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SEDIMENTARY BASIN DATABASE FOR WASHINGTON AND OREGON STATES FOR THE GEOLOGIC CARBON DIOXIDE ASSESSMENT

PIER COLLABORATIVE REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Golder Associates Inc. performed an inventory of sedimentary basins in the states of Oregon and Washington so that others may assess the suitability of these basins for geologic sequestration of carbon dioxide. The results of this inventory include a database (not included) and a report that summarizes the findings reported in the database. Of particular interest to assessment for geologic sequestration potential are the geometry and physical properties of the basins and saline aquifers in these two states—particularly formations that may serve as reservoirs or seals. Key geologic features that were catalogued in the database and explored in the report include details of recognized and potential oil and gas fields; physical geometries—including areal extent, depth, and thickness; physical properties—such as porosity, permeability, and reservoir yield factors; and geochemistry—notably, the mineralogy of the formation and aqueous quality. The geometry, physical properties, and geochemistry of any capping formations, and also trapping features (such as faults, folds, and stratigraphic features) were also collected.

Keywords: Geologic sequestration, WESTCARB, CO_2, Washington, Oregon, Puget Trough, Tofino-Fuca Basin, Willapa Hills Basin, West Olympic Basin, Willamette Trough, Ochoco Basin, Columbia Plateau, Hornbrook Basin, Chumstick-Swauk Basin, Coos Basin, Astoria-Nehalem Basin, Methow Basin, Whatcom Basin, Tyee-Umpqua Basin

Executive Summary

This report serves as a record of the preliminary characterization of sedimentary basins in the states of Oregon and Washington performed for the West Coast Regional Carbon Sequestration Partnership (WESTCARB). It was written with the intent that others may use this information to assess the suitability of these basins for geologic sequestration of carbon dioxide (CO_2). Three categories of sedimentary basins are described in this study—the western coastal basins of Washington and Oregon, basins east of the Cascade mountain range, and unconsolidated sedimentary basins. This grouping is based upon the differences in quality and quantity of data available for these provinces, as well as characteristic geological differences.

Of particular interest to the assessment of geologic formations for CO_2 storage are the geometry and physical properties of sedimentary basins and saline aquifers. Key geologic features of potential oil and gas fields, capping formations, and trapping features (such as faults, folds, and stratigraphic features) catalogued in the database and explored in this report include physical geometries (such as areal extent, depth, and thickness), physical properties (such as porosity, permeability, and reservoir yield factors), and geochemistry (such as mineralogy of the formation and aqueous quality).

Oregon's and Washington's western coastal basins are associated with a major Tertiary sedimentary belt of basins formed in a regional fore-arc environment. They are up to 9,000 meters (30,000 feet) deep and are underlain by Eocene oceanic basalt throughout. Many individual basin boundaries are uncertain at this time. Reviewed basins are as follows: Tofino-Fuca Basin, Western Olympia Basin, Willapa Hills Basin, Puget Trough Basin, Whatcom Basin, Astoria-Nehalem Basin, Tyee-Umpqua Basin, and Coos Basin.

Although basins east of the Cascade Mountains each have some characteristics that are favorable for potential sequestration, exploration and characterization of them are not as comprehensive as that for many of the Western Basins. Reviewed basins are as follows: Sub-Columbia River Basalt Plateau, Ochoco Basin, Methow Basin, Chumstick-Swauk Basin, and Hornbrook Basin.

Oregon's and Washington's unconsolidated sedimentary basins typically consist of Quaternary and Recent alluvium and lacustrine and aolian deposits overlying consolidated basins or volcanic plateau areas. Their relatively shallow character, the absence of distinct structural and/or physical traps, and the presence of groundwater make many of these basins less promising for CO_2 storage.

1.0 Introduction

Established in Fall 2003, WESTCARB (the West Coast Regional Carbon Sequestration Partnership) is one of seven research partnerships co-funded by the U.S. Department of Energy (DOE) to characterize regional carbon sequestration opportunities and to develop action plans for pilot-scale validation tests. WESTCARB is exploring opportunities in a six-state region (California, Oregon, Washington, Nevada, Arizona, and Alaska) for removing carbon dioxide (CO_2) from the atmosphere by enhancing natural processes and by capturing it at industrial facilities before it is emitted; both will help slow the atmospheric buildup of this greenhouse gas and its associated climatic effects.

A key part of the project is identifying subsurface locations to store the captured CO_2; such sinks are expected to include deep geologic formations (such as oil and gas reservoirs, and saline aquifers) that are essentially leak-proof. These potential sinks will then be matched with the major CO_2 sources such as the main utilities and industrial emitters.

DOE's intention is to combine WESTCARB's findings with those of the other six partnerships to create a national "carbon atlas" to better understand how sequestration technology can help the United States reduce the carbon intensity of its economy and mitigate climate changes.

On the basis of the source and geologic characterization, WESTCARB will prioritize geologic sequestration opportunities within the region and will propose pilot-scale projects that combine industrial CO_2 capture, CO_2 transport via pipeline, and injection into geologic formations for storage or enhanced oil recovery.

2.0 Experimental

Golder investigated the following data and information sources for the project:

- Published reports—particularly those produced by the U.S. Geological Survey (USGS), Washington Department of Natural Resources, Oregon Water Resources Department of Water Resources, and Oregon Department of Geology and Mineral Industries.
- A private online database, maintained by IHE Energy, that contains hydrocarbon exploration well information.
- Online abstracts of professional papers.
- Technical journals and books.

3.0 Results and Discussion

3.1. Consolidated Geologic Basins of Washington

3.1.1. Western Coastal Basins

This study's review of published reports identified several sedimentary basins associated with the western continental margin of Washington State. This section summarizes the character of these basins. The western coast of both states consists of a major Tertiary sedimentary belt of basins that formed in a regional fore-arc environment as the Juan de Fuca plate subducted beneath the North American Plate. The province has been subdivided into several basins, the boundaries of which are uncertain at this time.

These basins are characterized by up to 6,100 meters (m) (20,000 feet (ft)) of Tertiary sedimentary rocks deposited in embayments and shallow seas; throughout, the basins are underlain by Eocene oceanic basalt. Only in the major downwarp areas (the Puget-Willamette Trough) are the Tertiary sedimentary strata overlain by a significant amount of younger sediments. All of the basins in this region have been explored for hydrocarbon potential; one economically productive basin that has been in operation for gas extraction (and more recently for gas storage) is in the Chehalis Sub-basin (the Jackson Prairie Gas Field).

Tofino-Fuca Basin

Location

The Tofino-Fuca Basin is bounded by the Olympic Mountains to the south, extends beneath the Straits of Juan de Fuca, and is bounded to the north by Vancouver Island. The southern extent of the basin is marked geologically by the major west-east trending Crescent Thrust Fault zone which is between 8 and 13 kilometers (km) (5 and 8 miles) from the shoreline. The northern flank is exposed in a narrow belt of shallow- and deep-water marine Paleogene/Neogene strata along the southern coast of Vancouver Island.

Geology

Snavely et al. (1980) described this as a deep Tertiary marginal basin. The sedimentary sequence in the basin consists of more than 5,790 m (19,000 ft) of sandstone, claystone, and coal, which together represent deltaic to deep water depositional settings. The southern flank consists of more than 1,830 m (6,000 ft) of north-dipping middle Eocene to lower Miocene strata consisting of lithic arkosic to lithic turbidite sandstone, deep marine mudstone and subordinate polymict conglomerate and sedimentary breccias. The uppermost strata are deltaic facies (coal bearing) of the Clallam Formation. The basin base is considered to coincide with the top of the Crescent Formation, which is mostly oceanic basalt of early Eocene age.

The generalized sedimentary sequence of onshore rocks above the Crescent Formation (Tcr) is as follows:

Clallam Formation – L. Miocene, Mn(c) or Tc; nearshore sedimentary rocks (sandstone and conglomerate with minor siltstone).

Twin River Group – Oligocene-L. Eocene; includes the:

- Pysth Formation (Tp) – mostly massive mudstone and siltstone;
- Makah Formation (Tm) – siltstone and sandstone; and
- Hoko River Formation (Th) – interbedded sandstone and siltstone.

Lyre Formation – Eocene, Em(2l); marine sandstone and conglomerate.

Aldwell Formation – Eocene; Em(2a) or Ta; marine siltstone, sandstone and conglomerate.

Onshore, the sedimentary rocks are well exposed and have minimal Quaternary cover material.

Jackson et al. (2004) depict the basin in a SW-NE section, showing an asymmetrical syncline with a steeper dipping southern limb and the fold axis positioned about 8 km (5 miles) north of the shoreline.

Exploration

Several deep exploration wells have been drilled on the north coast of the Olympic Peninsula, in two clusters; one cluster is in northeastern Clallam County and another group is further east along the coast. No logs were available in published reports. However, Golder reviewed onshore borehole data for three wells drilled in the 1960s which encountered basement strata at depth of between 1,520 and 1,950 m (5,000 and 6,400 ft). Details for these and other wells in the basin have been included in the database.

Some geophysical (seismic) profiles have been developed across the basin, showing the relationship between the sedimentary sequences and basement rocks. The maximum sedimentary rock depth at coastline was about 4,880 m (16,000 ft), reaching as much as 7,600 m (25,000 ft) in the Strait.

Snavely et al. (1980) reported the following range of porosity and permeabilities for the Makah Formation, based on outcrops:

Porosity – from 20.4% to 20.7%.

Permeability – from 2.0 to 7.5 millidarcies (md).

No geographic or depth information were available for these parameters. Structural traps onshore are rare; only a few local normal, strike-slip, and thrust faults and a few minor faulted anticlines exist. In general, more evidence exists for offshore structural traps.

Western Olympic Basin

Location

The Western Olympic Basin is located directly west of the Olympic Mountains in Clallam and northern Jefferson Counties, and extends westwards offshore for at least 64 km (40 miles) (Wagner and Batatian 1985).

Geology and Structure

The onshore geology consists of outcrops of rocks of the Miocene and Eocene marine sedimentary rocks. As with the Tofino-Fuca Basin to the north, the basin basement is formed by the Crescent Formation basalts. The sedimentary rocks are overlain in places by unconsolidated deposits of Quaternary age. The sedimentary strata have an estimated total thickness of at least 2,740 m (9,000 ft), and the recognized formations are:

Quinault Formation – Pliocene-Miocene (PLMn); up to 1,520 m (5,000 ft) of nearshore sedimentary rocks (siltstone, sandstone, and conglomerate).

Hoh Assemblage – lower-mid Eocene; a sequence of marine rocks accreted to the continental margin:

- Lincoln Creek Formation – Oligocene-Eocene; up to 2,740 m (9,000 ft) of massive sandstones and tuffaceous siltstones.
- Skookumchuck Formation – mid-upper Eocene; up to 1,070 m (3,500 ft) of interbedded shallow marine and continental facies (arkosic sandstones and siltstone), and coal in upper and lower member.
- McIntosh Formation – mid-upper Eocene; up to 1,520 m (5,000 ft) of tuffaceous sedimentary rocks.

Exploration

Golder found information for about 30 exploration wells in the coastal area. The most detailed log information was reported by Rau and McFarland (1982; Sheet 1) for ten wells; all encounter the Hoh Assemblage at depths from 460 to 2,130 m (1,500 to 7,000 ft). However, none of the wells detected basement strata. Limited information was obtained for the remaining wells, with no more than the formation name reported at total drilled depth. Most of these wells report Miocene (Clallam Formation) at a depth of up to 2,290 m (7,500 ft).

Jackson et al. (2004) consider the sedimentary units of this basin to have relatively low oil and gas potential, as tectonic activity has disrupted structural traps.

Willapa Hills (Grays Harbor) Basin

Location

The Willapa Hills rise to about 940 m (3,100 ft) above sea level and are situated between the Olympic Mountains to the north and the Columbia River to the south. The basin is also thought to extend several km offshore (Wagner and Batatian 1985; see Section 5.1). The hills contain the most complete section of Tertiary igneous and sedimentary rocks in the state, from the Eocene Crescent Formation basalts (acting as the basement strata), through a thick sequences of Eocene-Miocene sedimentary and interlayered volcanic rocks.

Geology

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

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

Quinault Formation – Pliocene-Miocene (PLMn); nearshore sedimentary rocks (siltstone, sandstone, and conglomerate)

Montesano Formation – mid-upper Miocene (Mm(2m)); up to 910 m (3,000 ft) of fluvial, lacustrine, brackish water, shallow marine sediments.

Astoria Formation – lower-mid Miocene, Mm(1a); up to 1,070 m (3,500 ft) of marine sedimentary rocks (carbonaceous, fine-grained sandstone).

Hoh Assemblage – similar sequence to that in the Western Olympic Basin

Cowlitz Formation – Eocene (En(c) or Tco); unconformably overlie Crescent Formation; marine/non-marine siltstone and sandstone.

Northcraft Formation – Eocene (Evc(n)); up to 460 m (1,500 ft) of volcaniclastic deposits and lavas.

Snavely and Wagner (1982) interpreted a west-east, 48 km (30 mile) long cross-section including three deep, onshore wells and a seismic profile in Grays Harbor County. They show the base of the Skookumchuck Formation reaching a maximum depth of about 2,900 m (9,500 ft).

Exploration

Pauli (2002a) recognized at least four distinct episodes of submarine fan sedimentation in the basin. Two submarine fan sandstones (the basal Cowlitz and basal Lincoln Creek sandstones) correlate with the productive Clark and Wilson Sandstone at the Mist Field in northwestern Oregon (see Section 3.1) and the Zone 2 sandstone reservoir at Jackson Prairie Gas Storage Field (see Section 3.1.4 of Pauli 2002a).

Four potential Eocene and Oligocene reservoirs have been identified from oil and gas exploration wells, outcrop studies, and seismic interpretations. To date, only eight exploration wells have fully penetrated the Tertiary sedimentary sequence. One well (Union #1 Weyerhaeuser) provides the only subsurface data on porosity and permeability for two of the reservoirs, the basal Lincoln Creek and Cowlitz sandstones. Cores from the well sampled distal turbidites having 26%–33% porosity with up to 95 md permeability. Intra-Lincoln Creek channel sandstone's have 36%–46% porosity and 102–917 md permeability. Basal McIntosh sandstones sampled along the north flank of the Willapa Hills Uplift have 10%–22% porosity and 0.4–6.2 md permeability.

Some porosity and permeability data were reported for two wells (Milwaukee No.1 and Milwaukee Land Co. No. 1). The results are included in the database and are summarized in Table 1.

Table 1. Summary of porosity and permeability data for Willapa Hills Basin wells

Wells		Porosity (%)	Permeability (md)
Milwaukee No.1 and Milwaukee Land Co. No. 1 (33 samples)	Maximum	32.7	522
	Minimum	6.4	< 1
	Median	21.4	13

Rau and McFarland (1982) produced a 4-sheet report showing an interpretation of 47 exploration boreholes and wells in the coastal area from Clallam County (Forks River area), Jefferson County, Grays Harbor County and Pacific County (around Willapa Bay). The boreholes mostly encountered the Quinault Formation, Hoh Assemblage, and the basement Crescent Formation at variable depths. The Crescent Formation was only encountered in three wells located in Pacific County. The deepest well (located in coastal Grays Harbor County) described a minimum sedimentary thickness (Quinault and Hoh units) of 2,800 m (9,300 ft).

Puget Trough Basin

Location

The Puget Trough Basin is located in northwestern Washington, and occupies the generally low-lying region east of the Olympic Mountains and west of the Cascade Mountains. The southern extent of the basin is defined by the mergence of the Cascade Range and Coastal Range in Lewis and Cowlitz counties.

Geology

The basin was part of the major tectonically active fore-arc basin extending from the Frasier River Valley in British Columbia to Cottage Grove in west central Oregon (Willamette Trough), and varies from 100 to 190 km (60 to 120 miles) wide. The present shape and extent in Washington has resulted from recent tectonic and glacial events in the Tertiary-Quaternary periods. The complex structures principally resulted from the tectonic activity associated with the subduction of the Juan de Fuca plate beneath the North American plate.

The basin consists of up to 1,130 m (3,700 ft) of unconsolidated sediments of Pleistocene age overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. For the purpose of this assessment, the research team has included both unconsolidated and consolidated units as part of this basin discussion. However, this study treats the northernmost area (the Whatcom Basin) as a separate basin .

The geology of the Puget Trough is complex and interpretation is made difficult by the large volume of mostly glacially derived, unconsolidated sediments. Faulting and folding is abundant; many active faults are recognized (such as the NW-SE trending Seattle fault zone and the Whidbey Island faults). The major faults and fold belts are included in the electronic database. At least four major glacial advances and several partial advances have been recognized that modified the landscape. The unconsolidated sediments consist of Quaternary deposits in four sequences representing glacial periods.

The faulting as resulted in the formation of several major sub-basins:

Everett Sub-basin – bounded to the north and south by the North and South Whidbey Island Fault Zones, respectively, and attains a maximum thickness of between 3,050 and 4,270 m (10,000 and 14,000 ft), of which as much as 1,100 m (3,600 ft) is considered to be unconsolidated sediments (Jones 1994).

Seattle Sub-basin – located south of the South Whidbey Island fault and is bounded to the south by the Seattle fault and uplift; contains up to 4,570 m (15,000 ft) of sedimentary material, of which up to 1,130 m (3,700 ft) is unconsolidated.

Tacoma Sub-basin – located south of the Narrows Structure; up to 1,830 m (6,000 ft) thick (610 m (2,000 ft) of unconsolidated sediments).

Chehalis Sub-basin – occupies the southern portion of the Trough, south of the Olympic Gravity Anomaly. The unconsolidated sediment thickness is less than 120 m (400 ft) here.

Everett-Seattle-Tacoma Sub-basin Stratigraphy

Despite the presence of the Quaternary deposits, the Tertiary sedimentary rocks are exposed mostly near the basin margins and have been encountered in some deep exploratory borings. The key sedimentary formations recognized by researchers are:

Blakeley and Blakeley Harbor Formations – Oligocene-Eocene (OEm(b)); marine sedimentary rocks in the northern Puget Sound area of interbedded volcaniclastic sandstone, siltstone, shale, and conglomerate.

Puget Group – Eocene (Ec(2pg)); continental sedimentary rocks/deposits.

- Renton Formation (Ec(2r)) – continental sedimentary rocks/deposits (fine-medium grained, massive to cross-bedded arkosic sandstone).
- Tiger Mountain Formation (Ec(2t)) – continental sedimentary rocks/deposits.
- Tukmila Formation (Evc(t)) – volcaniclastic rocks/deposits (sandstone, siltstone and conglomerate).

The Crescent Formation is again believed to underlie the Tertiary sedimentary units throughout the western part of the basin. Walsh and Lingley (1991) presented an isopach map showing the thickness of Ulatian and Nazarian (lower-mid Eocene) rock in the subsurface for the entire

Puget Trough based on drilling records, measured sections, and outcrop patterns. These contours are included in the database.

Chehalis Sub-basin Stratigraphy

The Chehalis Sub-basin occupies the lowland area between the southern extent of Puget Sound in Thurston County, extending into Lewis County and northernmost Cowlitz County. This sub-basin has special economic significance as it is home to the Jackson Prairie Gas Storage Field; the storage reservoir has a potential capacity in excess of 1.4 billion cubic meters (m^3) (50 billion $ft.^3$) gas and currently houses 0.8 billion m^3 (28 billion $ft.^3$) gas with a daily delivery potential of 24 million m^3 gas/day (850 million $ft.^3$ gas/day).

The geology of the Chehalis consists of Tertiary sedimentary rocks (Eocene to Miocene age) deposited in a fore-arc basin over basaltic rocks. The key sedimentary formations are:

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

Pinotti (2002a, 2002b) reported that the Chehalis gas field's geologic structure was formed by a high angle reverse fault active from mid-Oligocene to Miocene time, trapping minor quantities of native gas. The fault plane over thrust Skookumchuck sand onto Oligocene Lincoln Creek mudstone and forms an elliptical arch around the north and west sides of the field. The fault became inactive at the time of the Miocene Columbia River Basalt flows.

Exploration

Many deep exploration holes have been drilled in the northern Puget Trough area, yet little specific information is available concerning formation thicknesses and engineering properties. About a dozen wells report the age of the deepest geologic unit encountered; the research team included these wells and depths in the database. Much seismic profile and gravity anomaly work has been carried out by government and research groups, with increasing interest following the 2001 Nisqually earthquake.

More than one hundred exploratory holes have been drilled in the Chehalis Sub-basin since the early 1900s, most of which are concentrated in west-central Lewis County. Most drilling terminated in the Eocene strata; the deepest well reached more than 3,050 m (10,000 ft) without encountering the volcanic basement rocks.

Walsh and Lingley (1991) present porosity data for six wells drilled in the Chehalis sub-basin. The porosity ranges from 3% to 39%, the highest of which were for a well drilled in the Jackson Prairie field (28% to 39%). These data are included in the database. Pauli (2002b) reported porosities for the Tertiary sandstones in the Chehalis Basin as typically exceeding 30%, with permeabilities between 1 and 4 darcies. Sharp (2002) reports that Cowlitz and basal Lincoln

Creek sands, which store gas at Jackson Prairie Field, have porosities up to 34% and permeabilities up to 3.2 darcies.

Cores collected from the basin's western margin near the Willapa Hills Uplift reportedly encountered numerous Skookumchuck Formation sandstones having excellent reservoir properties (porosity of 30%–38%, and permeability of 135–3,030 md) in a variety of sedimentary facies. Reservoir-quality sandstones have also been documented in oil and gas tests penetrating McIntosh Formation sandstones.

The database includes porosity values for core samples collected from several wells in the basin. These are summarized in Table 2.

Table 2. Summary of porosity and permeability data for Chehalis sub-basin wells

Wells		Porosity (%)	Permeability (md)
Jackson Prairie SU909 Hannum No. 2, Pacific Coast Coal No.1, Socal-Schroeder No.1, Socal-Whidbey No.1, Black Diamond No.4-13, Sqaulicum No.1, and Blessing Siler Comm. No.1	Maximum	38.9	3,920
	Minimum	3.7	30
	Median	14.5	82

Much of the economic exploration in the Seattle, Tacoma and Everett Sub-basins has been for groundwater purposes. Well-defined glacial aquifers have hydraulic conductivities in the range of 3 to 210 m/day (10 to 700 ft/day), with most test values in the range of 5 to 15 m/day (16.5 to 49.2 ft/day). The higher values are typically associated with coarse sand and gravel outwash or alluvial deposits. Individual aquifer thicknesses are typically from 30 to ~100 m (100 to a few hundred ft) thick, and are generally overlain by low permeable till, clay, and silt materials.

Whatcom Basin

Location

The Whatcom Basin is located in northwestern Washington, and is the northernmost part of the Puget Trough lowlands. The exact basin outline is uncertain due the cover of unconsolidated sediments and the complex geology towards the Cascade Range. However, the basin is separated from the Everett sub-basin to the south by the Vedder Mountain-Boulder Creek fault zone.

Geology

The geology of the basin consists of Quaternary glacial and interglacial deposits overlying Tertiary sedimentary rocks and pre-Tertiary rocks of the northwest Cascade Range. The Tertiary rocks consist of mainly those assigned to the Chuckanut and Huntingdon Formations whose deposition were controlled by tectonic activity (uplift and faulting). The upper parts of the western Cascade Range units, which consist of a stack of oceanic lithologic terranes, are considered for the purpose of this assessment as forming the basin basement. The sedimentary rock units lie above a major tectonic thrust fault (Shusksan) that separates the underlying terranes (Mesozoic metamorphic rocks beneath), forming the basin base.

The Chuckanut Formation (Eocene) consists of up to 6,100 m (20,000 ft) of arkosic sandstone, siltstone, conglomerate, and coal deposited in Eocene time. Individual members have maximum thickness of between 910 and 5,490 m (3,000 and 18,000 ft). The depositional environmental was a strike-slip, pull-apart basin that received detritus from local uplifts and distant sources. Deformation has produced broad to tight, N-W and W-E trending folds. The Huntingdon Formation (Oligocene-Eocene) is a moderately to well-sorted conglomerate, sandstone, siltstone, shale, and clay totaling up to 460 m (1,500 ft) of thickness.

The unconsolidated sediments are of Quaternary age, are of glacial origin and are shown by Jones (1999) to be up to 460 m (1,500 ft) thick near the Canadian border. This basin continues into the Fraser Valley of southern British Columbia.

Exploration

There has been a significant amount of exploration of the basin due to the presence of the coal measures which have been economically worked since the twentieth century. Methane potential is believed to be relatively good on the eastern basin limb, less so towards the west. Data for several exploration wells drilled in the basin has been included. Porosity and permeability data were available for core samples from three wells (formations were not specified). The results are included in the database and are summarized in Table 3.

Table 3. Summary of porosity and permeability data for Whatcom Basin wells

Wells		Porosity (%)	Permeability (md)
Squalicum No.1, Ross No. 1 and Hillebrecht No. 1 (13 samples)	Maximum	17.3	45.3
	Minimum	7.0	0.1
	Median	15.0	8.8

3.1.2. Central-Eastern Washington Basins

This section includes two major sedimentary basins located between the eastern margin of the Cascade Range and the Columbia Plateau province. It also included details of the sedimentary rocks known to underlie the thick sequence of the Columbia River Basalt Group (CRBG).

Sub-Columbia River Basalt Sedimentary Basin

Location

This area is defined as occurring east of the Cascade Mountains in Washington and northern Oregon, and in a geologic sense, west of the ancient cratonic margin. Although the basalt flows are more extensive, we are concerned here with the underlying sedimentary rocks.

Geology

The sedimentary rocks that pre-date the CRBG are not exposed in the Plateau area and much uncertainty exists to their exact extent and thickness. Most of the existing data have resulted from investigations associated with the Hanford Nuclear Facility in Grant, Benton, and Yakima counties. There is much ongoing research work in this province to characterize the basalt for possible natural gas storage (Riedel et al. 2002).

In general, the basin contains up to 4,570 m (15,000 ft) of layered Miocene lava flows (the CRBG) overlying as much as 10,060 m (33,000 ft) mid-Tertiary, non-marine sedimentary strata. The main sub-CRBG sedimentary formations that have been identified are as follows:

Wenatchee Formation – Oligocene (Oc(h)); up to 300 m (1,000 ft) of fluvial sandstones and shales. Also crops out in the Chiwaukum Basin.

Wildcat Creek Formation – Oligocene (Ovc(wc)); more than 300 m (1,000 ft) of tuffs and volcaniclastic sandstones.

Ohanapecosh Formation – Eocene (Ohm(oh)); tuffs and volcaniclastics.

Roslyn Formation – Eocene (Ec(2r)); more than 4,270 m (14,000 ft) of arkosic sandstones and black shale interbeds.

Chumstick Formation – Eocene (Ec(2ch)); more than 4,880 m (16,000 ft) of fluvial micaceous sandstone with conglomerate/shale interbeds.

Swauk Formation – Eocene (Ec(1s)); up to 4,570 m (15,000 ft) of fluvial arkosic sandstone, shale, and conglomerate.

Manatash Formation – Eocene (Ec(1m)); up to 920 m (3,000 ft) of fluvial sandstone, shale, and coal.

Reidel et al. (2002) recognized the Palouse Slope and Yakima Foldbelt as two key structural features in the Columbia Plateau province in defining the likely extent of the sub-basalt sedimentary strata. The Palouse Slope area overlies a crystalline basement high with a relatively thin (less than 90 m (300 ft)) sediment sequence between the basalt and basement. The underlying basement is metasedimentary rock of late Precambrian to Paleozoic age and is inferred to be part of the old continental craton. The Yakima Foldbelt to the west is underlain by a thick sequence of sediments that have been extensively investigated geophysically.

The western craton edge is estimated to coincide with the Ice Harbor dike swarm near longitude 119° west. Researchers also infer that the southern edge of the craton coincides with the Hite Fault Zone which marks the northern extent of the Blue Mountains province. This arc and the general basin outline have been included in the database.

Exploration

As mentioned, Golder found records for several deep exploration wells that were drilled between 1957 and 1989 through the base of the CRBG. Most of these wells were also drilled through the entire sedimentary sequence and into the crystalline basement. These wells are included in the database, along estimates of depths to the basin base, and thicknesses of the recognized formations. Some geophysical surveys have also yielded information regarding the lateral and vertical extent of the sedimentary units.

Myers and Price (1979) reported the results of magnetotelluric survey in the Pasco area conducted to determine the subsurface geometry for the Basalt Waste Isolation Project. The results, which consist of contours of depth to significant horizons and thicknesses, are included in the database.

Walsh and Lingley (1991) presented porosity data for three of the deep wells drilled in the basin. Most of the values are for the Roslyn Formation, and range between 4% and 22%, with the median about 13%. Porosity generally decreases with increasing depth. Some of the samples were of the Ohanapecoch Formation, and range from 13% to 17%. These data are included in the database and are summarized in Table 4.

Table 4. Summary of porosity data for sub-CRBG basin sandstones

Formation	Porosity (%)	
Swauk Formation (2 samples)	Maximum	7.9
	Minimum	4.9
	Median	6.4
Ohanapecosh Formation (4 samples)	Maximum	17.0
	Minimum	9.0
	Median	14.9
Wenatchee Formation (7 samples)	Maximum	16.1
	Minimum	9.1
	Median	14.0
Roslyn Formation (61 samples)	Maximum	22.1
	Minimum	3.9
	Median	12.0

The Rattlesnake Gas Field is located in the Yakima Foldbelt and is a low-pressure anticlinal trap in basalts containing natural gas. It is believed that the gas originated from coals in fluvial sediments underlying the basalt.

Methow Basin

Location

The Methow Basin is located on the eastern flank of the Cascade Range, and forms part of a more extensive sedimentary basin that extends into southern British Columbia, where it is called the Tyaughton Basin.

Geology

The geology of the basin consists of a thick sequence of Cretaceous sedimentary rocks, bounded by prominent faults; the Chiwack-Pastyn fault is to the northeast and the Ross Lake Fault zone (Hozemeen fault) is to the southwest. The sedimentary rocks are exposed throughout the basin, and the Washington DNR (McGroder et al. 1990) estimated the total sequence thickness (up to 3,960 m (13,000 ft)) based only on outcrops, as no deep exploratory wells have been drilled.

Haugerud et al. (2002) identified five Cretaceous-Tertiary sequences:

Pipestone Canyon Formation – Paleocene, (PAc(p)). Continental siltstone, sandstone, conglomerate, 670 m (2,200 ft) thick at type locality, thinning to the north. Contains substantial vertical jointing.

Pasayten Group (Cretaceous):

- Winthrop Sandstone – massive, fine-coarse sandstone, up to 3,960 m (13,000 ft) thick in the Goat Creek syncline).
- Virginia Ridge Formation – black mudstone, siltstone, and chert-lithic sandstone and conglomerate. Up to 3,960 m (13,000 ft) thick near Cady Point. Interfingers with Withrop sandstone.
- Goat Wall unit – redbeds and volcanics.

Patterson Lake Conglomerate – Cretaceous (Kcg(p)). Mudstone and interbedded sandstone and conglomerate; massively bedded.

Harts Pass Formation – L. Cretaceous, (Km(h)). Up to 2,440 m (8,000 ft) of marine sandstone, black shale, and conglomerates.

Newby Group – Jurassic-Cretaceous (KJm(n)). Volcanic lithic sandstone, conglomerate, siltstone, black shale, argillite, carbonate pods, and andesitic-dacitic volcanic rocks. Total thickness estimated as at least 1,830 m (6,000 ft). Includes the Twisp Formation (intensely folded argillites and sandstones).

Structure

Structurally, the basin contains a series of parallel thrust faults oriented NW-SE and similar-trending faulting (forming anticlines and synclines). The basin’s southeastern extent is marked surficially by the boundary with the younger CRBG sequence. It is likely that the basin's sedimentary sequence extends beneath the basalt flows.

Exploration

As mentioned above, no deep mineral exploration wells have been drilled in the basin, making the thickness and depth of the sedimentary formations difficult to determine. No information was available regarding engineering properties.

Chiwaukum and Swauk Basins

Location

The Chiwaukum and Swauk Basins are located on the eastern flank of the Cascade Range in Wenatchee County, and are two adjacent fault-controlled basins.

Geology

The Chumstick Graben forms an erosional lowland and sedimentary basin bounded by the Entiat Fault on the east and the Leavenworth Fault on the west. The sedimentary rocks crop out throughout the basin, and consist of up to 5,790 m (19,000 ft) of non-marine strata of Eocene age.

The main outcropping formation in the Chiwaukum Basin is the Eocene-age Chumstick Formation (Ec(2ch)). This unit is a thick (possibly as much as 1,520 m (5,000 ft)) sequence of continental sandstone and conglomerate, shale, and fanglomerate.

The Swauk Basin is located south and west of the Chumstick Basin, and its western boundary is defined by the major north-south Straight Creek Fault. The primary sedimentary unit is the Swauk Formation (lower-mid Eocene) which is considered to be the most extensive sedimentary formation in eastern Washington; it forms a 8 to 16 km (5 to 10 mile) wide belt extending west from the Columbia River along the southern slope of Wentachee Mountain and into the Cascade Range. The strata consist of several facies of conglomerate, arkosic sandstones, and shale. The Swauk Formation is also believed to underlie the Chumstick Formation in the Chiwaukum Graben (Gresens 1983).

As with the Methow Basin, the eastern extents of both basins are masked by the CRBG. Sedimentary rocks outcropping in the basins west of the basalt flow were encountered in deep borings drilled below the base of the CRBG on the western plateau, and it is likely that they extend to the ancient cratonic edge.

Exploration

No deep oil and gas exploration wells have been drilled in the basin, making the thickness and depth of the sedimentary formations difficult to determine. No information was available regarding engineering properties.

3.2. Consolidated Sedimentary Basins of Oregon

For the purpose of this assessment, the research team identified several consolidated sedimentary basins in Oregon that belong to the following three geographic provinces:

- Western Tertiary Basins.
- Columbia Plateau Basins.
- Intermontane, Non-marine Tertiary Basins.

The following sections provide summary details of these basins.

3.2.1. Western Tertiary Basins

The Western Tertiary Basins consists, in essence, of a single sedimentary province that evolved as a fore-arc environment in Tertiary time. The province occupies about 51,800 km^2 (20,000 square miles) of mostly marine sedimentary rocks extending from the Oregon coast to the foothills of the Cascade and Klamath Mountains. The sedimentary sequence consists of up to 6,100 m (20,000 ft) of mostly Eocene age, formed in littoral to deep-marine depositional environments.

Researchers and hydrocarbon prospectors have identified several sedimentary basins in the Coastal Ranges province, namely the Astoria, Nehalem, Tyee, and Coos Basins, for hydrocarbon exploration purposes. The Willamette Basin, which generally coincides with the lowland area, separates the Coastal Range and the Cascade Mountains. Definition of the exact extent of each of these basins is problematic due to the volcanic and sedimentary cover and tectonic deformation. However, the Oregon Department of Geology and Mineral Industries published a series of reports that describe the key characteristics of these economically-important basins using exploration well information as well as outcrop studies.

Astoria-Nehalem Basin

Location

The Astoria-Nehalem Basin is located in northwestern Oregon, in western Columbia, and eastern Clatsop counties, about 72 km (45 miles) northwest of Portland. The basin contains the only economically productive gas filed in Oregon (known as the Mist Gas Field), which occupies an area of about 13 km^2 (5 $mi.^2$) and was first produced from in 1979.

Geology

The base of the sedimentary basin coincides with the top of the oldest identified rock unit in the area, the Eocene-age Tillamook Volcanics (which consist of basalts and breccias) (Niem et al, 1990). The earliest sedimentary unit is the mid-Eocene Yamhill Formation (siltstones and shales); although the sedimentary units interfinger with the volcanics, the Yamhill does contain a prominent sandstone member.

The Cowlitz Formation overlies the Yamhill Formation, and consists of micaceous, arkosic-basaltic marine sandstone, siltstone, and mudstone. Of key importance is the gas-producing Clark and Wilson Sandstone which is overlain by a thick shale unit (Niem and Niem 1985).

A sequence of marine sedimentary units overlies the Cowlitz Formation, and consists of thick- to thin-bedded tuffaceous mudstone, siltstone, and sandstone. Key units include the Spencer, Keasey, Pittsburg Bluff, and Astoria Formations (all mid-upper Eocene).

The basin geology is complex due to the extensive folding and faulting. Normal and strike-slip faulting is common, with the predominant fault trend being northwest; some significant east-west and NE-SW faulting also exists. Faulted anticlines are reportedly the most common trap in the Mist Field.

Exploration

This basin has been more extensively drilled and tested than any other basin in Oregon, and records show at least 240 exploratory boreholes and wells in the area; more than half have descriptive logs and core records. These boreholes were drilled to depths of up to 3,440 m (11,300 ft). Golder obtained (from the Oregon Graduate Institute of Science and Technology (OGI) reports) records for 15 wells in the area (McKeel 1983). The logs were interpreted by the authors using Foraminifera correlation. All borings reported Tertiary sedimentary units, and most of the drilling encountered the Tillamook Volcanics at depths between 910 and 2,2250 m (3,000 and 7,300 ft). In the Nehalem Basin, some wells encountered up to 1,220 m (4,000 ft) of volcanics beneath the Cowlitz and above the Yamhill Formations.

As mentioned, the Clark and Wilson Sandstone is a gas-containing unit; gas pools are generally small (40 to 160 acres). The gas, which is mostly methane, was not likely generated in-situ, and was most likely generated in the Astoria Basin to the west or the northern Willamette basin to the south, before migration. Jackson et al. (2004) considers the Astoria area to have moderate potential for gas, and most of the basin lies offshore.

The database includes the stratigraphic details of the available borehole logs. No isopach maps were discovered in the existing literature, and developing such a map is problematic due to the lack of borings full penetrating the sedimentary sequence. Minimum thickness estimates are provided, however. Also included is some porosity and permeability data for the Clark and Wilson, and Cowlitz Sandstone units from the Texaco 6-1 well (Table 5).

Table 5. Summary of porosity and permeability data for Nehalem Basin sandstones

Unit		Porosity (%)	Permeability (md)
Clark and Wilson Sandstone (33 samples)	Maximum	31.9	1,400
	Minimum	18.9	18
	Median	26.0	195
U. Cowlitz Sandstone (14 samples)	Maximum	38.9	80
	Minimum	25.6	2.0
	Median	29.6	7.5
L. Cowlitz Sandstone (15 samples)	Maximum	13.3	1.0
	Minimum	0.7	1.0
	Median	9.1	1.0

Tyee-Umpqua Basin

Location

The Tyee-Umpqua Basin occupies the southern half of the Coastal Range, extending from a latitude near Salem, beyond Roseburg, to the junction of the Coastal Range with the Klamath Mountains. To the west are the younger basinal sediments of the Coos Basin.

Geology and Structure

The basin consists of more than 6,100 m (20,000 ft) of lower-middle Eocene sedimentary strata preserved in the Coastal Range hills. In fact, the basin contains two superimposed basins with different geologic trends and tectonic histories; the NE-SW trending early Eocene Umpqua Basin and the N-S trending Tyee Basin. The Umpqua Basin rocks represent a partially subducted accretionary wedge deposited in a trench or rifted continental margin, overlying and interfingering the lower Eocene Siletz River Volcanics that form basaltic crust. Later and after rotation, a new subduction zone formed to create the fore-arc environment in which the Tyee Basin rocks were deposited.

The main geologic units identified in the basin are:

- Spencer Formations – lower-mid Eocene; up to 150 m (500 ft) of arkosic sandstone (fluvio-deltaic)
- Bateman Formation – mid-upper Eocene; up to 760 m (2,500 ft) of arkosic sandstone (deltaic) and mudstone
- Elkton Formation – mid-Eocene; up to 910 m (3,000 ft) of mostly mudstone and minor sandstone.
- Tyee Formation – mid-Eocene; mostly 1,830 m (6,000 ft) of sandstone, deposited in shallow marine to non-marine deltaic (south) to slope and deep marine basinal margin (in north). The eastern margin is truncated by younger rocks or covered by younger volcanic rocks; the western margin is a passive sill or a seamount terrane of oceanic crust. Contains several recognized members.
- Umpaqua Group – upper Paleocene to lower Eocene; up to 3,050 m (10,000 ft) of mudstone, sandstone, and conglomerate (non-marine to deep marine origin). Prominent formations recognized in reports include the Camas Valley White Tail Ridge, Tenmile, and Bushnell Rock Formations.

The sedimentary basin basement is formed by the top of the Siletz River volcanics (basalt).

The southern Coastal Range consists of a major, N-S trending syncline with the younger (Elkton Formation) rocks surrounding the older Tyee Formation. Other similar trending folds produce secondary anticlines and synclines, and several NE-SW trending faults exist on the Range fringes.

Exploration

Many hydrocarbon exploration wells have been drilled in the Tyee area, the results for many are included in Niem et al. (1992) and Ryu et al. (1996). The former report presents a fence diagram containing an interpretation of the depth and thickness of the sedimentary units and, where encountered, the volcanic basement based on well and field exposures. These borings and interpretations are included in the database. The later report also includes some engineering property data (porosity and permeability) for field samples collected from field samples.

Ruy and Niem (1999) report that much of the primary porosity of the Tyee sandstone has been infilled during diagenesis, and that secondary porosity and permeabilities average 10.8% and 2.76 md, respectively. The porosity and permeability data included in the OGI reports are summarized in the database.

Coos Basin

Location and Extent

The Coos Basin is located in coastal southwestern Oregon in the Coastal Range Province. The basin extends from the western edge of the Tyee Basin and the Klamath Mountains and continues offshore.

Geology

The geology of the basin consists of marine sedimentary rocks of Tertiary age that were deposited as continental deltaic margin and deep-sea fan facies. The key units are as follows:

- Bastendorff Formation – upper Eocene to lower Oligocene; up to 880 m (2,900 ft) of thinly laminated siltstone and mudstone.
- Coaledo Formation – upper Eocene; up to 1,830 m (6,000 ft) of deltaic sandstones, and prominent coal seams.
- Bateman Formation – mid-Eocene; 305 m (1,000 ft) of sandstone (near-shore, deltaic).
- Tyee Formation – similar strata to those in the Tyee Basin; up to 1,520 m (5,000 ft) thick in the Coos Basin.
- Fluornoy Formation – mid-Eocene; between 305 and 1,520 m (1,000 and 5,000 ft) of sandstone and siltstone sequence.
- Looking glass Formation – lower Eocene; basal conglomerate and overlying fine-grained sandstone and siltstone sequence (up to 2,130 m (7,000 ft) thick).
- Roseburg Formation – lower Eocene-upper Paleocene; between 3,050 and 3,660 m (10,000 and 12,000 ft) of rhythmites and submarine basalts.

Exploration

Numerous hydrocarbon exploration borings have been drilled in the basin. McKeel (1984) presented interpretations of several borings for which logs were collected and described. None of the borings, drilled to maximum depths of between 920 and 3,900 m (3,000 and 12,800 ft), encountered non-sedimentary basement material. However, the formational thicknesses and elevations, and overall minimum sedimentary sequence thicknesses are included in the database. Newton (1980) presented porosity and permeability data for sandstone samples of the lower and upper Coalcedo, Fluornoy, and Roseburg Formations, summarized in Table 6.

Table 6. Summary of porosity and permeability data for Coos Basin sandstones

Unit		Porosity (%)	Permeability (md)
U. Coalcedo (3 samples)	Maximum	38.3	667
	Minimum	28.2	51
	Median	33.7	339
L. Coalcedo (7 samples)	Maximum	43.2	1,788
	Minimum	18.3	4.5
	Median	30.2	232
Fluornoy (6 samples)	Maximum	38.2	154
	Minimum	25.0	24.8
	Median	32.2	70
Roseburg (4 samples)	Maximum	32.6	384
	Minimum	10.0	15.4
	Median	19.8	24

3.2.2. Columbia Plateau Basins of Central and Eastern Oregon

Ochoco Basin

Location

The Ochoco Basin is located in central Oregon, in Crook and Wheeler counties. The precise basin geometry is uncertain as the sedimentary rocks are covered for the most part by the CRBG and exploratory drilling has been limited to four wells.

Geology

Sedimentary rocks of the basin depositionally overlie a diverse assemblage of accreted terranes in the Blue Mountains. Dorsey and Lenegan (2004) describe the Mitchell Inlier, which consists of exposed Cretaceous sedimentary rocks of marine origin:

Gable Creek Formation – U. Cretaceous, Cenomanian; a fluvio-deltaic conglomerate and sandstone.

Hudspeth Formation – L. Cretaceous, Albian; a widespread and thick sequence of marine mudstone with subordinate siltstone and sandstone.

Dorsey and Lenegan report the presence of up to 1,520 m (5,000 ft) of pebbly sandstone and conglomerate at one surface exposure. The inlier is surrounded by Tertiary volcanic rocks. The sedimentary units overlie Paleozoic metasedimentary rocks of the Baker Terrane. They also infer the extent of the basin (included in the database here).

Little published data exists on the geology of the area, but based on surface mapping, it has been considered a potential petroleum producing area. No commercial hydrocarbon discoveries have been made, though.

Some research has been performed on the diagenetic history of the Cretaceous sediments during burial beneath the volcanics. Although some low-grade metamorphosis occurred, logging and analysis indicate that some reasonable porosity exists in the deeper parts of the sequence (Summer and Verosub 1992).

Structure

Given the limited subsurface information, the overall basin structure is difficult to determine. Dorsey and Lenegan report a significant SW-NE trending anticline creating the Mitchell Inlier (described above), exposing the basement rocks and the Cretaceous units. They also report a west-east trending strike-slip fault in the area.

Exploration

Knowledge of the subsurface of the area is provided by four deep exploration holes completed between 1955 and 1981, located between 13 and 23 km (5 and 9 miles) south of Mitchell. The well logs and an interpretation are presented in Thompson et al. 1984. Two additional wells were drilled in Wheeler County (logs available) which encountered crystalline basement rocks at total drilled depth.

Hornbrook Basin

Location

The Hornbrook Basin is located in southern Oregon and extends into northernmost California. The defining Hornbrook Formation is one of many widely scattered Cretaceous units that crop out in various parts of Oregon. The rock outcrops form a narrow belt, about 130 km (50 miles) long, from just north of Medford to just south of Yreka in California. The basin’s true extent of the formation (and the basin) has been made difficult to determine, due to the large separation of outcrop areas, extensive cover of Tertiary volcanic rocks, limited exploratory drilling, and extensive deformation. However, some researchers have suggested that the basin may be continuous with the Ochoco Basin in central Oregon and the Great Valley in California.

Geology

The Hornbrook, Ochoco, and Great Valley sequence of California thought to have been formed as part of the same depositional basin, likely connected at depth beneath cover material. The basin developed along the northeastern margin of the Klamath Mountains, extending further northeast, connecting with the Ochoco Basin in the Mitchell area. Nilsen (1984) infers the likely extent of the Hornbrook-Ochoco Basin as being bounded by upland areas to the north (by the

Blue Mountains), east (by the Idaho batholith region), and west and southwest (by the Klamath Mountains). The basin may have been open to the paleo-Pacific Ocean to the northwest.

The Hornbrook Formation strata form three linked valleys in southern Oregon and northern California, defining the eastern edge of the Klamath Mountain province. The Medford-Bear Creek Valley is the only one of these located entirely within Oregon; the Cottonwood Creek Valley straddles the Oregon-California border and is offset from the Medford-Bear Creek Valley by the Siskiyou Summit fault.

The Hornbrook Formation rests unconformably on metamorphic and plutonic, Ordovician to late Jurassic age rocks of the Klamath Mountains. The Hornbrook strata generally dip moderately to the northeast. Tertiary volcanic and sedimentary rocks overlie the Hornbrook Formation to the west.

According to Nilsen (1984), the Hornbrook Formation has a total thickness of about 1,220 m (4,000 ft). He divided the Hornbrook Formation into five members, all of which consistently crop out in the Medford-Bear Creek Valley. The type section is located near the town of Hornbrook, located 13 km (5 mi.) south of the Oregon border in the Cottonwood Creek Valley. The members are (youngest to oldest):

- Blue Ranch Member – mostly mudstone with fine-grained sandstone interbeds. Contains the Rancheria Gulch and Hilt Bed sandstones. Total member thickness is 910 m (3,000 ft).
- Rocky Gulch Member – gray fine-medium grained sandstone. From 150 to 230 m (500 to 750 ft) thick.
- Ditch Creek Member – gray siltstone and fine-grained sandstone. Between 23 and 76 m (75 and 250 ft) thick.
- Osburger Creek Member – marine sandstone unit, includes some conglomerate, siltstone and shale. Between 76 and 152 m (250 and 500 ft) thick.
- Klamath Rover Member – non-marine, clast- and matrix-supported conglomerate; up to 90 m (300 ft) thick.

Exploration

The basin has attracted some attention for petroleum prospects since natural gas was discovered east of the outcrop areas in the Cascade Ranges (Law et. al, 1984). One well (drilled in 1984 about 48 km (30 miles) northeast of Yreka), encountered 610 m (2,000 ft) of sedimentary rocks with a show of oil or gas.

Kieghin and Law (1984) reported the following engineering properties for sandstone samples collected from the various members in northern California (Table 7).

Table 7. Summary of porosity and permeability data for Hornbrook Basin samples

Unit/Formation	Porosity (%)	Permeability (md)
Blue Gulch Sandstone	12.2–13.6	0.01
Holt Bed	18.6	0.8
Rocky Gulch Sandstone	6.3–12.8	0.18–1.2
Ditch Creek Siltstone	6.3–12.8	0.01–0.05
Osburger Creek Sandstone	6.7–13.1	0.01–0.89

Law et al. (1984) report results for analyses of 62 outcrop samples. They suggest that the nature of the organic matter present (type III kerogen) indicates the rocks have potential to generate gas with little to no oil, and that the rocks are immature to marginally mature with respect to thermal gas generation. However, the effects of weathering of the surface samples means that hydrocarbon potential may be overall slightly higher.

Snake River Basin

The Snake River Basin is located in easternmost Oregon, and extends into western Idaho. The basin sediments consist of semi-consolidated to well-consolidated tuffaceous lacustrine shales, siltstones and sandstones, alluvial sandstone and conglomerate, coal, and lava of Miocene-Pliocene age. In many places, the sedimentary rocks are themselves covered by Miocene basalts. According to Dole and Corcoran (1954), the total sedimentary sequence thickness is about 4,570 m (15,000 ft). The sedimentary rocks overlie Mesozoic volcanic rocks.

Several hydrocarbon exploration wells have been drilled in the basin, with oil and gas shows in a few of these boreholes. Locations of some of the deeper borings drilled in the basin are included. Information is limited, although some records indicate the final formation encountered at total depth.

Harney Basin

The Harney Basin is located in the northernmost area of the Basin and Range Province. The geology is believed to be similar to that of the Snake River Basin, consisting of thick continental sediments and lavas.

Some details for several wells drilled in the basin are included. Limited geologic information was available, however.

3.3. Unconsolidated Sedimentary Basins

As part of this assessment, the research team reviewed literature and information sources for several unconsolidated sedimentary basins in Washington and Oregon. The depositional environments include fluvial, lacustrine, glacial, and aeolian. All surficial units exhibit extensive outcrops in these basins.

3.3.1. Unconsolidated Basins of the Columbia Plateau Province (Washington)

Walla Walla Basin

The Walla Walla Basin is located in southeastern Washington (in Walla Walla County).

The basin geology consists of unconsolidated alluvial, wind-blown, and flood deposits overlying bedrock consisting of Columbia River Basalt flows.

- Unconsolidated sediments – consist of gravel and clay of Pleistocene age (alluvial fan and flood deposits), loess, and younger and older alluvial materials
- Columbia River Basalt – consists of a thick series of individual flows of the Saddle Mountains Basalt (youngest), Wanapum Basalt, and Grande Ronde Basalt (oldest).

The basalt has been folded and faulted since it was deposited, resulting in several compartmentalized fold- or fault-bounded blocks near the city of Walla Walla. The principal geologic structure is the Walla Walla syncline; the fold axis is roughly parallel to the axis of the Walla Walla valley, and plunges gently to the southwest. The elevation of the top of the basalt is lowest along the axis of the syncline and the thickness of the unconsolidated sediments is greatest to the west, along the axis of the syncline.

A map layer showing the interpreted elevation of the base of the unconsolidated sediments (or top of the underlying CRBG strata) in the main part of the valley is included as part of the database. The transmissivity of the unconsolidated sand and gravel aquifer in the Walla Walla Basin ranges from about 930 to 5,580 m^2/day (10,000 to 60,000 square feet (sq. ft)/day) with a hydraulic conductivity of 4 to 200 m/day (13 to 650 ft/day) (Golder 2004). The basalt aquifer is the most productive aquifer, and contains a number of high-capacity (greater than 3,800 liters/minute (1,000 gallons/minute)) production wells. Groundwater generally occurs in the contacts between basalt flows. The basalt aquifer transmissivity is variable and dependent on the thickness of the interbed zones, the number of interbed zones intersected, and the hydraulic conductivity of the materials in the interbed zones. The transmissivity of the basalt aquifer in the Walla Walla Basin has estimated to average about 750 m^2/day (8,000 sq. ft/day), and rarely exceeds 3,720 m^2/day (40,000 sq. ft/day).

Kittatas-Yakima-Selah Basins

These three unconsolidated basins extend eastward from the foothills of the Cascade Ranges Mountains onto the western edge of the Columbia Plateau Basin. The eastern portion of the basin (east of Cle Elum) transitions into the Yakima fold belt, consisting of structural basins filled with sedimentary and volcaniclastic sediments, and upland areas of volcanic rocks such as basalt.

The Ahtanum-Moxee basin is a synclinal structure bounded on the north by Yakima Ridge and Cowiche Mountain and on the south by Ahtanum Ridge and the Rattlesnake Hills. It is a basin within the larger Yakima River Basin.

An important geologic feature of the basin is the Yakima Fold Belt, which is a series of anticlinal ridges and synclinal valleys that predominantly trend east-west. The Belt covers roughly 14,000 square kilometers of the Columbia Basin, and was formed when basalt flows of the CRBG and interbedded sediments of the Ellensburg Formation were folded and faulted as a direct result of north-south compressional stresses. These structures are clearly exposed along road cuts when driving through the Selah Gap and Union Gap. The tops of the anticlines are represented by Selah Heights and Yakima Ridge on the north side of the valley, and by Ahtanum Ridge and the Rattlesnake Hills on the south side of the valley. The trend of the Yakima Ridge and Ahtanum Ridge anticlines changes east of the Yakima River, where the fold axes trend more northwesterly-southeasterly. Current research suggests that this shift is due to a major structural feature—the Olympic-Wallowa Lineament—which runs from northeastern Oregon to the tip of the Olympic Peninsula.

The general geology is summarized as follows:

- Alluvium– occurs at ground surface with thicknesses that generally range up to 60 m (200 ft).
- Thorp Gravel – underlies the alluvium within the Ahtanum Valley. The thickness of this unit varies up to 12 m (40 ft).
- Upper Ellensburg Formation – often subdivided into an upper coarse-grained member, a middle fine-grained member and a lower coarse-grained member. The Upper Ellensburg Formation is up to 530 m (1,750 ft) thick at the axis of the Ahtanum-Moxee basin syncline.

The CRBG and interlayered Lower Ellensburg Formation sediments underlie the Upper Ellensburg Formation. No CRBG thickness information is available in this area.

In the database, the general extent of unconsolidated sediments in the valley is indicated, and details of the thickness of the unconsolidated sediments and the depth to the top of the CRBG rocks (from Drost and Whiteman 1986; and Golder 2002) are also included. The basin thickness ranges from zero at the margins to almost 610 m (2,000 ft) at the center of the basin.

Permeability results for several groundwater production wells are also included. The estimated hydraulic conductivity for the Upper Ellensburg Formation ranges over five orders of magnitude from 0.2 to 0.62 to 690 m/day (2,265 ft/day); the average estimates for the upper and lower members are 4 m/day (13 ft/day) and 18 m/day (60 ft/day), respectively. The transmissivity of Upper Ellensburg Formation sediments ranges from 23 to 7,760 m^2/day (250 to 83,500 sq.ft/day). The basin's permeable units are currently being evaluated for aquifer storage/recharge projects to increase the area's water supply and improve the quality and reliability.

Toppenish-Satus Basin

The Toppenish and Satus Basins lie south of the Yakima Basin, and are separated by the Ahtanum Ridge. The surficial geology is similar to that in the Yakima Basin, and the thickness of unconsolidated sediments exceeded 305 m (1,000 ft) in the center of the Toppenish Basin (Drost and Whiteman 1986).

Pasco Basin

The Pasco Basin is at the eastern edge of the Yakima Fold Belt region, and is bordered to the south by the Columbia River and to the north by the Saddle Mountains. The basin is home to the Hanford Nuclear Reservation. The unconsolidated sediments consist of up to 240 m (800 ft) of Quaternary sediments (Drost and Whiteman 1986). No specific well information was available in this basin.

Quincy Basin

The Quincy Basin is located north of the Pasco Basin, east of the Columbia River. Despite it relatively large areal extent (approximately 1,950 km^2 (750 square miles)), the sediment thickness exceeds 120 m (400 ft) only at the central area (Drost and Whiteman 1986). No specific well information was available in this basin.

Spokane River Basin

The Spokane River Basin is located in eastern Washington and consists of up to 210 m (700 ft) of unconsolidated fluvial and fluvio-glacial sediments. The basin outline included in the database is based on the extent of the unconsolidated sediments. The base of the basin coincides with the top of the continental basement rocks (Precambrian, exposed in a few areas) and the CRBG rocks. The generalized geologic sequence in the region is as follows:

- Unconsolidated (Quaternary) deposits – comprise predominantly sands and gravels with minor amounts of silt and clay; during glacial advances and retreats up to the present day alluvial system.
- Basalt flows and intercalated sediments – consist of basalt rocks comprise Miocene age (Columbia River Basalt Group) flows intercalated with fluvial and lacustrine deposits of the Latah Formation (lacustrine silt and clay beds containing some fluvially deposited sand and gravel).
- Crystalline basement – comprises Precambrian metamorphics (quartzite, schist, and gneiss) and Mesozoic to early-Cenozoic plutonic rocks (granite).

The database includes contours of the elevation of the base of the unconsolidated sediments. The thickness ranges from zero where the basalt and crystalline bedrock outcrop to 210 m (700 ft) in the deepest parts of the Spokane River valley.

The unconsolidated sediments in the main Spokane River area (the Spokane Valley-Rathdrum Prairie Aquifer, or SVRP) are highly permeable and transmissive, and are heavily pumped heavily for municipal groundwater supplies. Hundreds of shallow groundwater wells have been drilled to extract the generally good quality water. The permeability of the sand and gravel aquifers associated with the flood events can exceed 150 m/day (500 ft/day). Groundwater in the basalt flows is also pumped. Table 8 summarizes the hydraulic properties of the various units.

Table 8. Summary of hydrologic properties for the Spokane River Basin units

Hydrogeologic Unit	Aquifer Area	Transmissivity m^2/day (ft^2/day)	Hydraulic Conductivity in m/day (ft/day)
Flood Sand and Gravel	SVRP	400–1,020,000 (4,320–11,000,000)	150–3,660 (500–12,000)
	Little Spokane River	930–48,200 (10,000–518,400)	160–>190 (530–>640)
	Deer Park	67–24,900 (722–267,400)	5–1,850 (16–6,077)
Lower Flood Sand and Gravel	Little Spokane River	930–3,700 (10,000–40,000)	30–70 (100–230)
Basalt	West Plains, Little Spokane River, Five Mile Prairie, Deer Park	2–18 (25–193)	0.05–3.7 (0.18–12.1)
Crystalline Basement	North End of Five Mile Prairie	—	0.3–26 (1–86)

Groundwater in the basin is generally of good to excellent quality. Total dissolved solids are generally less than 200 milligrams per liter (mg/L) within the alluvial sediments and less than 250 mg/L within the basalts (Golder 2003a, 2003b).

3.3.2. Willamette Lowland Trough

Location

The Willamette Trough is a flat-lying region bounded to the east by the Cascade Mountains, to the west by the Coastal Hills Range, and extends from the Lewis River in Washington to Eugene; both northern and southern extends coincide with upland areas where the Cascade and Coastal hills converge. For the purpose of this assessment, the research team used the findings of Woodward et. al (1998) to define the basin and geologic properties. The basin includes four broad basins: the Portland Basin, the Tualatin Basin, the Central Willamette Valley, and the Southern Willamette Valley. The land surface slopes northwards from about 140 m (450 ft) above mean sea level (msl) at Eugene to less than 15 m (50 ft) above msl near Portland.

Geology

The Willamette Valley consists of up to 610 m (2,000 ft) of unconsolidated basin fill sediments of continental origin (Quaternary age) overlying Columbia River Basalts (in the north) and Tertiary sedimentary and volcanic rocks (in the south). The basin was formed in response to tectonically induced subsidence in the area between the Coastal Ranges and the Cascade Mountains. The sediments were derived from a number of sources, including the surrounding uplands and the Columbia River; the uppermost basin fill deposits are a result of giant Columbia River floods in late Pleistocene time.

Marine sedimentary rocks and volcanics underlie the basin fill. The former are associated with the Tertiary basins described in Section 3 (such as the Tyee-Upmqua Basin); the latter consist of Columbia River Basalts, and are exposed in the northern part of the basin and separate the four main basin areas. The oldest outcropping rocks in the Basin are the Eocene volcanic rocks (Siletz River and Tillamook volcanics) that also underlie the marine sedimentary basins in the Coastal Range.

Gannet and Caldwell (1998) defined the following hydrostratigraphic sequence to develop a regional aquifer system for the basin:

- Willamette Silt Unit – Pleistocene-Holocene; up to 40 m (130 ft) of glacial outburst flood sediment
- Willamette Aquifer – Pliocene-Pleistocene; 6 to 180 m (20 to 600 ft) of coarse-grained fan and stream deposits.
- Willamette Confining Unit – Miocene-Pleistocene; up to 490 m (1,600 ft) of fine-grained alluvial fan and river deposits
- CRBG Aquifer – up to 305 m (1,000 ft) of Miocene basalts; underlying the unconsolidated sediments in the northern lowlands
- Basement Unit – includes Tertiary marine sedimentary and Eocene volcanic rocks

Hydraulic properties for these regional units are summarized in Table 9.

Table 9. Summary of hydrologic properties for Willamette Trough units

Unit	**Hydraulic conductivity in m/day (ft/day)**		
	Median	Range	Modeled
Willamette Silt	0.03 (0.1)	0.03–2.4 (0.01–8)	0.3 (1.0)
Willamette Aquifer	2.1–73 (7–240)	(0.01–2,130 (0.03–7,000)	61–183 (200–600)
Confining Unit	0.6 (2)	0.03–27 (0.01–90)	1.5 (5.0)
CRBG Aquifer	0.3 (1)	0.0003–230 (0.001–750)	0.8 (2.5)

McKeel (1984 and 1985) provides some information on the nature of the Tertiary sedimentary and volcanic rocks underlying the basin fill in the northern and southern parts of the basin, respectively. His analysis of borehole cores indicates that as much as 2,900 m (9,500 ft; in the south) and 4,420 m (14,500 ft; in the north) of Tertiary sedimentary rocks overlies basement volcanics. These sedimentary rocks are a continuation of these present in the Cascade Ranges to the west, and overlie the Tillamook Volcanics in the north and the Siletz River Volcanics in the south.

Exploration

Most of the activity in the Willamette Valley Lowlands has been aimed towards water resources. The area is heavily farmed and the unconsolidated and basalt aquifers contain water of excellent quality. More than 30 deep exploratory wells have been drilled in Lane, Linn, Polk, Marion, Yamhill, Washington, and Multnomah counties for hydrocarbon exploration. Golder reviewed the interpretation of 18 wells in McKeel (1984 and 1985) to estimate depths and thicknesses of the Tertiary sedimentary formations, and depth to economic basement. These data are included in the database.

3.3.3. Unconsolidated Basins of the Columbia Plateau Province in Oregon

Umatilla Basin

The Umatilla Basin is located in north-central Oregon (Umatilla and Morrow Counties), immediately south and adjacent to the Columbia River. The basin consists of up to 120 m (400 ft) of unconsolidated sediments deposited by wind and deposited glacially derived fine silt overlies the CRBG in much of the basin (Davies-Smith et al. 1988).

Coarse sediments derived from riverbed, flood, and other alluvial deposits occur locally with thicknesses up to ~100 m (several hundred feet). Interflows, consisting of sedimentary units between basalt flows, may be 60 m (200 ft) thick. The entire CRBG sequence may be as much as 1,830 m (6,000 ft) thick in the basin.

Much of the area is under administrative groundwater withdrawal limitations due to excessive irrigation use. Records show that one 104-m (340-foot) deep exploration well was drilled in 1955 about 6 km (4 miles) northeast of Pendleton (OWRD 2003). No driller's logs or core records exist for this well, however.

Deschutes Basin

The Deschutes Basin is located on the eastern flank of the Cascade Range and occupies the margin with the Basin and Range Province and the High Lava Plains regions. For this assessment, the research team considered the more extensive upper Deschutes Basin area, which is a sub-area of the larger Upper Deschutes River watershed (defined in Gannett et al. 2000); in particular, the sub-basins referred to as La Pine, Princeville, and Sister.

The geology of the sub-basins consists of Quaternary alluvium, overlying volcanic rocks. The Cascade Range (to the west) and the Tertiary (Miocene) and Quaternary lavas of the Columbia-Deschutes Plateau and Lava Plateau (to the east) form the basin boundaries.

The La Pine Sub-basin is essentially a faulted graben structure, with between 550 and 730 m (1,800 and 2,400 ft) of structural relief. The graben formed a depositional center initially filled with low-permeable material sediment and later coarser alluvium. The La Pine Sub-basin is the largest occurrence of Quaternary alluvium in the region. The sediments generally consist of a lower layer of mostly silt and sand layer (~100 m (several hundred feet) thick) overlain by up to 30 m (100 ft) of silt, sand and gravel. Some local water wells are as deep as 450 m (1,460 ft).

Most of the economically productive water wells are located in the upper alluvium; these wells yield from 38 to 1,140 liters/minute (10 to 300 gallons/minute), and the sediments have a reported hydraulic conductivity of 27 m/day (88 ft/day) (Lite and Gannett 2002). The high organic content in the lower alluvium has been noted as possible source for methane.

The alluvium generally overlies a sequence of fairly permeable volcanic deposits and highly permeable (Miocene-Pliocene) Deschutes Formation which consist of a variety of volcanic and sedimentary units. The Deschutes Formation overlies the low permeable John Day Formation. The John Day Formation consists of ~1,000 m (several thousand feet) of diagenetically altered volcanic and volcanically derived sedimentary rocks of Miocene-Eocene age.

Caldwell and Truini (1997) presented groundwater quality data (for general parameters such as specific conductance, general minerals, metals, and pH) for more than 20 wells located in the basin. These results are included in the database. The conductivity ranges from 60 to 866 microSiemens per centimeter (μS/cm). The report also summarized discharge water quality for seven springs; specific conductance ranges from 60 to 189 μS/cm.

Eight deep exploratory boreholes have been drilled, all located between 3 and 6 km (2 and 4 miles) south and south east of Bend, and were drilled to total depths of between 430 and 1,370 m (1,400 and 4,500 ft). Drilling logs exist for just two of these wells, neither of which was inspected for this project.

La Grande and Baker Basins

The La Grande Basin is located in northeastern Oregon, near the cities of La Grande and Elgin in Union county. The basin consist of broad, relatively thin (up to ~100 m (a few 100 ft)) and relatively continuous surficial alluvial sand and gravel deposited by the Grande Ronde and other braided rivers which flow from the Blue Mountains in the west and the Wallowas in the east onto a broad flat valley floor (Ferns et al. 2003). Groundwater depth is generally less than 6 m (20 ft) below land surface.

One exploratory borehole has been drilled in the basin is located less than 2 km (one mile) west of Union to a depth of 850 m (2,800 ft), likely terminated in the Tertiary basalts. No log or core records exist, however. The Baker Basin lies several km (a few miles) south of the La Grande Basin.

Pluvial Lake Basins of the Basin and Range Province

The Basin and Ranges geomorphic province occupies southern Oregon, and is a series of long, narrow, north-south trending, fault-block mountains alternating with broad sediment-filled basins (Orr and Orr 1999). This summary includes several of the largest basins which are in essence graben structures caused by the extensional tectonics that occurred in this region during Miocene to Pliocene time. The basins were fed water during the relatively wet Pleistocene, resulting in lakes.

The predominant surficial deposits in the basins are alluvium (gravel, sand, silt, and pyroclastic deposits), dune sand, fanglomerates, and playa deposits (silt, clay, and evaporates). Several basins still contain lakes. The basin floors are typically 1,220 m (4,000 ft) above mean sea level or higher. Many of the basins extend into the northern California and Nevada portions of the Basin and Ranges. The basins defined in this assessment are as follows:

- Klamath Lake Basin
- Fort Rock Basin
- Goose Lake
- Warner Valley
- Summer Lake
- Catlow Valley
- Alvord-Pueblo Valley

The basins typically overlie the Tertiary volcanic rocks which were laid down starting in the Miocene; the total volcanic sequence likely reached up to 3,050 m (10,000 ft). These volcanic rocks were subsequently heavily faulted and fissured. No information was available for the thickness of the unconsolidated sediments, but they are likely up to ~100 m (several hundred feet) thick.

The Klamath Lake Basin is the most westerly of these basins, and is located on the eastern flank of the Klamath Mountains. The basin contains unconsolidated fluvio-lacustrine deposits of diatomite, water-lain volcanic sediments, and tephra with localized alluvium, alluvial fans, and tallus. Sediments are generally thin (~10 m (tens of feet)) but can be up to ~100 m (hundreds of feet) near fault escarpments. The sediments are generally above the water table, though minor amounts of perched water do occur. The basin also includes a continental sedimentary unit, often referred to as the Yonna Formation. The unit consists of bedded sandstone, siltstone, laminated mudstone, and conglomerate and tuff, underlain and overlain by Miocene lava flows. The geologic sections in Sherrod and Pickthorn (1992) illustrate the formation to have a thickness of up to 760 m (2,500 ft).

Hydrocarbon prospectors drilled five wells between 1926 and 1931 in the basin within several km (a few miles) east and south of Klamath Falls; the maximum depth drilled was 1,330 m (4,365 ft). Included in the database are details for several of these wells. Minimal geologic information was available at this stage, although some borehole logs and cores exist for these and other wells drilled in the basin. Geothermal water was encountered in two of the wells. No engineering properties were available for this basin.

3.4. Petroleum Assessments

3.4.1. 1995 Outer Continental Report

In 1995, the U.S. Department of the Interior's Minerals Management Services prepared an assessment of the oil and gas resources of the Pacific Outer Continental Shelf (Dunkel and Piper 1997). The report defined the Washington-Oregon Assessment Area as consisting of a 48 to 80 km (30 to 50 mile) wide (starting 5 km (3 miles) offshore) by 640 km (400 mile) long region, stretching from Cape Flattery off the northwest coast of the Olympic Peninsula to just south of Cape Blanco in southwestern Oregon.

The assessment also defined six Neogene depositional centers (sub-basins) based on seismic profiles. The offshore geology of the region consists of a Paleocene-Miocene mélange (the Hoh Assemblage discussed in Section 3.1.1), overlain by turbidites deposited in a trench and slope environment. Structural features are generally trend north or northwest and include compressional folds and faults, dextral strike-slip faults and extensional faults.

Twelve exploratory wells and three Deep Sea Drilling Project coreholes were drilled in the offshore region. Hydrocarbon shows were encountered in eight of the well sites.

The report also identified five petroleum plays based on reservoir and trapping characteristics; the outlines of these are included in the database. The following is a brief summary of these plays:

- Growth Fault (conceptual) Play – Miocene-Pliocene sandstones deposited in deltaic and fan systems with growth fault traps. Hydrocarbon accumulations are expected to occur to about 2,440 m (8,000 ft) below the sea floor. Located off the coast of Washington (from Teawhit Head to the Columbia River mouth).
- Neogene Fan Sandstone (conceptual) Play – Miocene-Pliocene sandstones deposited in deltaic and fan systems with anticlinal, fault, and stratigraphic traps. Hydrocarbon accumulations may exist to about 3,660 m (12,000 ft) below the sea floor. Extends from Teawhit Head to Newport in Oregon.
- Neogene Shelf Sandstone (conceptual) Play – Miocene-Pliocene sandstones deposited in deltaic and fan systems on the continental shelf and upper slope, with anticlinal, fault and stratigraphic traps. Hydrocarbon accumulations may exist from 610 to about 3,660 m (2,000 to about 12,000 ft) below the sea floor. Extends from Cape Flattery to Cape Blanco.
- Paleogene Sandstone (frontier) Play – Eocene –Oligocene sandstones deposited in a shelf environment, and incorporate anticlinal, fault, and stratigraphic traps. The traps are expected to be between 610 and 6,100 m (2,000 and 20,000 ft) deep. Extends from Grays Harbor to Coos Bay.
- Melange Play – contains oil and associated gas in Eocene-Miocene sandstones, and extends from Cape Flattery to Cape Blanco. The upper part is considered to be turbidites, and the lower part is a tectonic mélange. Equivalent rocks are exposed in the Western Olympics area (see Section 3.1.1).

The Eel River Basin lies south of the Washington-Oregon Area basin, and extends a short distance into offshore Oregon waters. None of the associated drilling occurred north of the Oregon-California border. Therefore, for the purpose of this assessment, the research team considered this basin to be associated with California rather than with Oregon.

3.4.2. 1995 National Assessment of Oil and Gas Resources

The USGS Central Energy Team provides periodic assessments of the oil and natural gas endowment of the United States. The most recent, completely digital assessment of the entire United States was completed in 1995 and has been archived (U.S. Geological Survey Team 1995). The report defined three provinces that either fully or partially fall within the states of Oregon or Washington region. The assessment produced geologic reports and these provinces are:

- Province 4: Western Oregon-Washington Province. Includes all of Oregon and Washington north of the Klamath Mountains and west of the approximate Cascade Range crest, and extends offshore to the federal 5-km (3-mile) limit. The province covers an area of 103,600 km^2 (40,000 square miles). The regional geology consists of rocks accreted during the period of Mesozoic subduction. The fore-arc basin strata are as much as 6,100 m (20,000 ft) thick, onlapping the varied pre-Tertiary basement and Paleocene-Eocene volcanic basement.
- Province 5: Eastern Oregon-Washington Province. This province is bounded on the west by the approximate Cascade Range crest, on the north by the U.S.-Canadian border, on the east by the Idaho state line and on the south by the boundary with the Great Basin Province. The province covers and area of about 155,400 km^2 (60,000 square miles). The regional geology consists of mostly rocks of the Miocene Colombia River Basalt Group (up to 3,350 m (11,000 ft) thick) overlying Paleozoic and Mesozoic rocks associated with the ancient continental margin. The sedimentary rocks that form the basins and plays are located mostly in the western half of the province, and represent marine sediments deposited on the accretionary complex (Cretaceous) and less continuous, non-marine sediments (Paleocene-Eocene age).
- Province 19: Western Great Basin Province. This province is essentially the western part of the Great Basin geomorphic province, and occupies a total area of about 336,700 km^2 (130,000 square miles), of which about the northernmost quarter lies within Oregon borders. The regional geology consists of metamorphosed basement rocks of Paleozoic and Mesozoic age, with lacustrine and fluvial sedimentary basins developed in response extensional tectonics in Cretaceous-Cenozoic time.

Each province contains individual plays, either conventional (hypothetical) or unconventional. All of the plays consist of one or more of the sedimentary basins described in Section 3 of this report.

Only one of the plays (the Cowlitz-Spencer Gas Play in Province 4) is a confirmed play. The report also provides summary ranges of key engineering properties—notably porosity, permeability, and total organic carbon—for the significant geologic formations. The database includes the outlines of these provinces plus the parameter ranges.

3.4.3. Other Assessments

The American Association of Petroleum Geologists (AAPG) maintains an interactive website for worldwide oil and gas fields (http://gisudril.aapg.org/gisdemo/). Golder accessed this site to review the AAPG's data. The browser site includes several basins (both consolidated and unconsolidated) in Washington and Oregon that generally match the sedimentary basins described in earlier sections. No explicit fields were included for any of the basins, though.

4.0 Conclusions

Golder conducted a preliminary characterization of sedimentary basins in the states of Washington and Oregon as part of Phase I of WESTCARB's Geologic Carbon Dioxide Sequestration Assessment. The following conclusions were drawn based on the work performed and detailed in the report.

4.1. Western Coastal Basins

The study identified several sedimentary basins along the western continental margin of Washington and Oregon states. These basins are associated with a major Tertiary sedimentary belt of basins that formed in a regional fore-arc environment as the Juan de Fuca plate subducted beneath the North American Plate. These basins are characterized by up to 9,100 m (30,000 ft) of Tertiary sedimentary rocks deposited in embayments and shallow seas; throughout, the basins are underlain by Eocene oceanic basalt. In many cases, the individual basin boundaries are uncertain at this time. Although some basin depth and thickness interpretations were made and engineering properties for key formations exist, no storage volume estimates were attempted at this stage.

- <u>Tofino-Fuca Basin</u>. The Tofino-Fuca Basin occupies the northern edge of the Olympia Peninsula and extends beneath the Strait of Juan de Fuca. The sedimentary sequence consists of up to 7,600 m (25,000 ft) of sandstone, claystone, and coal in an asymmetrical syncline. Reported sandstone permeabilities range from 2.0 to 7.5 md and porosities from 20.4% to 20.7%. Structural traps onshore are rare, and only a few local normal, strike-slip, and thrust faults, and a few minor faulted anticlines, exist. Offshore structural traps appear to be more common.
- <u>Western Olympia Basin</u>. The Western Olympic Basin is located directly west of the Olympic Mountains and extends westwards offshore for at least 60 km (40 mi.). The Miocene and Eocene marine sedimentary rocks have an estimated total thickness of at least 2,700 m (9,000 ft). The Hoh Assemblage, which is the most prominent of these sedimentary rocks, was accreted to the continental margin. All of these units have relatively low oil and gas potential because tectonic activity has disrupted their structural traps.
- <u>Willapa Hills Basin</u>. The Willapa Hills Basin is located south of the Western Olympic Basin and contains up to 4,600 m (15,000 ft) of late Oligocene to Quaternary sedimentary strata overlying oceanic basalt basement. Two notable submarine fan turbidites (the basal Cowlitz and basal Lincoln Creek sandstones) show porosities of 26% to 33% and permeabilities up to 95 md. The younger McIntosh sandstone exhibit porosities and permeabilities up to 22% and 6.2 md, respectively. Four potential Eocene and Oligocene reservoirs have been identified from oil and gas exploration wells, outcrop studies, and seismic interpretations in this basin.
- <u>Puget Trough Basin</u>. The Puget Trough Basin occupies the generally low-lying region east of the Olympic Mountains and west of the Cascade Mountains. It consists of up to 1,100 m (3,700 ft) of unconsolidated sediments of Pleistocene age overlying up to 3,000 m

(10,000 ft) of Tertiary sedimentary rocks. Faulting and folding is abundant, resulting in the formation of several distinct sub-basins. The Chehalis sub-basin hosts the Jackson Prairie Gas Field—a once-economically productive gas reservoir; this field currently provides temporary storage for natural gas, and so provides a good analog for potential geologic storage of carbon dioxide. Skookumchuck Formation sandstones have excellent reservoir properties (porosity of 30% to 38%, and permeability of 135 to 3,030 md) in a variety of sedimentary facies.

- Whatcom Basin. Whatcom Basin occupies the northernmost part of the Puget Trough lowlands; however, the true basin outline is uncertain due to unconsolidated sediment cover and complex geology. The basin consists of Quaternary glacial and interglacial deposits overlying Tertiary sedimentary rocks and pre-Tertiary rocks of the northwest Cascade Range. The notable Chuckanut Formation (Eocene) consists of up to 6,000 m (20,000 ft) of arkosic sandstone, siltstone, conglomerate, and coals; individual members have maximum thickness of between 900 and 5,500 m (3,000 and 18,000 ft). Hydrocarbon exploration has been significant, mostly focusing on gas derived from the coal deposits. Reported sandstone porosity and permeability values range up to 17.3% and 45.3 md, respectively.
- Astoria-Nehalem Basin. This is located in northwestern Oregon, about 70 km (45 miles) northwest of Portland, and contains the only economically productive gas field (Mist Gas Field) in Oregon. This basin has been explored more than any other in the state. The prominent Cowlitz Formation consists of micaceous, arkosic-basaltic marine sandstone and a siltstone-and-mudstone sequence; this sequence includes the gas-producing Clark and Wilson Sandstone, which is overlain by a thick shale unit. Permeabilities and porosities are up to 1,400 md and 39%, respectively.
- Tyee-Umpqua Basin. This basin occupies the southern half of the Coastal Range in Oregon and consists of two superimposed basins with different geologic trends and tectonic histories. The basin contains more than 6,000 m (20,000 ft) of lower-middle Eocene sedimentary strata. One notable unit in this basin is the Tyee Formation sandstone, which has a total thickness of up to 1,800 m (6,000 ft) and average porosities and permeabilities of 10.8 percent and 2.76 md, respectively.
- Coos Basin. The Coos Basin is located in coastal southwestern Oregon in the Coastal Range Province, extending from the western edge of the Tyee Basin and continuing offshore. The basin consists of up to 4,000 m (13,000 ft) of marine sedimentary rocks of Tertiary age that were deposited as continental deltaic margin and deep-sea fan facies. Prominent sandstones possess porosities and permeabilities up to 43% and 1,800 md, respectively.

4.2. Basins East of the Cascade Range

This research identified several consolidated basins east of the Cascade Mountains in both Oregon and Washington. Although each basin has some characteristics that are favorable for potential sequestration, exploration and characterization are not as comprehensive as for many of the western basins.

- Sub-Columbia River Basalt Plateau. Several deep exploration boreholes identified a thick sequence of sedimentary rocks underlying the Columbia River Basalt Group. These rocks are not exposed in the Plateau area and much uncertainty exists to their exact extent and thickness. The basin contains up to 4,600 m (15,000 ft) of layered Miocene lava flows overlying as much as 10,000 m (33,000 ft) of mid-Tertiary, non-marine sedimentary strata.
- Ochoco Basin. This basin is located in south-central Oregon and has uncertain lateral extents due to only limited exploration and a thick volcanic cover. The capping is less well known, although the basin is buried beneath younger material.
- Methow Basin. The Methow Basin is located on the eastern flanks of the northern Cascade Range in Washington. The basin is fault-bounded and is believed to contain up to 4,000 m (13,000 ft) of Cretaceous-Tertiary sedimentary strata. Several significant marine sandstone members have been identified based on surface exposures. However, no deep exploration drilling has been performed and the basin has not been well characterized.
- Chumstick-Swauk Basin. This basin is located on the eastern flank of the Cascade Range to the south of the Methow Basin. The basin is a graben feature and contains up to 5,800 m (19,000 ft) of non-marine strata of Eocene age. As with the Methow Basin, no deep oil and gas exploration wells have been drilled in the basin, making the thickness and depth of the sedimentary formations difficult to determine. No information was available regarding engineering properties.
- Hornbrook Basin. The Hornbrook Basin is located in southern Oregon and extends into northernmost California. The basin is a narrow, 80-km (50-mile) long belt containing an undetermined thickness of Cretaceous units. The basin's true extent is uncertain due to the extensive cover of Tertiary volcanic rocks, limited exploratory drilling, and extensive deformation. The basin may be continuous with the Ochoco Basin and the Great Valley in California. Some hydrocarbon exploration in the basin encountered oil and gas shows. The limited sandstone porosities and permeabilities vary from 6.3% to 13.6% and up to 1.2 md, respectively.

4.3. Unconsolidated Sedimentary Basins

Numerous well-defined unconsolidated sedimentary basins were also identified as part of the study. They typically consist of Quaternary and Recent alluvium, lacustrine, and aolian deposits overlying consolidated basins or volcanic plateau areas. However, their relatively shallow character, the absence of a distinct structural and/or physical trap and the reliance of the public for groundwater supplies from many may make them less promising for sequestration purposes.

5.0 References

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6.0 Glossary

AAPG	American Association of Petroleum Geologists
CO_2	carbon dioxide
CRBG	Columbia River Basalt Group
DOE	U.S. Department of Energy
ft	feet
km	kilometers
m	meters
md	millidarcies
mg/L	milligrams per liter
OGI	Oregon Graduate Institute of Science and Technology
PIER	Public Interest Energy Research
RD&D	research, development, and demonstration
sq. ft/day	square feet per day
SVRP	Spokane Valley-Rathdrum Prairie Aquifer
USGS	U.S. Geological Survey
WESTCARB	West Coast Regional Carbon Sequestration Partnership
µS/cm	microSiemens per centimeter

Appendix A

Geologic Formations Referenced in this Report and Database

Appendix A

Geologic Formations Referenced in this Report and Database

Symbol[1]	**Formation/Unit Name**	**Age**	**Notes**
Western Tertiary Basins - Washington			
Q	Undifferentiated	Quaternary	Unconsolidated sediments
PLM(n)	Quinault Formation	Pliocene	
Mc(w)	Wilkes Formation	Miocene	
Mn(c)	Clallam Formation	Miocene	Tofino-Fuca Basin
OEm(lc)	Lincoln Creek Formation	Oligocene–Eocene	
OEc(h)	Huntingdon Formation	Oligocene–Eocene	Whatcom Basin
Em(2tr)	Twin River Group	Oligocene–Eocene	Tofino-Fuca Basin
En(sk)	Skookumchuck Formation	Eocene	
Ec(c)	Chuckanut Formation	Eocene	Whatcom Basin
Evc(n)	Northcraft Formation	Eocene	
Em(2m)	McIntosh Formation	Eocene	
Em(1h)	Hoh Assemblage	Early–Middle Eocene	Includes Astoria, Lincoln Creek, Skookumchuck and McIntosh Formations
Ev(c)	Crescent Formation	Early–Middle Eocene	
Ec(2pg)	Puget Group	Eocene	Puget Trough
Em(b)	Blakely Formation	Eocene	
Km(n)	Nanaimo Formation	Cretaceous	Whatcom Basin
Central-Eastern Washington Basins			
CRBG	Columbia River Basalt Group	Miocene	
Tsfj	John Day Formation	Miocene–Eocene	
Oc(w)	Wenatchee Formation	Oligocene	
Ovc(oh)	Ohanapecosh Formation	Oligocene	
Tct	Clarno Formation	Oligocene–Eocene	
Ec(1s)	Swauk Formation	Eocene	
Ec(2r)	Roslyn Formation	Eocene	
Western Tertiary Basins - Washington			
Tsd	Undifferentiated	Oligocene–Eocene	Sedimentary rocks
Tt	Tyee Formation	Middle Eocene	
Tco	Cowlitz Formation	Middle–Late Eocene	
Ty	Yamhill Formation	Middle–Late Eocene	
Tfe	Eugene Formation	Oligocene–Eocene	

Symbol[1]	Formation/Unit Name	Age	Notes
Tbr	Bushnell Rock Formation	Early Eocene	
Tmst	Marine sedimentary and tuffaceous	Miocene–Eocene	Pittsburg, Smuggler Cove, Northrup Formations
Tmsc	Marine siltstone, sandstone and conglomerate		Roseburg and Camas Valley Formations
Tmsc	Marine siltstone, sandstone and conglomerate		Umpqua Group (includes Lookingglass Formation)
Tu	Umpqua Group		
Tmsm	Marine siltstone, sandstone and conglomerate	Early Eocene	Umpqua Group (Roseburg and Camas Valley Formations)
Tss	Tuffaceous siltsones and sandstones	Middle–Late Eocene	Coaledo, Bateman, Sager Creek, and Keasey Formations
Ttv	Tillamook Volcanics	Middle–Late Eocene	
Tsr	Siletz Rover Volcanics	Eocene-–Paleocene	
Tes	Spencer Formation	Middle–Late Eocene	
Tee	Elkton Formation	Middle Eocene	Tyee Basin
Tms	Astoria Formation	Early–Middle Eocene	
Central-Eastern Oregon Basins			
Tcp	Picture Gorge Basalt	Early–Middle Eocene	
Tca	Carno Formation	Oligocene–Eocene	
Pz	Metasedimentary basement	Paleozoic	Baker Terrane
Ksc	Gable Creek Formation	Late Cretaceous	Ochoco Basin
Ksa	Hudspeth Formation	Early Cretaceous	Ochoco Basin

Note: [1] As used on the Washington 1:100,000 and Oregon 1:500,000 geologic maps