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Columbia Basin Ground Water Management Area

Subsurface mapping and aquifer assessment project--final project

08001605

GWMA Columbia Basin Ground Water Management Area

OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES
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December 29, 2009

Sean Mellon
Water Quality Grants and Loans Manager
Department of Ecology, Water Quality Program
P.O. Box 47600
Olympia, WA 98504-7600

RE: GWMA Subsurface Mapping and Aquifer Assessment Project
WSDOE Agreement No. G0800145
Final Project Performance Report as of October 31, 2009

Dear Sean:

In accordance with the Washington State Legislative Proviso of the 2007-2009 Biennial Capital Budget, Section 3036, and the WSDOE Agreement No. G0800145, all tasks for the GWMA Subsurface Mapping and Aquifer Assessment Project are now considered complete. We ask that you accept the enclosed Final Project Performance Report along with its attachments as documentation of the accomplishments of this two-year project.

We also would like to thank each of the members of the Ecology staff who worked with us on this project. Their assistance and support is appreciated.

If you have any questions regarding the report, please feel free to contact me at 509-488-3409.

Sincerely,

Carol Miller

Carol Miller
GWMA Project Coordinator

cc: Wayne Peterson - Washington State Department of Ecology
Jeff Nejedly – Washington State Department of Ecology
Mark Nielson – Franklin Conservation District

"Citizens and local government working together for safe drinking water."

GWMA Columbia Basin Ground Water Management Area

OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES

CITIZENS AND LOCAL GOVERNMENT WORKING TOGETHER FOR SAFE DRINKING WATER

Subsurface Mapping and Aquifer Assessment Project

Final Project Performance Report

A Summary of Work Performed
During the Period of
July 1, 2007 through October 31, 2009

Washington State Legislature Appropriation
Centennial Clean Water Fund Special Proviso 2007 - 2009
Biennial Capital Budget, Section 3036

Washington State Department of Ecology
Agreement No. G0800145

October 31, 2009

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COLUMBIA BASIN GROUND WATER MANAGEMENT AREA OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES

INTRODUCTION AND OVERVIEW:

The Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties within Washington State is a multi-partner effort to protect and improve ground water resources. The four counties share equally as the Lead Agency for the GWMA.

In February 1998, the Washington State Department of Ecology issued Designation Order Number 16 signed by Ecology Director, Tom Fitzsimmons, establishing Adams, Franklin and Grant Counties as the Columbia Basin Ground Water Management Area (GWMA) in accordance with Chapter 90.44 of the Revised Code of Washington (RCW) and Chapter 173-100 of the Washington Administrative Code (WAC). The order designated the Boards of County Commissioners of Adams, Franklin and Grant Counties as the GWMA Lead Agency.

In mid-2005, the GWMA Lead Agency and the Board of County Commissioners of Lincoln County petitioned Ecology to include Lincoln County into the GWMA. Ecology issued an amended Designation Order signed by Ecology Director Jay Manning in September 2005 to include Lincoln County within the boundary area of the GWMA and thereby designated the Board of Commissioners of Lincoln County as a member of the GWMA Lead Agency.

The Adams-Franklin-Grant-Lincoln County area represents approximately 8,159 square miles of the Columbia Plateau Aquifer System and share 95% of the Columbia Basin Irrigation Project. This arid region of Washington State receives on average less than 8" of rainfall annually. With a population of just under 180,000 people, nearly 100% obtain their potable water from groundwater drawing from both shallow and deep aquifers.

PLANNING AND IMPLEMENTATION OF THE GWMA PLAN:

The Columbia Basin Groundwater Management Area (GWMA) has two distinct phases. The first phase of the GWMA (1998-2001) was research and development of a Ground Water Management Area Plan. Local community leaders and stakeholders, conservation districts, area planning departments and health agencies, and agricultural producers led the effort to create the GWMA Plan through a community-based grassroots process involving all concerned groups and stakeholders. At the head of this effort was a coalition of the Boards of County Commissioners serving as the GWMA Lead Agency. The GWMA Plan was completed, approved and certified by the Washington Department of Ecology in December 2001 by Ecology Director Tom Fitzsimmons. A copy of the GWMA Plan is on file with the Washington State Department of Ecology.

Following final approval and certification of the GWMA Plan, the GWMA moved toward its second phase, implementation of the recommendations and projects outlined in the GWMA Plan. The GWMA Plan recognized the need to inform and guide the public toward groundwater protection and to develop a better understanding of the aquifer system within the Columbia Plateau Aquifer System.

Since 2001, GWMA has been actively mapping the basalt and sediment layers of the Columbia Plateau Aquifer System underlying Adams, Franklin, Grant and Lincoln Counties. The GWMA's *Subsurface Mapping and Aquifer Assessment Project* is part of the continuing activities to study and develop a better understand of groundwater flow and recharge within the complex basalt and sedimentary layers lying beneath the Columbia Basin.

The Washington State Legislature has appropriated $2.0 million in the 2007-2009 Biennial Capital Budget for the purpose of the Columbia Basin Groundwater Management Area's Subsurface Mapping and Aquifer Assessment Project in Adams and Lincoln Counties. This legislative appropriation appears within the budget of the Washington State Department of Ecology.

FINAL PERFORMANCE REPORT
OF THE
COLUMBIA BASIN GROUND WATER MANAGEMENT AREA
SUBSURFACE MAPPING AND AQUIFER ASSESSMENT PROJECT

Washington State Department of Ecology - Agreement No. G0800145
Summary of Work Performed: July 1, 2007 – October 31, 2009

DESCRIPTION OF ACTIVITIES ACCOMPLISHED DURING REPORTING PERIOD:

This is the final report of activities and accomplishments occurring by each of the tasks outlined in Ecology Agreement No. G0800145. The following is a summary of work performed by task for the full period of the agreement July 1, 2007 through October 31, 2009:

TASK #1 – PROJECT ADMINISTRATION/MANAGEMENT

TASK ELEMENT DESCRIPTION: Administrative and management activities are an important function and serve to implement directives of the GWMA Lead Agency (Boards of County Commissioners of Adams, Franklin, Grant and Lincoln Counties) and the GWMA Administrative Board, manage activities and projects, maintain direction and oversight, manage funding resources for GWMA projects, and provide an avenue for other water resource groups, entities and agencies to work together. Administrative activities include: project administration; records and fiscal management activities; performance and requirements; project management and coordination; conduct/coordinate/schedule project activities and assure quality control to meet task and project completion dates.

ACCOMPLISHMENTS: Throughout the life of the project agreement, GWMA administration consisting of the GWMA Lead Agency (the Boards of County Commissioners of Adams, Franklin, Grant, and Lincoln Counties), the GWMA Administrative Board and the GWMA staff and consultants worked together on a weekly and monthly basis to accomplish the following administrative/management activities as outlined in the agreement:

- Project Management and Oversight:
  - Regular monthly meetings were held with the GWMA Administrative Board to keep them updated and information on the progress of the project
  - Regular weekly staff meetings were held with key members of the project team which include GWMA staff, GSI Water Solutions and sub-contractors, S. S. Papadopulos & Associates and Franklin Conservation District staff to coordinate and monitor progress on project related tasks and activities.
  - Agency Partnerships: As project data became available through the digitizing of data collected for the project, staff responded to requests and shared information whenever possible among various agencies such as USGS, BOR and Ecology, and other area water resource groups.
  - Columbia River Management Plan: Staff participated in meetings of the CRMP Policy Advisory Group, the Technical Advisory Group and the Columbia River Commissioner's Forums held during this quarter.
  - Ecology Project Management Coordination: GWMA staff maintained regular contact with the Ecology project coordinator, Wayne Peterson, and other staff to provide regular updates and information relating to the project's progress.

- Records and Fiscal Management: Staff held regular budgetary oversight and coordination meetings relating to budgetary, records and fiscal management and reporting requirements. Fiscal records were audited regularly to maintain accuracy in budgetary reporting in accordance with the agreement.
- Report to the State Legislature: In April, staff organized and provided oversight and direction of efforts to distribute copies the legislative summary report titled *"Basalt Aquifer Recharge, Age, and Water Level in the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties, Washington Progress - Report of the Subsurface Geologic Mapping and Hydrogeologic Assessment Project*" to legislators and appropriate legislative committees as required by the grant.
- Final Project Technical Reports: Administrative staff worked with the project's consultants to oversee development and completion of technical reports on the project, along with the production and distribution of the final reports to Ecology, other state and federal agencies, local city and county planning agencies, and local and state elected officials.

TASK #2 – ASSESSMENT OF EXISTING DATA AND DEVELOPMENT OF A WORK PLAN

TASK ELEMENT DESCRIPTION: This task is phase one of the two-phases of the Subsurface Mapping and Aquifer Assessment Project. Phase one activities include an assessment of existing well-log data and geophysical data, and the creation of a work plan and associated scope of work to support the mapping and conceptual modeling elements of the second phase of the project.

ACCOMPLISHMENTS: In the early fall of 2007, GWMA consultants began assessing and analyzing existing well-log data and geophysical data collected during earlier phases of GWMA stratigraphic mapping work and created a work plan for the GWMA Subsurface Mapping and Aquifer Assessment Project. The work plan titled: *"Preliminary Data Collection, Data Interpretation, and Planning for the Subsurface Geologic Mapping and Aquifer Assessment Project"* was submitted to Ecology project management team and was approved in February 2008. The work plan prepared the basis and the scope of work for the mapping and conceptual modeling elements of this project.

TASK #3 – INFORMATION MANAGEMENT

TASK ELEMENT DESCRIPTION: Tasks include the development of fact sheets and educational materials to make informational available to stakeholders and the general public; development of a website for making data and information available to stakeholders and the general public; creation of a QAPP for water quality monitoring activities; development of subsurface mapping sets, control points, water quality and water level data; stakeholder projects; and presentations

ACCOMPLISHMENTS: During the agreement period, the following activities were accomplished:

- In October 2007, GWMA held a series of educational and informational field tours within the Lincoln County area for the purpose of demonstrating visible basalt and sediment layers at the surface for the purpose of developing an understanding among stakeholders, water resource groups, elected officials and community leaders about the goals and activities of the Subsurface Mapping and Aquifer Assessment Project.

- In January, 2009, as stipulated by the Washington State Legislature in the funding proviso, Staff prepared and presented a summary report of the early findings of the project and distributed copies the legislative summary report titled *"Basalt Aquifer Recharge, Age, and Water Level in the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties, Washington Progress - Report of the Subsurface Geologic Mapping and Hydrogeologic Assessment Project"* to legislators and appropriate legislative committees.
- In January through March 2009, GWMA staff held a series of public meetings to educate stakeholders on the initial findings of the technical activities relating to subsurface sediment and basalt mapping, groundwater age dating, groundwater geochemistry, and static water levels.
- In September 2009, GWMA staff and consultants presented findings to the Geological Society of America during their annual conference in Portland, Oregon.
- In October 2009, staff distributed copies of the five final technical project reports to state and federal agencies, local city and county planning agencies, and local and state elected officials.
- Staff and consultants prepared six large subsurface basalt and sediments cross-section posters in a "user friendly" format to make the technical elements and terminology of the project understandable to the general public.
- Staff developed, refined and maintained the GWMA website with the latest subsurface mapping and aquifer assessment technical documents, project information, and reports available to the general public.
- GWMA responded to requests from area residents, water resource groups, elected officials, and municipal and governmental agencies for information about the project and shared data with other agencies as requested.
- Staff attended and participated in area water resource group and agency meetings such as area watershed planning groups, the Columbia River Management Plan (CRMP) Policy Advisory Group, the Technical Advisory Group, and the County Commissioners Forum of the CRMP.
- Staff made presentations of the final technical reports to elected officials, county commissioners, city councils and other public forums in the four-county area.
- Staff created an educational video titled, "Flying the Lake Creek System" as an educational tool demonstrating decreased water availability in Lincoln County.

TASK #4– SUB-SURFACE MAPPING

TASK ELEMENT DESCRIPTION: This task contains two elements. The following is a summary of each of the elements under this task:

- Well Database Compilation: Use of existing data to guide extension of current geologic maps; map upper part of the Grande Ronde Basalt; subdivide Frenchman Springs Member of the Wanapum Basalt; edit/upgrade existing subsurface map sets with new well log data; resolve anomalies in earlier editions of geologic map sets.
- Sub-Surface Mapping: Update and maintain existing subsurface well interpretation spreadsheet database; construct digital interpreted well file database; make available on-line and via CD.

ACCOMPLISHMENTS: During the agreement period, the following activities were accomplished:

- Activities focused on gathering new well-log data, performing data analysis, preparing evaluations and conclusions of water level data, well construction information, digitizing subsurface geologic maps, interpreting basic physical framework for water level data, and report development for inclusion into final project technical reports.
- Updated and maintained subsurface well interpretation spreadsheet database; construct digitally interpreted well database file; made the information available to agencies and water resource groups on the GWMA website and via CD.
- Developed final project technical reports extending the GWMA's knowledge of the geologic framework of the upper part of the Grande Ronde Basalt layer; subdivisions of the Frenchman Springs Member of the Wanapum Basalt; and edited and upgraded existing subsurface mapping sets with new well log data; and, resolved anomalies in earlier editions of GWMA geologic map sets.

TASK #5 – AQUIFER ASSESSMENT AND EVALUATION

PROJECT DESCRIPTION: The Aquifer Assessment and Evaluation task contains three elements. The following is a summary of the full task descriptions (for a full description of the task, see the GWMA Scope of Work or Ecology's Agreement G0800145):

- *Groundwater Sub-Basin Delineation:* Identify and delineate possible aquifer subdivisions and sub-basins (potential recharge sources: geologic-hydrogeologic controls influencing groundwater occurrence and movement). Work focuses on evaluating existing and new water level and water quality data, assessment of controls and characteristics of groundwater movement and recharge through these sub-basins. Identify and map probable recharge source area geospatially located and potential groundwater flow paths away from these recharge areas through stratiform aquifer system. Locate boundaries and barriers (vertical and stratiform) within geospatial framework for possible influences on groundwater movement within sub-basins.
- *Groundwater Flow Conditions within Sub-Basins*: Compile, collect and interpret existing well construction, well video, borehole geophysics, well pumping, water level and hydrochemistry information in sub-basins to interpret potential recharge water sources, groundwater age, barriers/impediments to groundwater flow, pathways and timescales, and interconnections between aquifer systems.
- *Detailed Studies, Data Collection and Hypothesis Testing*: Assess, evaluate and validate basic assumptions and interpretations with respect to GWMA's conceptual model of basalt groundwater flow system. Data may include surface/subsurface geologic data; hydrogeologic data; and hydro-chemical data.

ACCOMPLISHMENTS: During agreement period, the following activities were accomplished:

- Work focused on Groundwater Sub-Basin Delineation consisting of evaluation and analysis of existing and new water level and water quality data, assessment of controls and characteristics of groundwater movement and sub-basin recharge. Identify and mapped probable recharge source areas geospatially located and potential groundwater flow paths away from these recharge areas through the stratiform aquifer system. Located boundaries and barriers (vertical and stratiform) within geospatial framework for possible influences on groundwater movement within sub-basins. Identified and delineated aquifer subdivisions and sub-basins for potential geologic-hydrogeologic controls influencing groundwater occurrence and movement.

- *Groundwater Flow Conditions within Sub-Basins*: Compiled, collected and interpreted existing well construction data, well videos, borehole geophysics, well pumping, water level data and hydrochemistry information in sub-basins interpreting recharge water sources, identification of groundwater age, location of barriers/impediments to groundwater flow, pathways and timescales, and interconnections between aquifer systems.
- *Detailed Studies, Data Collection and Hypothesis Testing*: Assessed, evaluated and validated data relative to surface/subsurface geologic data; hydrogeologic data; and hydrochemical data and applied interpretations with respect to the development of a conceptual model of the basalt groundwater flow system lying beneath the four-county area of the GWMA.
- Developed final report centered on interpretation of analytical data and results from the June-July 2008 well sampling, water level data, interpretation of geologic and well construction data relative to water quality and water level data analysis, and conceptual model development.

TASK #6– CONCEPTUAL MODEL DEVELOPMENTS

PROJECT DESCRIPTION: The Conceptual Model Development task contains three elements.

- Basalt Groundwater Model: Facilitate communication between project teams, trace project and task progress; schedule work and refine working hydrogeologic hypotheses and conceptual models on regional and sub-basin level as data and information are developed. Prepare monthly progress reports and communicate new information to project team, GWMA leadership and stakeholders, and to Ecology.
- Model Project Technical Report: Prepare a conceptual basalt hydrogeologic model to address both water quantity and water quality. Model to consist of existing and new information and data developed during course of project: Potential sources of groundwater recharge and fate of water moving through basalt aquifer system; probable sources of ancient groundwater recharge; boundaries and barriers within groundwater flow; primary groundwater flow paths through basalt aquifer system.
- Basalt Model Synopsis Report: Develop summary report describing results of the project.

ACCOMPLISHMENTS: During agreement period, the following activities were accomplished:

- Work focused on facilitation of communication between project teams, GWMA leadership and stakeholders and Ecology project management; moved project forward and monitored task progress throughout the life of the project; scheduled work and refined testing of hydrogeologic hypotheses and conceptual models on regional and sub-basin level as data and information were developed; assessed and evaluated water level, water quality and geologic data collected for the project.
- Developed and executed draft technical reports on geologic mapping, geologic framework, conceptual model, water level data, and water age dating and water geochemical content in June 2009.
- A peer review process was conducted during the period of June-August 2009 to seek comment on the draft technical documents. Copies of these reports were distributed for peer review to geological and hydrogeological management and staff of DOE, USGS, DNR, EPA-Region 10, BOR, WSU, EWU, private sector geological and hydrogeological

consultants, local governments and elected officials. Comments were received and considered for edits in the final editions of the project's technical documentation.

- The GWMA Administrative Board accepted five final technical report documents in September, 2009 as follows:
  - "A Summary of Columbia River Basalt Group Physical Geology and its Influence on the Hydrogeology of the Columbia River Basalt Aquifer System: Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, June, 2009"
  - "Geologic Framework of Selected Sedimentary and Columbia River Basalt Group Units in the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties, Edition 3, June 2009"
  - "Groundwater Geochemistry of the Columbia River Basalt Group Aquifer System: Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties, June, 2009"
  - "Groundwater Level Declines in the Columbia River Basalt Group and their Relationship to Mechanisms for Groundwater Recharge: A Conceptual Groundwater System Model, Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties, June, 2009"
  - "Multiple Tracer Study of Recharge Mechanisms and the Age of Groundwater in the Columbia River Basalt Group Aquifer System: Columbia Basin Ground Water Management Area of Adams, Franklin, Grant and Lincoln Counties – July, 2009"

BUDGETARY SUMMARY OF EXPENDITURES:

Budget Expenditure Summary - Agreement No. G0800145: The following is a summary of total expenditures during the period of July 1, 2007 through October 31, 2009 broken down by each of the six tasks related to activities of the GWMA Subsurface Mapping and Aquifer Assessment Project and the remaining balance within each of the tasks:

Columbia Basin Ground Water Management Area
ECOLOGY AGREEMENT #G0800145
BUDGETARY SUMMARY FOR THE PERIOD OF:
July 1, 2007 – October 31, 2009

CODE	Project Description	Budget	Total Expenditures	Remaining Balance
TASK 1	Project Management	$ 191,125.00	$ 195,029.48	$ (3,904.48)*
TASK 2	Data Assmt/Work Plan	$ 75,000.00	$ 74,951.43	$ 48.57
TASK 3	Info Management	$ 129,235.00	$ 101,260.00	$ 27,975.00
TASK 4	Subsurface Mapping	$ 448,100.00	$ 378,038.05	$ 70,061.95
TASK 5	Studies/Data Coll/Test	$ 776,835.00	$ 748,675.90	$ 28,159.10
TASK 6	Concept Model Dev	$ 379,705.00	$ 374,637.42	$ 5,067.58
TOTAL		$ 2,000,000.00	$ 1,872,592.28	$ 127,407.72

Note: The period of Agreement No. G0800145 was originally established for July 1, 2007 through June 30, 2009. Due to the fact that the project had not reached completion for technical report writing and peer review process during the period of the grant an extension was granted to October 31, 2009 to allow for completion of the project.

*Task 1- Project Management: Expenditures for administration and grant/fiscal management relating to project's oversight and fiscal reporting activities were more than originally allocated in the agreement due to extension of the agreement period from June 30, 2009 to October 31, 2009 to allow time for project completion.

GWMA has accomplished all fiscal and grant management requirements in accordance with this agreement. Regular quarterly reports were prepared and submitted to Wayne Peterson, the Ecology Project Manager; Brian Brada, grant officer; Jeff Nejedly, fiscal management; and, Guy Gregory, Spokane Office. As the various activities, materials and documents, reports and information relating to the project were completed or became available during each quarter; these documents were noted in the quarterly reports and were presented as attachments to the appropriate quarterly report. A copy of these documents have been filed with the grants officer and placed in the appropriate file.

CONCLUSIONS AND SUMMARY OF THE GWMA SUBSURFACE MAPPING & AQUIFER ASSESSMENT PROJECT:

Findings of the GWMA's Subsurface Mapping & Aquifer Assessment Project have been fully defined in each of the five technical documents noted above in this report. Per the directive of the Washington State Legislature and the full summary report delivered in February, 2009 to the appropriate Legislative Committees, the following is a brief summary of the findings presented:

1. **NO GROUND WATER CONNECTION TO LAKE ROOSEVELT:** Geologic mapping and geochemistry demonstrate there is no surface or ground water connection between Lake Roosevelt and the regional basalt aquifer system. Consequently, the lake is not providing any natural recharge to Columbia Basin ground water.

2. **MOST DEEP WELLS ARE PUMPING WATER OLDER THAN 10,000 YEARS OLD AND RECEIVE ONLY MINIMAL RECHARGE:** The geochemistry data taken from the deep wells sampled in the four-county area of the GWMA indicate that most of the natural ground water being pumped from the basalt aquifer system is over 10,000 years old and receives limited recharge. Evidence suggests recharge occurs along layers, and not vertically through the basalt layers. Recharge of shallower and deeper portions of the basalt aquifer system occurs in some areas.

3. **AQUIFER LEVELS ARE DECLINING, AND THE DEEPER AQUIFER IS DECLINING THE FASTEST:** Water level records show groundwater mining is occurring with many wells within the GWMA and is declining faster than they can naturally be recharged. Deeper within the aquifer system many areas show long-term water level declines with little evidence of natural recharge. While there is evidence of natural recharge on the edge of the GMWA, the effects are limited.

In accordance with the Washington State Legislature Proviso directive and the Washington State Department of Ecology Agreement G0800145, GWMA has successfully completed each of the tasks as they were defined in the agreement.

We wish to thank all members of the Ecology staff who have participated with us throughout the period of this project and for their assistance in helping us to move the project through its various phases to its completion.

ATTACHMENTS:

Included with this final performance report is the following final documentation of the project which was produced in the final quarter of the project agreement period:

- Project Report to the Washington State Legislature in February, 2009, titled, "Basalt Aquifer Recharge, Age, and Water Level in the Columbia Basin Ground Water Management Area,", February 2009.

- Electronic Copy of all Five of the Final Technical Reports as previously noted by title in this report.

- Copies of various hydrogeologic cross-sections and educational materials produced and distributed at the Geologic Society of America Conference and to water resource groups and stakeholders describing the GWMA Subsurface Mapping and Aquifer Assessment Project.

- Video titled, "Flying the Lake Creek System" which was produced for educational purposes and utilized during presentations to county and city officials, community leadership, and water resource groups meetings.

A hard copy of each of these reports is available upon request. Due to the large size of these documents we have made the report available electronically. If you would like a fully printed version of these reports, please contact:

Carol Miller
GWMA Project Coordinator
170 W. Broadway
Othello, Washington 99344
Phone: 509-488-3409
Email: cmiller@cbgwma.org

Basalt Aquifer Recharge, Age, and Water Level in the Columbia Basin Ground Water Management Area

A Subsurface Geologic Mapping and Hydrogeologic Assessment Project Progress Report
February 2009

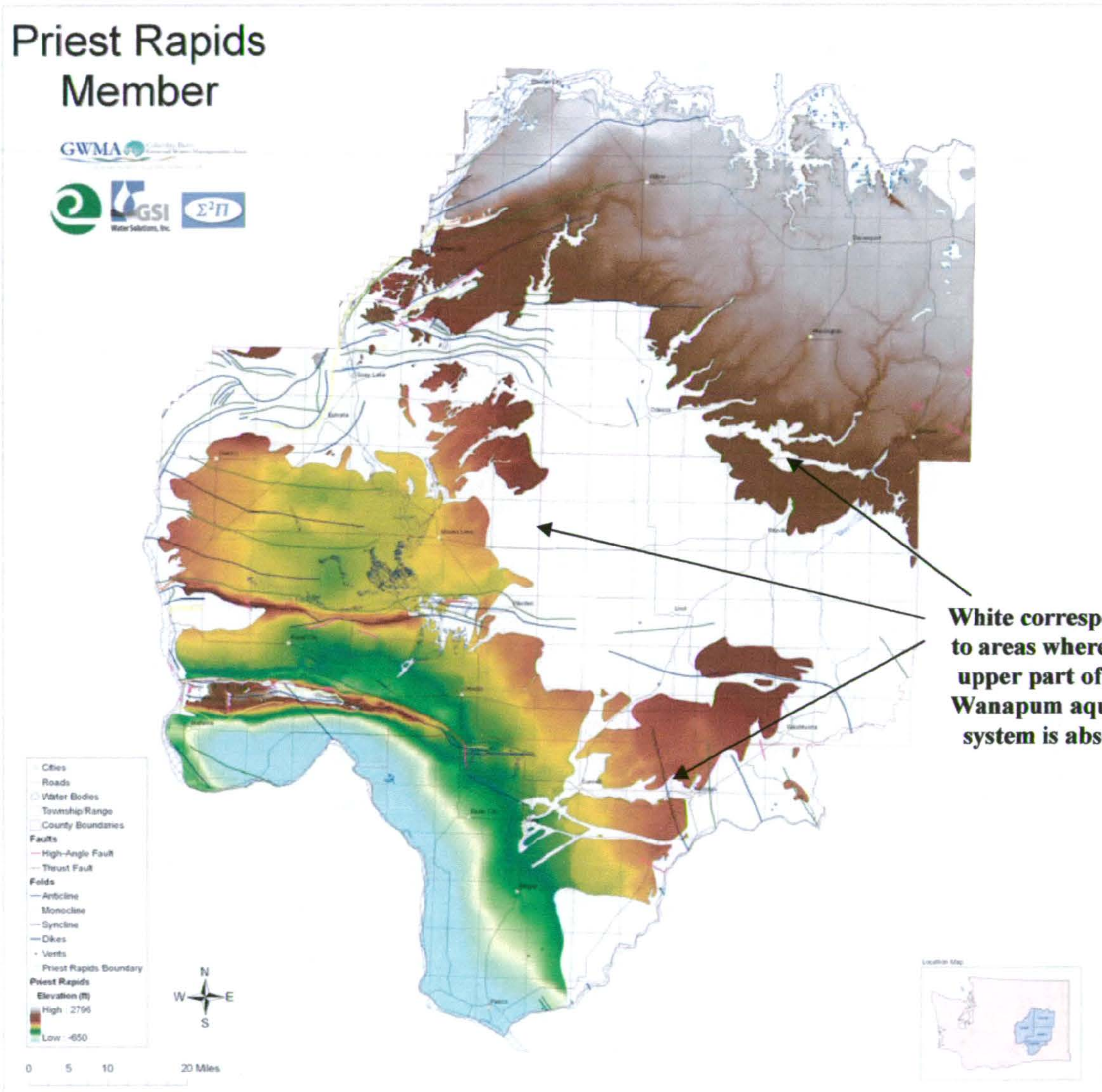
GWMA Columbia Basin Ground Water Management Area

OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES

INTRODUCTION

The Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties (the GWMA) currently encompasses approximately 8,300 square miles in south-central Washington **(Figure 1)**. When first designated in February 1998, in response to concerns about elevated nitrate-N concentrations in groundwater, the GWMA included all of Franklin, Grant, and Adams Counties. In 2005 Lincoln County was added to the GWMA, and the GWMA charter was expanded to include all groundwater quality issues in the four counties.

Figure 1. Map showing the extent of the GWMA and the elevation of the top of the Priest Rapids basalt. This map generally shows the extent of the upper part of the Wanapum aquifer system, and illustrates its' fragmented nature.



Scientific, mitigation, planning, and outreach activities dealing with groundwater quality within the GWMA largely are guided by the GWMA Plan. Based on conclusions presented in the GWMA plan and Ecology review comments on the GWMA plan, GWMA stakeholders decided that there was a need to identify the aquifers contributing groundwater to GWMA sampling wells, the extent of those aquifers, and the recharge sources (if any) for these aquifers. To support this, the GWMA Subsurface Geologic (or Hydrostratigraphic) Mapping Project was started in 2000. At this time, the subsurface geologic mapping effort has mapped the distribution of the major geologic features and units that influence ground water occurrence and movement beneath the GWMA.

GWMA's subsurface geologic mapping efforts have been done in phases tied to changing GWMA priorities and funding availability. These phases were as follws:

1. During 2000, 2001, and 2002 the mapping project focused on the shallower parts of the basalt aquifer system in Adams, Franklin, and Grant Counties. ***This work was done to better understand the occurrence of nitrate in the shallower portions of the basalt aquifer system.***
2. Between 2002 and 2004 the sediments overlying the basalt aquifer system in the 3 original GWMA counties were mapped. ***The sediments were mapped to better assess the impacts of nitrate bearing shallow ground water on private, single family domestic exempt wells.***
3. Beginning in 2006 and continuing through the current effort which began earnest late in 2007, the mapping efforts have extended into Lincoln County (flowing the addition of Lincoln County to the GWMA) and downwards into deeper parts of the basalt aquifer system. ***This emphasis on the deeper basalt aquifer system, especially within the Grande Ronde Basalt, has been driven by the growing concern for sustaining deep aquifer production wells for both agriculture and municipalities.***

As a part of the recent subsurface mapping work, GWMA's efforts have begun to evolve, focusing more and more on understanding ground water sources. This change in emphasis is a direct consequence of the legislative mandate which funded the GWMA mapping efforts in 2007, 2008, and 2009. Specifically, this work was funded by a direct appropriation from the Washington State Legislature, which was directed to the GWMA via the Washington Department of Ecology (Ecology). A key objective of this work, as mandated by the Washington State Legislature, was to:

"...submit a report to the appropriate committees of the legislature describing the dynamic relationship between groundwater and surface water in the region."

To that end, GWMA hydrogeologists currently are working on a report that refines and upgrades the GWMA geologic database and geographic information coverage (GIS) by essentially completing the subsurface geologic mapping portions of GWMA's subsurface mapping project and using this information in conjunction with water quality, water level, and well testing data (both existing and new) to test and refine the conceptual model describing ground water flow in the aquifers underlying the GWMA and the relationships of this groundwater to surface waters, including recharge. The basic project approach used to accomplish this goal is described in a work plan produced in mid 2007. The remainder of this progress report focuses on key aspects of this larger effort, especially as it relates to the legislative request that accompanied the funding authorization.

This progress report is subdivided into several sections which address the basic legislative request, including:

1. A discussion of the potential recharge, or lack of recharge, of the Columbia River basalt aquifer system beneath the GWMA that comes from the Lake Roosevelt pool. ***Our work***

suggests there is little or no recharge of the basalt aquifer system underlying GWMA from Lake Roosevelt.

2. The potential for recharge of this aquifer system from areas lying east of the GWMA boundary. ***This may be occurring, but the impact of this recharge on the regional aquifer system appears to be minimal.***
3. A review of groundwater geochemistry data collected by GWMA scientists to investigate the age and potential for modern recharge of the aquifer system. ***The deep ground water system is dominated by waters 10,000 or more years old.***
4. An evaluation of water level data in wells within the GWMA. This data was examined to assess the degree of connection between the different parts of the CRB aquifer system. ***Ground water in the GWMA appears to occur in sub-basins displaying limited connections.***
5. A review of GWMA's conceptual model of how ground water recharges CRBG aquifers, moves through those aquifers and potential discharges from those aquifer systems.

It is not the intent of this report to describe all of the work and results of the current GWMA subsurface mapping and aquifer assessment effort. That will be done later in the spring of 2009 in one or more technical reports currently being prepared by GWMA hydrogeologists.

CRBG AQUIFER SYSTEM AND LAKE ROOSEVELT

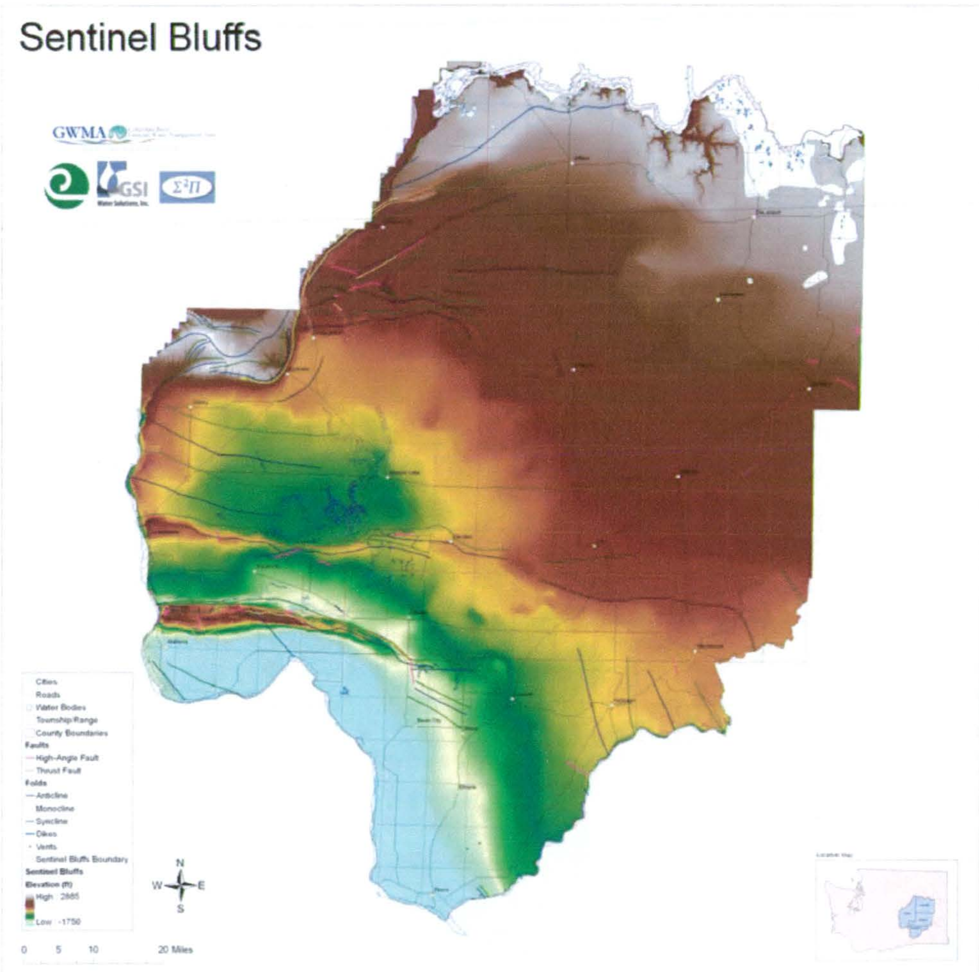
Lake Roosevelt, the reservoir impounded by Grand Coulee Dam, lies on the northern edge of the Columbia Basin and the basalt aquifer system hosted by the Columbia River Basalt. This aquifer system characteristically consists of a series of individual water-bearing zones, or aquifers, that are confined between the widespread layered basalts that comprise the Columbia River basalt. Each of these layers, which are stacked one a top the other, typically range from 50 to 150 feet thick, and the tops and bottoms of them consist of rubbly to vesicular rock that can host groundwater. The zones between each basalt flow layer are known as interflow zones and they consist of the bottom few feet of one basalt flow layer and the upper few feet of the underlying layer. **Figure 2** shows the extent and elevation of the top of the deeper aquifer system in GWMA, the Grande Ronde system.

Groundwater within this layered basalt system moves down slope (down dip) away from recharge areas. Recharge generally occurs where an interflow zone is close to the ground surface and in contact with surface water, such as a stream, river, lake, or reservoir, or in high precipitation areas. Within the Columbia Basin, high precipitation areas usually are at higher elevations around the edge of the Basin or on high ridges within the basin (where precipitation is significantly higher than in the low land central basin). Surface water, where present, usually is found in the deep coulees and in areas where basalt interflow zones are exposed in major river canyons.

In and near the GWMA, the largest body of surface water is Lake Roosevelt. Given that, the GWMA team looked at the physical relationship between Lake Roosevelt and the basalt aquifer system to evaluate the potential for recharge of GWMA basalt aquifers by the reservoir. This was done using a combination of subsurface geologic maps produced through the subsurface geologic mapping effort and water level data previously collected by the Department of Ecology as part of their long term aquifer monitoring program in the Columbia Basin. Based on this information, GWMA's basic conclusion is that Lake Roosevelt is not a source of significant, if any, recharge to the Columbia River basalt aquifer system.

Aquifer hosting interflow zones in the basalt aquifer system, with only one exception within the GMWA, simply do not come into physical contact with Lake Roosevelt. Everywhere along the length of the reservoir within GWMA, basalt almost everywhere is found several hundred feet above the reservoir pool. In fact, the basalt lies atop granite and other older pre-basalt rocks (basement) that are very impermeable. This basement rock physically separates the basalt aquifer system from the water found in Lake Roosevelt. There is no way for water within the reservoir to go up hill across the basement rocks above the reservoir and into the basalt interflow zones found along the crest of the ridges above the Reservoir. **Figures 3 and 4** illustrate this physical relationship.

Figure 2. This map shows the basic extent and elevation of the top of the more regionally extensive Grande Ronde aquifer system. As will be discussed below, there is only a small amount of natural recharge to this system.



This observation is confirmed by water level data in a a number of wells where Ecology has collected water level data over the past 20 to 30 years. Water levels in these wells are several hundred feet higher than the pool elevation. If the primary recharge mechanism for the basalt aquifer system being measured by these wells was the reservoir, water levels in them would be at or below the reservoir pool elevation. This tells us that the primary influence for water level in these wells is related to recharge at elevations higher than the reservoir pool. **Figure 3** shows this relationship.

Figure 3. In this north to south cross-section we see water levels in basalt wells up to 500 feet higher than the Lake Roosevelt pool. Water from the lake is not the source of the water seen in these wells. Granite buried beneath the basalt prevents water from moving south out of the lake and into the basalt aquifer system.

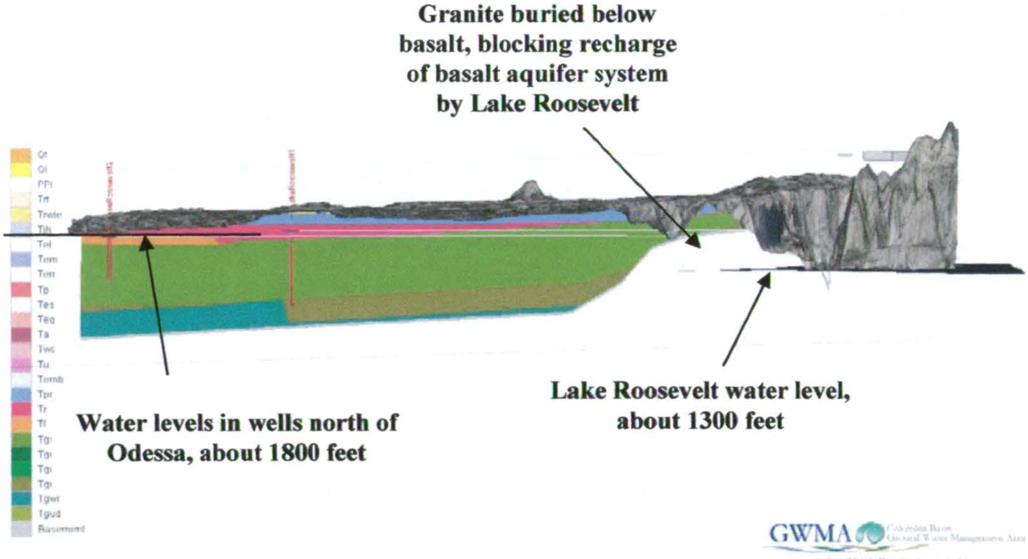


Figure 4. In this view we are looking from the north to the south, across Lake Roosevelt we see the granite basement which underlies the basalt aquifer system cropping out above the Lake Roosevelt pool. This prevents recharge of the basalt aquifer system by the lake.

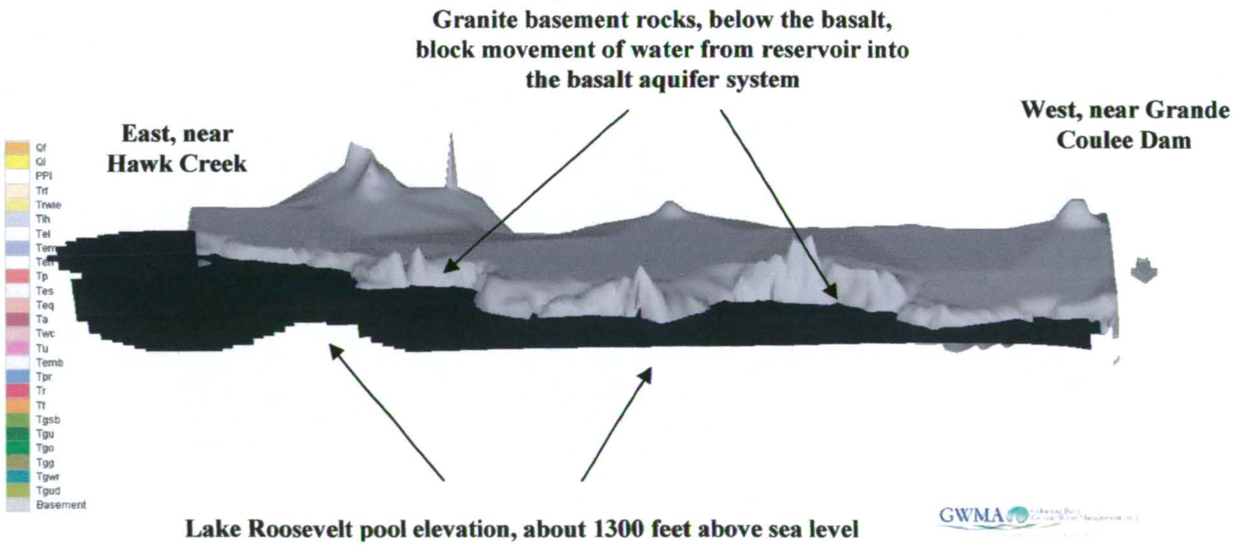


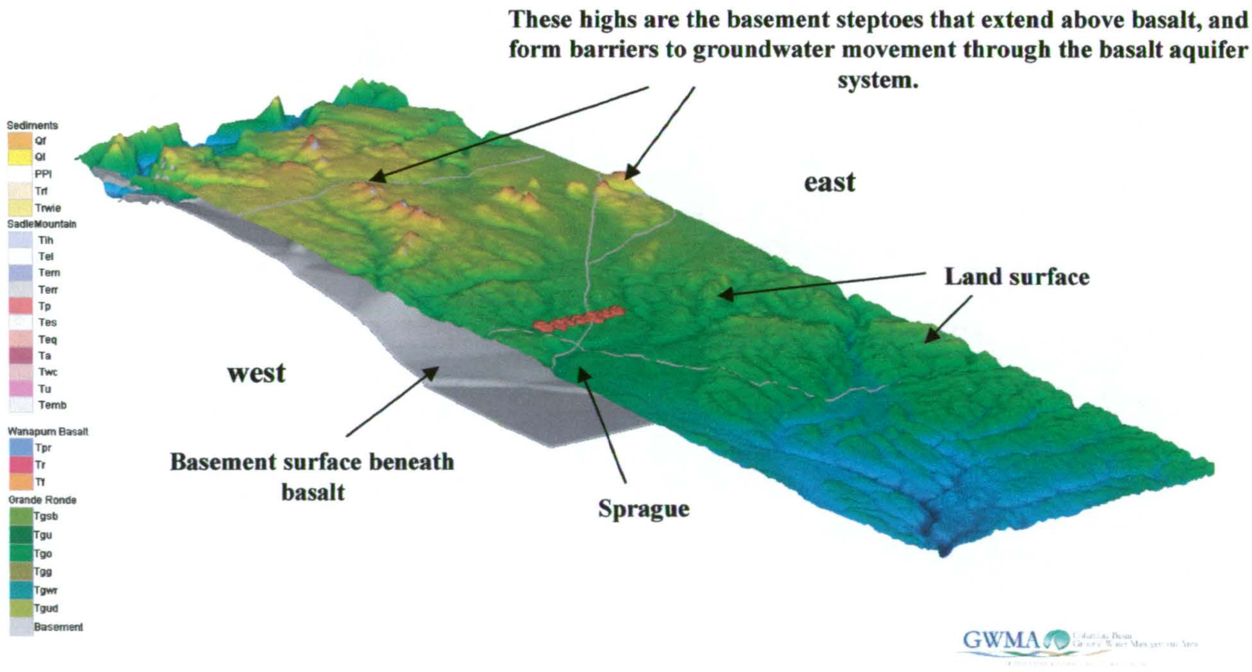
Figure 3 also shows the presence of a basement ridge buried beneath the basalt and separating the basalt aquifer system from the reservoir pool. This ridge, which our mapping shows extends the full length of Lake Roosevelt on the northern edge of GWMA provides a further physical barrier to recharge of the basalt aquifer system by the reservoir.

The one exception to this is at Hawk Creek north of Davenport, Washington. In this area the basalt system does come into physical contact with the reservoir, and local basalt water wells suggests local recharge of basalt by the reservoir. However, GWMA's subsurface basalt mapping again shows that the buried basement surface may be highe enough south of the reservoir to greatly restrict, if not completely block, the southward movement of reservoir recharge through the basalt and into the regional basalt aquifer system.

RECHARGE FROM THE EAST OF GWMA

The subsurface geologic mapping effort also traced the extent of buried basement highlands within GWMA southwards in the eastern portion of Lincoln County **(Figure 5)**. In this part of GWMA, as well as the eastern portion of the State, these buried basement highlands occasionally come to the surface, forming hills projecting above the basalt. These hills, known as steptoes, are like their namesake Steptoe Butte, common in northeastern Lincoln County (in GWMA) as well as western Spokane County and central Whitman County. Where present, these buried hills probably form barriers to groundwater movement from the higher precipitation areas along the Idaho/Washington border into the greater GWMA region.

Figure 5. This map projection for eastern Lincoln County and adjacent portions of western Spokane County shows the presence of the steptoes in this area that form basement highlands that block ground water movement from west to east, out of Spokane County and into the GWMA.

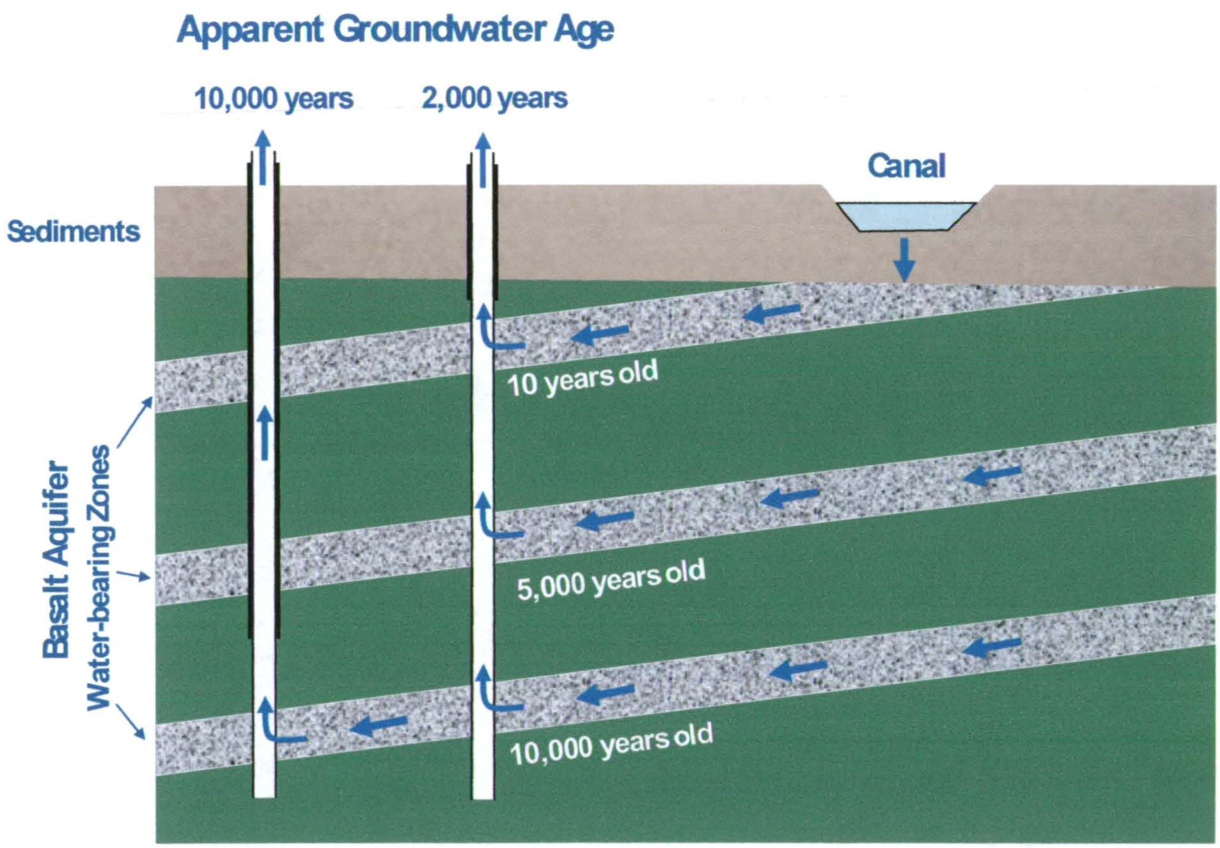


This relationship holds true for the West Plains area of western Spokane County. Again, these basement highlands, buried beneath the basalt, form buried hills that interrupt the lateral continuity of basalt interflow zones, and the potential movement of ground water eastwards into the GWMA region.

GROUND WATER GEOCHEMISTRY, AGE, AND RECHARGE RELATIONSHIPS

The water sources that recharge the aquifer system, and the length of time it has taken for water from various sources to arrive at the location of a given well are recorded in the chemistry of groundwater. In particular, different recharge sources (ancient glacial meltwater, irrigation waters, recharge from present-day surface waters such as lakes, rivers, and canals) can be identified using geochemical tracers and groundwater dating methods.

Figure 6. Age tracer data and apparent groundwater recharge ages are used to identify connections to present day recharge sources.



As part of this study to characterize the aquifer system, selected irrigation, municipal and private supply wells, as well as surface water bodies representing potential recharge sources, were sampled and analyzed for a suite of geochemical and isotopic parameters including major and trace element concentrations, stable isotopes, dissolved gases and age tracers (radiocarbon, tritium, atmospheric chlorofluorocarbons or CFCs) in order to elucidate the origins and hydrochemical evolution of the groundwater and, in particular, to evaluate recharge relationships and timescales in the deeper basalt aquifer system. Tritium and CFCs are used to identify and quantify recent recharge components (a few decades to a few years old), whereas radiocarbon is useful for identifying groundwater that is hundreds to tens of thousands of years old. By combining data for age tracers with different characteristic timescales, it is possible to estimate the time elapsed since the water entered the subsurface and also to identify mixtures of older and younger groundwater in production wells. This information was used in conjunction with the geologic model to identify connections to current potential sources of recharge in the aquifer system.

As shown in **Figure 6**, relatively young groundwater recharge ages (less than 50 years) are generally found for shallow wells open to unconfined sediment aquifers, indicating direct connections to present day recharge sources (canals, seasonally water-filled coulees, creeks and lakes). In samples from some deeper municipal supply wells in basalt which are open over large vertical intervals, age tracers indicate the produced groundwater is a mixture of old (thousands of years) and young water entering from different flow zones with different connections to present day recharge. This data is used in combination with static water level trends, to evaluate the sustainability of current water extraction rates on a local and regional scale. Radiocarbon and stable isotope data, and the absence of detectable tritium and CFCs, indicate that groundwater produced from deep irrigation wells in the Odessa area completed in the lower Grande Ronde basalt layers is more than 10,000 years old. This part of the aquifer system has not been recharged since the end of the last ice age when climate conditions were cooler and wetter than present. Some specific examples of these findings are given below.

Royal City – Recharge to Wanapum Aquifers Keeps Up With Demand (Figure 7)
In the Royal City area in western Grant County, between the Frenchman Hills and the Saddle Mountains, municipal supply wells completed in the shallow basalt system (Wanapum) have apparent radiocarbon ages up to 1300 years old and detectable tritium indicating that part of the groundwater is less than 50 years old. This is direct evidence of a mixture of older water probably originating as precipitation on the Frenchman Hills and as well recent recharge from leakage beneath the nearby Frenchman canal. Static levels in these wells are stable, indicating that the recharge from natural and anthropogenic (canal leakage) sources is sufficient to meet municipal water demands in this part of GWMA.

Moses Lake Well 18 – Wanapum Well Recharged by the East Low Canal (Figure 8)
Moses Lake Well 18 is also completed in the Wanapum (Lower Roza and Frenchman Springs Formations) and has historically stable static water levels. The water from this well is less than 50 years old as indicated by radiocarbon, tritium and CFC data, which implies a direct connection to nearby East Low Canal through Roza/Upper Frenchman Springs flow zones.

Moses Lake Well 17 – Upper Grande Ronde Well With Limited Recharge (Figure 9)
Moses Lake Well 17 is a deep well sealed into the Upper Grande Ronde (Sentinel Bluffs). Static water levels in this well are declining. The apparent radiocarbon age for groundwater produced by this well is approximately 6000 years, but contains detectable tritium, indicating a mixture of old and young water. The proportion of recharge from young water component is estimated to be less than 20 % and is too little to offset withdrawals (i.e. 80 % of the water production is derived from storage, therefore water levels are declining). There are no geologic features indicating a direct connection to surface water, therefore the young recharge component likely represents limited vertical leakage through the many uncased wells present in the vicinity of the town of Moses Lake. Current production rates from this well therefore are not sustainable as there is no reliable source of recharge to this part of the aquifer.

Figure 7. Royal City supply wells produce a mixture of old and young water derived from a combination of leaky canals and natural recharge on the nearby Frenchman Hills, respectively.

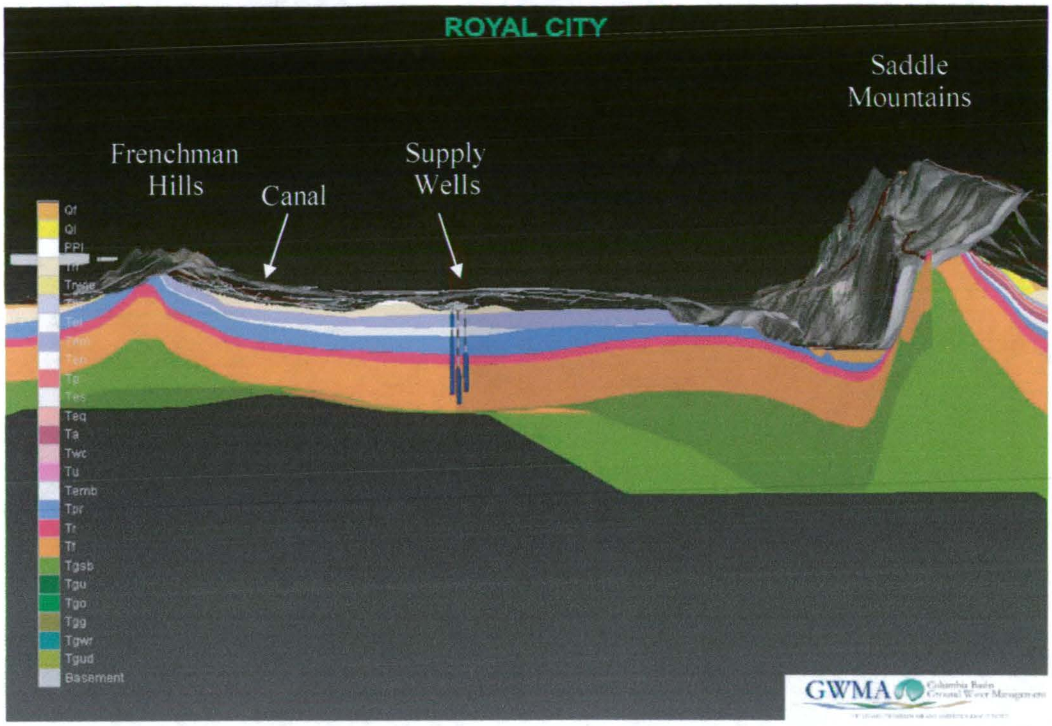


Figure 8. Moses Lake Well 18 receives most of its recharge from canal leakage. Nearby, the lower Roza and upper Frenchman Springs units are cut by the East Low Canal, thus providing a direct connection to surface water recharge.

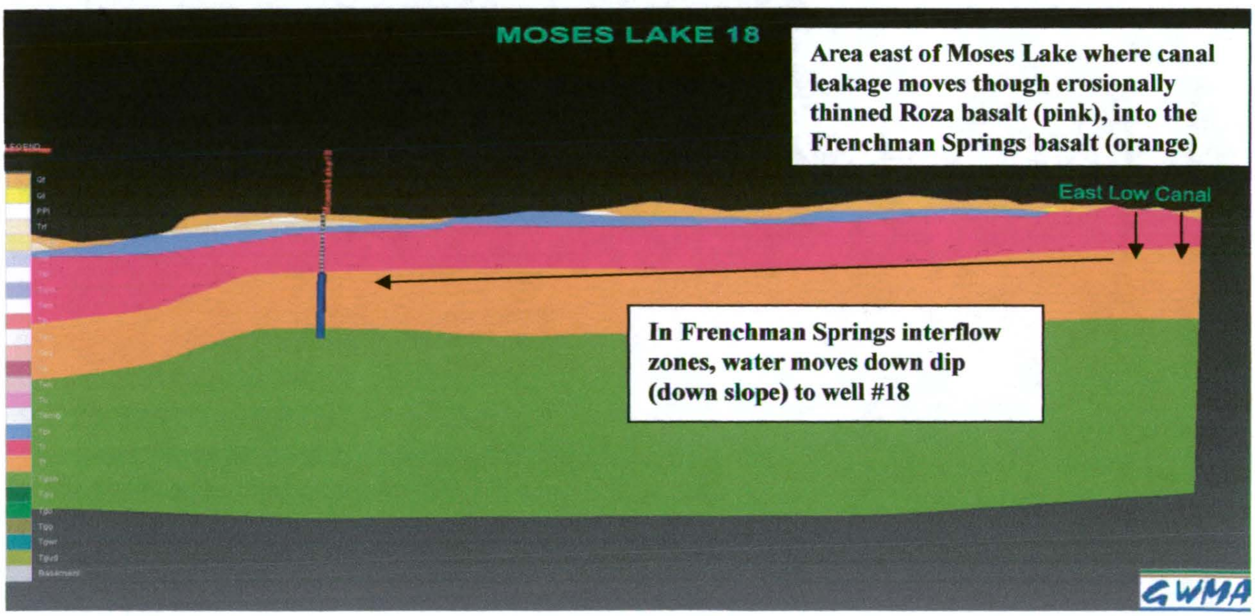
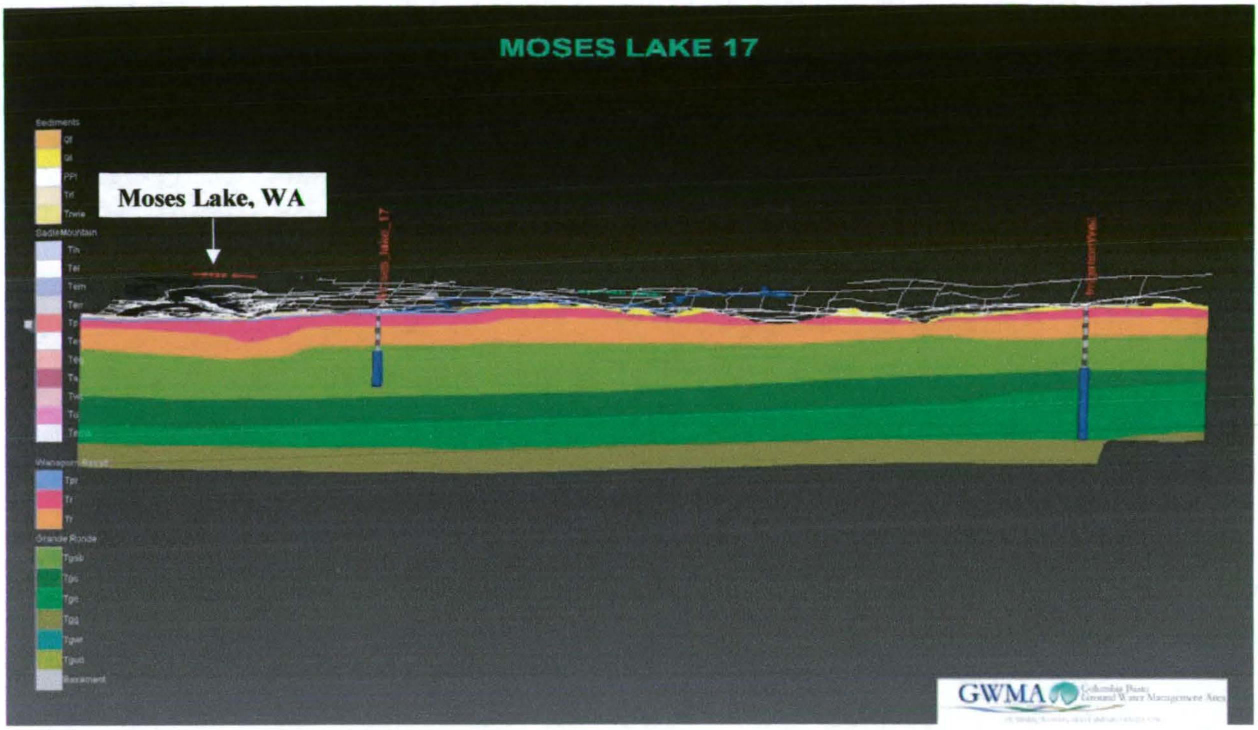


Figure 9. Moses Lake Well 17 (left) in the Upper Grande Ronde see minor evidence of leakage from shallow water sources. This is inferred to be predominantly the result of leakage through the several hundred wells drilled in the immediate are of Moses Lake, Washington. A deep irrigation well near Odessa (right, about 20 miles east of Moses Lake) which is constructed deeper into the Grande Ronde aquifer system shows no geologic connection to present recharge sources.



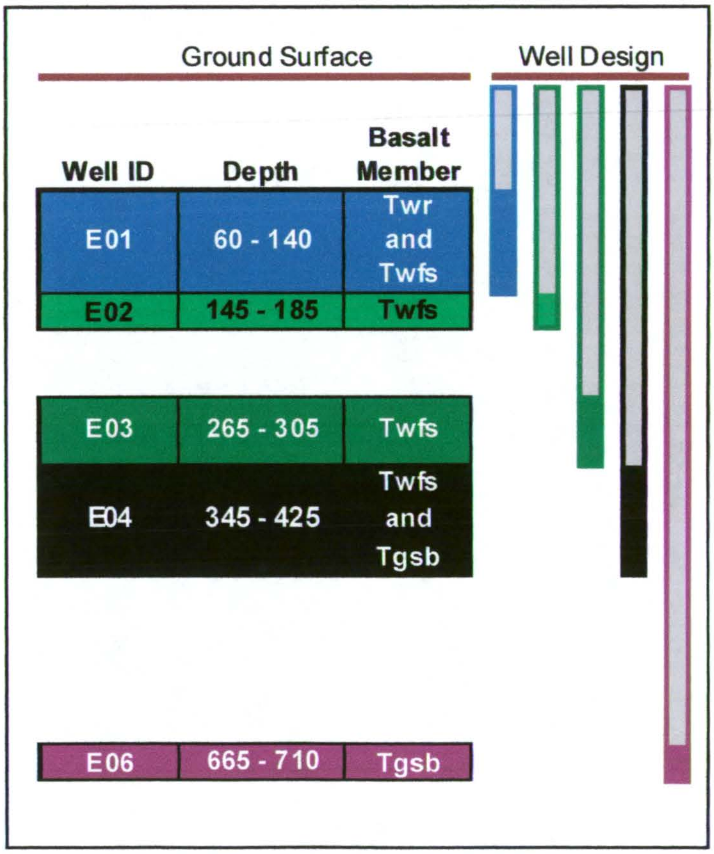
Odessa Area Deep Irrigation Wells – No Recharge to Lower Grande Ronde (Figure 9)
Deep irrigation wells sealed into the Lower Grande Ronde aquifer system in the Odessa subarea approximately 20 miles east of Moses Lake have declining static water levels, apparent radiocarbon ages ranging from 10,000 to 20,000 years and generally no detectable tritium or CFCs. In one example illustrated in Figure 4, a recently drilled well completed in the Umtanum and Ortley units with an apparent radiocarbon age of 15,800 years shows no geologic connection to any surface water recharge sources. The groundwater produced from this well is essentially non-renewable.

HISTORICAL GROUND WATER LEVEL DATA

Ecology has measured groundwater levels for up to 40 years in numerous wells distributed throughout the Columbia Plateau and the GWMA. As part of this effort, Ecology and the U.S. Geological Survey (USGS) constructed a number of multi-level observation well clusters around the GWMA in the 1970s and early 1980s to evaluate the state of the groundwater resource and the response of the basalt aquifers to development away from the direct influence ("noise") of a pumping well. **Figure 10** shows a schematic representation of one of the multi-level well clusters.

Groundwater elevation measurements obtained during the same discrete time period can be used as an indicator of possible connection between groundwater and surface water and how well connected the basalt interflow zones are laterally and vertically. Regular measurements taken over a number of years, particularly from non-pumping wells, provide a record of pumping and recharge to the interflow zones monitored by the well. The water level measured in each well represents the water pressure in the interflow zone(s) open to the well. Similarities and differences in the levels and the trends between each well of a multi-well cluster define the relationship with interflow zones monitored each wells in the cluster. If good vertical connection exists between interflow zones, we would expect the water levels in different zones to be similar, and to react similarly over time. Conversely, differences in levels and/or trends indicate vertical separation between the monitored zones.

Figure 10. This diagram shows the design of a multi-level well cluster south of Odessa. A multi-level observation well actually consists of a collection of several wells in a single borehole with each well extending to a different depth and open to a different interflow zone(s). Cement grout plugs are used to seal the space between each well to prevent leakage between the zones monitored in the borehole.



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Observations from Multi-level Well Clusters

Review of historical groundwater levels from multi-level well clusters demonstrate that there is little vertical flow between the basalt interflow zones, and the aquifers comprised of these zones are separate and distinct. The water levels from multi-level well clusters located throughout the GWMA corroborate this observation. **Figures 11 and 12** show a vertical profile of historical water level trends in two different parts of the GWMA,

Figure 11. This diagram shows the historical water level record since 1973 for a multi-level well cluster located west of Odessa. The three wells shown from this cluster are open to different intervals between the lowest portion of the Wanapum Basalt (Twfs) and the deeper members of the Grande Ronde Basalt.

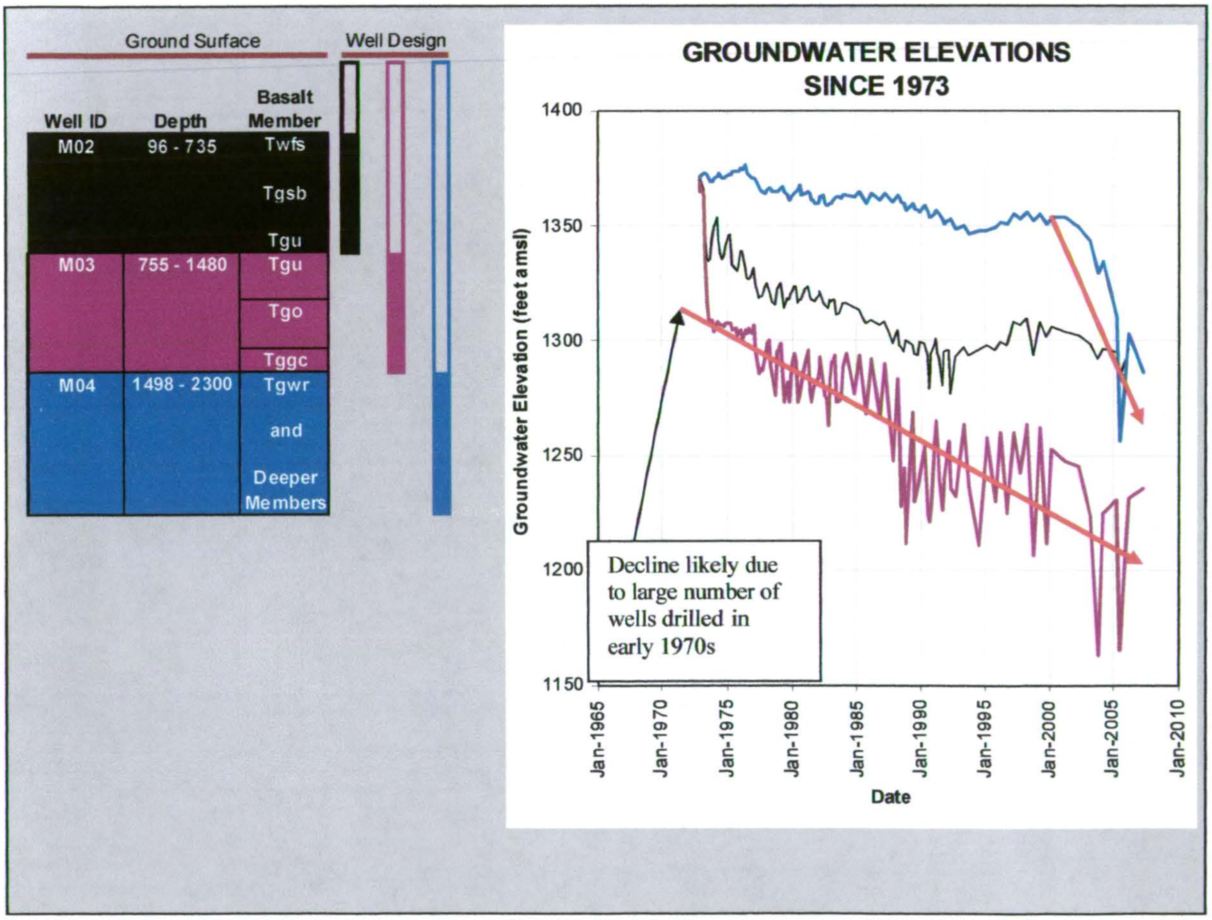
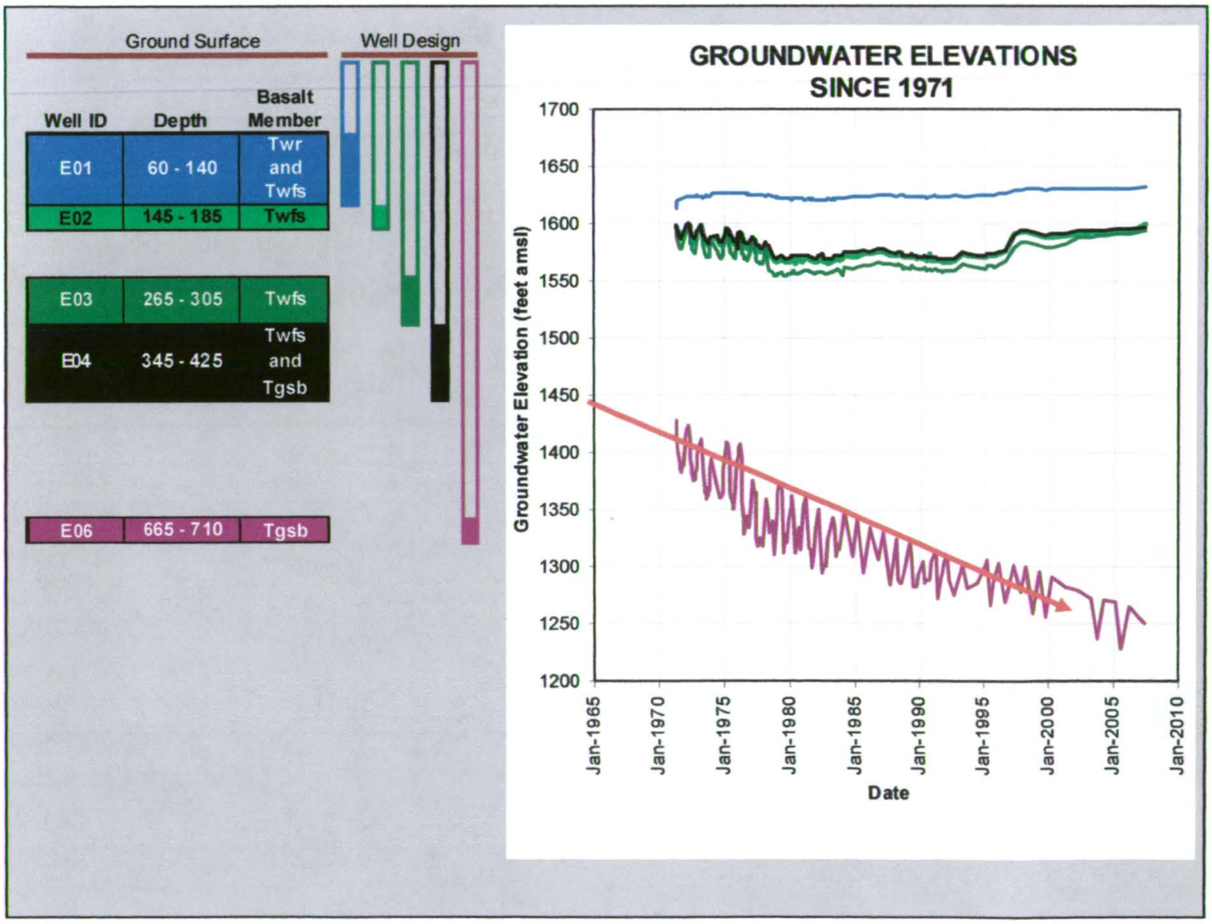


Figure 11, which depicts water levels from a multi-well cluster west of Odessa, shows that each zone has a distinctly different water level. While all three zones show declining water levels from the beginning of monitoring in 1973, each zone shows a different trend, and those differences are maintained over the entire record. The shallowest zone (M02) experiences the most declines

between 1973 and 1990, whereas the deepest zone (M04), exhibits a lesser water level decline over the same period, followed by a drastic increase in the rate of decline after 2000. This increase in the rate of decline in the deeper zone reflects the shift in pumping from shallower to deeper aquifers in the Odessa area. The relatively high water level in the deepest zone illustrates a high degree of confinement and isolation from the shallower zones. While the drilling into the deep zone would restore the water level in a well that was originally completed in one of the shallower zones, the sharp rate of decline also shows that the deepest zone is isolated from the others, and that the higher water level condition realized by drilling into deeper zones is temporary.

Figure 12. This diagram shows the historical water level record since 1971 for a multi-level well cluster located in southern Adams County. Three of the wells shown from this cluster are open to the Roza and different portions of the Frenchman Springs members of the Wanapum Basalt. A fourth is open to the bottom of the Wanapum and top of the Grande Ronde Basalt. The fifth (B05) is open to the upper Grande Ronde Basalt.



The water levels in the multi-level well cluster shown in **Figure 12** also show that each zone is vertically distinct and separate. The water levels in wells completed in Wanapum interflow zones are significantly higher than the well completed in the Grande Ronde and show recovery from pumping in the 1970s. Water levels in the Grande Ronde show relatively heavy pumping pressures and decline throughout the period of record.

Water level elevations and historical trends in multi-level well clusters in the GWMA were evaluated with respect to the geologic framework of the Columbia River Basalt. The water level data clearly show that basalt interflow zones form separate and distinct aquifers, In addition, the data corroborate anecdotal evidence that groundwater levels in the monitored aquifers hosted by the Grande Ronde Basalt are declining. Declines in the aquifers in the Grande Ronde in areas where deep well irrigation is prominent commonly exceed 100 to 150 feet. These observations have several implications:

First, the data show that natural recharge to the aquifers in the Grande Ronde Basalt is minimal, and at a slow rate where it occurs. Recharge to the aquifers in the Grande Ronde Basalt is minimal because of the lack of vertical connection between shallow and deep aquifer zones, and a sparcity of both possible recharge locations and recharge water. The potential for recharge decreases with depth in the Grande Ronde. Specific reasons that recharge to the aquifer zones in the Grande Ronde Basalt is minimal include:

- There are few places where interflow zones that can receive recharge are exposed to surface water or precipitation, and the amount of exposure diminishes to zero with depth in the Grande Ronde Basalt. In other words, the deeper aquifers in the Grande Ronde are not connected to surface waters anywhere in the GWMA.
- The interflow zones that are exposed are relatively thin and do not provide much area for precipitation or surface water to infiltrate.
- Leakage from shallower basalt interflow zones to deeper zones is very small.
- Precipitation and winter/spring runoff is small in magnitude compared to pumping.

A second implication of the ground water level record in GWMA wells is that existing groundwater supplies in the deeper basalt units are not reliable or sustainable in the long-term, and thus continuing to drill deeper into progressively lower aquifers in the Grande Ronde Basalt is only a temporary solution for declining water levels and pumping rates.

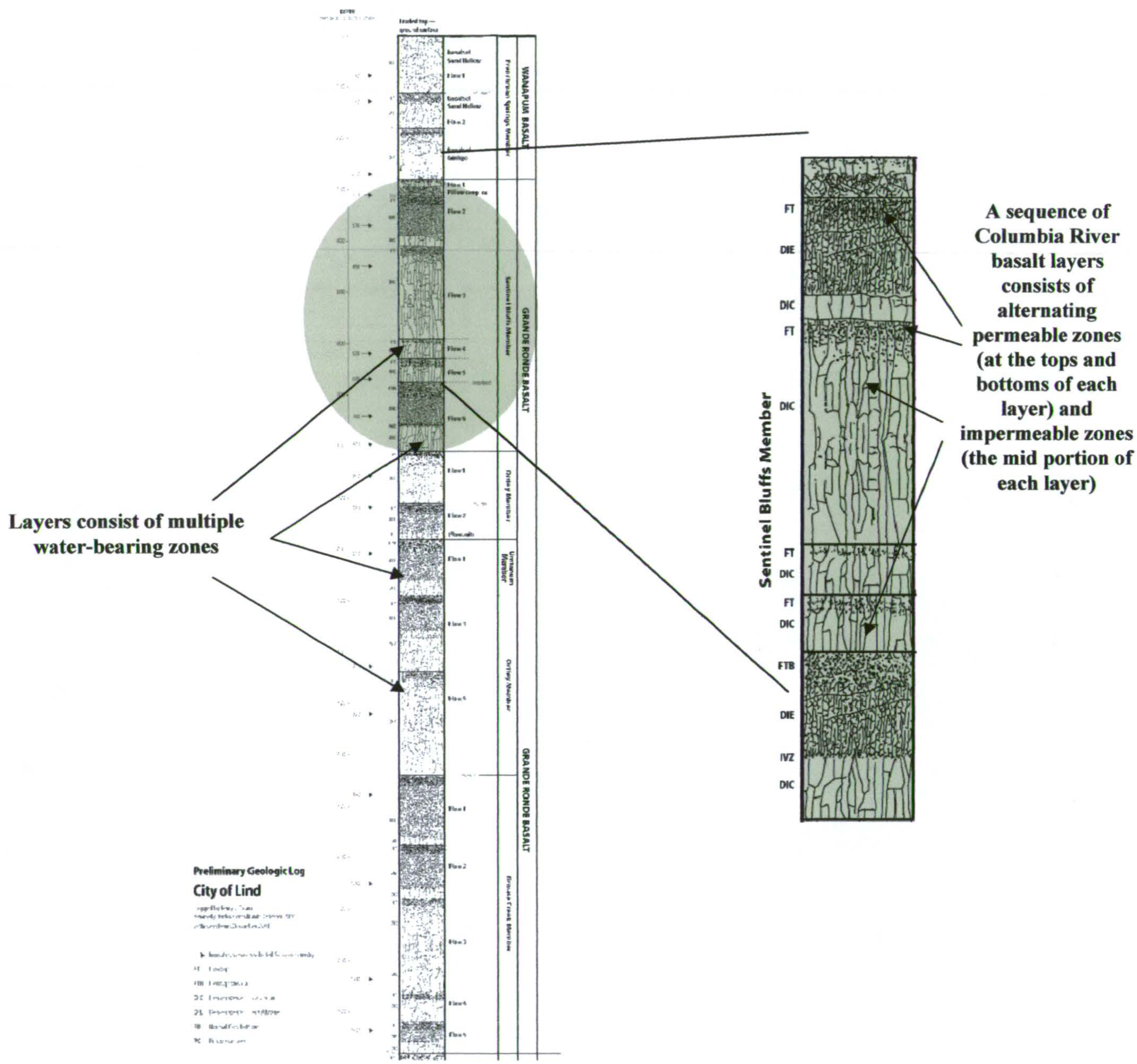
GEOLOGIC CONTROLS ON COLUMBIA RIVER BASALT AQUIFER SYSTEM IN THE GWMA

The thick sequence of layered flood-basalt flows of the Columbia River basalt are prime sources of potable groundwater throughout their extent in Washington, Oregon, and Idaho. Having a realistic and accurate understanding of how ground water enters and moves through these flood-basalt flows is of fundamental importance to anyone working with Columbia River basalt aquifer systems (e.g. resource assessments, contaminant transport/fate, aquifer storage/recovery, regulatory assessment).

One of the most extraordinary features of the Columbia River basalt is the physical dimensions of individual basalt flow layers. A conceptual understanding of the nature of Columbia River basalt flows plays a critical role in accurately interpreting some of the unique hydrogeologic aspects of the basalt. During the peak period of basalt eruptive activity (Grande Ronde and Wanapum Basalts) it was common for eruptive events to rapidly (~2 to ~12 weeks) emplace individual flows having volumes of 500 to >1,000 mi^3 and for the lava to cover areas >10,000 mi^2 creating the largest known lava flows on the Earth. This combination of huge volume and rapid emplacement typically produced simple sheet flows 50 to >300 feet thick.

Columbia River basalt flows are typically very widespread, covering an average area of 10,000 mi^2. This, coupled with the physical geologic characteristics of CRBG flows indicates they formed as lateral extensive, uninterrupted sheets. This differs markedly from more typical compound basalt flows which display numerous, interfingering, discontinuous, lenticular layers. The net hydrologic result of this is that the aquifers within the sheet flows typical of the CRBG occur as a series of layered, tabular, confined features whereas **(Figure 13)**.

Figure 13. This drawing shows the presence of multiple, permeable layers within a typical sequence of Columbia River basalt. These layers, which usually occur every 50 to 150 feet, have the potential old ground water, if they can receive recharge.



Aquifer horizons within the Columbia River basalt generally are associated with intraflow structures at the top (e.g., vesicular flow-top, flow-top breccias) and bottom (e.g., flow-foot breccias, pillow lava/hyaloclastite complexes) of sheet flows **(Figure 13)**. The interiors of thick sheet flows (in their undisturbed state) are for all practical purposes essentially impermeable and act as aquitards, typically creating a series of "stacked" confined aquifers within the Columbia River basalt aquifer system.

The dominant groundwater flow pathway within this aquifer system is horizontal to sub-horizontal along individual, laterally extensive, interflow zones. Given the physical properties of the Columbia River basalt, outcrop observations, and interpretations of well hydraulics vertical groundwater movement through undisturbed basalt flow interiors is small to essentially non-existent. However, vertical groundwater movement between layered CRBG aquifers is possible, but occurs predominantly under specific geologic conditions where basalt flow interiors are disturbed or truncated.

Figures 14, 15, 16, 17, and 18 illustrate the main geologic features that influence the lateral continuity of Columbia River basalt layers and the characteristics of the aquifers within them.

Figure 14. This photograph shows basic geologic relationships in a fault zone.

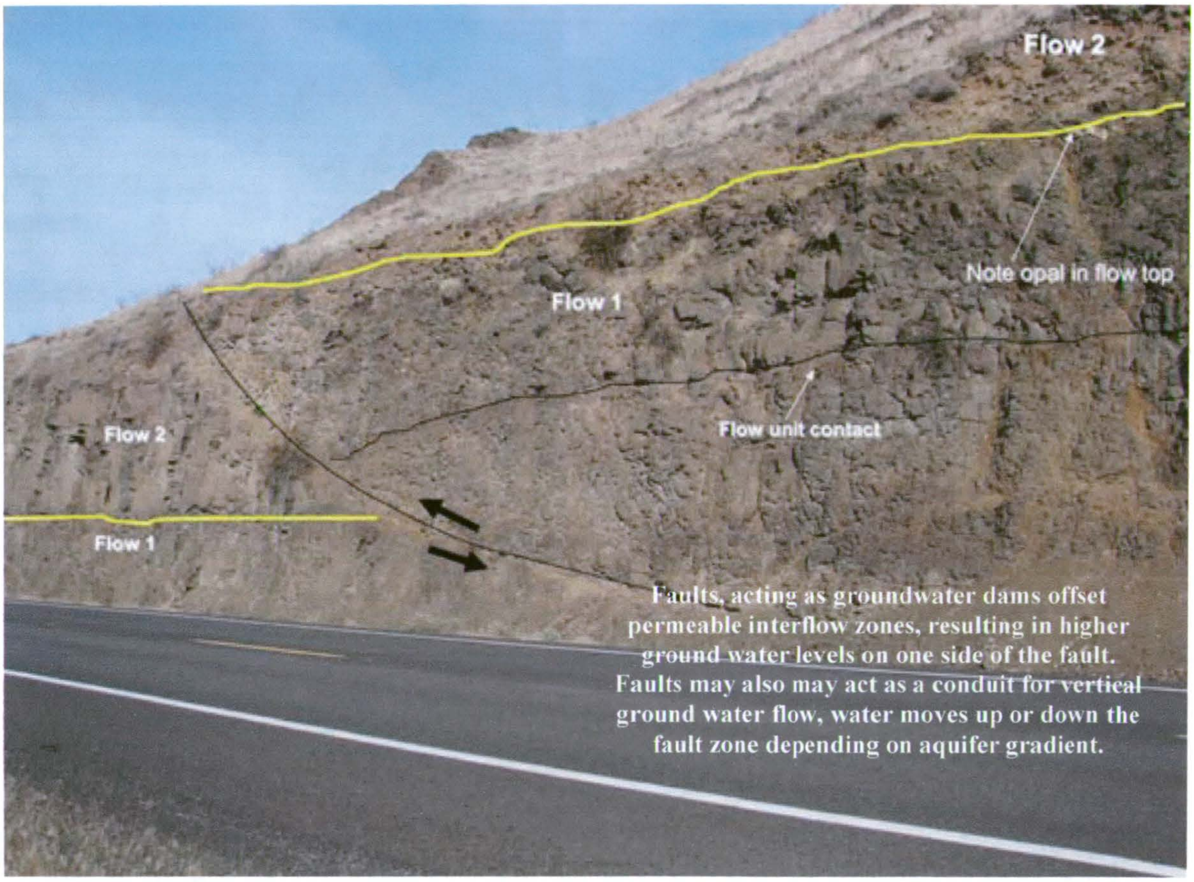


Figure 15. Folds also can control the basalt aquifer system, usually forming barriers to ground water flow, and subdividing the aquifer system into ground water sub basins. Ground water systems on either side of these folds typically do not display significant hydrologic connection.

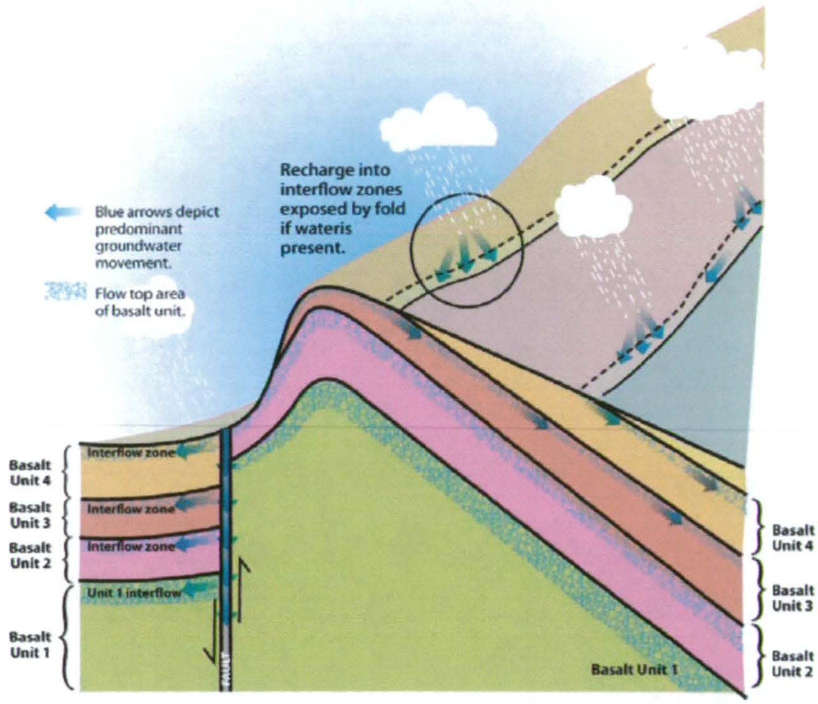


Figure 16. Feeder dikes, from which Columbia River basalt lave flows erupted millions of years ago, form long, nearly vertical subsurface features which probably form boundaries to groundwater flow.

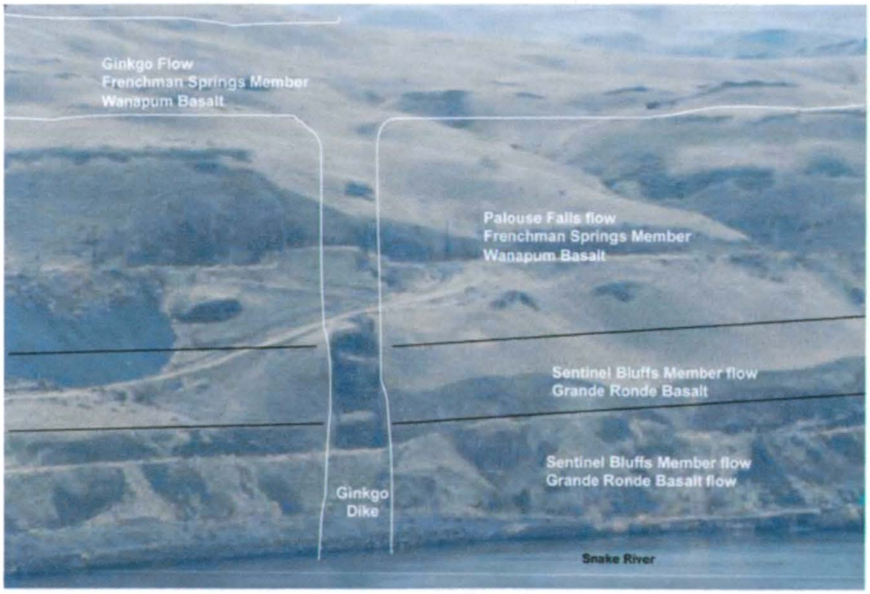
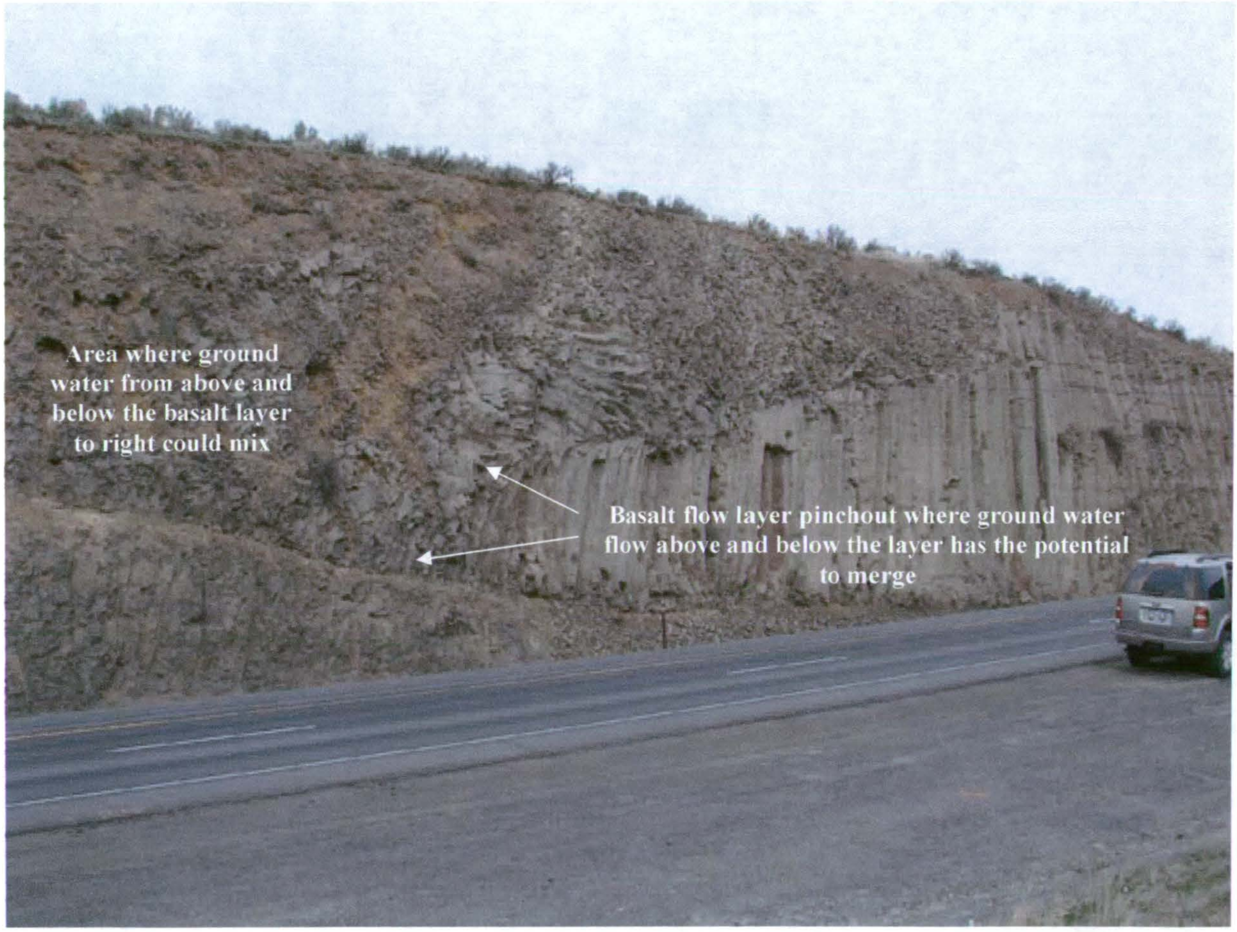


Figure 17. Columbia River basalt flow layers are known to pinch out. These pinchouts essentially mark the lateral termination of individual basalt flow layers. Where layers pinchout, the impermeable flow interior is absent and potentially water-bearing flow tops and bottoms are in direct hydrologic connection. Flow margins create very limited (single flow) vertical connections.



The current Columbia Basin GWMA subsurface geologic mapping and aquifer assessment project has mapped the distribution of the major geologic units comprising the CRBG aquifer system, and the features within it that potentially effect the lateral distribution of individual aquifers. In addition, this work, which includes an evaluation of water level trends and ground water geochemistry provides GWMA scientists with important clues into the nature of: (1) aquifer continuity and extent, (2) aquifer interconnection, or the lack of that interconnection, (3) ground water recharge and the potential age of ground water within the CRBG aquifer system, and (4) ground water discharge, or the lack of that, especially from deeper portions of the system. The results of this project also give GWMA stakeholders insights into how to better manage the aquifer system, including ways to evaluate recharge project feasibility.

Figure 18. Deep coulees cut into basalt layers, allowing interconnection of successive interflow zones. The coulees also expose interflow zones to surface water and shallow groundwater. Interflows may discharge to, or be recharged from, coulees (or both). Erosional channels (such as coulees) can breach multiple basalt layers creating the potential for a more extensive vertical connection.

CONCLUSIONS - CONCEPTUAL GROUND WATER MODEL FOR THE GWMA

Based on the results of GWMA's subsurface geologic mapping and aquifer assessment project, the following basic conclusions with respect to natural aquifer recharge and the source of basalt aquifer ground water in much of the GWMA are drawn.

1. ***There is little or no recharge of the basalt aquifer system underlying GWMA from Lake Roosevelt.***
2. ***There is a potential for recharge of the basalt aquifer system from areas lying east of the GWMA boundary. However, the impact of this recharge on the regional aquifer system appears to be minimal.***

3. ***The deep ground water system is dominated by waters 10,000 or more years old, suggesting that the deep aquifer system was recharged during the Ice Age floods.***
4. ***Ground water in the GWMA appears to occur in sub-basins displaying limited connections.***

These observations are consistent with the geologic controls on ground water movement that we have interpreted from the subsurface geologic mapping, ground water geochemical analysis, and water level data evaluation done for this project.

Based on these observation and interpretations, the ground water recharge and flow system in the Columbia River basalt aquifers underlying the GWMA is characterized by a series of separate, water-bearing layers found in interflow zones at the tops and bottoms of individual basalt flow layers. These interflow zone layers, or aquifers, are separated by the dense, solid, unfractured basalt rock that forms the bulk of the basalt geology of the Columbia Basin. The places where these interflow zone aquifers can receive recharge are where they are at and near the surface in direct hydrologic connection with surface water and high precipitation areas. Once water enters these zones it moves more-or-less horizontally along individual basalt flow layers. Vertical movement of ground water through dense, uninterrupted basalt flow layers is small.

The understanding of the Columbia River basalt aquifer system within the GWMA that has resulted from this work has given GWMA stakeholders a clear picture of how this aquifer system works, where it receives natural recharge, and how artificial recharge activities can be used better manage Columbia River basalt aquifer ground water resources.

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February 2009

Basalt Aquifer Recharge, Age, and Water Level

In the

Columbia Basin Ground Water Management Area
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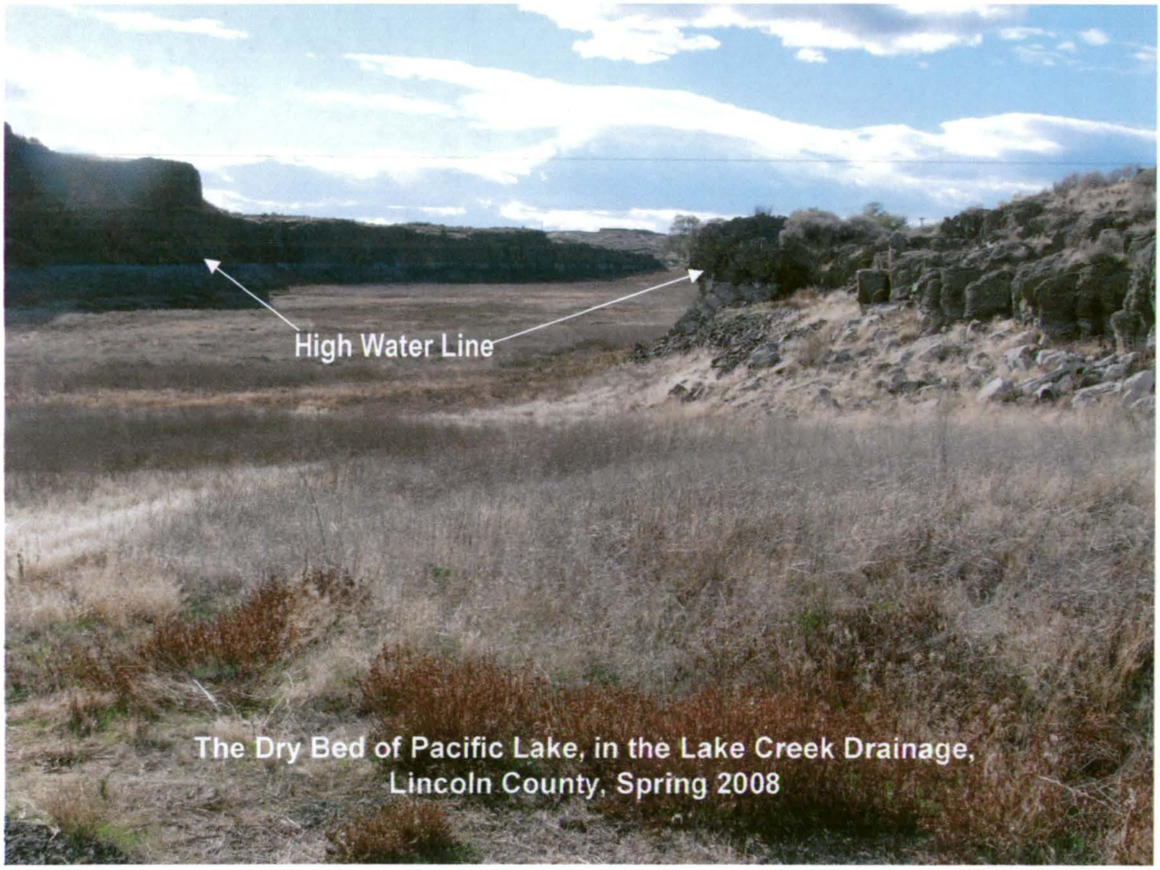
Progress Report of the Subsurface Geologic Mapping and Hydrogeologic Assessment Project



The Dry Bed of Pacific Lake, in the Lake Creek Drainage, Lincoln County, Spring 2008

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EXECUTIVE SUMMARY

This report summarizes significant findings from the Columbia Basin Ground Water Management Area's (GWMA) current, and soon to be completed, subsurface geologic mapping and aquifer assessment project. These findings include:

1. Natural recharge of the Columbia Basin GWMA basalt aquifer system across the region is limited, but there is evidence of locally important recharge in some areas.
2. Beneath much of the eastern GWMA, including the Odessa Sub-Area deep basalt ground water is very old and experiences very little modern recharge.
3. In the central GWMA deep basalt ground water also is very old, but some modern artificial recharge is occurring via artificial and natural pathways.
4. Basalt aquifers in the GWMA are subdivided by a variety of geologic features which limit, and in some cases block, both vertical and lateral ground water movement. Ground water levels in some of these areas has experienced little significant decline, while in others it has dropped several hundred feet.
5. The last period of significant natural regional recharge of the basalt aquifer system occurred over 10,000 years ago, near the end of, or following, Pleistocene Cataclysmic Flooding.

These findings, and the data and information upon which they are based, provides GWMA stakeholders with the tools and knowledge to:

1. Better evaluate changing aquifer conditions related to ground water pumping and recharge.
2. Develop monitoring, modeling, and mitigation measures that address areas of concern and can be used to track improvements in the aquifer system as a result in changes in resource management.
3. Prioritize resources to be used to address ground water concerns in and around the GWMA.

INTRODUCTION

The Columbia Basin Ground Water Management Area (GWMA) of Adams, Franklin, Grant, and Lincoln Counties encompasses approximately 8,300 square miles in south-central Washington **(Figure 1)**. When first designated in February 1998, in response to concerns about elevated nitrate-N concentrations in groundwater, the GWMA included all of Franklin, Grant, and Adams Counties. In 2005 Lincoln County was added to the GWMA, and the GWMA charter was expanded to include all groundwater quality issues in the four counties.

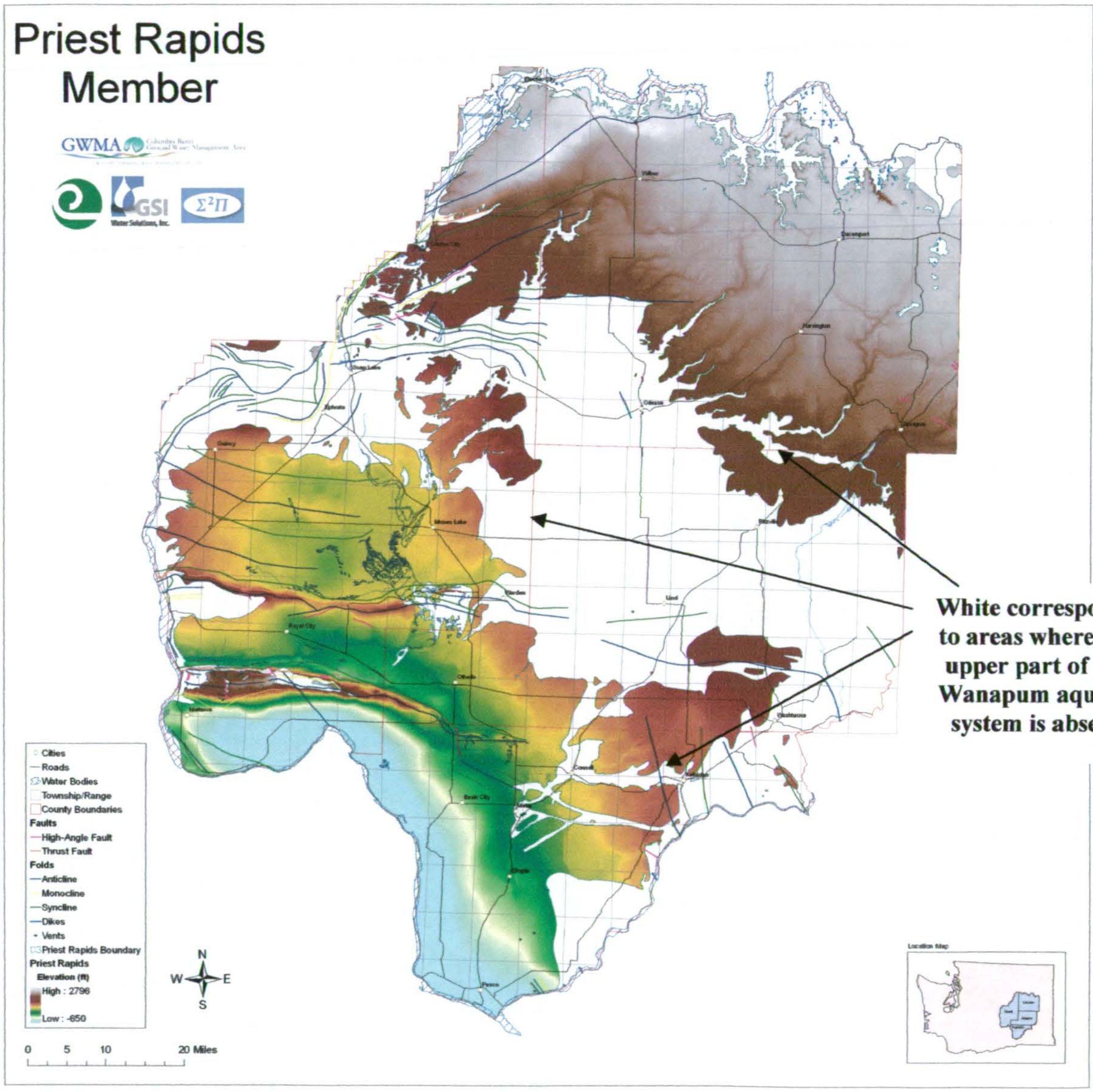
Scientific, mitigation, planning, and outreach activities dealing with groundwater quality within the GWMA largely are guided by the GWMA Plan. Based on conclusions presented in the GWMA plan and Ecology review comments on the GWMA plan, GWMA stakeholders decided that there was a need to identify the aquifers contributing groundwater to GWMA sampling wells, the extent of those aquifers, and the recharge sources (if any) for these aquifers. To support this, the GWMA Subsurface Geologic (or Hydrostratigraphic) Mapping Project was started in 2000. At this time, the subsurface geologic mapping effort has mapped the distribution of the major geologic features and units that influence ground water occurrence and movement beneath the GWMA.

GWMA's subsurface geologic mapping efforts have been done in phases tied to changing GWMA priorities and funding availability. These phases were as follows:

1. During 2000, 2001, and 2002 the mapping project focused on the shallower parts of the basalt aquifer system in Adams, Franklin, and Grant Counties. ***This work was done to better understand the occurrence of nitrate in the shallower portions of the basalt aquifer system.***
2. Between 2002 and 2004 the sediments overlying the basalt aquifer system in the three original GWMA counties were mapped. ***The sediments were mapped to better assess the impacts of nitrate bearing shallow ground water on private, single family domestic exempt wells.***
3. Beginning in 2006 and continuing through the current mapping effort which began in late 2007, the mapping efforts have extended into Lincoln County (following the addition of Lincoln County to the GWMA in 2005) and downwards into deeper parts

of the basalt aquifer system. ***This emphasis on the deeper basalt aquifer system, especially within the Grande Ronde Basalt, has been driven by the growing concern for sustaining deep aquifer production wells for both agriculture and municipalities.***

Figure 1. Map showing the extent of the GWMA and the elevation of the top of the Priest Rapids basalt. This map generally shows the extent of the upper part of the Wanapum aquifer system, and illustrates its' fragmented nature.



As a part of the recent subsurface mapping work, GWMA's efforts have begun to evolve, focusing more and more on understanding ground water sources. This change in emphasis is a direct consequence of the legislative mandate which funded the GWMA mapping efforts in 2007, 2008, and 2009. Specifically, this work was funded by a direct appropriation from the Washington State Legislature, which was directed to the GWMA via the Washington Department of Ecology (Ecology). A key objective of this work, as mandated by the Washington State Legislature, was to:

"...submit a report to the appropriate committees of the legislature describing the dynamic relationship between groundwater and surface water in the region."

To that end, GWMA hydrogeologists currently are working on a report that refines and upgrades the GWMA geologic database and geographic information coverage (GIS) by essentially completing the subsurface geologic mapping portions of GWMA's subsurface mapping project and using this information in conjunction with water quality, water level, and well testing data (both existing and new) to test and refine the conceptual model describing ground water flow in the aquifers underlying the GWMA and the relationships of this groundwater to surface waters, including recharge. The basic project approach used to accomplish this goal is described in a work plan produced in mid 2007. The remainder of this report focuses on key aspects of this larger effort, especially as it relates to the legislative request that accompanied the funding authorization and the significant findings listed at the beginning of the report. It is not the intent of this report to describe all of the work and results of the current GWMA subsurface mapping and aquifer assessment effort. That will be done later in the spring of 2009 in one or more technical reports currently being prepared by GWMA hydrogeologists.

This report is subdivided into several sections which address the basic legislative request and GWMA's significant findings. These are:

1. A discussion of the potential recharge, or lack of recharge, of the Columbia River basalt aquifer system beneath the GWMA that comes from the Lake Roosevelt pool. ***Our work suggests there is little or no recharge of the basalt aquifer system underlying GWMA from Lake Roosevelt.*** However, localized basalt aquifer recharge from Lake Roosevelt does occur in the Hawk Creek area, although its regional significance appears to be limited.

2. The potential for recharge of the GWMA basalt aquifer system from other surface water bodies found around the edge of the GWMA. ***There is evidence for recharge related to some surface waters, especially in the northwestern and eastern portions of GWMA.*** However, the regional influence of this potential recharge appears to be limited.
3. A review of groundwater geochemistry data collected by GWMA scientists to investigate the age and potential for modern recharge of the aquifer system. ***The deep ground water system is dominated by waters 10,000 or more years old.*** This finding does not preclude the presence of younger ground water in the deep basalt aquifer system. In fact, in areas with large numbers of wells, such as near towns, there is evidence of shallow, younger waters contributing some recharge to these deeper, older ground waters.
4. An evaluation of water level data in wells within the GWMA. This data was examined to assess the degree of connection between the different parts of the CRB aquifer system. ***Ground water in the GWMA appears to occur in sub-basins displaying limited connections.*** Although not completely understood at this time, these sub-basins generally seem to be defined by both known and suspected folds, faults, and feeder dikes. In addition, the basalt aquifer system is clearly stratified, or layered. Each layer consists of one or more water bearing intervals displaying common water level trends, geochemistry, and recharge areas.
5. A review of GWMA's conceptual model of how ground water recharges CRBG aquifers moves through those aquifers and potential discharges from those aquifer systems. ***The basic thesis of this conceptual model is that ground water occurrence, recharge, and movement is controlled by the geologic framework. This geologic framework results in a layered, compartmentalized ground water system where some portions receive significant natural and artificial recharge and some portions do not.***

Understanding this framework, as we now do, provides GWMA stakeholders with a powerful tool box to use in monitoring the different portions of the ground water system, devising strategies to mitigate against further ground water level decline and the reduction in ground water supplies, and build ground water models which can be used to study the impacts of different actions, including artificial recharge.

CRBG AQUIFER SYSTEM AND LAKE ROOSEVELT

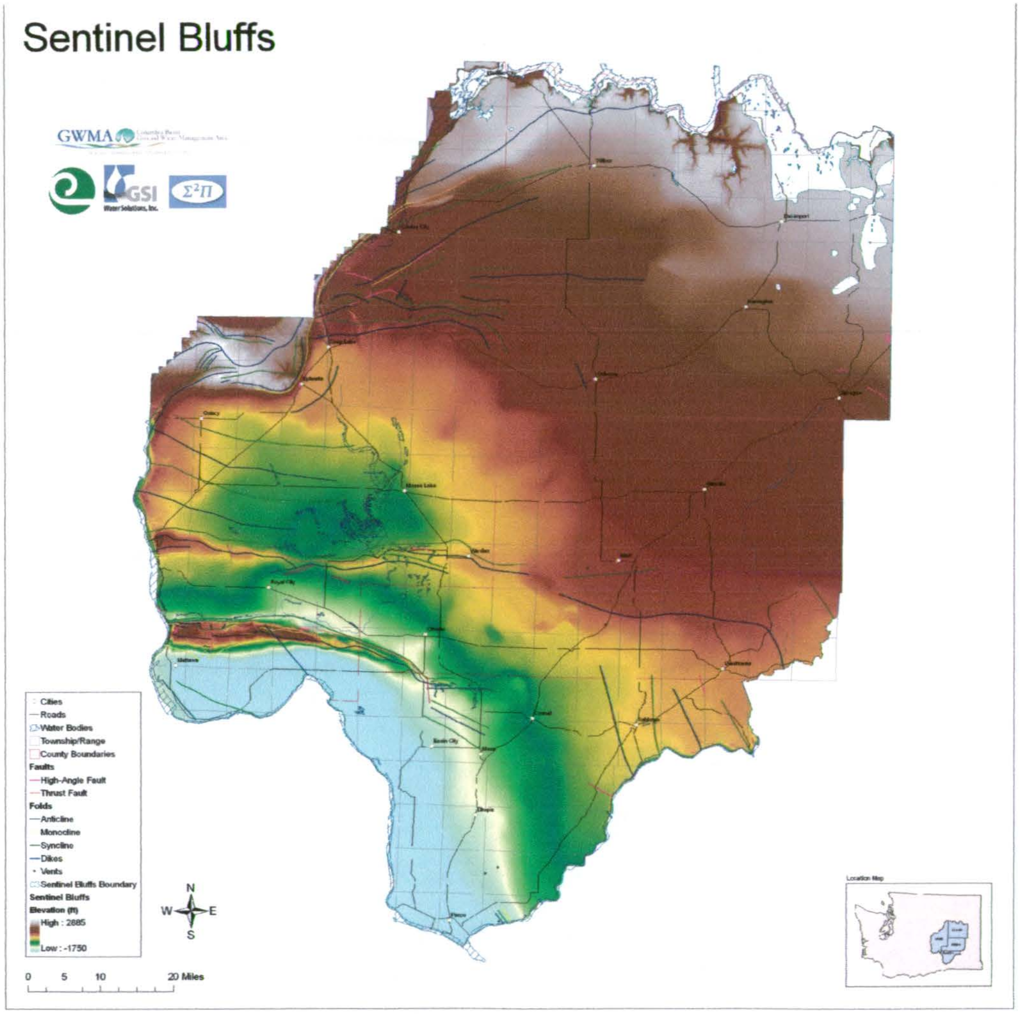
Lake Roosevelt, the reservoir impounded by Grand Coulee Dam, lies on the northern edge of the Columbia Basin and the basalt aquifer system hosted by the Columbia River Basalt. This aquifer system characteristically consists of a series of individual water-bearing zones, or aquifers, that are confined between the widespread layered basalts that comprise the Columbia River basalt. Each of these layers, which are stacked one a top the other, typically range from 50 to 150 feet thick, and the tops and bottoms of them consist of rubbly to vesicular rock that can host groundwater. The zones between each basalt flow layer are known as interflow zones and they consist of the bottom few feet of one basalt flow layer and the upper few feet of the underlying layer. **Figure 2** shows the extent and elevation of the top of the deeper aquifer system in GWMA, the Grande Ronde system.

Groundwater within this layered basalt system moves down slope (down dip) away from recharge areas. Recharge generally occurs where an interflow zone is close to the ground surface and in contact with surface water, such as a stream, river, lake, or reservoir, or in high precipitation areas. Within the Columbia Basin, high precipitation areas usually are at higher elevations around the edge of the Basin or on high ridges within the basin (where precipitation is significantly higher than in the low land central basin). Surface water, where present, usually is found in the deep coulees and in areas where basalt interflow zones are exposed in major river canyons.

In and near the GWMA, the largest body of surface water is Lake Roosevelt. Given that, the GWMA team looked at the physical relationship between Lake Roosevelt and the basalt aquifer system to evaluate the potential for recharge of GWMA basalt aquifers by the reservoir. This was done using a combination of subsurface geologic maps produced through the subsurface geologic mapping effort and water level data previously collected by the Department of Ecology as part of their long term aquifer monitoring program in the Columbia Basin. Based on this information, GWMA's basic conclusion is that Lake

Roosevelt is not a source of significant, if any, recharge to the Columbia River basalt aquifer system.

Figure 2. This map shows the basic extent and elevation of the top of the more regionally extensive Grande Ronde aquifer system. As will be discussed below, there is only a small amount of natural recharge to this system.



Aquifer hosting interflow zones in the basalt aquifer system, with only one exception within the GMWA, simply do not come into physical contact with Lake Roosevelt. Everywhere along the length of the reservoir within GWMA, basalt almost everywhere is found several hundred feet above the reservoir pool. In fact, the basalt lies atop granite and other older pre-basalt rocks (basement) that are very impermeable. This basement rock physically separates the basalt aquifer system from the water found in Lake Roosevelt. There is no way for water within the reservoir to go up hill across the basement rocks above the reservoir and into the basalt interflow zones found along the crest of the ridges above the Reservoir. **Figures 3 and 4** illustrate this physical relationship.

This observation is confirmed by water level data in a number of wells where Ecology has collected water level data over the past 20 to 30 years. Water levels in these wells are several hundred feet higher than the pool elevation. If the primary recharge mechanism for the basalt aquifer system being measured by these wells was the reservoir, water levels in them would be at or below the reservoir pool elevation. This tells us that the primary influence for water level in these wells is related to recharge at elevations higher than the reservoir pool. **Figure 3** shows this relationship.

Figure 3 also shows the presence of a basement ridge buried beneath the basalt and separating the basalt aquifer system from the reservoir pool. This ridge, which our mapping shows extends the full length of Lake Roosevelt on the northern edge of GWMA, provides a further physical barrier to recharge of the basalt aquifer system by the reservoir.

Figure 3. In this north to south cross-section we see water levels in basalt wells up to 500 feet higher than the Lake Roosevelt pool. Water from the lake is not the source of the water seen in these wells. Granite buried beneath the basalt prevents water from moving south out of the lake and into the basalt aquifer system.

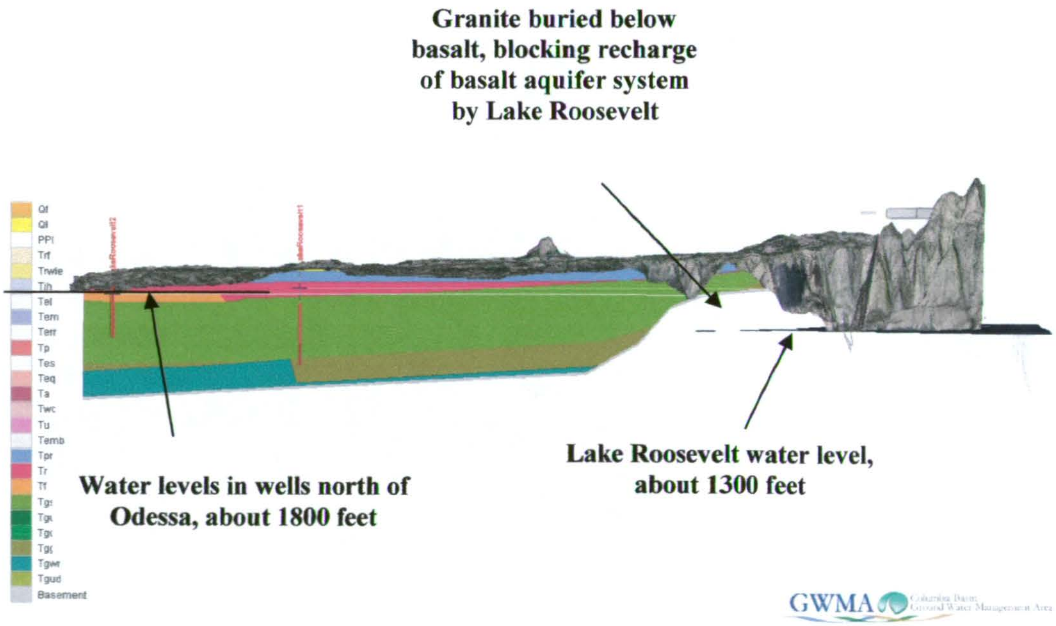
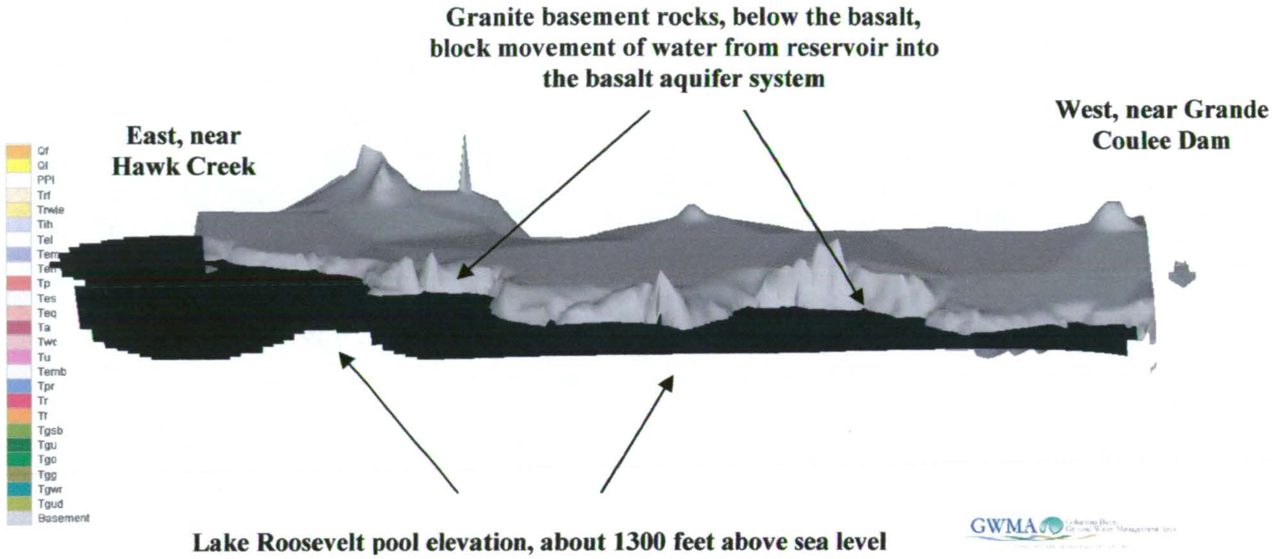


Figure 4. In this view we are looking from the north to the south, across Lake Roosevelt we see the granite basement which underlies the basalt aquifer system cropping out above the Lake Roosevelt pool. This prevents recharge of the basalt aquifer system by the lake.



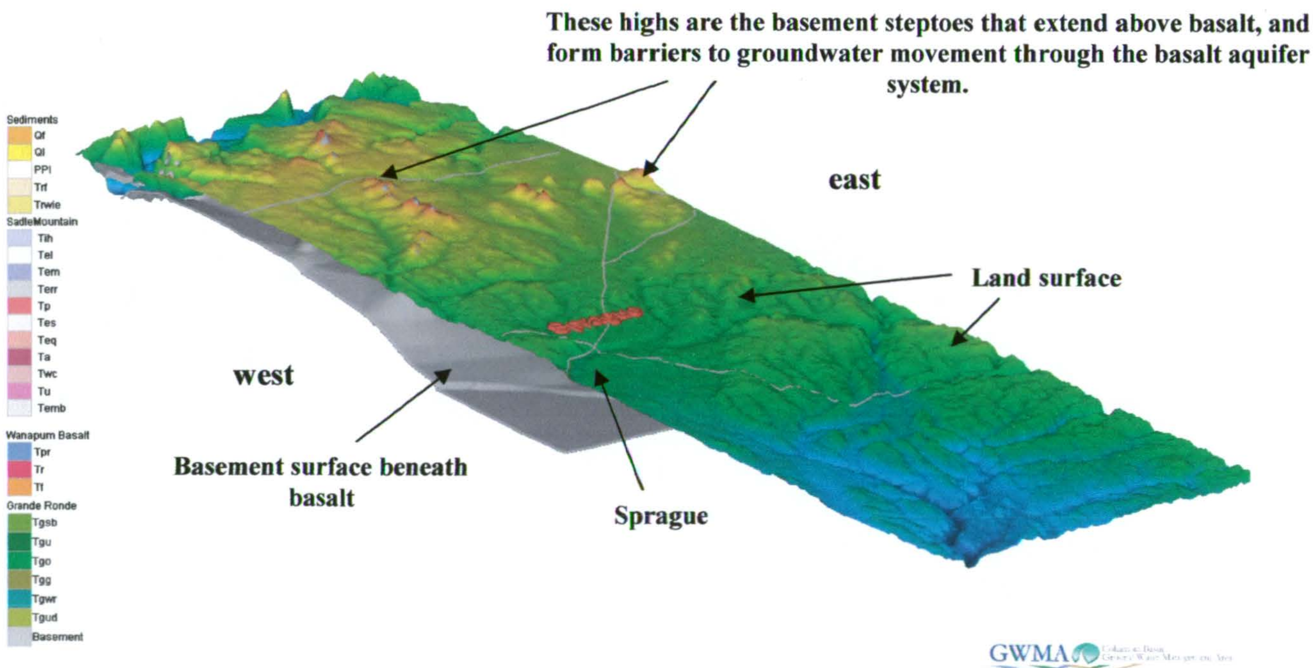
The one exception to this is at Hawk Creek north of Davenport, Washington. In this area the basalt system does come into physical contact with the reservoir, and local basalt water wells suggests local recharge of basalt by the reservoir. However, GWMA's subsurface basalt mapping again shows that the buried basement surface may be high enough south of the reservoir to greatly restrict, if not completely block, the southward movement of reservoir recharge through the basalt and into the regional basalt aquifer system.

The results of this portion of the project lend a certain imperative to the proposed Lincoln County Rehydration Project. As was pointed out at the beginning of this report, and as will be described later in this report, modern, regional, natural ground water recharge has likely not occurred since the end of Pleistocene Cataclysmic Flooding 10,000 or more years ago. This is simply due to the physical disconnect between the basalt aquifer system and the Columbia River in the upper end of the GWMA, namely Lake Roosevelt. An effort like the proposed Lincoln County project is one way to redress this lack of modern, regional recharge.

RECHARGE FROM THE EAST OF GWMA

The subsurface geologic mapping effort coupled with the ground water geochemical sampling results from GWMA's 2008 efforts provides intriguing clues about potential basalt aquifer recharge in the eastern portion of GWMA. The subsurface geologic mapping effort traced the extent of buried basement highlands within GWMA southwards in the eastern portion of Lincoln County **(Figure 5)**. In this part of GWMA, as well as the eastern portion of the State, these buried basement highlands occasionally come to the surface, forming hills projecting above the basalt. Such a hill, known as a steptoe, are like their namesake Steptoe Butte, common in northeastern Lincoln County (in GWMA) as well as western Spokane County and central Whitman County. In GWMA's eastern Lincoln County these buried hills potentially form barriers to groundwater movement from the higher precipitation areas along the Idaho/Washington border into the greater GWMA region. Such a barrier would prevent, or severally limit, ground water in western Spokane County, if present, from moving west into GWMA.

Figure 5. This map projection for eastern Lincoln County and adjacent portions of western Spokane County shows the presence of the steptoes in this area that form basement highlands that block ground water movement from west to east, out of Spokane County and into the GWMA.



South of this area though, basically from the area around Sprague, Washington and south to the Snake River the steptoe system may not exert the same basic controls. In this region the presence of surface streams, upper Crab Creek, Sprague Lake and Cow Creek, and the Palouse River all point to at least the potential for basalt aquifer recharge from surface water. Ground water geochemistry for basalt wells just a few miles west of Sprague Lake is suggestive of relatively young ground water recharge. Unfortunately, at this time GWMA investigators have not been able to determine the fate of this relatively young recharged ground water. Anecdotal comments by local well owners, and the inferred presence of a major basalt dike system suggests this recharged ground water does not move west into the central GWMA in any significant quantity.

What we have seen in the Sprague Lake area causes us to look in other areas of the GWMA where relatively plentiful surface water is present and can act as a potential recharge source for ground water. GWMA investigators have identified several areas where surface water is present in some quantity, the geologic framework appears favorable for ground water recharge, and anecdotal comments by local well owners suggest long-term water level declines as a result of historical and current ground water pumping has not been a problem. These areas include the vicinity of lower Banks Lake, the lower Palouse River, and the Snake River at and below Lower Monumental Dam. With further investigations, these and other similar, but now dry portions of the GWMA (such as Lake Creek in Lincoln County) will provide GWMA stakeholders with important clues on how to manage the aquifer system.

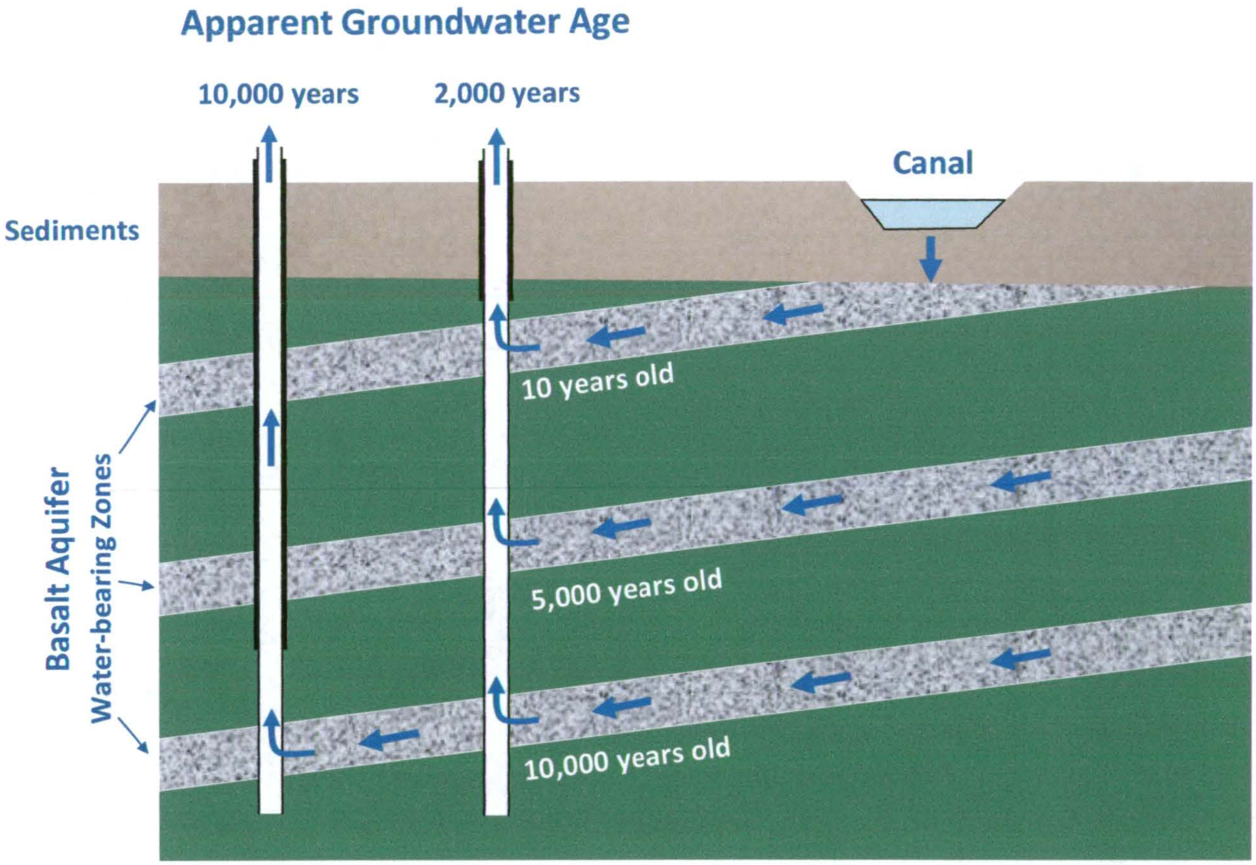
GROUND WATER GEOCHEMISTRY, AGE, AND RECHARGE RELATIONSHIPS

The water sources that recharge the aquifer system, and the length of time it has taken for water from various sources to arrive at the location of a given well are recorded in the chemistry of groundwater. In particular, different recharge sources (ancient glacial melt water, irrigation waters, and recharge from present-day surface waters such as lakes, rivers, and canals) can be identified using geochemical tracers and groundwater dating methods.

As part of this study to characterize the aquifer system, selected irrigation, municipal and private supply wells, as well as surface water bodies representing potential recharge sources, were sampled and analyzed for a suite of geochemical and isotopic parameters including major and trace element concentrations, stable isotopes, dissolved gases and age tracers (radiocarbon, tritium, atmospheric chlorofluorocarbons or CFCs) in order to elucidate the origins and hydrochemical evolution of the groundwater and, in particular, to evaluate recharge relationships and timescales in the deeper basalt aquifer system. Tritium and CFCs are used to identify and quantify recent recharge components (a few decades to a few years old), whereas radiocarbon is useful for identifying groundwater that is hundreds to tens of thousands of years old. By combining data for age tracers with different characteristic timescales, it is possible to estimate the time elapsed since the water entered the subsurface and also to identify mixtures of older and younger groundwater in production wells. This information was used in conjunction with the geologic model to identify connections to current potential sources of recharge in the aquifer system.

As shown in **Figure 6**, relatively young groundwater recharge ages (less than 50 years) are generally found for shallow wells open to unconfined sediment aquifers, indicating direct connections to present day recharge sources (canals, seasonally water-filled coulees, creeks and lakes). In samples from some deeper municipal supply wells in basalt which are open over large vertical intervals, age tracers indicate the produced groundwater is a mixture of old (thousands of years) and young water entering from different flow zones with different connections to present day recharge. This data is used in combination with static water level trends, to evaluate the sustainability of current water extraction rates on a local and regional scale. Radiocarbon and stable isotope data, and the absence of detectable tritium and CFCs, indicate that groundwater produced from deep irrigation wells in the Odessa area completed in the lower Grande Ronde basalt layers is more than 10,000 years old. This part of the aquifer system has not been recharged since the end of the last ice age when climate conditions were cooler and wetter than present. Some specific examples of these findings are given below.

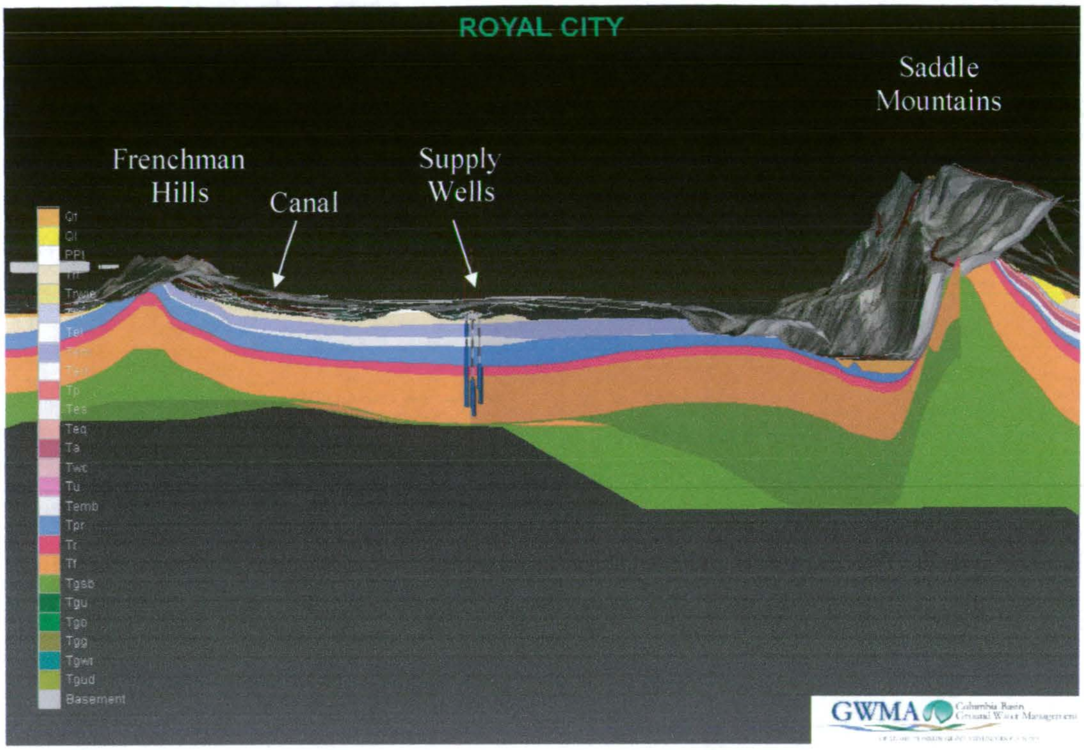
Figure 6. Age tracer data and apparent groundwater recharge ages are used to identify connections to present day recharge sources.



Royal City – Recharge to Wanapum Aquifers Keeps Up With Demand (Figure 7)

In the Royal City area in western Grant County, between the Frenchman Hills and the Saddle Mountains, municipal supply wells completed in the shallow basalt system (Wanapum) have apparent radiocarbon ages up to 1300 years old and detectable tritium indicating that part of the groundwater is less than 50 years old. This is direct evidence of a mixture of older water probably originating as precipitation on the Frenchman Hills and as well recent recharge from leakage beneath the nearby Frenchman canal. Static levels in these wells are stable, indicating that the recharge from natural and anthropogenic (canal leakage) sources is sufficient to meet municipal water demands in this part of GWMA.

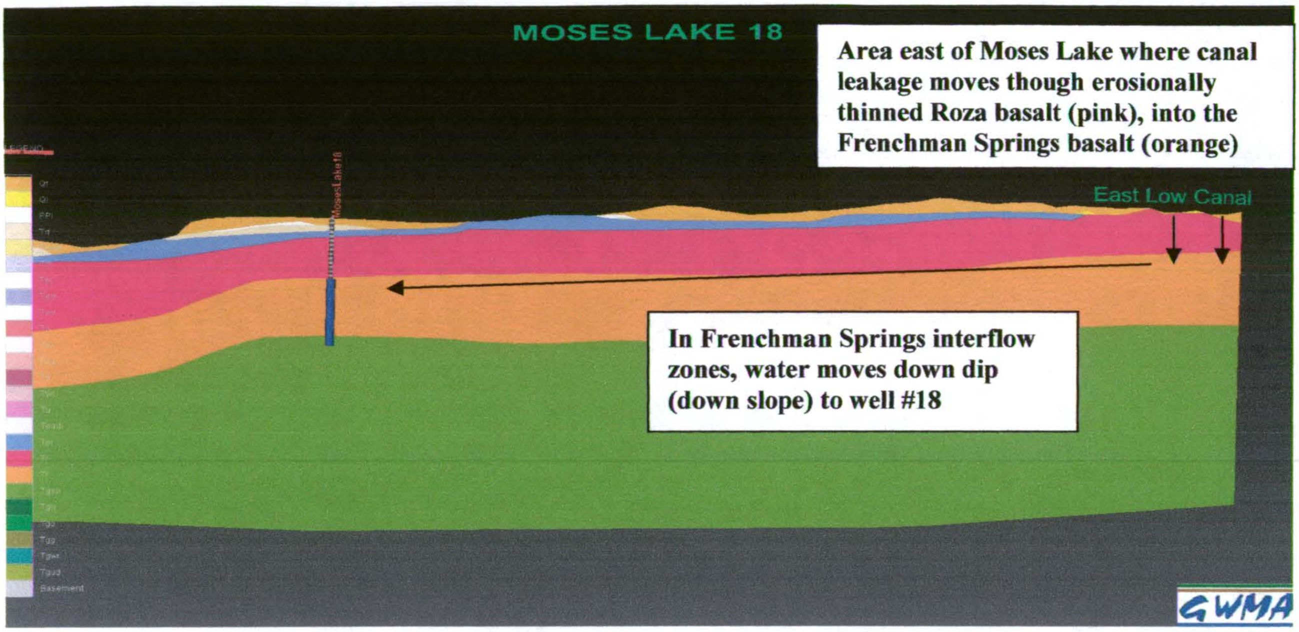
Figure 7. Royal City supply wells produce a mixture of old and young water derived from a combination of leaky canals and natural recharge on the nearby Frenchman Hills, respectively.



Moses Lake Well 18 – Wanapum Well Recharged by the East Low Canal (Figure 8)

Moses Lake Well 18 is also completed in the Wanapum (Lower Roza and Frenchman Springs Formations) and has historically stable static water levels. The water from this well is less than 50 years old as indicated by radiocarbon, tritium and CFC data, which implies a direct connection to nearby East Low Canal through Roza/Upper Frenchman Springs flow zones.

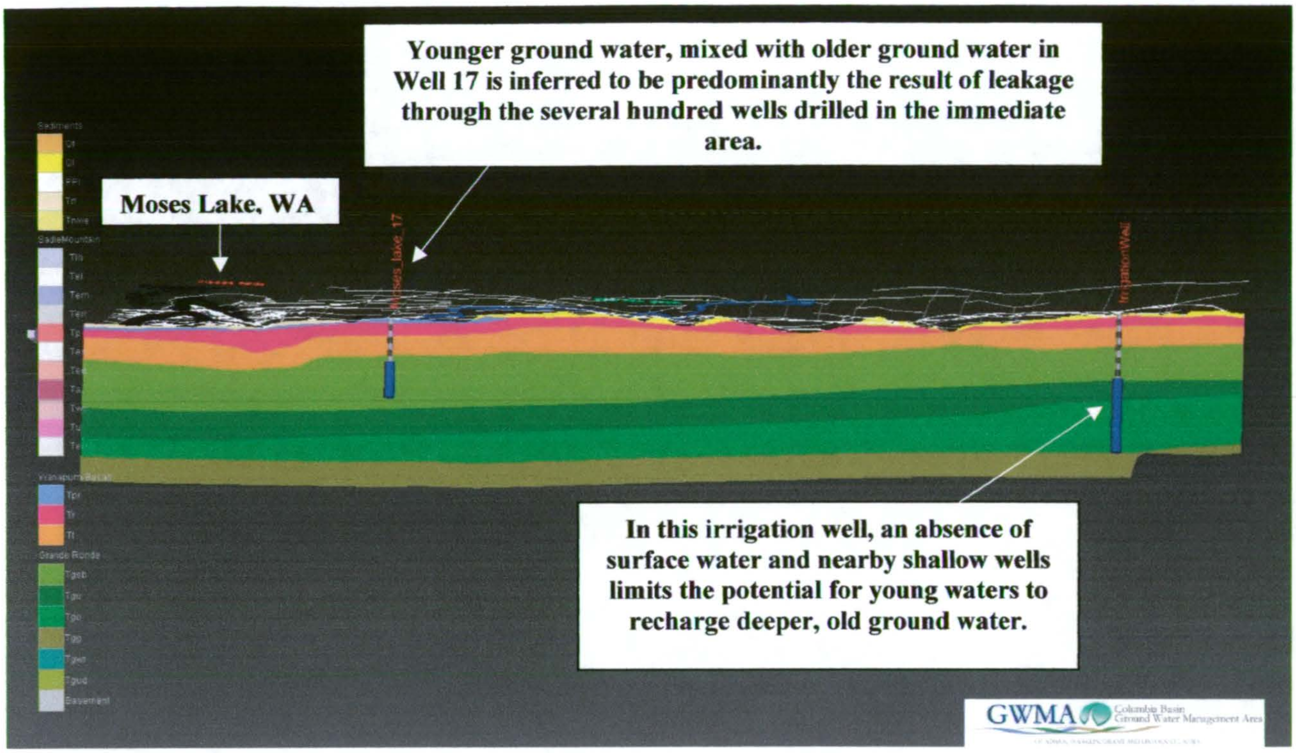
Figure 8. Moses Lake Well 18 receives most of its recharge from canal leakage. Nearby, the lower Roza and upper Frenchman Springs units are cut by the East Low Canal, thus providing a direct connection to surface water recharge.



Moses Lake Well 17 – Upper Grande Ronde Well With Limited Recharge (Figure 9)

Moses Lake Well 17 is a deep well sealed into the Upper Grande Ronde (Sentinel Bluffs). Static water levels in this well are declining. The apparent radiocarbon age for groundwater produced by this well is approximately 6000 years, but contains detectable tritium, indicating a mixture of old and young water. The proportion of recharge from young water component is estimated to be less than 20 % and is too little to offset withdrawals (i.e. 80 % of the water production is derived from storage, therefore water levels are declining). There are no geologic features indicating a direct connection to surface water, therefore the young recharge component likely represents limited vertical leakage through the many uncased wells present in the vicinity of the town of Moses Lake. Current production rates from this well therefore are not sustainable as there is no reliable source of recharge to this part of the aquifer.

Figure 9. Moses Lake Well 17 (left) in the Upper Grande Ronde sees minor evidence of leakage from shallow water sources. In a deep irrigation well about 20 miles east of Moses Lake which is constructed deeper into the Grande Ronde aquifer system shows no geologic connection to present recharge sources.



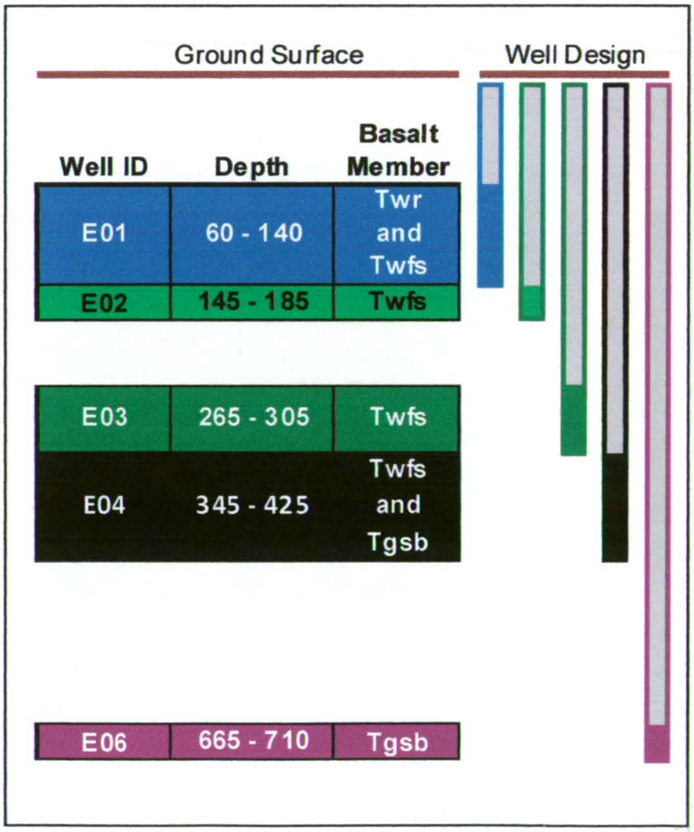
Odessa Area Deep Irrigation Wells – No Recharge to Lower Grande Ronde (Figure 9)

Deep irrigation wells sealed into the Lower Grande Ronde aquifer system in the Odessa subarea approximately 20 miles east of Moses Lake have declining static water levels, apparent radiocarbon ages ranging from 10,000 to 20,000 years and generally no detectable tritium or CFCs. In one example illustrated in Figure 4, a recently drilled well completed in the Umtanum and Ortley units with an apparent radiocarbon age of 15,800 years shows no geologic connection to any surface water recharge sources. The groundwater produced from this well is essentially non-renewable.

HISTORICAL GROUND WATER LEVEL DATA

Ecology has measured groundwater levels for up to 40 years in numerous wells distributed throughout the Columbia Plateau and the GWMA. As part of this effort, Ecology and the U.S. Geological Survey (USGS) constructed a number of multi-level observation well clusters around the GWMA in the 1970s and early 1980s to evaluate the state of the groundwater resource and the response of the basalt aquifers to development away from the direct influence ("noise") of a pumping well. **Figure 10** shows a schematic representation of one of the multi-level well clusters.

Figure 10. This diagram shows the design of a multi-level well cluster south of Odessa. A multi-level observation well actually consists of a collection of several wells in a single borehole with each well extending to a different depth and open to a different interflow zone(s). Cement grout plugs are used to seal the space between each well to prevent leakage between the zones monitored in the borehole.



Groundwater elevation measurements obtained during the same discrete time period can be used as an indicator of possible connection between groundwater and surface water and how well connected the basalt interflow zones are laterally and vertically. Regular measurements taken over a number of years, particularly from non-pumping wells, provide a record of pumping and recharge to the interflow zones monitored by the well. The water level measured in each well represents the water pressure in the interflow zone(s) open to the well. Similarities and differences in the levels and the trends between each well of a multi-well cluster define the relationship with interflow zones monitored each wells in the cluster. If good vertical connection exists between interflow zones, we would expect the water levels in different zones to be similar, and to react similarly over time. Conversely, differences in levels and/or trends indicate vertical separation between the monitored zones.

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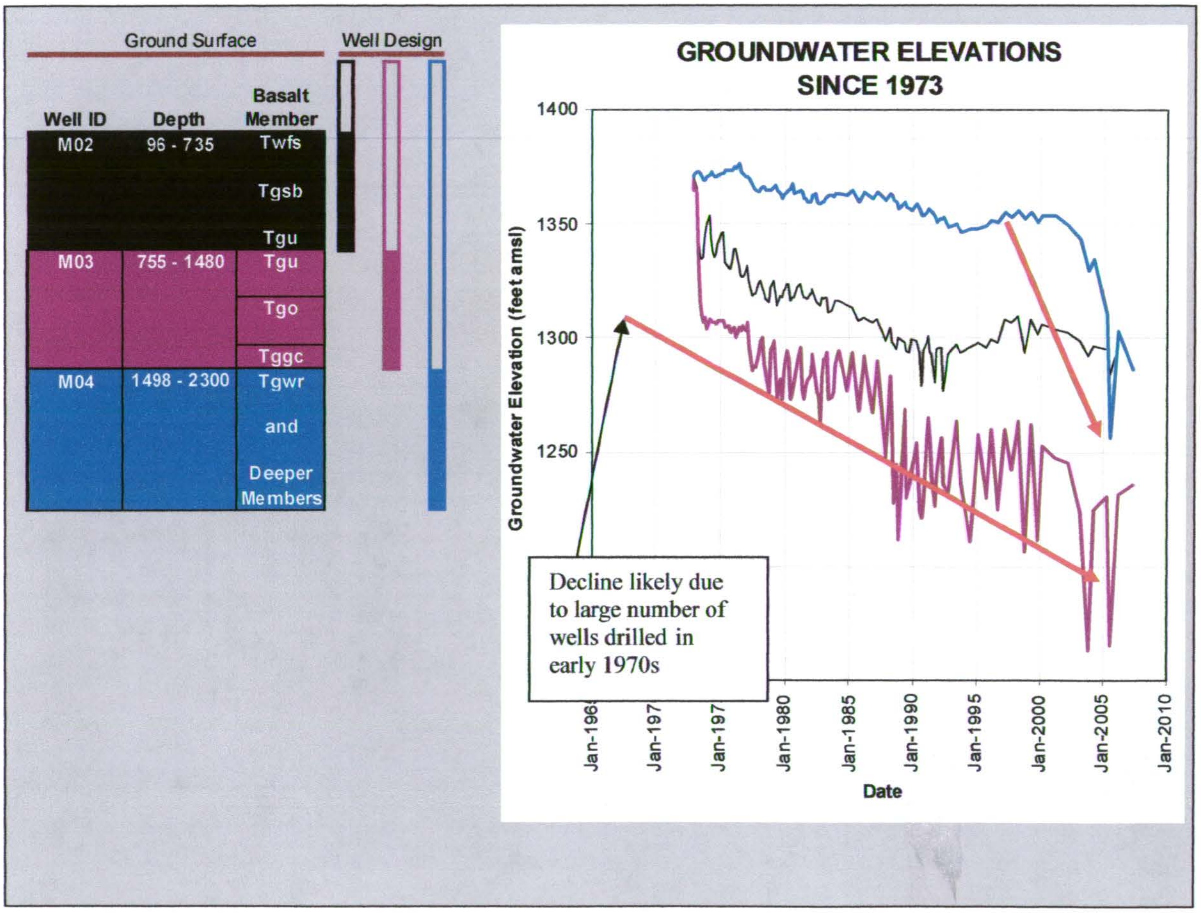
Observations from Multi-level Well Clusters

Review of historical groundwater levels from multi-level well clusters demonstrate that there is little vertical flow between the basalt interflow zones, and the aquifers comprised of these zones are separate and distinct. The water levels from multi-level well clusters located throughout the GWMA corroborate this observation. **Figures 11 and 12** show a vertical profile of historical water level trends in two different parts of the GWMA.

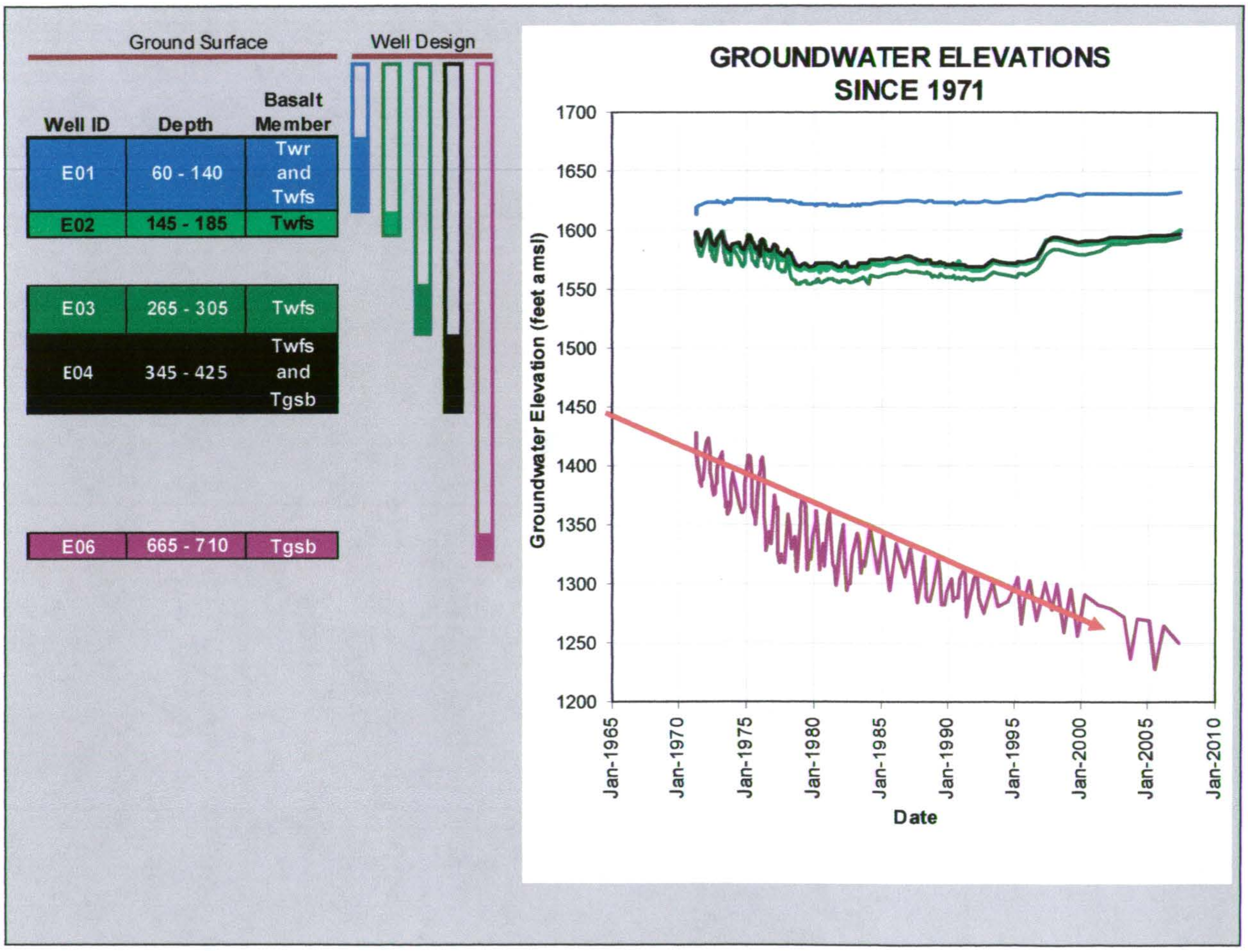
Figure 11, which depicts water levels from a multi-well cluster west of Odessa, shows that each zone has a distinctly different water level. While all three zones show declining water levels from the beginning of monitoring in 1973, each zone shows a different trend, and those differences are maintained over the entire record. The shallowest zone (M02) experiences the most declines between 1973 and 1990, whereas the deepest zone (M04), exhibits a lesser water level decline over the same period, followed by a drastic increase in the rate of decline after 2000. This increase in the rate of decline in the deeper zone reflects the shift in pumping from shallower to deeper aquifers in the Odessa area. The relatively high water level in the deepest zone illustrates a high degree of confinement and isolation from the shallower zones. While the drilling into the deep zone would restore the water level in a well that was originally completed in one of the shallower zones, the sharp rate of decline also shows that the deepest zone is isolated from the others, and that the higher water level condition realized by drilling into deeper zones is temporary.

Figure 11. This diagram shows the historical water level record since 1973 for a multi-level well cluster located west of Odessa. The three wells shown from this cluster are open to different intervals between the lowest portion of the Wanapum Basalt (Twfs) and the deeper members of the Grande Ronde Basalt.



The water levels in the multi-level well cluster shown in **Figure 12** also show that each zone is vertically distinct and separate. The water levels in wells completed in Wanapum interflow zones are significantly higher than the well completed in the Grande Ronde and show recovery from pumping in the 1970s. Water levels in the Grande Ronde show relatively heavy pumping pressures and decline throughout the period of record.

Figure 12. This diagram shows the historical water level record since 1971 for a multi-level well cluster located in southern Adams County. Three of the wells shown from this cluster are open to the Roza and different portions of the Frenchman Springs members of the Wanapum Basalt. A fourth is open to the bottom of the Wanapum and top of the Grande Ronde Basalt. The fifth (B05) is open to the upper Grande Ronde Basalt.



Water level elevations and historical trends in multi-level well clusters in the GWMA were evaluated with respect to the geologic framework of the Columbia River Basalt. The water level data clearly show that basalt interflow zones form separate and distinct aquifers. In addition, the data corroborate anecdotal evidence that groundwater levels in the monitored aquifers hosted by the

Grande Ronde Basalt are declining. Declines in the aquifers in the Grande Ronde in areas where deep well irrigation is prominent commonly exceed 100 to 150 feet. These observations have several implications:

First, the data show that natural recharge to the aquifers in the Grande Ronde Basalt is minimal, and at a slow rate where it occurs. Recharge to the aquifers in the Grande Ronde Basalt is minimal because of the lack of vertical connection between shallow and deep aquifer zones, and a sparcity of both possible recharge locations and recharge water. The potential for recharge decreases with depth in the Grande Ronde. Specific reasons that recharge to the aquifer zones in the Grande Ronde Basalt is minimal include:

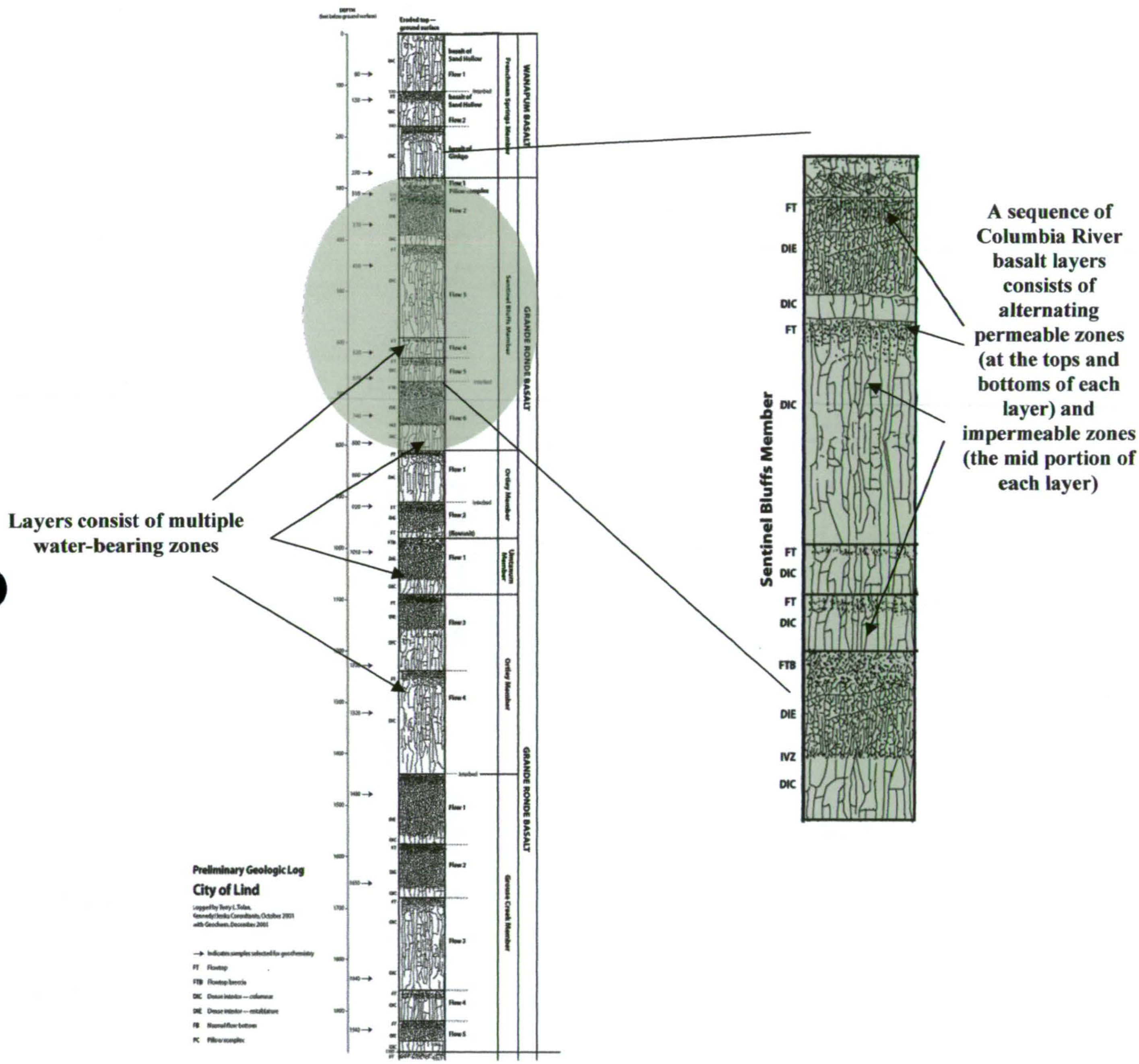
- There are few places where interflow zones that can receive recharge are exposed to surface water or precipitation, and the amount of exposure diminishes to zero with depth in the Grande Ronde Basalt. In other words, the deeper aquifers in the Grande Ronde are not connected to surface waters anywhere in the GWMA.
- The interflow zones that are exposed are relatively thin and do not provide much area for precipitation or surface water to infiltrate.
- Leakage from shallower basalt interflow zones to deeper zones is very small.
- Precipitation and winter/spring runoff is small in magnitude compared to pumping.

A second implication of the ground water level record in GWMA wells is that existing groundwater supplies in the deeper basalt units are not reliable or sustainable in the long-term, and thus continuing to drill deeper into progressively lower aquifers in the Grande Ronde Basalt is only a temporary solution for declining water levels and pumping rates.

GEOLOGIC CONTROLS ON COLUMBIA RIVER BASALT AQUIFER SYSTEM IN THE GWMA

The thick sequence of layered flood-basalt flows of the Columbia River basalt are prime sources of potable groundwater throughout their extent in Washington, Oregon, and Idaho. Having a realistic and accurate understanding of how ground water enters and moves through these flood-basalt flows is of fundamental importance to anyone working with Columbia River basalt aquifer systems (e.g. resource assessments, contaminant transport/fate, aquifer storage/recovery, regulatory assessment).

Figure 13. This drawing shows the presence of multiple, permeable layers within a typical sequence of Columbia River basalt. These layers, which usually occur every 50 to 150 feet, have the potential old ground water, if they can receive recharge.



One of the most extraordinary features of the Columbia River basalt is the physical dimensions of individual basalt flow layers. A conceptual understanding of the nature of Columbia River basalt flows plays a critical role in accurately interpreting some of the unique hydrogeologic aspects of the basalt. During the peak period of basalt eruptive activity (Grande Ronde and Wanapum Basalts) it was common for eruptive events to rapidly (~2 to ~12 weeks) emplace individual flows having volumes of 500 to >1,000 mi^3 and for the lava to cover areas >10,000 mi^2 creating the largest known lava flows on the Earth. This combination of huge volume and rapid emplacement typically produced simple sheet flows 50 to >300 feet thick.

Columbia River basalt flows are typically very widespread, covering an average area of 10,000 mi^2. This, coupled with the physical geologic characteristics of CRBG flows indicates they formed as lateral extensive, uninterrupted sheets. This differs markedly from more typical compound basalt flows which display numerous, interfingering, discontinuous, lenticular layers. The net hydrologic result of this is that the aquifers within the sheet flows typical of the CRBG occur as a series of layered, tabular, confined features whereas **(Figure 13)**.

Aquifer horizons within the Columbia River basalt generally are associated with intraflow structures at the top (e.g., vesicular flow-top, flow-top breccias) and bottom (e.g., flow-foot breccias, pillow lava/hyaloclastite complexes) of sheet flows **(Figure 13)**. The interiors of thick sheet flows (in their undisturbed state) are for all practical purposes essentially impermeable and act as aquitards, typically creating a series of "stacked" confined aquifers within the Columbia River basalt aquifer system.

The dominant groundwater flow pathway within this aquifer system is horizontal to sub-horizontal along individual, laterally extensive, interflow zones. Given the physical properties of the Columbia River basalt, outcrop observations, and interpretations of well hydraulics vertical groundwater movement through undisturbed basalt flow interiors is small to essentially non-existent. However, vertical groundwater movement between layered CRBG aquifers is possible, but occurs predominantly under specific geologic conditions where basalt flow interiors are disturbed or truncated.

Figures 14, 15, 16, 17, and 18 illustrate the main geologic features that influence the lateral continuity of Columbia River basalt layers and the characteristics of the aquifers within them.

Figure 14. This photograph shows basic geologic relationships in a fault zone.

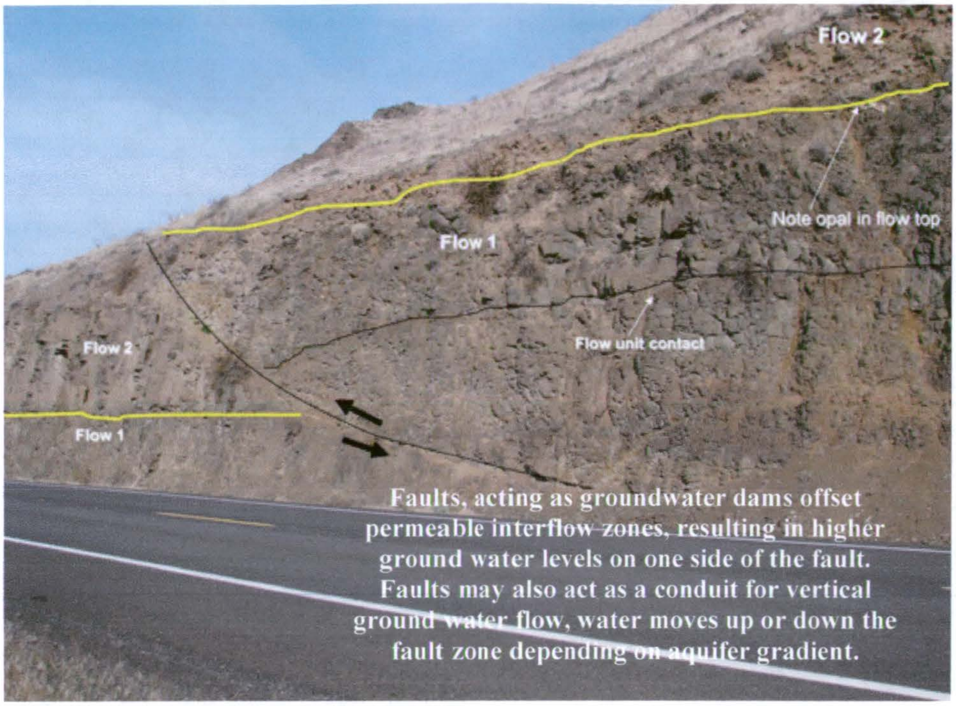


Figure 15. Folds also can control the basalt aquifer system, usually forming barriers to ground water flow, and subdividing the aquifer system into ground water sub basins. Ground water systems on either side of these folds typically do not display significant hydrologic connection.

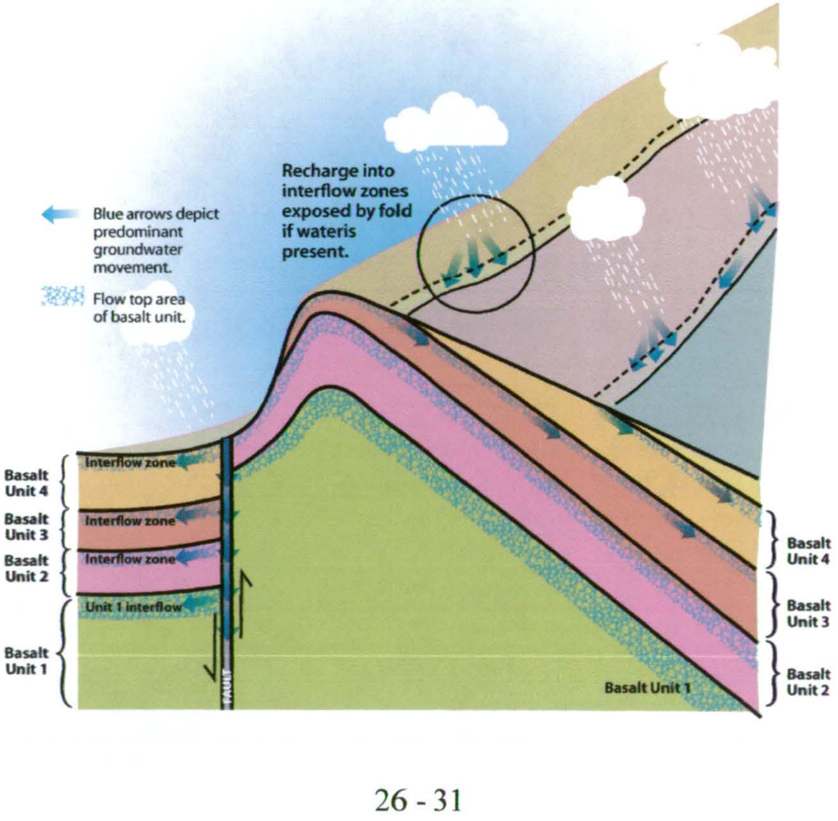


Figure 16. Feeder dikes, from which Columbia River basalt lave flows erupted millions of years ago, form long, nearly vertical subsurface features which probably form boundaries to groundwater flow.

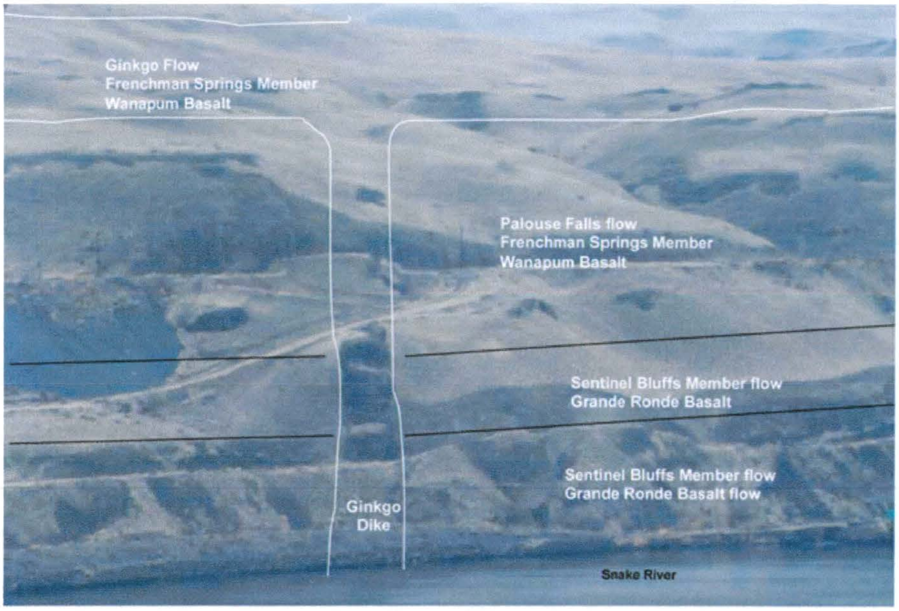
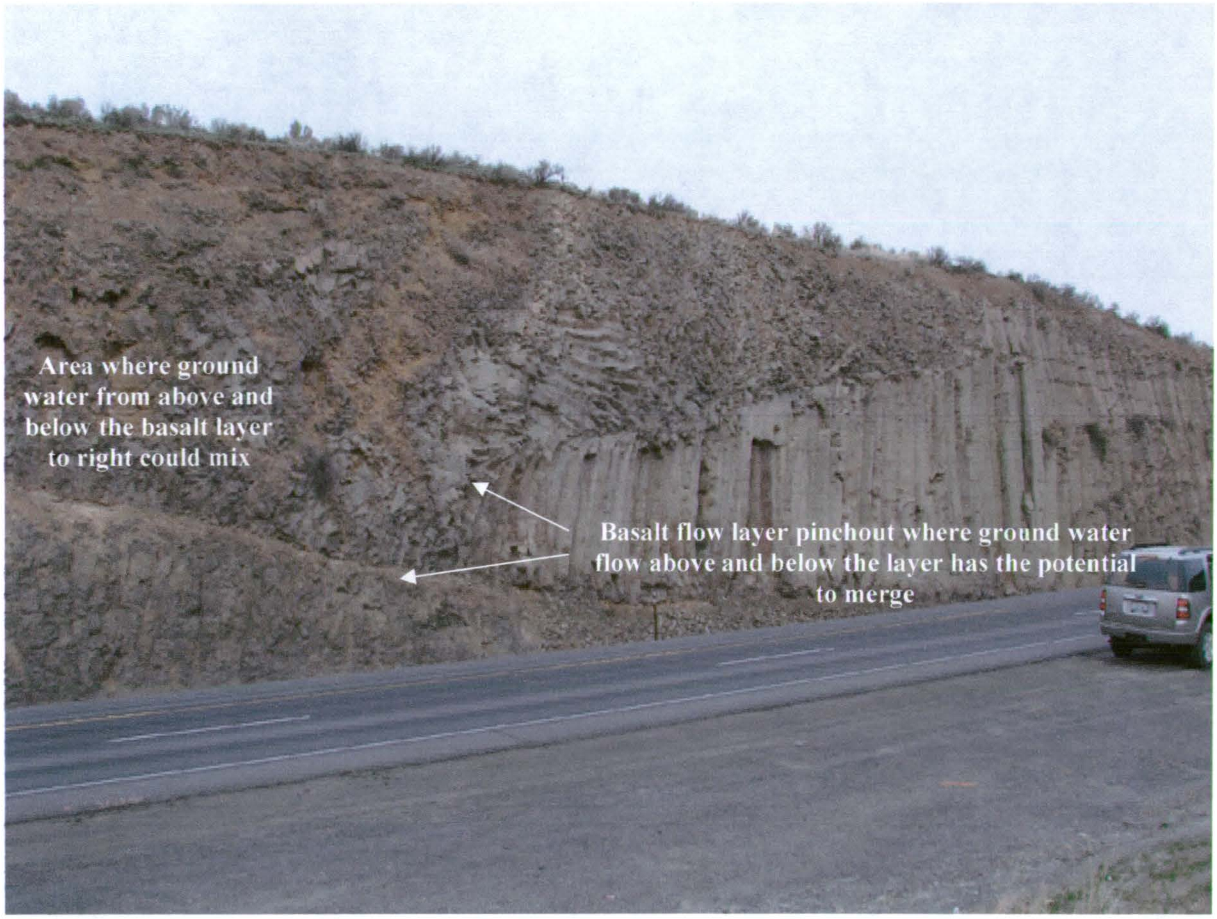


Figure 17. Columbia River basalt flow layers are known to pinch out. These pinchouts essentially mark the lateral termination of individual basalt flow layers. Where layers pinchout, the impermeable flow interior is absent and potentially water-bearing flow tops and bottoms are in direct hydrologic connection. Flow margins create very limited (single flow) vertical connections.



The current Columbia Basin GWMA subsurface geologic mapping and aquifer assessment project has mapped the distribution of the major geologic units comprising the CRBG aquifer system, and the features within it that potentially effect the lateral distribution of individual aquifers. In addition, this work, which includes an evaluation of water level trends and ground water geochemistry, provides GWMA scientists with important clues into the nature of:

(1) Aquifer continuity and extent,

(2) Aquifer interconnection, or the lack of that interconnection,

(3) Ground water recharge and the potential age of ground water within the CRBG aquifer system, and

(4) Ground water discharge, or the lack of that, especially from deeper portions of the system.

The results of this project also give GWMA stakeholders insights into how to better manage the aquifer system, including ways to evaluate recharge project feasibility.

Figure 18. Deep coulees cut into basalt layers, allowing interconnection of successive interflow zones. The coulees also expose interflow zones to surface water and shallow groundwater. Interflows may discharge to, or be recharged from, coulees (or both). Erosional channels (such as coulees) can breach multiple basalt layers creating the potential for a more extensive vertical connection.

CONCLUSIONS - CONCEPTUAL GROUND WATER MODEL FOR THE GWMA

Based on the observations and interpretations summarized here, ***the ground water recharge and flow system in the Columbia River basalt aquifers underlying the GWMA is characterized by a series of separate, water-bearing layers found in interflow zones at the tops and bottoms of individual basalt flow layers. These interflow zone layers, or aquifers, are separated by the dense, solid, unfractured basalt rock that forms the bulk of the basalt geology of the Columbia Basin. The places where these interflow zone aquifers can receive recharge are where they are at and near the surface in direct hydrologic connection with surface water and high precipitation areas. Once water enters these zones it moves more-or-less horizontally along individual basalt flow layers. Vertical movement of ground water through dense, uninterrupted basalt flow layers is small.***

The data and information upon which our basic understanding of the basalt aquifer system underlying the GWMA is based provides us with some important understandings of ground water recharge and occurrence, including:

1. ***Natural recharge of the Columbia Basin GWMA basalt aquifer system across the region is limited, but there is evidence of locally important recharge in some areas.***
2. ***Beneath much of the eastern GWMA, including the Odessa Sub-Area deep basalt ground water is very old and experiences very little modern recharge.***
3. ***In the central GWMA deep basalt ground water also is very old, but some modern artificial recharge is occurring via artificial and natural pathways.***
4. ***Basalt aquifers in the GWMA are subdivided by a variety of geologic features which limit, and in some cases block, both vertical and lateral ground water movement. Ground water levels in some of these areas has experienced little significant decline, while in others it has dropped several hundred feet.***
5. ***The last period of significant natural regional recharge of the basalt aquifer system occurred over 10,000 years ago, near the end of, or following, Pleistocene Cataclysmic Flooding.***

These findings, and the data and information upon which they are based, provides GWMA stakeholders with the tools and knowledge to:

1. Better evaluate changing aquifer conditions related to ground water pumping and recharge.
2. Develop monitoring, modeling, and mitigation measures that address areas of concern and can be used to track improvements in the aquifer system as a result in changes in resource management.
3. Prioritize resources to be used to address ground water concerns in and around the GWMA.

Columbia Basin groundwater research, new project discussed at conference

The nearly decade long geologic mapping and aquifer assessment work by the Columbia Basin Ground Water Management Area (GWMA) was highlighted last month during the Geological Society of America's annual conference in Portland, Ore.

"This is a great honor and a testament to the integrity of the GWMA's research. We have generated an important view of this complex, multi-layered ground water system and I'm looking forward to our scientific research being showcased at this prestigious academic event," commented executive director Paul Stoker.

Stoker was the leadoff speaker for the Monday afternoon session with his presentation, "Aquifer Declines and Scant Modern Recharge in the Columbia Basin Ground Water Management Area."

GWMA science team leaders joining Stoker at the conference and providing presentations include four scientists with GSI Water Solutions, Inc.: hydrogeologists Dr. Kevin Lindsey, John Porcello and Walt Burt; basalt geologist Terry Tolan; and Dr. Dimitri Vlassopoulos, a geochemist with S.S. Papadopulos. The team also submitted seven scientific papers summarizing the study's research methodology and key findings.

This year the state Legislature appropriated $2.5 million for GWMA to create a working hydrologic ground water model and assess the feasibility of aquifer storage and rehydration of the depleting ground water table in the Columbia Basin. The organization has to complete the model and submit a report by July 1, 2011.

GWMA is currently finalizing project planning and work scope documents with the state Department of Ecology for conducting the hydrology study, which will build on the organization's subsurface mapping and aquifer assessment research.

Lindsey, who is leading the modeling effort, summed up the new legislative directive: "Our job is to create a working ground water hydrologic model and determine the potential for rehydrating the aquifers and creating ground water storage. The results of our research to date reveal ground water in the Columbia Basin is mostly ancient with only minor recharge occurring in particular ground water sub-basins. The aquifer assessment research identified the existence of geologic structures that can influence the movement and presence of ground water and create sub-basins."

"Local interest and participation is critical to the success of our research."

GWMA Executive Director Paul Stoker

Remarking on the importance and use of a working hydrologic model, Stoker added, "The ground water model will be a tool to aid decision-making for land use and building permits, aquifer storage and recharge projects, evaluating water permit management and regulation, economic and resource development, water use, well permits and water transfers."

Providing the board with a proposed outline of preliminary sub-basins, Stoker continued, "Our research indicates the four counties can be segregated into eleven potential ground water sub-basins. I would remind the Board that these are preliminary and based on current data, and therefore, subject to change. That being said, this is our best estimate and provides us an important starting point in coordinating public input and data collection."

GWMA ground water sub-basins are defined as areas where geologic structures and conditions influence ground water in specific ways that create hydrologic differences between ground water areas and users.

In describing the work plans and schedule for the project, Stoker noted "GWMA will be hiring an experienced, master's level hydrogeologist, and a trained GIS analyst to begin ground water sub-basin mapping in the next few months. We anticipate starting field work in January 2010.

"At that time, we will encourage ground water users in the Columbia Basin, in particular municipalities and deep well irrigators, to contact us regarding the modeling research, well use and field tests, and how they fit into these ground water sub-basins," Stoker added. "As you know local interest and participation is critical to the success of our research. Essentially, we're offering well owners and ground water users an opportunity to learn more about their ground water, including how old it is, where it is coming from, and importantly, is it being recharged."

Stoker said the Legislature has requested that the GWMA report to describe ground water conditions, water balance and recharge, and importantly, how much water is needed to address the aquifer decline. The hydrologic model will demonstrate how the system works and the feasibility of recharge – how deep, where, when and how fast.

Regarding likely recharge locations, Stoker said, "The GWMA mapping study suggests where the basalt zones surface are the likely target areas for artificial recharge, so those locations are where we will want to focus our attention."

Information about the Columbia Basin GWMA and the mapping study can be found online at http://www:cbg-wma.org. Well owners and operators in Adams, Grant, Franklin and Lincoln counties are encouraged to contact the project office in Othello at (509) 488-3409 for more information.

Oral Presentations of Hydrogeologic Studies Conducted by the Columbia Basin Ground Water Management Area

2009 Portland GSA Annual Meeting (18-21 October 2009)

Session No. 131 | **Monday, 19 October 2009**

1:30 PM-5:30 PM, Oregon Convention Center: B110/111/112

Sixth Columbia River Basalt Symposium II: Volcanism, Tectonism, Petrology, and Hydrogeology 2009
(Mineralogical Society of America; GSA Structural Geology and Tectonics Division; GSA Hydrogeology Division)

Stephen P. Reidel, Terry Tolan, Victor Camp, John Wolff, Ray Wells, Martin E. Ross and Barton S. Martin, Presiding

Paper #	Start Time	
	1:30 PM	Introductory Remarks
131-1	1:35 PM	AQUIFER DECLINES AND SCANT MODERN RECHARGE IN THE COLUMBIA BASIN GROUND WATER MANAGEMENT AREA (GWMA) OF ADAMS, FRANKLIN, GRANT, AND LINCOLN COUNTIES, WASHINGTON: **STOKER, Paul**, Columbia Basin Ground Water Management Area, 449 E. Cedar Boulevard, Othello, WA 99344, pstoker@smwireless.net
131-2	1:55 PM	GEOLOGIC FEATURES IN THE COLUMBIA RIVER BASALT GROUP (CRBG) AQUIFER SYSTEM THAT FORM VERTICAL FLOW PATHWAYS AND SUBDIVIDE THE REGIONAL GROUNDWATER FLOW SYSTEM: EXAMPLES FROM THE COLUMBIA BASIN GROUND WATER MANAGEMENT AREA (GWMA) OF SOUTH-CENTRAL WASHINGTON: **LINDSEY, Kevin A.**, GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336, klindsey@gsiwatersolutions.com, TOLAN, Terry, GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, PORCELLO, John, GSI Water Solutions, Inc, 55 SW Yamhill, Portland, OR 97204, and BURT, Walt, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204
131-3	2:10 PM	EFFECTS OF FAULTS AND STRATIGRAPHIC VARIABILITY ON GROUNDWATER FLOW IN COLUMBIA RIVER BASALT GROUP AQUIFERS: **BURT, Walt**, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204, wburt@gsiwatersolutions.com, WELLS, Ray E., U.S. Geological Survey, 345 Middlefield Rd, MS 973, Menlo Park, CA 94025, CONLON, Terrence D., Oregon Water Science Center, U.S. Geological Survey, 2130 SW 5th Ave, Portland, OR 97201, TOLAN, Terry L., GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, and PORCELLO, John J., GSI Water Solutions, Inc, 55 SW Yamhill Street, Suite 400, Portland, OR 97204
131-4	2:25 PM	INFLUENCE OF WELL CONSTRUCTION ON WATER LEVEL INTERPRETATIONS IN AQUIFERS OF THE COLUMBIA RIVER BASALT GROUP: **PORCELLO, John J.**, GSI Water Solutions, Inc, 55 SW Yamhill Street, Suite 400, Portland, OR 97204, jporcello@gsiws.com, TOLAN, Terry L., GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, LINDSEY, Kevin A., GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336, and BURT, Walt, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204
131-5	2:40 PM	GROUNDWATER RECHARGE AND RESIDENCE TIMES IN THE COLUMBIA RIVER BASALT AQUIFER SYSTEM, WASHINGTON: **VLASSOPOULOS, Dimitri**[1], KARANOVIC, Marinko[2], JOHNSON, Vern[3], GAZIS, Carey A.[4], TOLAN, Terry[5], and LINDSEY, Kevin A.[5], (1) S.S. Papadopulos & Associates, Inc, 510 SW Third Avenue, Suite 200, Portland, OR 97204, dimitri@sspa.com, (2) S. S. Papadopulos & Associates, Inc, 7944 Wisconsin Avenue, Bethesda, MD 21771, (3) Richland, WA 99352, (4) Department of Geological Sciences, Central Washington Univ, Ellensburg, WA 98926, (5) GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336

2009 Portland GSA Annual Meeting (18-21 October 2009)

Paper No. 131-1

Presentation Time: 1:35 PM-1:55 PM

AQUIFER DECLINES AND SCANT MODERN RECHARGE IN THE COLUMBIA BASIN GROUND WATER MANAGEMENT AREA (GWMA) OF ADAMS, FRANKLIN, GRANT, AND LINCOLN COUNTIES, WASHINGTON

STOKER, Paul, Columbia Basin Ground Water Management Area, 449 E. Cedar Boulevard, Othello, WA 99344, pstoker@smwireless.net

The Columbia Basin GWMA encompasses approximately 8,300 square miles in south-central Washington. This region hosts a large agricultural industry home to several hundred thousand people. With very few exceptions, much of the region relies almost completely on groundwater for industrial and potable supplies, and even a large portion of the irrigation needs. The central role of groundwater in the life of the Columbia Basin was one of the catalysts behind formation of GWMA. When first designated in February 1998 the goal of the GWMA was to define and implement on a local level actions designed to reduce nitrate-N concentrations in groundwater. In 2005 the GWMA charter was expanded to include all groundwater quality issues in its region. At the same time, GWMA began to become more involved in groundwater resource issues as concerns over declining well production and CRBG aquifer water levels mounted, especially in the Odessa Sub-Areas.

The GWMA is a pro-active, voluntary, local planning effort. It is a forum for local citizens to develop locally based solutions to the groundwater issues and to lessen the need for mandated control measures. The GWMA is like so many other entities, agencies, and organizations involved in some way with water in the Pacific Northwest. The actions that GWMA leaders, citizens, and stakeholders must undertake to insure a healthy supply of water, all require the insight, support, and knowledge of the scientific community. The GWMA, and all of these local entities need the science to: (1) better evaluate changing aquifer conditions related to contamination, pumping, and recharge; (2) develop monitoring, modeling, and mitigation measures that address areas of concern and can be used to track improvements in the aquifer system as a result in changes in resource management, and (3) prioritize resources to be used to address ground water resource concerns. To do that the scientific community must help GWMA, and groups like GWMA, identify tools to use to tackle issues, and to do that the scientific community must be engaged with us, and with each other.

2009 Portland GSA Annual Meeting (18-21 October 2009)

Paper No. 131-2

Presentation Time: 1:55 PM-2:10 PM

GEOLOGIC FEATURES IN THE COLUMBIA RIVER BASALT GROUP (CRBG) AQUIFER SYSTEM THAT FORM VERTICAL FLOW PATHWAYS AND SUBDIVIDE THE REGIONAL GROUNDWATER FLOW SYSTEM: EXAMPLES FROM THE COLUMBIA BASIN GROUND WATER MANAGEMENT AREA (GWMA) OF SOUTH-CENTRAL WASHINGTON

LINDSEY, Kevin A., GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336, klindsey@gsiwatersolutions.com, TOLAN, Terry, GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, PORCELLO, John, GSI Water Solutions, Inc, 55 SW Yamhill, Portland, OR 97204, and BURT, Walt, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204

Studies in the 21,500 km^2 Columbia Basin GWMA are identifying geologic features in the regional CRBG aquifer system that impact recharge and groundwater flow. CRBG lava flows typically are laterally widespread, covering large areas (>12,900 km^2). Aquifers within the CRBG generally are associated with intraflow structures at the top and bottom of individual sheet flows. Intraflow structures such as breccias, pillow lava complexes, and coarse sedimentary interbeds form interflow zones that often have excellent reservoir properties and can be exceptional aquifers. The interiors of thick, undisturbed sheet flows have very limited permeability, and form aquicludes and aquitards. The net hydrologic result of this is that CRBG water-bearing zones typically occur as a series of layered, planar-tabular, confined aquifers that extend many kilometers, and the dominant groundwater flow within these strata is parallel to the dip of individual, laterally extensive, interflow zones.

Groundwater movement in this stratiform system can be disrupted by geologic features. Groundwater movement between interflow zones occurs naturally where: (1) sheet flows pinch out creating limited (single flow) vertical connections where the flow interior ends; (2) erosional windows that connect one or more interflow zones; and (3) active faults provide open fractures across multiple, impermeable, layered, flow interiors.

Several of these features also act to limit lateral continuity within the CRBG aquifer system, including: (1) canyons and coulees (erosional features) which act as hydraulic drains in the shallow system, truncating the portions of the aquifer system they cross-cut and (2) faults and associated folds (such as Yakima Folds and regional monoclines) form major barriers to groundwater movement as deformation destroys primary porosity. Also, CRBG dikes which cross-cut the stratiform CRBG aquifer system break the lateral continuity of permeable interflow zones. The cumulative effect of these features is to form areas in the CRBG aquifer system where natural recharge may occur, and to compartmentalize the aquifer system, potentially forming sub-regional aquifer systems with limited interconnection.

2009 Portland GSA Annual Meeting (18-21 October 2009)
Paper No. 131-3
Presentation Time: 2:10 PM-2:25 PM

EFFECTS OF FAULTS AND STRATIGRAPHIC VARIABILITY ON GROUNDWATER FLOW IN COLUMBIA RIVER BASALT GROUP AQUIFERS

BURT, Walt, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204, wburt@gsiwatersolutions.com, WELLS, Ray E., U.S. Geological Survey, 345 Middlefield Rd, MS 973, Menlo Park, CA 94025, CONLON, Terrence D., Oregon Water Science Center, U.S. Geological Survey, 2130 SW 5th Ave, Portland, OR 97201, TOLAN, Terry L., GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, and PORCELLO, John J., GSI Water Solutions, Inc, 55 SW Yamhill Street, Suite 400, Portland, OR 97204

Faults that transect Columbia River Basalt Group (CRBG) flows often create linear zones of low permeability that affect the lateral continuity of groundwater flow in aquifers hosted by CRBG interflow zones. Faulting has been shown to disrupt the principal directions of anisotropy in the CRBG by offsetting tabular, permeable interflow zones and creating linear features of low horizontal and high vertical permeability. A series of cross-cutting faults thus may create hydrologically isolated areas within the CRBG and/or provide vertical pathways for groundwater movement between otherwise isolated CRBG interflow zones. The hydrogeologic significance of faults was recognized by early CRBG researchers on the basis of often dramatic head differences within the same stratigraphic interval on either side of a fault, and sharp departures from the ideal Theis response to pumping, indicative of a linear "impermeable" boundary.

Recent changes in long-term pumping, implementation of ASR pilot testing, and detailed geologic mapping of the CRBG in the Tualatin Basin and Central Willamette Basin have provided opportunities to evaluate the hydraulic characteristics of faults. Several recent studies have documented varying degrees of hydraulic continuity within individual CRBG units across some faults, including several of those with significant vertical and/or lateral displacement. A preliminary evaluation of hydraulic response across faults within the CRBG suggests a range of hydraulic behavior depending on the nature and age of faulting and the magnitude and duration of the hydraulic stress.

Complicating interpretation of hydraulic test data in the CRBG is lateral stratigraphic variability of individual basalt flows, which greatly affects the hydraulic properties of interflow zones. These "facies" changes result in hydraulic responses that are similar to "positive" (higher permeability) or "negative" (lower permeability) boundaries, and they may lead to an erroneous interpretation of the existence of a fault. The spectrum of hydraulic characteristics of faults illustrates the importance of developing a thorough understanding of the geologic framework of the CRBG aquifers to accurately interpret and predict responses to stresses.

2009 Portland GSA Annual Meeting (18-21 October 2009)
Paper No. 131-4
Presentation Time: 2:25 PM-2:40 PM

INFLUENCE OF WELL CONSTRUCTION ON WATER LEVEL INTERPRETATIONS IN AQUIFERS OF THE COLUMBIA RIVER BASALT GROUP

PORCELLO, John J., GSI Water Solutions, Inc, 55 SW Yamhill Street, Suite 400, Portland, OR 97204, jporcello@gsiws.com, TOLAN, Terry L., GSI Water Solutions, Inc, 1020 North Center Parkway, Ste F, Kennewick, WA 99336, LINDSEY, Kevin A., GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336, and BURT, Walt, GSI Water Solutions, Inc, 55 SW Yamhill Street, Ste. 400, Portland, OR 97204

The Columbia River Basalt Group (CRBG) hosts a series of laterally extensive, vertically stratified confined aquifers throughout its regional extent. In the CRBG, a fundamental geologic control is the vertical compartmentalization of stratiform water-bearing zones, which are contained in discrete, laterally extensive interflow zones that are separated by thick, laterally extensive layers of dense, massive, low-permeability basalt (the flow interior). Not all CRBG interflow zones are saturated, and those that are can have significantly different pressure heads. Given the hydraulic characteristics of individual CRBG water-bearing zones, correctly interpreting and evaluating the condition of CRBG aquifers from groundwater elevation data (static water levels) requires an understanding of both CRBG geology and well construction details. Uncased water supply wells in the CRBG often span and cross-connect multiple interflow zones and have water levels that represent composite conditions (pseudoequilibrium) produced within the wellbore. CRBG wells that are open to multiple interflow zones, often within different stratigraphic portions of the CRBG, only provide a measurement of a composite pressure head and do not provide any meaningful data for regional resource evaluation. In contrast, meaningful CRBG water level data can be obtained from wells that are cased and sealed into individual interflow zones that have been stratigraphically identified. For example, in the Columbia Basin Ground Water Management Area in south-central Washington, a state-monitored network of observation wells completed in individual interflow zones shows that groundwater levels in the Wanapum Basalt have been relatively unchanged during the past few decades, while groundwater levels have been declining in interflow zones of the underlying Grande Ronde Basalt. This type of vertical resolution in water level trends illustrates how an observation network containing wells that target stratigraphically specific interflow zones for production and monitoring allows spatial and temporal evaluation of groundwater conditions in a manner that a group of uncased wells open to multiple interflow zones (and CRBG units) cannot provide.

2009 Portland GSA Annual Meeting (18-21 October 2009)

Paper No. 131-5

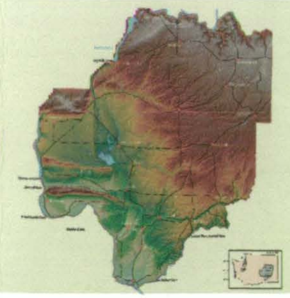
Presentation Time: 2:40 PM-2:55 PM

GROUNDWATER RECHARGE AND RESIDENCE TIMES IN THE COLUMBIA RIVER BASALT AQUIFER SYSTEM, WASHINGTON

VLASSOPOULOS, Dimitri[1], KARANOVIC, Marinko[2], JOHNSON, Vern[3], GAZIS, Carey A.[4], TOLAN, Terry[5], and LINDSEY, Kevin A.[5], (1) S.S. Papadopulos & Associates, Inc, 510 SW Third Avenue, Suite 200, Portland, OR 97204, dimitri@sspa.com, (2) S. S. Papadopulos & Associates, Inc, 7944 Wisconsin Avenue, Bethesda, MD 21771, (3) Richland, WA 99352, (4) Department of Geological Sciences, Central Washington Univ, Ellensburg, WA 98926, (5) GSI Water Solutions, Inc, 1020 North Center Parkway, Suite F, Kennewick, WA 99336

As part of an ongoing study of the Columbia River Basalt Group (CRBG) aquifer system within the Columbia Basin Ground Water Management Area (GWMA) in south-central WA, selected irrigation, municipal, and domestic wells and surface waters were sampled for a suite of geochemical and isotopic tracers, including major and trace elements, stable isotopes (O, H, C), dissolved gases (He, Ne, Ar, N2), and age tracers (3H, 14C, CFCs, and SF6), to identify sources of groundwater and, in particular, to evaluate recharge relationships in the deeper parts of the CRBG aquifer system. Detectable CFCs, SF6, and 3H indicate relatively short residence times (ranging from a few years to a few decades) for groundwater from shallow sediment aquifers and the upper parts of the basalt aquifer system. Discordant recharge ages for multiple age tracers in samples from some supply wells that are open over large depth intervals indicate intra-borehole mixing of groundwater from different portions of the CRBG aquifer system. Apparent 14C ages in these wells range from recent to several thousand years, and likely represent a flow-weighted average (mixture) of the tracer concentrations in the aquifer system contributing water to the well. In the central part of GWMA, 14C, dissolved gas, and stable isotope data from deep (>500 m) irrigation wells completed and sealed into the Grande Ronde Basalt indicate that much of the deeper groundwater is more than 10,000 years old, and was recharged during the Pleistocene-early Holocene under cooler and wetter conditions than present. Traces of CFCs, SF6, and tritium detected in some of these wells suggest admixture of small amounts (<2 %) of modern water. While this could be partly due to sample contamination, the admixture is also likely indicative of a small degree of hydraulic continuity (natural and/or man-made) with the shallower portions of the CRBG aquifer system. This study demonstrates that natural recharge to the deeper parts of the CRBG aquifer system (i.e., Grande Ronde Basalt) throughout much of the GWMA is presently very limited, but was apparently higher in the past. This finding has significant implications for CRBG groundwater availability and renewability in the study area.

A Conceptual Groundwater System Model for the Columbia River Basalt Group (CRBG) in the Columbia Basin Ground Water Management Area (GWMA) of South-Central Washington



by John J. Porcello[1], Terry L. Tolan[1], Kevin A. Lindsey[1], Walter C. Burt[1], Dimitri Vlassopoulos[2]

[1]GSI Water Solutions, Inc. [2] S. S. Papadopulos & Associates, Inc.

GWMA Columbia Basin Ground Water Management Area

OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES

GSI Water Solutions, Inc.

Nature of the Problem

The Columbia Basin GWMA encompasses approximately 8,300 square miles in four agricultural counties in the Columbia Plateau of south-central Washington. Land settlement in this region began during the 1880s, accompanied by the development of dry-land wheat farming. During the early 1960s, wheat growers found that markedly greater crop yields could be obtained by irrigating. Landowners in Adams and Lincoln Counties, mostly unserved by surface irrigation projects, turned to groundwater for irrigation supplies. In these two counties, groundwater levels have declined several hundred feet, streamflows have decreased, and lakes have gone dry. Groundwater from the CRBG is the sole source of water in much of these counties. If groundwater level declines continue and create future water shortages, the subsequent decreases in crop yields may cost the region a few hundred to almost 5,000 agricultural jobs (Razack and Holland, 2007).

Early Evidence of Limited Interconnection between Stratiform Aquifers

Early researchers found evidence that the stratiform aquifers in the CRBG reside in basalt interflow zones that have limited interconnection, except via uncased wells or where structural or erosional features are present. In a study of several CRBG groundwater basins (Newcomb, 1959), the U.S. Geological Survey (USGS) noted that it was common for groundwater levels in basalt to drop as much as 100 feet during drilling when advancing a borehole just a few feet. The report concluded that groundwater is present in separate, compartmentalized zones in the CRBG, with little vertical connection between any two water-bearing interflow zones that are separated by an individual basalt flow. From the mid-1960s through the mid-1980s, several USGS studies inside GWMA, including Luzier and Burt (1974), identified large groundwater level declines in Adams and Lincoln Counties, and concluded that downward cascading of groundwater in uncased wells was a significant cause of the declines. Later, at the Hanford Site just west of GWMA, the U.S. Department of Energy (USDOE, 1988) published several years' worth of hydrogeologic research for the Basalt Waste Isolation Project. This research, which examined the suitability of constructing a deep, mined, repository in the CRBG for the final disposal of high-level nuclear waste, resulted in a finding that "the concept that significant, areally distributed, vertical groundwater flow through cooling and tectonic fractures is a general phenomenon in the central Columbia Plateau probably is incorrect based on hydrochemical data."

GWMA's Studies of Interconnection

GWMA's recent studies of hydrogeologic and groundwater quality data have found multiple indications that interconnection between stratiform aquifers is limited, except where uncased wells are present or where folds, coulees, or basalt pinchouts exist.

Basalt Pinchout Near Quincy, WA

Wilson Creek Coulee

Surface Hydrology

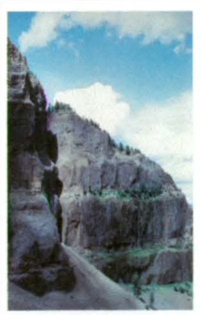
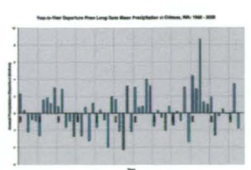


Table Mountain Near Stevenson, WA

Regionally in the CRBG, springs are found on canyon sidewalls at the elevations where basalt interflow zones lie, but not at the elevations of dense basalt interiors. Coulees also act to connect surface water and groundwater. In GWMA, where pumped interflow zones contact a coulee floor, streamflows can be reduced by the pumping-induced lowering of groundwater levels. For example, in the lower Lake Creek drainage of southern Lincoln County, where heavily pumped interflows of the lower Wanapum Basalt and upper Grande Ronde Basalt contact the coulee floor, two formerly prominent features (Delzer Falls and Pacific Lake) are now dry even though precipitation has been average or slightly above normal during the past three decades. Farther upstream, where these same pumped interflow zones lie at depth and do not contact the coulee floor, Coffee Pot Lake and other nearby lakes are not dry.

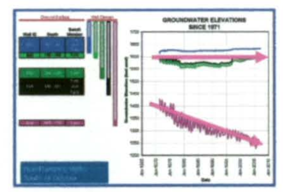
Coffee Pot Lake
(Middle Reach of Lake Creek Drainage)

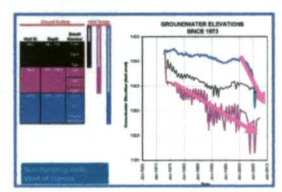
Pacific Lake
(Lower End of Lake Creek Drainage)



Groundwater Levels in Observation Wells

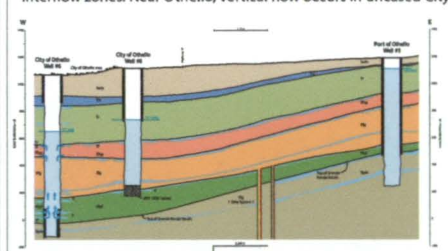
Non-pumping wells show different hydrogeologic conditions with depth in the CRBG. South of Odessa, the Wanapum Basalt (Tw) has shown much less water level variation with time than the underlying uppermost (Sentinel Bluffs) member of the Grande Ronde Basalt (Tgsb), which has shown much deeper water levels and a continual decline in those levels. West of Odessa, three observation wells in the Grande Ronde Basalt show a pronounced change in the vertical gradient with depth and different rates of water level decline. Additionally, the deepest piezometer showed only modest declines in water levels until 2000, when the declines accelerated in conjunction with continued well deepenings into deep Grande Ronde Basalt aquifers in this area.

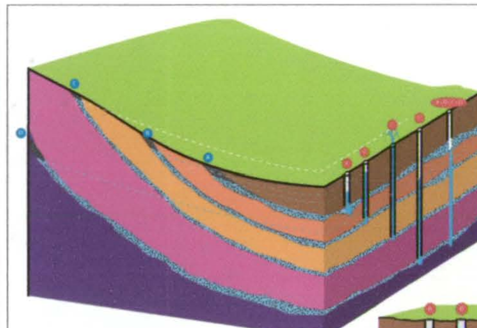


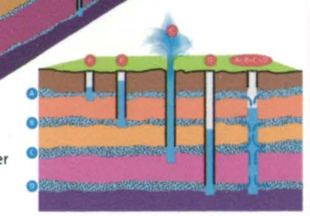


Groundwater Levels in Water Supply Wells

Water wells also provide evidence of limited interconnection between stratified basalt interflow zones. Near Othello, vertical flow occurs in uncased City Well #6 because of pressure differences between interflow zones. In contrast, City Well #8 and Port Well #3 do not cross-connect multiple interflows with different water pressures and do not experience cross-borehole flow. These differences would not exist if the interflow zones were strongly interconnected.







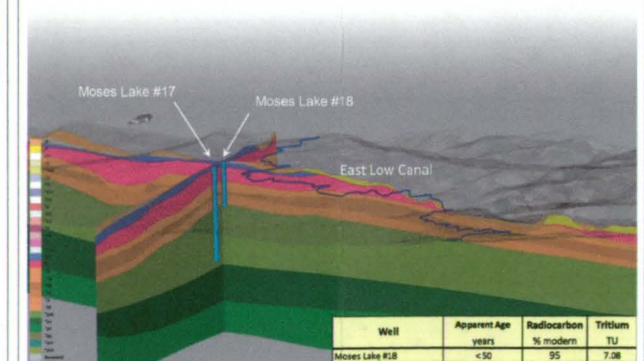
Geologic and Well Construction Influences

Two significant factors controlling the static water level (or potentiometric surface*) in a well are:
1) the location and elevation where interflow zones are exposed and receive recharge, and
2) the well's construction. Older interflow zones may be exposed at lower elevations than younger ones by erosional features such as coulees, or geologic structures such as faults and folds. Where wells connect interflow zones with very different recharge areas and water levels, vertical flow within the well occurs between interflow zones, and the water level in the well is a combination of the water levels in all of the interflow zones (see the block diagram). Differences in the depths of wells and well seals also affect the occurrence of cross-borehole flow and the water level in a well.

*Potentiometric Surface, also known as piezometric surface, isopotential level, and pressure surface. When confined aquifers are tapped by wells, water from the aquifer will rise within the well casing representing an imaginary surface which can be represented by contours of hydraulic head. This map of contoured hydraulic heads provides an indication of horizontal groundwater flow. However, groundwater flow is three-dimensional, and interpretations of flow based on a potentiometric surface map alone may be misleading (Poehls and Smith, 2009).

Recent Geochemical and Age Dating Evidence

Geochemical and isotopic studies indicate relatively young groundwater ages (ranging from a few years to a few decades) for water shallow sedimentary aquifers and the uppermost CRBG, whereas Grande Ronde Basalt wells that are sealed through the Wanapum Basalt contain groundwater that is more than 10,000 years old. Wells that are open to large vertical intervals in the CRBG have discordant ages ranging from recent to several thousand years, indicating intra-borehole mixing of groundwaters that enter the well from different portions of the CRBG aquifer system via the uncased borehole. An example is at the City of Moses Lake. City Well #18, which contains modern water, is completed in Wanapum Basalt interflow zones that are cut by the East Low Canal. City Well #17, which contains much older water, is completed in deeper Grande Ronde Basalt interflow zones that do not have a direct connection to surface water recharge.



Well	Apparent Age years	Radiocarbon % modern	Tritium TU
Moses Lake #18	<50	95	7.08
Moses Lake #17	5,800	24	3.97

Basic Elements of the Conceptual Groundwater System Model for the Columbia Basin GWMA

Groundwater Recharge. The CRBG is not recharged by the Columbia or Spokane Rivers at the upgradient edge of GWMA, but may receive some recharge from the Snake River in the southern-most portion of GWMA. Periodic streamflows in coulees may recharge the uppermost basalts in localized outcrop areas, but not the deeper basalts which have little surface exposure in GWMA. Prior to groundwater development, surface water in the coulee floors could not appreciably infiltrate into the basalt because water levels in the interflow zones were at or above ground surface beneath the lakes and connecting drainages. Yet with the onset of groundwater development and the subsequent lowering of groundwater levels, lakes have disappeared and streamflows have decreased, despite average to above-average rainfall during the past three decades.

Groundwater Discharge. Regional-scale discharge from the Grande Ronde Basalt appears to be limited in magnitude. Data from the nearby Hanford Site suggest that a hypothetical 1-foot water column would take between 1,000 and 3 billion years to migrate upward out of the Grande Ronde Basalt into the overlying Wanapum Basalt, let alone to the nearby Columbia River.

Interconnection of Stratiform Aquifers. The stratiform nature of CRBG water-bearing zones creates significant degrees of cross-connection only via uncased wells and where stratigraphic and structural features are present (pinchouts, coulees, folds, and possibly certain faults). Geologic, hydrologic, geochemical, and tracer data, when evaluated in an integrated manner, together indicate that natural interconnection is otherwise minimal.

Summary. During the Pleistocene, abundant surface water was present because of the wetter climate and the multiple cataclysmic Missoula Floods. These floods moved across the Columbia Plateau and created temporary lakes as much as 1,000 feet deep in places, allowing significant recharge to the underlying basalt at locations where interflow zones were at or near ground surface. Since then, because of the arid climate, less recharge has occurred, particularly to the Grande Ronde Basalt. Before large-scale groundwater development began in the 1970s, the water-bearing zones in the Grande Ronde Basalt essentially constituted a subsurface "reservoir" with little to no inflows or outflows. Since then, groundwater pumping has not been offset by groundwater recharge, resulting in a net decrease in the volume of groundwater in storage. Well deepening is only a temporary solution because deeper aquifers contain older water and receive little, if any, recharge. Artificial recharge may be a viable method for recharging shallower basalt interflow zones (in the Wanapum Basalt and the upper portion of the Grande Ronde Basalt) that are exposed in coulee floors and channeled scablands.

Abstract

The CRBG hosts a regional aquifer system that is the primary, and in many cases the only, water supply for numerous communities, small water systems, individual homes, industry, and agriculture in south-central Washington. In the central portion of the semi-arid Columbia Plateau, primarily in Adams County and southern Lincoln County, the CRBG aquifer system has experienced significant water level decline, which is a significant concern to water resources managers in the region.

The GWMA has conducted a Subsurface Geologic Mapping and Hydrogeologic Assessment project to map the geologic framework of the CRBG aquifer system in the region and develop a conceptual model of the groundwater flow system. Like previous studies, this project has concluded that the occurrence and movement of groundwater in the CRBG is governed by 1) its geologic features (lithology, folding, faulting, the areal extent of individual interflow zones [including lateral pinchouts], the presence of buried structures [granitic bedrock highs or vertical basalt dikes], the distribution of feeder dikes, and the presence of erosional features [coulees]); and 2) its exposure to surface water sources (lakes, rivers, streams, canals, irrigation). The subsurface geologic mapping, along with updated evaluations of long-term groundwater elevation trends and recent geochemical and age-dating sampling studies conducted for the project, have resulted in two fundamental conclusions regarding current groundwater use: 1) the common practice of deepening wells is only a temporary solution to mitigating declining groundwater levels and well yields, and 2) the gradually increased pumping from deeper CRBG aquifers (primarily the Grande Ronde Basalt [GRB]) is tapping ancient sources of water that receive little, if any, recharge near groundwater pumping centers or at the margins of GWMA. While the long-term outlook for deep GRB water supplies is not promising within the GWMA, restoration of historical groundwater supplies in shallower (predominantly Wanapum Basalt) aquifers via artificial recharge may be possible in certain areas because of the prevalence of Wanapum Basalt exposures in coulee floors and in the channeled scablands of the northern portion of the Columbia Basin.

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REGIONAL GROUNDWATER GEOCHEMISTRY OF THE COLUMBIA RIVER BASALT AQUIFER SYSTEM, SOUTH-CENTRAL WASHINGTON

S.S. PAPADOPULOS & ASSOCIATES
Environmental & Water-Resource Consultants

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From Volcanoes to Vineyards: Living with Dynamic Landscapes
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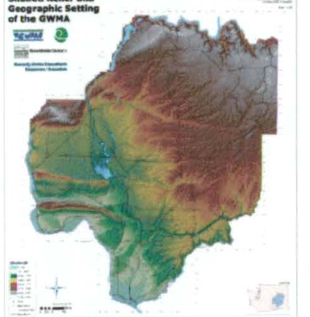
ABSTRACT

The chemical evolution of groundwaters in Columbia River Basalt Group (CRBG) aquifers within the Columbia Basin Ground Water Management Area (GWMA) in south-central Washington is investigated using exploratory data analysis methods in conjunction with geochemical modeling and natural tracers, to identify chemical signatures and compositional vectors that (1) serve as proxies for groundwater age (residence time) and (2) can be used to identify, map and distinguish potential recharge sources on both regional and local scales. Spatial hydrochemical patterns that reflect the relative residence times of groundwater can be mapped in three dimensions using geochemical signatures including the cation ratio (Na+K)/(Na+K+Ca+Mg), nitrate, fluoride and ^{14}C, as well as multivariate analysis (hierarchical cluster analysis, principal components analysis), and reveal regional flow patterns and the nature and spatial distribution of recharge to different portions of the CRBG aquifer system in the GWMA. The hydrochemical analysis identified evidence for several contrasting sources of present-day recharge in the area: (1) surface waters of relatively low dissolved solids content that likely enter the shallower basalt aquifers locally where interflow zones are intersected by drainage channels (coulees) with perennial or episodic surface water flows; (2) infiltration of waters with higher TDS and nitrate associated with agricultural activities mainly within the Columbia Basin Irrigation Project on the western side of the GWMA; (3) regional recharge from the east and northeast; and (4) isolated occurrences of relatively unevolved water in areas characterized by chemically more evolved groundwater, indicating a local effect due to cross-connecting wells, pumping from multiple aquifers, or leaky surface seals. With the exception of localized and limited effects attributable to well construction artifacts, a large portion of the deeper Grande Ronde aquifer system in the central GWMA has not received significant recharge since the Pleistocene-early Holocene.

Shaded Relief and Geographic Setting of the GWMA



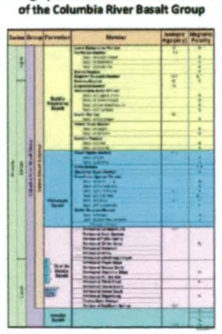
The CRBG consists of several hundred individual basalt flows of Miocene age, often covering many hundreds to several thousand square km, with total thickness up to several km. The water-bearing horizons are generally limited to the zones between adjacent lava flows, resulting in a series of vertically stacked aquifers that can be confined over large areas.

Hydrogeologic Framework

Aquifer horizons within the CRBG are generally associated with intraflow zones between adjacent lava flows. The permeability of dense lava flow interiors is generally very low and these tend to act as aquitards, creating a series of vertically stacked confined aquifers within the CRBG aquifer system.

Groundwater flow is dominantly horizontal to sub-horizontal along the individual, laterally extensive, interflow zones. Vertical groundwater movement through undisturbed basalt flow interiors is greatly restricted, based on the physical properties of the Columbia River basalt, outcrop observations, and well test interpretations. Although some vertical groundwater movement between layered CRBG aquifers is possible, it likely occurs only under specific localized conditions (e.g. where basalt flow interiors are disturbed by geologic features such as by folds or faults, truncated by flow pinch outs or erosional windows, or where they are artificially cross-connected by penetrating wells).

Stratigraphic Relations and Nomenclature of the Columbia River Basalt Group



Basalt-Water Interactions and Chemical Evolution of Groundwaters

Basalt Mineralogy

The primary igneous mineralogy of Columbia River basalts consists of plagioclase feldspar (labradorite), pyroxene (augite), and iron oxides (titanomagnetite), with minor amounts of apatite, olivine, and metal sulfides set in a glassy to cryptocrystalline matrix. After the emplacement and burial of the CRBG lava flows, low-temperature water-rock interactions resulted in formation of secondary mineral phases including clay minerals (nontronitic (Fe-rich) smectite), silica polymorphs (e.g. amorphous silica, cryptocrystalline quartz), and zeolites (e.g. clinoptilolite), with lesser amounts of iron oxyhydroxides, calcite, and pyrite (Ames, 1980; Benson and Teague, 1982; Hearn et al, 1985).

Groundwater Chemistry

The chemical composition of groundwater within the CRBG aquifer system reflects (1) the source and chemical composition of the recharge water, (2) the nature and dissolution /precipitation rates of primary and secondary mineral phases, and (3) the residence time of water in the aquifer system. The geochemical controls on groundwater composition and chemical evolution in parts of the CRBG aquifers has been the subject of a numerous studies (Deutsch et al, 1982; Early et al, 1986; Hearn et al, 1985, 1990; Johnson et al. 1993; Reidel et al, 2002; Steinkampf et al, 1985; Steinkampf, 1989; Steinkampf and Hearn, 1996; USDOE, 1988; Warner, 1989).

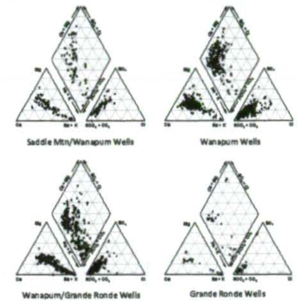
The chemical evolution of groundwater in CRBG aquifers is influenced by two major processes: (1) dissolution of basalt by carbonic acid and (2) silicate hydrolysis. The chemical evolution path begins with the initial reaction of oxygenated, weakly acidic, CO_2-charged meteoric waters with the basaltic rocks in the outcrop/recharge areas along ridges or regional outcrops. In recharge areas where a significant soil zone is present, additional CO_2 can be generated by microbial oxidation of soil organic matter, increasing the reactivity of the recharging water.

Infiltration of precipitation and other surface waters initially results in dilute Ca-Mg-HCO_3 type water. As groundwater moves along regional flow paths, toward the center of the basin, progressive silicate hydrolysis and dissolution results in an increase in silica and pH (from 7 to 10), while fluoride and chloride are leached from the basalt matrix. Precipitation and ion-exchange reactions further modify the water by removing calcium and magnesium in exchange for sodium, resulting in Na-HCO_3 type water. Long groundwater residence times during which secondary minerals (iron-rich smectite clays, zeolites, calcite, and silica) precipitate also result in removal of calcium, magnesium, potassium, iron, carbonate, and silica from basalt groundwaters.

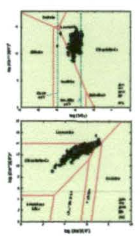
The highly chemically evolved (deeper and older) groundwaters often contain elevated fluoride concentrations (up to several tens of mg/L) in the Grande Ronde aquifers of the central Columbia Basin. Local anomalies of elevated sulfate and dissolved methane are also superimposed on the general evolutionary sequence described above. For example, on the eastern side of the Pasco Basin, deep Grande Ronde Basalt aquifers are high in dissolved sulfate but devoid of dissolved methane. On the western side of the basin, high dissolved methane occurs with low dissolved sulfate (Johnson et al. 1993). Localized areas of methane occurrence, with stable carbon and hydrogen isotope signatures indicating a thermogenic source (likely generated from sedimentary rocks buried beneath the basalts), occur near the Cold Creek fault in the northwestern part of the Pasco Basin. Lower methane concentrations appear to be of biogenic origin (Johnson et al. 1993).

Sulfate in CRBG groundwater has three potential sources. The first is the dissolution of accessory primary sulfide minerals, such as pyrite, by oxygenated recharge waters. The second is the dissolution of anhydrite or gypsum from sedimentary interbeds interlayered with the basalt. Sulfate minerals in the interbeds are likely to be of either eolian or evaporitic (caliche) origin. The third source is agricultural chemicals present in groundwater recharge in irrigated areas. Sulfide has been detected sporadically and is probably derived from microbial sulfate reduction.

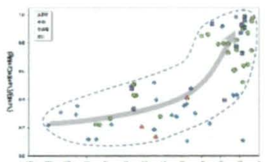
Nitrate is variably present within the basalt aquifers, its main source being fertilizers used in agricultural irrigation. As such, nitrate is a potentially useful tracer of recently recharged waters that have entered the basalt aquifers either through natural or artificial pathways (e.g. wells with leaky seals).



Piper diagrams illustrating sodium enrichment trend in CRBG groundwaters. This trend is characteristic of the chemical evolution of groundwater as a result of basalt-water interaction.

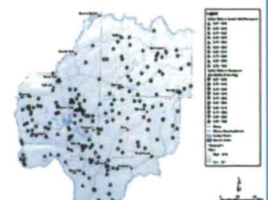


Activity diagrams showing most groundwaters are in the stability field of clinoptilolite and silica.

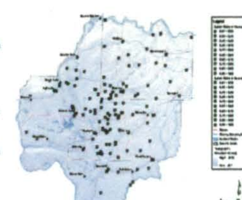


(Na+K)/(Na+K+Ca+Mg) cation ratio as a function of ^{14}C activity of CRBG groundwaters. Arrow indicates general trend with increasing groundwater age. The cation ratio is mapped (see below) to reveal spatial patterns of chemical evolution that mimic the regional flow system.

Cation ratio of groundwater from Wanapum wells. Less chemically evolved waters occur in the eastern and northern parts of GWMA reflect the regional recharge pattern from the east and north. The source of this recharge would likely be natural precipitation and surface waters. In the western GWMA, additional recharge is received from the Columbia Basin Irrigation Project.

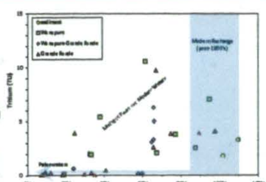


Cation ratio of groundwater from Grande Ronde wells exhibits more of a bulls-eye pattern, although this is only a partial picture because of the paucity of GR wells in western Grant and Franklin counties. Younger, less evolved waters occur in the north, northwest, east and southeast portions of the GWMA, which is indicative of potential regional recharge in these areas where the overlying Wanapum is thin and the Grande Ronde Basalt lies at or near the surface. More evolved waters are located in the central GWMA (e.g. Odessa) where wells tapping the GR aquifers are typically more than 300 m deep and in many cases more than 600 m deep.



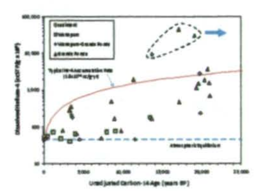
Chemical and Isotopic Tracers of Recharge Sources - Present and Past

^{14}C and ^{3}H content discriminates modern groundwater (<50 years old, with detectable ^{3}H and ^{14}C >85 pmc), paleowater (untritiated water with reduced ^{14}C) and mixed groundwaters with reduced ^{14}C and detectable ^{3}H. Most of the GR wells sampled produce paleowaters.

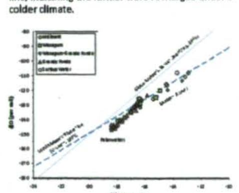


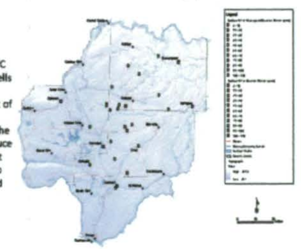
Dissolved ^{4}He (derived from U/Th decay) levels are consistent with old ^{14}C ages calculated for many GR waters (samples that plot close to the red line). Waters plotting between the red and dashed curves represent mixtures of old and young waters. Some waters with higher ^{4}He (circled) may indicate rocks with higher U content or much older waters mixed with young water. Some old waters (up to 12 kyr) with unusually low ^{4}He appear to be old groundwater used for irrigation that has partially re-equilibrated with the atmosphere during infiltration.

Paleowaters are isotopically depleted relative to modern groundwaters and surface waters which plot along the present-day local meteoric water line, indicating the former were recharged under a colder climate.

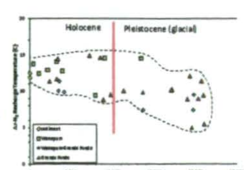


The spatial distribution of ^{14}C content in GR wells within GWMA shows that most of the wells in the central part of the study area produce paleowaters that are thousands to tens of thousand of years old.





Recharge temperatures estimated from dissolved gas concentrations also show an apparent cooling trend with increasing groundwater age. The gradual shift to warmer temperatures at ~10 kyr BP coincides with the waning Pleistocene Ice Age.

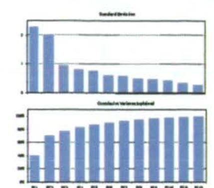


Exploratory Data Analysis

Principal Components Analysis

PCA was performed using a singular value decomposition of the data matrix (695 samples with 13 variables – 10 major ions, temperature, pH, and TDS). Major ion and TDS concentrations were log-transformed, and all data were centered and scaled to unit variance.

Standard deviation (eigenvalues) of the PCs and the cumulative amount of the data variance explained (scree plot) are shown at right. The first 2 components are significant and account for ~70% of the variance. PC3 is marginally significant.

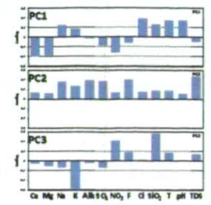


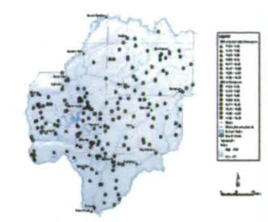
Variable loadings on the first three principal components are shown at right.

PC1 shows +ve loadings on Na, K, F, SIO_2, temperature and pH, and –ve loadings on Ca and Mg and therefore represents hydrochemical evolution or groundwater aging.

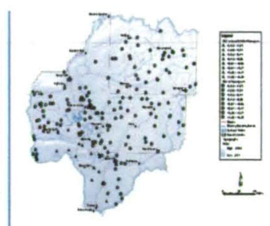
PC2 shows +ve loadings on all variables and may represent recharge of high TDS irrigation waters or evapo-concentration.

PC3 shows +ve loadings on NO_3 and SIO_2 and may represent chemical effects of recharge waters reacting with silica-rich suprabasalt sediments.

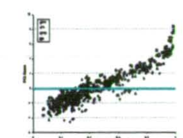




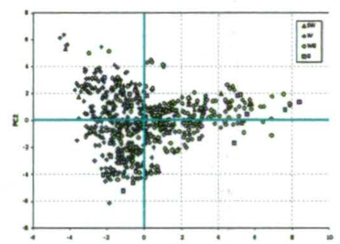
Mapping of PC1 scores (aging) for Wanapum wells

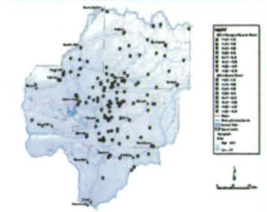


Mapping of PC2 scores (recharge source) for Wanapum wells

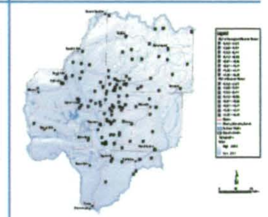


Strong positive correlation of PC1 with cation ratio confirms its usefulness as a proxy of groundwater age.





Mapping of PC1 scores (aging) for Grande Ronde wells

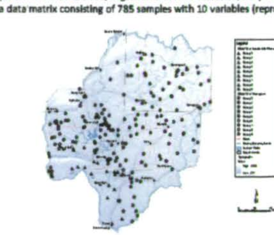


Mapping of PC2 scores (recharge source) for Grande Ronde wells

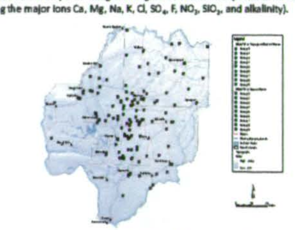
Biplot of PC1 against PC2 shows high +ve scores on PC2 are associated with –ve scores on PC1 (i.e. relatively young waters with high dissolved solids). High –ve scores on PC2 are also associated with –ve scores on PC1. The extremes in PC2 likely represent different sources of recharge to the basalt: (1) infiltrating irrigation waters with elevated TDS (+ve) and (2) low TDS waters which may include precipitation, lakes, streams, rivers and/or canals that cross outcrops of interflow zones.

Hierarchical Cluster Analysis

Cluster analysis is an unsupervised pattern recognition technique that uncovers intrinsic structure or underlying behavior of a data set without making a priori assumptions about the data, in order to classify the objects (i.e. samples) of the system into categories or clusters based on their degree of similarity. Hierarchical clustering (HCA) is the most common approach used in which clusters are formed sequentially, by starting with the most similar pair of objects and forming higher clusters step by step. The Euclidean distance gives the similarity between two samples and a 'distance' can be represented by the difference in analytical values between two samples (Reimann et al, 2008). The significance of the clusters generated by HCA in terms of underlying physical processes (different water sources, degree of chemical evolution, etc.) can often be inferred by examining the ranges of chemical compositions within and between individual clusters. HCA was performed on a data matrix consisting of 785 samples with 10 variables (representing the major ions Ca, Mg, Na, K, Cl, SO_4, F, NO_3, SIO_2, and alkalinity).

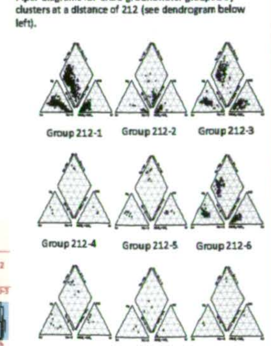


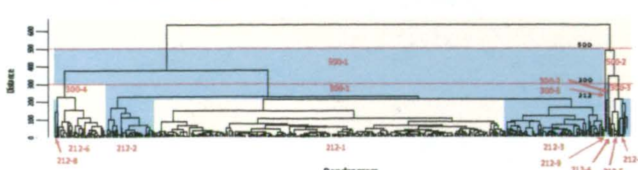
HCA classification of Wanapum wells



HCA classification of Grande Ronde wells

Piper diagrams for CRBG groundwater grouped by clusters at a distance of 212 (see dendrogram below left).





Dendrogram

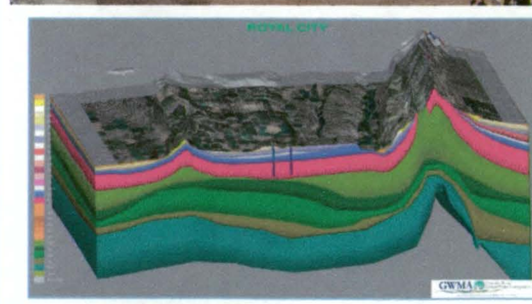
Discussion and Conclusions

Geochemical analysis of the CRBG aquifer system identified several contrasting sources of recharge in the area:

- Surface waters of relatively low dissolved solids content that likely enter the basalt aquifers where interflow zones are intersected by drainage channels with perennial or episodic surface water flows;
- Infiltration of irrigation waters with higher dissolved solids content and nitrate associated with agricultural land use, particularly within the boundaries of the Columbia Basin Irrigation Project on the western side of the GWMA;
- Regional recharge from the east and northeast; and
- Isolated occurrences of relatively young water in areas characterized by chemically more evolved paleowaters, indicating a local effect due to cross-connecting wells, pumping from multiple aquifers, or leaky surface seals.

The general patters of recharge from these sources indicate:

- Shallow groundwater wells open to unconfined sediment aquifers and shallow CRBG units generally have relatively young recharge ages (i.e., a significant fraction of the water is less than 50 years old), indicating direct connections to present-day recharge sources, both natural and artificial (precipitation, seasonally water-filled coulees, creeks, lakes, irrigated farmlands and canals).
- Wells in and near municipalities are often found to contain mixed-age groundwater. In samples from some deeper CRBG wells used for municipal water supply which are open over large vertical intervals and produce from multiple water-bearing zones, the produced groundwater is a mixture of older (thousands to tens of thousands of years) and young water entering from different basalt interflow zones, with variable connections to present day recharge sources. Because the occurrence of mixed-age groundwaters in the vicinity of cities and towns cannot be easily or reasonably attributed to any inherent geologic features, the likelihood that the presence of mixed waters is due to a local high density of wells commingling younger and older groundwater must be considered.
- Deep CRBG irrigation wells (those that penetrate more than 100 meters into the Grande Ronde Basalt and have deep seals) are producing almost exclusively from aquifers that contain Pleistocene-age groundwater, with no evidence of ongoing modern recharge. Carbon-14 and stable isotope data, and the general absence of detectable tritium and CFCs, indicate that groundwater produced from these deep irrigation wells in the central part of the GWMA (i.e., the Odessa Subarea) is generally more than 10,000 years old. The deeper parts of the aquifer system have apparently not been recharged to any significant degree since the end of the Pleistocene, when surface water was present in greater abundance in the area and could recharge units that no longer naturally access recharge under the current semi-arid climate conditions.



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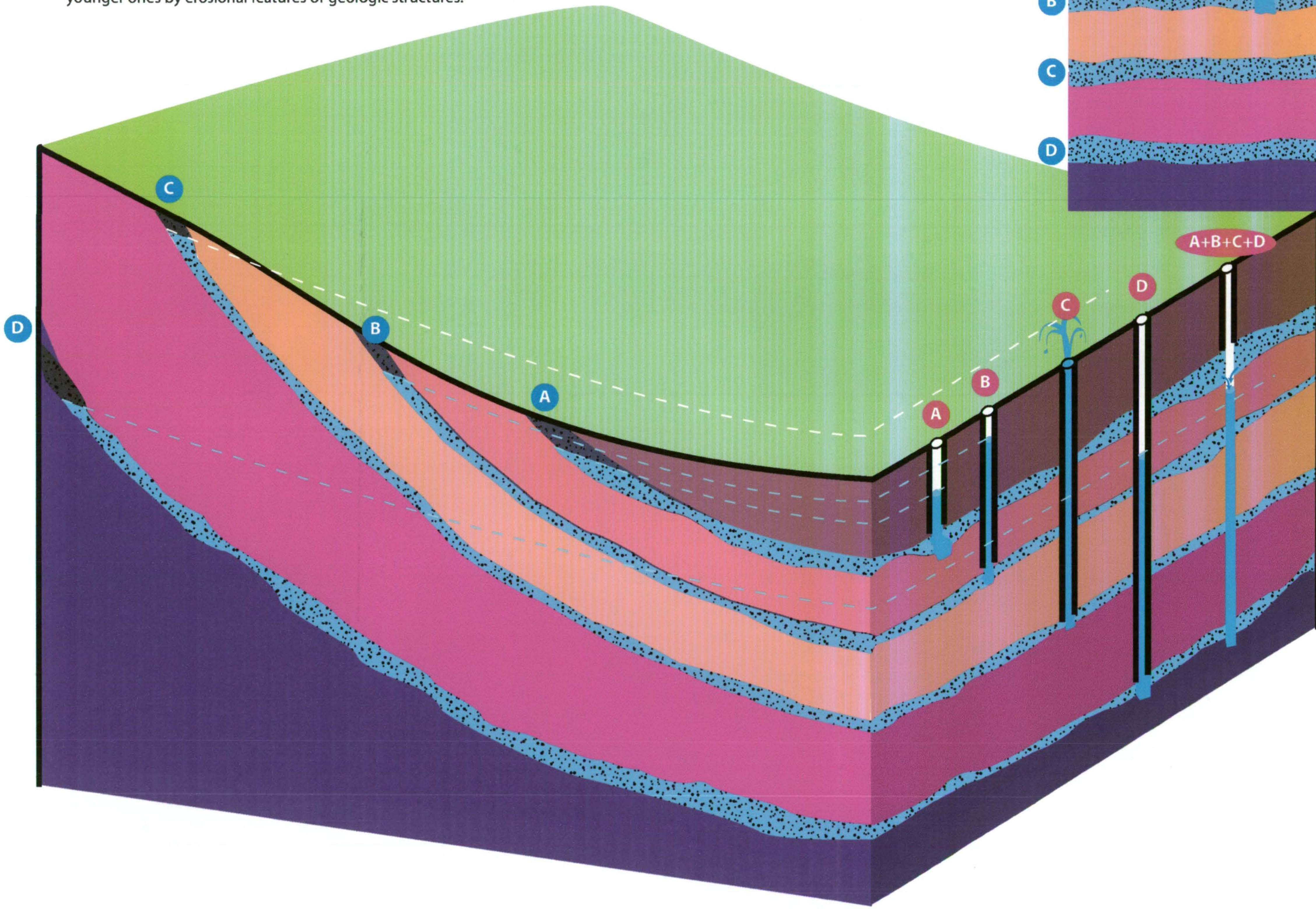
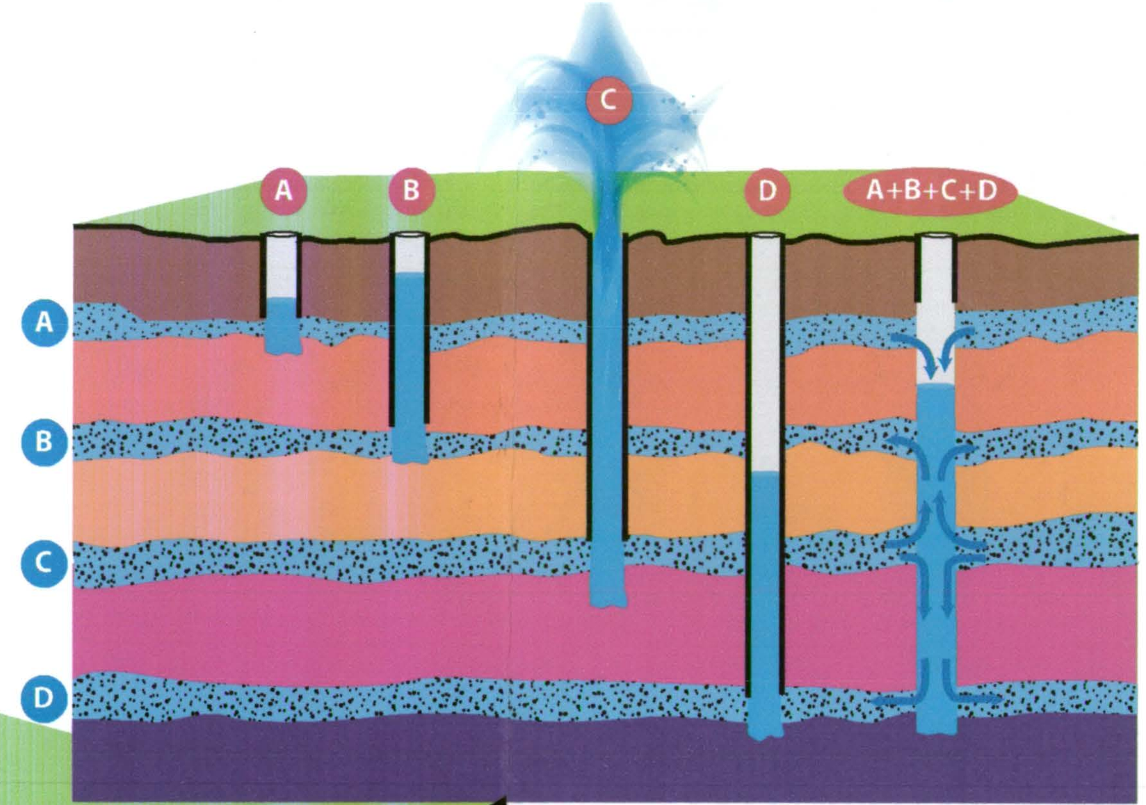
Water Levels

This diagram illustrates how water levels in Columbia River basalt wells are explained by the geology. The location and elevation where an interflow zone is exposed and receives recharge determines the water level for that interflow zone. Where wells connect interflow zones with very different recharge areas and water levels, vertical flow within the well occurs between interflows and the water level in the well is a combination of the water levels in all of the interflows. In this diagram, Interflow D is exposed to recharge at a lower elevation than the others, resulting in a correspondingly lower groundwater level. Older interflows may be exposed at lower elevations than younger ones by erosional features or geologic structures.





In this case, the well on the right connects all four zones with different water levels, lowering the water level below that in interflows A, B and C. This exposes interflow A to air, causing water to cascade into the well. Also, water flows from interflow C into interflows B and D.

Water Levels

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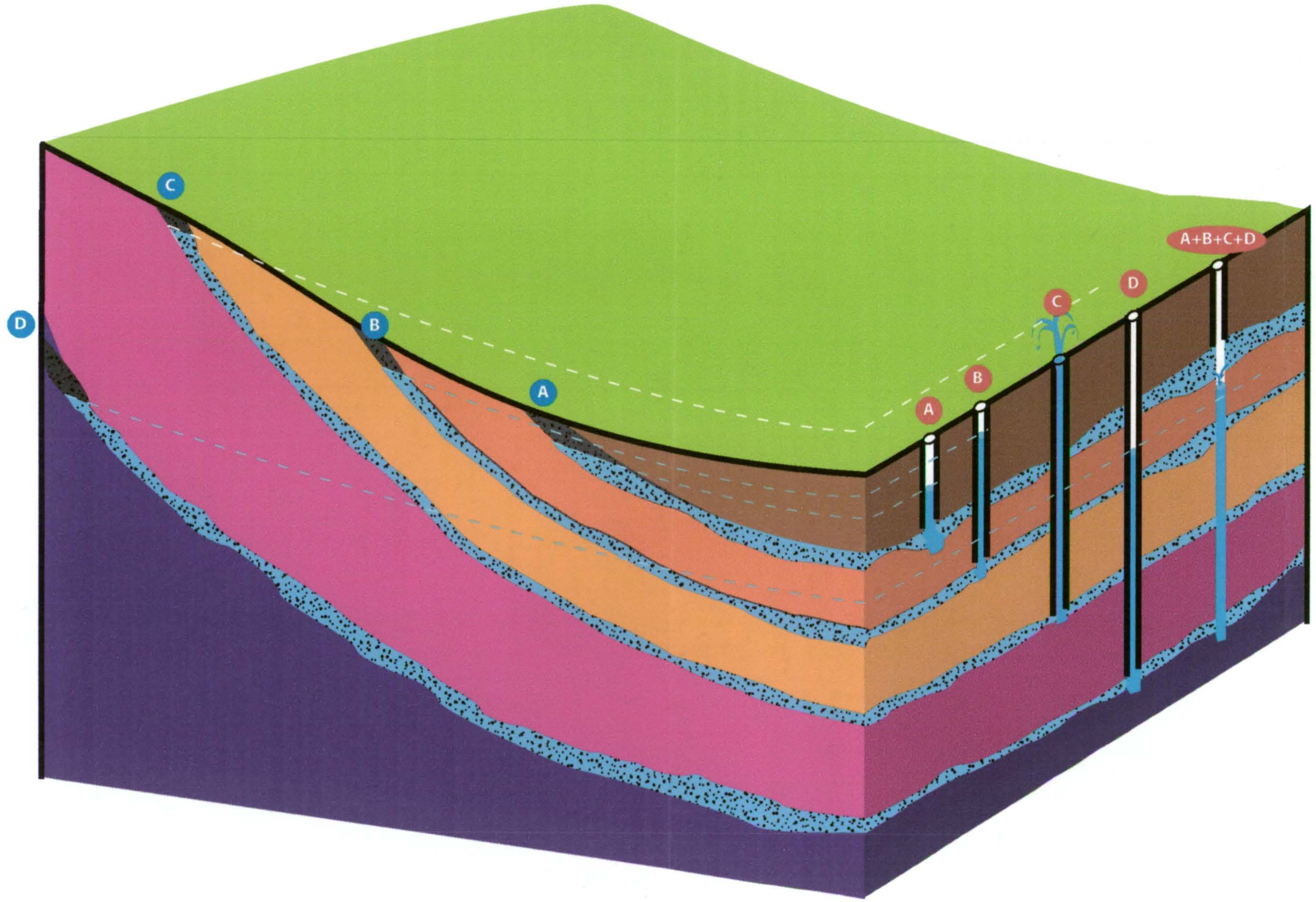
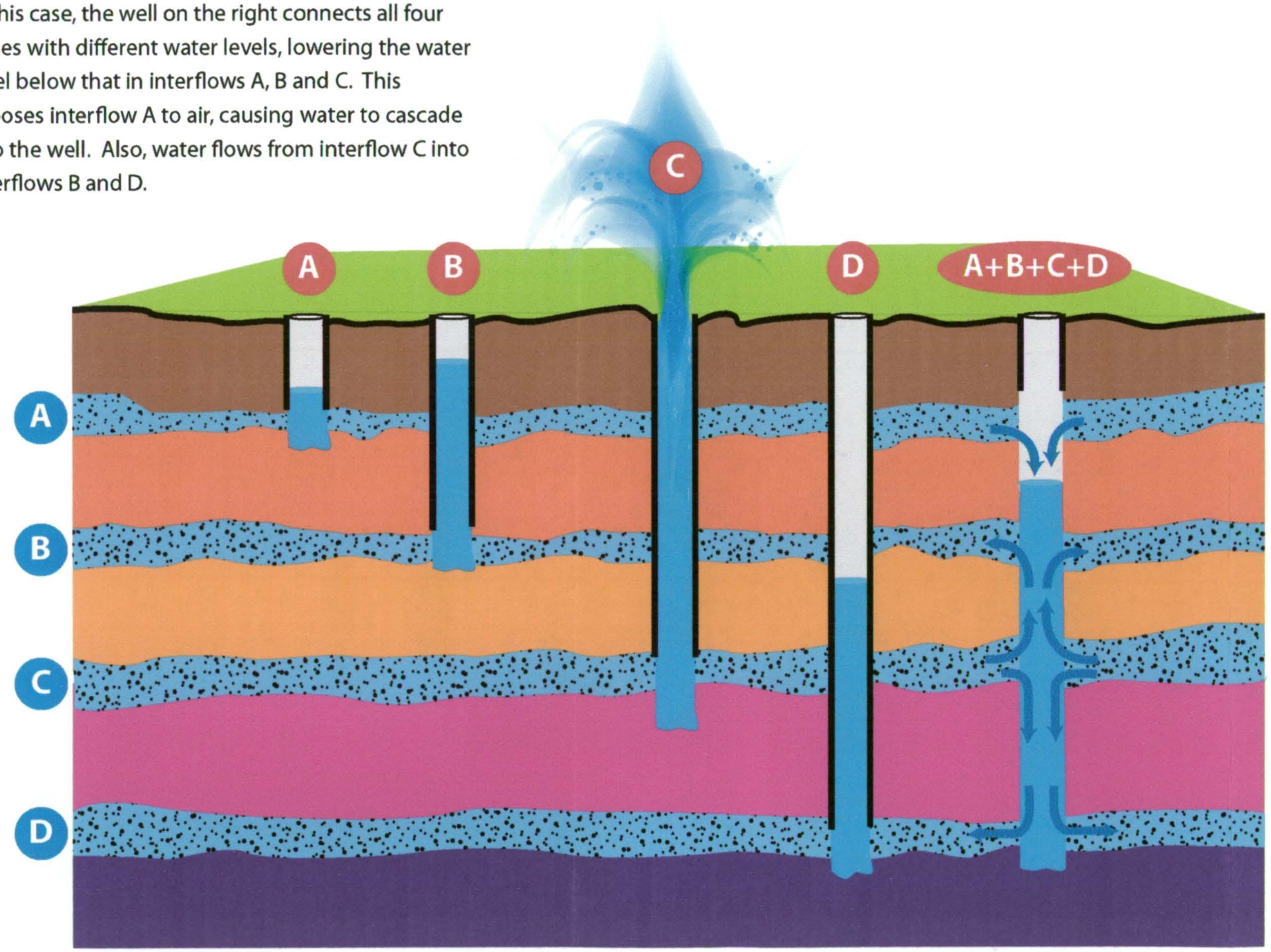
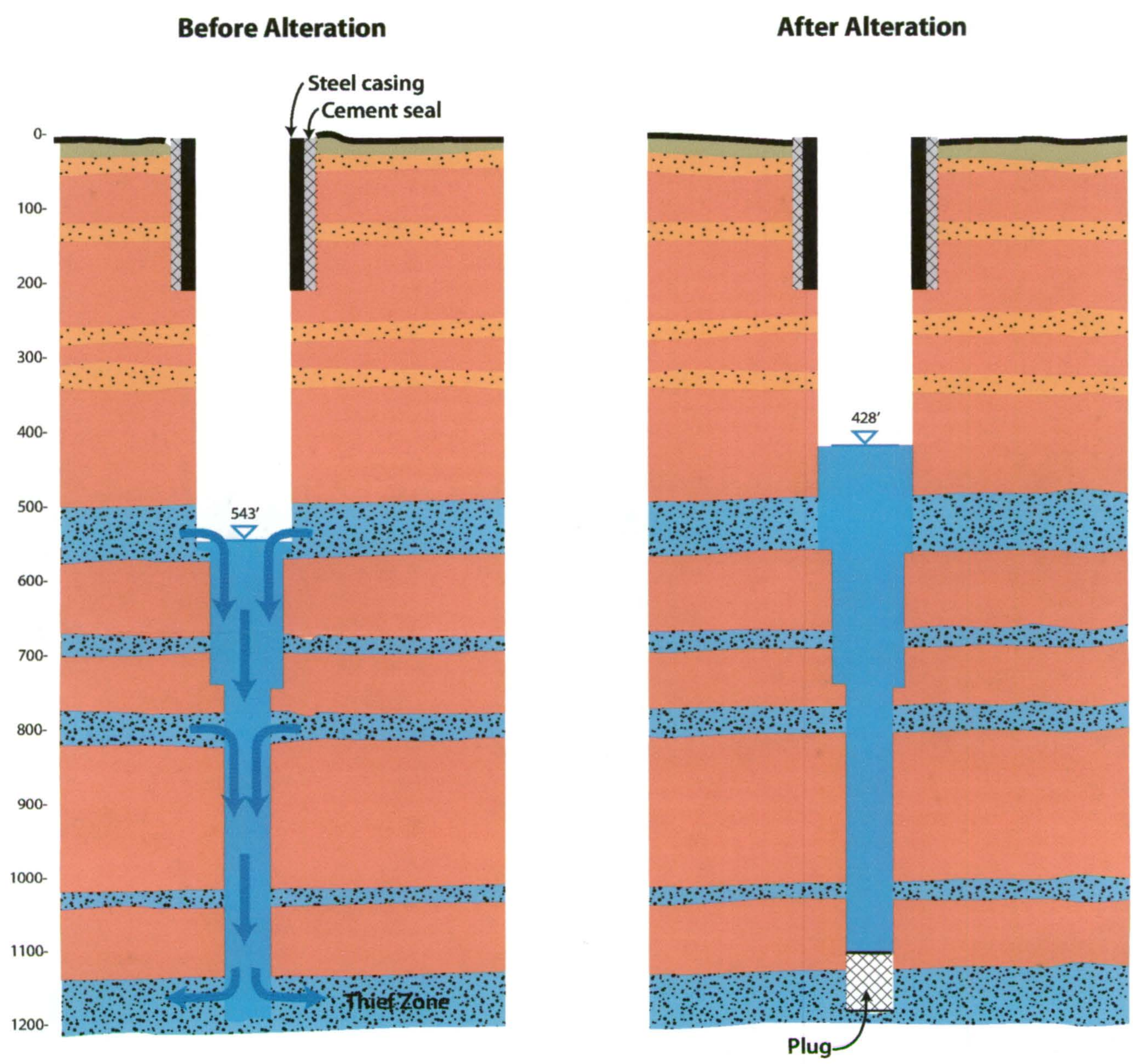
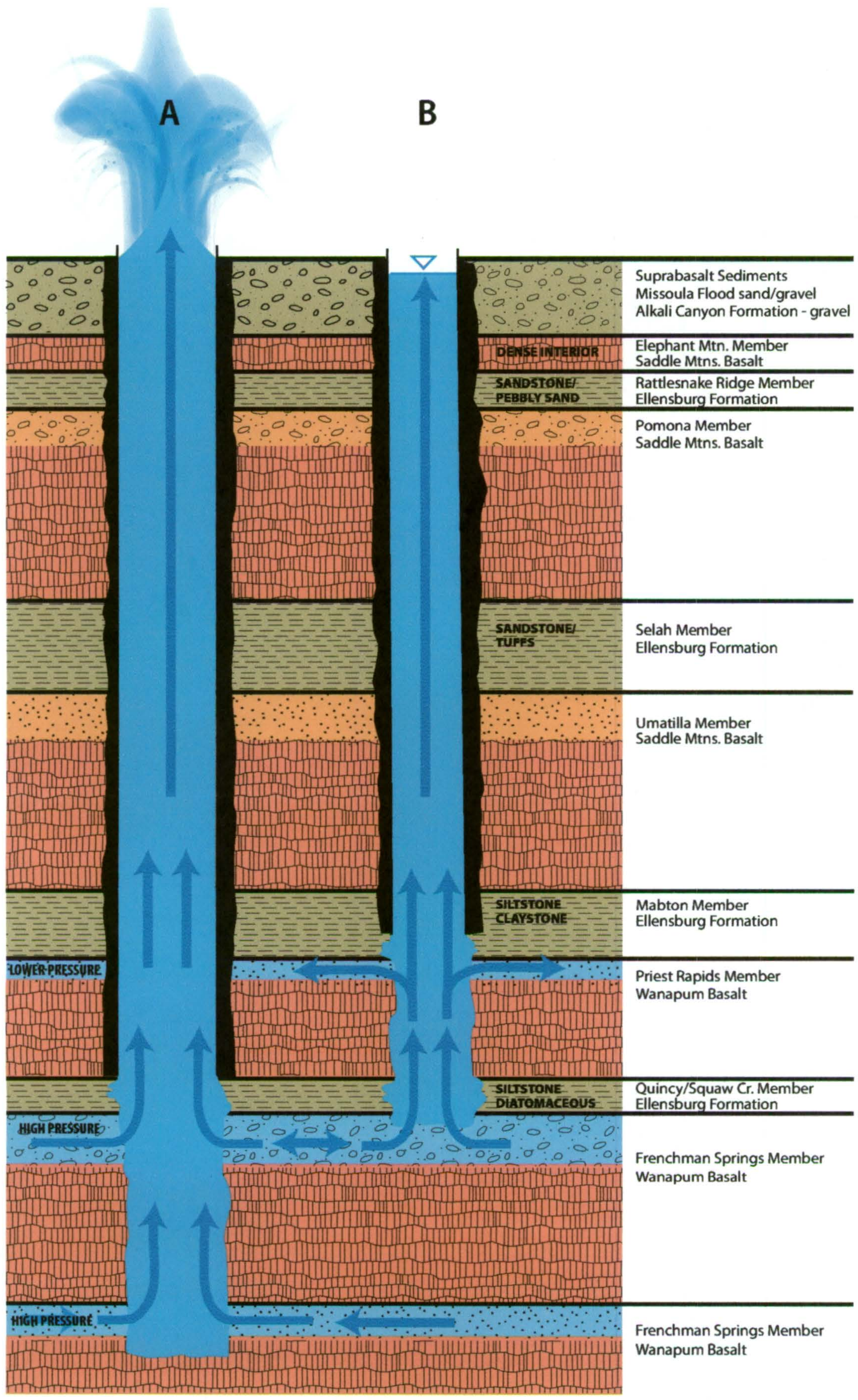


In this case, the well on the right connects all four zones with different water levels, lowering the water level below that in interflows A, B and C. This exposes interflow A to air, causing water to cascade into the well. Also, water flows from interflow C into interflows B and D.

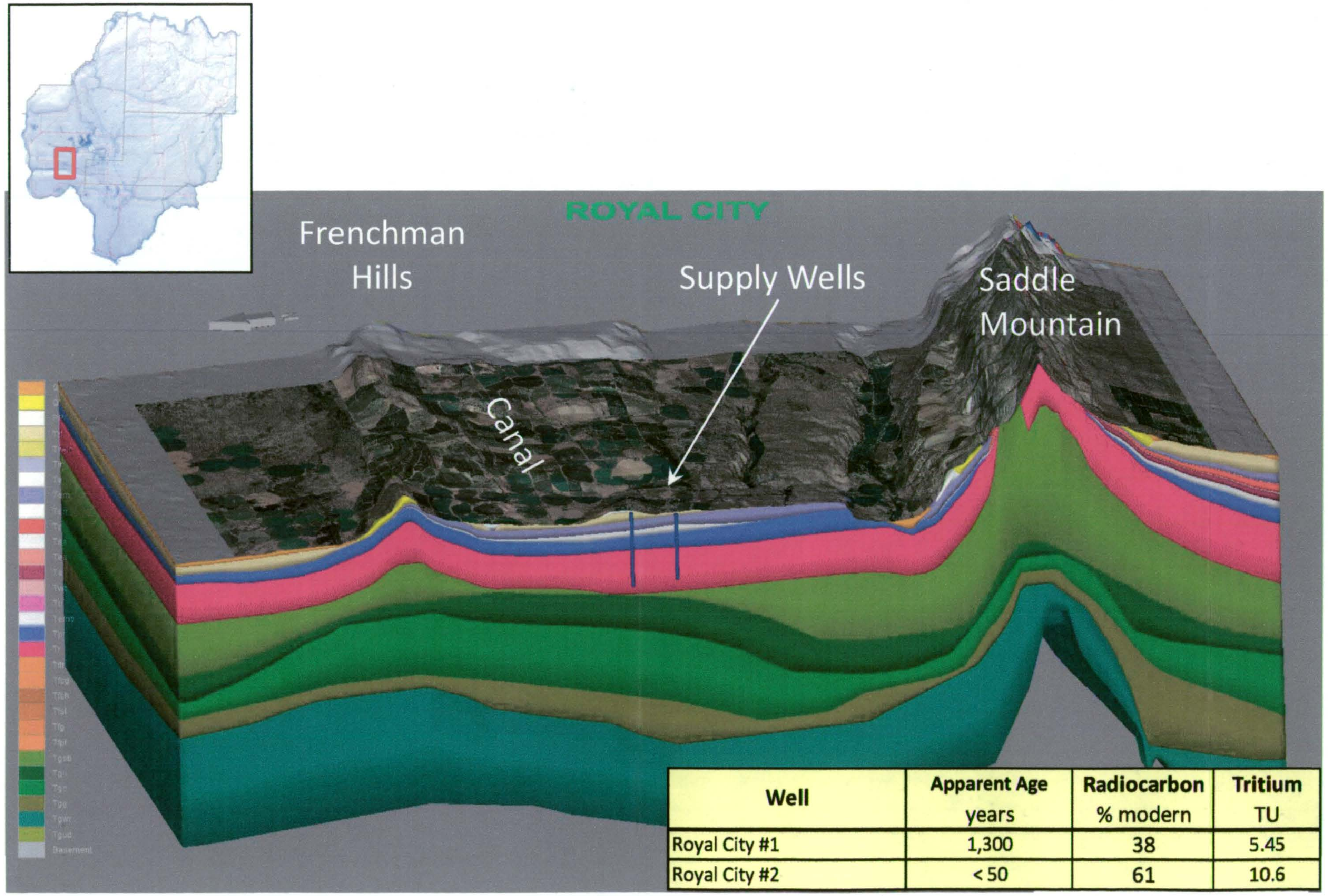




The effect of identification and sealing of a thief zone are depicted in this drawing of an existing Columbia River Basalt well. A thief zone at the bottom of the well was identified in 2005 by indications of strong downhole flow in a video camera survey of the well. After the lowest zone in the well was sealed with a concrete plug, the water level in the well rose 115 feet.

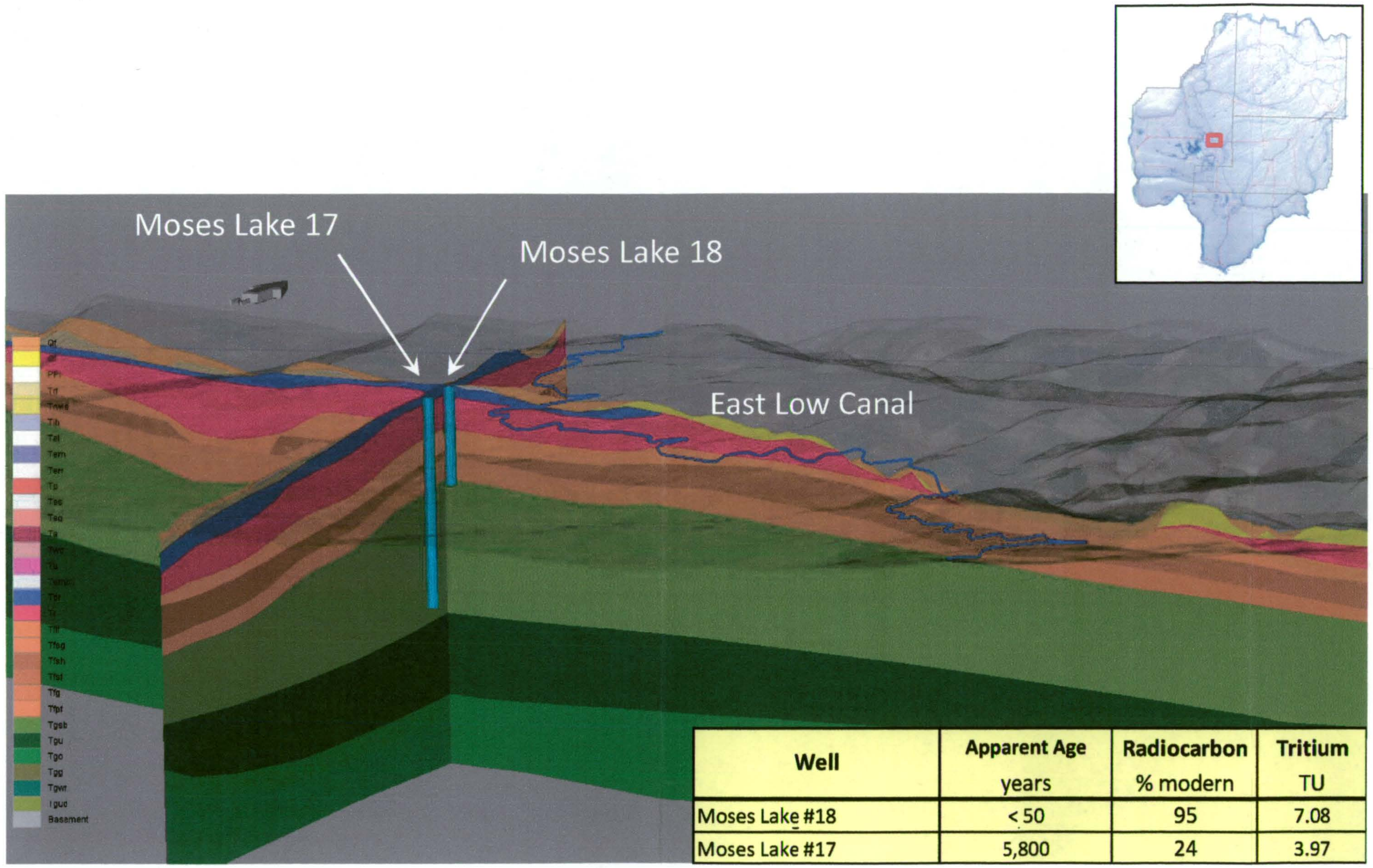


These depictions of actual wells in the same general area show how one well that is not open to a low pressure "thief zone" (A) has a higher water level than a well that is open to the thief zone (B). In this case, the thief zone reduces the pressure sufficiently that the well does not flow at the surface.



Well	Apparent Age years	Radiocarbon % modern	Tritium TU
Royal City #1	1,300	38	5.45
Royal City #2	< 50	61	10.6

Figure 23. Geologic block diagram of part of Royal Basin showing locations of Royal City supply wells 1 and 2 in relation to recharge sources.



Well	Apparent Age years	Radiocarbon % modern	Tritium TU
Moses Lake #18	< 50	95	7.08
Moses Lake #17	5,800	24	3.97

Figure 24. Moses Lake Wells 17 (upper Grande Ronde) and 18 (Wanapum). Well 18 receives most of its recharge from canal leakage. Nearby, the lower Roza and upper Frenchman Springs units are cut by the East Low Canal thus providing a direct connection to surface water recharge. Well 17 also receives some modern recharge but the absence of evidence for a direct geologic connection to surface water suggests this is largely through wellbore leakage from the many wells in the area.