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Field Activity Plan: Characterization Test for CO_2 Sequestration in the Columbia River Basalt Group

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1.0 FIELD TEST OBJECTIVES

This field test is designed to confirm the feasibility of permanently and safely sequestering large quantities of CO_2 within deep flood basalt formations. Because large-scale basalt formations occur in numerous locations in the United States and around the world (MCGRAIL et al., 2006), this research is expected to result in valuable data that can be used to support CO_2 emission reduction strategies in this country and elsewhere, particularly India. Detailed information on worldwide continental flood basalts and their relative volumes can be found in McGrail et al. (2003).

Specific technical objectives of the proposed 36 month field test include 1) assess the local/large-scale basalt reservoir and adjacent formation responses to CO_2 injection, 2) track the migration of the CO_2 within the injection reservoir, and evaluate containment of the CO_2 for comparison with reservoir modeling predictions, and 3) evaluate the rate of CO_2 mineralization for comparison with previously developed laboratory-derived predictions.

2.0 SITE DESCRIPTION

The basalt field pilot test is proposed to be conducted within a deep flood-basalt formation zone that is part of the Columbia River Basalt Group (CRBG). Regionally, basalt formations of the CRBG are extensive covering over 77,200 mi^2 of portions of eastern Washington, northeastern Oregon and western Idaho (Figure 2.1), and with a total estimated volume of more than 53,700 mi^3 (REIDEL et al., 2002). Collectively, over 300 individual CRBG flows have been identified within the region, which attain a maximum composite thickness of greater than 16,000 ft within the central portion of the Columbia Basin (Figure 2.2).

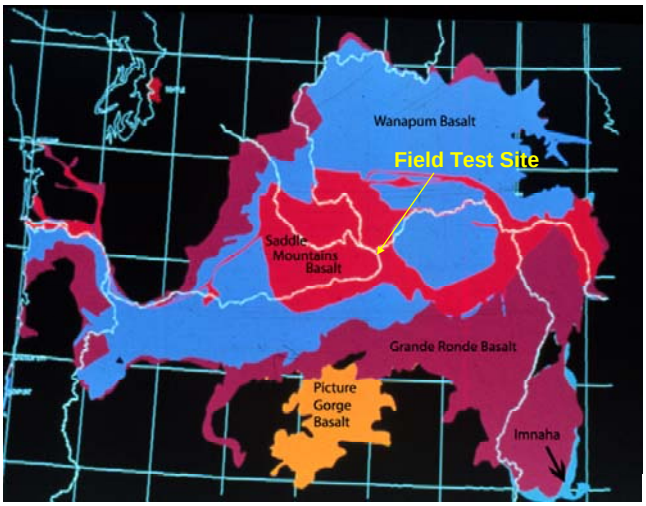


Figure 2.1. Surface Areal Extent of Basalt Formations of the Columbia River Basalt Group (modified from Reidel et al. 2002)

The location of the proposed field test site is shown in Figures 2.1 and 2.2 with respect of regional areal extent, composite thickness, and geologic structural relationships within the CRBG. Anticipated subsurface geologic conditions at the field test site are shown in Figure 2.3, which are based on extrapolations from surrounding borehole characterization information. As shown, the expected approximate subsurface formation thicknesses at the field test site (from surface) include: 60 to over 230 ft of surficial alluvial deposits; 800 ft of combined Saddle Mountains Basalt Formation (5 basalt flows) and sedimentary interbeds of the Ellensburg Formation (4 to 5

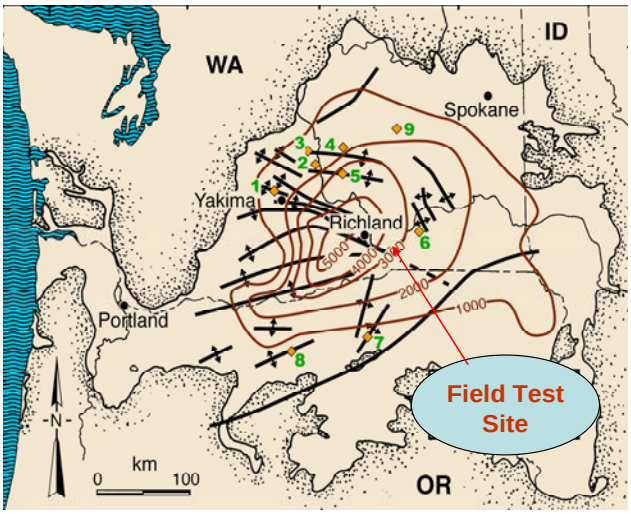


Figure 2.2. Regional Thickness and Structure Map for the Columbia River Basalt Group (modified from Reidel et al., 2002)

sedimentary interbeds); 900 ft of Wanapum Basalt (6 to 9 basalt flows); 5 to 40 ft of Vantage interbed/paleosol horizon; >6,000 ft of Grande Ronde Basalt/undifferentiated CRB (>20 basalt flows); >1,000 ft undifferentiated sub-basalt, sedimentary formation deposits; and the underlying crystalline/metamorphic basement complex. Of particular hydrogeologic importance is the presence of the Vantage interbed/paleosol horizon that serves as a regional low permeability horizon separating groundwater within the underlying Grande Ronde and overlying Wanapum Basalts (Reidel et al., 2002). Groundwater within the Grande Ronde Basalt and below is expected to be brackish and sulfide-rich, with high concentrations of fluoride that exceed maximum concentration limits as specified in National Primary Drinking Water Regulations (40 CFR 141.62).

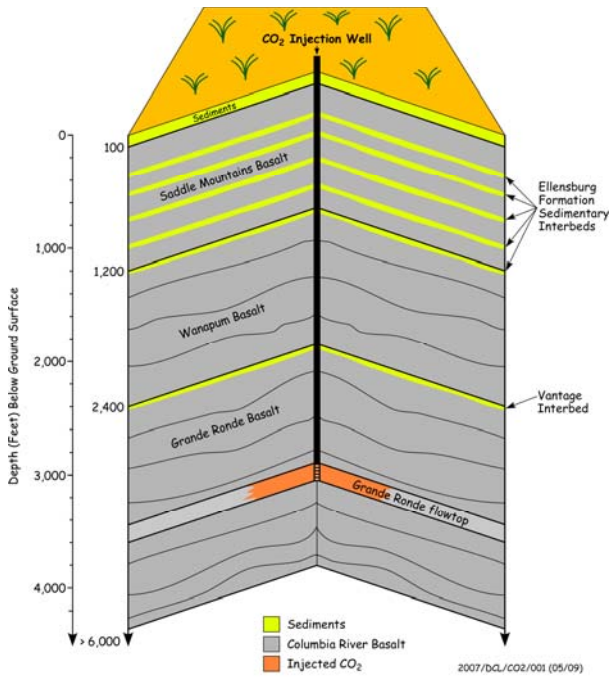


Figure 2.3. General Stratigraphic/ Depth Relationship of Injection Zone and Overlying Formations

The target injection horizon for the field pilot study will be a permeable interflow zone within the Grande Ronde Basalt, at a depth of ≥700 ft below the Vantage interbed horizon that represents the formational contact between the Wanapum and Grande Ronde Basalts (see Figure 2.3). Basalt interflow zones are composite permeable interflow features within basalts that consist of a rubbly basalt flow top and the adjoining, overlying brecciated basalt flow bottom. Individual basalt interflow zones are separated by relatively dense and low-permeability flow interior sections that comprise the bulk of the composite basalt formation section. The target interflow zone for the field test study will be selected based on results of the Phase 1 hydrologic test characterization conducted at the site. The initial Phase 1 characterization will likely identify a number of candidate Grande Ronde interflow zones suitable for CO_2 injection within the depth interval of ~2,500 to 4,000 ft; however, the initial target horizon will be the shallowest interflow zone having sufficient thickness (≥30 ft), permeability (k ≥ 1 darcy), effective porosity (n_e ≥ 0.1), and overlying caprock thickness (≥ 100 ft). The depth selection criteria (i.e., shallowest acceptable Grande Ronde reservoir horizon) is based on facilitating geophysical monitoring/imaging of the CO_2 injected as part of the field test pilot study.

The proposed field test location is situated approximately 11 miles south of Pasco, Washington in lightly inhabited agricultural and industrial-zoned land in western Walla Walla County, within eastern Washington State (Figure 2.4). Figure 2.5 shows a satellite image that displays general features in the immediate area of the proposed field test pilot study, which is located in the northern ~700 acre parcel of the Port of Walla Walla, Attalia Property 1, within the northern half of Section 2, Township 7N, Range 31E, and the southeast quarter of Section 35, Township 8N, Range 31E. If necessary, the proposed field test may extend to the western portion of Section 1, Township 7N, Range 31E. The field test site is located ~1 to 2 miles east of the Columbia River and northeast of the Boise Cascade Corporation industrial facility (Figure 2.5). The test site is surrounded to the north by the J.R. Simplot Company feedlot and private railroad line, to the east by the Worden Farms irrigated agricultural circles, and to the south by the Port of Walla Walla fiber farm development. Running approximately N-S adjacent to the western boundary of the site, is U.S. Highway 12. A small gravel road provides access to the site.

A distinct advantage of the proposed test study area is its location within the Columbia Basin where the composite basalt formations have the highest aggregate thickness within the region, i.e., ≥ 10,000 ft for the test study area (see Figure 2.2). A disadvantage for the test study area is the lack of available site-specific information of the hydrogeologic characteristics for deep basalt formations underlying the site. Detailed hydrogeologic characterization information for deep basalt formations is available, however, from the Hanford Site (located ~25 mile northwest of the site; see Figure 2.4) as summarized in DOE (1988) as well as in the report on a Canoe Ridge natural gas storage test well (REIDEL et al., 2002), located ~35 miles southwest of the Wallula site, that can be used for test site characterization design and expected basalt reservoir performance.

Figure 2.4. Regional Location Map of Field Test Site

Of possible concern to local residents and businesses is the potential for the CO_2 pilot test study to disrupt or interfere with daily business operations and residential activities. Under the assumption of overlying caprock containment, numerical simulations indicate a limited CO_2 plume within the injection interflow reservoir, extending only ~500 ft from injection borehole location. Because of the limited CO_2 volume injected, restricted plume migration and depth of separation, there is virtually no possibility that the CO_2 pilot test study will interfere with distant surrounding business operations or residential activities. The nearest business is the J.R. Simplot Company feedlot located more than 0.5 miles to the north and the nearest resident is in the town of Wallula approximately 2 miles to the south.

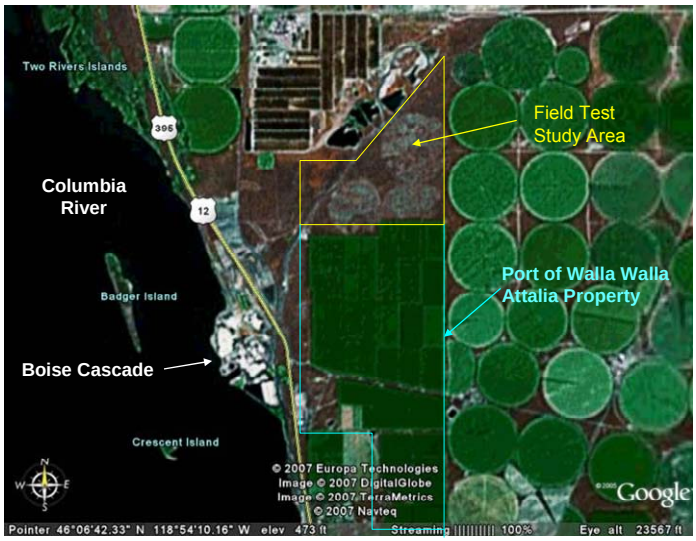


Figure 2.5. Google Earth View of Field Test Study Area

3.0 SCHEDULE

A detailed schedule and list of tasks for execution of this Field Activity Plan is provided in the Appendix. Key milestones identified in this schedule are as follows:

Table 3.1. Key Milestones for Basalt Characterization Field Study

Milestone Description	Completion Date
Complete 2D Seismic Survey	08/31/2007
Washington State DOE Issues UIC Permit	11/09/2007
Begin CO_2 Injection	06/27/2008
Complete Crosswell Seismic Surveys	09/04/2008
Complete Basalt Core Sample Retrieval	04/28/2010
Decision on Transition of Wells to Commercial Operations	06/16/2010

Post-injection monitoring will begin immediately after CO_2 injection is complete, and will continue through the end of the project. A decision will be made at the end of the testing as to whether the wells will be utilized to support commercial operations on the site or plugged and abandoned.

4.0 REGULATORY COMPLIANCE & PERMITTING

Because this field test is funded in part by the U.S. Department of Energy, the project must comply with National Environmental Policy Act (NEPA) procedures. The function of a NEPA review is to evaluate potential environmental impacts associated with federally-funded projects and consider methods to minimize or eliminate those impacts. NEPA compliance will be coordinated with DOE National Energy Technology Laboratory staff.

In addition, permitting for this study will be coordinated with the Washington State Department of Ecology. The CO_2 injection well will be registered as appropriate under Washington Administrative Code 173-218, the "Underground Injection Control program." A Class V injection well permit will be submitted, which is consistent with national EPA guidance on permitting pilot-scale tests under the regional carbon partnerships.[1] Based on regional inferences, groundwater within the Grande Ronde Basalt and underlying formations is expected to be brackish and sulfide-rich, with high concentrations of fluoride that exceed maximum concentration limits as specified in National Primary Drinking Water Regulations (40 CFR 141.62).

The following additional requirements have been identified:

Water Effluents

Discharges of carbon dioxide and tracer materials to the subsurface will comply with the "State Waste Discharge Permit Program" and "Water Quality Standards for Ground Water" requirements as described under Washington Administrative Code 173-216 and 173-200. Washington Department of Ecology will be consulted to determine whether a Waste Discharge Permit will be required.

[1] http://www.epa.gov/safewater/uic/pdfs/guide_uic_carbonsequestration_final-03-07.pdf

Air Emissions

As discussed in Section 6.0, gas phase tracers are planned to be used in this study that are injected separately or are co-injected with the CO_2. Air emissions associated with these tracers and CO_2 do not require permits or approvals from the State of Washington either because the project is a source type not subject to the regulations, or the tracers are not subject to regulation. However, one proposed tracer, SF_6, is subject to regulation for other source types and a voluntary notification to State of Washington Department of Ecology staff will be made concerning the planned use and injection of a minor amount of this tracer.

Biological Resources

In accordance with the Endangered Species Act and other resource protection laws, Battelle biologists will survey the proposed injection site for threatened or endangered plant or animal species as necessary. Based on preliminary reviews, it appears unlikely that sensitive plant or animal species are present at the site.

Cultural Resources

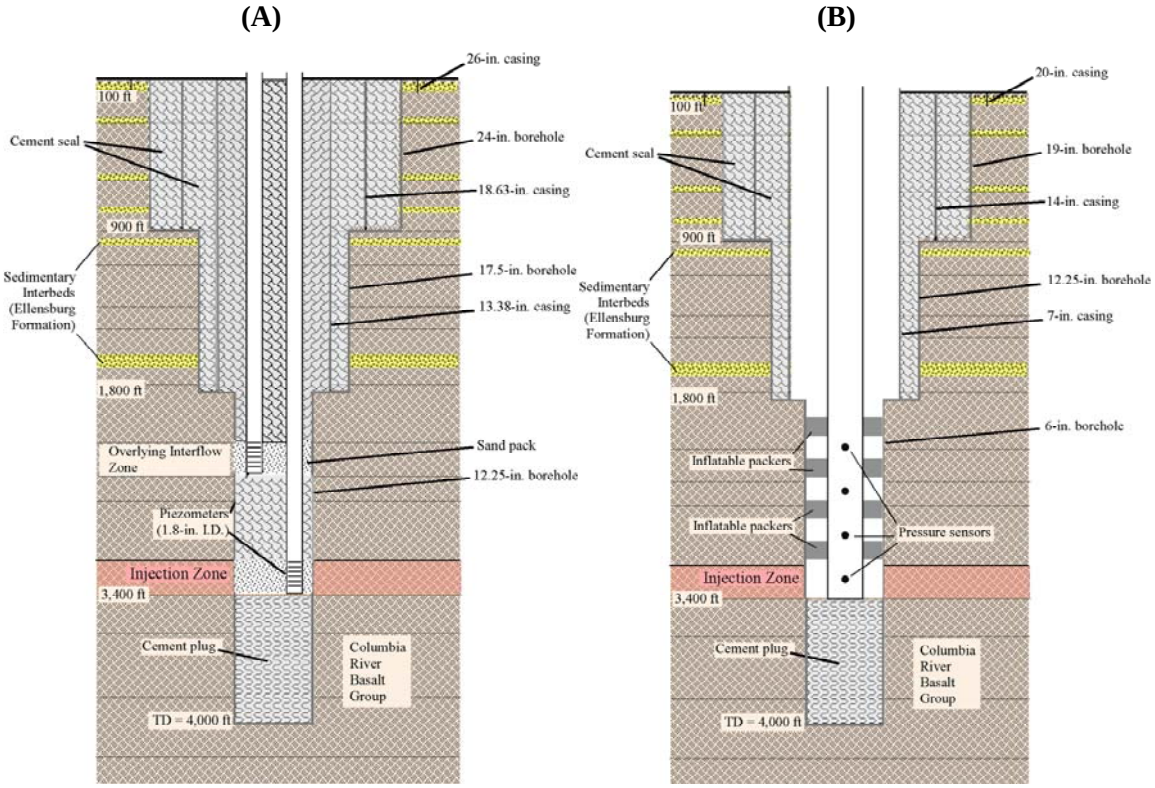
In compliance with the National Historic Preservation Act, Battelle archeologists will survey the proposed injection site for the presence of sensitive historic or prehistoric artifacts as necessary. Due to the previously disturbed nature of the site, it seems unlikely that sensitive artifacts will be found.

5.0 SITE PREPARATION, EQUIPMENT, AND MATERIALS

Site preparation includes all activities associated with preparing the field test location to facilitate characterization and monitoring of the pre-injection, injection and post-injection phases. This includes: site grading; installation of dedicated power; delivery and installation of surface/containment tanks; trailer/housing installations; drilling of the injection and monitoring boreholes; and installation of surface CO_2 monitoring equipment at and surrounding the borehole sites.

The field test borehole network for providing the initial deep hydrogeologic characterization information for field test site will include: 1) Pilot Borehole; 2) Injection Borehole; 3) three shallow basalt (i.e., ~900 ft) geophysical monitoring boreholes for imaging the areal extent of the injected CO_2 within the injection reservoir, and 4) two geochemical assessment coreholes. The Pilot Borehole will be the principal borehole for acquiring detailed hydrogeologic information for the site (i.e., hydrologic testing, hydrochemical sampling, wireline geophysical surveys) and will be drilled initially to a depth of ~4,000 ft. Based on the results obtained during the Phase 1 pre-injection characterization (see Section 6.1), a suitable basalt interflow zone will be selected for the CO_2 field test pilot study injection. The borehole will be cemented back to immediately below the injection interflow zone horizon, and either a nest-piezometer or multi-level monitoring system (e.g., Westbay Instruments, LTD) installed within the borehole. This borehole will serve as the principal monitoring borehole during the injection and post-injection phases of the field pilot study. A final decision has not been made pertaining to which monitoring system will be utilized. The final decision will be made based on an assessment of cost versus the value of additional information obtainable using the multi-level monitoring system. The nested piezometer installation is considered to be the base-case monitoring system to be used for the field pilot study. Figures 4.1A and 4.1B display depictions of the monitoring system installations for the nested piezometer and multi-level monitoring systems, respectively.

Figure 5.1. Pilot Borehole Design with Alternative Monitoring System Deployments: A) Nested-Piezometer; and B) Multi-Level Monitoring Installations



Based on the results obtained from the Pilot Borehole, an adjacent (i.e., ~250 to 500 ft distance) Injection Borehole will be drilled and completed to the targeted basalt injection zone horizon. The Injection Borehole will be used during pre-injection characterization (Section 6.1) tests, and serves as the site for injection CO_2 during the field study.

Three shallow basalt (i.e., ~900 ft) geophysical monitoring boreholes (diameter of 9 7/8 inches and cemented casing I.D. of 5 inches) will be drilled at equally spaced, radial distance of ~500 ft surrounding the Deep Injection Borehole for the purpose of imaging the migration and areal extent of the CO_2 within the interflow zone reservoir, during the active injection and post-injection phases. A map plan view of the deployment of the Pilot, Injection, and shallow geophysical monitoring boreholes is shown in Figure 5.2. Although the exact location for the field pilot study has not been determined, it is expected to be located within the northern ~700 acre parcel of the Port of Walla Walla, Attalia Property 1 (Figure 2.5), with existing road accessibility. Power and water will have to be run to the test site.

Additionally, a slant or deviated corehole will be drilled from the Injection Borehole during the post-injection phase (e.g., at 1 to 2 years following injection). The objective is to extract core from the injection interflow zone for the purpose of assessing geochemical reactions between the injected CO_2 and host basalt rock. The slant or deviated corehole drilling will be accomplished using wedges set within the borehole at suitable distances above the injection horizon that will provide representative core samples within the injection interflow zone at distances between ~50 to 100 ft from the Injection Borehole. Figure 5.3 shows a schematic of the Injection Borehole with the two deviated geochemical coreholes.

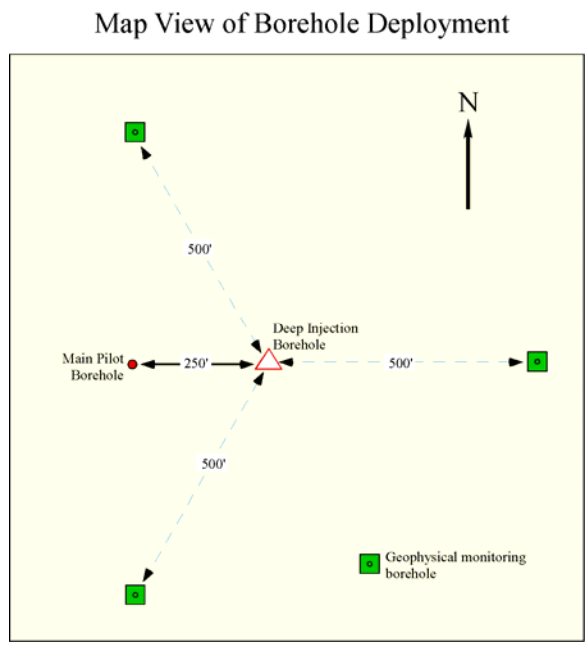


Figure 5.2. Site Plan Layout of Field Pilot Study Boreholes

6.0 SITE CHARACTERIZATION

Site characterization activities are grouped within three major phases: pre-injection, injection, and post-injection. The primary objective of the pre-injection phase is to characterize the hydraulic and storage characteristics of candidate Grande Ronde Basalt interflow zones and to select the interflow horizon for the field pilot injection study. The principal focus during the injection characterization phase is to delineate the extent of the injected CO_2 plume within the host interflow zone, and to assess both areal and potential cross-formational hydrologic response from the CO_2 injection. The main objective of the post-injection phase is to characterize the in-situ geochemical reactions that occur between the injected CO_2 within the reservoir host rock horizon, and to assess any potential resultant changes to hydraulic and storage characteristics within the injection interflow horizon.

6.1 Pre-Injection Characterization

The pre-injection characterization phase is divided into two sub-phases (Phases 1 and 2) that are identified and tied specifically to the two major deep characterization boreholes to be drilled at the test site. Phase 1 is associated with conducting a surface seismic survey and undertaking hydrogeologic characterization activities performed within the Pilot Borehole.

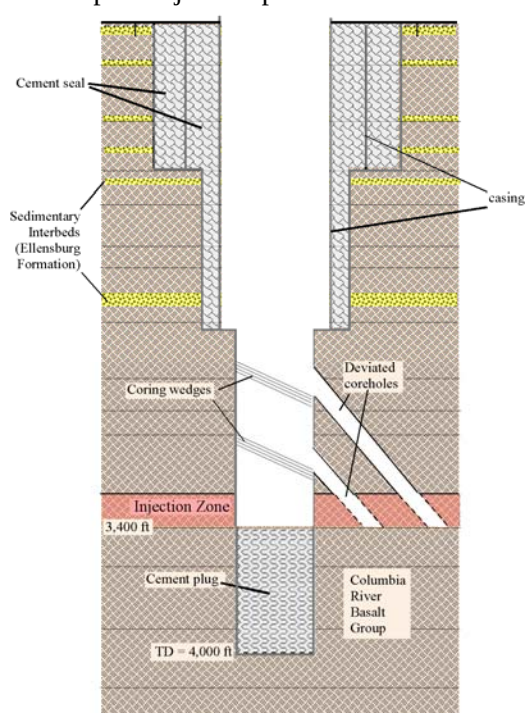


Figure 5.3. Injection Borehole with Deviated Geochemical Coreholes

Because the proposed injection site is remote from a well-characterized basalt stratigraphy in the local area, assessment of the geology through acquisition of 2D surface seismic data is considered critical. The proposed injection site is within a few miles of one of a number of large tectonic faults (Figure 6.1) that are characterized by displacement of basalt layers and the presence of through-going cracks and fractures that allow fluids to migrate and mix vertically. Some of these faults cut the surface of the bedrock and could provide conduits for CO_2 to migrate vertically. Detecting such fault structures through site characterization is a prerequisite of any geologic sequestration project (not unique to basalts). The seismic survey will be used to ensure the injection well is located in an area devoid of these structures.

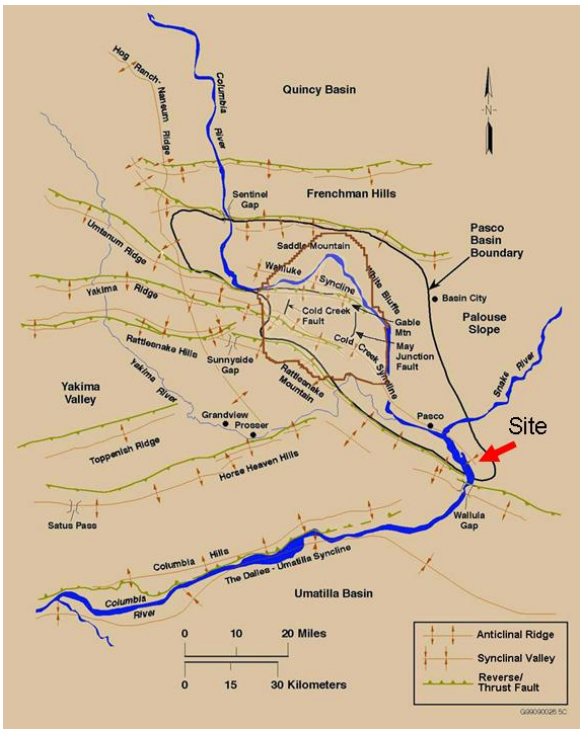


Figure 6.1. Location of Major Regional Faults (Reidel, et al., 2002)

One line of 2D surface seismic acquisition will be acquired over the site of the Pilot Borehole prior to drilling. The line will be approximately 5 miles long and will be designed to employ recent advances in surface seismic technology. These data will be processed by a commercial seismic vendor and interpreted to determine if the basalt strata in the vicinity display indications of tectonic disruption that could jeopardize the injection or containment of the CO_2 (see details of the surface seismic method in Section 8.2.1)

As previously discussed, the Pilot Borehole will be drilled first at the site and its primary objective is to identify viable interflow zone candidates within the Grande Ronde Basalt, and to select the interflow horizon to be used in the field pilot study. Specifically, Phase 1 testing will identify whether the candidate injection interflow horizon has sufficient permeability (i.e., hydraulic conductivity) and favorable storage characteristics to accept injection of a maximum of 3,000 metric tons of CO_2 over a two to four-week time period. Additionally, the pre-injection characterization activities serve to establish baseline formation conditions for assessing the impact of CO_2 injection during the injection and post-injection characterization phases. The Phase 1 pre-injection characterization phase will be implemented during and following the drilling of the Main Pilot Characterization Borehole, which will occur as part of the Site Preparation activities (Section 5.0). Phase 1 pre-injection characterization activities include: conducting a suite of wireline borehole geophysical surveys, conducting a single-well vertical seismic profile (VSP), performing a series of single-well hydrologic tests, and collection of representative groundwater samples for hydrochemical/isotopic and dissolved gas characterization.

A suite of wireline borehole geophysical surveys and a VSP survey will be conducted within the Pilot Borehole. The wireline borehole surveys will include: caliper/APS, resistivity, neutron, gamma, sonic/acoustic, density, neutron magnetic resonance (NMR), formation micro-imager (FMI), combined gamma spectroscopy (RST-A), cement-bond, dynamic fluid-logging (fluid-temperature and flowmeter), and gyroscopic surveys. This wireline geophysical information is important in establishing in-situ baseline characteristics in proximity to the borehole, and will provide a basis for evaluating potential

formational property changes in the area immediately surrounding the borehole due to the CO_2 injection. Of particular note is the dynamic pumping test/fluid-logging survey, which will be used to assess the general permeability distribution within the open borehole section (i.e., ~1,800 to 4000 ft), and to identify candidate injection interflow horizons. The VSP, which will be conducted immediately following completion of the wireline surveys, is acquired by activating an acoustic source on the ground surface and capturing the reflected seismic signals via geophones in the wellbore. These data are important for imaging the 3D nature of the rocks away from the well bore, providing depth control for the images produced by the 2D surface seismic technology, and for providing baseline data for monitoring time-lapse growth of the CO_2 plume with cross-well seismic (see details of these methods in Section 8.2.1.3)

Based on these results, a series of single-well hydrologic tests will be conducted on the identified most favorable interflow zones for more detailed hydraulic characterization. These interflow tests will be accomplished by utilizing a downhole straddle-packer system to isolate the individual interflows from the surrounding open-borehole section. The associated test (pressure) responses monitored at the Pilot Borehole will be analyzed to provide pre-injection local-scale estimates for injection zone transmissivity, storativity, aquifer model behavior (e.g., leaky vs. nonleaky aquifer; single vs. double-porosity media system), and well-formation conditions (well loss, formation damage/well skin). The test characterization sequence will include both slug tests and a constant-rate injection and/or pumping test. Following completion of Phase 1 pre-injection activities, the borehole will be cemented back to the base of the selected injection interflow zone and a monitoring system installed within the borehole, as shown in Figures 4.1A and 4.1B. The Pilot Borehole will serve as the main facility for monitoring baseline pressure responses during: the active drilling of the Injection Borehole; for multi-well hydraulic tests initiated from the Injection Borehole (Phase 2); and during the CO_2 injection and post-injection phases.

Phase 2 of the pre-injection test characterization is associated with hydrogeologic characterization activities that are initiated and conducted within the Injection Borehole. This borehole will be drilled following the drilling, testing, and installation of the monitoring system within the Pilot Borehole. The primary objective of Phase 2 characterization activities is to provide more detailed and larger-scale information pertaining to hydraulic and storage properties, lateral continuity, and leakage characteristics of the injection interflow zone selected during the Phase 1 characterization. The Phase 2 pre-injection characterization phase will be implemented during and following the drilling of the Injection Borehole, which will occur as part of the Site Preparation activities (Section 5.0). Phase 2 pre-injection characterization activities include: conducting a suite of wireline borehole geophysical surveys, performing a series of longer-duration single-and multi-well hydrologic tests, and collection of representative groundwater samples for hydrochemical/isotopic and dissolved gas characterization. Of particular note are two ***drill-and-test*** zones during the advancement of the Injection Borehole. The first occurs at the Vantage interbed horizon, which marks the time-stratigraphic contact between the Wanapum and Grande Ronde Basalts. This contact has been observed regionally to represent a low permeability aquitard horizon that separates groundwater occurring within both basalt formations (REIDEL et al., 2002). The contact depth will be known from Phase 1 characterization results obtained from the Main Pilot Borehole, and this horizon will be cored within the Injection Borehole. Selected core intervals will be submitted for laboratory permeability testing. In addition, the first permeable interflow zone above (in the Wanapum Basalt) and below (in the Grande Ronde Basalt) this stratigraphic contact will be hydraulically tested and representative groundwater samples collected for detailed hydrochemical and isotopic analysis. The second *drill-and-test* zone will be within the low-permeability caprock above the selected injection interflow horizon. The depth of the selected injection zone will be known from Phase 1 characterization results obtained from the Pilot Borehole, and the overlying caprock horizon will be cored

within the Injection Borehole. Selected caprock core intervals will be submitted for laboratory permeability testing. Low-permeability borehole testing of the cored caprock interval will be conducted prior to borehole advancement into the underlying injection interflow zone. Examples of successful low-permeability caprock hydraulic testing within basalt formations are presented in Spane and Thorne (1985) and Thorne and Spane (1985).

After caprock testing, the borehole will be completed by advancing the borehole to the base of the underlying injection interflow zone. Selected intervals will be cored and subjected to petrographic analysis for comparison with post-injection cores collected to assess the extent of mineralization reactions. A series of hydrologic tests will be then be conducted on the injection interflow horizon within the Injection Borehole as part of the Phase 2 characterization. The associated test (pressure) responses monitored at the Injection Borehole and within the nearby Pilot Borehole (distance ~ 250 ft) during testing will be analyzed to provide pre-injection local and intermediate-scale (inter-well) estimates for injection zone transmissivity, storativity, aquifer model behavior (e.g., leaky vs. nonleaky aquifer; single vs. double-porosity media system), and well-formation conditions (well loss, formation damage/well skin). The test characterization sequence will include: slug and slug interference tests, a step-drawdown test, constant-rate injection and/or pumping test, and possibly a mini-frac test. Figure 6.2 summarizes the hydrologic test parameters and the scale-of-investigation that can be resolved with these characterization methods.

As discussed in Novakowski (1989), Spane (1996), and Spane et al. (1996), due to their relative rapid response characteristics and ease of performance, slug or pulse interference tests are particularly attractive for initial site characterization. The characteristics of a pressure interference response (i.e., amplitude and pattern) observed at the Pilot Borehole that is generated from a slug test conducted at Injection Borehole is highly sensitive to the storativity, S, of the injection zone, while the transmission of the pressure interference response is controlled largely by the injection zone transmissivity, T. Predicted slug interference responses at the Pilot Borehole, as a function of S and T, are shown in Figure 6.3 and Figure 6.4, respectively for the listed test parameters.

Step-drawdown tests are used primarily for determining well-loss conditions and determining the optimum injection or pumping rate for the following constant-rate test. The constant-rate test will provide detailed hydraulic characterization information for the injection interflow zone, and be used to identify aquifer model behavior and well-formation conditions. Aquifer model identification is facilitated through the use of diagnostic pressure derivative analysis, as discussed in Horne (1990), and Spane and Wurstner (1993). Groundwater sampling for hydrochemical/isotopic and dissolved gas characterization will be collected in concert with the step-drawdown and/or constant-rate testing activities. A supplemental multi-well, forced-gradient tracer test will be considered following completion of this hydrologic test sequence, should the hydraulic and storage property estimates from these tests indicate that a tracer test could be conducted within a reasonable test period (e.g., 5 days). Multi-well tracer tests are particularly well-suited for determining the effective porosity and longitudinal dispersivity. These formation transport parameters are important input for modeling and predicting the areal extent of the injected CO_2 plume within the interflow zone horizon.

Mini-frac tests will also be considered for the injection reservoir and sections within the overlying caprock layer. Mini-frac tests are commonly used for determining the minimum threshold injection pressure that will produce incipient fracture failure within the test interval surrounding the borehole. For reservoir zone characterization, information concerning the injection fracture pressure is important for the proper design of any subsequent reservoir hydrofrac programs for enhancement of existing permeability

and storage characteristics. For caprock characterization, determining the minimum in-situ caprock fracture pressure is important for management of sequestered CO_2 within the underlying reservoir zone(s), since injection pressures exceeding this value will produce the onset of incipient caprock fracturing and subsequent reservoir leakage. In addition, results from the mini-frac tests can be analyzed for determining the in-situ stress regime for the tested formations.

Assuming the pre-injection characterization tests confirm the anticipated favorable hydrologic properties within one or more interflow zones, the project will proceed to the injection phase. Alternatively, in the unlikely event that hydrologic test results are considered to be unfavorable, the Injection Borehole could be deepened to other candidate interflow zone horizons and the pre-injection characterization activities repeated.

Test Method	Hydrologic Parameter[a]						Test Scale		
	T	K_h	K_D	S	L	W_L	Local	Intermed.	Large
Slug	√	√		x			√		
Slug Interference[b]	√	√	x	√	√		√	√	
Step-Drawdown/Recovery	√	√	√	√	√	√		√	
Constant-Rate Pumping/Injection – Drawdown & Recovery[b]	√	√	√	√	√			√	√
Low-Permeability, Multi-Step Injection	√	√					√		

(a) Hydrologic Parameter Nomenclature

T = test interval transmissivity
K_h = equivalent hydraulic conductivity; equal to T divided by test interval length or aquifer thickness
K_D = vertical anisotropy K_v/K_h
S = storativity; dimensionless
L = leakage response
W_L = well loss

(b) assumes multi-well data available for test analysis

Note: √ = provides quantitative information
x = only provides inferential/qualitative information

Figure 6.2. Summary of Hydrologic Test Methods Used for Pilot Test Site Phase 2 Characterization Investigation (modified from Reidel et al., 2002)

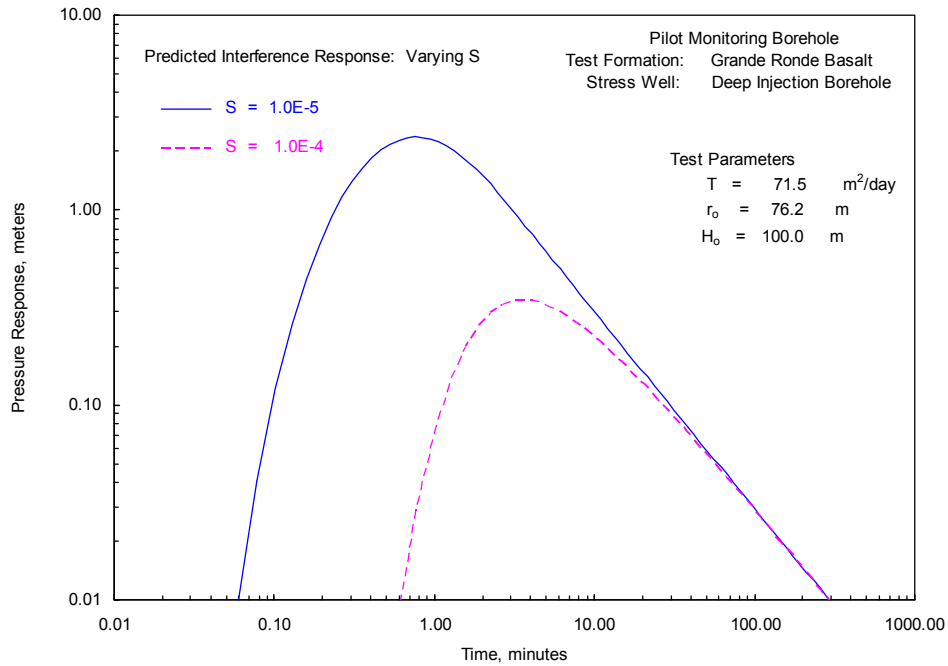


Figure 6.3. Predicted Slug Interference Test Response Characteristics at the Pilot Monitoring Borehole, as a Function of Injection Interflow Zone Storativity

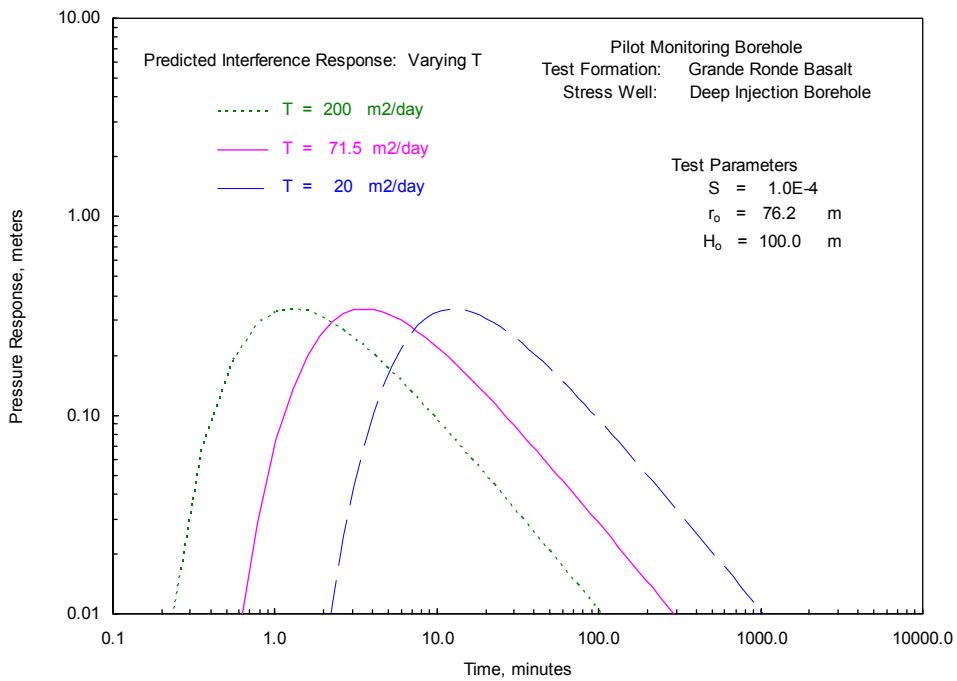


Figure 6.4. Predicted Slug Interference Test Response Characteristics at the Pilot Monitoring Borehole, as a Function of Injection Interflow Zone Transmissivity

6.2 Injection Characterization

The principal focus of injection characterization phase is to delineate the extent of the injected CO_2 plume within the host interflow zone, and to assess both areal and potential cross-formational hydrologic

response effects (i.e., hydraulic communication) from the extended CO_2 injection, as monitored using geophysical sensors and standard hydrologic pressure monitoring systems. Baseline conditions that were established during the pre-injection characterization phase will serve as the basis for delineating plume migration during and following the active CO_2 injection phase. Microseismic sensors installed in the three, shallow geophysical boreholes (Figure 5.2) will provide continuous recordings of acoustic emissions related to slippage of fractures, crack formation and movement of the CO_2 plume. These data will provide the principal geophysical characterization during the injection phase.

Prior to initiation of CO_2 injection, the candidate injection interflow zone will be isolated within the Deep Injection Borehole with a downhole test system. The downhole test system will consist of an inflatable packer/pressure probe and downhole shut-in tool valve assembly. The associated pressure responses monitored at the injection well and within the nearby Pilot Borehole during the active CO_2 injection phase will be monitored and analyzed for indications of possible changes in injection zone hydraulic and storage properties and cross-formational leakage. The pressure responses will be monitored using downhole pressure transducers and inflatable packer systems. Pressure responses may also be monitored at more distant surrounding wells; however, none of these well facilities are completed within the deep candidate injection zone basalt formation (i.e. Grande Ronde), and are currently in use. These more distant monitoring sites, therefore, will only afford cross-formational response monitoring capabilities. Because of the anticipated low hydrologic pressure stresses that may be imposed at the Pilot Borehole and these more distant monitoring site locations, enhanced external stress removal methods (i.e., for barometric and earthtide effects) described in Rasmussen and Crawford (1997) and Spane (1999; 2002) will be employed to facilitate identification of injection phase pressure effects.

The CO_2 will be transported by rail from the source/supplier directly either to Pasco, Washington or to a side rail system in proximity to the Boise Cascade Corporation Wallula Mill and the field pilot study area. The CO_2 will then be trucked the short distance to the field study location. The CO_2 will be unloaded from the delivery trucks to a surface storage container/vessel. The CO_2 will be maintained at a uniform temperature within the storage vessel during the entirety of the injection phase. Efforts will be implemented to maintain a continuous, constant CO_2 injection rate; although a systematic, pulsed, injection option is possible, due to CO_2 supply disruptions (See Section 7.0). The CO_2 injection rate selected for the field pilot study will be based on the estimated injection zone hydraulic and storage properties obtained during the pre-injection characterization phase. Based on anticipated hydraulic property conditions, the active CO_2 injection phase will likely be completed within a 2 to 4 week period, assuming no delays in delivery of CO_2 to the site. A suite of partitioning and conservative hydrochemical tracers (see Section 8.0) will be incorporated and administered at the beginning and near the end of the injection phase and monitored for detection at nearby Pilot Borehole. Tracer breakthrough and recovery patterns will provide additional information concerning CO_2 reaction/mineralization percentages, reaction rates, and bulk effective porosity and dispersivity conditions within the injection reservoir during active injection phase conditions.

A residence time of 12 to 24 months is anticipated for the injected CO_2 to reside and react with the basalt reservoir before initiating post-injection characterization and monitoring activities. It should be noted that because of the long length of time during the injection/residence time period, the inflation packer systems used to isolate the injection reservoir in the Injection Borehole may be replaced with mechanical, compression-type packer system to ensure reservoir isolation integrity during the extended pilot test residence/reaction period.

6.3 Post-Injection Characterization

The primary objective of the post-injection phase is to characterize the in-situ geochemical reactions of the injected CO_2 within the reservoir host rock horizon, to assess any potential resultant changes to hydraulic and storage characteristics within the injection interflow zone, and to geophysically image plume growth. The post-injection characterization phase will be implemented following completion of the designed injection residence period. Post-injection characterization activities include: drilling of two deviated geochemical coreholes, conducting a suite of wireline borehole geophysical surveys, and performing a series of comparative hydrologic tests.

The slant or deviated geochemical coreholes will be drilled from the Injection Borehole, after removal of the reservoir isolation packer system from the borehole, as shown in Figure 5.3. The coreholes will be deviated at an angle (using an installed borehole wedge) that will ensure intersecting the injection zone horizon at distances of ~50 to 100 ft from the central injection borehole. The primary objective of this pos-injection characterization activity is to retrieve injection zone basalt cores and formation fluid samples for detailed geochemical characterization of potential secondary mineralization that may be associated with the CO_2 injection process. This is a key post-injection characterization activity for verifying and assessing in-situ CO_2 reaction/mineralization rates. The coreholes will be drilled after 12 to 24 months of reaction time has elapsed following CO_2 injection. Formation fluid samples will be obtained from the CO_2 injection horizon, but in the aqueous phase zone beneath the supercritical CO_2 bubble.

Selected wireline borehole geophysical surveys will be conducted within the Injection Borehole prior to corehole drilling. The post-injection geophysical surveys selected will be based on an evaluation of wireline survey results conducted during the pre-injection phase characterization. The wireline borehole surveys, however, will likely include: resistivity, neutron, gamma, sonic/acoustic, density, neutron magnetic resonance (NMR), formation micro-imager (FMI), combined gamma spectroscopy (RST-A), and dynamic fluid-logging (fluid-temperature and flowmeter). The post-injection wireline geophysical information will be compared with the results obtained during the pre-injection characterization phase to evaluate potential formational property changes in the area immediately surrounding the borehole due to the CO_2 injection.

Additionally, the series of detailed hydrologic tests conducted during the pre-injection phase for the injection zone within the Injection Borehole will be repeated during the post-injection characterization. The associated pressure responses will be monitored in similar fashion both at injection borehole and within the nearby Pilot Borehole during the post-injection testing. The post-injection tests will be compared to pre-injection results to assess potential formational property changes (i.e., transmissivity, storativity, leakage) over the intermediate-scale (inter-well) distance. In addition to this final, post injection hydrologic test sequence, periodic slug or pulse interference testing will be performed as an indication of changes to the CO_2 injection plume during the post-injection time period.

7.0 INJECTION TEST DESIGN

As discussed previously in Section 6.2, CO_2 will be transported by rail from the source/supplier directly to Pasco, Washington, or to the side rail system near Boise Cascade and the field test study area. The CO_2 will then be trucked to the field pilot test site location. The CO_2 will be unloaded from the delivery trucks to a surface storage vessel. The CO_2 will be maintained at a uniform temperature within the storage vessel during the entirety of the injection phase. Currently, two CO_2 injection test design strategies are being considered for the field pilot test study: a constant-rate and a systematic, pulse

injection. A constant-rate injection is the preferred test design strategy, and provides the best quantitative measure for characterizing injection zone hydrologic properties. Implementing this injection strategy, however, requires a nearly steady supply of CO_2 to the field pilot test site. If a steady supply of CO_2 can not be guaranteed to the site, then a pulsed injection test design will be implemented. Under this injection design option, the CO_2 would be repeatedly injected as pulses over a fixed-period of time (e.g., 8-hours). The individual injection pulses would be conducted at a fixed, constant-rate and after the injection period, a set recovery period would be observed prior to initiating the next pulse injection cycle. This type of injection strategy is analogous to sinusoidal hydrologic testing (BLACK and KIPP, 1981; YOUNG et al., 2002), and hydrologic properties can be derived for the injection zone based on the analysis of the associated pressure amplitudes and time-lag relationships observed at surrounding monitoring facilities. The specific design of the pulsed injection option can be realized based on analysis results obtained from the Phase 1 and 2 pre-injection hydrologic test characterization.

8.0 MEASUREMENT, MONITORING, AND VERIFICATION PLAN

8.1 Atmospheric and Soil Monitoring

Although it is highly unlikely that any CO_2 would reach the surface during or after CO_2 injection, a single eddy covariance station will be installed to monitor over the expected plume footprint. The station would be installed prior to injection and removed shortly after injection terminates.

Dedicated soil gas probes will be placed at discrete points along 4 orthogonal transects extending away from the injection well. Starting at the injection well, the soil-gas probes would be spaced at 100, 200, 500, and 1,000 ft to provide complete coverage of the plume area. Vadose zone soil gas samples would begin being collected monthly as early as possible ahead of injection (to establish background variability) and would continue on a monthly basis until site closure. Soil-gas samples would be analyzed for CO_2 and other target analytes, including tracers co-injected with the CO_2 (e.g., perfluorohydrocarbon tracers) and stable carbon and oxygen isotopes to differentiate leaked CO_2 from other sources (e.g., biogeochemical CO_2).

8.2 Geophysical methods

Surface seismic reflection is the method of choice for assessing integrity of storage reservoirs and seals. This method provides detailed images of the subsurface, covers large areas, and provides abundant information about the reservoir's physical and structural properties. Historically, surface seismic reflection has a poor history of imaging beneath flood basalt terranes (PUJOL et al., 1989). The basalt flow/interbed stratigraphy of flood basalt terranes causes strong reverberations in the data, obscuring coherent reflections that may be present (JARCHOW et al., 1994). The quality of surface-based 2D seismic data is improving as a result of renewed seismic-based, sub-basalt natural gas exploration in the Northwest. The most successful application of 2D seismic is expected to result from using closely spaced surface sensors, multiple seismic wave sources and recording

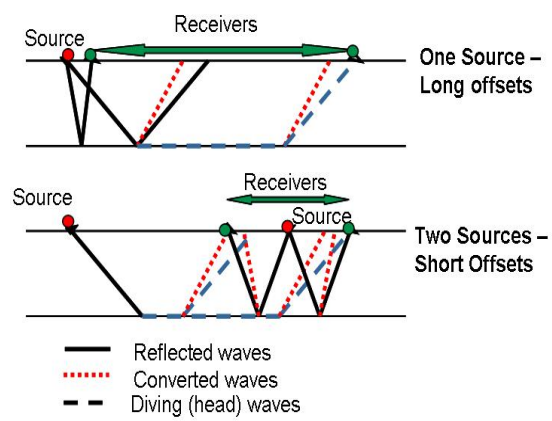


Figure 8.1. Schematic cross sections illustrating long and short source-receiver offsets, converted P-S seismic waves and refracted (diving waves)

both P (compressional) wave data and P-S, which is converted wave shear data (Figure 8.1). The converted wave shear data are greatly influenced by fractures in basalt. In addition some long source-receiver offset data will be acquired to benefit from the refracted or diving wave. These data greatly enhance the signal to noise ratio.

Geophysical monitoring will focus on crosswell seismic imaging, vertical seismic profiles (VSP), and passive seismic monitoring. These seismic methods involve placing either sources or receivers, or both, in wellbores, which reduces the amount of seismic wave scattering and increases both lateral and vertical resolution. Crosswell seismic methods will have higher spatial resolution of the injection volume than surface-based methods or VSP's, but do not image the entire vertical section. Modern cross-well analysis methods best provide an image of subsurface structure in the vicinity of the injection zones, as well as a tomographic view of the velocities between the wells (DONG et al., 2005).

One of the most established wellbore-based methods for characterizing the reservoir is the vertical seismic profile or VSP. Vertical seismic profiles are less expensive than cross-well tomography, as less equipment and processing is necessary. The VSP geophones are placed down the well and record surface-generated seismic waves to image the subsurface. These surface seismic sources have a variety of location geometries, from zero-offset (ZVSP, source next to the wellhead), to walk-away surveys (where the source is activated at a number of stations progressively moving away from the wellhead), to fully 3D geometries to best image the desired target. 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).

Passive seismic technology is a continuously recording modality and is an essential component of the monitoring program. To obtain high-resolution results using passive seismic to monitor CO_2 injection, geophones will be placed in boreholes, as deep and close to the reservoir as possible. The geophones will record acoustic point-source signals that are induced by CO_2 injection and reservoir readjustment. The signals can be used to locate, in 3D, where micro-earthquakes occur. Passive seismic monitoring maps locations of crack formation and may help discern the dimensions and extent of the injected CO_2 "bubble". Passive seismic monitoring is a standard technology that has been used in reservoir monitoring and to track the growth of induced fractures during hydraulic stimulation of oil and gas wells (RUTLEDGE et al., 2004; AKE et al., 2005). The recorded waves are inverted for their hypocenter location and for focal mechanism solutions to determine the sense of motion on cracks as they open or move. Installed seismographs can also continuously monitor natural seismic activity.

The recorded signal and the separation of the geophones control the resolving power of all of the seismic methods. Higher recorded frequencies and higher spatial sampling result in smaller objects being imaged. In general, downhole sources and receivers provide higher, more broadband energy than surface instruments.

8.2.1 Seismic Monitoring

The basic seismic monitoring program consists of continuous-recording passive seismic geophones in monitor wells, and pre- and post-injection cross-well seismic tomography. Pre-injection cross-well measurements between the characterization well and the injection well will establish baseline conditions for comparison with post-injection measurements, and will provide the most complete time-lapse images of changes in the subsurface. In addition to measurements taken immediately after completion of injection, an third cross-swell survey, conducted after the planned residence time would establish the feasibility of

seismic monitoring for detecting the extent of channeling of the plume within the reservoir, as well as for discerning *in situ* mineralization and equilibration of the CO_2.

8.2.1.1 Passive seismic

Passive seismic monitoring will be conducted before CO_2 injection, during CO_2 injection, and after CO_2 injection. Passive seismic will be started about 3 months prior to injection, and continue after injection for several months. The passive seismic monitoring will use 3-component geophones (to obtain fracture sensitive converted P-S waves) placed downhole, as close to the reservoir as possible.

The geophones continuously record seismic waves that result from background acoustic emissions (both natural seismic events and induced events such as reservoir fracturing due to pressure build-up or cracking of the rock caused by groundwater unloading). Microseismicity induced by very small scale hydraulic fracturing during CO_2 injection provide information about 3D fracture density and orientation, as well as data on the geomechanical (stress) behavior of the rock mass. This information is crucial to evaluate the feasibility and sustainability of CO_2 geosequestration in basalts. Seismic events are expected to be around magnitude Mw -2.0 to 1.5 ($m_0 = 1.0 \times 10^{13}$ to 10^{18} dyne-cm), with a characteristic corner frequencies of about 100 Hz up to a few hundred Hz.

The passive seismic acquisition will involve using a PC-based data acquisition system that insures all downhole receivers from the both the passive and active (VSP and crosswell) experiments are recorded on the same system. Fifteen Hz geophones will be used in the downhole array; for the passive experiments, the system will trigger on a pre-determined threshold. The system will be monitored about once a week. If a good internet connection can be established, the system can be remotely monitored and data can be directly downloaded. A filter bank and uphole amplifiers can be installed to pre-process the data. These data will allow the determination of precise fracture growth locations, moment scalars, focal mechanisms and stress tensor inversion from the passive experiment.

8.2.1.2 Vertical Seismic Profiling (VSP)

VSPs involve using downhole geophones to record surface sources. The advantage is that the energy travels one-way from the source to the receiver, and scattering and attenuation of the seismic wave are greatly reduced.

The first step in acquiring a VSP is to perform 2D modeling of the basalt layers and the seismic raypaths (Figure 8.2). This requires a basic geologic model of formation tops and a sonic log to provide local seismic velocities.

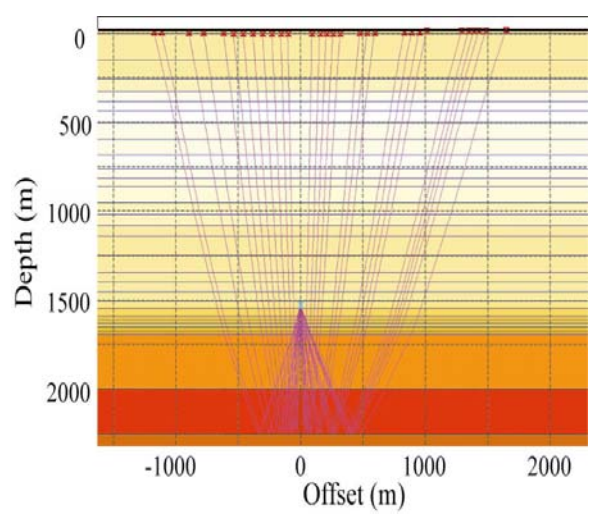


Figure 8.2. Example of the 2D modeling of rock layers and raypaths. This modeling is used to determine the optimal locations of the seismic source on the surface, and the geophone placement within the well.

Vertical seismic profiles can be acquired with a wide variety of seismic source configurations (Figure 8.3). The zero offset 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 form the well, in one or multiple directions. The preferred program for site characterization associated with the pilot well is to

acquire a line from the Pilot Borehole to the location of the injection well. Imaging of fractures in the basalts will be optimized by using multicomponent 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.

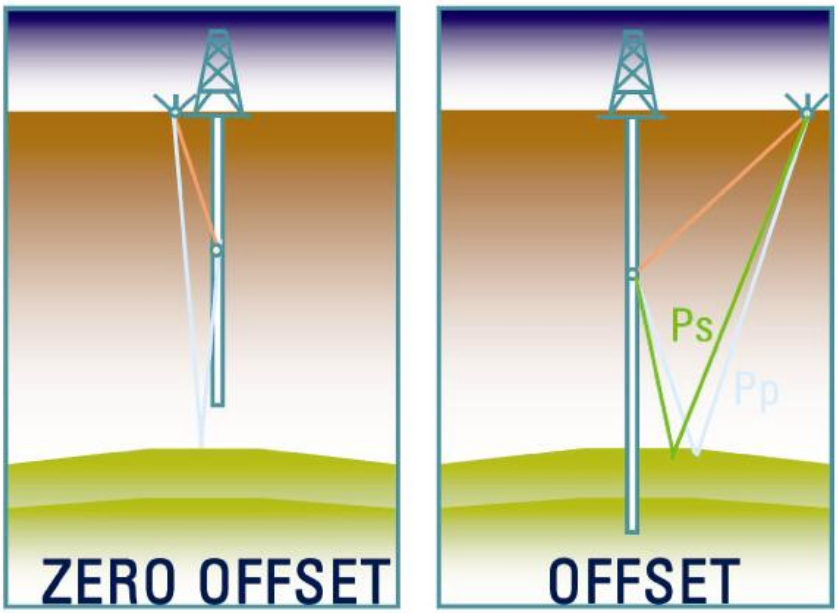


Figure 8.3. **Example of the acquisition lay-outs for ZVSP (zero offset) and offset VSP data**

8.2.1.3 Cross-well seismic tomography

Crosswell seismic tomography (Figure 8.4) will be used to image the 4D or time-lapse changes in CO_2 saturation, thereby tracking the expanding CO_2 plume. This technology is different from the other seismic methods in that it involves placing both geophones and seismic source into wellbores. Activation of a non destructive source in the monitoring well reduces the distance the seismic energy must travel; either one-way to surface receivers or directly across the intervening basalt to tomographic receivers in another borehole. This configuration greatly increases the signal to noise ratio and the frequency content of the recorded signal. The exact placement of geophones and sources will need to be repeatable to ensure valid time-lapse analysis of the CO_2 plume.

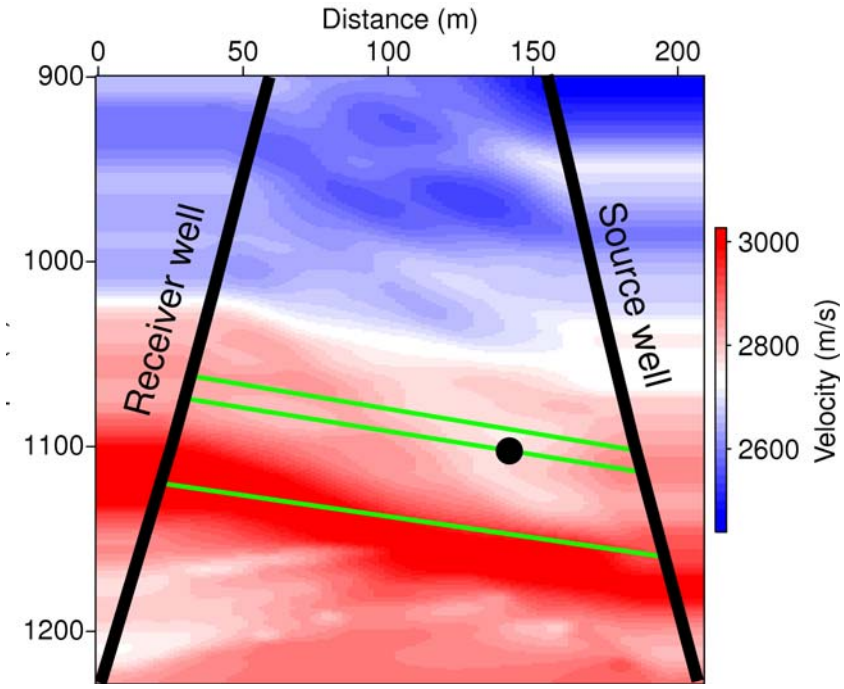


Figure 8.4. **Example of Data from Crosshole Seismic Tomography. Three sources and three receivers in two wells are shown for illustration in this cross section view. Depth on the left of the figures is in meters; the black dot represents the injection well between the two wells involved in the crosswell data collection**

Pre- and post-injection crosswell seismic tomography will be conducted between the Deep Injection Borehole and a geophysical monitoring well; configured to place the injection well and the injection zone between the two wells that contain seismic sources and receivers. Seismic sources and geophones will be carefully placed to ensure repeatability.

8.2.2 Borehole Geophysics

Borehole logs provide highly sampled, *in situ* physical and chemical information about the host rock and gases and fluids within the pore space. In combination with the geochemical tracer data, borehole logs will be used to calibrate and validate numerical reactive transport simulations.

Wireline logging activities will:

- Study and re-evaluate existing borehole logging data.
- Run a full suite of wireline logs (caliper, density, neutron porosity, electrical imaging, acoustic and NMR) in the injection and monitoring wells to establish borehole conditions.
- Run selected logs after CO_2 injection to monitor changes in rock and fluid properties.

The wireline logging activities to be conducted include:

- Platform Express - Highly Integrated Triple Combo - GR, Thermal Neutron, Density, MicroLog, Resistivity. This basic logging suite provides measures of porosity (density and neutron) and basic lithology (GR, neutron, and density). The Accelerator Porosity Sonde (APS) is a more advanced epithermal neutron tool that can be substituted for the Platform Express. It will provide a better

neutron measurement because it is less sensitive to matrix effects. The minimum hole size is 6" but other tools are available that can go down to around 4".

- Geochemical Profiling - Elemental capture spectroscopy (ECS) provides elemental concentrations for Si, Ca, Fe, S, Ti, and Gd. These data can be used to estimate matrix density and used to calculate density porosity. In addition, these data can be combined with other log measurements to develop a mineralogic model for the formation. Minimum hole size is 6". The carbon/oxygen ratio will be measured with a Reservoir Saturation Tool (RST).
- Formation Micro-Imager (FMI) – Provides oriented electrical conductivity of the borehole wall. Vertical and horizontal resolution is 0.2 inch. The log is very useful for mapping fractures, defining brecciated zones, and determining orientation of contacts. This tool requires water in the borehole. Minimum hole size is 6.25". Although there is a slim-hole tool that can measure in 4.5" borehole, the slimhole tools are quite rare.
- Sonic Scanner - Advanced sonic tool that provides measure of compressional velocity, shear velocity in three axes, and Stoneley wave velocity. Data can be used to a) tie to seismic, b) estimate porosity and compare to nuclear porosities collected with other tools, c) fracture mapping , and d) estimation of rock mechanical properties. Minimum hole size is 4.75".
- Gravity Profiling - Gravity measurements are sensitive to changes in formation density and can be used to monitor the injected CO_2 in these locations. Gravity measurements have already been employed for monitoring CO_2 capture and storage. Nooner et al. (2007) collected time-lapse gravity data over the Utsira Formation in the Sleipner gas field in order to study the behavior and physical properties of the injected CO_2. On land, the smaller density contrast of supercritical gas plus the larger reservoir depths will require the gravity change due to CO_2 injection be measured using borehole gravimeters. Borehole devices are capable of measuring gravity changes to a precision of about 10 μGal, with the added benefit of being able to make measurements much closer to the injected mass. This would allow easy and rapid detection of gravity changes associated with CO_2 injection as well as a robust way to calculate *in situ* CO_2 mass, particularly in conjunction with gamma-gamma density, resistivity, and fracturing imaging from conventional well logs and laterally mapped flow geometry from seismics. Coordination and combined analysis of the cross-well seismic and borehole gravity surveys will enable the 3D geometry of the injected CO_2 plume to be tracked and estimation of its in situ mass and saturation.

8.3 Geochemical Monitoring

8.3.1 Tracers

Chemical tracers will be a key aspect of planned MM&V activities. Tracer tests are known to be effective in the characterization of several subsurface flow and reactive transport properties, including kinematic porosity, permeability, phase volume fractions, kinetics of sorption, dissolution, microbial transformations, ion exchange phenomena, dispersion and formation damage (BACHMAT et al., 1988; HAGGERTY et al., 2001; DAVIS et al., 2002). A suite of tracers will be designed to: 1) interact with the CO_2, water and mineral phases of the reservoir, 2) limit the problem of interference from naturally occurring CO_2 background concentrations, and 3) provide a statistically superior monitoring and characterization method due to the redundancy built in by using multiple tracers. The method is based on established principles of tracing in geological systems (ZEMEL, 1995). A pre-injection tracer test will be performed using a soluble tracers [KBr, penta-fluorobenzoic acid (PFBA), or 2,2-dimethyl-3-pentanol (DMP)] to establish the basic hydrologic properties such as porosity, hydraulic conductivity, and

dispersion. During the CO_2 injection phase, pulses of different gas tracers will be added to the CO_2 stream. The leading tracer candidates are SF_6, CH_3F, and CH_2F_2 (perfluorohydrocarbons) and noble gas tracers (^3He, ^{78}Kr, ^{124}Xe). Because each of these inert tracers has unique physical properties (diffusivity, solubility), the multi-tracer approach allows for the determination of CO_2/water multi-phase transport parameters. These tracers can be detected with enormous sensitivity, thus the required levels for injection are quite small. The successful application of gaseous tracers requires a thorough pre-characterization of ambient ground waters within the target injection zone as well as within the shallow aquifer zones above the injection zone to establish the pre-injection concentrations. Since we anticipate using SF_6 and noble gas isotopes as tracers during the CO_2 injection, we will determine the concentration of these gases in the ambient ground waters, both at reservoir depth and from water samples in shallow wells located around the site prior to CO_2 injection.

At set times during the injection period, breakthrough curves (BTC) of the different injected tracer pulses will be collected. The succession of BTCs for each tracer during this phase, when analyzed together and in comparison with the pre-injection BTCs, will reveal information about the fate and transport of injected CO_2 as a function of time. The injected tracers will also serve as sensitive markers for vadose zone and surface gas monitoring that will allow us to recognize if leakage occurs during or following the pilot test.

8.3.2 Water Chemistry

Water chemistry analysis will be performed in the reservoir of injection and in each aquifer system overlying the aquifer. Critical parameters to be measure are: pH, Eh, dissolved O_2, temperature, conductivity, major, minor, and minor trace elements, stable isotopes, tracers, colloids, and microbes. Samples will be collect at high frequency during the first two months following injection and then one sampling campaign approximately every 2 to 4 months (20 samples per event). A U-tube sampling device or Westbay system will be used in the injection and monitoring wells to collect fluid and gas samples during the experiment. Changes in the aqueous concentrations/ratios of naturally occurring trace element also will be monitored as a means to assess the CO_2 mineralization process.

8.3.3 Microbiological Monitoring

To understand the in-situ microbial dynamics in response to CO_2 injections, a piggyback activity with the geochemical monitoring activities will be performed for evaluation of the impact of CO2 injection on the *in situ* microbial community in the injection reservoir. Few field experiments of this nature have been conducted, and prior theoretical work has suggested that biotic reactions may cause an increase in the concentration of sulfide, Fe, Mn, reduced gases, hydrocarbons, ammonia, and organic acids. In particular, lower pH after CO_2 injection may affect methanogenic and acetogenic communities. Sampling of the pre- and post-injection reservoir fluids, in conjunction with planned geochemical sampling via U-tube and/or Westbay systems, will enable determination of the rate of return of the reservoir to pre-injection conditions and enable a crucial test of theoretical predictions, including any potential unanticipated microbiological dynamics such as the microbial conversion of CO_2 to methane gas.

8.3.4 In Situ Probes

Pressure and temperature probes will be installed in the Injection and Pilot Boreholes. We will monitor the temperature and pressure, and electrical conductivity continuously prior to and after the injection.

9.0 SITE CLOSURE AND RESTORATION

Because the field site is being considered for possible commercial-scale sequestration operations, site closure and restoration activities will be contingent upon the potential use of the Injection and Pilot

Boreholes to support sequestration operations. Should a determination be made that these wells are not needed, each would be plugged and abandoned. After cutting off the injection casing, each well would be backfilled with cement. Plugging and abandonment of wells is controlled by the Washington State Department of Ecology.

10.0 DATA MANAGEMENT

The testing program outlined in this Field Activity Plan will generate large amounts of data that requires quality control and electronic access for the principal investigators and private industry partners. Electronic access will be controlled through a password protected Sharepoint site. A web master will be assigned to control access authorizations, permission levels, data input, and modifications.

11.0 HEALTH AND SAFETY

All work will be performed in accordance with applicable environmental, safety, and health (ES&H) requirements defined in Battelle's Standards Based Management System (SBMS) Categories - ES&H and with an understanding of the Safety Rights and Responsibilities subject area. This accident prevention program complies with regulations promulgated under the Washington Industrial Safety and Health Act (WISHA). All site personnel will promptly report accidents, injuries, ES&H deficiencies, emergencies, and off-normal events as described in the emergency response plan, and when the condition is stabilized, to the single point of contact (375-2400) as described in the Event Reporting subject area. A field ES&H Plan will be prepared as required by the Project Management subject area. This plan will include an emergency plan with information on emergency services at the site. Subcontractors to Battelle (e.g., drilling and geophysical contractors) will have a safety and health plan or job safety analysis (JSA) for the work they are to perform that complies with Battelle's Field ES&H Plan for the project and WISHA requirements. An approved safety plan or job-specific JSA must

- List the tasks to be accomplished within the scope of work,
- Identify hazards associated with each task, and
- Specify controls required to address each hazard (engineered controls, administrative controls, and personal protective equipment).

Plan of the day meetings and periodic and ad hoc safety meetings will be conducted to coordinate operations and communicate information regarding hazards, unsafe acts, near misses, accidents and lessons learned. All personnel working on site will have stop work authority should they encounter unsafe acts or conditions. Contractors will be expected to have an inspection and preventative maintenance program for their equipment to minimize potential for equipment failure. Contractors will provide evidence that their workers have the requisite medical fitness, training, and experience to perform their assigned duties.

Site preparation and characterization will include use of other heavy equipment and drilling operations involving a variety of mechanical hazards, including falls from elevated platforms, overhead and impact hazards from hoisting and rigging, pinch points at cable drums and sheaves, tripping hazards from cables and hydraulic hoses, etc.

Although the likelihood of significant surface leaks of CO_2 is very low, effects on human health could occur upon an accidental release. The presence of large volumes of compressed CO_2 during injection activities, although relatively short in duration, would represent a potential health issue because of the high injection pressures, possibility of oxygen depravation, and other adverse reactions if on site personnel were exposed to high concentrations of CO_2. Being denser than air, CO_2 can concentrate in

low-lying or confined areas if not dispersed or mixed with air by winds. Contingency plans in the unlikely event of an accidental large CO_2 release will be prepared by Battelle, complete with an audible and visual warning system, escape procedures, and emergency notification plans. The action limit for the warning system will be set at 2500 ppm, which is half the threshold limit value (TLV) of 5000 ppm. Handling and injection of CO_2 at the site will only be performed by trained personnel. All on-site personnel during injection activities will be trained on CO_2 hazards and emergency procedures.

12.0 PUBLIC PARTICIPATION

The field study outlined in this plan will represent the first sequestration test of any kind in the Pacific Northwest and as such it is expected to generate a significant amount of public interest. The technical team will organize the outreach opportunities to address the most pressing issues associated with Carbon Capture and Sequestration (CCS). Public participation in the project will be built around the following:

- Hold one or more "neighbor/community" meetings to keep the local neighboring residents, tribal representatives, and businesses apprised of the activities on the site and to understand and address any of their concerns.
- Cooperate and participate with Washington Department of Ecology in holding any public meeting that they may deem necessary.
- Prepare informational pamphlets/brochure/fact sheets for distribution in the community and elsewhere that describer carbon capture and storage in general and the pilot project specifically.
- Hold a forum at the Walla Walla Community College Center for Water & the Environment.

The technical team will strive to meet the information requests by working with the developer and the Big Sky Partnership outreach coordinator to organize the public participation such that information is effectively shared but that work continues uninterrupted. Additionally, it is expected that policy and regulatory organizations such as Washington Department of Ecology and Washington State representatives will have an interest the progress of the field test. These entities will be engaged from the first stages of the project to facilitate the permitting process and to assist to the extent possible, in the development of state regulatory path for CCS in Washington State. Every effort will be made to foster these relationships and will be organized by the technical team to insure that there is a consistent approach and that the correct information is shared that neither puts the field test nor the development company at risk. The technical team will also identify key activities associated with the field test that might be suitable for press and local and state official involvement, including visits to the site.

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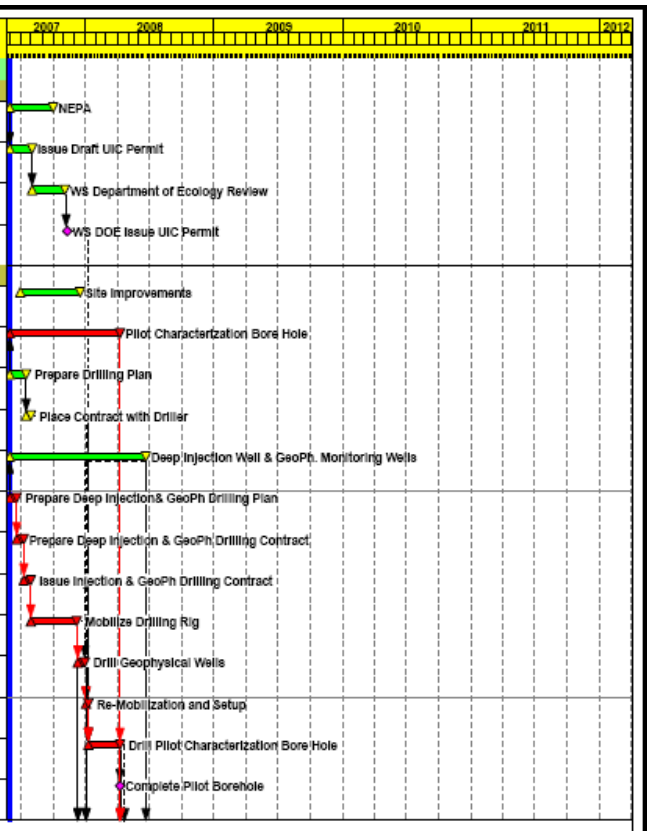
14.0 APPENDIX

Detailed Schedule for Basalt Characterization Test

Act Type	Activity ID	Activity Description	Orig Dur	Early Start	Early Finish
Big Sky Basalt Pilot					
Permitting					
Task	20	NEPA	86	01JUN07*	02OCT07
Task	30	Issue Draft UIC Permit	43	01JUN07	01AUG07
Task	40	WS Department of Ecology Review	66	02AUG07	02NOV07
Finish milestone	50	WS DOE Issue UIC Permit	0		09NOV07
Site Preparation and Drilling					
Task	100	Site Improvements	117	02JUL07*	17DEC07
Hammock	420	Pilot Characterization Bore Hole	219*	30MAY07	09APR08
Task	440	Prepare Drilling Plan	33	30MAY07	16JUL07
Task	450	Place Contract with Driller	10	17JUL07	30JUL07
Hammock	480	Deep Injection Well & GeoPh. Monitoring Wells	270*	30MAY07	19JUN08
Task	490	Prepare Deep Injection& GeoPh Drilling Plan	15	30MAY07	19JUN07
Task	500	Prepare Deep Injection & GeoPh Drilling Contract	13	20JUN07	09JUL07
Task	510	Issue Injection & GeoPh Drilling Contract	15	10JUL07	30JUL07
Task	520	Mobilize Drilling Rig	91	31JUL07	07DEC07
Task	530	Drill Geophysical Wells	14	10DEC07	31DEC07
Task	531	Re-Mobilization and Setup	5	02JAN08	08JAN08
Task	532	Drill Pilot Characterization Bore Hole	65	10JAN08	09APR08
Finish milestone	534	Complete Pilot Borehole	0		09APR08



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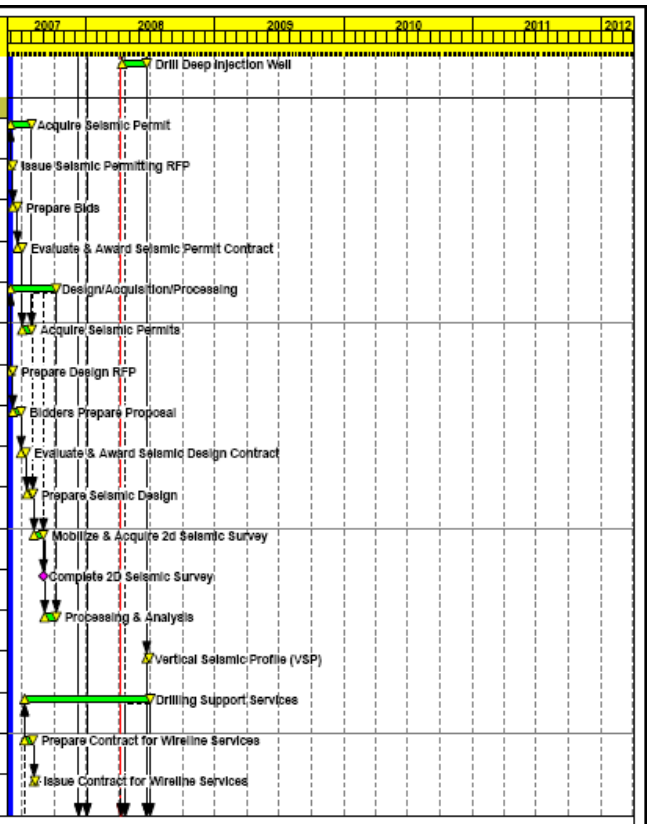
Act Type	Activity ID	Activity Description	Orig Dur	Early Start	Early Finish
Task	540	Drill Deep Injection Well	50	11APR08	19JUN08
Site Characterization					
Hammock	300	Acquire Seismic Permit	42*	01JUN07	31JUL07
Task	310	Issue Seismic Permitting RFP	5	01JUN07*	07JUN07
Task	320	Prepare Bids	10	08JUN07	21JUN07
Task	330	Evaluate & Award Seismic Permit Contract	7	22JUN07	02JUL07
Hammock	340	Design/Acquisition/Processing	90*	01JUN07	08OCT07
Task	350	Acquire Seismic Permits	20	03JUL07	31JUL07
Task	360	Prepare Design RFP	5	01JUN07*	07JUN07
Task	370	Bidders Prepare Proposal	15	08JUN07	28JUN07
Task	380	Evaluate & Award Seismic Design Contract	10	29JUN07	13JUL07
Task	390	Prepare Seismic Design	15	16JUL07	03AUG07
Task	400	Mobilize & Acquire 2d Seismic Survey	20	05AUG07	31AUG07
Finish milestone	402	Complete 2D Seismic Survey	0		31AUG07
Task	410	Processing & Analysis	25	04SEP07	08OCT07
Task	550	Vertical Seismic Profile (VSP)	5	20JUN08	26JUN08
Hammock	560	Drilling Support Services	250*	09JUL07	30JUN08
Task	580	Prepare Contract for Wireline Services	20	09JUL07*	03AUG07
Task	590	Issue Contract for Wireline Services	5	06AUG07	10AUG07



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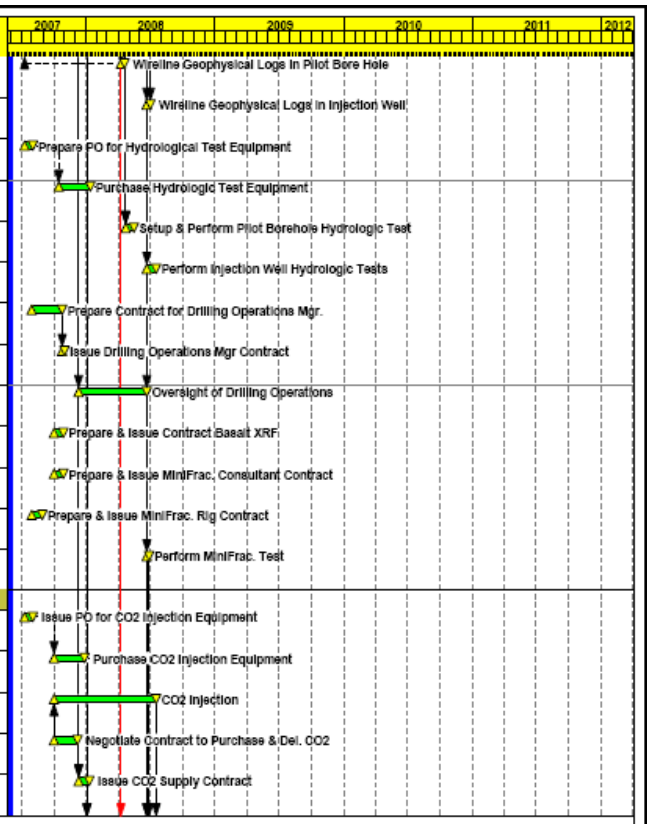
Act Type	Activity ID	Activity Description	Orig Dur	Early Start	Early Finish
Task	592	Wireline Geophysical Logs in Pilot Bore Hole	7	10APR08	18APR08
Task	650	Wireline Geophysical Logs in Injection Well	7	20JUN08	30JUN08
Task	660	Prepare PO for Hydrological Test Equipment	20	09JUL07*	03AUG07
Task	670	Purchase Hydrologic Test Equipment	60	15OCT07*	11JAN08
Task	680	Setup & Perform Pilot Borehole Hydrologic Test	20	21APR08	16MAY08
Task	690	Perform Injection Well Hydrologic Tests	20	20JUN08	17JUL08
Task	790	Prepare Contract for Drilling Operations Mgr.	60	01AUG07*	24OCT07
Task	830	Issue Drilling Operations Mgr Contract	5	25OCT07	31OCT07
Task	840	Oversight of Drilling Operations	136	10DEC07	19JUN08
Task	870	Prepare & Issue Contract Basalt XRF	20	01OCT07*	26OCT07
Task	880	Prepare & Issue MiniFrac. Consultant Contract	20	01OCT07*	26OCT07
Task	890	Prepare & Issue MiniFrac. Rig Contract	20	01AUG07*	28AUG07
Task	950	Perform MiniFrac. Test	5	20JUN08	26JUN08
CO2 Injection					
Task	850	Issue PO for CO2 Injection Equipment	20	09JUL07*	03AUG07
Task	860	Purchase CO2 Injection Equipment	60	01OCT07*	27DEC07
Hammock	600	CO2 Injection	204*	01OCT07	17JUL08
Task	610	Negotiate Contract to Purchase & Del. CO2	46	01OCT07*	05DEC07
Task	620	Issue CO2 Supply Contract	20	10DEC07	09JAN08



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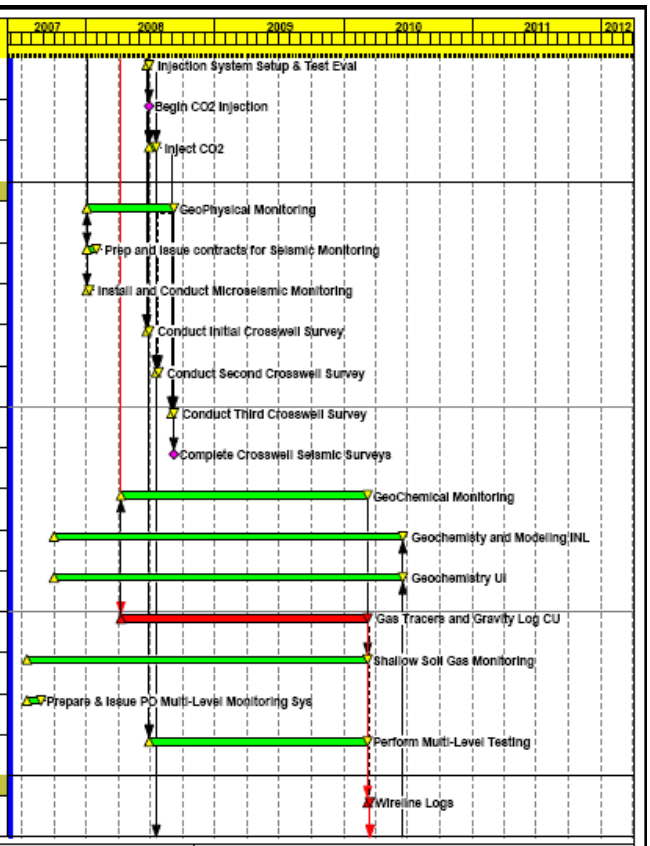
Date	Revision	Checked	Approved

Act Type	Activity ID	Activity Description	Orig Dur	Early Start	Early Finish
Task	630	Injection System Setup & Test Eval	5	20JUN08	26JUN08
Start milestone	635	Begin CO2 Injection	0	27JUN08	
Task	640	Inject CO2	15	27JUN08	17JUL08
MM&V					
Hammock	700	GeoPhysical Monitoring	177*	02JAN08	04SEP08
Task	705	Prep and Issue contracts for Seismic Monitoring	20	02JAN08	29JAN08
Task	710	Install and Conduct Microseismic Monitoring	5	02JAN08	08JAN08
Task	720	Conduct Initial Crosswell Survey	5	20JUN08	26JUN08
Task	730	Conduct Second Crosswell Survey	5	18JUL08	24JUL08
Task	740	Conduct Third Crosswell Survey	5	29AUG08	04SEP08
Finish milestone	745	Complete Crosswell Seismic Surveys	0		04SEP08
Hammock	750	GeoChemical Monitoring	500*	10APR08	10MAR10
Task	755	Geochemisty and Modeling INL	703	01OCT07*	16JUN10
Task	757	Geochemistry UI	703	01OCT07*	16JUN10
Task	760	Gas Tracers and Gravity Log CU	500	10APR08	10MAR10
Task	820	Shallow Soil Gas Monitoring	687	16JUL07*	10MAR10
Task	960	Prepare & Issue PO Multi-Level Monitoring Sys	30	16JUL07*	24AUG07
Task	970	Perform Multi-Level Testing	444	27JUN08	10MAR10
Post Injection Characterization					
Task	855	Wireline Logs	5	11MAR10	17MAR10



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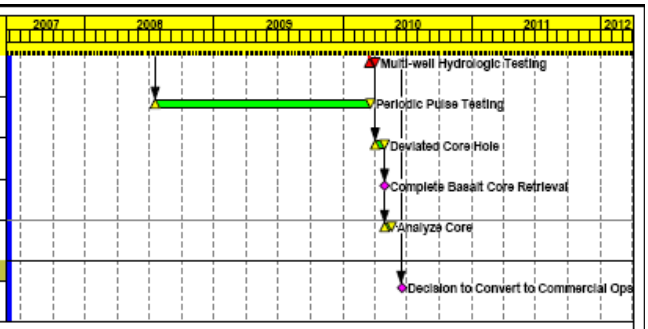
Act Type	Activity ID	Activity Description	Orig Dur	Early Start	Early Finish
Task	900	Multi-well Hydrologic Testing	10	18MAR10	31MAR10
Task	910	Periodic Pulse Testing	436	18JUL08	19MAR10
Task	920	Deviated Core Hole	20	01APR10	28APR10
Finish milestone	925	Complete Basalt Core Retrieval	0		28APR10
Task	930	Analyze Core	15	29APR10	19MAY10
Site Closure					
Finish milestone	940	Decision to Convert to Commercial Ope	0		16JUN10



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