Title
Storage estimates – Washington and Oregon onshore and offshore sedimentary basins

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STORAGE ESTIMATES – WASHINGTON AND OREGON ONSHORE AND OFFSHORE SEDIMENTARY BASINS

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TECHNICAL MEMORANDUM

TO:	Larry Myer, Ph.D. – CIEE	**DATE:**	February 10, 2009
CC:	Paul La Pointe, Ph.D., L.H.G.		
FR:	Stephen D. Thomas, L.HG.	**OUR REF:**	063-1282.100
RE:	**STORAGE ESTIMATES – WASHINGTON AND OREGON ONSHORE AND OFFSHORE SEDIMENTARY BASINS**		

1.0 INTRODUCTION

This technical memorandum presents the approach, results and conclusions for the estimated storage CO_2 capacity for the onshore and offshore sedimentary basins in the states of Washington and Oregon. This memorandum follows an earlier report prepared by Golder for the WESTCARB team that identified all onshore sedimentary basins in these two states, and provided background information of their physical and hydraulic properties, and provides the first storage estimates. This memorandum follows the guidelines presented in the US Dept. of Energy's *Methodology for Development of Geologic Storage Estimates for Carbon Dioxide* (March 2008) for making the estimates.

2.0 ONSHORE SEDIMENTARY BASINS

Tables 1 and 2 list the sedimentary basin identified in the Phase 1 study (Golder, 2006) in the states of Washington and Oregon respectively. These tables also include basin area estimates, and indicators of whether representative well logs exist, whether the basin is deeper than 800 meters and if a resource estimate can be made. Storage estimates could only be made for basins for which the target formation had reservoir volume below 800 m and for which logs were available to determine porosity and lithology. Figures 1 and 2 show the locations of these basins as currently defined.

2.1 Geologic Data

Since the Phase 1 report was prepared, Golder obtained new geologic data for four basins in the two states; the Willapa Hills and Puget Basins in Washington, and the Astoria-Nehalem and Tyee-Umpqua basins in Oregon. The new data consist of published borehole logs for hydrocarbon exploration wells. The data for the Washington basins were obtained from log databases provided by M.J. Systems (a private company located in Denver, Colorado) (M.J. Systems, 2008). The data for the Oregon basins was obtained from Oregon's Department of Geology and Mineral Industries log database (ODOGMI, 2008).

The borehole log data was used to revise the initial resource estimates presented in the Phase 1 study. The new data enabled basin-specific estimates of sandstone porosity to be made. For the purpose of estimating the resource volumes, a porosity of zero was assumed for other geologic units such as siltstone, shale, claystone and coal. The analyses used lithologic and neutron-density logs. First, the lithologic logs were used to determine the percent of sandstone in each borehole. Basin-wide sandstone percentages were calculated by averaging the values from the available logs in each basin. Between 5 and 18 lithologic logs were used in each basin (Table 3).

TABLE 1

Onshore Consolidated Sedimentary Basins – Washington State

Basin Name	Geomorphic Province	Approx. Basin Area (sq. km.)	Well Logs?	Depth >800m?	Estimate Storage?
Tofino-Fuca Basin	Western Tertiary	1,044 3.0	Y	Y	Y
West Olympic Hills Basin	Western Tertiary	1,360 4.0	Y	Y	Y
Willapa Hills Basin	Western Tertiary	6,731 5.0	Y	Y	Y
Whatcom Basin	Western Tertiary	955 6.0	Y	Y	Y
Puget Trough	Western Tertiary	25,206 7.0	Y	Y	Y
Methow Basin	Cascades-CRBG	2,838 8.0	N	Y	N
Chiwaukum-Swauk Basins	Cascades-CRBG	2,905 9.0	N	Y	N

TABLE 2

Onshore Consolidated Sedimentary Basins – Oregon State

Basin Name	Geomorphic Province	Approx. Basin Area (sq. km.)	Well Logs?	Depth >800m?	Assess for Storage?
Astoria-Nehalem	West Coast Tertiary	4,716	Y	Y	Y
Willamette Trough	West Coast Tertiary	6,718 10.0	Y	Y	Y
Tyee-Umpqua Basin	West Coast Tertiary	16,213 11.0	Y	Y	Y
Ochoco Basin	Eastern Oregon	22,967	Y	Y	Y
Coos Basin	Western Tertiary	2,420	Y	Y	N
Hornbrook Basin	Eastern Oregon	636	N	Y	N

The neutron-density logs were used to calculate the sandstone porosity in each borehole. Only boreholes with both lithologic and neutron-density logs were used for the analysis; the lithologic logs were used to identify the sandstone and the neutron-density logs were used for the calculation. For each basin between 1 and 7 boreholes had both lithologic and neutron-density logs (Table 3). Neutron porosity and density porosity values for each sandstone unit were obtained from the logs and the total porosity was calculated using the root mean square formula (Asquith et. al, 1982), where:

$$Total\ Porosity = \sqrt{\frac{(Neutron\ Density)^2 + (Density\ Porosity)^2}{2}}$$

A weighted average porosity was determined for each borehole. The gross porosity for a basin was calculated by multiplying the average sandstone porosity by the percent of sandstone calculated from the lithologic logs. The porosity values are shown in Table 3.

TABLE 3

Revised Porosity Estimates

Basin	Number of Well Logs Used to Determine Sandstone Thickness	Average Sandstone Thickness (ft)	Number of Well Logs Used to Determine Porosity	Revised Gross Porosity Estimate
Puget Trough	11	1,727	1	16.2%
Willapa Hills	8	762	2	6.3%
Astoria-Nehalem	18	891	7	6.8%
Tyee-Umpqua	5	2,932	2	8.7%

2.2 Resource Estimation Assumptions

The analysis approach that was used followed the guidelines in the US DOE manual. The results are summarized in Table 4. The following key assumptions were made:

1. Basin areas (Tables 1 and 2):
    a. For Puget Trough, the basin extent was based on the 800-meter isopachs that were included in the sediment thickness data set developed previously.
    b. For all other basins, the basin outlines were determined by evaluating published geologic maps that show outcropping units, and previous estimates of basin extents.
2. Net basin sediment thickness
    a. For Puget Trough basin, the isopachs were used. Within the basin extent under consideration, these range from 800 to 10,000 meters. The average sediment thickness was 4,500 meters.
    b. For all other basins, the basin thicknesses were based on information contained in available borehole logs.

The uppermost 800 meters of all basins was excluded for the purpose of estimating total basin volume.

3. Porosity. The determination of a representative porosity for each basin to estimate resource was made in one of two ways for each basin. Firstly, porosity values were estimated for the four basins in which borehole logs included lithologic neutron-density logs (Table 3). These four basins are the Puget Trough, Willapa Hills, Tyee-Umpqua and Astoria-Nehalem, and the values ranged from 6.3 to 16.2 percent. For the remaining ten basins, a single value of 7.5 percent was used for the resource assessment, which is approximately the average for the Willapa Hills, Astoria-Nehalem and Tyee-Umpqua basins. This value is expected to change if future drilling and logging provide better estimates of net porosity.

4. Carbon Dioxide Density. The density of CO_2 in the subsurface is known to vary depending on pressure and temperature conditions. In general, the density increases with increasing depth below atmospheric (land surface) conditions. For the purpose of this assessment, the uppermost 800 meters of geologic material were excluded from consideration. Therefore, the CO_2 density conservatively determined for a depth of 800 meters, and was applied for all basins regardless of the total depth of each. This density was 469 kg/m^3.

2.3 Results

Tables 4 and 5 summarize the resource estimates (mass of CO_2) for the five Washington and four Oregon onshore basins, respectively. Resource estimates are included assuming both low and high Efficiency Factors (E) of 0.01 and 0.04, respectively, and a range of minimum, average and maximum basin effective sediment thicknesses (no minimum thickness was determined for the Whatcom, Ochoco and Willamette Trough Basins). All six resource estimates for each basin are included in the GIS database.

In Washington state, the Puget Trough has by far the largest potential, with average mass estimates ranging from 86.4 $x10^6$ to 345.4 $x10^6$ Mt (Figure 2). The remaining four Washington basins have a combined average resource potential of between 3.9 $x10^6$ and 15.5 $x10^6$ Mt. In Oregon state, the four onshore basins have a combined average resource potential of between 16.7 $x10^6$ and 66.9 $x10^6$ Mt (Figure 3). The Tyee-Umpqua Basin has the largest potential in the state, constituting 63 percent of the Oregon total.

TABLE 4

Resource Estimates for Washington Basins

Basin Name	Basin Area (sq. km.)	Effective Sediment Thickness (meters)			Storage Estimate (Mt x 10^3)						Basin Class
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Tofino-Fuca	1,044	732	2,545	1,655	NA	NA	608	2,431	935	3,740	4
West Olympic	1,360	224	2,054	1,075	107	429	514	2,056	982	3,930	4
Willapa Hills	6,731	369	2,845	1,173	737	2,948	2,340	9,360	5,676	22,704	4
Whatcom	995	325	1,758	1,258	-	-	423	1,691	591	2,363	4
Puget Trough	25,206	4,500	4,500	4,500	86,360	345,441	86,360	345,441	86,360	345,441	4

Notes:

Mt – thousands of metric tons. E – Efficiency factor (as defined by USDOE Guidance document). Basin Class – assigned level of confidence (see US Dept of Energy, 2008).

TABLE 5

Resource Estimates for Oregon Basins

Basin Name	Basin Area (sq. km.)	Effective Sediment Thickness (meters)			Storage Estimate (Mt x 10^3)						Basin Class
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Astoria-Nehalem	4,716	361	2,891	1,440	545	2,181	2,175	8,700	4,368	17,470	4
Willamette Trough	6,718	NA	2,259	792	-	-	1,873	7,490	5,338	21,353	4
Tyee-Umpqua	16,213	417	3,397	1,597	2,767	11,067	10,586	42,346	22,522	90,087	4
Ochoco	22,967	NA	1,515	259	-	-	2,093	8,374	12,235	48,941	4

Notes:

Mt – thousands of metric tons. E – Efficiency factor (as defined by USDOE Guidance document). Basin Class – assigned level of confidence (see US Dept of Energy, 2008).

3.0 OFFSHORE BASINS

3.1 Resource Estimation Assumptions

The continental margin along the western boundary of Washington and Oregon rests on a subduction zone. In this area the oceanic crust of the Juan de Fuca plate is being thrust underneath the North America plate. This process resulted in development of the Cascade Range, the Olympic Mountains and an offshore trench, now filled with sediment, located along the base of the continental slope. The subduction also produced a series of north-south basins that were gradually uplifted as much as 1 to 2 km (Kulm and Fowler, 1974) and these are now located within the continental shelf (see Map 1; McLean and Wiley, 1987). Large-scale extensional growth faults are a dominant feature offshore Washington and shale diapirs are present offshore Washington and Oregon.

The basin fill (Eocene and younger) is primarily sedimentary but may contain localized deposits of volcanic rock (Snavely and Wanger, 1980). The sediment thickness is typically greater than 10,000 feet and in some areas as much as 20,000 feet. Basement rock was produced by Miocene underthrusting which produced a melange. Tables 6 and 7 summarizes the lithostratigraphic sequence as interpreted from a well near Ocean City, Washington (Palmer and Lingley, 1989). Figure 7 shows the locations of the six identified off-shore basins and the sediment isopachs.

A total of 96 million barrels (MM bbl) of oil and 650 billion cubic feet (Bcf) of gas are estimated to be economically recoverable from the Washington-Oregon assessment area. No accumulations of resources have been discovered in the Washington-Oregon assessment area.

TABLE 6

Interpreted Offshore Geologic Sequence

Geologic Age	Unit	Description
Quaternary/Pliocene	Quaternary deposits and Quinault Formation	Shallow marine siltstone, sandstones, conglomerate and siltstone.
Middle to Upper Miocene	1.Montesano Formation Siltstone member 2.Montesano Formation Sandstone member 3.Montesano Formation Claystone member	Claystones and siltstones with minor sandstone interbeds. Thick sandstones minor shale interbeds. Claystones with interbedded sandstones.
Middle Miocene to Upper Oligocene	Hoh Rock Assemblage	Sandstone with abundant siltstones and claystones.
Upper to Middle Eocene	Ozette Melange	Interbedded sandstones, siltstones and claystones.

TABLE 7

Geologic Properties for Offshore Sequence

Geologic Age	Thickness	Porosity	Permeability
Quaternary/Pliocene	300 to 500 ft	High porosity. No apparent confining layer.	High permeability
Pliocene	800 to 1,200 ft	25%	100 to 10,000 md
M. Miocene- U. Miocene - Siltstone - Sandstone - Claystone	 600 to 1,000 ft 200 to 800 ft 4,000 to 8,000 ft	 20% 20% 10 to 20%	 0.1 md 1000 md 0.1 to 5 md
M. Miocene – U. Oligocene	5,000 ft	10-20%	0.1-0.4 md
Eocene (basalts)	unknown	unknown	Unknown

The Washington-Oregon assessment area is approximately 400 miles in length and 30 to 50 miles wide. Water depth in the area ranges from approximately 100 feet to 600 at the shelf-slope boundary. Within this region six (6) basins have been identified base on a limited number of offshore borings and seismic reflection transects (Figure 1).

The quality of the data varied greatly within and among the various surveys. Furthermore, none of the seismic data were acquired in a conventional grid. Consequently, these data are more useful for regional tectonic studies and less useful for prospect delineation or for mapping the extent of clastic sedimentary deposits such as the Montesano sandstones.

3.2 Results

Table 6 summarizes the resource estimates (mass of CO_2) for the six offshore basins. Resource estimates are included assuming both low and high Efficiency Factors (E) of 0.01 and 0.04, respectively, for an average basin effective sediment thicknesses. Both resource estimates for each basin are included in the GIS database.

The resource estimates range from 0.8 $x10^6$ Mt to 3.1 $x10^6$ Mt for the smallest basin (Newport; 4 percent of the offshore total) to 7.48 $x10^6$ Mt to 29.9 $x10^6$ Mt for the largest basin (Heceta; 35 percent of the offshore total) (Figure 4).

TABLE 8

Resource Estimates for Offshore Washington and Oregon Basins

Basin Name	Basin Area (sq. km.)	Effective Sediment Thickness (meters)			Storage Estimate (Mt x 10^3)						Basin Class
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Olympic	4,930	-	3,810	-	-	-	6,610	26,440	-	-	3
Willapa	4,190	-	2,290	-	-	-	3,372	13,488	-	-	3
Heceta	5,581	-	3,810	-	-	-	7,483	29,932	-	-	3
Astoria	1,611	-	2,290	-	-	-	1,296	5,186	-	-	3
Newport	975	-	2,290	-	-	-	785	3,139	-	-	3
Coos	2,420	-	2,290	-	-	-	1,947	7,790	-	-	3

4.0 REFERENCES

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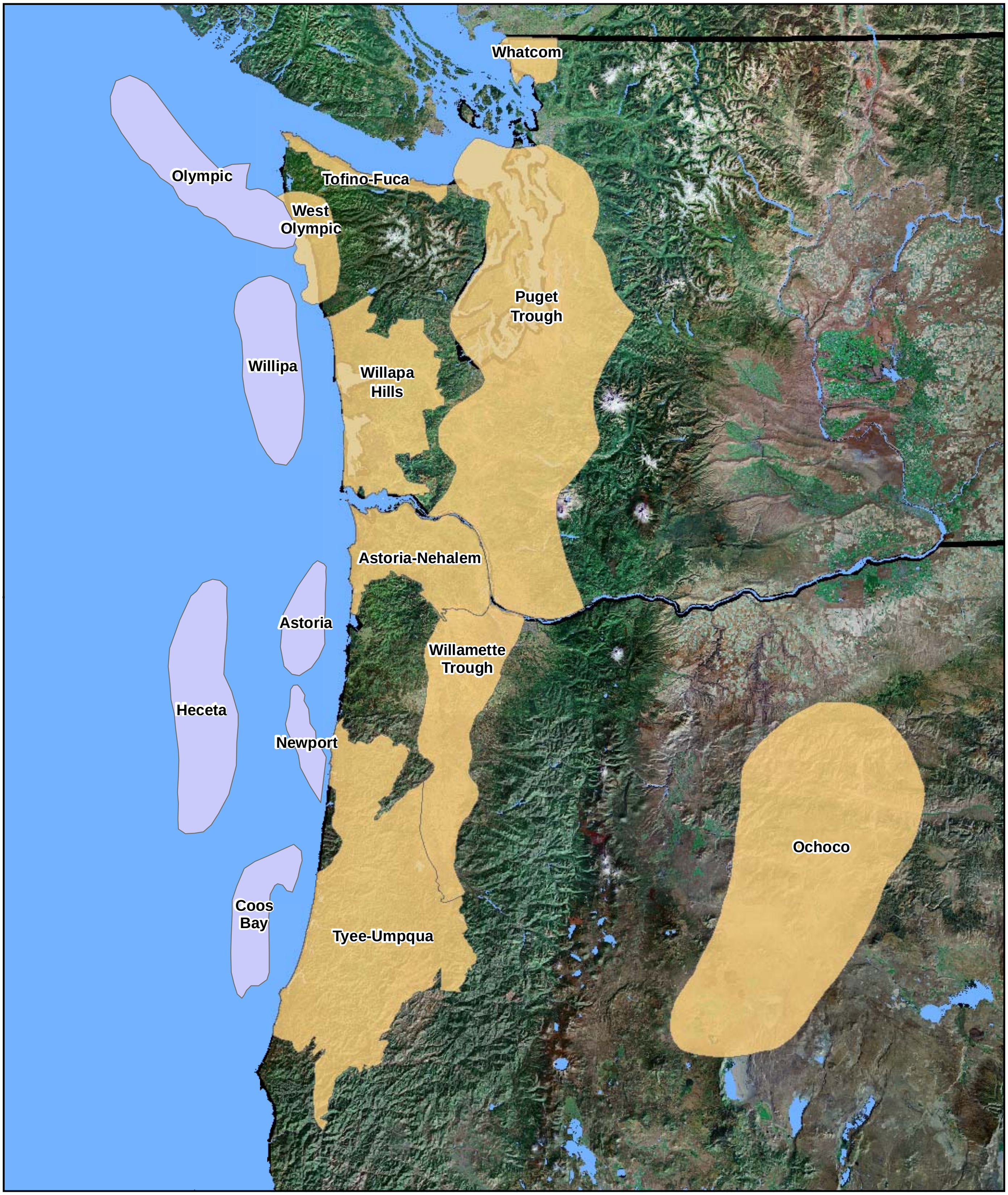
FIGURES



This figure was originally produced in color. Reproduction in black and white may result in a loss of information.

LEGEND

- Offshore Basin
- Onshore Basin

0 300000

Scale in Feet

Map Projection:
Washington State Plane
North Zone NAD 1983

Source:
EarthSat, ESRI

N

FIGURE 1

LOCATION OF ONSHORE AND OFFSHORE SEDIMENTARY BASINS, WASHINGTON AND OREGON

CIEE/WESTCARB PROJECT PHASE II/USA

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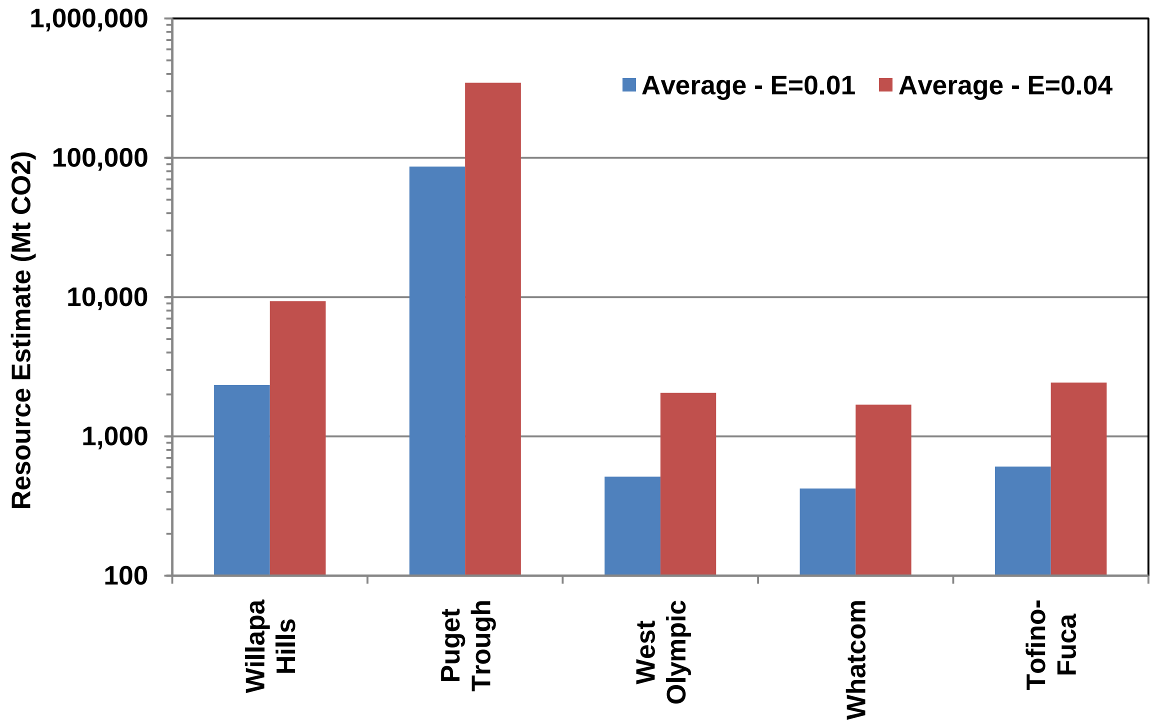

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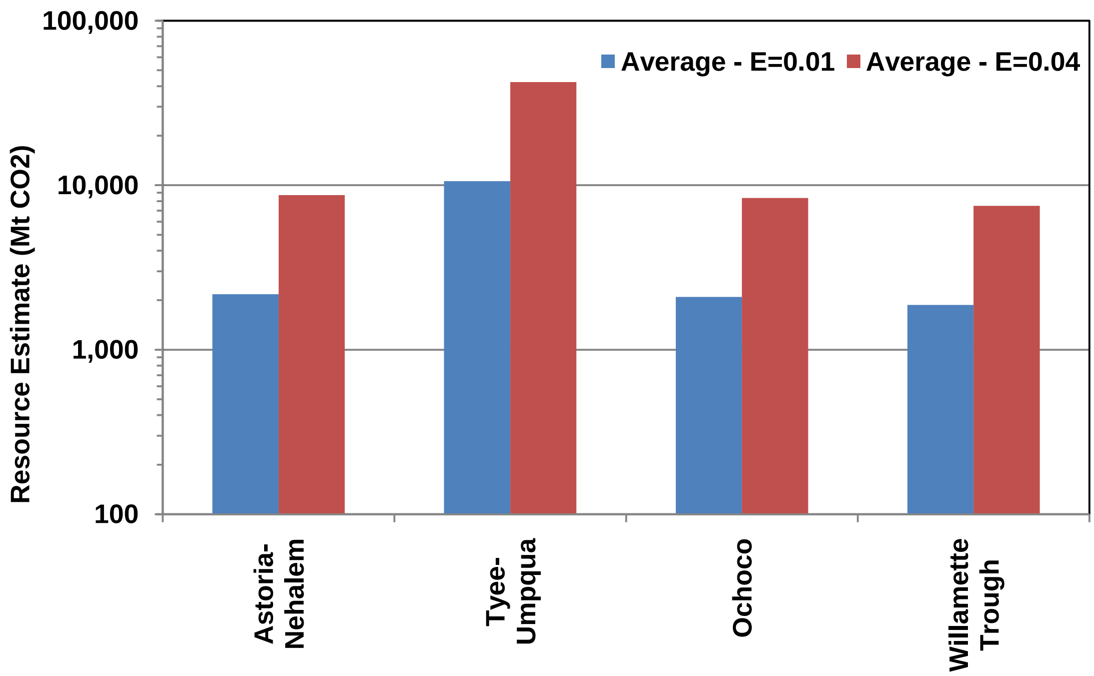
	REVIEWED	PLP	FILE No.	WA-OR_basins.pptx	FIGURE No.	2



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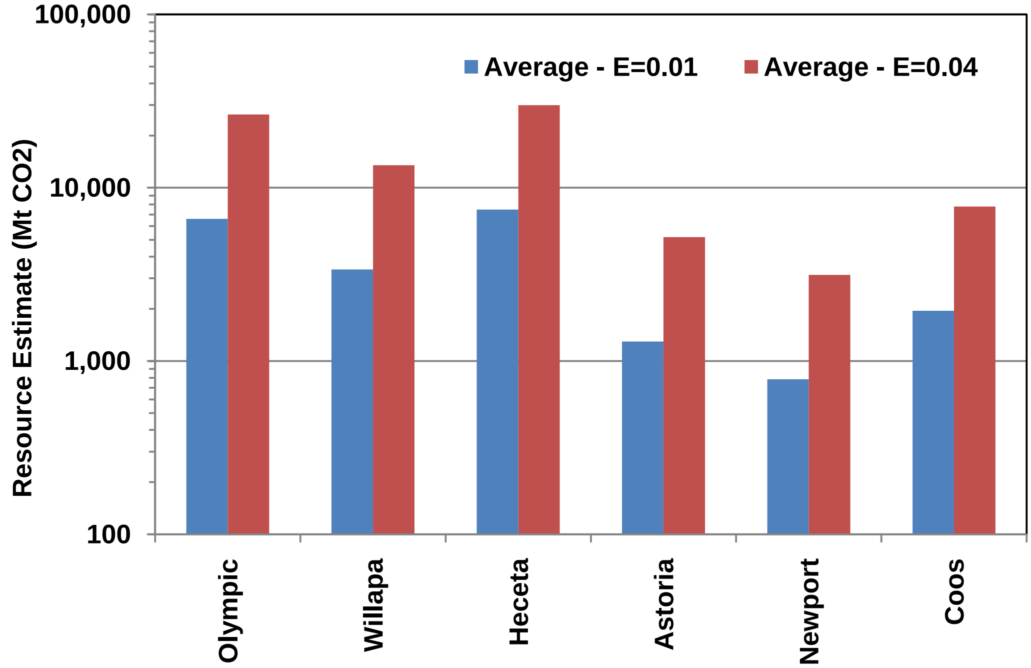

Golder Associates	TITLE	Resource Estimates for Offshore Washington and Oregon Basins					
WESTCARB – Resource Estimates for Washington and Oregon Basins	DRAWN	SDT	DATE	1/16/09	PROJECT No.	063-1282.100	
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	REVIEWED	PLP	FILE No.	WA-OR_basins.pptx	FIGURE No.	4	