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Carbon-14 dating of ground water in the Palouse Basin of the Columbia river basalts

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Summary Delineation of the spatial distribution of ground water that is several thousands of years old can provide an important piece of the puzzle in the evaluation of long-term, ground water resource sustainability under pumping conditions. Ground water for municipal and local water supplies within the Palouse Basin of eastern Washington and northern Idaho are derived almost entirely from two basalt aquifer systems. Decades of continual water level declines in the deeper aquifer system in response to interstate pumping have suggested that this high transmissivity, low storativity aquifer system is being mined. Average water level declines in the deeper aquifer system have been on the order of 0.46 m (1.5 ft) per year for the past 40-plus years. Carbon-isotopic measurements on dissolved inorganic carbon were used to provide information on the relative ages of the ground water pumped from various locations within the basin. Mass balance modeling of hydrochemical reactions together with steep, downward vertical gradients throughout the basin suggest that the ground water being withdrawn currently required several thousand years to traverse spatially variable sequences of loess, fluvial sediments, and basalt flows with associated sedimentary interbeds, that overlie the primary producing zones in the basin. Restrictions to the vertical movement of recharge water such as low permeability, overburden deposits, well-developed fragipans, and thick, low permeability, sedimentary interbeds increase in the eastern portion of the Palouse Basin compared to the western portion. This has resulted in accumulation of the oldest ground water in the topographically highest areas of the basin adjacent to the basin divide.

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Introduction

The Palouse Basin is a complex, interstate, ground water basin located in eastern Washington and northern Idaho (Fig. 1). The local communities of Pullman, Colfax and

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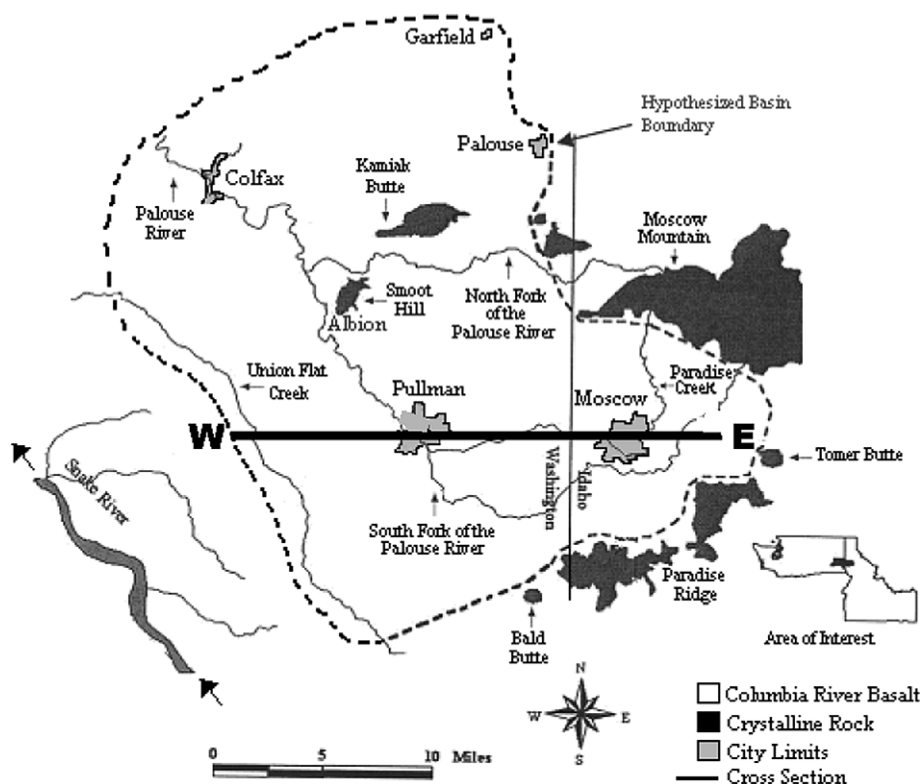


Figure 1 Bedrock-geologic and hydrographic map of the study (modified after Hopster, 2003). The Palouse Basin is located in northern Idaho and eastern Washington, in and around the towns of Moscow, Idaho and Pullman, Colfax, and Palouse, Washington. The bold line W–E represents the approximate trace of the generalized geologic cross-section shown in Fig. 2.

Palouse, Washington, and Moscow, Idaho, plus Washington State University and the University of Idaho depend entirely on two basalt aquifer systems of the Columbia River Basalt Group (CRBG) for their water resources. The deeper aquifer system has been developed more heavily in recent decades because of the better quality water, and the more reliable supply. However, despite success by the four major pumping centers in stabilizing annual pumping rates over the past decade, water levels have continued to decline throughout the basin. This has raised concerns about ground water mining of the Pleistocene Age resource. This study focuses on evaluation of the residence times of ground water at selected locations in the Palouse Basin, and correlation of these "age dates" to specific geologic and hydrogeologic conditions that controlled residence time prior to development of the basin beginning in the 1890s. Ground water samples for isotope ratios of carbon (^{14}C and ^{13}C in dissolved CO_2), oxygen ^{18}O , and general water chemistry were collected for the basalt aquifer systems, specifically concentrating on the deeper system. Samples were collected from existing municipal and domestic wells, and therefore, the spatial distribution of sampling points was predetermined. These data were used to help evaluate the characteristics of pre-development, ground water movement, and the paucity of current recharge to the deep aquifer system in the basin. The original conceptual, hydrogeologic model that ground water in the basin ages along flow paths in both the vertical and horizontal directions was not supported by the age dates when evaluated together with mass balance modeling of hydrochemical reactions. Only results

of reaction path modeling along potential vertical flow paths were consistent with water samples collected from wells in the basin. This suggests strongly that the measured age dates reflect long travel times along low hydraulic conductivity, vertical flow paths rather than long horizontal travel distances across the basin.

Hydrogeologic setting

The Palouse Basin is situated on the eastern margin of the Columbia Plateau, encompassing an area of about 610 km^2 (235 mi^2) (Fig. 1). The geology in the area consists of crystalline basement rock (granite and metasediments), overlain unconformably by basalt flows and interbedded sediments of the CRBG. The CRBG is overlain unconformably by fluvial deposits (Latah Formation) and thick units of Pleistocene loess of the Palouse Formation (Fig. 2). These Miocene basalts are part of an extensive sequence of lava flows that entered the Palouse Basin from the west and south, and inundated the pre-existing bedrock topography. Three ground water producing formations of the CRBG exist in the basin; from the base upward these formations include the: Imnaha, Grande Ronde, and Wanapum (Fig. 2). Stream and lacustrine sediments were deposited as interbeds throughout the sequence of basalt flows due to damming of drainages as individual basalt flows advanced into the basin. These sedimentary interbeds are thickest near the city of Moscow, and many pinch out completely to the west. A thick sedimentary interbed of the Latah Formation, consisting of clay, silt, sand, and gravel, separates the Wanapum

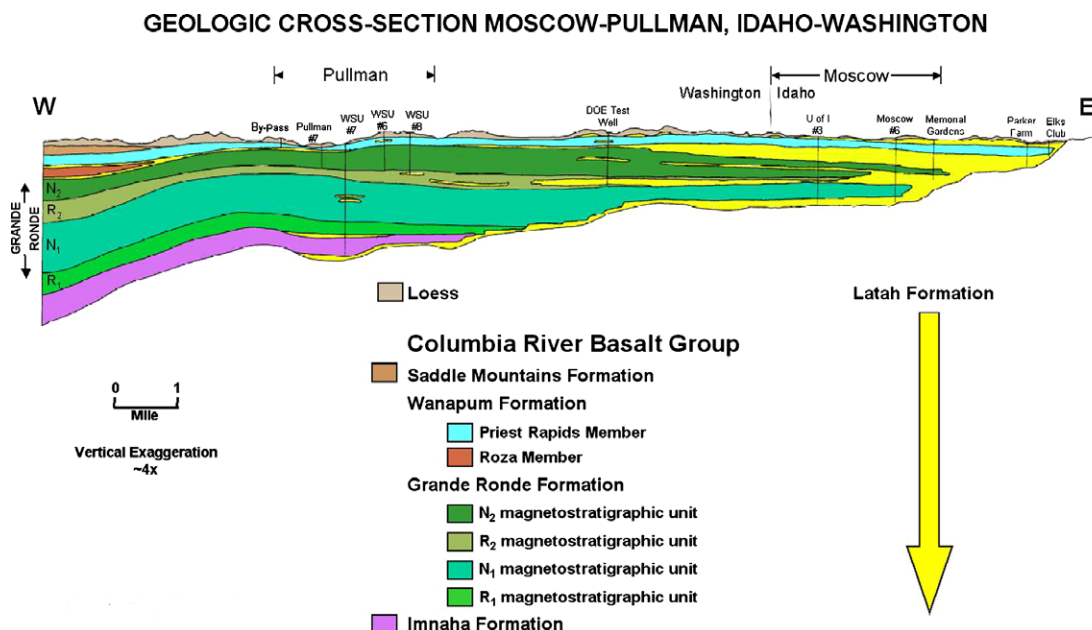


Figure 2 Generalized geological cross-section of the Palouse Basin (modified after Bush and Garwood, 2004). *Note:* The Upper Grande Ronde is differentiated from the Lower Grande Ronde by a change in magnetic polarity. See Fig. 1 for location of cross-section.

Formation from the Grande Ronde Formation under most of the eastern half of the basin.

The ground water basin boundaries to the east are formed by granite of the Palouse Range, including Moscow Mountain. Granite and metasediments of Bald Butte, Paradise Ridge and Tomer Butte form the basin boundaries to the south and southeast, respectively. Metasediments and granite of Kamiak Butte, Smoot Hill, and other prominent hills represent surface expressions of basement rocks to the north and northwest (Fig. 1). The western boundary of the basin is undefined. No natural ground water discharge from the deeper aquifer system that supplies Moscow and Pullman has been identified at the deepest points in the basin along the Snake River Canyon (topographically 574 m (1883 ft) and 526 m (1725 ft) lower than the cities of Moscow and Pullman, respectively), or anywhere else, based on $\delta^{18}\text{O}$ data (Hopster, 2003).

Two major aquifer systems exist within the Wanapum and Grande Ronde Formations in the basin (Fig. 2). The primary ground water resource system in the Palouse Basin is the Grande Ronde aquifer system. Total thickness of the Grande Ronde aquifer system exceeds 700 m (2300 ft) west of Pullman, and thins to zero along basin boundaries near Moscow and Palouse. Individual flows range in thickness from less than one meter (3 ft) to more than 50 m (160 ft) (Bush and Seward, 1992). The Wanapum aquifer system is the primary ground water resource for rural residents within the basin limits. Thickness of the Wanapum Formation ranges from 0 to 76 m (250 ft) within the basin (Hooper and Webster, 1982).

Ground water in the layered basalts exists in perched zones as well as in unconfined and confined multiple aquifer systems. Ground water flow occurs through intraflow structures within the sparsely fractured interiors of single flow units, and within the highly fractured, vesicular, interflow

zones between successive flow units (DOE, 1981; Long, 1978). Fig. 3 illustrates the typical physical characteristics of Columbia River Basalt flows. Interiors of the lava flows generally have low porosity and low hydraulic conductivity while interflow zones have high porosity and high hydraulic conductivity (DOE, 1981). Basalt interiors typically form confining layers between successive interflow zones; these

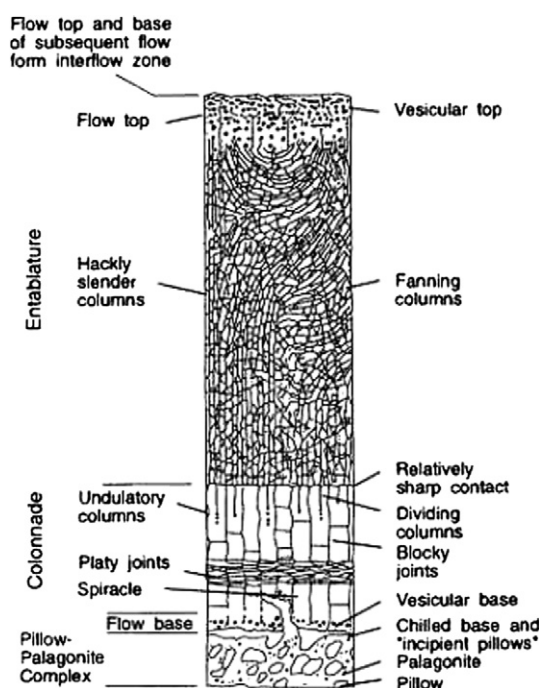


Figure 3 Physical characteristics of Columbia River Basalt Group flows (modified after Swanson and Wright, 1978).

multiple aquifer/aquitard systems generally are poorly connected vertically (DOE, 1986). Within the Palouse Basin, aquifers characteristically exhibit lateral hydraulic connections over several kilometers in response to pumping in the major municipal pumping centers (Owsley, 2003).

Previous investigations

The first, extensive hydrogeologic investigation of the Palouse Basin was conducted in the 1890s by Russell (1897). He noted the paucity of significant springs discharging from the Wanapum and Grande Ronde Formations along tens of kilometers of outcrop in river canyons during the early stages of ground water development in the basin. This lack of visible natural ground water discharge is consistent with a small amount of recharge to the aquifer systems. However, it is possible that ground water discharge occurs as flow directly into the Snake River or as underflow to a discharge area farther west. Russell (1897) also noted the fact that the first shallow wells drilled in the Pullman and Moscow areas flowed at the land surface. However, most of these wells were left uncapped, and water levels soon fell below land surface.

Ongoing geologic and hydrogeologic studies in the local area are focused primarily on evaluation of ground water resource sustainability within the basin. Conceptual models of recharge in the basin have ranged from the mechanisms of infiltration of areally distributed precipitation, to the possibility of percolation from losing streams in the eastern part of the basin (Bauer and Vaccaro, 1990; Barker, 1979; Heine-mann, 1994; Kopp, 1994; Lum et al., 1990; Johnson, 1991; Muniz, 1991; O'Brien et al., 1996; Provant, 1995; Smoot and Ralston, 1987). Additionally, it has long been hypothesized that infiltration of runoff from the Palouse Range recharges sediments interbedded with the basalts on the eastern side of the basin (Lin, 1967; Jones and Ross, 1972; Pierce, 1998). Each of these proposed scenarios suggested relatively short travel times to the basalt aquifers (e.g., on the order of years to hundreds of years). Crosby and Chatters (1965a) conducted the first investigation of ground water residence times within the Palouse Basin; based on the methods described in Crosby and Chatters (1965b), they found that radiocarbon age dates in the Moscow–Pullman area range between 8500 and 31,000 years Apparent Radiocarbon Age (BP). Overall, Crosby and Chatters (1965a) found a general relationship of increasing age with increasing depth. However, samples were collected primarily from the upper, shallow aquifer system in the Wanapum Formation; only four out of 50 samples were taken from the Grande Ronde aquifer system.

An analysis of $\delta^{18}\text{O}$ concentrations in ground water and meteoric water was completed in the Palouse Basin by Larson et al. (2000), focusing primarily on the evaluation of various conceptual models for recharge in the basin. They found that ground water in the Grande Ronde aquifer system has $\delta^{18}\text{O}$ values statistically distinct from ground water in the Wanapum aquifer system and other shallow lithologic units. Grande Ronde ground water samples consistently yielded $\delta^{18}\text{O}$ values between -15.4‰ and -17.5‰ . These values generally are depleted relative to Wanapum ground water samples ($\delta^{18}\text{O}$ values between -14.9‰ and -15.7‰), and ground water from the loess and shallow

fluvial sediments ($\delta^{18}\text{O}$ values between -12.6‰ and -14.7‰). Larson et al. (2000) showed that the deep ground water in the basin was not recharged under the present climatic conditions, and that shallower aquifer systems were recharged more recently.

Hopster (2003) investigated the physical, ground water recharge/discharge mechanisms in the basin. This investigation provided insight into the controls exerted by spatially variable, overburden thicknesses on recharge to the basalt aquifers within the basin. The overburden consists primarily of rolling hills comprised of low hydraulic conductivity loess, underlain in areas by fluvial sediments. Lateral hydraulic conductivity values of the overburden materials defined by Vaccaro (1999) from specific-capacity data range from 8.8×10^{-6} to 5.2 cm/s (2.9×10^{-7} to $1.7 \times 10^{-1} \text{ ft/s}$), and regional values derived from a ground water flow model range from 1.5×10^{-5} to $4.0 \times 10^{-1} \text{ cm/s}$ (5.0×10^{-7} to $1.3 \times 10^{-2} \text{ ft/s}$). McDaniel et al. (2001), Brooks et al. (2000) and O'Geen (2002) concluded that fragipans present in the soils, and paleosols of the loess deposits allow very little recharge to infiltrate on an annual basis. They indicated that the impeding effect of fragipans is greater on the east side of the basin (i.e., in the direction of increasing rainfall and soil development).

Nonpumping water level measurements suggest that under the present-day conditions, ground water potential decreases with depth throughout most of the basin. Historical water level data show that ground water levels in the Grande Ronde aquifers have been declining steadily while present-day water levels in the Wanapum aquifer system have been relatively stable except for seasonal fluctuations due to increased summer-time pumping, and spring-time recharge. Large-scale aquifer tests have shown that lateral hydraulic connections between various Grande Ronde pumping centers exist over distances of several kilometers; however, no vertical hydraulic connections between the Grande Ronde aquifer system and the overlying Wanapum aquifer system were measured over pumping periods ranging from 6 to 48 h (Owsley, 2003).

The objectives of this study were to use radiocarbon dating techniques, along with $\delta^{18}\text{O}$ data and general water chemistry data for the basin to evaluate the spatial variability of ground water residence times in the Grande Ronde aquifer system in the Palouse Basin. Ground water samples and water level data were collected for the Grande Ronde aquifer system through existing, domestic and municipal wells throughout the basin. Further details about the sampling protocol, water chemistry results, and hydrogeology are presented in Douglas (2004).

Methods

Ground water samples were collected for 31 wells within the study area between 2001 and 2003 (Fig. 4). Most samples were collected from the Grande Ronde aquifer system; however, additional ground water samples also were collected from the Wanapum aquifer system, the surficial loess deposits, and granitic bedrock in the basin. Water samples were collected after purging the well casing and plumbing, and before passage through water treatment systems. Temperature, pH, and alkalinity were measured in the field.

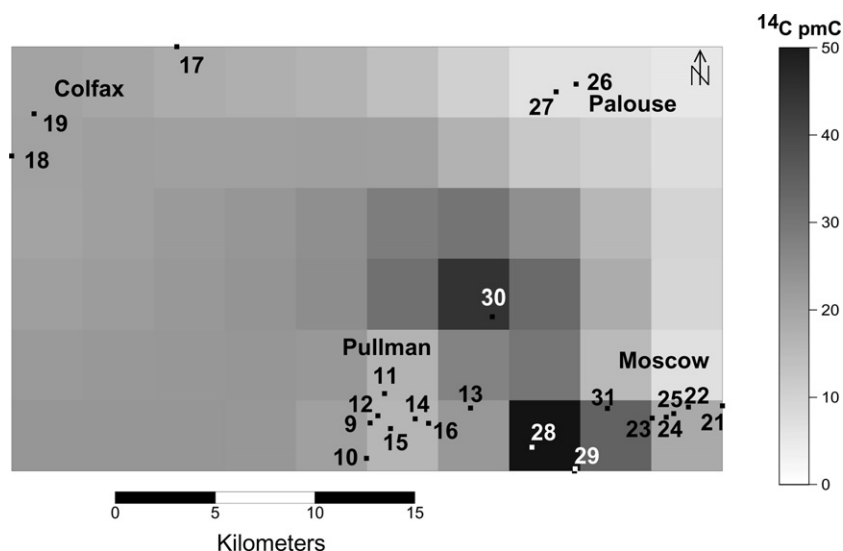


Figure 4 Shaded cell map of ground water ^{14}C (pmc) concentrations in the Grande Ronde aquifer system (Douglas, 2004). Well samples are identified through a sample number given in Table 1. Darker cells represent areas of younger waters. Two of the cells located around wells 30 and 29 are relatively the youngest ground water found to date in the Grande Ronde aquifer system. These two areas could suggest potential recharge areas for the Grande Ronde system. *Note:* limited funding for this investigation precluded measurement of tritium concentrations to evaluate potential mixing between young and old waters.

Alkalinities were measured with a digital titrator. The water samples for both ^{14}C and ^{13}C were collected in 50 l (13 gallon) Nalgene™ carboy bottles, and capped immediately. The same day in the lab, $\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$ and NH_4 were added to each sample to quantitatively precipitate BaCO_3 . The water was then decanted, and the precipitate for each sample was transferred to a separate, labeled 1.0 l HDPE Nalgene™ bottle for shipment to the Lab. The carbonate precipitate was analyzed for ^{14}C and ^{13}C by Beta Analytics Inc., in Miami, Florida.

^{14}C results are reported as percentage of the modern standard (pmc) and as the Apparent Radiocarbon Age (BP). ^{13}C results are expressed as $\delta^{13}\text{C}$, which is the deviation in per mil (parts per thousand) of the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample, relative to the Pee Dee belemnite international standard (Craig, 1957). Water chemistry was analyzed in the Department of Geological Sciences at the University of Idaho. Major anion concentrations were determined on an ion-chromatograph (IC), and major cation analyses were performed using a Perkin–Elmer, Optima 3000XL® Inductively Coupled Plasma–Atomic Emission Spectrometer (ICP–AES) equipped with an axial torch. Oxygen-18 analyses were performed by automated CO_2 equilibration (Epstein and Mayeda, 1953), and gas-source mass spectrometry at the Geoanalytical Lab at Washington State University, and reported as $\delta^{18}\text{O}$ relative to VSMOW (Gat and Gonfiantini, 1981).

Geochemical modeling

The ground water chemistry in the basin is predominantly of the calcium bicarbonate type (Cotton, 1982; Nelson, 2003; Nelson et al., 2004). The ^{14}C ages are primarily related to the original ^{14}C content of the water as it percolated through the soil zone (Crosby and Chatters, 1965a). The

radioactive age of ground water is given by the general law of radioactive decay

$$t = \frac{\lambda}{\ln 2} \ln \frac{A_0}{A} \quad (1)$$

where t is the travel time in years, between the recharge location and sampling location, λ is the half-life of ^{14}C (5730 ± 30 years), A is the measured ^{14}C activity (in pmc) of dissolved inorganic carbon (DIC) in the sample (downgradient well), and A_0 is the ^{14}C activity of DIC in the recharge water (upgradient well).

Crosby and Chatters (1965a) suggested that isotopic exchange does not occur in the basalts, and that no corrections of the raw $^{14}\text{CO}_2$ ages are necessary based on the fact that the associated ^{13}C values are very similar between samples of recent perched water and old deep ground water. In addition, unlike the conditions identified near Saskatoon, Saskatchewan, Canada by Bacon and Keller (1998) where CO_2 is depleted in ^{14}C near the water table, Bacon (1997) found that $^{14}\text{CO}_2$ concentrations in the gas phase of the vadose zone in the Palouse Basin are modern, containing bomb radiocarbon. While Bacon and Keller's study was limited to one location between Moscow and Pullman, it supports the assumption that the initial ^{14}C concentration at the recharge point, A_0 , can be taken as 100 pmc. Uncorrected ages are calculated on this basis neglecting any subsequent hydrochemical reactions. However, $\delta^{13}\text{C}$ values were found to vary by approximately 5 per mil, and these variations may reflect gains or losses of CO_2 by reactions subsequent to recharge. Therefore, conventional adjustment models based on water chemistry and $\delta^{13}\text{C}$ were also applied using NETPATH (Plummer et al., 1994). Because the Palouse Basin is not a carbonate terrain, and is primarily a silicate environment, only adjustment models that are applicable to silicate terrains were utilized.

NETPATH considers several well-known methods for age date adjustment. The adjustment model of Mook (1980) was determined to be the most applicable to the study area, and was considered the only appropriate model for silicate terrains. The Mook (1980) model is based on ^{13}C values, and does not assume that cations or alkalinity necessarily come from dead carbonates.

Corrected ages derived by the Mook (1980) model differed from the uncorrected age dates by only 1.0–1.7%. Even with addition of these small corrections, the relative age relationships remained the same among the wells throughout the basin, and so the spatial age patterns are preserved. Therefore, for purposes of this specific investigation, measured ^{14}C concentrations in pmc are used for spatial analysis.

Results and discussion

The distribution of ^{14}C in the ground water is highly variable and reflects complex, vertical migration pathways between the land surface and producing zones at depth. Concentrations of ^{14}C in the ground water samples (Table 1) from the lower portion of the Grande Ronde aquifer system ranged from 4.1 to 20.8 pmc. Concentrations of ^{14}C ranged from 15.4 to 58.6 pmc in ground water samples from the upper portion of the Grande Ronde aquifer system. Ground water from the Wanapum aquifer system and from the loess deposits yielded concentrations of ^{14}C between modern and 33.4 pmc. The corresponding ages ranged from 13,000 to 26,400 years (BP) for the lower portion of the Grande Ronde

Table 1 Isotopic characteristics, uncorrected ages and stratigraphic data for sampled wells

#	Well name	Geologic layer	Uncorrected age (BP)	^{14}C , pmc	Detection limits ($\pm$)	$\delta^{13}\text{C}$, ‰ PDB	$\delta^{18}\text{O}$, ‰ VSMOW
1	Butters	Granite	6100	48.0	50	−15.2	−17.38
2	Gentry ^a	Granite	Modern	104.5	0.5 pmc	−18.1	−15.38
3	UIGRS ^a	Alluvium	Modern	115.8	0.79 pmc	−16.4	−14.72
4	Loess6A ^a	Loess	1600	82.6	40	−13.2	n/a
5	Stalnaker ^a	Wanapum	14,600	17.1	50	−16.3	−15.62
6	COM2 ^a	Wanapum	8700	35	40	−16.2	−16.58
7	COM3 ^a	Wanapum	9100	33.3	120	−15.8	−16.38
8	UI5	Wanapum	3300	67	60	−15.7	−15.15
9	COP3 ^a	Grande R.	13,000	20.8	150	−14.6	−16.70
10	COP5 ^a	Grande R.	16,300	14	230	−13.1	−17.07
11	COP6 ^a	Grande R.	17,100	12.6	200	−13.5	−17.06
12	COP7	Grande R.	16,500	13.7	150	−15.1	−17.06
13	WSU5 ^a	Grande R.	14,300	17.7	120	−14	n/s
14	WSU6 ^a	Grande R.	21,100	7.8	190	−12.8	−17.57
15	WSU7	Grande R.	18,000	11.4	180	−15.1	−18.23
16	WSU8	Grande R.	18,400	10.8	160	−14.8	−17.97
17	Glemwood ^a	Grande R.	15,500	15.3	120	−15.3	−17.29
18	Fairview ^a	Grande R.	15,100	16.0	130	−14.9	−17.27
19	Claystreet	Grande R.	14,000	18.4	120	−16	−17.65
20	COM6 ^a	Grande R.	23,700	5.7	310	−11	−17.34
21	COM6	Grande R.	22,600	6.5	220	−12.3	−18.41
	COM6 ^b		18,600				
	COM6 ^c		31,000				
22	COM8 ^a	Grande R.	21,100	7.8	290	−11.6	−17.25
	COM8 ^b		19,700				
23	COM9	Grande R.	19,100	9.9	180	−14.6	−18.45
24	UI4	Grande R.	19,700	9.2	160	−15.9	−18.49
25	UI3	Grande R.	20,500	8.4	300 ^d	−15.9	−18.66
	UI3 ^b		23,800				
26	Palouse1 ^a	Grande R.	21,900	7.1	120	−13.1	−17.04
27	Palouse2	Grande R.	26,400	4.1	350	−13.7	−18.37
28	Paulson	Grande R.	15,500	15.4	170 ^d	−14.9	−18.07
29	Brawdy	Grande R.	4400	58.6	70 ^d	−15.7	−16.75
30	McGreevy	Grande R.	6600	44.8	80 ^d	−16.1	−17.23
31	Ch. Electric	Grande R.	11,800	23.9	100 ^d	−14.8	−18.03

Unless indicated otherwise, samples were collected in 2003. Wells 17, 26, 27, 28, 29, 30 and 31 are shallow Grande Ronde wells (Douglas, 2004).

n/s, Not sampled.

^a Sample collected in 2001.

^b Sample collected in 1964 by Crosby and Chatters (1965a).

^c Sample collected in 1965 by Crosby and Chatters (1965a).

^d Samples analyzed through extended counting procedure.

aquifer, and from 4400 to 11,800 years (BP) for the upper portion of the Grande Ronde aquifer. Ages ranged from modern to 14,600 years (BP) for the Wanapum aquifer system and loess deposits. $\delta^{18}\text{O}$ results are consistent with results reported by Larson et al. (2000) for the Grande Ronde Formation, Wanapum Formation, and loess deposits.

Fig. 4 presents a kriged, shaded cell map of measured ^{14}C content for both the lower and upper parts of the Grande Ronde aquifer system. As noted, lower concentrations represent longer residence times and greater ages. The mapped distribution suggests that the oldest ground waters exist in the northeast and eastern portions of the basin. Significantly younger waters occur in a zone between Moscow and Pullman. This particular area has received considerable attention in previous studies. Foxworthy and Washburn (1963) suggested that a potential ground water barrier exists between the cities of Moscow and Pullman based on differences in water level fluctuations and ground water chemistry. Several, large scale aquifer tests conducted between Moscow, Pullman, and Palouse, and between Pullman, Moscow and Palouse, indicate the existence of a hydraulic boundary between Moscow and Pullman (Owsley, 2003). In addition, the crest of a subsurface anticlinal fold in the Grande Ronde basalts has been mapped in the same area (Bush, 2004). Newcomb (1969) suggested that faults associated with anticlinal folds commonly produce ground water barriers in basalts of the CRBG. Taken together, these findings suggest that the relatively recent ages observed may reflect the hydraulic effects of a subtle zone of geologic discontinuity which allows relatively rapid recharge flow into the Grande Ronde in this area.

It has been suggested previously that the spatial distribution of overburden thickness in the basin could influence vertical infiltration rates (Hopster, 2003; O'Geen et al., 2005). Fig. 5 shows overburden thickness relative to sampling locations for Fig. 4. This overburden consists primarily of low hydraulic conductivity loess, which forms irregular dune-like hills with relief up to 60 m (197 ft) (Busacca, 1989), and fluvial sediments of the Latah Formation.

Loess-derived soils contain fragipans and horizons with fragic character that restrict vertical percolation of water (McDaniel et al., 2001). Fragipans are brittle subsurface soil horizons that exhibit high bulk density, and restrict the movement of water and roots (Soil Survey Staff, 1993). O'Geen (2002) and O'Geen et al. (2002, 2005) identified buried paleofragipan horizons in the Palouse Basin through detection of abrupt changes in Cl^- concentrations. They found that areally distributed recharge in nonindurated overburden sediments is less in the eastern part of the basin than in the western part because the soils and deep regolith display a greater degree of associated fragipan development. Although a direct relationship between overburden thicknesses shown in Fig. 5 with the age dates shown in Fig. 4 does not exist for the entire basin, the oldest and youngest waters found to date exist where the overburden is thick and thin, respectively.

The mapped variability of Grande Ronde ages observed in Fig. 4 may also be partly due to the variable thicknesses of the overlying Wanapum Formation and interbeds of the Latah Formation (Fig. 2). Teasdale (2002) noted the Wanapum Formation thins in a westerly direction throughout the Palouse Basin. The Wanapum ranges in thickness from 43 to 61 m (140–200 ft) in the east compared to zero to 31 m (100 ft) in the west. The sedimentary Latah Formation sediments separating the Wanapum Formation from the Grande Ronde Formation also have a similar trend in thickness (Teasdale, 2002), ranging from 18 to 67 m (60–220 ft) in eastern areas of the Palouse Basin around the cities of Palouse and Moscow (Fig. 2). In comparison, thickness of the Latah Formation throughout the rest of the basin is relatively uniform, ranging from 6 to 12 m (20–40 ft).

The trends in thickness of the loess, Wanapum Formation, and Latah Formation are general and are not always consistent throughout the Basin. In addition, all units are heterogeneous. As a result, the ^{14}C concentrations and thus "ages" of the water do not decrease uniformly to the west or vertically with depth because of the potential variability in the trends, variations in soil development and variations

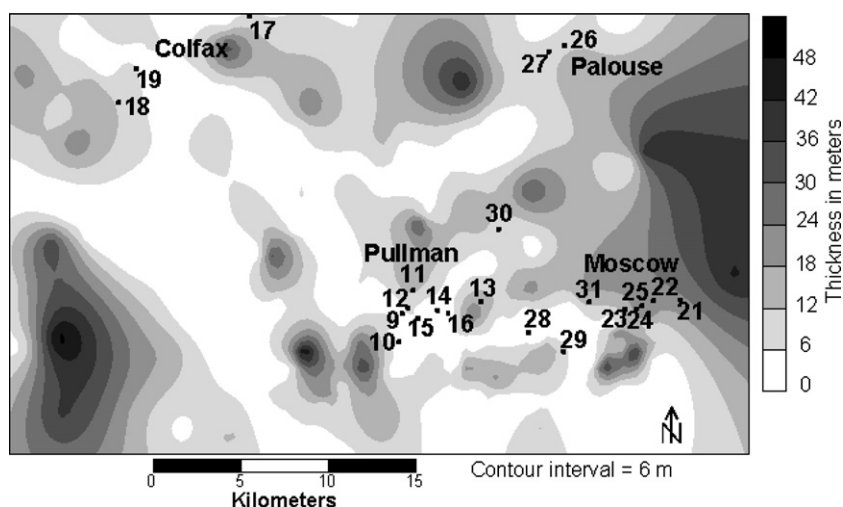


Figure 5 Isopach map of overburden thickness in the Palouse Basin (modified after Hopster, 2003). Darker areas represent greater overburden thicknesses while lighter areas have little to no overburden. Wells shown are Grande Ronde sampling points (Figs. 4 and 5, and Table 1).

in topography. However, the general depth/concentration relationship (or lack thereof) is believed to be closely related to the thickness and grain size distribution of the Latah Formation spatially. Youngest waters in the Grande Ronde basalts clearly exist where the Latah Formation is thin, and oldest waters exist where the Latah Formation is thickest and primarily fine grained.

Fig. 6 shows ^{14}C (pmc) concentrations for individual wells relative to the depth of the producing zones. In the Wanapum aquifer system, a very wide range of ^{14}C values exists (17.1–67 pmc), over a relatively narrow range of well depths. The variable age dates likely reflect the fact that the Wanapum aquifer system is known to receive recharge seasonally in response to high flows in local streams. In addition, water levels in the Wanapum aquifer system are in a state of quasi-equilibrium on an annual time frame as annual withdrawals are balanced by recharge. Therefore, mixing of young water with old water must occur locally within the Wanapum aquifer system. A relationship appears to exist between increasing depth of the producing zones and lower ^{14}C concentrations in the Grande Ronde aquifer system.

Several factors are believed to contribute to this trend in the Palouse Basin. Ground water flow in horizontally layered Columbia River basalts occurs primarily within interflow zones between individual basalt flows, and wells completed in these interflow zones draw water radially from poten-

tially large horizontal distances. Water within individual interflow zones is expected to be similar in age because recharge water must traverse similar vertical, travel distances. Large-scale aquifer tests in the Grande Ronde aquifer system (Owsley, 2003) consistently yielded high horizontal hydraulic conductivity values and low storativity values for the relatively thin (e.g., 1–3 m), interflow producing zones. Vaccaro (1999) also reported large lateral hydraulic conductivity values, up to 1.9 cm/s (6.1×10^{-2} ft/s) and, by contrast, small vertical hydraulic conductivity values only up to 3.0×10^{-4} cm/s (1.0×10^{-5} ft/s) for basalts of the CRBG. This is consistent with the morphologies of the basalt flows (Fig. 3) and, on the other hand, with control of the observed age distribution by low vertical flow rates. Thus we suggest that generally slow vertical flow rates give rise to the general "aging" of waters with depth observed in Fig. 6, while pedological and thickness variability of shallow units causes the mapped variation in ages across the Basin which appears as the scatter in Fig. 4.

A similar isotopic age dating study was conducted on municipal water wells in the Lewiston Basin, Idaho, 19 km (30 mi) south of the Palouse Basin (Douglas et al., 2005). Ground water samples were collected in this basin from ten existing municipal wells completed in the Grande Ronde basalt aquifer system. Samples were analyzed for isotopes of carbon (^{14}C and ^{13}C), oxygen (^{18}O), deuterium (^2H), and tritium

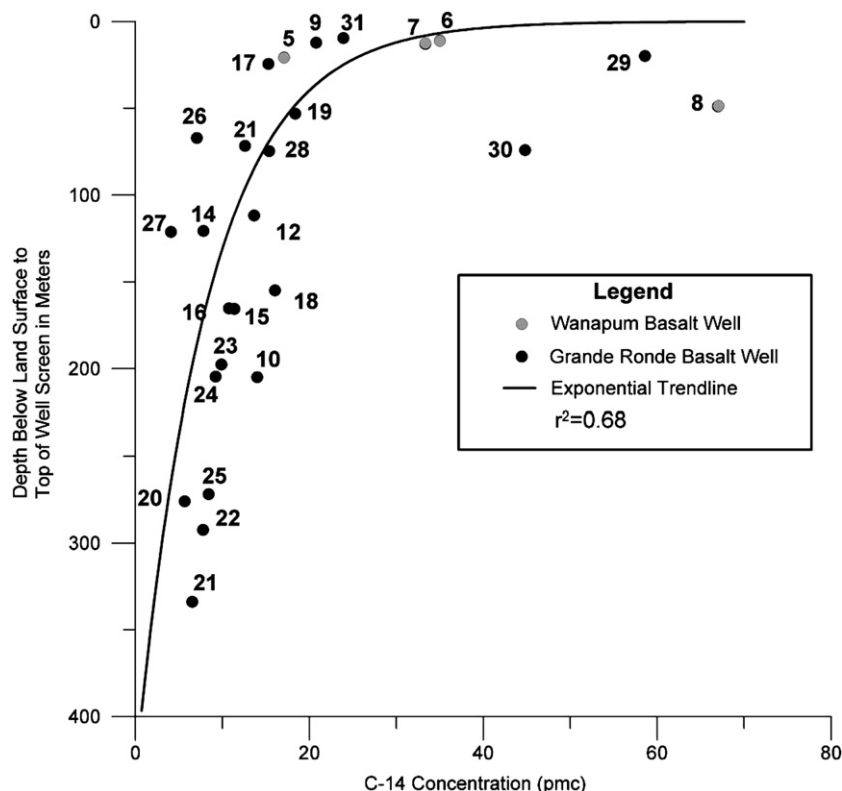


Figure 6 Arithmetic plot of ^{14}C concentration versus depth to the top of the well screen in each well for ground water samples collected from the Grande Ronde and Wanapum aquifer systems. Wanapum ^{14}C concentrations are highly variable at relatively similar well depths. Grande Ronde ^{14}C concentrations exhibit a general relationship of increasing age (lower ^{14}C pmc) with depth (deeper producing zones). Ages for the two Grande Ronde wells (30 and 29) that fall outside of the general trend potentially represent mixing with younger recharge water. Wanapum wells are 5, 6, 7 and 8. Note: data for wells 30, 29 and 8 were not used to generate the curve fit.

(^3H) with the ^{14}C ages ranging from 2830 to 34,670 years. As observed in the Palouse Basin, a similar relationship was identified between increasing ^{14}C age and increasing depth of the well production zones. Tritium was found above the detection limit in five out of the ten wells; however, these five wells are located directly adjacent to the two local rivers, the Clearwater River and Snake River. The relative water levels in the wells, and of the rivers indicated that the five wells likely were drawing modern water from the rivers. Absence of tritium in the remaining five wells coincided with the oldest ^{14}C ages in that basin.

Three wells in this study (20, 22 and 25; Table 1) were also sampled and dated by Crosby and Chatters (1965a). They found similar ages. This consistency over a period of 40 years suggests that the well capture zones are negligibly affected by vertical leakage (and mixing) of younger water, even under prolonged pumping-induced gradients. This is perhaps not surprising in light of a very rough comparison of Grande Ronde pumping withdrawals to aquifer-system storage. Present pumping rates correspond to a vertical flux, averaged over the estimated basin area (Fig. 1), of approximately 2 cm per year. Extrapolation of this figure over the past 40-plus years gives a conservatively large estimate of cumulative Grande Ronde pumpage of 80 cm. If the basin-scale average effective porosity of the aquifer system is 10% (Larson et al., 2000), then 80 cm of water corresponds to 8 m (26 ft) of aquifer thickness. In other words, in a simple basinwide model of complete plug-flow vertical displacement of water in response to pumping, waters from a given depth today are only about 8 m (26 ft) deeper than they were more than 40 years ago. This result depends on a highly approximate porosity parameter, and pumping-induced drawdowns indicate that full displacement has not occurred. Also the calculation neglects spatial variability in general, and hydrodynamic dispersion in particular. For these reasons, the results must be regarded with caution. The results do, however, offer insight into the apparent persistence of Grande Ronde age distributions over nearly half a century of ground water exploitation.

Summary and conclusions

Uncorrected ^{14}C ages can be treated as actual ages based on evidence that biochemical and hydrochemical reactions exert only small effects on $^{14}\text{CO}_2$ in Palouse Basin ground waters. Ground water in the lower Grande Ronde system is the oldest water in the basin, and is of Pleistocene Age based on measured ^{14}C (pmc) concentrations. Based on this reasoning, it is concluded that ground water derived by deep Grande Ronde wells in the basin was recharged during the Pleistocene. A possible zone of Holocene recharge in the upper part of the Grande Ronde may exist in a zone between the cities of Pullman and Moscow. Overall, a general trend of decreasing ^{14}C (pmc) concentrations with depth of well penetration exists throughout the basin. This pattern suggests that ground water ages reflect primarily vertical travel times from the land surface to the sampled locations. This shift in ground water ages with depth is consistent with ^{14}C ages reported by Crosby and Chatters (1965a). $\delta^{18}\text{O}$ samples are consistent with results presented by Larson et al. (2000), which identify deep Grande Ronde samples as the

most depleted in $\delta^{18}\text{O}$, and statistically different from Holocene recharge. Several factors, such as overburden thickness, fragipan development, thickness of the Wanapum Formation, and thickness of the Latah Formation, may collectively contribute to the restriction of vertical migration of infiltrating recharge water. These restricting factors are more prevalent in the eastern section of the Palouse Basin compared to the western section.

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