Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Columbia Basin of Oregon, Washington, and Idaho, and the Western Oregon-Washington Basins

By Jacob A. Covault, Madalyn S. Blondes, Steven M. Cahan, Christina A. DeVera, Philip A. Freeman, and Celeste D. Lohr

Chapter D of
Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources
Edited by Peter D. Warwick and Margo D. Corum

Open-File Report 2012–1024–D

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
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Suggested citation:
Covault, J.A., Blondes, M.S., Cahan, S.M., DeVera, C.A., Freeman, P.A., and Lohr, C.D., 2013, Geologic framework for the national assessment of carbon dioxide storage resources—Columbia Basin of Oregon, Washington, and Idaho, and the Western Oregon-Washington basins, chap. D *of* Warwick, P.D., and Corum, M.D., eds., Geologic framework for the national assessment of carbon dioxide storage resources: U.S. Geological Survey Open-File Report 2012–1024–D, 19 p., *http://dx.doi.org/10.3133/ofr20121024d*.

ISSN 2331-1258 (online)

Editors' Preface

By Peter D. Warwick and Margo D. Corum

The 2007 Energy Independence and Security Act (Public Law 110–140) directs the U.S. Geological Survey (USGS) to conduct a national assessment of potential geologic storage resources for carbon dioxide (CO_2) and to consult with other Federal and State agencies to locate the pertinent geological data needed for the assessment. The geologic sequestration of CO_2 is one possible way to mitigate its effects on climate change.

The methodology that is being used by the USGS for the assessment was described by Brennan and others (2010), who revised the methodology by Burruss and others (2009) according to comments from peer reviewers, members of the public, and experts on an external panel. The assessment methodology is non-economic and is intended to be used at regional to subbasinal scales.

The operational unit of the assessment is a storage assessment unit (SAU), composed of a porous storage formation with fluid flow and an overlying fine-grained sealing unit. Assessments are conducted at the SAU level and are aggregated to basinal and regional results. SAUs have a minimum depth of 3,000 feet (ft), which ensures that the CO_2 is in a supercritical state (and thus occupies less pore space than a gas). Standard SAUs have a maximum depth of 13,000 ft below the surface, a depth accessible with average injection pipeline pressures (Burruss and others, 2009; Brennan and others, 2010). Where geologic conditions favor CO_2 storage below 13,000 ft, an additional deep SAU is assessed.

The assessments are also constrained by the occurrence of relatively fresh formation water; any formation water having a salinity less than 10,000 parts per million (ppm, which is equivalent to milligrams per liter, mg/L) total dissolved solids (TDS), regardless of depth, has the potential to be used as a potable water supply (U.S. Environmental Protection Agency, 2009). The U.S. Environmental Protection Agency (2008) has proposed a lower limit of 10,000 ppm (mg/L) TDS for water in rocks to be used for injection of CO_2. Therefore, the potential storage resources for CO_2 in formations where formation waters have salinities less than 10,000 ppm (mg/L) TDS are not assessed (Brennan and others, 2010).

This report series contains geologic descriptions of each SAU identified within the assessed basins and focuses on the particular characteristics specified in the methodology that influence the potential CO_2 storage resource. Although assessment results are not contained in these reports, the geologic framework information will be used to calculate a statistical Monte Carlo-based distribution of potential storage space in the various SAUs following Brennan and others (2010). Figures in this report series show SAU boundaries and cell maps of well penetrations through the sealing unit into the top of the storage formation. Wells sharing the same well borehole are treated as a single penetration. Cell maps show the number of penetrating wells within one square mile and are derived from interpretations of incompletely attributed well data (IHS Energy Group, 2011; and other data as available), a digital compilation that is known not to include all drilling. The USGS does not expect to know the location of all wells and cannot guarantee the amount of drilling through specific formations in any given cell shown on cell maps.

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Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.58999	square kilometer (km^2)
	Volume	
million barrels of oil (MMBO)	1,000,000	barrel (bbl), (petroleum, 1 barrel=42 gal)
barrel (bbl), (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
billion cubic feet gas (BCFG)	1,000,000,000	cubic foot (ft^3)
	Permeability	
Darcy (D)	9.869233×10^{-13}	square meter (m^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F–32)/1.8
Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources—Columbia Basin of Oregon, Washington, and Idaho, and the Western Oregon-Washington Basins

By Jacob A. Covault, Madalyn S. Blondes, Steven M. Cahan, Christina A. DeVera, Philip A. Freeman, and Celeste D. Lohr

Abstract

The 2007 Energy Independence and Security Act (Public Law 110–140) directs the U.S. Geological Survey (USGS) to conduct a national assessment of potential geologic storage resources for carbon dioxide (CO_2). The methodology used by the USGS for the national CO_2 assessment follows that of previous USGS work. The methodology is non-economic and intended to be used at regional to subbasinal scales.

This report identifies and contains geologic descriptions of three storage assessment units (SAUs) in Eocene and Oligocene sedimentary rocks within the Columbia, Puget, Willapa, Astoria, Nehalem, and Willamette Basins of Oregon, Washington, and Idaho, and focuses on the characteristics, specified in the methodology, that influence the potential CO_2 storage resource in those SAUs. Specific descriptions of the SAU boundaries as well as their sealing and reservoir units are included. Properties for each SAU, such as depth to top, gross thickness, porosity, permeability, groundwater quality, and structural reservoir traps, are provided to illustrate geologic factors critical to the assessment. The designated sealing unit in the Columbia Basin is tentatively chosen to be the ubiquitous and thick Miocene Columbia River Basalt Group. As a result of uncertainties regarding the seal integrity of the Columbia River Basalt Group, the SAUs were not quantitatively assessed. Figures in this report show SAU boundaries and cell maps of well penetrations through sealing units into the top of the storage formations. The cell maps show the number of penetrating wells within one square mile and are derived from interpretations of incompletely attributed well data, a digital compilation that is known not to include all drilling. The USGS does not expect to know the location of all wells and cannot guarantee the amount of drilling through specific formations in any given cell shown on the cell maps.

Introduction

The following sections describe the geology parameters that were used to define the carbon dioxide (CO^2) storage assessment units (SAUs) in the Columbia Basin of Eastern Oregon, Washington, and Idaho, and the Western Oregon and Washington Basins. The geologic descriptions of these basins were compiled into this report because of the similar geology and geographic location for these basins.

Columbia Basin of Oregon, Washington, and Idaho

By Jacob A. Covault, Madalyn S. Blondes, Steven M. Cahan, Christina A. DeVera, Philip A. Freeman, and Celeste D. Lohr

The Columbia Basin of Oregon, Washington, and Idaho extends across an area of approximately 63,000 mi^2 between the Cascade Range, the Blue Mountains, and the Rocky Mountains (Campbell, 1989; Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989) (fig. 1). A distinguishing characteristic of the Columbia Basin is the ubiquitous and thick (as much as 15,000 ft) Miocene Columbia River Basalt Group, which comprises deposits from approximately 300 continental tholeiitic flood-basalt flows (Tolan and others, 1989; Reidel and others, 2002; Brownfield, 2008) (figs. 1 and 2). The Columbia Basin includes four regions differentiated according to style of tectonic deformation: Yakima fold belt, Palouse slope, Blue Mountains, and embayments along the eastern basin margin (Reidel, Fecht, and others, 1989) (fig. 1). The Yakima fold belt is located in the western and central parts of the basin and comprises anticlinal ridges and synclinal valleys with northwest-southeast structural trends (Reidel and others, 2002) (fig. 1). The Palouse slope is located to the northeast and includes only minor faults and low-amplitude, long-wavelength folds (Swanson and others, 1980). The Blue Mountains are located to the south and compose a broad, northeast-trending anticlinorium that extends over 150 mi from the Cascade Range to the embayments along the eastern basin margin (Reidel, Fecht, and others, 1989) (fig. 1).

Subsidence of the Columbia Basin was focused in the region now occupied by the Yakima fold belt since early Tertiary and persisted through the Miocene (Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989). Subsidence kept pace with the rate of Columbia River Basalt Group flow emplacement during the Miocene (Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989). The region contemporaneously underwent north- to south-directed compression, which deformed the flood basalts into the Yakima folds (Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989). Contemporaneous subsidence, basalt production, and fold growth are interpreted to be linked to oblique subduction along the convergent plate margin offshore North America to the west and back-arc spreading associated with crustal extension to the east (Reidel, Fecht, and others, 1989; Reidel, Tolan, and others, 1989; Campbell and Reidel, 1994).

Rocks older than the Miocene Columbia River Basalt Group generally include Eocene and Oligocene, thick (as much as 25,000 ft), arkosic sandstone, conglomerate, and mudstone interbedded with coal and volcanic rocks (Campbell, 1989; Campbell and Reidel, 1994; Reidel and others, 2002; Golder Associates, Inc., 2007; Brownfield, 2008) (fig. 2). These units include the Swauk, Manastash, Chumstick, Roslyn, and Wenatchee Formations, among others, and they are generally interpreted to represent nonmarine deposition (Campbell, 1989; Golder Associates, Inc., 2007; Brownfield, 2008) (fig. 2). Other formations older than Miocene strata were not considered to have reservoir potential.

The only hydrocarbon production in the Columbia Basin was from the Rattlesnake Hills gas field, which was discovered in 1913 as a result of drilling a water well into the Columbia River Basalt Group (Hammer, 1934; Campbell and Reidel, 1994; Brownfield, 2008) (fig. 1). The field was developed in 1930 and produced approximately 1.3 billion cubic feet of gas (BCFG), likely derived from sedimentary rocks interbedded with or underlying the basalt (McFarland, 1979; Brownfield, 2008). Exploration wells have been drilled since the Rattlesnake Hills gas field was abandoned in 1941, and drill-stem tests confirmed the presence of gas; however, the wells were deemed noncommercial and abandoned (Campbell and Reidel, 1994; Reidel and others, 2002; Brownfield, 2008). There has been no oil and gas production in the Columbia Basin since 1941 (Brownfield, 2008).

Columbia Basin Carbon Dioxide Storage Resource Assessment

An Eocene-Oligocene composite reservoir unit was defined, but not quantitatively assessed for CO_2 storage in the Columbia Basin. This unit includes two SAUs: a relatively shallow SAU, at drilling depths between 3,000 and 13,000 ft, and a deeper SAU, at drilling depths greater than 13,000 ft. Potential reservoir units include siliciclastic rocks of the Swauk, Manastash, Chumstick, Roslyn, and Wenatchee Formations (Brownfield, 2008) (fig. 2). The extent of the storage formations is defined by the geologic characteristics of the reservoirs and overlying Miocene Columbia River Basalt Group and the subsurface physical properties of CO_2 as described in Burruss and others (2009) and Brennan and others (2010). The following section describes the SAUs defined in the Columbia Basin. The ubiquitous and thick (as much as 15,000 ft) Miocene Columbia River Basalt Group was evaluated as a potential seal for the underlying Eocene-Oligocene composite reservoir unit. Preliminary investigations, described in the following section, suggest that, though isolated, relatively impermeable components of the Columbia River Basalt Group might exist that effectively seal small regions. However, their areal extents have not been sufficiently mapped to the scale of the entire Columbia Basin. Therefore, according to the standards of the CO_2 assessment methodology, the Columbia River Basalt Group is not considered an adequate regional seal (Brennan and others, 2010). However, the potential for some areas of the basalt to serve as local sealing units led to the nonquantitative assessment by the USGS CO_2 assessment project.

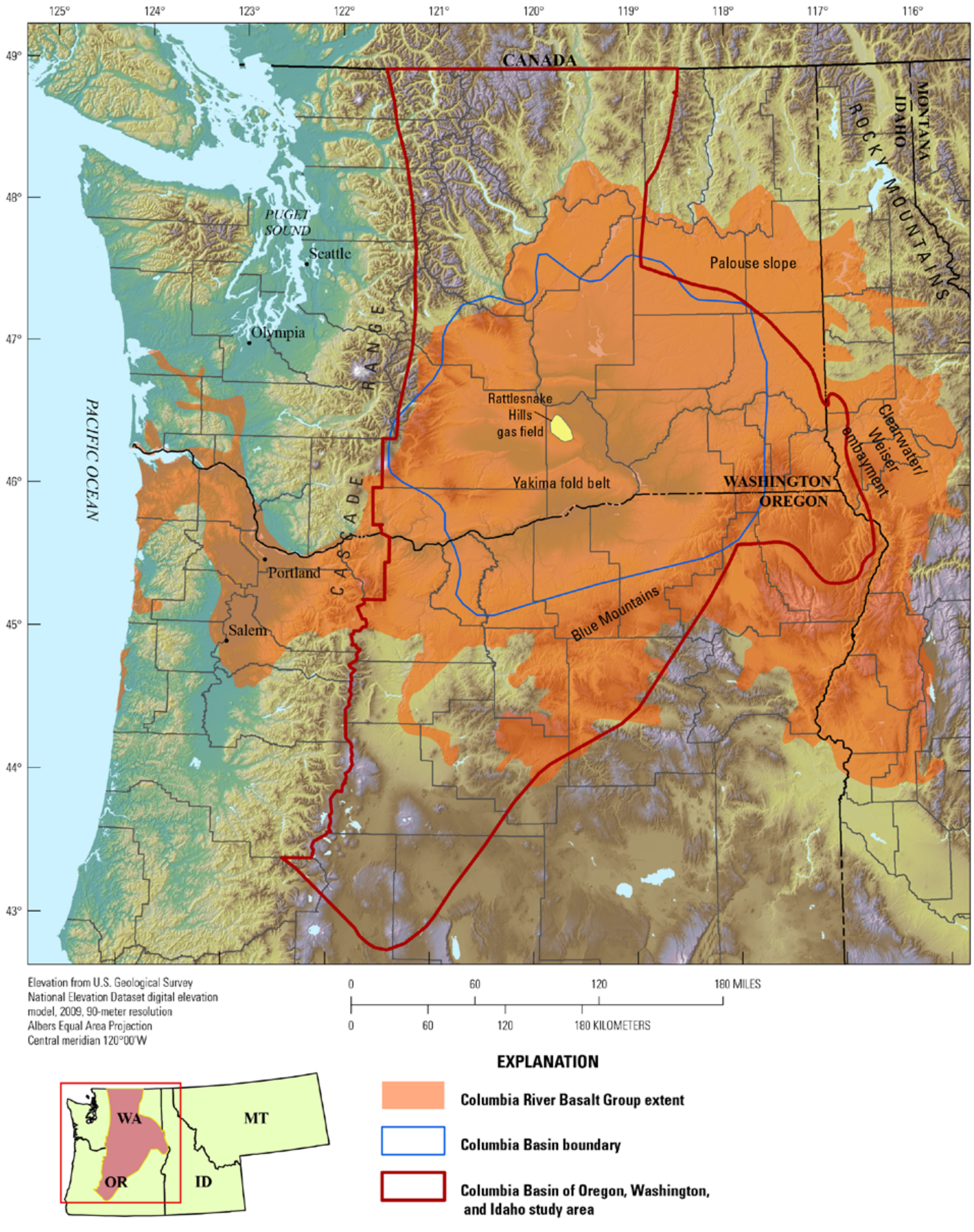

Figure 1. Map of the Pacific Northwest and Columbia Basin, Oregon, Washington, and Idaho. Study area for the Columbia Basin of Oregon, Washington, and Idaho, outlined in red, is modified from Brownfield (2008). Columbia Basin boundary, outlined in blue, is modified from Wilson and others (2008, their fig. 1; see also Campbell, 1989). Extent of Columbia River Basalt Group from Reidel and others (2002).

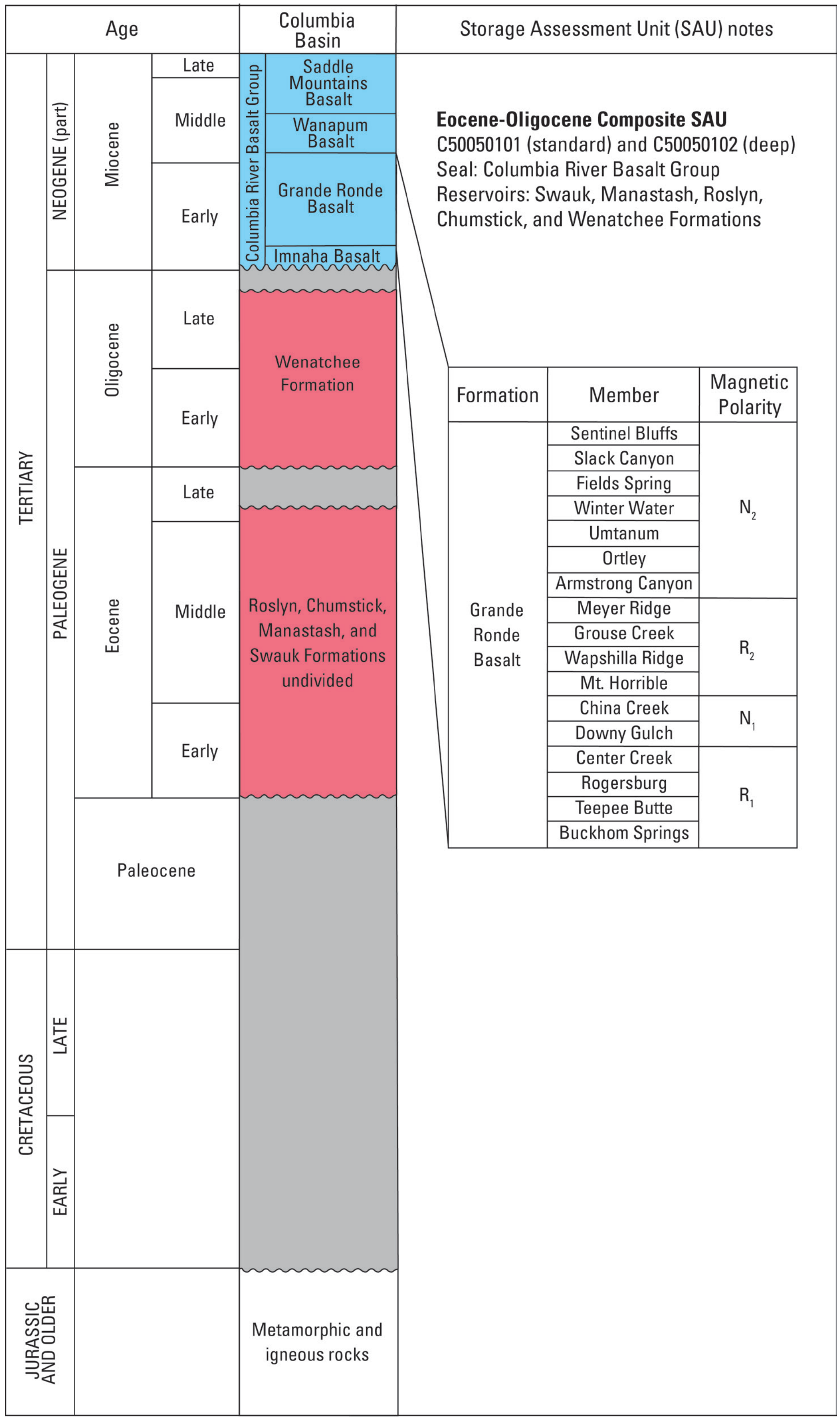

Figure 2. Generalized stratigraphic column of geologic units in the Columbia Basin, Oregon, Washington, and Idaho. Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray sections represent stratigraphic gaps. The Johns Creek flow described in the text exists just below the N_1-R_2 (normal-reverse) magnetostratigraphic boundary of the Grande Ronde Basalt (Reidel, 1983). Modified from figure 5 of Brownfield (2008) and figure 2.3 of Reidel and others (2002).

Eocene-Oligocene Composite Standard SAU C50050101 and Eocene-Oligocene Composite Deep SAU C50050102

Prospective rocks for CO_2 storage older than the Miocene Columbia River Basalt Group generally include Eocene and Oligocene, thick (approximately 7,000 ft on average, locally as much as 25,000 ft), arkosic sandstone, mudstone, and conglomerate interbedded with coal and volcanic rocks (Campbell, 1989; Campbell and Reidel, 1994; Tennyson, 1995; Reidel and others, 2002; Golder Associates, Inc., 2007; Brownfield, 2008) (figs. 2 and 3). Siliclastic rocks include the Swauk, Manastash, Roslyn, Chumstick, and Wenatchee Formations (Campbell, 1989; Golder Associates, Inc., 2007; Brownfield, 2008) (fig. 2). The lower and middle Eocene Swauk Formation comprises as much as 15,000 ft of predominantly medium- to coarse-grained arkosic sandstone interbedded with mudstone and conglomerate in the Yakima fold belt region (Campbell, 1989; Golder Associates, Inc., 2007). The Swauk Formation also includes andesitic to rhyolitic volcaniclastic rocks (Campbell, 1989; Brownfield, 2008). The upper part of the Swauk Formation is interpreted to be age equivalent to the Manastash Formation (Newman, 1977; Johnson, 1985; Campbell, 1989; Brownfield, 2008), which locally comprises as much as 3,200 ft of fine- to medium-grained arkosic sandstone, mudstone, and coal (Lewellen and others, 1985; Golder Associates, Inc., 2007; Brownfield, 2008). The Manastash Formation is unconformably overlain by the Miocene Columbia River Basalt Group (Brownfield, 2008). The contact between the Manastash Formation and the Columbia River Basalt Group is located south of the Yakima River near Roslyn (Brownfield, 2008). The Swauk Formation is unconformably overlain by the Eocene Teanaway Formation, which predominantly includes basalt and volcaniclastic strata as much as approximately 8,000 ft thick (Campbell, 1989; Brownfield, 2008). The middle and upper Eocene Roslyn Formation overlies the Teanaway Formation (Campbell, 1989; Brownfield, 2008). The Roslyn Formation achieves a thickness of as much as 8,500 ft and predominantly includes fine- to medium-grained arkosic sandstone, mudstone, and coal (Campbell, 1989; Brownfield, 2008). The middle and upper Eocene Chumstick Formation comprises medium- to coarse-grained arkosic sandstone with mudstone, conglomerate, and siliceous tuff of uncertain thickness in the Columbia Basin (Campbell, 1989; Brownfield, 2008). Much of the Oligocene fill of the Columbia Basin includes volcanic and volcaniclastic strata. However, the Oligocene Wenatchee Formation, which unconformably overlies the middle and upper Eocene Roslyn and Chumstick Formations, includes as much as 1,000 ft of quartz-rich sandstone and mudstone (Campbell, 1989; Golder Associates, Inc., 2007; Brownfield, 2008). These Eocene-Oligocene siliciclastic strata are generally interpreted to represent nonmarine deposition in alluvial-fan, fluvial, and lacustrine environments (Brownfield, 2008). The Eocene-Oligocene predominantly siliciclastic strata are overlain by ubiquitous and thick (as much as 15,000 ft) continental tholeiitic flood basalts of the Miocene Columbia River Basalt Group (Tolan and others, 1989; Reidel and others, 2002; Brownfield, 2008) (fig. 2). The Columbia River Basalt Group is tentatively considered a potential sealing unit for the underlying Eocene-Oligocene composite reservoir. The CO_2 assessment methodology requires a regional fine-grained seal, usually mudstone, for any potential SAU (Brennan and others, 2010). A number of studies exist on natural gas storage (Reidel and others, 2002) and mineral carbonation sequestration in basalts (McGrail and others, 2006); however, few studies address whether or under what conditions basalts act as an effective seal for supercritical CO_2 storage in sedimentary basins (Blondes and Covault, 2011).

Basalt has a wide range of porosity and permeability, depending on the intraflow structure (for example, vesicular flow boundaries, colonnade, and entablature), depth, and degree of mineralization within the pore space. Flow boundaries can have porosities up to 80 percent, and the vertical colonnade joints can have permeabilities greater than 1 darcy (D) (U.S. Department of Energy, 1988; Reidel and others, 2002; Petford, 2003). However, the smaller and more randomly oriented cooling joints of the entablature intraflow zones can have permeabilities less than 1 microdarcy (μD) (U.S. Department of Energy, 1988; Reidel and others, 2002; Petford, 2003). Moreover, burial metamorphism to prehnite-pumpellyite facies can decrease porosity to approximately 2 percent (Neuhoff and others, 1999). Hydrologic studies show chemical isolation of water between flow entablatures (Reidel and others, 2002), suggesting this particular intraflow zone might serve as an effective seal. Therefore, for the Columbia Basin, we interpret that a sufficient regional seal would require at least one entablature within a single flow spanning the entire SAU.

Some units within the Columbia River Basalt Group cover nearly the entire basin. For example, the informal Sentinel Bluffs member of the Grande Ronde Basalt extends greater than 70,000 km^2 (Reidel and others, 2002). However, no single, relatively impermeable entablature has been measured to cover nearly the same area. The areal extent of the McCoy Canyon flow entablature of the Sentinel Bluffs member (fig. 2) is documented over less than 1,000 km^2 (Reidel and others, 2002), which is only approximately 1 percent of the area of the entire Columbia Basin. The informal Center Creek member of Reidel and others (2002) and Johns Creek flow of the Grande Ronde Basalt (fig. 2) in Eastern Oregon and Washington and Western Idaho are composed almost entirely of entablature, but no single unit is mapped that is greater than approximately 20 km wide (Reidel, 1983). Therefore, according to the standards of the CO_2 assessment methodology, the Columbia River Basalt Group is not considered an adequate regional seal (Brennan and others, 2010). Isolated, relatively impermeable entablature units might exist that effectively seal small regions, but their areal extents have not been sufficiently mapped to the scale of the entire Columbia Basin.

In light of the uncertainty of the effectiveness of the Columbia River Basalt Group as a regional seal, the Eocene-Oligocene composite section is nonquantitatively assessed for CO_2 storage potential in the Columbia Basin. Two SAUs are evaluated: (1) Eocene-Oligocene Composite Standard SAU C50050101, between 3,000- and 13,000-ft subsurface depth, and (2) Eocene-Oligocene Composite Deep SAU C50050102, below 13,000-ft subsurface depth (fig. 3). The SAU boundaries are defined by the 3,000- and 13,000-ft drilling depths from a thickness map of the Columbia River Basalt Group overlying the Eocene-Oligocene sedimentary rocks (Reidel and others, 2002) and eight wells provided by Golder Associates, Inc. (Paul Lapointe, oral commun., January 2011). The ranges of total storage formation thickness for the SAUs were determined from an isopach map of Tertiary sedimentary rocks underlying the Columbia River Basalt Group (Campbell, 1989). Brownfield (2008) summarized that the porosities of the Eocene Swauk, Roslyn, and Chumstick Formations range from approximately 4 to 22 percent; porosity of the Oligocene Wenatchee Formation ranges from 6 to 20 percent (Lingley and Walsh, 1986; Walsh and Lingley, 1991; Myer, 2005; Golder Associates, Inc., 2007). Johnson and others (1997) reported very low porosity and permeability measurements from two samples of the Chumstick Formation (1.2-percent porosity and 0.02-millidarcy (mD) permeability and 6.8-percent porosity and 0.8-mD permeability). One measurement from the Chumstick Formation from Western Oregon indicated 200-mD permeability (Nehring Associates Inc., 2010). A relatively small proportion of greater than 1-D permeability is interpreted for the shallow Eocene-Oligocene Composite SAU C50050101 based on gravel-size sediment representing alluvial-fan and fluvial deposition (Brownfield, 2008). Porosity and permeability values are interpreted to diminish with depth (Ehrenberg and others, 2009). Accordingly, we reduced the porosity range of the Eocene-Oligocene Composite Deep SAU C50050102 by approximately 50 percent of the range of the shallower Eocene-Oligocene Composite SAU C50050101. Brownfield (2008) warns that potential Eocene-Oligocene reservoirs contain volcaniclastic grains that have been altered to clays and zeolites, thereby potentially reducing porosity and permeability.

The Columbia Basin lacks water-quality information for the Eocene-Oligocene Composite SAUs. However, data of Reidel and others (2002) show that groundwater in the overlying Columbia River Basalt Group is not suitable for irrigation or domestic use because its fluoride concentrations exceed the drinking-water standard by greater than 10 fold. Moreover, Reidel and others (2002) noted that other constituents in groundwater of the Columbia River Basalt Group can exceed State of Washington water-quality standards, including those for iron and manganese.

In addition to aforementioned uncertainties regarding the seal integrity of the Columbia River Basalt Group, proximity to the Cascadia subduction zone might pose a seismic hazard capable of compromising seals as a result of great earthquakes (Petersen and others, 2008). Great Cascadia earthquakes are interpreted to recur on average every 500 years based on paleoseismic studies of coastal subsidence and tsunami deposits (for example, Atwater and Hemphill-Haley, 1997; Petersen and others, 2008). USGS calculations of peak ground accelerations in the Columbia Basin have a 2-percent probability of exceeding approximately 0.1 to 0.3 times the force of gravity in a 50-year interval (Petersen and others, 2008).

The SAUs within the Columbia Basin were not quantitatively assessed; therefore, residual- and buoyant-trapping pore volumes were not calculated. However, Reidel and others (2002) identify a relatively large area (approximately 9,000 mi^2) dominated by anticlinal structural traps in the Yakima fold belt region. Moreover, Johnson and others (1997) suggested that the Eocene-Oligocene sedimentary rocks in the Columbia Basin represent unknown, potentially large natural gas reservoirs, which might also store large volumes of CO_2.

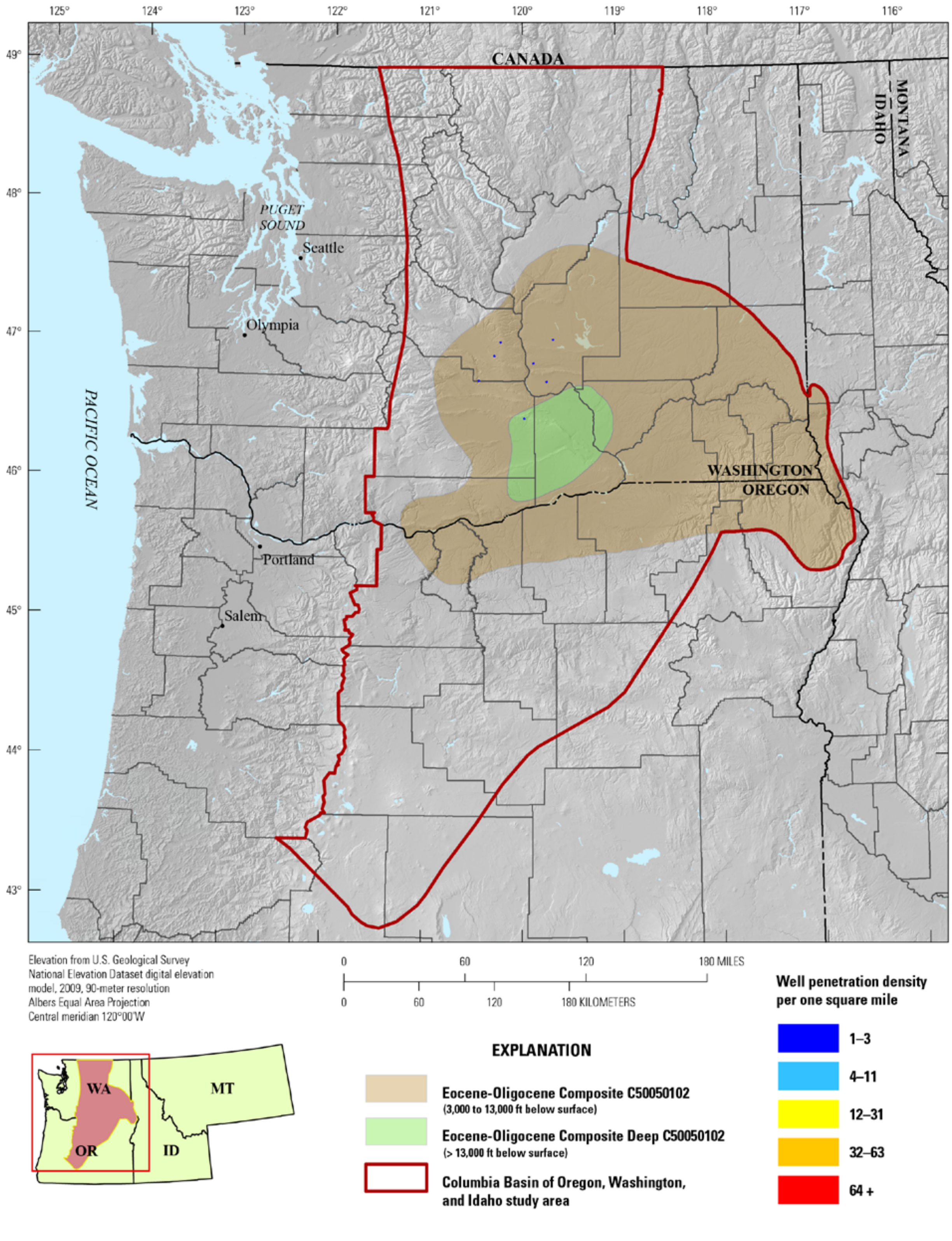

Figure 3. Map of the U.S. Geological Survey storage assessment boundaries for the Eocene-Oligocene Composite Storage Assessment Units in Oregon, Washington, and Idaho. Study area for the Columbia Basin of Oregon, Washington, and Idaho outlined in red is modified from Brownfield (2008). Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the composite reservoir top.

Western Oregon-Washington Basins

By Jacob A. Covault, Steven M. Cahan, Christina A. DeVera, Philip A. Freeman, and Celeste D. Lohr

Prospective basins for CO_2 storage in the onshore part of Western Oregon and Washington fall within the central to western parts of the U.S. Geological Survey National Oil and Gas Assessment (NOGA) Western Oregon and Washington Province, which extends southward from the Canadian border to the Klamath Mountains of Oregon (Brownfield, 2011) (fig. 4). These basins include, from north to south, Puget, Willapa, Astoria, Nehalem, and Willamette Basins (Golder Associates, Inc., 2007), which generally reside within the approximately 17,000-mi^2 Western Oregon and Washington Conventional Gas Assessment Unit (50040101) and the Tertiary Marine Gas Assessment Unit (50040201) of Brownfield (2011) (fig. 4). The eastern boundary of the prospective region for CO_2 sequestration is the Cascade Range (fig. 4). The western boundary is generally delineated, from north to south, by the highlands of the Olympic Mountains and the 3-mile limit of Washington and Oregon State waters (fig. 4). The Puget, Willapa, Astoria, Nehalem, and Willamette Basins are elliptical depocenters (Snavely and Wagner, 1980; Armentrout and Suek, 1985; Golder Associates, Inc., 2007; Brownfield, 2011) (fig. 4) that initiated during the Eocene in the forearc region of a collisional continental margin across which the Juan de Fuca oceanic plate has been subducting beneath North America (Atwater, 1970). During the Eocene, oblique plate convergence promoted the development of strike-slip faults and rapidly subsiding basins in Western Oregon and Washington (Johnson, 1985). The Cascade Range and volcanic arc initiated in the late Eocene and early Oligocene and was followed by Miocene emplacement of flood basalt of the prolific Columbia River Basalt Group (Tolan and others, 1989; Reidel and others, 2002; Brownfield, 2011). The Olympic Mountains and Coast Ranges were uplifted during the Oligocene to Pliocene (Brownfield, 2011).

Greater than 15,000 ft of Tertiary arkosic sandstone and mudstone with coal were deposited in discrete depocenters of Western Oregon and Washington, including the Puget, Willapa, Astoria, Nehalem, and Willamette Basins (Armentrout and Suek, 1985; Johnson and others, 1997; Golder Associates, Inc., 2007; Brownfield, 2011) (fig. 4). Forearc deposition is interpreted to have occurred in a variety of depositional settings, from nonmarine fluvial to deep-marine submarine-fan environments (Brownfield, 2011). Brownfield (2011) noted that Eocene sandstone formations are promising reservoirs because they contain smaller proportions of volcanic detritus, and as a result, they are less susceptible to deterioration of reservoir quality by alteration of unstable volcanic lithic grains (Armentrout and Suek, 1985; Snavely, 1987). The provenance of the arkosic sand grains was the Idaho batholith of eastern Oregon and Washington (Brownfield, 2011). Eocene reservoir rocks include the Raging River Formation, the Puget Group, and the Skookumchuk, Cowlitz, Tyee, and Spencer Formations (Golder Associates, Inc., 2007; Brownfield, 2011) (fig. 5). Figure 5 shows additional, time-equivalent Eocene formations, which were not assessed for CO_2 storage. Reservoir-prone formations are interpreted to be regionally overlain by several thousand feet of tuffaceous mudstone of the upper Eocene Cowlitz and upper Eocene and Oligocene Keasey, Lincoln Creek, and Blakeley Formations, which constitute a regional seal (Armentrout and Suek, 1985).

Some gas was produced from the Eocene rocks near Bellingham, Wash., and approximately 12,000 barrels of oil and associated gas were produced near Aberdeen, Wash. (fig. 4). The only current hydrocarbon production in Western Oregon and Washington is from the Mist gas field in northwest Oregon (fig. 4) where from 1979 to 2008, 65 billion cubic ft of gas (BCFG) had been produced from the Eocene Cowlitz Formation. The U.S. Geological Survey assessed both undiscovered conventional oil and gas and undiscovered continuous (unconventional) gas in the Western Oregon and Washington Province, resulting in estimated mean volumes of 2,214 BCFG of undiscovered natural gas and 15 million barrels of oil (MMBO) (Brownfield, 2011). The mean estimated volume of gas for the Western Oregon and

Washington Conventional Gas Assessment Unit (50040101) is 454 BCFG, with an estimated mean size of the largest reported gas field of 85 BCFG (Brownfield, 2011). The assessed mean undiscovered volume of oil in the Tertiary Marine Gas Assessment Unit (50040201) is 15 MMBO, with estimated means of 22 BCFG for associated gas and 1 million barrels of natural gas liquids. The mean size of the largest expected oil field is 9 MMBO.

Western Oregon-Washington Basins Carbon Dioxide Storage Resource Assessment

An Eocene composite reservoir unit is assessed for CO_2 storage in the Puget, Willapa, Astoria, Nehalem, and Willamette Basins (fig. 6). Prospective reservoirs include the Raging River Formation, Puget Group, and Skookumchuck, Cowlitz, Tyee, and Spencer Formations (Golder Associates, Inc., 2007; Brownfield, 2011) (fig. 5). The extent of the reservoir storage units is defined by the geologic characteristics of the reservoirs and overlying seals and the subsurface physical properties of CO_2 as described in Burruss and others (2009) and Brennan and others (2010). The following section describes the composite SAU defined in the Puget, Willapa, Astoria, Nehalem, and Willamette Basins of Western Oregon and Washington (figs. 4 and 6). The SAU is similar in areal extent and includes similar reservoirs as the USGS NOGA Western Oregon and Washington Conventional Gas Assessment Unit (50040101) and the southern part of the Tertiary Marine Gas Assessment Unit (50040201) of Brownfield (2011).

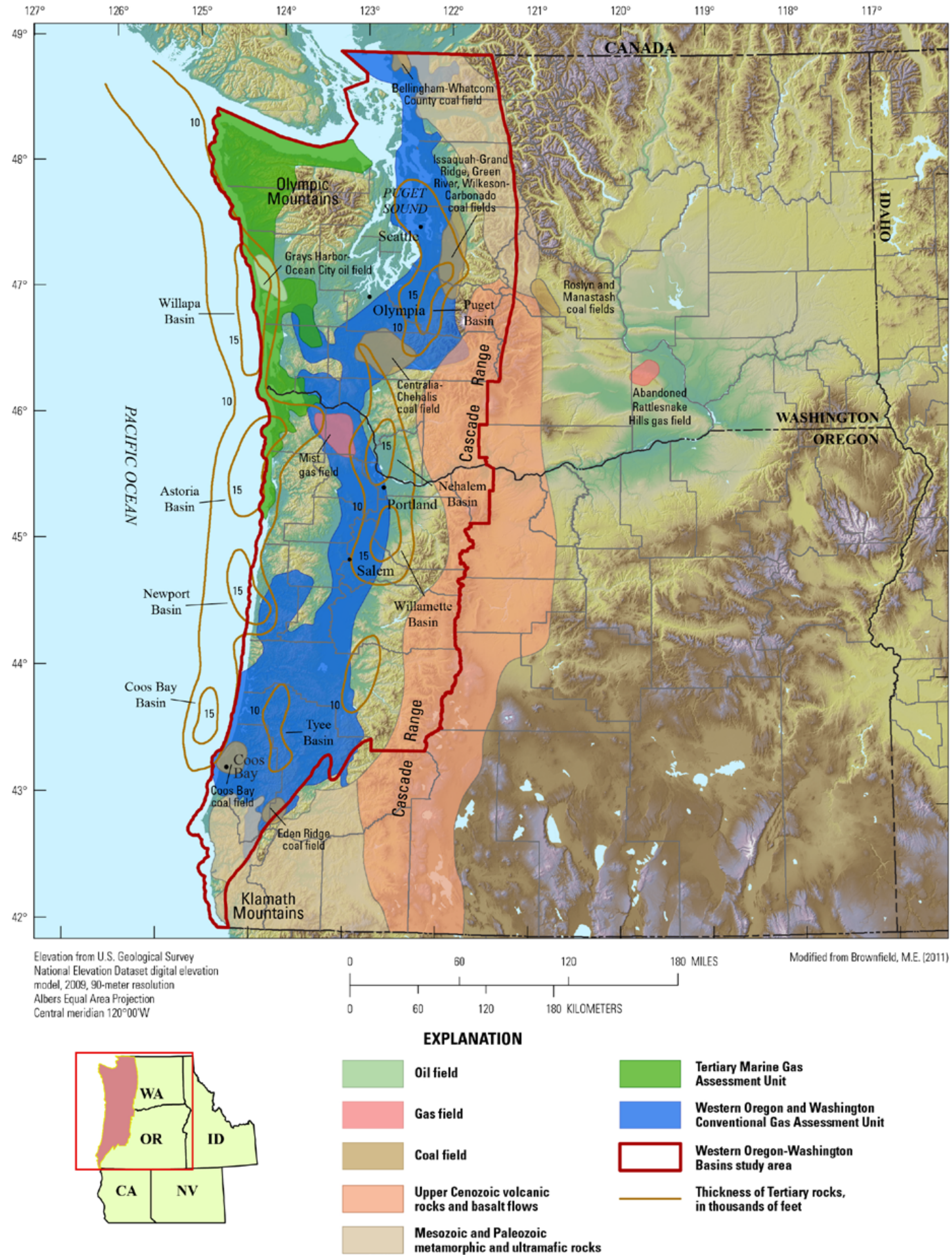

Figure 4. Locations of selected Tertiary basins in Western Oregon and Washington and approximate locations of oil, gas, and coal fields. Isopach contours of Tertiary rocks are in thousands of feet. Study area for the Western Oregon and Washington Basins outlined in red, modified from Brownfield (2011). Western Oregon and Washington Conventional Gas Assessment Unit (50040101) is highlighted in dark blue (Brownfield, 2011). Tertiary Marine Gas Assessment Unit (50040201) is highlighted in green (Brownfield, 2011). Modified from Braislin and others (1971), Snavely and Wagner (1980), Armentrout and Suek (1985), and Brownfield (2011).

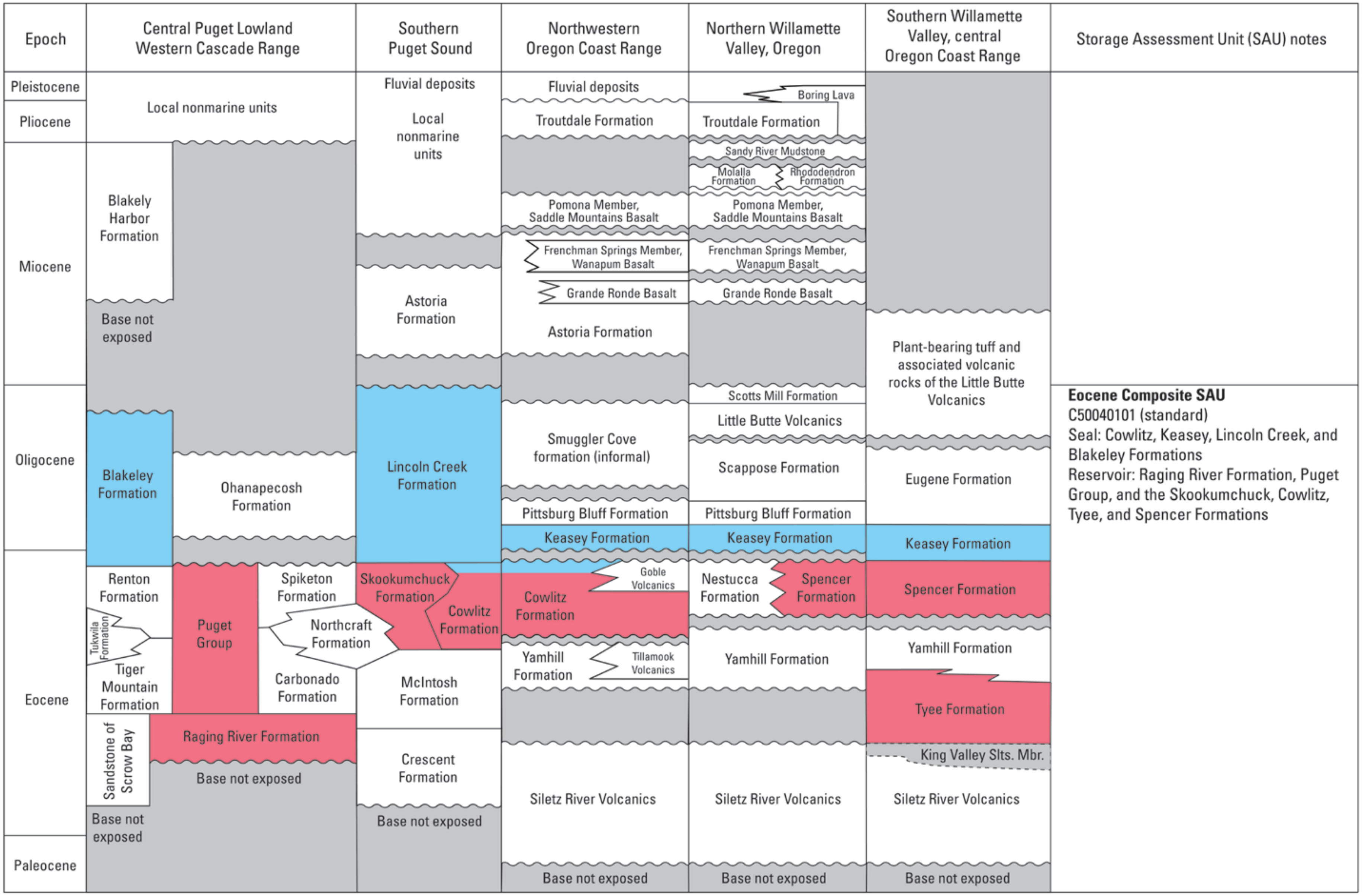

Figure 5. Generalized columns of stratigraphic units in Western Oregon and Washington. Storage assessment units consist of a reservoir (red) and regional seal (blue). Wavy lines indicate unconformable contacts, and gray sections represent stratigraphic gaps. Modified from figures 5 and 8 of Brownfield (2011).

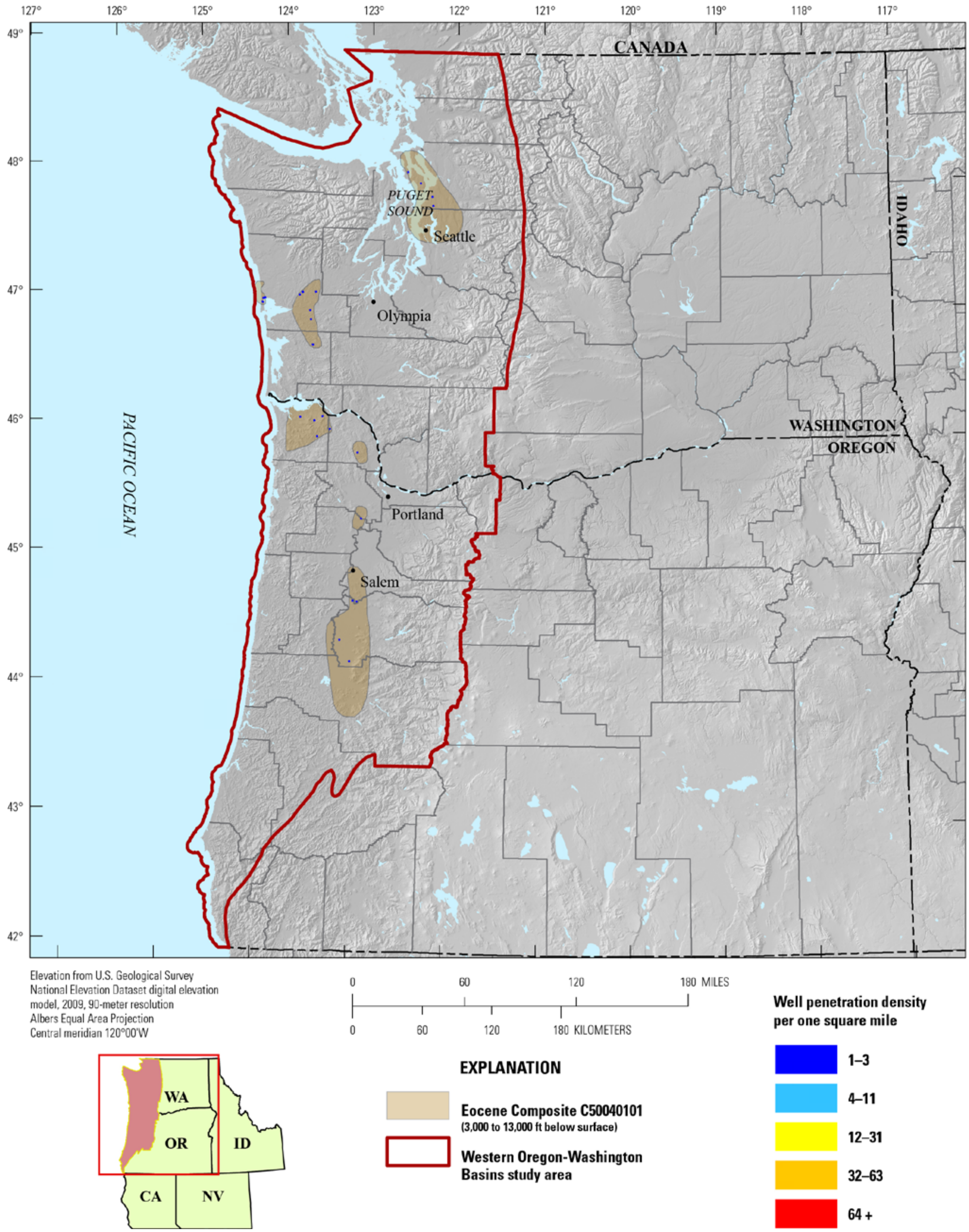

Figure 6. U.S. Geological Survey (USGS) storage assessment unit (SAU) boundary for the Eocene Composite SAU in Western Oregon and Washington. Study area for the Western Oregon and Washington Basins outlined in red is modified from Brownfield (2011). Grid cells (one square mile) represent counts of wells derived from ENERDEQ well database (IHS Energy Group, 2011) that have penetrated the reservoir formations tops.

Eocene Composite SAU C50040101

Prospective rocks for CO_2 storage generally include Eocene, thick (approximately 5,000 ft on average) arkosic sandstone and mudstone interbedded with coal (Armentrout and others, 1983; Armentrout and Suek, 1985; Golder Associates, Inc., 2007; Brownfield, 2011) (figs. 4 and 5). Eocene reservoir rocks include the Raging River Formation, Puget Group, and Skookumchuk, Cowlitz, Tyee, and Spencer Formations (Armentrout and others, 1983; Golder Associates, Inc., 2007; Brownfield, 2011) (fig. 5). The northern part of the Puget Basin includes the lower and middle Eocene Raging River Formation, which achieves a thickness of as much as 3,000 ft of fine-grained sandstone, mudstone, and conglomerate (Armentrout and others, 1983; Johnson and O'Connor, 1994; Brownfield, 2011). The middle and upper Eocene Puget Group is present throughout the Puget Basin where it overlies the Raging River Formation in the north (Brownfield, 2011). South of the Puget Basin and in the Willapa Basin, the middle and upper Eocene Skookumchuck and Cowlitz Formations regionally achieve a thickness of as much as 9,500 ft (Armentrout and others, 1980; Brownfield, 2011). The Cowlitz Formation in the Willapa Basin is predominantly siltstone with arkosic sandstone and coal (Golder Associates, Inc., 2007; Brownfield, 2011). The Cowlitz Formation is also present in the Astoria and Nehalem Basins where it comprises approximately 4,200 ft of fine- to medium-grained arkosic and lithic sandstone with conglomerate and mudstone (Golder Associates, Inc., 2007; Brownfield, 2011). In the Willamette Basin, the middle and upper parts of the Tyee and Spencer Formations are prospective reservoirs (Brownfield, 2011). The Tyee Formation can reach a thickness of as much as 6,000 ft of sandstone (Golder Associates, Inc., 2007). Locally, the Spencer Formation unconformably overlies the Tyee Formation and includes a thickness of as much as 2,000 ft of arkosic sandstone and mudstone with coal (Brownfield, 2011). The Spencer Formation is interpreted to be widespread in the subsurface of the Willamette Basin and to be temporally equivalent to the upper part of the Cowlitz Formation (Brownfield, 2011). Overlying these Eocene prospective reservoir formations are regionally extensive sealing units, which include several thousand feet of tuffaceous mudstone of the upper Eocene Cowlitz and upper Eocene and Oligocene Keasey, Lincoln Creek, and Blakeley Formations (Armentrout and Suek, 1985) (fig. 5). The reservoir formations are interpreted to generally represent deposition in nonmarine fluvial and shallow-marine deltaic environments (Brownfield, 2011). The overlying sealing formations are interpreted to represent regionally extensive deposition of fine-grained, arc-derived, tuffaceous sediment as a result of forearc-basin subsidence and consequent shoreline transgression (Armentrout and Suek, 1985; Snavely, 1987; Brownfield, 2011). Brownfield (2011) highlights additional prospective Eocene reservoirs and petroleum systems in the Coos Bay region of southern Oregon and the Olympic Peninsula of Washington (fig. 4). However, prospective strata are too shallow (less than 3,000-ft drilling depth) and (or) lack a regional sealing formation, which precludes their assessment for CO_2 sequestration following the methodology of Burruss and others (2009) and Brennan and others (2010).

The Eocene Composite SAU (C50040101), including the Raging River Formation, Puget Group, and Skookumchuck, Cowlitz, Tyee, and Spencer Formations, is a potential reservoir unit for CO_2 storage in Western Oregon and Washington between 3,000- and 11,000-ft subsurface depth (fig. 6). The SAU boundary is defined by the 3,000-ft drilling depth to the top of Eocene sandstone-dominated stratigraphic units from nearly 250 well penetrations (IHS Energy Group, 2010; Paul Lapointe, Golder Associates, Inc., oral commun., January 2011). The majority of the well data (greater than 200 wells) were provided by Golder Associates, Inc. (Paul Lapointe, oral commun., January 2011). Stratigraphic picks by Golder Associates, Inc. (2007) from wells in the Willamette Basin indicate more Tyee Formation relative to Spencer Formation. However, Brownfield (2011) reported that the Spencer Formation is widespread in the subsurface of the Willamette Basin and the Tyee Formation is more common to the south, in the Tyee and Coos Bay Basins (Armentrout and others, 1983). The middle Eocene Tyee and upper Eocene Spencer Formations are interpreted to be broadly equivalent for the purposes of this assessment.

The range of total storage formation thickness for the SAU was determined from an isopach map of Tertiary sedimentary rocks of Western Oregon and Washington (Snavely and Wagner, 1980) and regional subsurface stratigraphic correlations of Armentrout and others (1983). The thickness of the net porous interval was constrained from net sandstone thickness measurements in the Puget, Willapa, Astoria, and Nehalem Basins provided by Golder Associates, Inc. (Paul Lapointe, oral commun., January 2011). Golder Associates, Inc. (2007) indicates porosity of the Eocene sedimentary rocks generally is less than 40 percent with a median range from approximately 10 to 30 percent. Permeability generally is less than 4 D, with a median range from approximately 1 to 195 mD (Golder Associates, Inc., 2007). Reservoir-quality measurements from a single well in the Astoria and Nehalem Basins indicate 25-percent porosity and 200-mD permeability in Eocene rocks (Nehring Associates Inc., 2010).

Limited water-quality data from the southern Puget Basin indicate relatively saline groundwater (greater than 10,000 ppm of total dissolved solids) (Breit, 2002), and Whitehead (1994) indicates relatively saline groundwater in pre-Miocene rocks west of the Cascade Range. However, the sparse, limited distribution of water-quality data does not preclude the possibility of local fresh groundwater.

Proximity to the Cascadia subduction zone might pose a seismic hazard capable of compromising seals as a result of great earthquakes (Petersen and others, 2008). Great Cascadia earthquakes are interpreted to recur on average every 500 years based on paleoseismic studies of coastal subsidence and tsunami deposits (for example, Atwater and Hemphill-Haley, 1997; Petersen and others, 2008). USGS calculations of peak ground accelerations in Western Oregon and Washington have a 2-percent probability of exceeding approximately 0.3 to 1.0 times the force of gravity in a 50-year interval (Petersen and others, 2008).

The minimum and most likely buoyant-trapping pore volumes were determined using methods described in Brennan and others (2010) and Blondes and others (2013). Maximum buoyant-trapping pore volume was calculated from the product of (1) the combined areas of oil and gas fields shown in figure 5 of Brownfield (2011), the Mist gas field and the Grays Harbor-Ocean City oil field, which overlap the Eocene Composite SAU (C50040101), and reservoirs of producing fields (Nehring Associates, Inc., 2010); (2) the maximum net-porous-interval thickness from productive Astoria, Nehalem, and Willapa Basins; and (3) the maximum porosity (Brennan and others, 2010).

Acknowledgments

We thank the West Coast Regional Carbon Sequestration Partnership and especially Lorraine Hwang (California Institute for Energy and Environment) and Paul Lapointe (Golder Associates, Inc.) for their help in supplying geologic information used in this review. We thank Michael Brownfield (U.S. Geological Survey) for consultation prior to the publication of NOGA assessments for Western Oregon and Washington. The content and presentation of this report benefited greatly from the technical reviews of Rosalind Helz and Michael Brownfield.

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ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20121024d