monitoring program at an acceptable cost. The major monitoring system components are employed across the CO_2 storage reservoir, caprock, drinking water sources, soil, and atmosphere. Monitoring wells provide for detection of changes in pressure, temperature, and liquid and gas composition. Monitors for potable aquifer and reservoir seal integrity are planned for this project. Shallow soil and atmospheric monitoring provide coverage over larger spatial scales but have limitations with respect to sensitivity. Each of the planned components of the monitoring program is briefly discussed next.

6.1 Soil Gas Monitoring Network

An important component of the monitoring program is shallow soil gas monitoring. Through use of perfluorinated carbon tracer compounds (PFTs) co-injected with the primary CO_2 stream that can be detected at parts per quadrillion levels (Watson et al., 2007), a highly sensitive detection network will be deployed within the area of influence around the injection well. We will use two PFTs, perfluorodimethylcyclobutane (PDCB) and perfluoro-1,3,5-trimethylcyclohexane (PTCH) and inject them to yield diluted concentrations in the injected CO_2 that are approximately 5 times above detectable levels. These two PFTs have substantially different molecular weights and thus should have different travel times in the subsurface. They are both likely to be transported ahead of any CO_2 release and thus will provide some lead time in detecting potential leakage.

Surface monitoring will be achieved by a combination of atmospheric and soil vapor sampling within a few hundred meters of the injection well. As shown in Figure 6.1, soil vapor samples will be collected within a 200-m radius of the injection well, and atmospheric samples will be collected at the perimeter of this area. Specifically, soil vapor samples will be collected using a buried porous pipe system designed to intercept the gases passing through a large cross-section of the soil. The pipe will form a crenulated closed loop; gas within the pipe will be circulated by a fan system through a sampling chamber containing activated carbon sample tubes for sorption of PFTs. The circular area will be divided into 4 quadrants, each of which will be sampled by a separate closed-loop system. The pipe will be located at 1 depth, well above groundwater levels which are tens of meters deep, and below common rooting depths for agricultural crops. Atmospheric samplers will consist of the same type of activated carbon sampling tubes suspended inside solar radiation shields and mounted on posts 2 m above the ground surface. These will integrate over a much larger area than the soil vapor samplers, thus providing some indication of leakage outside the perimeter of the circular area. Should leakage be detected, additional atmospheric samplers will be deployed to help isolate the source. A background site located upwind and several km from the injection point will also be equipped with an atmospheric and a soil-vapor collection system.

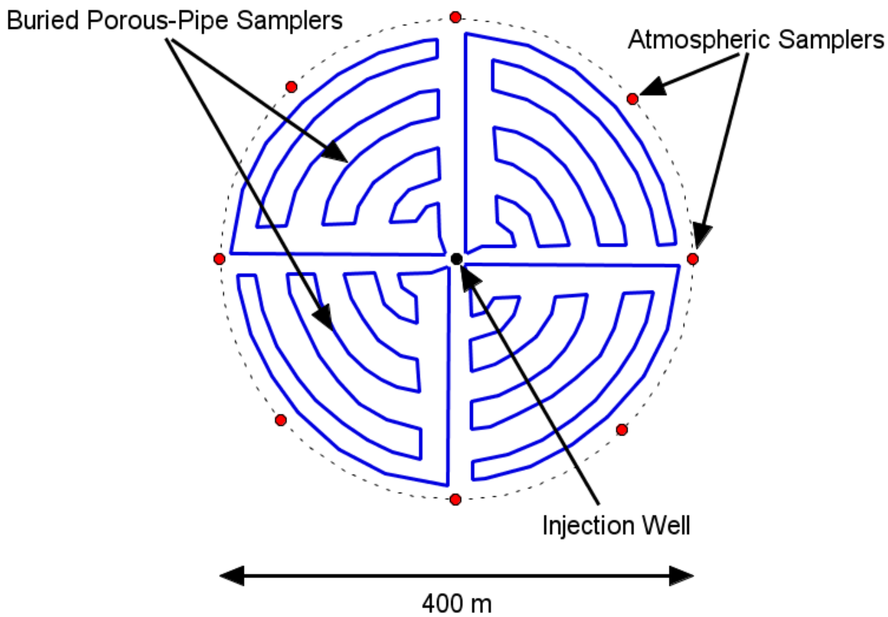

Figure 6.1. Layout for proposed surface monitoring system. Closed-loop porous pipe (blue line) is buried 1 m deep and within 200 m radius of injection well. Atmospheric samplers (red dots) are located 2-m above ground at perimeter of soil vapor sampling system.

Additional monitoring for PFTs will be accomplished by analysis of gas isolated from water samples collected in the observation wells. This will provide early warning in the highly unlikely occurrence of leakage and allow time for mitigation before surface breakthrough occurs.

The sampling scheme will involve monthly collection of samples during the first quarter after start of injection, followed by quarterly collection for the remaining operating period of the project. Duplicate sample tubes will be collected for each time period. To minimize analytical costs for the surface monitoring, one-fourth of these samples (single repeat at end of 1^{st}, 2^{nd}, and 4^{th} quarters) will be analyzed initially and the remainder archived. If positive results are obtained, additional archived samples will be analyzed. Analysis for at least six common PFTs will be performed by the Tracer Technology Group at Brookhaven National Laboratory using gas chromatography with electron-capture detection after a catalytic oxidation step to remove interferences. The four PFTs not injected will serve as background analytes for quality control.

6.2 Vertical Seismic Profiling

Seismic surveys are among the most important monitoring tools available for a CO_2 storage project. Seismic techniques measure the velocity and energy absorption of low-frequency sound waves, generated artificially or naturally, through the earth. The transmission is modified by the nature of the rock and the fluids it contains. Seismic wave generators and sensors may both be on the surface (conventional seismic) or the sensors may be deployed in wells with the sources on the surface (vertical seismic profiling). It is also possible for both the sensors and sources to be subsurface, causing the wave pulses to travel horizontally through the reservoir (inter-well or cross-well tomography). By taking a series of surveys over time, it is possible to trace the distribution of the CO_2 in the reservoir, down to resolution of free-phase CO_2 of approximately 5%.

Because VSP wellbore geophones are placed in the wellbore closer to reservoirs, and because signal to noise ratios and dominant frequency of VSP signals are higher than those measured by surface seismic, VSPs have considerable potential for imaging the near wellbore geological structure throughout the entire vertical section, and provide critical depth calibration for the surface seismic and microseismic events (PUJOL et al., 1989).

The first step in acquiring a VSP is to perform 2D modeling of the basalt layers and the seismic raypaths (Figure 6.2). This requires a basic geologic model of formation tops and a sonic log to provide local seismic velocities.

Vertical seismic profiles can be acquired with a wide variety of seismic source configurations A zero offset VSP provides imaging immediately around the wellbore; the seismic sources for offset VSP's are most commonly located as a series of stations at increasing distances from the well, in one or multiple directions. Imaging of fractures within the basalts will be optimized by using multi-component geophones in the wellbore. Converted P-S waves are more sensitive to fractures, and a comparison of the velocity of the P and P-S waves is often a powerful tool in identification of fracture intensity.

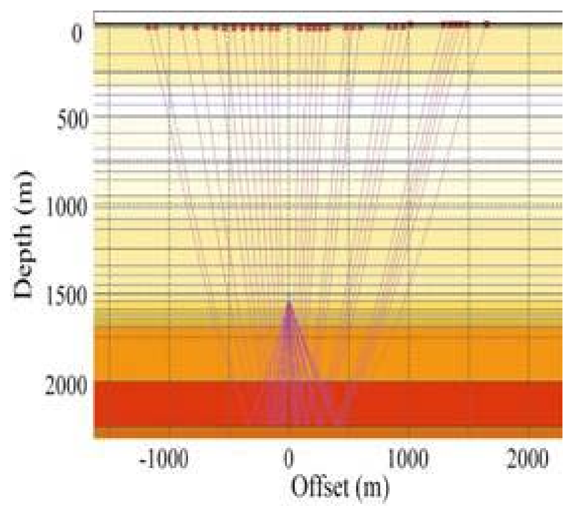

Figure 6.2. Example of the 2D modeling of rock layers and raypaths. This modeling is used to determine the optimal locations of the seismic source on the surface, and the geophone placement within the well.

For the ICCS Demonstration site, 2D VSP surveys will be conducted, using one monitoring well to accommodate the downhole geophone array, as a means for delineating details of the subsurface geology of the regional Umtanum caprock and vertical and horizontal extent of injected CO_2 over the section below the regional caprock, and as is feasible over deeper reservoirs . The survey design consists of a zero offset VSP and two walk away VSP transects, approximately 4,000 ft in length, centered on the monitoring well. A baseline survey will be conducted prior to injecting CO_2 and a post-injection VSP survey will be conducted after one year of CO_2 injection. The monitoring well will be located approximately 400 ft from the injection well along the azimuth of the horizontal component of maximum stress (N45W) and up dip (SE) to the subtle structural dip. A feasibility study will be conducted to determine the exact transect length, orientation and source spacing as well as appropriate depth of the monitoring well and the placement of the receiver array in the well. Monitoring assumptions for VSP monitoring is shown in Table 6.1.

Table 6.1. Monitoring Assumptions for VSP Surveys

MVA Technology	Site Details	Event Description
2D VSP	• Length of transects approx 4,000 ft with source points every 25 to 50 ft. • Direction of transects to be based on structure and stress orientation. • Feasibility study will determine details, including monitoring well depth, source spacing, and receiver placement/spacing.	• One baseline VSP survey and one repeat VSP survey after one year of CO_2 injection • Each survey will include a zero offset and two walk-away transects.

6.3 PSInSAR Imaging

Ground-surface deformation resulting from injection of CO_2 can, under certain conditions, be measured by satellite InSAR (interferometric synthetic aperture radar; PSInSAR is an international trademark for InSAR technology). InSAR uses two or more synthetic aperture radar images to generate maps of surface deformation using differences in the phase of the waves returning to the satellite. In ideal conditions, InSAR is highly accurate providing sensitivity and accuracy approaching one millimeter in the vertical direction.

During a monitoring event, the satellite emits beams of radar waves towards the earth and records the reflect rays. The information gathered from the satellite includes the signal intensity and the phase of the wave. The intensity can be used to characterize the ground material and the material's orientation while the phase can be used to measure height. InSAR's measurements are taken line-of-sight with the satellite. Satellites are not pointed directly at the earth, but at an oblique angle that could be as high as 30 degrees meaning that the InSAR is actually measuring the component of the surface motion that is oriented obliquely towards the satellite. Over time, a location can experience a significant horizontal motion in addition to the vertical motion, rendering the trigonometric methods of calculating vertical motion invalid. GPS provides an ideal anchor allowing line-of-sight InSAR measurements to be accurately converted into true vertical motions. In effect, the InSAR results are locked into the GPS in a geomechanically acceptable way.

Repeat InSAR surveys can detect topographic change as small as several millimeters in sparsely vegetated areas where good correlation between successive images can be obtained. Lateral resolution is tens of feet, suggesting that InSAR should be able to detect subtle topographic response to elastic and inelastic strata expansion that commonly accompanies subsurface fluid injection. Areas where ideal surface conditions do not exist in terms of reflectivity corners are added as reflection points for the radar.

At the Boise-Cascade Site, a baseline InSAR survey will be taken prior to injection and two other surveys will be completed during the 1 year injection period. Monitoring assumptions are summarized in . Integrating borehole tiltmeters and InSAR with GPS is an excellent method of compensating for each of their shortcomings. InSAR topographic change and tiltmeter data can be combined to examine the surface projection of plume migration and to compare surface change data with modeled and subsurface data on plume extent. Monitoring assumptions for InSAR technology are shown in Table 6.2.

Table 6.2. Monitoring Assumptions for InSAR

MVA Technology	Site Details	Event Description
InSAR	• Corners will be placed on site for reflectivity	• One baseline event prior to injection • Two events during the one year injection period

6.4 Tiltmeter Array

An array of borehole tiltmeters will be installed around the injection well and in an area overlying and beyond the one year CO_2 plume for early detection of injection related surface deformation. Borehole tiltmeters offer continuous deformation measurements with extremely high sensitivity and accuracy, allowing reservoir-level processes to be observed quickly before deformation magnitude enters the lower sensitivity regime of InSAR or GPS. The extreme sensitivity of the meters allows for the identification of subtle deformation patterns that are superimposed on top of broad, regional deformation originating from bulk emplacement of CO_2 within the target reservoir. The surface deformation caused by the subsurface fluid injection is capable of being of measured in the microradians range.

At the ICCS proposed sequestration site, approximately 75 tiltmeters will be installed around the injection well in a footprint with a radius equal to 100 to 120 percent of the injection depth plus the modeled radius of the injection plume (Figure 6.3). Although equal spacing is ideal, the placement of the meters can be flexible to accommodate agricultural land use issues and cultural features. With the ability to measure data at the microradian level, the tiltmeters are sensitive to various surface phenomena including daily temperature variations. To account for this, the tiltmeters are placed shallow (40 ft) boreholes and cemented in place to isolate them from surface noise and thermal effects. The meters are equipped with a battery/solar power system and radio for remote data transmission to a base station where the data is collated and uploaded in real-time through a telemetry system. A GPS reference station and three GPS measurement monuments containing solar power, antenna and radio systems will be installed for continuous, high-precision 3-axis monitoring. Background data will be continuously collected at the site for at least two months prior to the start of injection to determine instrument behavior and noise Data collection will continue through the year of injection and results will be processed monthly and posted on the vendor's secure website. Monitoring assumptions for the ICCS Site are summarized in Table 6.3.

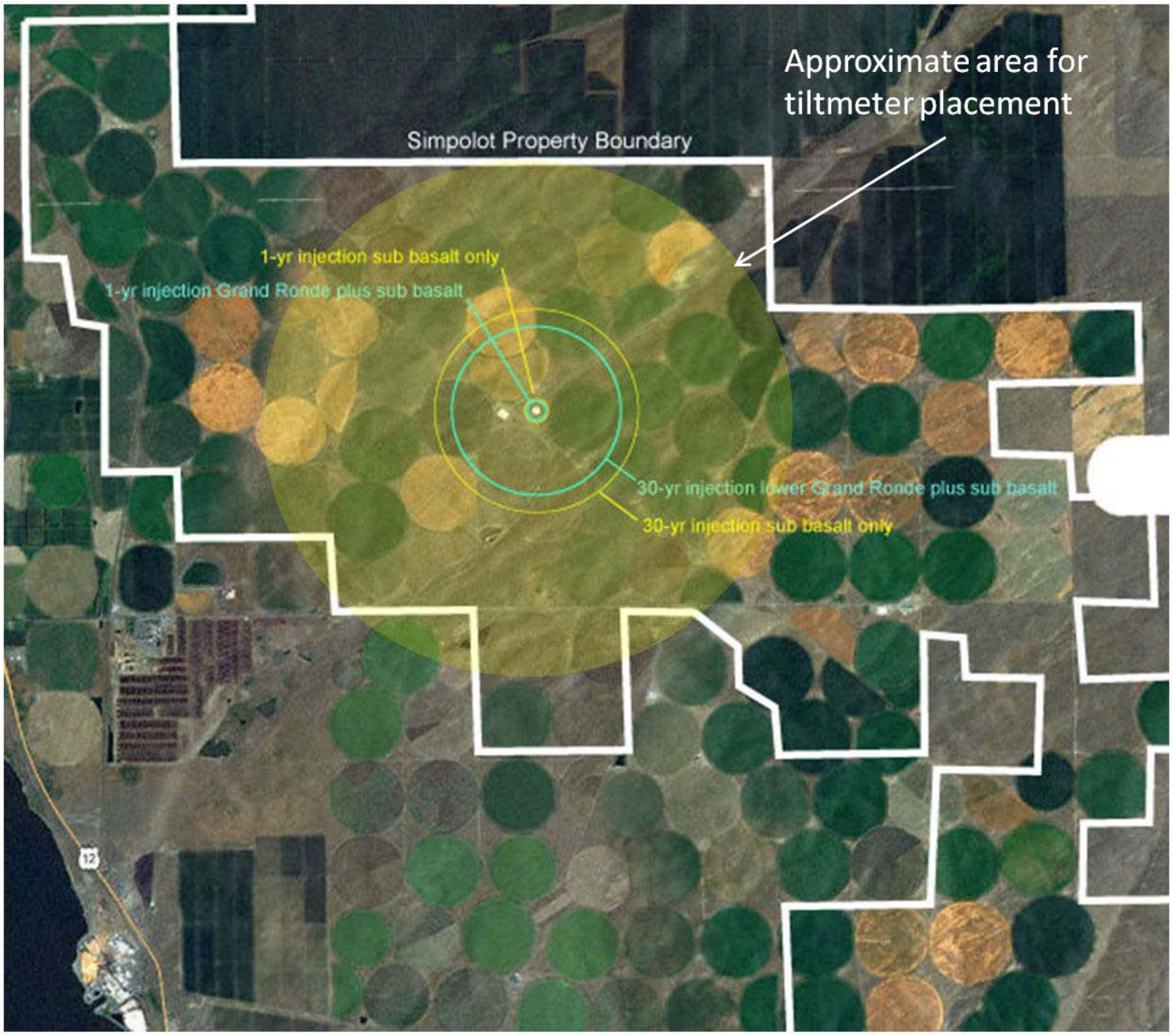

Figure 6.3. Area of ICCS Site Tiltmeter Monitoring Shown in Yellow

Table 6.3. Monitoring Assumptions for Borehole Tiltmeters

MVA Technology	Site Details	Event Description
Tiltmeters	• Array of 75 tiltmeters placed around injection well • 1 base GPS station for data collection • 3 GPS monuments	• Continuously collect data for two months prior to injection • Continuously collect data through the one year injection period • Monthly results posted to vendor's website • Quarterly reports

6.5 Monitoring Well

A multi-level monitoring well will be located approximately 400 ft south east of the injection well, along the azimuth of the horizontal component of maximum stress (N45W) and up dip to the subtle structural dip. A feasibility study will be conducted to determine the appropriate depth and location of the monitoring well. The monitoring well system (Figure 6.4) is designed to monitor three zones, but could easily be expanded to include additional shallow aquifers. The current three zones are, (in descending order): the porous flow top above the Umtanum regional caprock seal, the first porous flow top below the Umtanum seal, and the uppermost CO_2 injection zone.

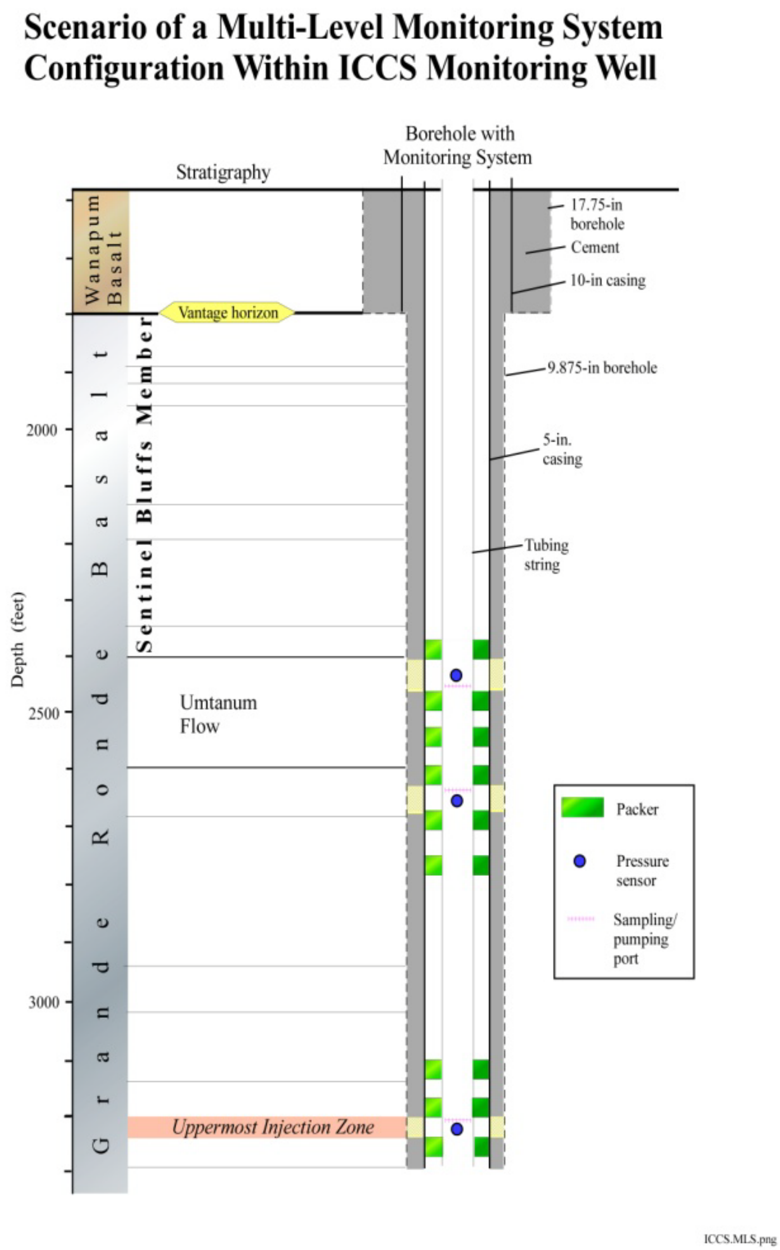

Figure 6.4. Proposed Configuration of multi-level monitoring system

7.0 Conclusions

The project will result in unique commercialization avenues due to the opportunity for "carbon negative" operations. The commercial potential of sequestration would also be expanded by the project's focus on large-scale geologic sequestration in basalt formations, which may be replicable in other areas of the country (e.g. Southeastern U.S.) where deep basalts are present but conventional storage options are limited (MCGRAIL et al., 2006). Although the basic EFG+ technology has been commercially proven, the Boise installation would be the largest to date, and the first on a biomass flue gas source. The EFG+ solvent formulation and process configuration have been significantly improved in the past several years. Demonstrating these advancements on a large scale would certainly improve the commercialization opportunities of the EFG+ technology for broader CCS markets.

Table 7.1 shows the energy, operating and capital cost estimates for the proposed biomass boiler and CCS system. Three columns of data are shown in the analysis. The first column shows the data for the current state of the Boise mill with respect energy, costs, and CO_2 sources impacted by the proposed project. The second and third data columns show the same data after the proposed project implementation, with and without the CCS system running, respectively. The biggest shift shown in Table 7.1 is the displacement of the Boise mill's natural gas boilers and current hog fuel boiler (HFB). These boilers currently generate 350,000 lbs per hr of steam at 250 psig/ 500ºF. The new biomass boiler would be capable of producing this same steam supply, in addition to 260,000 lbs per hr of steam for the CO_2 capture system and 11.2 MW electricity output. If the CCS system were not operated (last column in Table 7.1) due to insufficient CO_2 valuation, etc. the proposed biomass boiler would be capable of fully condensing the CO_2 capture system steam into an additional 23.5 MW of electricity.

The fossil-fuel-based emissions are summarized in Table 7.1 to determine the net CO_2 impact. Currently, CO_2 from natural gas sources generates 145 kilotons of CO_2 per year that would be eliminated with the biomass boiler implementation. Furthermore, the equivalent CO_2 from generating 11.2 MW of electricity is 38.4 kilotons per year would be eliminated in the first of the two biomass scenarios (CCS online), and reduced by 80.6 kilotons per year in the CCS offline scenario. Finally, the fossil fuel equivalent of the sequestered biomass-based is 1.8X greater than from equivalent fossil fuel sources (SPATH and MANN, 2004). This results in an equivalent reduction in CO_2 of 986 kilotons per year from sequestration alone. Using these values the net CO_2 reduction for the proposed project, versus current state, is 1169 kilotons of CO_2 per year with the CCS system online, and 264 kilotons with the CCS system offline. Indeed, both of these operational modes offer a significant net reduction in CO_2 emissions.

From an economics standpoint, operating the CCS system would require CO_2 credits via a carbon tax or other market mechanism. Based on the pricing assumptions in Table 7.1, the breakeven point for operating the CCS system versus producing net additional electricity corresponds to roughly $20 per ton of CO_2, which is considered a conservative value in many carbon market price projections. Table 7.1 shows the net revenue savings shown for the biomass boiler/CCS system at approximately $17 million per year for both the CCS online and offline cases. This level of savings justifies the industrial cost share portion of the proposed project and is believed to be consistent with a return on capital investment for similar future investments once the technology is demonstrated, monetization methods CO_2 credits have been established, and equipment costs have been optimized.

Table 7.1 Estimates of Operating Costs/Savings and Capital Costs for the Proposed Biomass Boiler and CCS System

	Current State	New Biomass Boiler with CCS. Old HFB Shut Down.	
		CCS Online	CCS Offline
Existing Natural Gas Fired Boilers			
Natural gas consumption (MMBTU/hr)	220		
Steam supplied to mill (250 psig/ 500°F, kpph)	200		
Existing Hog Fuel Boiler			
Hog fuel (biomass) consumption (dry, lbs/hr)	26,301		
CO2 generated from hog fuel (tons per year)	220,233		
Amount of natural gas co-firing on a BTU basis	20%		
Natural gas consumption (MMBTU/hr)	58		
Steam supplied to mill (250 psig/ 500°F, kpph)	150		
New Hog Fuel Boiler (no natural gas co-firing)			
Hog fuel (biomass) consumption (dry, lbs/hr)		111,970	111,970
CO2 generated from hog fuel (tons per year)		937,576	937,576
Total steam production (1000 psig & 900°F, kpph)		562	562
Steam supplied to mill (250 psig/ 500°F, kpph)		350	350
Captured CO2 (tons per yr)		547,500	0
Steam required for CCS system (kpph)		260	0
Net new electrical power generation (MW)		11.2	34.7
CO2 Emissions Summary for Fossil Fuels			
Total CO2 generated from natural gas (tons per year)	145,065	0	0
Equiv CO2 from electrical gen (11.2 MW basis, tons/yr)	38,411	0	-80,594
Fossil fuel equivalent of captured CO2 (1.8X, tons/year)		-985,500	0
Total equivalent CO2 generated (tons per year)	183,475	-985,500	-80,594
Annual Operating Costs and Savings			
Natural gas cost ($ per MMbtu)	$5	$5	$5
Hog fuel cost ($ per MMbtu)	$3	$3	$3
Electricity price ($ per MW-h)		$50	$84
Market value of CO2 ($ per ton)	$0	$19	$0
Natural gas cost (millions per year)	$12	$0	$0
Hog fuel cost (millions per year)	$6	$25	$25
Approximate non-energy costs for CCS (millions per year)	$0	$3	$0
Electricity savings/ revenue (millions per year)	$0	$5	$24
Carbon credit revenue (millions per year)	$0	$22	$0
Net savings versus current state (millions per year)	***$0***	***$17***	***$17***
Capital Costs			
New biomass power boiler system (millions)	$0	$250	$250
CO2 capture plant (millions)	$0	$168	$168
Injection well/ pipeline/ monitoring (millions)	$0	$40	$40
Total project cost (millions)	***$0***	***$458***	***$458***

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9.0 Acronyms

ACWP	Actual Cost of Work Performed
AKART	All Known, Available, and Reasonable Methods
BAC	Budget at Completion
BCWP	Budgeted Cost of Work Performed
CCS	Carbon Capture and Sequestration
CFR	Code of Federal Regulations
CDD	Conceptual Design Document
CRBG	Columbia River Basalt Group
CV	Cost Variance
DCC	Direct Contact Cooler
DEQ	Department of Environmental Quality
EAC	Estimate at Complete
EFG+	Econamine FG Plus^{SM} Technology developed by Fluor Corporation
EPA	Environmental Protection Agency
ETC	Estimate to Complete
EV	Earned Value
EVMS	Earned Value Management System
EPCM	Engineering, Procurement, Construction, Management
ESSB	Engrossed Substitute Senate Bill
GHG	Greenhouse Gas
GS	Geologic Sequestration
HS&E	Health, Safety, and Engineering
HSS	Heat Stable Salts
ISO	International Standard Organization
MCL	Maximum Contaminant Level
MEA	Monoethanolamine
MMT	Million Metric Tons
PMO	Project Management Office
PMP	Project Management Plan
PNWD	Pacific Northwest Division
PNW	Pacific Northwest
ppmv	Parts per Million by Volume
QA	Quality Assurance
RCP	Regional Carbon Partnership
SBMS	Standards Based Management System
$SCCO_2$	Supercritical CO_2
SOPO	Statement of Project Objectives
SV	Schedule Variance
UIC	Underground Injection Control
WADoE	Washington State Department of Ecology
WAC	Washington Administrative Code
VAC	Variance at Complete