Chapter 2: Study Area Description

This chapter summarizes the physical setting of Lincoln County, including its geography and surface hydrology, climate and habitat, and geology and hydrogeology. Much of this information was derived from previous reports, including Water Resource Inventory Area (WRIA) 43 and WRIA 53 Phase 1 and Phase 2 assessment reports (Kennedy/Jenks 2005) and Columbia Basin Ground Water Management Area (GWMA) reports (GWMA 2009a, 2009b, 2009c, 2009d), Columbia Basin GWMA databases and geographic information system (GIS) data, and Lincoln County Planning Department GIS databases.

The study area for the Lincoln County Passive Rehydration Project is the eastern and northern part of the Odessa Groundwater Management Subarea (see Figure 2).

2.1 Geography and Surface Hydrology

Geography

Lincoln County encompasses approximately 1.49 million acres, or approximately 2,335 square miles in eastern Washington (see Figure 1). The Columbia River and Spokane River (as Lake Roosevelt) mark the northern boundary of the county. Grant County, Adams County, and Spokane County border Lincoln County to the west, south, and east, respectively.

Lincoln County's landscape varies from forested uplands and canyons in the north near Lake Roosevelt to irrigated farmlands, dryland farms, range ground, grasslands, shrub steppes, and rocky scablands (see Figure 4). Less than 1% of the county is found in towns and communities. The largest of these include Reardan, Davenport, Lincoln, Creston, Wilbur, Odessa, Harrington, Almira, and Edwall (Figures 1 and 4). In addition, a number of small private housing developments occur in the northern part of the County, near Lake Roosevelt.

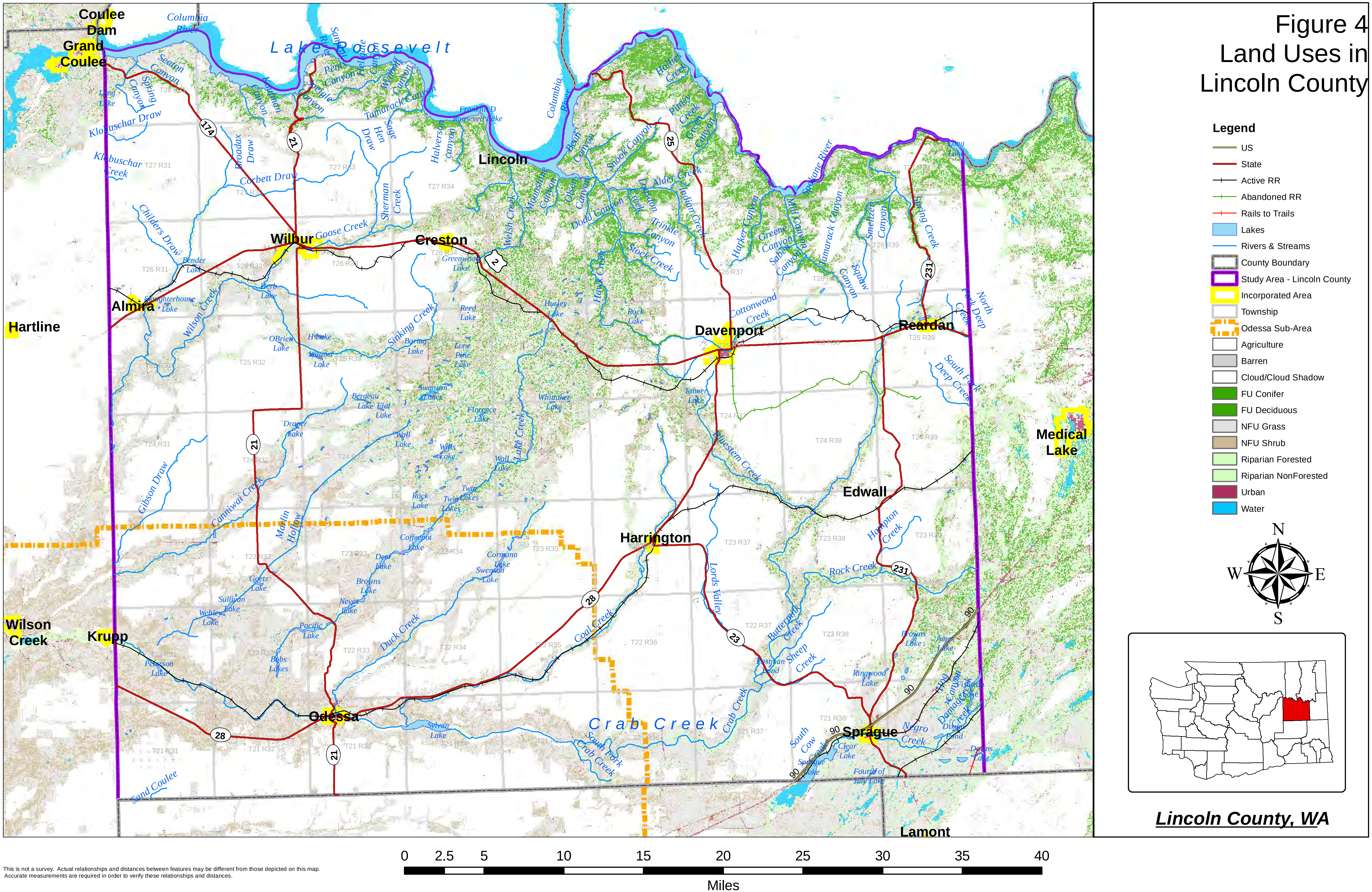
The upland areas of northern and northwestern Lincoln County generally consist of high, partially wooded hills overlooking Lake Roosevelt, and isolated, largely unwooded hills such as Creston Butte and those found in the east near the Spokane County line. The hills overlooking Lake Roosevelt delineate where the Columbia River canyon was incised into the Columbia Basin, and where the CRB abuts against the igneous and metamorphic rocks of the adjacent Okanagan Highlands. This hilly landscape overlooking the Columbia River (Lake Roosevelt) is characterized largely by woodlands, small-scale farming, grazing, and rural residential development. At the base of these hills, adjacent to the Columbia River, many terraces and benches are devoted to irrigated orchards and vineyards, and to residential developments. The isolated hills, such as Creston Butte, are devoted largely to grassland habitat and grazing uses. Elevations across the northern tier of the County range from highs of 2,400 to 2,600 feet above mean sea level (MSL) to lows of approximately 1,270 feet MSL adjacent to Lake Roosevelt.

South of the uplands adjacent to Lake Roosevelt, the landscape slopes generally downward to the south and southwest in the Crab Creek watershed, reaching elevations of approximately 1,400 to 1,660 feet MSL where Crab Creek exits the County. The Crab Creek watershed encompasses the bulk of the county. Within the Crab Creek watershed the land surface generally consists of basalt bedrock scablands separated by rolling hills. The scablands are characterized by isolated buttes, deep, steep-sided canyons, and locally chaotic drainages and deep potholes (Figure 5). The nature of the scablands generally changes from the north (up-slope) to the southwest (down-slope). In the north-central portion of the county, the scablands are characterized by a chaotic, very poorly developed drainage system. To the south, scablands are more linear and associated with specific drainages. Where these drainages become more defined, they form canyons (more commonly referred to as coulees), which in many cases are carved 100 to 300 feet or more into basalt bedrock. These coulees and associated scablands range from less than 1 mile to several miles across.

Within the scablands, stock grazing, small localized irrigated farming, and habitat management activities are the most common land uses. The hills found between the scablands generally consist of wind-deposited silts and fine sands (loess), which commonly are subjected to dryland agriculture, grazing, and habitat uses. These loess hills (Figure 6) are similar in appearance to the hill county of the Palouse Slope located to the south in Adams and Whitman counties.

Surface Hydrology

Historically, perennial streams flowed through many of these scabland drainages, and lakes were common. The feature in Lincoln County's landscape of particular note to this project is Crab Creek and the series of drainages that generally flow to the south and southwest into Crab Creek off the drainage divide adjacent to the Lake Roosevelt valley. Crab Creek—and from east to west its major tributaries Rock Creek, Bluestem Creek, Lords Valley Creek, Coal Creek, Duck Creek, Lake Creek, Marlin Hollow, Canniwai Creek, and Wilson Creek (Figures 1 and 4)—lies in the scabland valleys originally scoured into the Lincoln County landscape by the Pleistocene Missoula flood waters that spilled over the drainage divide in northern Lincoln County and flowed south into the Columbia Basin. Lake Creek, and to a lesser extent the other Crab Creek tributaries, host a number of lakes, several of which are now dry.



This is not a survey. Actual relationships and distances between features may be different from those depicted on this map. Accurate measurements are required in order to verify these relationships and distances.

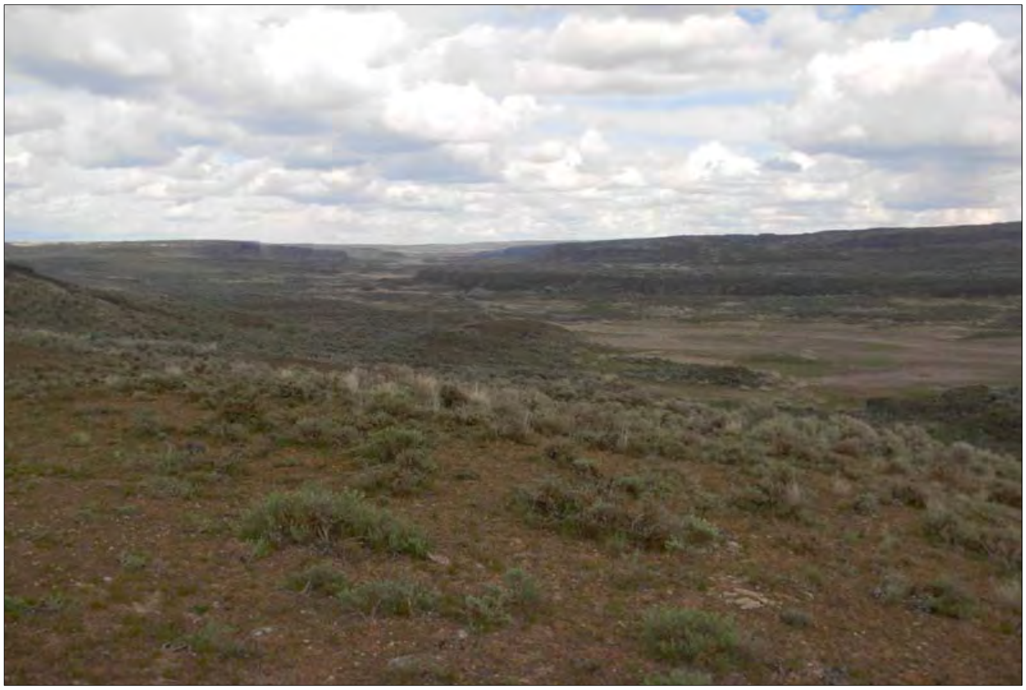


Figure 5. Photograph of the Lake Creek Coulee between Deer Lake and Taveres Lake

The topography seen in the photograph is typical of the area where the stream drainages are located in scabland coulees.

Figure 6. A Typical Landscape in the Northern Part of the Columbia Basin and Lincoln County

In the foreground is a rocky scabland tract, while the hills in the background are loess-covered hills.

2.2 Climate and Habitat

Climate

Precipitation amounts and patterns, as well as temperature and evapotranspiration regimes, are strongly influenced by air masses and storms that come from the west, southwest, and north-northeast. Those that come from the west across the Cascade Range bring high moisture content and moderate temperatures, although the majority of the moisture in these air masses is dropped on the Cascade Range as rain and snow. Air masses that come from the southwest are more typically hot and dry. Arctic air from the north and continental influences from the east cause winters to be cold and relatively long. When two or more of these predominant air masses mix, some of the highest precipitation storm events occur.

These different weather patterns, coupled with the topography of Lincoln County, result in climates in the County that combine characteristics typical of semi-arid mountain foothill climates with those more typical of semi-arid grassland and steppe climates. The foothills-like climate predominates in the northern part of the county adjacent to Lake Roosevelt, where precipitation is greater. South- and north-facing slopes and canyons offer cooler local microclimates. The grassy steppes and farmlands found south of the highlands bordering Lake Roosevelt lie within the semi-arid climates that dominate the bulk of the county.

Climatic data for the area is found in the Western Regional Climate Center (WRCC) database and is summarized in reports for WRIAs 43 and 53. The WRCC compiles and maintains climatic data from the National Oceanographic and Atmospheric Administration (NOAA), the Natural Resource Conservation Service Snowpack Telemetry System (SNOTEL), and regional cooperators that operate individual recording stations (WRCC 2009). Generally, these climatic data show that annual precipitation varies from approximately 7 to 16 inches per year, with higher amounts prevailing at the higher elevations of northern Lincoln County. The period from July through October is generally the driest time of the year. Except in the coldest months, evapotranspiration exceeds precipitation.

Habitat

Given the climate described above, the bulk of Lincoln County lies within a semi-arid shrub steppe ecosystem. Major plant types in this ecosystem are shrubs (such as sagebrush, hopsage, greasewood, and bitterbrush) and perennial bunchgrasses (such as bluebunch, needle-and-thread, Idaho fescue, and Sandberg's bluegrass). Numerous annual and perennial wildflowers (such as phlox, mariposa lily, fleabanes, and locoweeds) thrive in the spaces between shrubs and bunchgrasses. Much of the shrub steppe is also plagued with non-native plant species such as cheat grass and Russian thistle.

Animal species populating the area include many mammals such as mule deer, jack rabbits, coyotes, bobcats, and various rodent species. Bird species found within the study area include horned larks, sage sparrows, sage thrashers, Brewer's sparrows, sage grouse, and vesper sparrows.

In northern Lincoln County, on the highlands and in the canyons along the drainage divide between Lake Roosevelt and the Crab Creek drainage, the semi-arid shrub steppe habitat transitions into a mixed steppe and forest habitat. This transition generally corresponds to areas where annual precipitation exceeds 12 to 14 inches, and temperatures are slightly lower than to the south. This is commonly seen on sheltered north-facing slopes and canyons.

Fisheries

Fisheries in the project area consist of those found in Lake Roosevelt and those found in the Crab Creek drainage. The Lake Roosevelt fishery is a dynamic system influenced by large reservoir fluctuations, limited habitat, and abundant non-native fish species (BPA 1999). Extreme reservoir level fluctuations, especially drawdown, likely result in high levels of entrainment of fish from Lake Roosevelt. BPA (1999) reports 20 species from 8 families being collected in its survey of the fishery. The most abundant species captured was rainbow trout, followed by walleye, lake whitefish, largescale suckers, and Kokanee salmon. Other species surveyed are white sturgeon, carp, northern pikeminnow, tench, longnose sucker, bridgelip sucker, Chinook salmon, mountain whitefish, brown trout, eastern brook trout, burbot, sculpin, smallmouth bass, black crappie, and yellow perch. The BPA survey indicated a healthy population of brown trout, and reductions in largescale suckers, walleye, and rainbow trout. The hatchery Kokanee population has been stable. Closure of the Spokane Arm to fishing during the walleye spawning season has protected the walleye from over-harvest. Interactions between native and non-native species add complexity to the system when these species compete and habitat utilization when non-native fish prey on native fish.

Information on fish species in the Crab Creek drainage appears to be limited, and a systematic examination of this fishery was not found. The upper Crab Creek watershed assessment (Kennedy/Jenks 2005) indicates that the system historically contained trout; however, presence of the species is uncertain. Anecdotal reports suggest that westslope cutthroat trout, hatchery rainbow trout, brook trout, brown trout, and Kokanee were introduced to the watershed in the early 1900s. Between 2001 and 2003, Eastern Washington University collected data at various locations within the Crab Creek Watershed that indicate interior redband rainbow trout may exist in the Crab Creek drainage along with hatchery-origin rainbow trout (Kennedy/Jenks 2005). Non-native salmonids (brook trout and brown trout) have historically been stocked in the watershed and have contributed to the fishery resource of the watershed. Anecdotal evidence suggests that portions of the watershed support a robust and self-sustaining population of the fish species listed above.

Lakes in the Crab Creek drainage, at least those that still contain water, contain a mix of cold water and warm water fish. In June 2003, the Washington Department of Fish and Wildlife Warmwater Enhancement Program conducted fisheries surveys on Upper and Lower Twin Lakes in the Lake Creek Drainage (WDFW 2005). Six fish species were collected from Upper and Lower Twin Lakes: largemouth bass, pumpkinseed sunfish, rainbow trout, brown bullhead, yellow perch, and black crappie. Current management strategies were recommended for Upper Twin Lake, while an increase in predator abundance was recommended for Lower Twin Lake. Coffeepot Lake, part of the Lake Creek system, is reported to sustain rainbow trout, largemouth bass, and smallmouth bass.

2.3 Geology and Hydrogeology

The geology and hydrogeology of the project area will have a profound impact on one of the two primary goals of the project: recharging a portion of the CRB aquifer system that has been overdrafted by groundwater pumping in the Odessa Groundwater Management Subarea. The proposed rehydration project will need to be implemented in areas where rehydrated lakes and streams can recharge the underlying CRB aquifer system, and once recharged, that water will need to be able to migrate southward into the Subarea. Section 2.3 summarizes the geologic and hydrogeologic conditions present in the project area that will eventually influence the ability of a possible project to recharge the CRB aquifer system.

Lincoln County lies on the northern edge of the Columbia River flood basalt province where the CRB pinches out against the metamorphic and crystalline igneous rocks of the Okanagan Highlands (Figure 7). The major geologic units found within Lincoln County include (1) supra-basalt sediments and continental flood basalt of the Columbia River Basalt Group (CRBG), and (2) the metamorphic and crystalline igneous rocks underlying the CRBG. This section summarizes basic information about the geology and hydrogeology of Lincoln County as it relates to the potential to influence the proposed project. The reader is referred to other reports cited in this document for more detailed information about the geology and hydrogeology of the greater Lincoln County area.

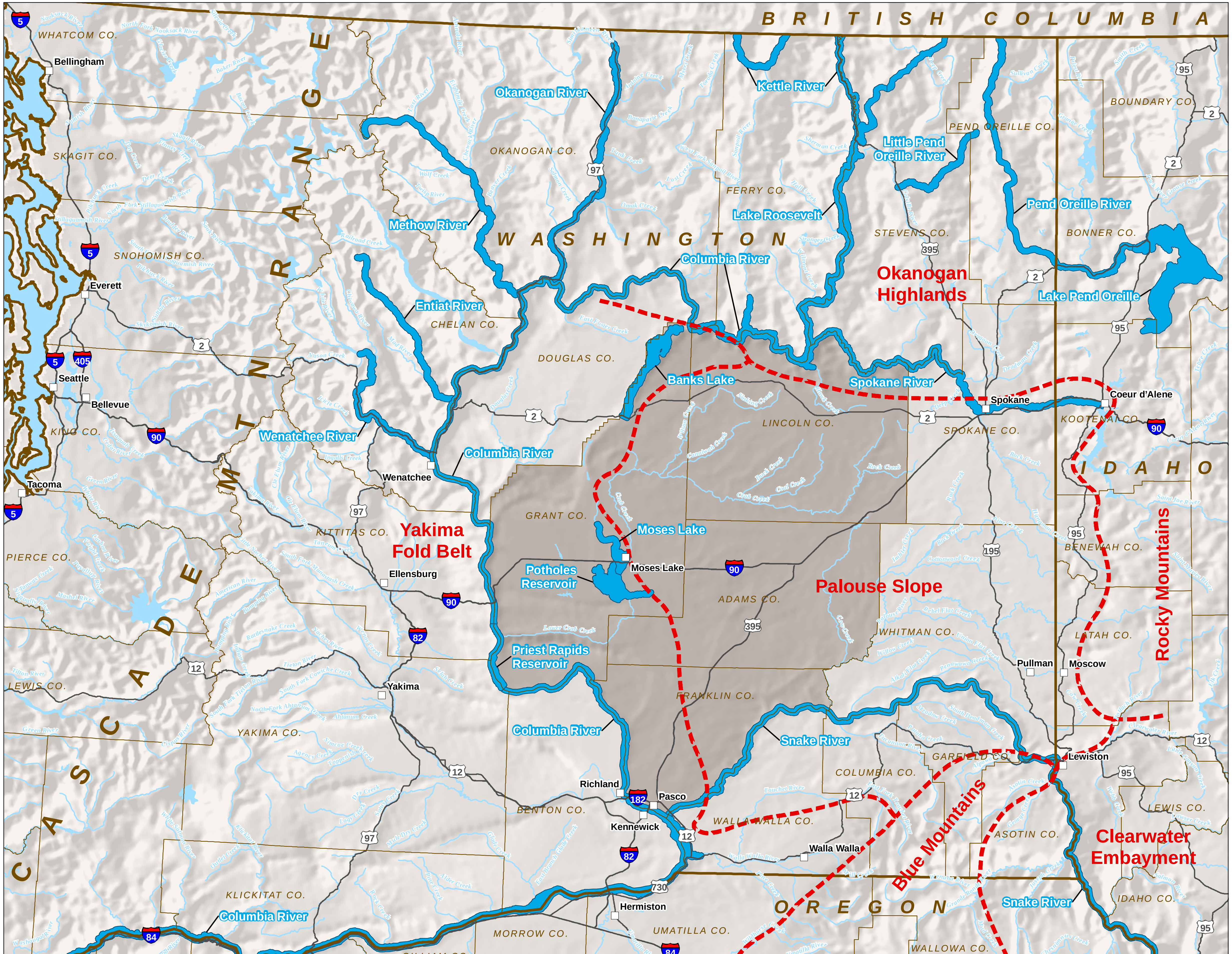


Figure 7

Regional Physiographic Setting

Lincoln County, Washington

LEGEND

Regional Geographic Locations

- Structural Regions of the Columbia Plateau Regional Aquifer System
- Major Water Features
- Counties of Interest

All Other Features

- Cities
- County Boundary
- State Boundary
- Freeways and Major Highways
- Watercourses
- Waterbodies

N

0 10 20 30 40

Miles

MAP NOTES:

Date: February 10, 2011

Data Sources: ESRI

GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure1_Regional_Geographic_Locations.mxd, Date: February 10, 2011 2:13:33 PM

2.3.1 Soils

Soil types in Lincoln County range from silt loams to sandy and gravelly soils, to rocky soils directly on bedrock. The silt loams, which dominate the rolling hills between the major drainages, are mostly well-drained. In many areas, layers of calcium carbonate and silica hardpan (caliche/duripan) are present. Much of the active modern farming is done on these soils, and these soils typically have been farmed in the past. Unaltered intact silt loam soils are rare because the area has been used for agriculture and livestock grazing for many decades. Nevertheless, the infiltration capacity of these soils is relatively low. If these soils are found at rehydrated locations where other factors suggest that basalt aquifer recharge potential is high, then it might be necessary to improve permeability to enhance infiltration capacity.

The sandy and gravelly soils are most common in and around coulees. These soils typically are developed on Pleistocene Missoula flood deposits, including sand and gravel bars deposited in and adjacent to the coulees. These soils have a relatively high infiltration capacity, and little or no site modifications would be necessary if these materials are found at a location that is deemed appropriate for recharge for other reasons. These types of substrates are common in coulees where most, if not all, future potential recharge projects would occur. In such areas, recharge potential for the underlying basalt aquifer system would be high.

Thin, rocky soils are present in scablands where a thin veneer of rocky silt and sand has developed directly upon bedrock. Generally, basalt aquifer recharge would not be widespread on these thin, rocky soils developed over bedrock because the bedrock typically has extremely low to essentially no infiltration capacity (USDOE 1988). However, there may be cases where an underlying basalt substrate is dominated by a rubbly and/or brecciated interflow zone. In such cases, the infiltration capacity of such soils could be favorable for basalt aquifer recharge. These later examples would be targeted as preferred basalt aquifer recharge areas as they were identified in the field.

2.3.2 Suprabasalt Sediments

Suprabasalt sediments (the sediments overlying the top of basalt) in Lincoln County consist predominantly of Pleistocene- to Holocene-aged alluvium, Pleistocene Missoula flood deposits, and Pleistocene loess. Using GWMA's regional mapping (GWMA 2009a, 2009b) and 1:100,000 scale surface geologic maps published by the State of Washington (Gulick 1990; Gulick and Korosec 1990; Joseph 1990; Waggoner, 1990a, 1990b), these sediments were subdivided into two basic units—coarse Quaternary alluvium and fine-grained Quaternary deposits—for the purposes of this report.

Coarse Quaternary alluvium. Coarse Quaternary alluvium consists of mixed silt, sand, and gravel (Figure 8) deposited predominantly by Pleistocene Missoula flood waters and to a lesser extent by post-flood stream reworking of flood deposits and colluvial processes on hill slopes. These strata are most commonly found in and adjacent to coulees, stream and river canyons, and steep cliffs cut into bedrock. In some areas these materials may form benches in canyons and coulees. Pleistocene Missoula flood deposits can be found almost everywhere flood waters scoured the Lincoln County landscape, from terraces adjacent to Lake Roosevelt to gravel bars along Crab Creek. The other coarse Quaternary deposits are very limited spatially, and are found at the base of steep slopes and localized along modern stream channels. According to subsurface geologic maps created by the Columbia Basin GWMA, the thickness of this unit in the study area ranges from less than 10 feet to as much as 100 feet (GWMA 2009b).

Fine-grained Quaternary deposits. Fine-grained Quaternary deposits consist predominantly of silt, silty sand, and very fine sand loess (Figure 9) and form the rolling hill topography between the major drainage valleys that cross-cut Lincoln County. This unit is largely absent within coulees and drainages that are possible sites for passive recharge. GWMA's subsurface geologic maps show the unit varying from less than 10 feet to as much as 120 feet thick in Lincoln County (GWMA 2009b). Its distribution is largely controlled by the depth of cataclysmic flood erosion that formed the scabland coulees that cross-cut the area and dissect the hills where these strata are found.

Figure 8. Photograph of a 30- to 50-Foot Thick Sequence of Pebble to Boulder Gravel Deposited by the Pleistocene Missoula Floods

Typical of the Pleistocene Missoula flood deposits commonly seen in coulees and scabland tracts throughout the region.

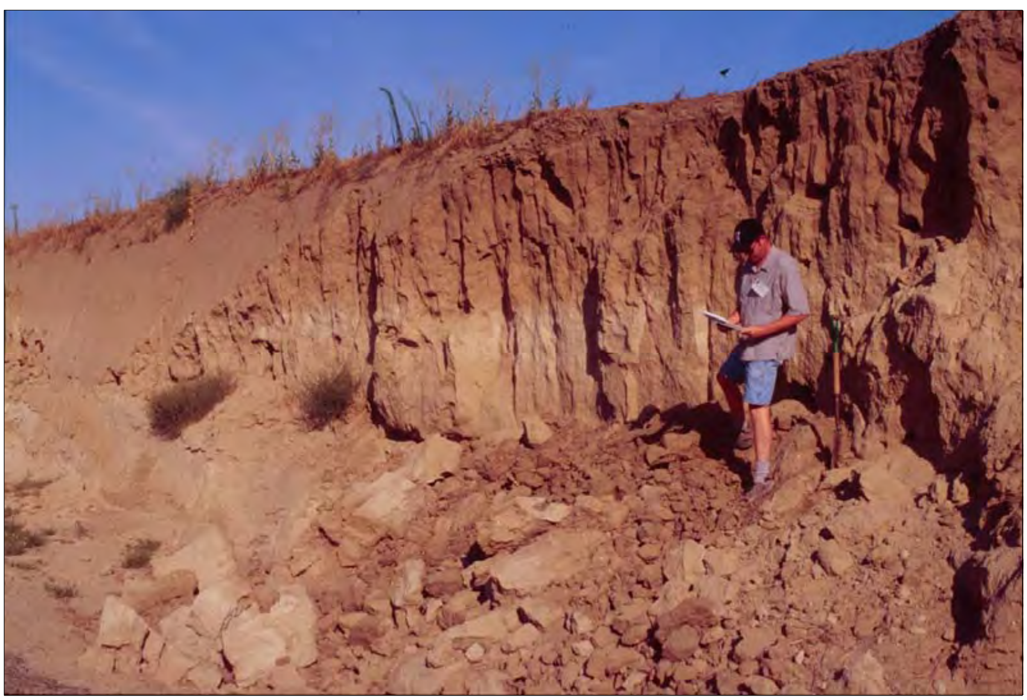


Figure 9. Photograph of a Typical Loess Embankment Exposed in a Road Cut

Suprabasalt Sediment Hydrology. Vadose zone conditions, and consequently infiltration capacity, in the suprabasalt sediments are controlled by physical heterogeneities within these coarse to fine strata. These heterogeneities would result in complex flow paths that include downward percolation, upward diffusion, and lateral movement of vadose zone moisture. For example, local perched aquifers could exist where discrete areas or lenses of fine-grained materials exist and act as barriers to downward percolation. Clearly, a potential future recharge area would have better infiltration capacity and aquifer recharge potential if it is underlain by coarse suprabasalt sediments rather than fine sediments.

Saturated suprabasalt sediments, and the suprabasalt sediment aquifer system, more commonly occur in coarse Quaternary sediments found within scabland tracts, than in the fine-grained Quaternary sediments found covering the hills bordering the scablands. As with the vadose zone, where saturated suprabasalt sediments are present in a potential recharge area, coarse-grained strata generally will be more conducive to recharge than fine sediments. The base of the suprabasalt aquifer is defined as the top of the CRBG. The lateral extent of the suprabasalt aquifer in Lincoln County is controlled by surface CRB outcrops and areas of Quaternary sediment deposition within coulees and canyons. These physical features result in a suprabasalt sediment aquifer that is very discontinuous, with hydraulic continuity between different areas of saturated sediment being extremely limited. The limited continuity between occurrences of the suprabasalt aquifer suggests that recharge areas targeting these strata will be localized at specific locations up and down any targeted stream drainage.

Estimated suprabasalt sediment aquifer thicknesses in the county range from less than 10 feet up to as much as 100 feet, generally depending on the thickness of valley fill in any given reach of a coulee. Where a suprabasalt sediment aquifer is present, depth to water (DTW) is relatively shallow and ranges from less than 10 feet up to 60 feet. Estimated water table elevations in the system are approximately 1,200 to 1,300 feet above mean sea level (AMSL) in the southwestern part of the county, and 2,200 to 2,300 feet AMSL in the northern part of the county. However, because the suprabasalt aquifer system is localized by basalt bedrock topography, a single, countywide suprabasalt sediment aquifer is not present.

Where it occurs in Lincoln County, the suprabasalt sediment aquifer system typically is unconfined. Elsewhere in the region, measured hydraulic conductivity for coarse strata analogous to the Quaternary coarse unit ranges from 2,000 to 25,000 feet/day with effective porosity greater than 10% (USDOE 1988). Within the Quaternary fine-grained unit, hydraulic conductivities will be several orders of magnitude lower.

Because average annual precipitation is low (less than 16 inches) and the summer season is hot and dry, natural surface recharge for the suprabasalt sediment aquifer from precipitation (rain and snowmelt) most likely is small. In addition, because the majority of precipitation that falls in the area occurs in the winter and spring, the small amount of natural recharge that occurs takes place primarily in the winter and spring. In addition, given the local climatic conditions found across the county, natural recharge decreases to the southwest across the county as elevations and precipitation decrease.

Bauer and Vaccaro (1987, 1990) and Vaccaro (2007) describe methodologies for estimating aquifer recharge from natural precipitation. Generally, natural recharge will be 10% or less of natural precipitation. However, where irrigation occurs, some artificial recharge is likely because the amount of water available on the surface and in shallow soils can periodically exceed evapotranspiration.

Surface discharge from the suprabasalt sediment aquifer system in the study area is most likely into streams, lakes, and ponds where they are present in coulees. The degree of hydraulic continuity with the underlying basalt aquifer system is discussed in Section 2.3.6.

2.3.3 Columbia River Basalt Group (CRBG)

The CRBG is a thick sequence of more than 300 continental tholeiitic flood basalt flows that cover an area of more than 59,000 square miles in Washington, Oregon, and western Idaho (Tolan and Reidel 1989, Camp et al. 2003, Camp and Ross 2004) with a maximum thickness of over 10,000 feet. Numerous reports describe a variety of CRBG topics, ranging from petrology, to stratigraphy, to emplacement, to tectonics, to hydrology. Several of the more recent compilations of CRBG geology and hydrogeology are found in PNNL (2002), GWMA (2009a, 2009b, 2009d), Kahle et al. (2009), and Tolan et al. (2009).

The CRBG has been divided into a host of regionally mappable units (Figure 10) based on variations in physical, chemical, and paleomagnetic properties, and stratigraphic position between flows and packets of flows (Swanson et al. 1979a, Beeson et al. 1985, Reidel et al. 1989b, Bailey 1989). The CRBG in the Columbia Basin region is subdivided into four formations. These formations are, from youngest to oldest, the Saddle Mountains Basalt, Wanapum Basalt, Grande Ronde Basalt, and Imnaha Basalt (Swanson et al. 1979a, 1979b). These formations have been further subdivided into members defined, as are the formations, on the basis of a combination of unique physical, geochemical, and paleomagnetic characteristics. These members can be, and often are, further subdivided into flow units (e.g., Beeson et al. 1985).

Series		Group		Formation	Member	Isotopic Age (m.y)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
					Ice-Harbor Member	8.5	
					Basalt of Goose Island		N
					Basalt of Martindale		R
					Basalt of Basin City		N
					Buford Member		R
					Elephant Mountain Member	10.5	N, T
	Middle				**Pomona Member**	12	R
					Esquatzel Member	N	
					Weissenfels Ridge Member		
					Basalt of Slippery Creek		N
					Basalt of Tenmile Creek		N
					Basalt of Lewiston Orchards		N
					Basalt of Cloverland		N
					Asotin Member	13	
					Basalt of Huntzinger		N
					Wilbur Creek Member		
					Basalt of Lapwai		N
					Basalt of Wahluke		N
					Umatilla Member		
					Basalt of Sillusi		N
					Basalt of Umatilla		N
				Wanapum Basalt	**Priest Rapids Member**	14.5	
					Basalt of Lolo		R
					Basalt of Rosalia		R
					Roza Member		T, R
					Shumaker Creek Member		N
					Frenchman Springs Member		
					Basalt of Lyons Ferry		N
					Basalt of Sentinel Gap		N
					Basalt of Sand Hollow	15.3	N
					Basalt of Silver Falls		N, E
					Basalt of Ginkgo	15.6	E
					Basalt of Palouse Falls		E
					Eckler Mountain Member		
					Basalt of Dodge		N
					Basalt of Robinette Mountain		N
					Vantage Horizon		
				Grande Ronde Basalt	**Member of Sentinel Bluffs**	15.6	N_2
					Member of Slack Canyon		
					Member of Fields Spring		
					Member of Winter Water		
					Member of Umtanum		
					Member of Ortley		
					Member of Armstrong Canyon		
	Lower			Prineville Basalt	**Member of Meyer Ridge**		R_2
					Member of Grouse Creek		
					Member of Wapshilla Ridge		
					Member of Mt. Horrible		
					Member of China Creek		N_1
					Member of Downy Gulch		
				Picture Gorge Basalt	**Member of Center Creek**		R_1
					Member of Rogersburg		
					Teepee Butte Member		
					Member of Buckhorn Springs	16.5	
				Imnaha Basalt			R_1
							T
							N_0
						17.5	R_0

G02060100-1C

Figure 10. Stratigraphic Nomenclature of the CRBG

From Tolan et al. (1989) and Reidel et al. (1989a).

Vertical exposures through CRBG flows reveal that they generally exhibit the same basic three-part internal arrangement of intraflow structures. These features, which originated either during the emplacement of the flow or during the cooling and solidification of the lava after it ceased flowing, are referred to as the flow top, flow interior, and flow bottom (Figure 11).

The flow top is the crust that formed on the top of a molten lava flow. Flow tops commonly consist of glassy to very fine-grained basalt that is riddled with countless spherical and elongate vesicles, and contains variable amounts of basalt rubble (Figure 12). Flow interiors are dense, non-vesicular, glassy to crystalline basalt that contains numerous contraction joints (termed cooling joints) that formed when the lava solidified (Figure 13). Joints are organized regularly and form perpendicular to cooling surfaces (Figure 13). With alteration, cooling joints are filled in with precipitated minerals, resulting in greatly diminished permeability. The character of the flow bottom largely is dependent on the environmental conditions the molten lava encountered as it was emplaced. They can be thin, vesicular, and glassy if the flow encountered dry ground. Pillow complexes (Figure 14) formed if the lava flowed into a body of water.

Interflow zones are the intervals between successive lava flows that can contain various combinations of flow top (from the underlying flow) and flow bottom (from the overlying flow) features. Interflow zones are hydrogeologically important (and important to this project) in that they host aquifers and, where they outcrop, can serve as basalt aquifer recharge and/or discharge sites. If a sediment interbed is present between the two flows, it would also be part of the interflow zone. The physical characteristics of basalt flow structures are important because they exert fundamental influences on groundwater occurrence and movement within the CRBG.

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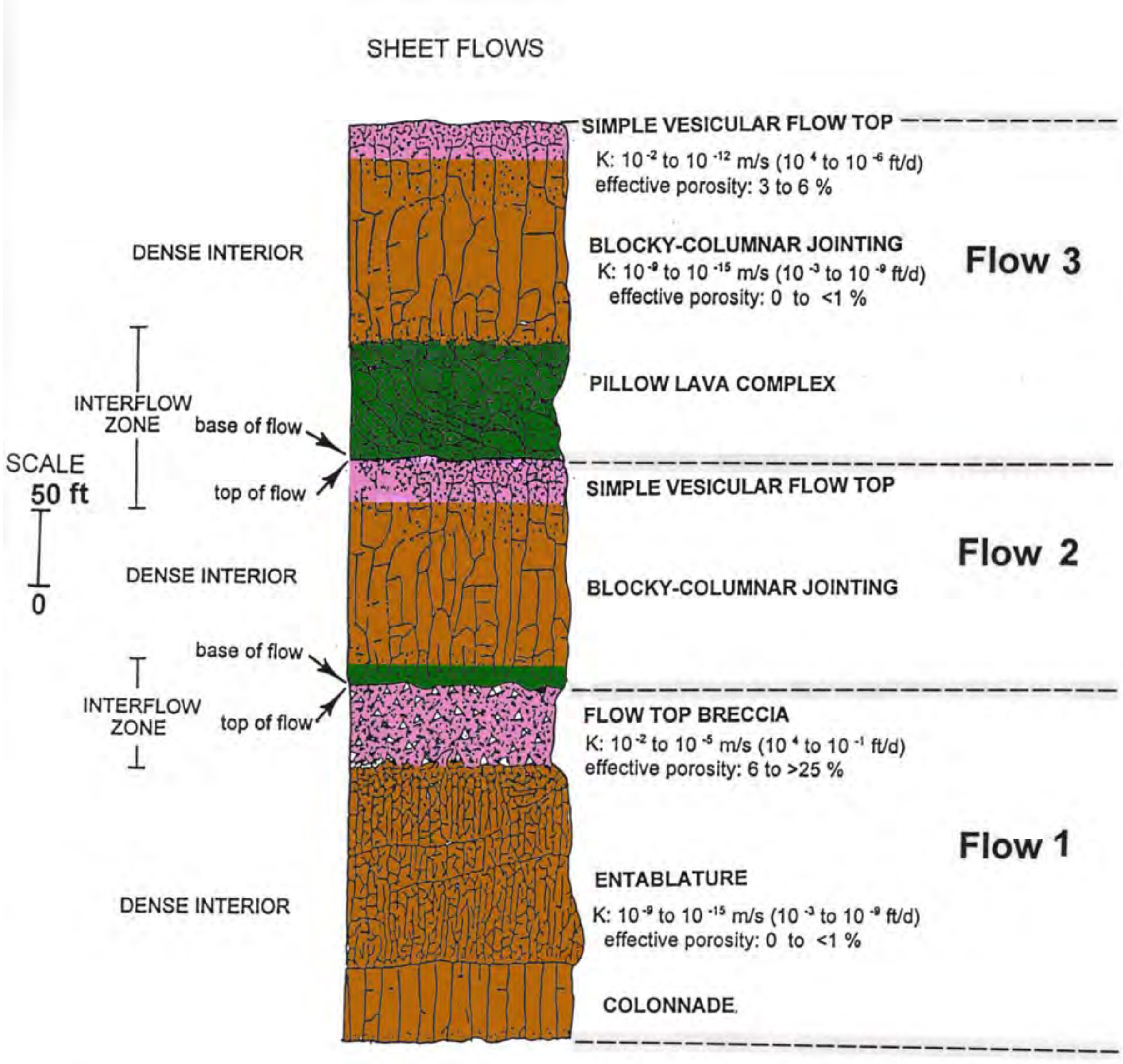

Figure 11. Internal Structure of CRBG Flows

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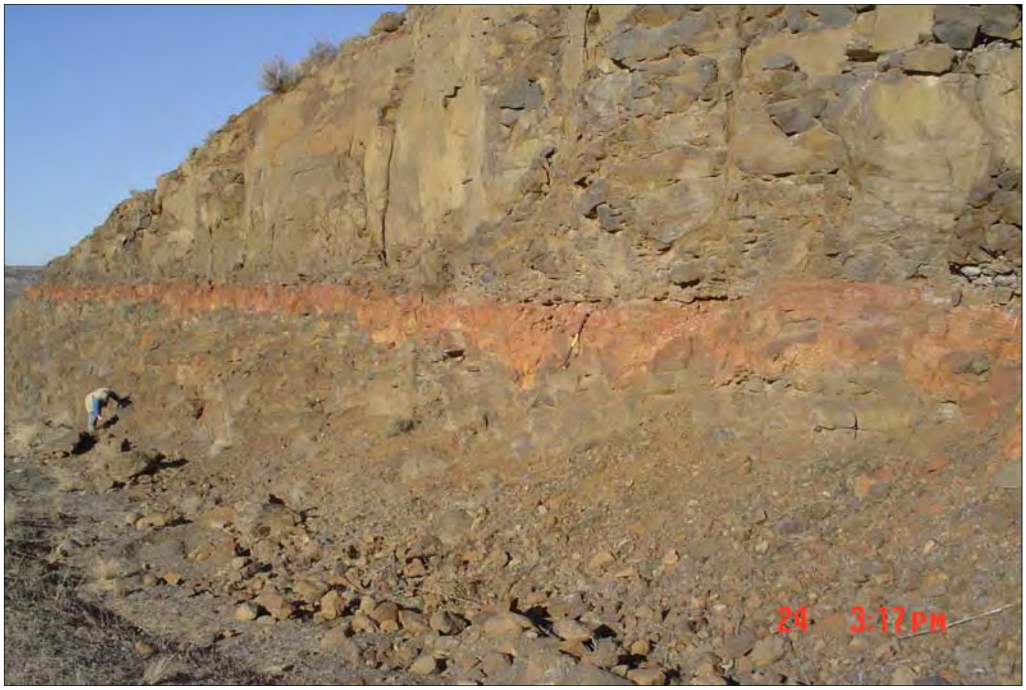

Figure 12. Photograph of a Simple Flow Top in the CRBG

The flow top is marked by the red banded interval in the middle of the outcrop.

Figure 13. Photograph of Entablature–Collonade of a Typical Dense Flow Interior

Entablature (above); colonnade (below).

Figure 14. Photograph of a Pillow Lava Complex at the Base of a CRBG Flow

The Wanapum Basalt and Grande Ronde Basalt are the two CRBG units that underlie the study area. Table 2, based on GWMA mapping (GWMA 2009b), lists the primary suprabasalt sediment and CRBG units and their thickness ranges beneath the immediate study area. The Wanapum Basalt ranges from less than 100 to 400 feet thick and the Grande Ronde Basalt ranges from 1,000 to over 3,400 feet thick.

Table 2. Summary of the Main Geologic Units Underlying the Project Area

Geologic unit	Thickness range (feet)	Comments
Coarse Quaternary alluvium	0-100	Localized in and near coulees and scablands
Quaternary fine-grained unit	0-120	Predominantly loess
Priest Rapids Member (WB)	0-400	Absent in southwest corner of county
Roza Member (WB)	0-300	Absent from western 1/3 of county
Sentinel Gap, Frenchman Springs Mbr (WB)	0-150	Absent from northern and eastern part of county
Sand Hollow, Frenchman Springs Mbr (WB)	0-120	Only present in south-central and southwestern part of county
Ginkgo, Frenchman Springs Mbr (WB)	0-50	Only present in southwestern most corner of county
Sentinel Bluffs Member (GRB)	0-800	Underlies almost all of county
Umtanum Member (GRB)	0-300	Absent beneath northern half of county
Ortley Member (GRB)	0-600	Absent beneath northern half of county
Grouse Creek Member (GRB)	0-400	Absent in northeastern and northwestern corners of county
Wapshilla Ridge Member (GRB)	0-500	Underlies most of county
Undifferentiated Grande Ronde Basalt	0->2,000	Only beneath southern half of county
Pre-basalt basement	>20,000	Underlies all of county

WB – Wanapum Basalt; GRB – Grande Ronde Basalt

CRBG Stratigraphy – Wanapum Basalt

The Priest Rapids Member (the uppermost widespread CRBG unit in the county), Roza Member, and the Frenchman Springs Member of the Wanapum Basalt are found in Lincoln County. In addition, dikes and associated vent systems for the Roza and the Priest Rapids Members were identified in the County during reconnaissance work for this project and during the course of GWMA field investigations.

Priest Rapids Member. The top of the Priest Rapids Member, although modified by erosion in many areas, generally dips to the south-southwest across much of the county (Figure 15). In the northernmost part of the County it locally dips to the north. Because this is the uppermost CRBG unit in the county, its distribution has been influenced by post-emplacement incision. It is absent from many of the larger coulees seen in the county, including long reaches of Sinking Creek, Lake Creek, Coal Creek, and Crab Creek. In addition, the unit appears to be absent from a large portion of the southwestern part of the county. Where present, the unit ranges in thickness from less than 50 feet to over 400 feet.

Priest Rapids Member dikes are inferred to be present in the eastern and north-central portions of the county for two basic reasons. One is the presence of the unit in northern Lincoln County, high on the paleoslope inferred to have been present during emplacement in the Miocene (Fecht et al. 1987, Tolan et al. 1989, Smith et al. 1989), which would require eruptive vents to have extended well north into the area now occupied by the county (Tolan et al. 2009). The other is that this area lies on the northwestern projection of feeder dikes that are known to occur to the south. Reconnaissance done for this study, and GWMA field investigations, provide some confirmation of the extent of the Priest Rapids dike system with the discovery of Priest Rapids near vent facies in a road cut on Duke Lake Road north of Odessa, Washington, in Sections 5 and 6, Township 22 North, Range 34 East. The general inferred extent of this dike system is shown in Figure 15, which shows the mapped extent of the Priest Rapids Member in the study area.

Roza Member. Like the overlying Priest Rapids Member, the top of the Roza Member generally dips to the south-southwest where the unit is present (Figure 16). The Roza Member also is absent from many of the larger coulees, where it has been completely incised through. However, unlike the Priest Rapids Member, the Roza Member is present across much of the southwestern corner of the county and is absent from the eastern and northeastern part of the county. Where present, the thickness of the member varies from less than 100 to 300 feet.

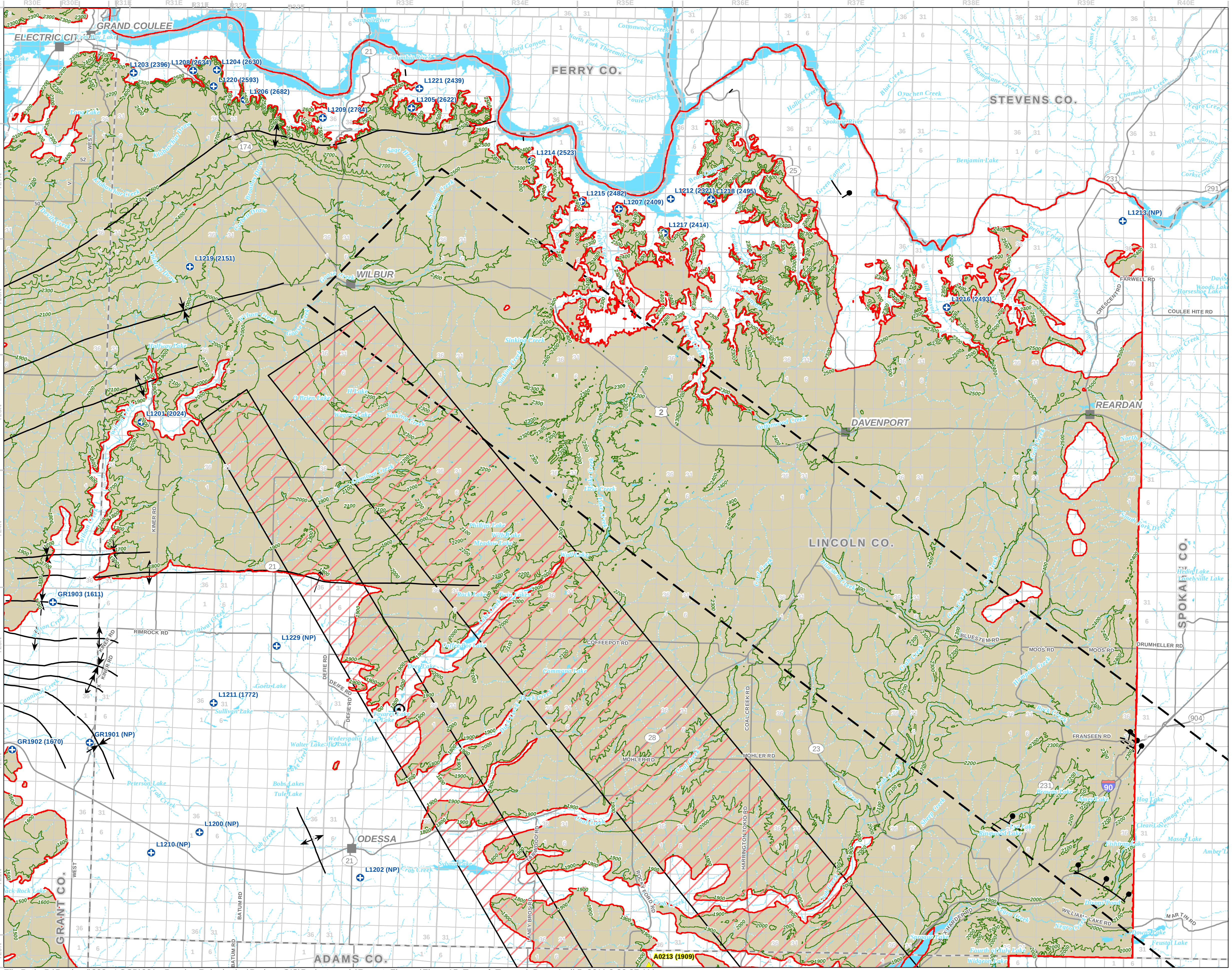

FIGURE 15

Structure Contour Map of the Top of the Priest Rapids Member (Tpr) of the Wanapum Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tpr is Within 200 feet of the Top of Basalt
- Tpr Pinchouts
- Top of Tpr - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5 Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure15_Top_of_Tpr.mxd, Date: April 5, 2011 9:30:37 AM

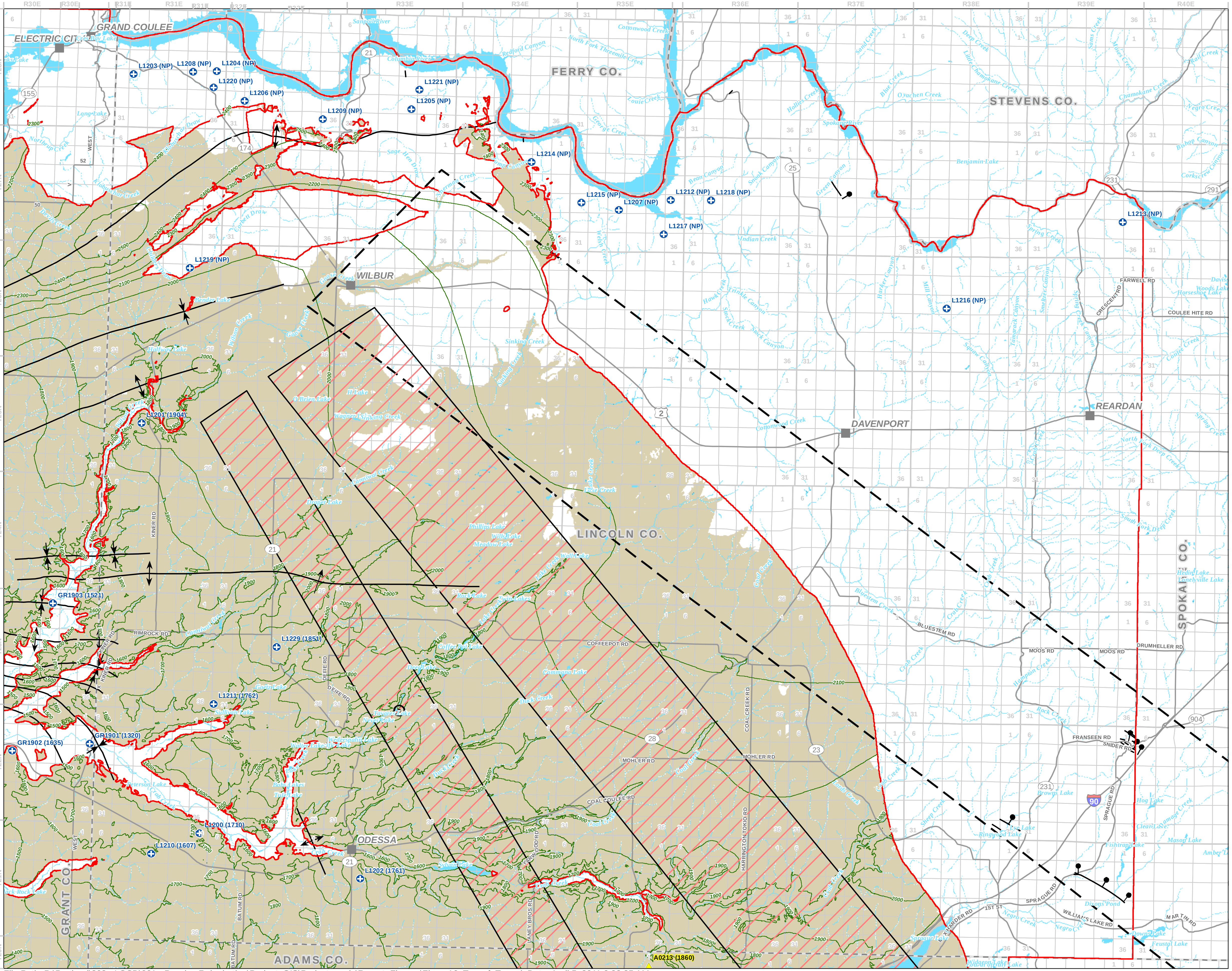

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FIGURE 16

Structure Contour Map of the Top of the Roza Member (Tr) of the Wanapum Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tr is Within 200 feet of the Top of Basalt
- Tr Pinchouts
- Top of Tr - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:

Date: April 5, 2011

Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

Roza Member dikes are inferred to be present in the eastern and north-central portions of the county for two basic reasons. One is the presence of the unit in northern Lincoln County, high on the paleoslope inferred to have been present during emplacement in the Miocene (Fecht et al. 1987, Tolan et al. 1989, Smith et al. 1989), which would require eruptive vents to have extended well north into the area now occupied by the county (Tolan et al. 2009). The other is that this area lies on the northwestern projection of feeder dikes and associated near vent rocks that are known to occur to the south. Reconnaissance done for this study, and GWMA field investigations, provide some confirmation of the extent of the Roza Member dike system with the discovery of near vent facies rocks (Figure 17) in a road cut on Downs Road in the Crab Creek coulee approximately 5 miles east of Sylvan Lake Duke Lake Road north of Odessa, Washington, in Sections 5 and 6, Township 22 North, Range 34 East, and the presence of a pair of dikes found in Lake Creek at Tavares Lake (Figure 18). The inferred extent of this dike system is shown on Figure 16, which shows the mapped extent of the Roza Member in the study area.

Figure 17. Platy, Rubbly Strata Typical of Near Vent Facies in the CRBG

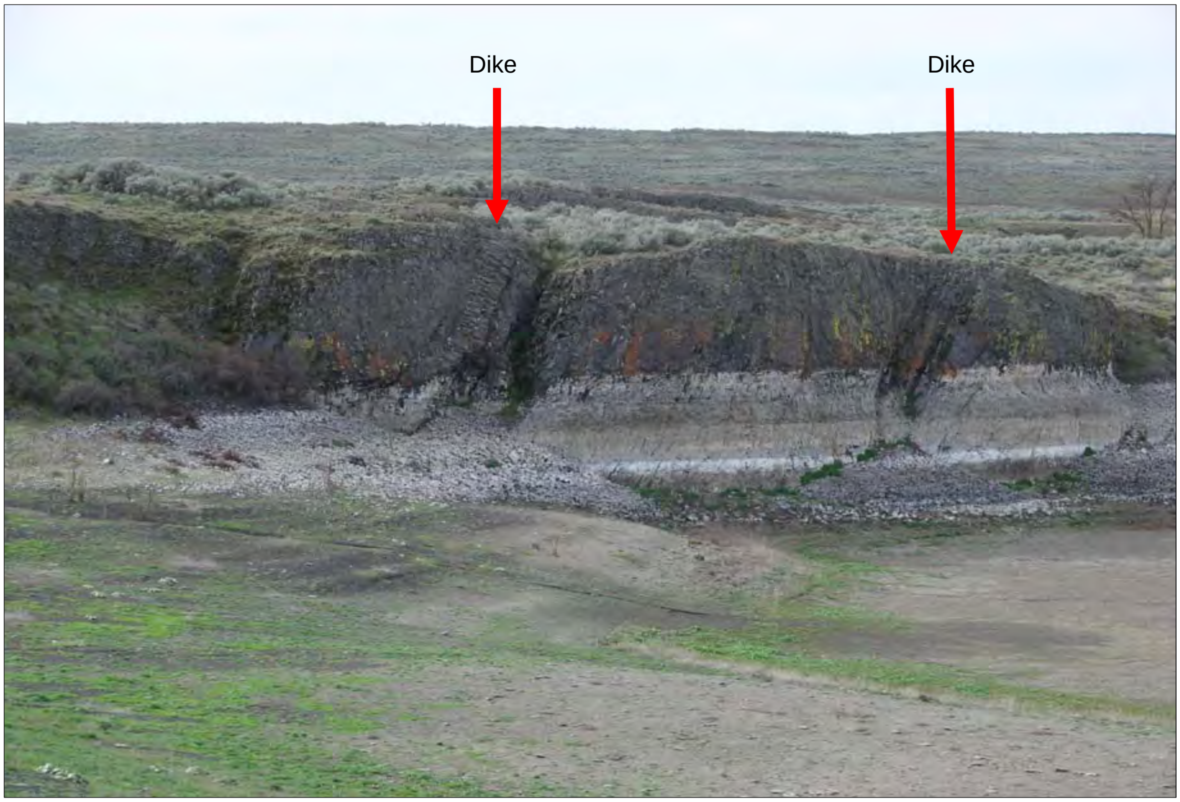


Figure 18. Two Subvertical Dikes of the Roza Member at Taveres Lake

Frenchman Springs Member. The Frenchman Springs Member is the least extensive of the Wanapum units in Lincoln County, being largely restricted to the southern and southwestern portions of the county. Of the six Frenchman Springs Member sub-units mapped south of Lincoln County (GWMA 2009b), only two are present to any extent in Lincoln County: the basalt of Sentinel Gap (Figure 19), and the basalt of Sand Hollow (Figure 20). The basalt of Ginkgo is only in the extreme southwestern corner of the county. Like the other Wanapum units, the tops of Frenchman Springs Member units generally dip to the south-southwest where they are present, and they commonly are completely eroded through (especially in lower Crab Creek). Total Frenchman Springs Member thickness, where it is present, ranges from less than 50 feet to as much as 320 feet.

Dikes for Frenchman Springs units have not been identified in Lincoln County, although the mapped extent of the units, compared to the inferred paleoslope at the time of emplacement, suggests they might be present beneath the southwestern portion of the county.

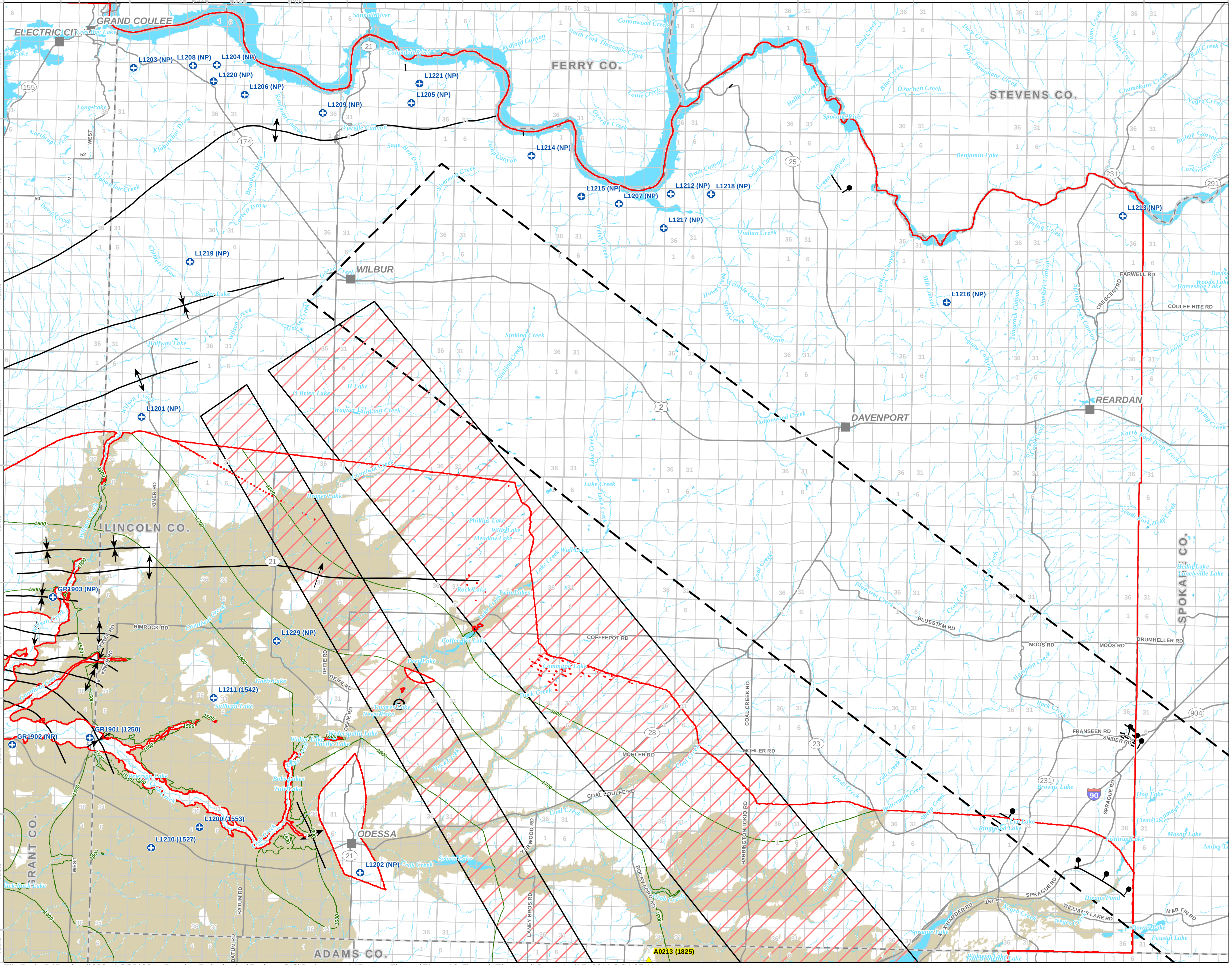


FIGURE 19

Structure Contour Map of the Top of the Sentinel Gap Unit (Tfsg) of the Frenchman Springs Member of the Wanapum Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tfsg is Within 200 feet of the Top of Basalt
- Tfsg Pinchouts
- Top of Tfsg - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

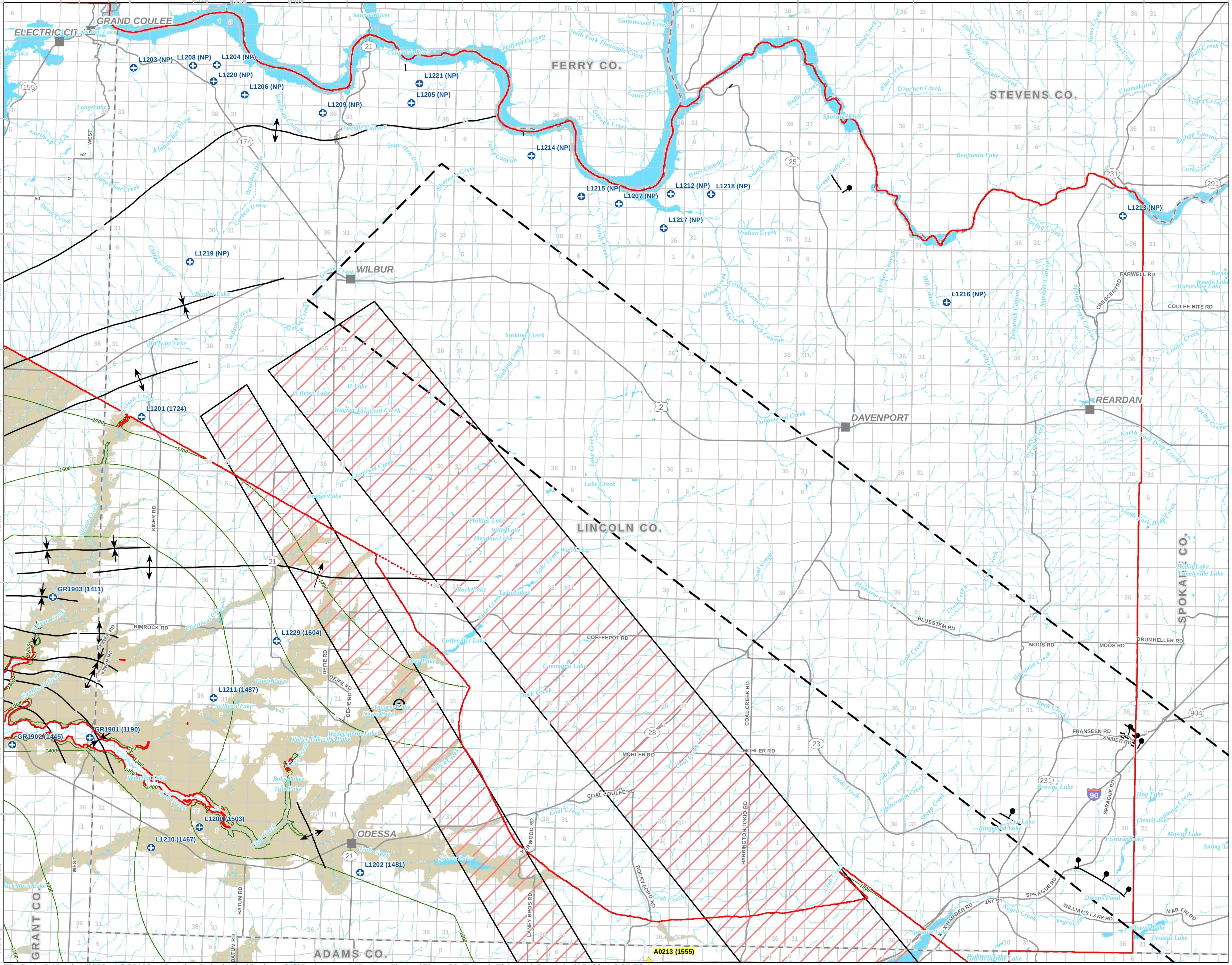
GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure19_Top_of_Tfsg.mxd, Date: April 5, 2011 9:34:07 AM

FIGURE 20

Structure Contour Map of the Top of the Sand Hollow Unit (Tfsh) of the Frenchman Springs Member of the Wanapum Basalt

Lincoln County, Washington



LEGEND

- Areas Where Top of Tfsh is Within 200 feet of the Top of Basalt
- Tfsh Pinchouts
- Top of Tfsh - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure20_Top_of_Tfsh.mxd, Date: April 5, 2011 9:35:52 AM

Ring Dikes. Pleistocene Missoula flood scours expose numerous ring structures in the surface of the CRBG. These structures are quasi-circular in plan view and usually have rims raised above their centers. It has been suggested that ring dikes were formed when lava flowed over water, resulting in steam explosions that caused radial jointing and fracturing of the rock (Jaeger et al. 2003).

Ring dikes, occurring within the area proposed for the rehydration project, are associated with the Roza Member, and less commonly the Priest Rapids Member, of the Wanapum Basalt. The greatest concentration of known ring dikes lies in the Lake Creek drainage, extending from where it empties into the Crab Creek drainage to the northeast just above Wall Lake (Figure 21). A high concentration of ring dikes also exists in the Crab Creek drainage around the town of Odessa and near the eastern end of Sylvan Lake (east of Odessa).

In general, the surface exposure pattern of ring dikes in the study area follows the trends of the respective drainages in which the ring dikes occur. However, it is likely that many unexposed ring dikes associated with Roza Member exist in the study area. These unexposed dikes could be covered by loess, alluvium, and/or the Priest Rapids Member of the Wanapum Basalt in many areas.

CRBG Stratigraphy – Grande Ronde Basalt

Subsurface mapping by the Columbia Basin GWMA (GWMA 2009b) shows the known and inferred extent of five major upper Grande Ronde Basalt units beneath Lincoln County. These units are the Sentinel Bluffs Member, Umtanum Member, Ortley Member, Grouse Creek Member, and Wapshilla Ridge Member.

Several of these members, as mapped by GWMA, are composites of multiple Grande Ronde units, with those of lesser extent included within the units mapped by GWMA. Units below the Wapshilla Ridge Member are not mapped by GWMA because it is likely that they occur only deep beneath the southernmost portion of the county. The presence of Grande Ronde dikes has not been reported in Lincoln County, although it would not be surprising if dikes for one or more of the units mapped for this effort are present because of unit extent and inferred paleoslope at the time of emplacement. The occurrence and distribution of the Grande Ronde Basalt members mapped beneath the area by GWMA are described below.

Sentinel Bluffs Member. The Sentinel Bluffs Member (Figure 22) underlies almost all of Lincoln County with its top generally dipping to the south-southwest, except near Lake Roosevelt, where it commonly dips to the north. Where present, the unit ranges from 200 to 800 feet thick, and likely contains up to seven interflow zones. The Sentinel Bluffs Member is exposed at, or present within 200 feet of, the top of basalt throughout much of the Crab Creek drainage, including many of the tributaries being considered for this project, and in the northern portion of Lincoln County on and near the highlands bordering Lake Roosevelt.

Umtanum Member. The Umtanum Member (Figure 23) and the underlying Ortley Member (Figure 24) are only present beneath the central to southern portions of Lincoln County, pinching out beneath the Sentinel Bluffs Member. Based on this distribution, these units are not exposed in Lincoln County, and because of the thickness of the Sentinel Bluffs Member these units are generally some hundreds of feet below the ground surface. Given the likely maximum thicknesses of the Umtanum, approximately 300 feet thick, and the Ortley, approximately 600 feet thick, they likely contain several interflow zones. The tops of both units dip south-southwest.

Grouse Creek Member. The Grouse Creek Member (Figure 25) is more widespread than the overlying Umtanum and Ortley Members, and is found along at least portions of the highlands above Lake Roosevelt in north-central Lincoln County. Throughout most of its extent the top of the unit dips to the south-southwest, except near Lake Roosevelt, where it may dip, at least locally, to the north. The thickness of the unit, where present, ranges from approximately 200 feet to 400 feet.

Wapshilla Ridge Member. The Wapshilla Ridge Member (Figure 26) is the deepest individual Grande Ronde unit mapped by GWMA (2009b) in the Lincoln County area. It also is almost as widespread as the Sentinel Bluffs Member and is found at, or near, the top of basalt throughout much of the CRBG's northernmost extent near Lake Roosevelt. Like other Grande Ronde units, it appears to generally dip to the south-southwest, and it ranges in thickness from approximately 100 feet to over 500 feet to the south. As the unit thickens, the number of interflow zones it contains likely increase.

Beneath southernmost Lincoln County, Grande Ronde units underlying the Wapshilla Ridge Member are present (Reidel et al. 1989b, GWMA 2009b). However, the lack of deep geologic control wells makes identification of specific units difficult. For that reason, GWMA only maps an undifferentiated Grande Ronde unit beneath the southern portion of Lincoln County. Beneath the southern edge of Lincoln County these undifferentiated Grande Ronde strata may exceed 2,000 feet in thickness.

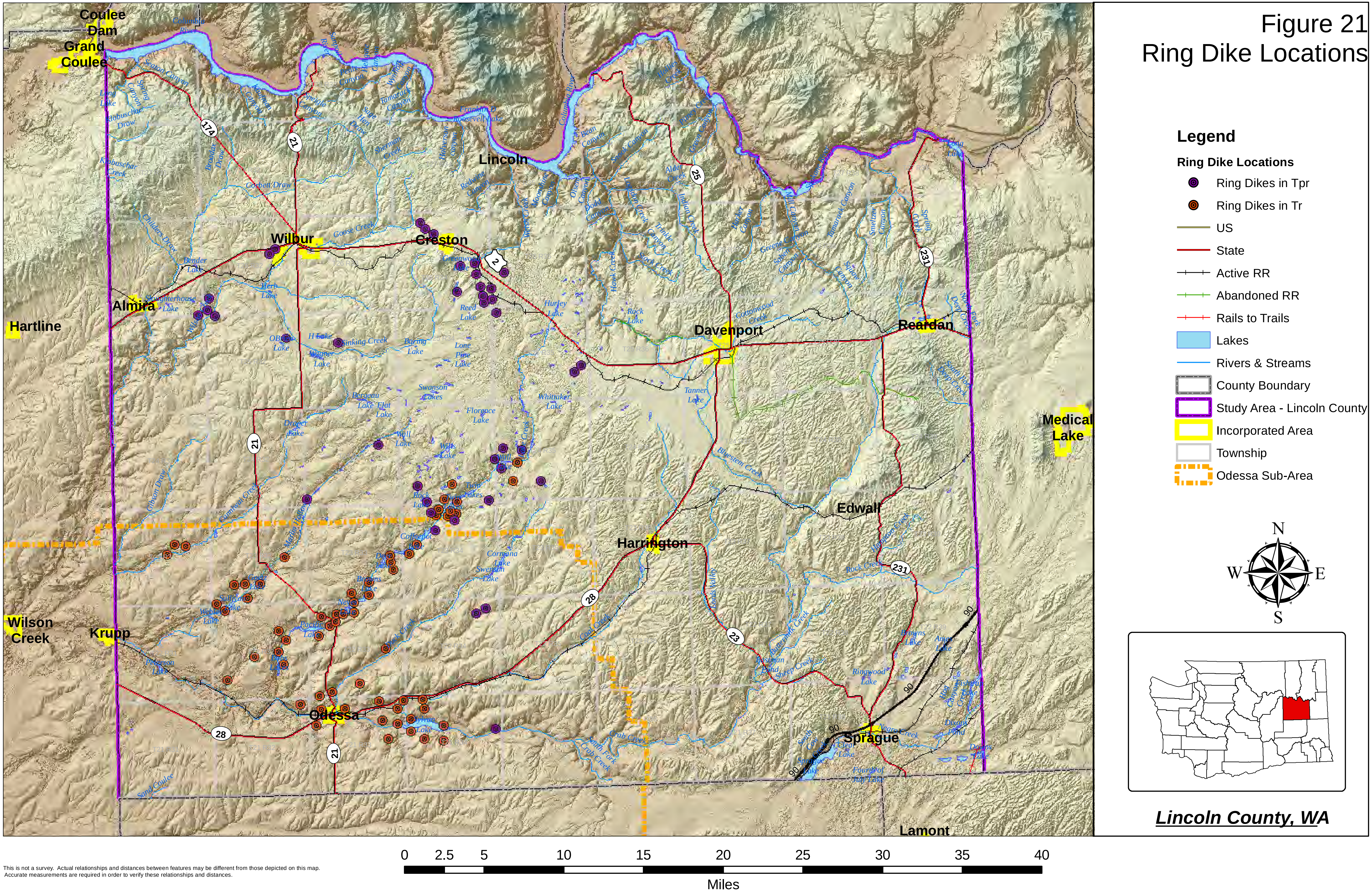


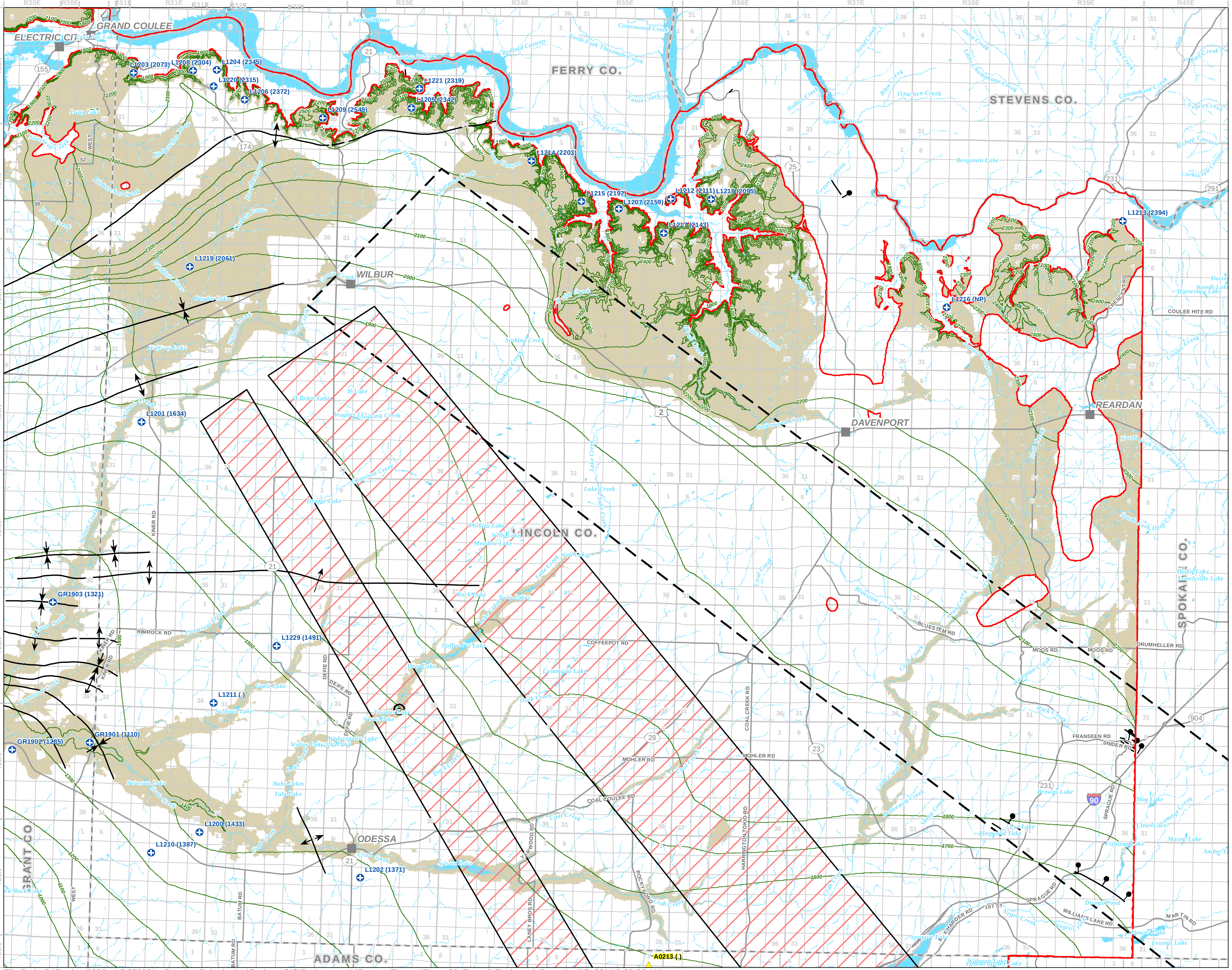
Figure 21
Ring Dike Locations

This is not a survey. Actual relationships and distances between features may be different from those depicted on this map. Accurate measurements are required in order to verify these relationships and distances.

FIGURE 22

Structure Contour Map of the Top of the Sentinel Bluffs Member (Tgsb) of the Grande Ronde Basalt

Lincoln County, Washington



LEGEND

- Areas Where Top of Tgsb is Within 200 feet of the Top of Basalt
- Tgsb Pinchouts
- Top of Tgsb - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perrenial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure22_Top_of_Tgsb.mxd, Date: April 5, 2011 9:38:30 AM

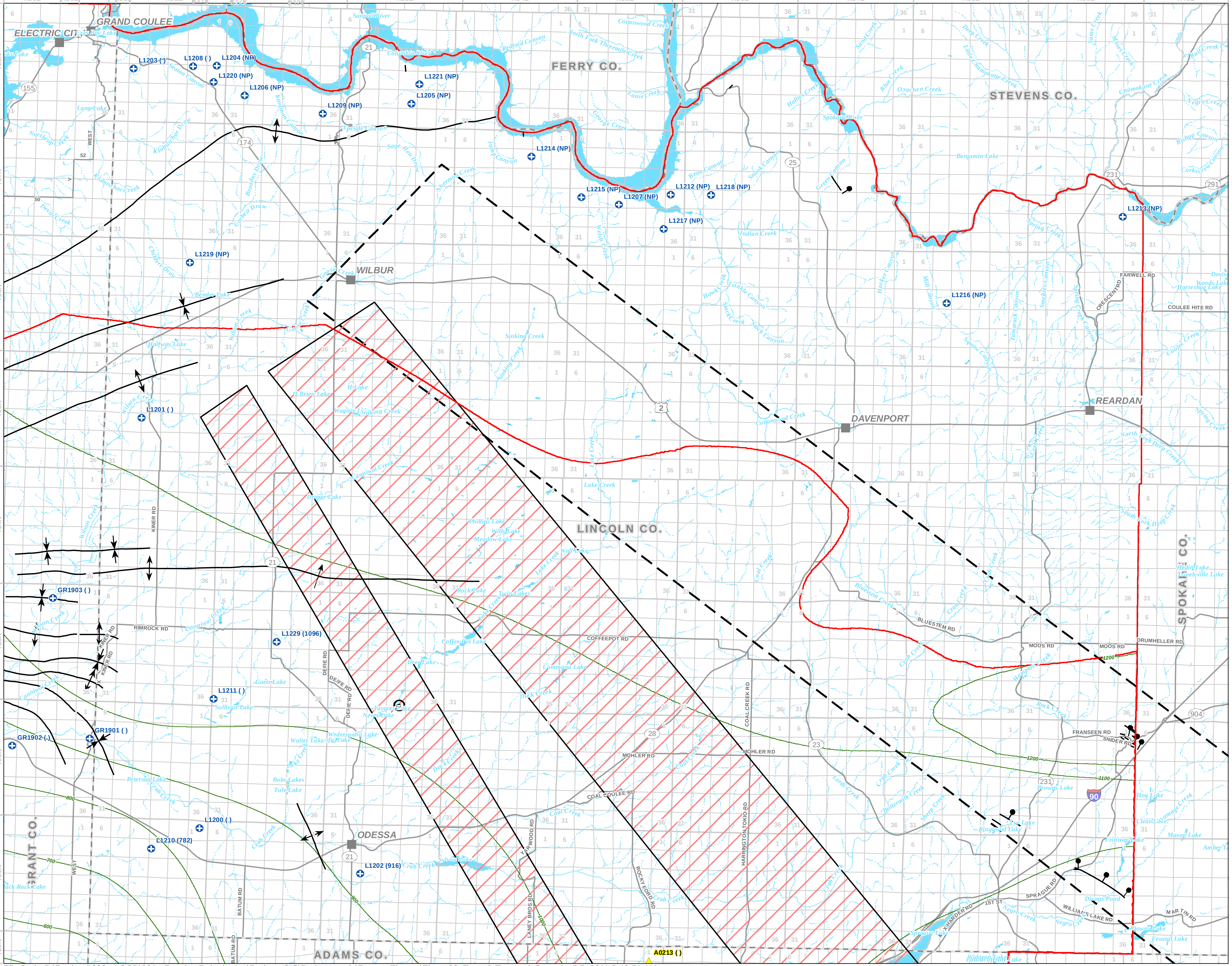


FIGURE 23

Structure Contour Map of the Top of the Umtanum Member (Tgu) of the Grande Ronde Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tgu is Within 200 feet of the Top of Basalt
- Tgu Pinchouts
- Top of Tgu - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

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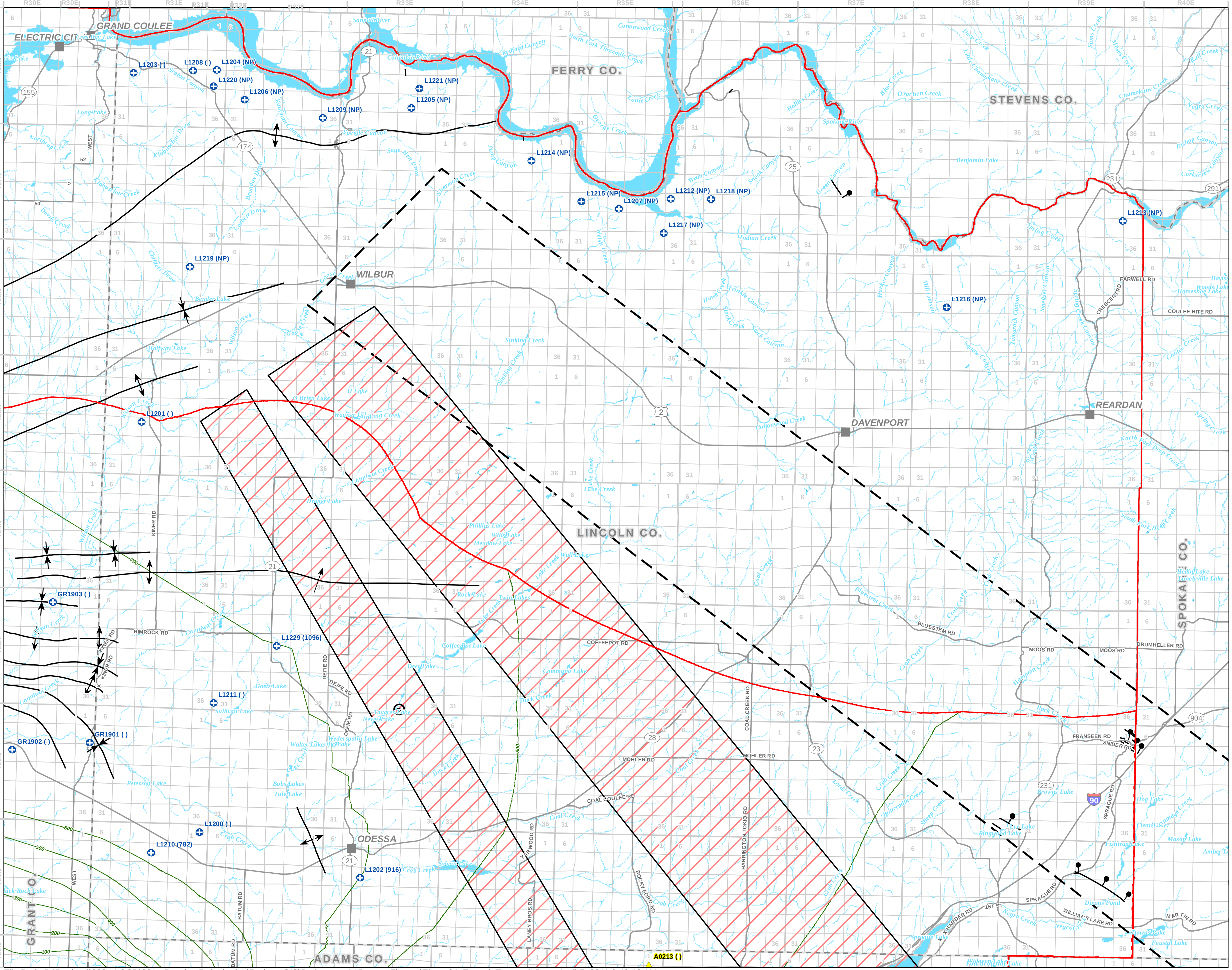

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FIGURE 24

Structure Contour Map of the Top of the Ortley Member (Tgo) of the Grande Ronde Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tgo is Within 200 feet of the Top of Basalt
- Tgo Pinchouts
- Top of Tgo - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perrenial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

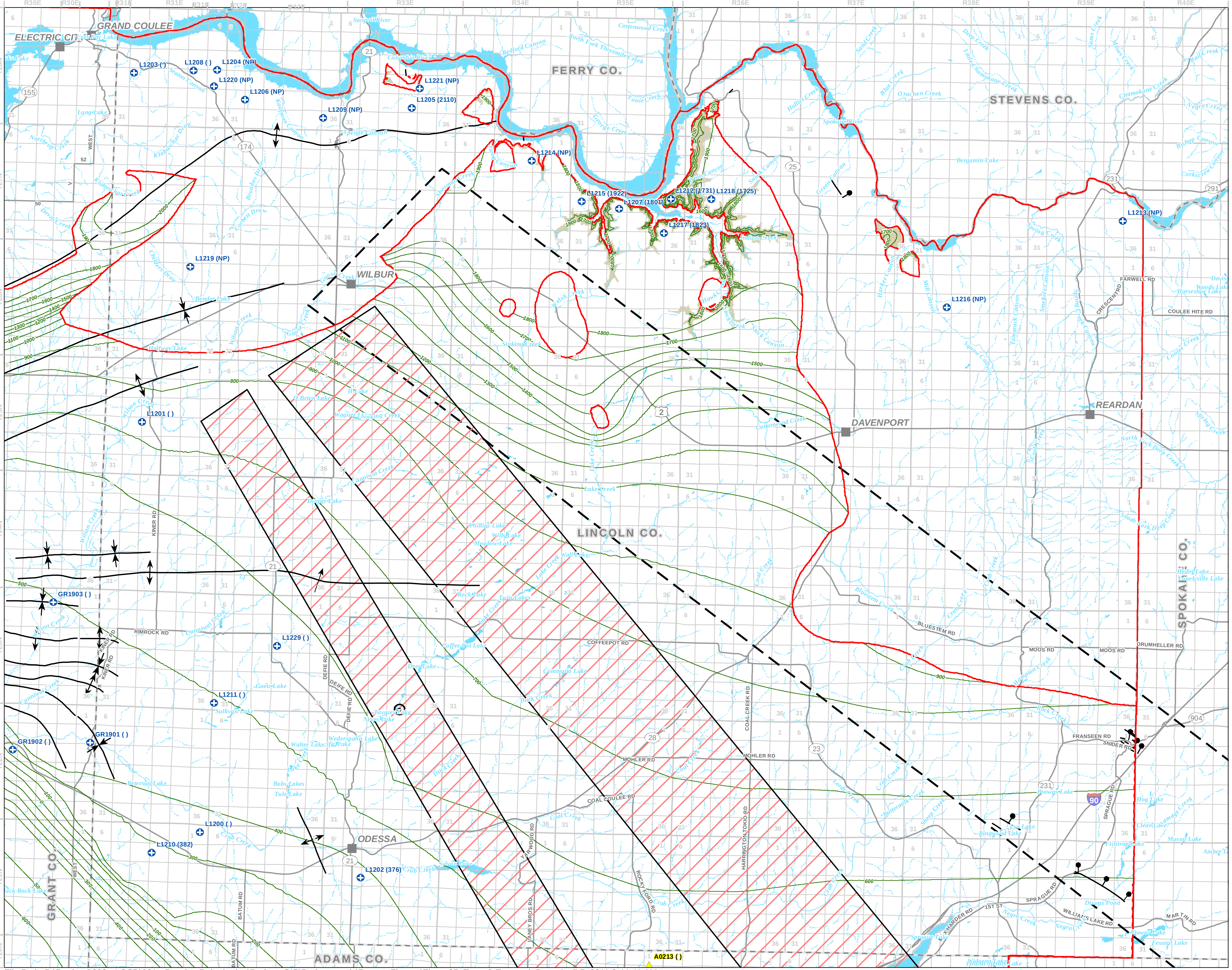

FIGURE 25

Structure Contour Map of the Top of the Grouse Creek Member (Tgg) of the Grande Ronde Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tgg is Within 200 feet of the Top of Basalt
- Tgg Pinchouts
- Top of Tgg - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perennial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5
Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

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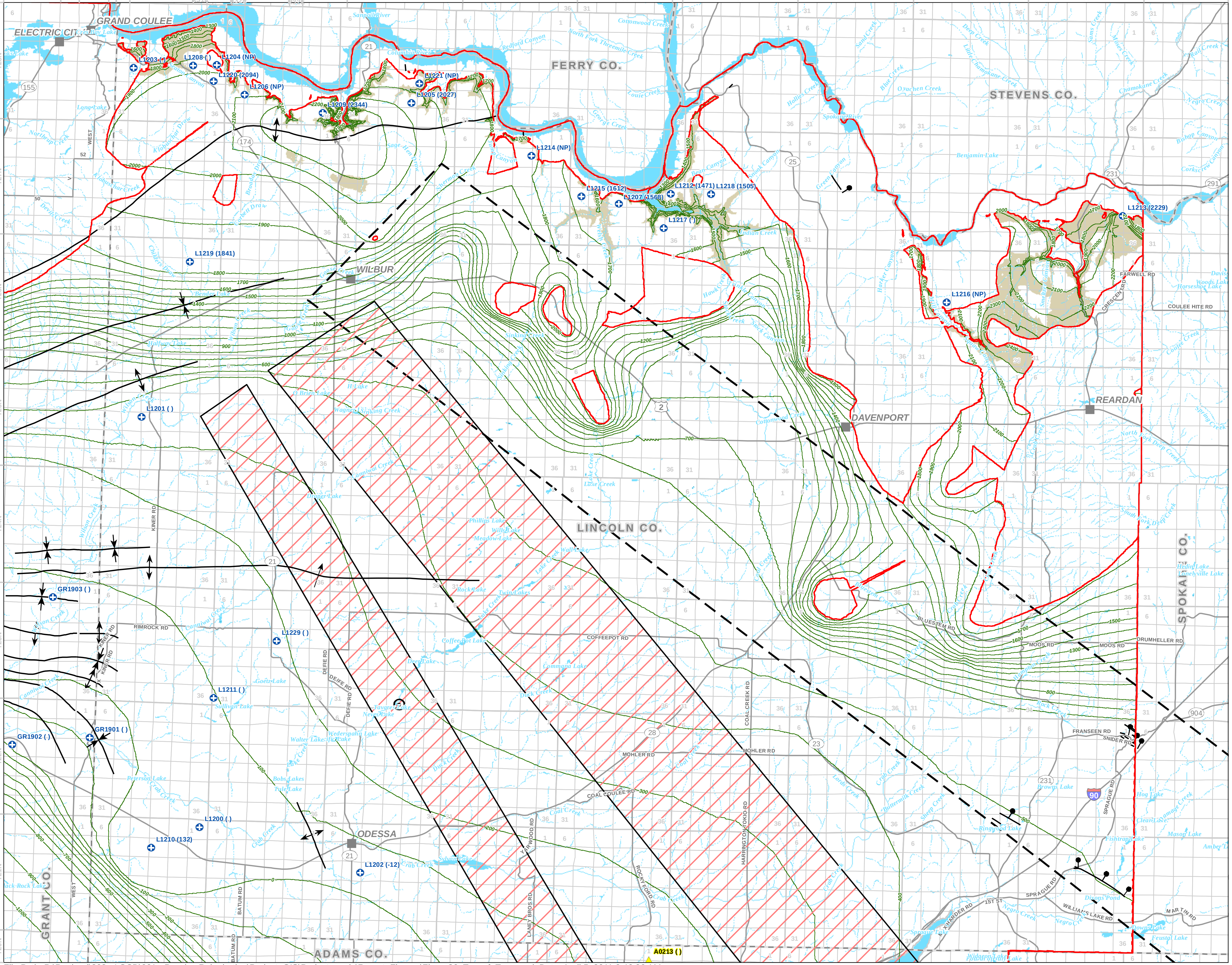

FIGURE 26

Structure Contour Map of the Top of the Wapshilla Ridge Member (Tgwr) of the Grande Ronde Basalt

Lincoln County, Washington

LEGEND

- Areas Where Top of Tgwr is Within 200 feet of the Top of Basalt
- Tgwr Pinchouts
- Top of Tgwr - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perrenial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

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2.3.4 Pre-Basalt Rocks

Field reconnaissance and existing geologic maps (Joseph 1990, Waggoner 1990a) show that the CRBG overlies a variety of older crystalline intrusive and metamorphic rocks. These pre-basalt rocks are reported to consist predominantly of granite and related felsic crystalline rocks and low to medium grade metamorphic rocks, especially quartzites and phyllites. These rocks crop out along most of the southern shore of Lake Roosevelt, in steptoe buttes found across the area, in the canyon bottom along the middle reaches of Hawk Creek, and in the highlands to the north and east of the study area. Fracture zones and shear zones, including faults, are known to cross-cut these rocks. The pre-basalt basement within the study area dips to the south from highs near Lake Roosevelt (greater than 3,200 feet elevation) to 1,200 feet below ground surface (Figure 27). Local exposures of the pre-basalt rocks forming hills (such as Creston Butte) that project upward and through the CRBG are known as steptoe buttes, or steptoes. Steptoes and similar but buried pre-basalt rock highs lying beneath the top of the CRBG are generally thought to be part of the pre-CRBG topography buried, or mostly buried, as the CRBG was emplaced.

2.3.5 Structural Geology

Most of Lincoln County, and essentially all of the proposed project area, lie on the northeastern part of the Palouse Slope structural subprovince (Figure 7). This subprovince comprises much of the eastern half of the Columbia Plateau and is characterized by a regional dip slope (<1 to 2 degrees) extending from highs of 3,000 feet in westernmost Idaho and east-central Washington to lows of less than 300 feet in south-central Washington (Myers and Price 1979, USDOE 1988). Deformation on the Palouse Slope is primarily characterized by north to northwest trending and several east–west trending folds with little or no apparent topographic expression (Swanson et al. 1980, Tolan and Reidel 1989). Dips on these folds typically are less than 5 degrees.

In Lincoln County, major mapped structures consist predominantly of folds (Figures 15, 16, 19, 20, 22, 23, 24, 25, and 26). Faults do not seem to be common, at least as portrayed on the available 1:100,000 geologic maps. Major mapped structures in Lincoln County, generally from north to south, include the following:

- A generally east–west trending anticline that follows the crest of the highlands above Lake Roosevelt in the northwestern portion of the County (Waggoner 1990a). As this anticline extends west into Grant County its mapped orientation changes to northeast–southwest and it generally parallels Banks Lake (Gulick and Korosec 1990).
- East of this structure, generally along Lake Roosevelt, several faults are mapped in the pre-basalt rocks, including recently mapped faults in the Hawk Creek drainage that appear to bound the pre-basalt rock high exposed in the Hawk Creek Canyon (Derkey and Hamilton 2009).

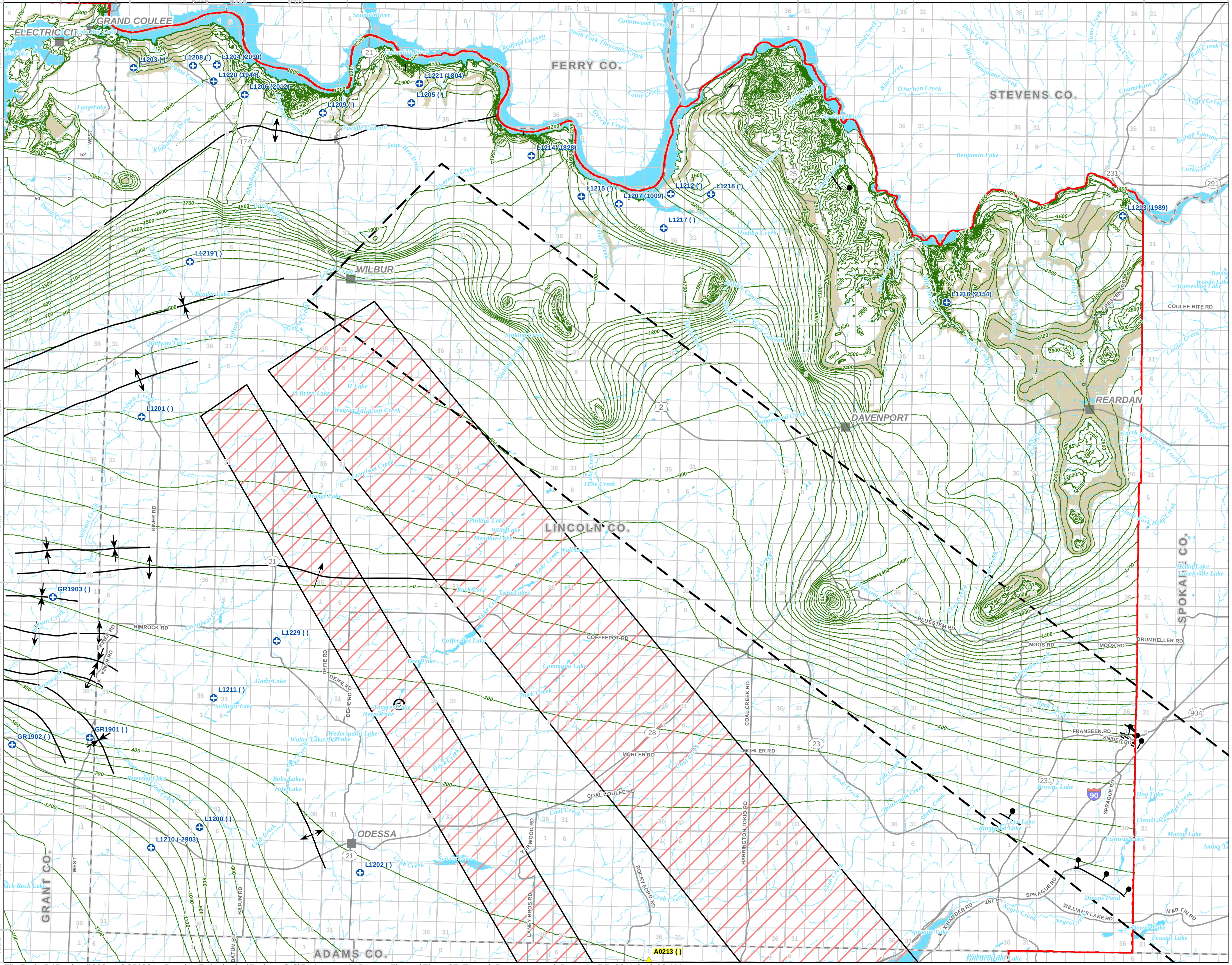
- South of the east–west anticline noted above in the first bullet a series of generally east–west, parallel low-amplitude anticlines and synclines are mapped (Waggoner 1990a). With the exception of two of them, these folds extend eastwards only a few miles into Lincoln County.
- The two folds noted as exceptions in the previous bullet above both extend over 8 miles eastward into Lincoln County. The northern of these two folds is a syncline that lies north of Wilson Creek and extends eastward from the county line almost to Wilbur. The southern of these two folds is an anticline that becomes a north-dipping monocline as it extends eastward across the middle reaches of Canniwai Creek and Marlin Hollow.
- West of Odessa, Washington, Gulick (1990) shows a few northwest–southeast oriented folds crossing Crab Creek. South of Crab Creek along the Lincoln County–Adams County line, and south, no structures (folds or faults) are mapped (Gulick 1990).

Reconnaissance done for this project and by GWMA found evidence for additional low-amplitude folds in the study area. North of Odessa, Washington, at Coffee Pot Lake, an anticline has been incised into by the Lake Creek coulee (Figure 28). This anticline lies a few miles southeast of the monocline noted in the preceding bullets. East of Sylvan Lake the Crab Creek coulee also has incised through at least one anticline. Based on the reconnaissance done to-date, these low-amplitude folds appear to have northwest–southeast orientations.

FIGURE 27

Structure Contour Map of the Top of the pre-CRBG Basement Rocks and the Undifferentiated Grande Ronde Basalt

Lincoln County, Washington



LEGEND

- Areas Where Top of Basement is Within 200 feet of the Top of Basalt
- Basement Pinchouts
- Top of Basement - 100 foot Contours
- Control Wells
- Geophysics Wells (Completed)

Existing Geologic Structure

- High-Angle Fault
- Anticline
- Monocline
- Syncline
- Roza Dike Outline
- Fracture Zone
- Vents

Existing Features

- Cities
- Counties
- Highways and Major Roads
- Perrenial Watercourse
- Intermittent Watercourse
- Perennial Waterbody
- Intermittent Waterbody

N

0 2.5 5 7.5

Miles

MAP NOTES:
Date: April 5, 2011
Data Sources: Franklin Conservation District, WA DNR, USGS, ESRI

GSI Water Solutions, Inc.

File Path: P:\Portland\368 - LCCD\001 - Passive Rehydration\Project_GIS\Project_mxds\Report_Figures\Figure27_Top_of_Basement.mxd, Date: April 5, 2011 9:49:02 AM

Figure 28. Photograph of a Low-Amplitude Anticline Exposed at the Narrows on Coffee Pot Lake

Basalt outcrops in the center foreground are dipping to the right at several degrees. The line shows the approximate shape of the fold on the opposite side of Coffee Pot Lake.

2.3.6 CRBG Hydrogeology

Groundwater in the CRBG regionally, and beneath the study area, generally is confined, occurring in water-bearing intervals hosted by interflow zones that may or may not include interbedded Ellensburg Formation sediments (Gephart et al. 1979, Hansen et al. 1994, Packard et al. 1996, Sabol and Downey 1997, USDOE 1988). Groundwater occurring within interflow zones is found in joints, vesicles, fractures, intergranular pores in basalt breccias and sediment interbeds, and other features that create permeable strata at the tops and bottoms of individual CRBG layers.

Physical Hydraulic Properties. Table 3 summarizes basic hydrologic properties of CRBG interflow structures and sedimentary interbeds of the Ellensburg Formation. Horizontal hydraulic conductivity of CRBG flow tops and bottoms ranges from 1 x 10^{-6} to 1,000 feet per day (feet/day) and averages 0.1 feet/day. The most hydraulically productive interflow zones will be at the high end of this range of hydraulic conductivities. Assuming a physical pathway for water movement is present through crystalline-glassy dense basalt flow interiors, vertical and horizontal hydraulic conductivity in dense flow interiors is 3 to 6 orders of magnitude less than those seen in flow tops and bottoms (USDOE 1988). Given this large difference in hydraulic conductivity, and the general lack of interconnected pore space in dense basalt flow interiors, CRB flow tops and bottoms serve as the primary conduit for lateral groundwater flow in the CRBG.

Ellensburg Formation interbeds have horizontal hydraulic conductivities ranging from 1×10^{-6} to 1 feet/day, averaging 0.01 to 0.1 feet/day for various interbeds (USDOE 1988). Obviously those interbeds dominated by coarse clastic sediment will have the highest hydraulic conductivities.

Table 3. Summary of Hydraulic Conductivity Values Typical for CRBG Interflow Structures and Sedimentary Interbeds

Feature		Hydraulic Conductivity Ranges ft/day	Hydraulic Conductivity Ranges m/day (approx. conversion)	Reference	Comments
Flow Tops	Kh	1×10^{-6} to 1,000	3×10^{-7} to 3×10^{2}	USDOE 1988	Average = 0.1 ft/day
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE 1988	
		1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey 1997	Measured near Lind, Washington
Flow Interiors	Kh	1×10^{-9} to 1×10^{-3}	3×10^{-10} to 3×10^{-4}	USDOE 1988	Approximately 5 orders of magnitude less than flow tops
	Kv	3×10^{-9} to 3×10^{-3}	9×10^{-10} to 9×10^{-4}	USDOE 1988	
		1×10^{-5} to 1×10^{-1}	3×10^{-6} to 3×10^{-2}	Sabol and Downey 1997	Measured near Lind, Washington
Flow Tops	Kh	7×10^{-3} to 1,892	2×10^{-3} to 6×10^{2}	Whiteman et al. 1994	Vertically averaged for Saddle Mountains Basalt
	Kh	7×10^{-3} to 5,244	2×10^{-3} to 2×10^{3}		Vertically averaged for Wanapum Basalt
	Kh	5×10^{-3} to 2,522	5×10^{-3} to 6×10^{2}		Vertically averaged for Grande Ronde Basalt
Ellensburg Formation Interbeds	Kh	1×10^{-6} to 1	3×10^{-7} to 3×10^{-1}	USDOE, 1988	Average for various interbeds = 0.01 to 0.1 feet/day
	Kh	1×10^{-6} to 100 feet/day	3×10^{-7} to 3×10^{1}	Sabol and Downey 1997	Measured for interbeds in Pasco Basin

Kh = horizontal hydraulic conductivity
Kv = vertical hydraulic conductivity

Given the planar-tabular nature of the CRBG, the occurrence and distribution of water-bearing interflow zones within it also display a planar-tabular character (USDOE 1988, PNNL 2002, GWMA 2009, Tolan et al. 2009). With this planar-tabular host rock fabric, one would surmise that the predominant groundwater flow directions within this aquifer system are parallel to, and down-dip, in it. Hydrographs from nested piezometers available to monitor water levels in the CRBG system (Figure 29) and reconstructed wells (Figure 30) suggest a degree of hydrologic separation within the CRBG aquifer system imparted by the layered, planar-tabular nature of the host rocks. This separation, interpreted to reflect stratigraphic controls on groundwater occurrence and hydraulic connection, is plainly seen on the two example hydrographs. Figure 29 shows at least two separate water level trends over time, indicating limited hydraulic connection between the water-bearing intervals being monitored. Figure 30, on the other hand, shows what happens when a single well is reconstructed to monitor multiple water-bearing intervals. The water levels diverge, have different long-term trends, and the deepest of the three levels being monitored has the highest water levels.

Water Levels. Within this planar-tabular rock and aquifer system, and given the multiple water levels commonly observed within it at a given location, construction of a single water level map for it is problematic. Nevertheless, some basic observations with respect to water levels within this aquifer system beneath Lincoln County are as follows:

- Depending on which water-bearing zones(s) an individual well is open to, depth to water throughout the region varies from approximately 20 to as deep as 800 feet below ground surface (bgs). Generally, these shallower depths will likely be associated with low yield zones in the Wanapum Basalt, especially where lateral continuity is disrupted by incised coulees. Deeper water levels will more commonly be associated with Grande Ronde zones, especially in the areas of deep well irrigation in the central to southern portion of the study area.
- These depths to water generally correspond to water level elevations ranging from approximately 1,295 to 2,350 feet AMSL.
- This decrease in water level with depth is a criterion used by some entities to differentiate between a shallower water level Wanapum groundwater system and a deeper water level Grande Ronde groundwater system. However, such a criterion should be used with caution because historically some Grande Ronde wells displayed water levels significantly higher than those found in overlying Wanapum portions of the aquifer system (see Figure 30).
- **CRB Aquifer System Recharge.** Pre-basalt basement rock highlands beneath the northern portion of Lincoln County likely form a hydrologic barrier separating the CRBG aquifer system from Lake Roosevelt. This hydrologic barrier prevents recharge of the CRBG system by Lake Roosevelt.

- In the absence of recharge from Lake Roosevelt, direct recharge to shallow CRBG aquifers results from infiltration of precipitation, runoff, and irrigation within (and along the margins of) the Columbia Basin (Newcomb 1959; USDOE 1988; Hansen et al. 1994; GWMA 2009a, 2009d). Infiltration has been variously interpreted to be (a) vertically downward along faults, (b) past the ends of flow pinch-outs, (c) where CRBG flows are breached by erosional windows, (d) on highlands within and bordering the Columbia Basin, and (e) through dense flow interiors. Recharge of the deeper Wanapum and Grande Ronde aquifers is inferred to occur largely from interbasin groundwater movement originating around the edge of the Columbia Basin in areas where exposures of these deeper units occur (Gephart et al. 1979, USDOE 1988, Hansen et al. 1994) and downward through overlying CRBG flows (Hansen et al. 1994, Bauer and Hansen 2000).
- GWMA's recent work (GWMA 2009) suggests that the depth of effective infiltration and recharge through planar-tabular dense interiors probably does not exceed 2 or 3 interflow zones, or approximately 200 to 300 feet. Work by Farley et al. (2006) also shows that such connections to surface water will be greatly hindered if sediments overlying the top of basalt are fine-grained. Within the Lincoln County project area, fine-grained sediments are rare in the coulees that would likely be targeted in a potential future rehydration project.
- Regardless of the source of recharge to the CRBG aquifer system, groundwater age dating by GWMA (GWMA 2009c) suggests that the rate of recharge to deep into the CRB aquifer system is slow because groundwater more than a few hundred feet deep in the CRBG aquifer system usually is thousands, to several tens of thousands of years old. Based on GWMA's groundwater geochemical data, much of the water in the CRBG aquifer system was introduced into the system in the Pleistocene. Areas where younger groundwater has been found in Lincoln County commonly are associated with coulees, suggesting these erosional features facilitate recharge to at least portions of the CRBG system, including the upper Grande Ronde (GWMA 2009c). The proposed pilot project will test this observation.
- Based on the physical geology of the CRBG summarized above, it seems likely that vertical groundwater movement into and through multiple, dense, CRBG basalt flow interiors is restricted and that groundwater movement into and through the aquifer system is primarily down-dip along interflow zones. With that, primary natural recharge pathways into the CRBG aquifer system are through erosionally thinned units, around erosional and emplacement pinch-outs, through open faults and tectonic fractures, and in up-dip areas where units thin and pinch out. All of these features have the potential to allow successive interflow zones to come into contact with each other and surface water sources, if present, forming direct hydraulic connections.

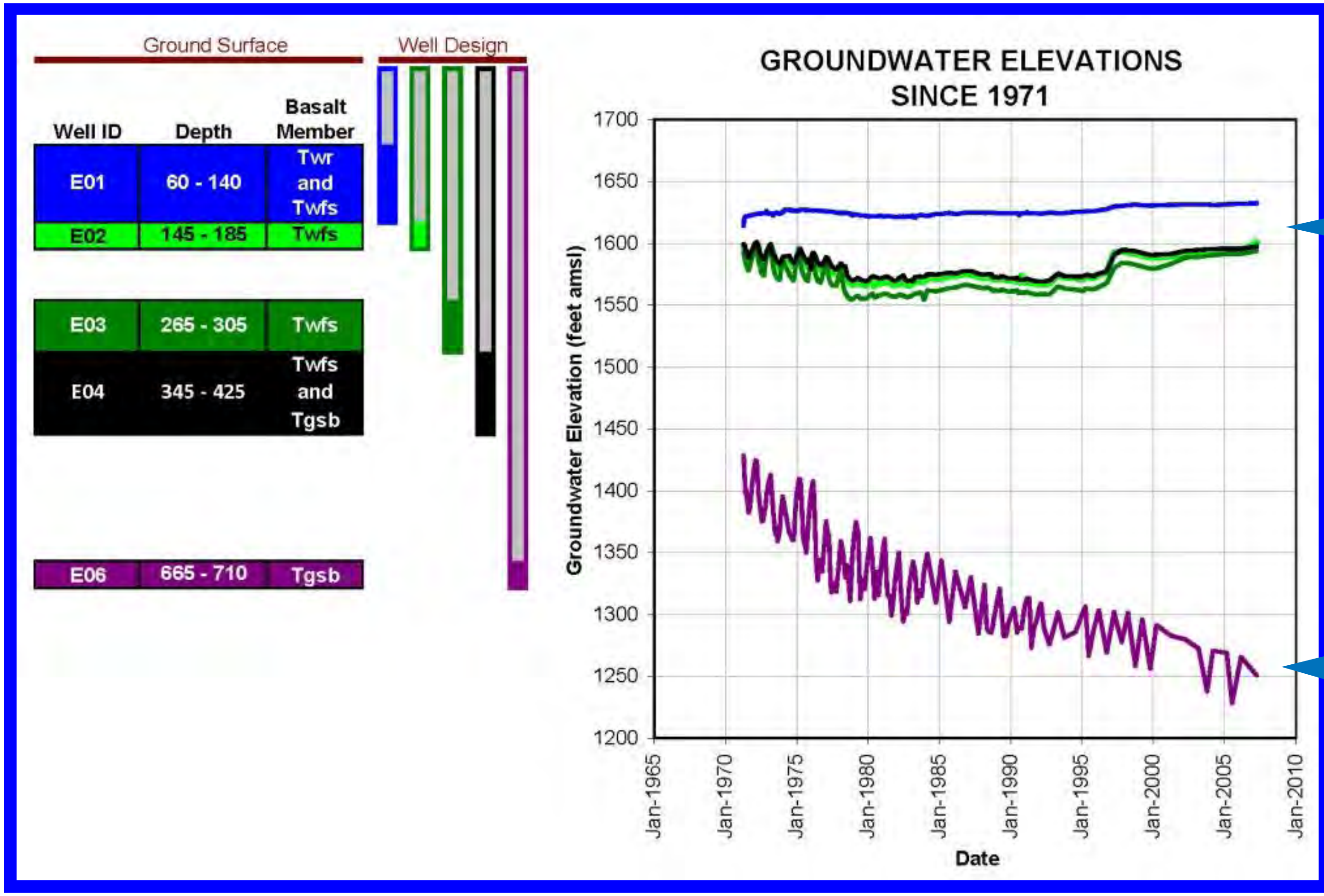
- Finally, the impact of uncased and unsealed wells on recharge in the aquifer system cannot be discounted. Uncased wells penetrating water-bearing units of both the Wanapum and Grande Ronde formations would allow for passive dewatering of the upper zones by cascading and down-hole flow into deeper zones.

- **Conceptual CRB Aquifer Groundwater Flow System.** The Priest Rapids and Roza Members of the Wanapum Basalts are exposed in many coulees in the study area and hence recharge could occur at exposed interflow zones. The Frenchman Springs Member of the Wanapum Basalt is present only in the southwest portion of the study area (Figures 19, 20). Therefore, the potential for recharge at exposed interflow zones and interbeds of the Frenchman Springs Member exists in those areas.

- The two members of the Grande Ronde Basalt with the most surface or near surface occurrence are the Sentinel Bluffs Member (the upper mapped member) and the Wapshilla Ridge Member (the deepest mapped member). The Sentinel Bluffs Member is at or near the surface beneath much of the western portion of the Crab Creek (and tributary) coulee system (Figure 22). In the northern part of the county, this member and the Wapshilla Ridge Member are exposed in the highlands and canyons overlooking Lake Roosevelt (Figures 22, 26). In both of these terrains, recharge directly into these units seems likely, if water is present. Recharge into the other three Grande Ronde Members would be hindered by their lack of near surface occurrence. However, the down-dip increase in units (shown in Figure 31) suggests one possible recharge pathway being formed as successive interflow zones bifurcate in the down-dip direct.

- Beneath the study area, groundwater flow directions in CRBG aquifers generally are toward the south-southwest (Drost and Whiteman 1986, USDOE 1988, Hansen et al. 1994). Potential discharge areas for deeper portions of the aquifer system, especially within the Grande Ronde Basalt, are uncertain, but groundwater flow is inferred to be generally southwestward with discharge speculated to occur south of the Pasco Basin (USDOE 1988) where folds and faults bring the Grande Ronde closer to the surface. Hansen et al. (1994) and Bauer and Hansen (2000) have also speculated that discharge from deep CRBG aquifers may be directly upward through multiple dense basalt flow interiors into major rivers like the Columbia and Snake.

- In and around the Lincoln County project area discharge from much of the shallow aquifer system, especially portions hosted by the Wanapum Basalt, may be fairly local because much of the system is completely dissected by Pleistocene Missoula flood-cut coulees. In such settings these shallower water-bearing zones, where they contain water, will discharge to coulees in spring lines. This would be to the lakes, streams, and surface springs that occur within coulees in the study area. Historically, recharge to these surface water bodies was considerable, but it has likely diminished in recent decades due to factors such as increased groundwater pumping from basalt aquifers. Water-bearing interflow zones in the area, which lie below the depth of incision of the deepest coulees, likely do not discharge to the surface in Lincoln County. Instead, this groundwater exits the county, moving down-gradient into adjacent Grant and Adams counties.



Deepest piezometer in this group has highest water in group.

This hydrograph displays different trend than shallower hydrgraphs.

Figure 29. Hydrographs from a nested piezometer well in Lincoln County

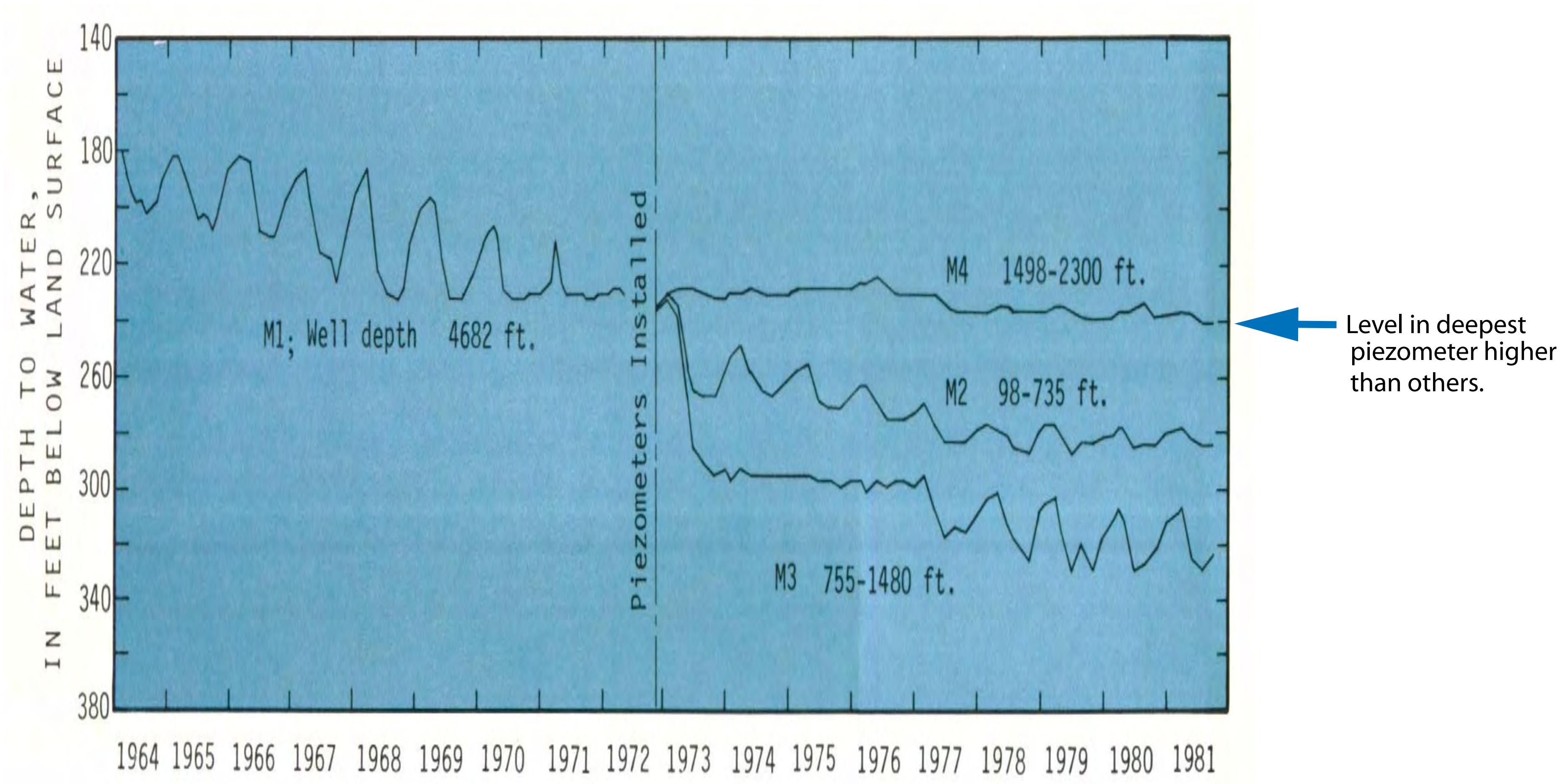
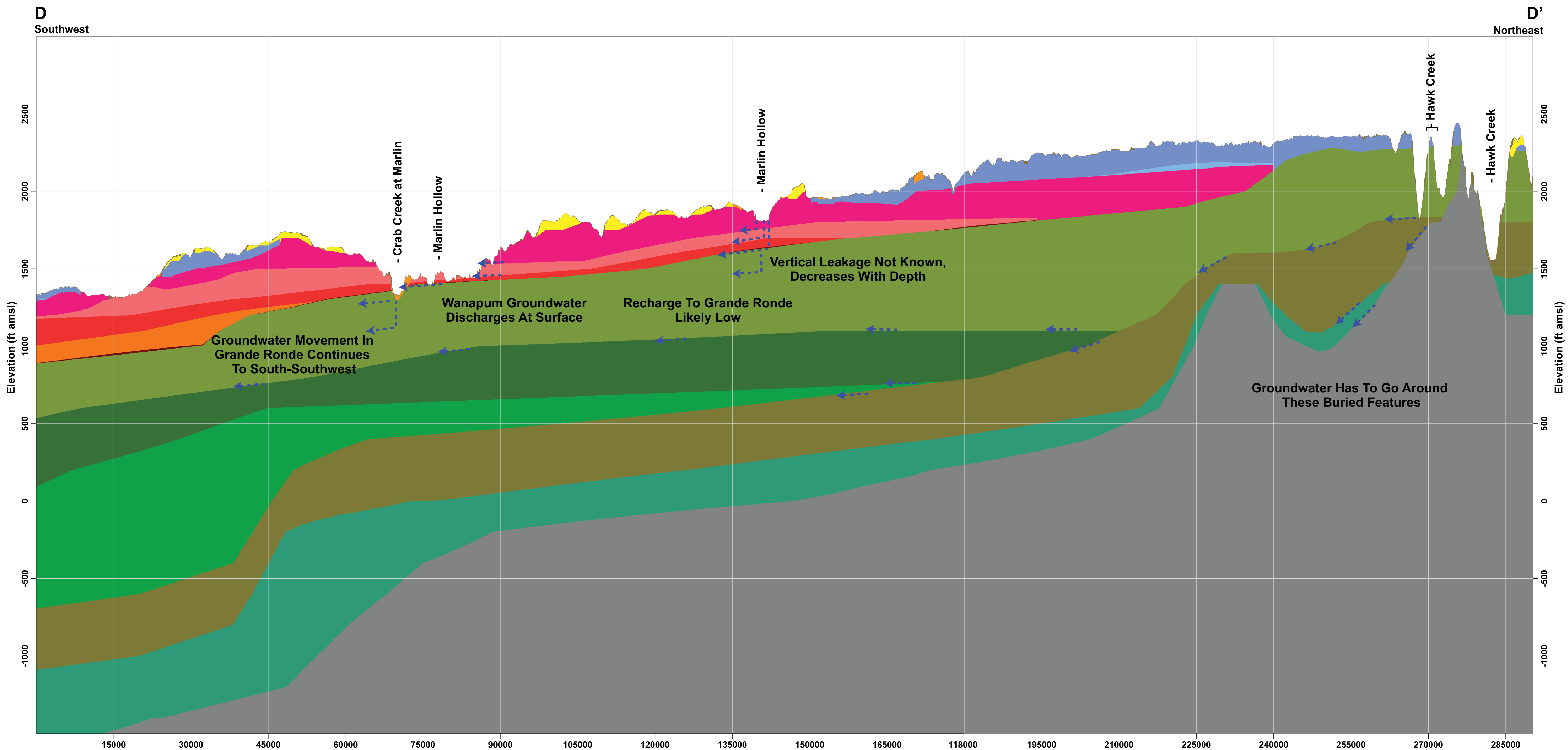
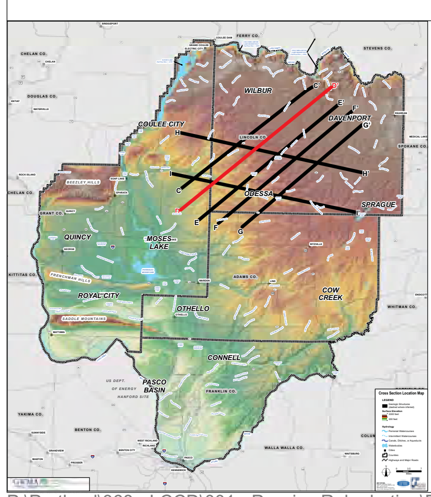


Figure 30. Hydrographs showing water level(s) in a well following reconstruction as a nested piezometer.





LEGEND

Ground Surface

Suprabasalt Sediment Units

Qf

Ql

Wanapum Basalt Units

Tpr

Teqc

Tr

Tf

Tfsg

Tfsh

Tfg

Tev

Grande Ronde Basalt Units

Tgsb

Tgu

Tgo

Tgg

Tgwr

Basement

Inferred Groundwater Movement

N

FIGURE 31

Cross Section D-D'

Southwest to northeast oriented geologic cross-section through western Lincoln County

Cross-section illustrates some basic conceptualizations of the CRBG groundwater system

SCALE

500 feet

30x Vertical Exaggeration

15,000 feet

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