WRIA 54 Delimiting geologic structures affecting water movement and flow direction of the CRBG West Plains aquifer.

DOE CONTRACT #11-1056

<u>TECHNICAL MEMORANDUM TO ACCOMPANY THE STRUCTURAL GEOLOGY MAP OF THE WEST PLAINS REGION</u>

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I. INTRODUCTION

The West Plains region is located just west of Spokane in Spokane and Lincoln Counties, Washington and is bounded to the north by the Spokane River, south by uplands and basalt scablands, east by Latah Creek and the Spokane Valley Aquifer, and to the west by loess covered hills and basalt lowlands. Increasing development and population growth in the eastern portion of the West Plains requires further understanding of the complex geohydrologic system. The complicated geologic history of eastern Washington and the West Plains spans billions of years and the rock types found in the region can be closely tied to the hydrology of the area. Geohydrology of the Spokane Area is strongly influenced by three major rock types 1) Pre-Neogene basement rock, 2) Miocene Columbia River Basalt Group (CRBG) and sedimentary interbeds (e.g. the Latah formation) that define the Columbia Plateau, and 3) Quaternary alluvium and glacial flood deposits that have molded the scablands of eastern Washington.

This report begins with a brief overview of the regional geology and structural history of the mountainous areas adjacent to the West Plains region of the Columbia Plateau region, followed by a summary of our original scientific research on the pre-Neogene rocks and structures exposed in the isolated hills and ridges located in the West Plains as well as high density fracture zones, such as the Cheney Fracture Zone. General structures in the northwest region of the US are presented in Figure 1.

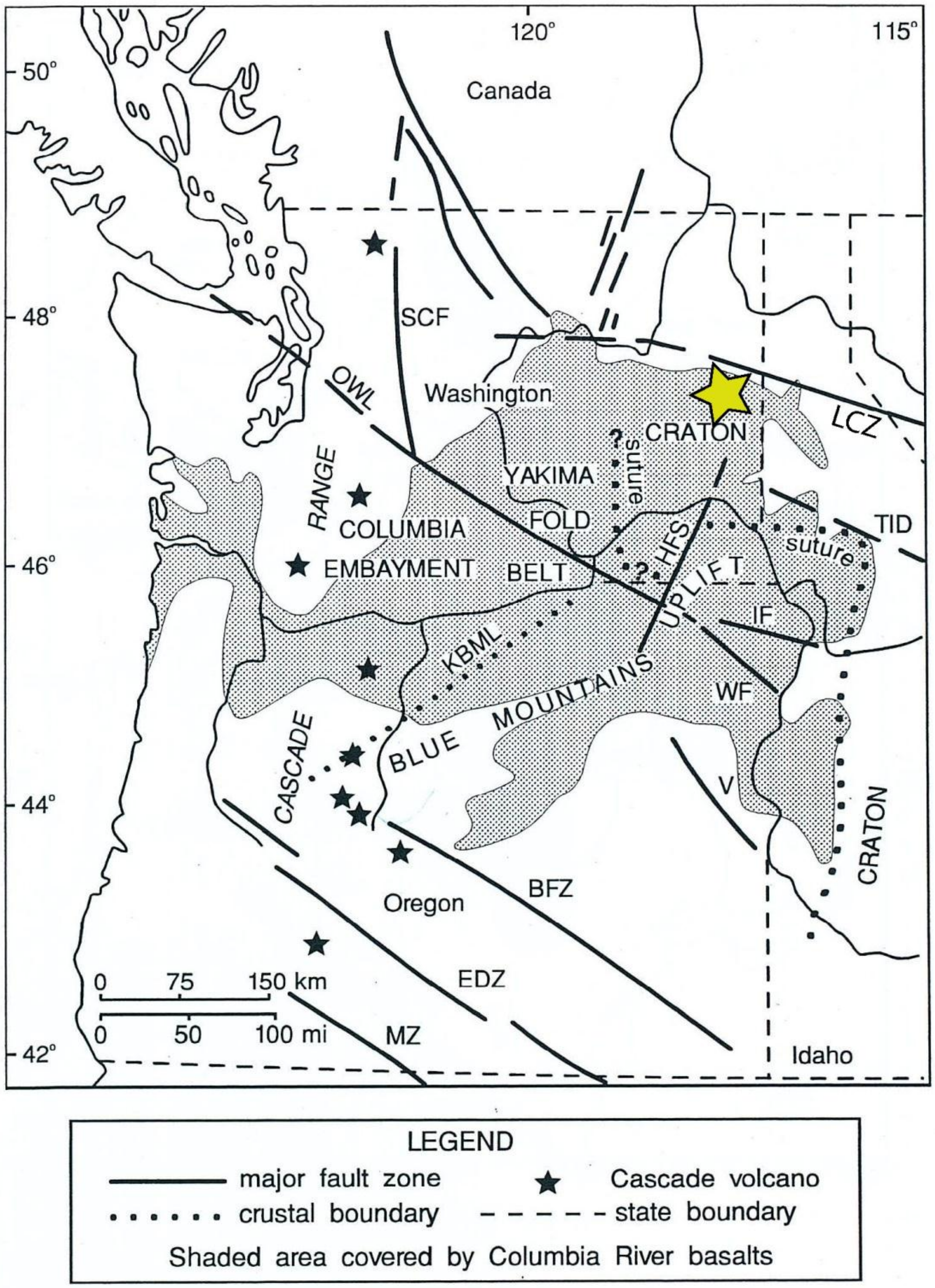

Figure 1. *Map of the northwest US with major regional structures including the Olympic-Wallowa lineament (OWL), Hite fault system (HF), Lewis-Clark zone (LFZ), Straight Creek fault (SCF), Trans-Idaho discontinuity (TID). Yellow star denotes approximate location of the West Plains. Map modified from Kuehn (1995).*

Pre-Neogene bedrock and CRBG generally have low permeability due to the geologic processes that form the rocks. Pre-Neogene rocks have undergone compaction and cementation of pore space (diagenesis) or (re) crystallization minerals during igneous cooling and/or metamorphism. The CRBG units are flood basalt, which generally have low-permeability, but flow contacts can have higher permeability due to increased vesicles, fracturing, and weakness between flows. Miocene sedimentary interbeds (Latah Formation) are highly variable and can either act as permeable zones or aquitards.

Though the Pre-Neogene basement and CRBG units generally have reduced permeability, geologic structures can enhance groundwater flow (permeability) by brittle fracturing and faulting, or by the ductile warping of bedding. Classically, brittle deformation can form either 1) *joints*, which are localized fractures with no vertical off-set, or 2) *faults*, which form deformation zones on the spans of inches to 10's of feet (centimeters to kilometers) and exhibit vertical displacement of pre-existing rock (Figure 2). Both joints and faults are commonly found in groups, or sets, such as the Cheney Fracture Zone. Fracturing of rock can drastically influence and increase groundwater flow (Haneberg, 1995) and is the natural basis for the process of "hydro-fracturing or hydrofracking." Brittle structures have been found to form spatially complex hydrogeologic systems in the Denver area (Caine and Tomusiak, 2003). However, fractures and fault damage-zones can also become compressed or cemented/backfilled during geologic processes, which could result in a zone of decreased permeability. Ductile folding of rocks, such as anticlines and synclines, can orient high permeability zones between bedding. Mapping geologic structures during this study has involved extensive segregation of the three major rock types, and formations, in the West Plains.

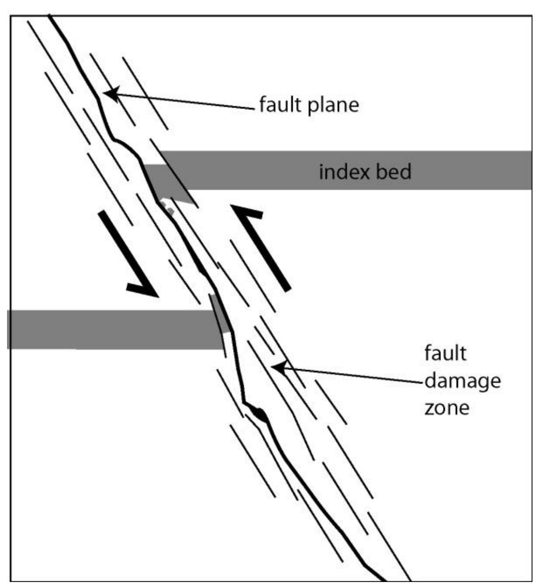

Figure 2. *Basic fault zone terminology that relates to hydrology. Cross-section of an idealized reverse fault illustrating the complex damage zone produced during displacement.*

Projection of the major regional structures from the surrounding mountainous regions under the CRBG, and younger, cover in the northern Columbia Plateau is generally dependent on the proper identification of Pre-Neogene basement, specifically Mesoproterozoic to Cambrian rocks exposed in many isolated outcrops and steptoes. A general geologic time scale is presented in Figure 3. U-Pb age dating of plutonic rocks completed during the contract period also helped constrain projected faults and igneous systems associated with past tectonic regimes; ages are presented in *Section 5: U-Pb Ages*. Localized faults and regional tectonism can be difficult to identify in the West Plains without geochemistry, but define potential groundwater migrations paths along zones of weakness in the rock. The completed geologic mapping of 450 sq. miles of the Spokane West Plains region from Cheney to Edwall and north to the Spokane River has never been undertaken in such detail before and has proved invaluable for this study and most likely for research in the future.

Era	***Period (millions of year ago)***	***Epoch (millions of year ago)***
Cenozoic	Quaternary	Holocene (0 to 0.2)
		Pleistocene (0.2 to 2)
	Neogene	Pliocene (2 to 5)
		Miocene (5 to 23)
	Paleogene	Oligocene (23 to 34)
		Eocene (34 to 56)
		Paleocene(56 to 66)
Mesozoic	Cretaceous (66 to 146)	
	Jurassic (146 to 202)	
	Triassic (202 to 251)	
Paleozoic	Permian (251 to 299)	
	Carboniferous (299 to 359)	
	Devonian (359 to 416)	
	Silurian (416 to 444)	
	Ordovician (444 to 488)	
	Cambrian (488 to 542)	
Precambrian - Proterozoic - Neoproterozoic (542 to 1,000) - Mesoproterozoic (1,000 to 1,600) - Paleoproterozoic (1,600 to 2,500) - Archean (2,500 to 3,850) - Hadean (3,850 to ~4,500)		

Figure 3. *Generalized geologic time scale, modified from the Geological Society of America, 2009 geologic time scale.*

II. Pre-Neogene Accreted Terrains & Morphological Belts

The continental crust we live on today could not have been present without billions of years of geologic activity. The fact that we have surface and ground water depends on a basic understanding of the concept of tectonic terranes, or morphogeological belts, and continental accretion is essential prior to deciphering the pre-CRBG rocks of the West Plains. In fact, the Pacific Northwest is a collage of disparate and commonly far-traveled lithospheric terranes (allochthons) that have accreted to the western margin of the North American continent, adding several hundred kilometers oceanward of the craton since the early Jurassic (Fuentes et al., 2011). Generally, the terranes accreted along the Cordilleran have been divided into five northwest-trending morphogeological belts that are parallel to the continental margin: 1) Insular, 2) Coast, 3) Intermontane, 4) Omineca and 5) Foreland belts (Figure 4). Each of the belts records its own unique history of complex depositional and tectonic relationships in response to crust-lithosphere interactions associated with collision, subduction, uplift and rifting. Felsic plutons ranging in age from Cretaceous to Eocene intrude into older basement rocks in all the morphogeological belts, varying in composition from granite to granodiorite to quartz monzonite. The two eastern belts, Omineca and Foreland, are most relevant to our discussion of the West Plains geology.

The *Omineca Belt* is the most complex and varied of the five belts and is composed of variably metamorphosed sedimentary rocks and granites, ranging in age from Precambrian to Jurassic. High-grade metamorphism associated with accretion of the Omineca Belt was measured as early Cretaceous rocks from the terrane (Plint et al., 1992). During this time the crust east of the Omineca Belt was undergoing thin-skinned deformation, forming a series of stacked (imbricated) faults in the Foreland Belt.

The foreland thrust sheets continued to develop while the subsequent morphogeological belts were accreted. Thrust sheets were segmented by west- to northwest-trending transcurrent faults, such as the Lewis and Clark fault zone and Olympic Wallowa lineament (OWL) that are depicted in Figure 1 (Fuentes et al., 2011). These northwest directed linear faults constitute wide zones of weakness in the bedrock which easily eroded and give rise to long curvilinear river valleys (e.g. Clark, Coeur d'Alene, and St. Joe) between the mountain ranges in northern Idaho. Plutonic rocks are limited to a few small isolated exposures because this belt has not been as tectonically uplifted or as deeply dissected as those morphogeological belts to the west.

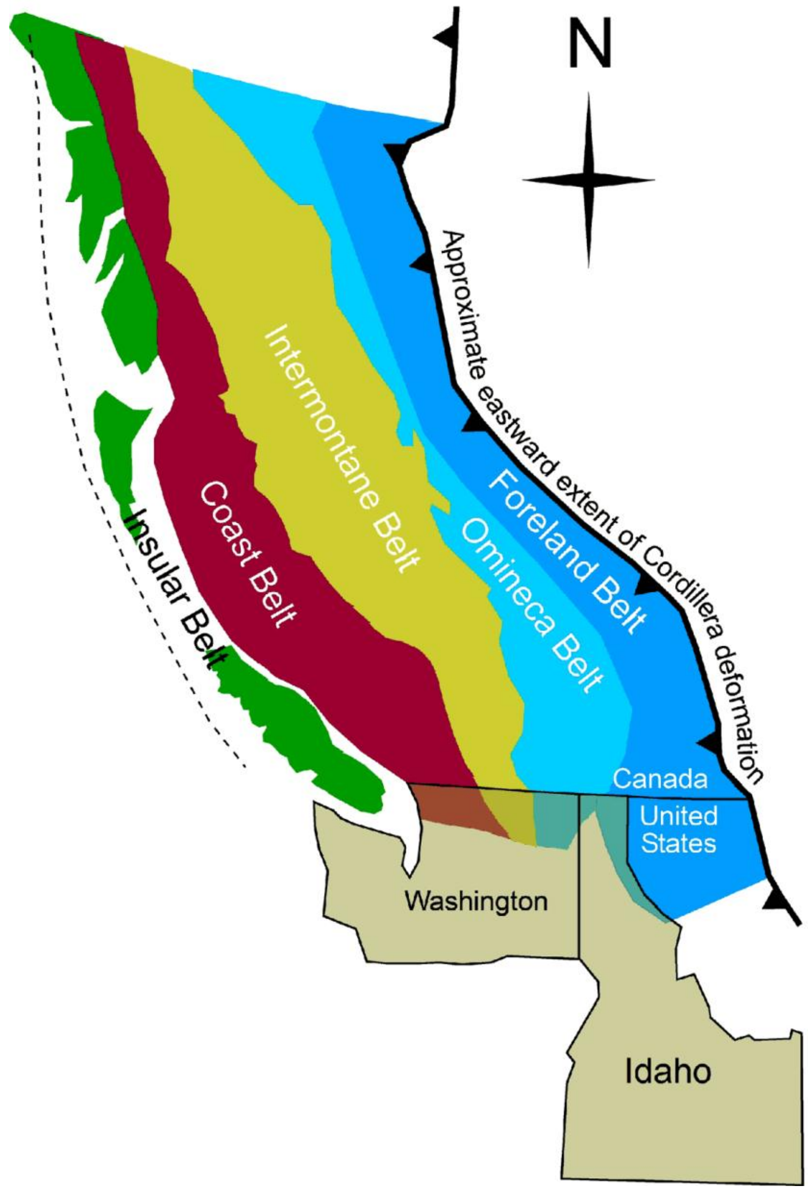

Figure 4. *Morphogeological Belts of the Pacific Northwest (from Digital Geology of Idaho)*

By the Eocene, accretion of the younger terranes and thrusting in the Foreland Belt was finishing. Beginning in the Paleocene and Eocene epochs an “orogenic reversal” allowed the western North American plate to relax (Lister and Forster, 2008). This extensional regime resulted in magmatic activity and doming and un-roofing of the mid crustal region of the Omineca Belt, forming metamorphic core complexes (Figure 5). The Eocene is also associated with an increase in volcanism along western US. The boundary between the Omineca and the Foreland Belt is defined locally by the Purcell Trench. Contacts between these units, folding, and faulting can significantly control geohydrology.

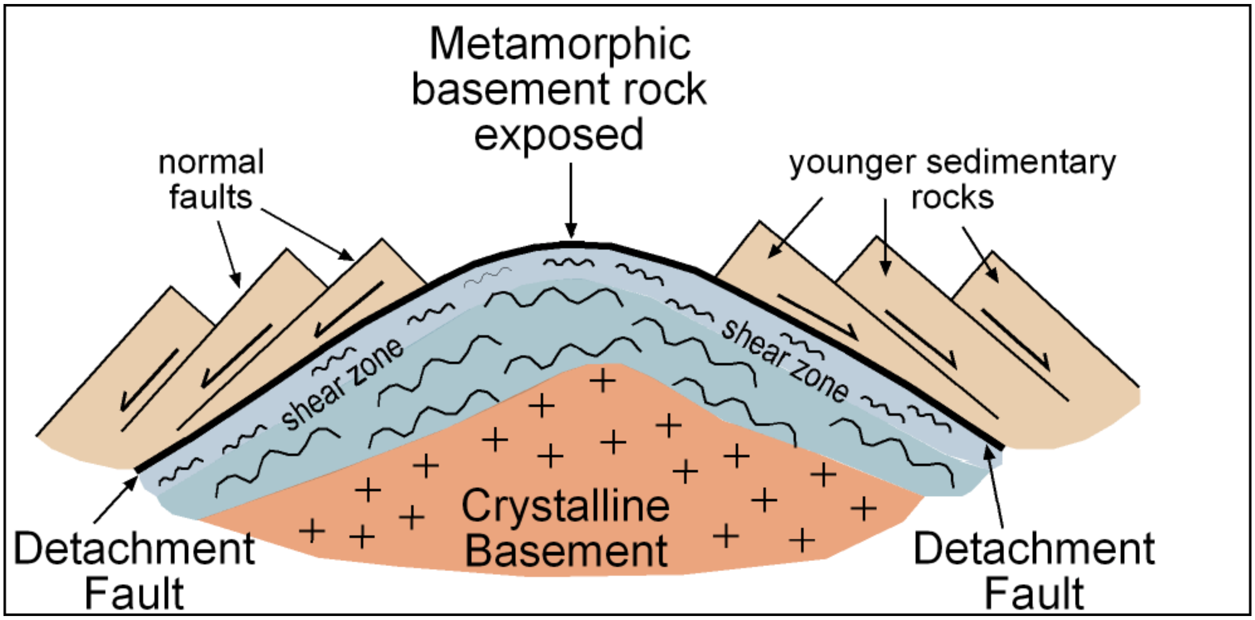

Figure 5. *Idealized cross-section of a metamorphic core complex (sketch by Paul K. Link from Idaho State University)*

III. PRE-NEOGENE BEDROCK GEOLOGY

The age of the igneous and sedimentary bedrock spans over 1.4 billon years and is divided into (1) Mesoproterozoic Belt Supergroup, (2) Mesoproterozoic Deer Trail Group, (3) Neoproterozoic Windermere Group, (4) uppermost (Ediacaran) Neoproterozoic and Paleozoic rocks, and (5) Cretaceous and Paleogene granitic rocks. Metamorphic rocks found within the Priest River core complex will be discussed in the section on structure.

The Mesoproterozoic Belt Supergroup is a thick (9 mile+) succession of siliciclastic and carbonate sedimentary rocks in the northwestern United States and adjacent Canada. The Purcell Trench separates Belt facies into two outcrop areas: (1) the Clark Fork-Eastport Sequence to the east, and (2) the Newport Sequence in the hanging wall of the Newport fault to the west. In addition to the Belt Supergroup sequence, lower Belt formations are thought to be the protolith (original rock) of the paragneiss found within the Priest River core complex.

The Mesoproterozoic Deer Trail Group is the lithostratigraphic equivalent to the upper part of the Belt Supergroup, but is separated from the Newport Belt sequence to the northwest by the Jumpoff Joe fault. Rocks of the Deer Trail Group are pervasively phyllitic or slaty and noticeably more deformed that either of the Belt sequences. In addition, differences in lithostratigraphy and thicknesses between correlative units of the Belt and Deer Trail indicate that they were farther apart when they were deposited.

The Neoproterozoic Windermere Group is up to 5 miles in thickness and consists of a lithologically varied sequence of coarse-grained clastic sedimentary rocks with intervals of volcanic rocks. The Windermere Group overlies the Deer Trail Group, but is absent east of the

Jumpoff Joe fault where the Belt Supergroup sequences are disconformably overlain by Cambrian rocks. The Windermere Group is also characterized by extreme differences in thickness and lithofacies over short distances within its outcrop area in northwest Washington. These differences are interpreted as due to syndepositional faulting associated with the initial stages of late Neoproterozoic intracontinental rifting (750-575 Ma) preceding actual continental separation and drift of North America and Siberia in late Ediacaran and earliest Cambrian time.

Mid-Cambrian rocks are present above the Clark Fork-Eastport Sequence: the 400 ft (120 m) thick Gold Creek Quartzite, the 80 ft (25 m) thick Rennie Shale, and the 2000 ft (600 m) thick Lakeview Limestone. Across the Purcell Trench to the west, Paleozoic rocks overlying the Clark Fork-Eastport sequence of the Belt Supergroup are limited to the 1,500 ft (460 m) thick Neoproterozoic to Cambrian Addy Quartzite, which is present just east of the Jumpoff Joe fault near Chewelah. Paleozoic rocks ranging from the Cambrian to Carboniferous occur above the Deer Trail Group west of the Jumpoff Joe fault, but the post-Ordovician rocks occur in small, widely separated outcrop areas (Miller and Clark, 1975).

There are no observed Mesozoic sedimentary rocks and only a few scattered outcrops of Eocene fluvial rocks preserved in grabens. However, Mesozoic to Eocene granitic rocks are thought to underlie almost 50 percent of the southern Omineca Belt. Most of the granitic rocks fall into two distinct petrogenetic suites: (1) upper crustal hornblende-biotite and (2) mid-crustal muscovite-biotite or two mica granites which are present in the Priest River Complex. Eocene shallow-intrusive (hypabyssal) rocks are present in areas characterized by early Paleogene to Eocene extension.

REGIONAL STRUCTURES

Rocks within the Pacific Northwest record a complex and varied structural history from the Neoproterozoic to the Eocene. The region adjacent to the West Plains is characterized by Cretaceous compression followed by Eocene and localized Paleogene extension which resulted in several discrete periods of igneous intrusion, folding, normal and reversed faulting, and repeated reactivation of faults during succeeding periods of tectonic movements. Major structural features include the (1) Jumpoff Joe fault, (2) Lewis & Clark fault zone, (3) Purcell Trench, (4) Priest River complex and Newport fault, and (5) Eocene normal faults. A brief summary of these major structural features, active in the past 100 million years (my), aids in understanding the pre-CRBG bedrock geology and how the basement topography might be interpreted within the West Plains region (Figure 6).

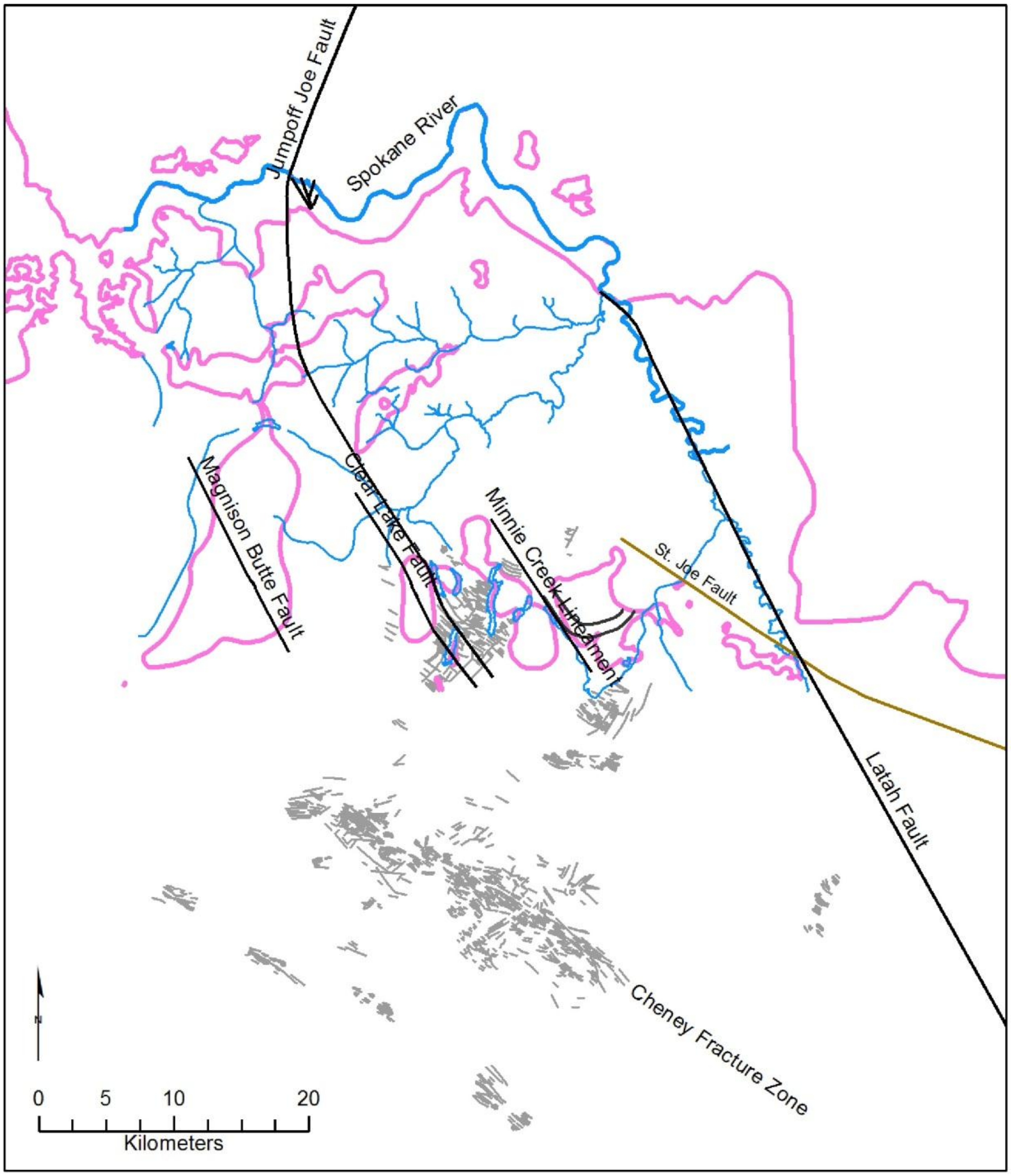

Figure 6. *Major structures in the West Plains region, high density fracture zones are depicted in gray and basement-basalt surface contact are in pink.*

Jumpoff Joe Fault

The Jumpoff Joe fault is the major structural feature associated with Cretaceous crustal shortening. This west-dipping thrust fault carries the Mesoproterozoic Deer Trail Group, the overlying Neoproterozoic Windermere Group and "thick" early Paleozoic section over the Belt Supergroup and "thin" early Paleozoic section along its entire length. The Jumpoff Joe fault has been mapped for over 45 miles (72 km), from the Canadian border in northeast Washington southward to Springdale. The actual fault is exposed in only a few places in that distance because it is masked by surficial deposits and intruded by Cretaceous and Eocene plutons.

The trace of the Jumpoff Joe fault north of the Spokane River was inferred beneath surficial deposits or where plutons have obliterated its trace because the Deer Trail Group, Windermere Group and the thick Ediacaran to Lower Cambrian quartzites are present only to the west of this structure. Although the trace of the Jumpoff Joe fault has never been extended south of the Spokane River, it can now be projected southward under the CRBG cover an additional 25 miles (40 km) to Clear Lake (McCollum et al., in press).

Lewis & Clark Fault Zone

The northwest trending Lewis and Clark fault zone can be traced from Helena, MT to the Wallace and Lake Coeur d'Alene area where the basement becomes covered by the CRBG before entering Washington. It is likely that this fault system continues westward into Spokane County and that the St. Joe fault, which marks the southernmost boundary of the Lewis and Clark fault zone, traverses the West Plains somewhere between Four Lakes and Airway Heights (McCollum et al., in press). The Lewis & Clark fault zone has been considered a portion of a series of step-over faults that includes the Olympic-Wallowa lineament, which may have similar characteristics (Kuehn 1995).

Purcell Trench

The Purcell Trench is a fault bounded and glacially modified valley several miles wide which trends northward from Lake Coeur d'Alene into Canada. There is a strong metamorphic and deformational change across the Purcell Trench and few structures have been traced across it. The eastern edge of the Priest River complex abruptly ends at the Purcell Trench and none of the east-west directed faults found within the Lewis-Clark fault zone have been projected across it (Doughty and Price, 1999).

Priest River Metamorphic Core Complex and the Newport Fault

The Priest River metamorphic core complex is an exhumed midcrustal paragneiss (sedimentary protolith) and orthogneiss (plutonic protolith) intruded by two-mica granites that is exposed west of the Purcell Trench. The exhumation of the Priest River complex occurred between 55 my and 46 my and became structurally detached from the overlying upper crustal rocks along the Newport fault. The eastern portion of this complex is occupied by the Spokane Dome, an anticlinal structure with plunges to the south where it is structurally terminated by the right-lateral St. Joe fault (Doughty and Price, 1999).

Midcrustal amphibolite (high-grade metamorphism formed at mid-crustal level) grade metamorphic gneisses are characterized by the mineral assemblage quartz-plagioclase-orthoclase-biotite-sillimanite-garnet. The Hauser Lake Gneiss (paragneiss), whose protolith is the Prichard Formation at the base of the Belt Supergroup, is the dominant rock type and underlies most of the exposed core of the Priest River complex. The Newman Lake Gneiss (orthogneiss) is a phenocrystic (large feldspar laths is a finer grain mass) granodiorite which intruded during the Cretaceous and since been metamorphosed and tectonically interleaved with the Hauser Lake Gneiss during the early Paleogene. The informally named gneiss of Chester Creek is at a slightly lesser metamorphic grade and is thought to be the lower portion of the overlying Ravalli Group. This paragneiss does not appear to be intruded by orthogneiss and is probably detached by faults from the Hauser Lake Gneiss.

IV. PRE-NEOGENE GEOLOGY OF THE WEST PLAINS

Exposure of the older bedrock in West Plains is confined to isolated hills and ridges which project above highest surface elevation of the CRBG at 2450 ft (750 m) and in drainages where the covering basalt has been removed by erosion. A summary discussion of these exposures is included in this report, mostly excerpted from an "in press" scientific article by McCollum et.al. This is followed by projecting the most probable trace of the major structures under the CRBG cover in the West Plains, allowing for a new element to be used in depicting the buried pre-CRBG topography and its effect on the aquifer system.

Several distinct units have been recognized in the sedimentary rocks present in the steptoes of the northeastern portion of the Columbia Plateau. Griggs (1973) divided the Belt Supergroup (Winston & Link, 1993; Elston et al., 2002) sedimentary rocks exposed between Latah Creek and Medical Lake area into those which were primarily quartzose and those that were largely calc-silicate, and assigned them to the Burke and Wallace formations respectively. Sedimentary rocks in Lincoln County, consisting primarily of quartzite, phyllite and argillite, were correlated by Griggs (1973) to similar rocks found in the Turtle Lake 15' quadrangle (Becraft & Weis, 1963), and presumed to be Paleozoic in age. Joseph (1990) updated some of the geologic unit nomenclature and reassigned sedimentary rocks west of Medical Lake to formations within the Mesoproterozoic Deer Trail Group (Miller & Whipple, 1989), and recognized that quartzites could be as young as Cambrian in age. The recent discovery of early Middle Cambrian fossils at a small steptoe on the southeast side of Clear Lake (Hamilton et al., 2003), in rocks previously mapped as Mesoproterozoic Wallace Formation by Griggs (1973) and Joseph (1990), confirmed the presence of Cambrian strata and provided the impetus for reexamining the geology of a larger area of steptoes in the northern Columbia Plateau region.

The geologic mapping by both Griggs (1973) and Joseph (1990) shows two distinct Belt Supergroup lithologies which could be distinguished in the region between Medical Lake and Latah Creek. The greenschist (low-grade metamorphism) facies siliciclastic-dominated units exposed east of Four Lakes to Rosa Butte were assigned to the Ravalli Group, and the predominantly calc-silicate rocks exposed west of Four Lakes to Silver Lake were assigned to the Wallace Formation, Piegan Group. The discovery of sillimanite and orthoclase minerals together in a silica-rich paragneiss at the north end of Needham Hill by the McCollum's led to remapping the Four Lakes area.

The Ravalli Group is restricted to exposures from Latah Creek westward to Fish Lake and Prosser Hill. The predominant rock type is quartzofeldspathic sandstone with muscovite and randomly oriented clots of biotite and chlorite in a hornfels texture. Phyllitic interbeds are present in some areas, but they are seldom well exposed. In the area from Fish Lake and Prosser Hill, granitic pegmatites become more common and isolated patches of small red garnets are found locally near these intrusives.

The northern Needham Hill area is composed of amphibolite facies rock including sillimanite-orthoclase quartz paragneiss and strongly lineated orthogneiss intruded by numerous granitic pegmatites. McCollum et al. (in press) named this region of high-grade metamorphic rocks the Needham Outlier and suggest that it is the tectonically displaced southern portion of the Priest River metamorphic core complex.

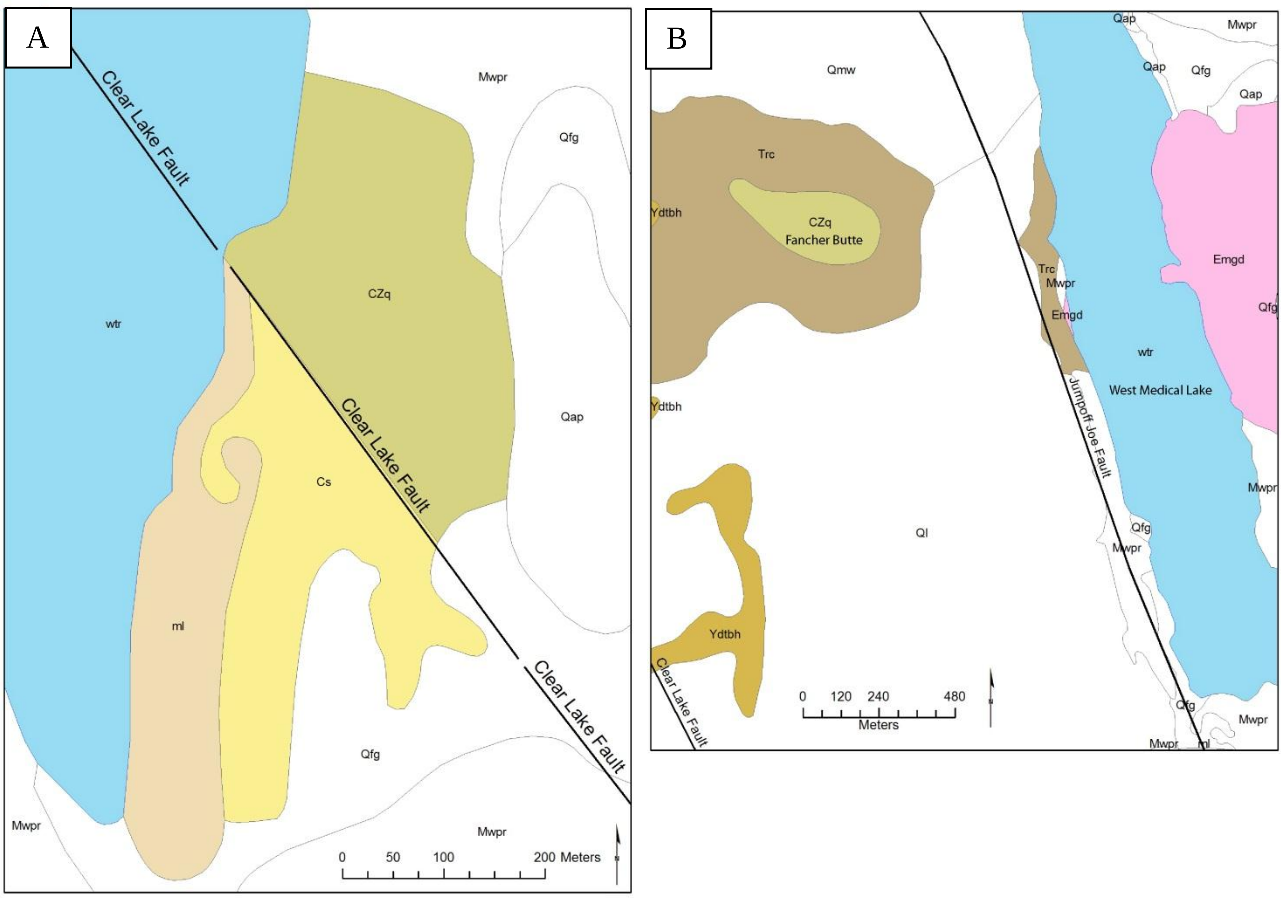

Figure 7. *Maps depicting two faults in the West Plains region. A) the normal fault movement along the Clear Lake fault that has uplifted Cambrian quartzite (CZq) relative to the hanging wall, locally composed of Cambrian shale and phyllite (Cs). B) Map illustrating the easternmost outcrop of the Mesoproterozoic Buffalo Hump formation of the Deer Trail Group (Ydtbh) to the west and Eocene granodiorite of Medical Lake (Emgd) to the east. The structural contact is regionally considered the Jumpoff Joe Fault, and is inferred along the west side of West Medical Lake based up on mapping by Joseph (1990).*

McCollum et al. (in press) assigned the calc-silicate (metamorphosed limestone) and pelites (metamorphosed mudrock) exposed on Wrights Hill northward to Olson Hill to the Mesoproterozoic Piegan Group, Belt Supergroup. Excellent exposures occur from the eastern flank of Riddle Hill to the southern flank of Olson Hill. Relationships between the Eocene granodiorite of Medical Lake to gabbro and the dark, coarse grained, mylonitic (extreme crusting), hornblende-biotite gneiss and schist are well exposed along the shoreline of Granite and Willow lakes. Interlayered calc-silicate and biotite schist layers are complexly folded and boudinaged (tectonic stretching causing sausage shaped layers) near the intrusive granodiorite.

Cambrian, Neoproterozoic and Mesoproterozoic strata are present in steptoes west of the West Medical Lake-Jumpoff Joe fault zone. Early Middle Cambrian fossiliferous shale, phyllite and limestone are present in the Clear Lake area, and Ediacaran to Lower Cambrian quartzites occur from Clear Lake to Grays and Gettys Buttes north of Reardan and west to Edwall.

Exposures of the underlying Neoproterozoic Windermere Group are limited to an isolated outcrop area located on the east side of Crab Creek at the north end of Pleasant Valley. A light colored phyllite with thin greenstone intervals were assigned to the Huckleberry Formation based on a geochemical analysis of the greenstone preformed during this study which is consistent with those reported by Miller and Clark (1975) for the Huckleberry Formation in Stevens County.

Rocks assigned to formations within the Mesoproterozoic Deer Trail Group are widely exposed from Magnison and Hanning buttes north to Laupp Lake and the Spokane River. A light and dark laminated argillite, assigned to the McHale Slate by Joseph (1990), underlies Hanning Butte, Magnuson Butte and the southern end of a low ridge northwest of Edwall. Joseph (1990) noted that the argillaceous sandstone and siltite occurring at Laupp Lake, Gettys Butte, and on Fancher Butte could be assigned to the Mesoproterozoic Deer Trail Group.

Granitic rocks of probable Mesozoic and/or Paleogene age have been mapped in the area west of Spokane, where they rise above the overlying Columbia River Basalt in isolated steptoes and crop out along the Spokane River canyon and its tributaries where they have cut through the basalts. The limited exposure has made it difficult to understand the field and contact relationships between different bodies of granite as well as their regional context. Zircon dating of these isolated plutons provided the data needed to compare them with the better exposed and studied Colville igneous complex to the northwest and Kaniksu batholith and Priest River MCC to the east.

V. U-Pb Ages

Age dating of the isolated granitic plutons allows for a better understanding of the tectonic region present during their formation, and thus contributes to placing them into a regional context. Based on methods presented by Gashing et al. (2010), U-Pb zircon geochronological data was obtained by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) performed at WSU for twelve granitoid samples from the West Plains, error (±) is approximately 2% of the age. These samples are of an 1) alaskite and aplite of Wellpinit Hill at

97 my, 2) Loon Lake Granite from Little Falls Dam at 92 my, 3) biotite granite of Long Lake Dam at 82 my, 4) biotite granite of West Point at 68.7 my, 5) biotite granite of McDowell Hill at 61 my, 6) lineated porphyritic biotite granite of Coulee Creek at 60 my, 7) pegmatite intruding Loon Lake Granite at 53 my, 8) porphyritic rhyolite of Mathews Lake at 51 my, 9) biotite-hornblende granite of Little Chamokane Creek at 50 my, 10) porphyritic plagioclase granite of Little Falls at 49 my, 11) biotite-hornblende granodiorite of Medical Lake at 49 my, 12) and biotite granite of Eleanor at 46 my.

VI. PRE-NEOGENE STRUCTURAL GEOLOGY OF THE WEST PLAINS

Major regional structures mapped in the mountainous regions to the north and east probably extend under the northern Columbia Plateau, but the extensive CRBG and Ice Age flood sediment cover masks these faults to such a large extent that any discussion of their presence must rely mostly on a "best fit" scenario within the limited pre-CRBG exposures. Several northwest-trending features (Figure 6), including the Latah lineament ("fault" of Derkey & Hamilton, 2002 and 2003), the Rosa Butte fault, the St. Joe fault, the Minnie Creek lineament, the southern extension of the Jumpoff Joe fault and West Medical Lake fault of Joseph (1990), the Clear Lake fault, and the Magnison Butte fault occur within the projected trend of the Lewis and Clark fault zone to the southeast. Some of these features may be projected along lineaments or abrupt changes in geology or topography to the east of the study area in the northeastern Columbia Plateau. Actual pre-CRBG bedrock exposure of the faults in the study area is limited.

The eastern boundary of the West Plains delimited by a conspicuous 50-mile-long linear feature that trends N30^{o}W in what is now the lower reach of the Latah Creek in Hangman Valley and a segment of the Spokane River to the north. Derkey and Hamilton (2002, 2003) believed that this linear feature was formed by a structure they named the Latah fault and that it was active into the Miocene. Although our current research suggests that this lineament may reflect a fault in the basement rock, there is little evidence that the Miocene lake deposits and intervening basalt flows were displaced.

The St. Joe fault is a prominent structural feature in the southern portion of the Lewis and Clark fault zone of northern Idaho and adjacent Montana, with a trend of N70^{o}W (070^{o}) for its exposed length of over 100 miles (161 km). It has a long structural history of movement, but most evidence suggests that it is a right-lateral fault with 12 miles (19 km) of displacement across it. McCollum et al. (in press) projected the trace of the St. Joe fault along strike under the CRBG in northeastern Washington on the basis of contrasting geology, metamorphism and surface lineaments of drainages believed to reflect structural weakness in the underlying bedrock.

The Minnie Creek lineament occurs in a small prominent valley west of Four Lakes and continues southward to Cheney. This half mile wide, parallel sided valley trends N30^{o}W (030^{o}) and is floored by basalt. This basalt filled valley separates two contrasting suites of metamorphic rocks of the Belt Supergroup exposed on Needham Hill to the east and Wrights Hill to the west. This lineament probable reflects a structure in the pre-CRBG, but without seismic profiles, it is impossible to say more.

The West Medical Lake fault of Joseph (1990) occurs between coeval Mesoproterozoic rock assemblages assigned to the Belt Supergroup to the east and Deer Trail and Windermere groups to the west. At least two possible structural interpretations exist within a regional context. The first possibility is that the West Medical Lake fault is part of an en echelon series of N30^{o}W lineaments and structures such as the Latah, Rosa Butte, Minnie Creek, Clear Lake and Magnison Butte with little known displacement. The second possibility is that the West Medical Lake fault represents the southern continuation of the Jumpoff Joe fault, which is the bounding structure separating the Deer Trail and Windermere groups of the Kootenay Arc region (Watkinson & Ellis, 1987), from the Belt Supergroup immediately to the east (Miller and Clark, 1975). For now, the West Medical Lake and Jumpoff Joe structures are used together as the tectonic dividing line between the two major Mesoproterozoic formational groups, as shown in Figure 7.

The Clear Lake fault is a high angle normal fault that is exposed in a roadcut as it crosses Clear Lake Road near the Fairchild Recreation Facility on Clear Lake (Figure 7). Middle Cambrian fossiliferous shale and phyllite to the west of this fault has been down dropped a thousand feet or more against the Lower Cambrian to Neoproterozoic quartzite on the east side. This is the only structure where the expected down to the west sense of displacement can be demonstrated.

The Magnison Butte fault occurs as a fairly continuous belt of silicified breccia which crosses this hill and separates the McHale Slate from the Buffalo Hump Formation, Deer Trail Group. An adit low on the south side of the hill exposes the fault, which appears to be a high angle structure, but no sense of displacement can be ascertained. The only other structure in this area is exposed on the top of Hanning Butte, where a high angle north-south silicified and mineralized zone cuts across the McHale Slate with little apparent offset.

VII. CRBG STRUCTURAL GEOLOGY OF THE WEST PLAINS

Faulting and folding, so apparent in the CRBG to the southwest (Reidel, 1984; Watkinson and Hooper, 2000), are either absent or masked by the surficial cover in the West Plains region. Fracturing and lineaments are far more common here and may reflect the structural weaknesses present in the underling basement.

Perhaps the structures that most influence the hydrology of the CRBG in the West Plains are the deep, high density fracture zones (HDFZ) so prominent on aerial photos covering the flood swept basalt scabland found in the Cheney-Palouse Tract. The most prominent of these is the Cheney Fracture Zone depicted on the geologic maps of Griggs (1973) and Joseph (1990). An example of the grouping and general orientation of HDFZ are illustrated in Figure 8. A closer look at the joint patterns shows that they are commonly found in conjugate fractures generally associated with brittle deformation. Generally, the conjugate fractures are found at 30^o (Figure 9). As shown in Figure 10, the orientations of the fractures in the West Plains appear to have similar trends to regional structures that would have been formed under similarly oriented stress regimes. Therefore, there is a strong likelihood that HDFZ in the West Plains region, such as the Cheney Fracture Zone may be manifestations of basement structures. If this is the case, the fractures could reflect highly faulted basement that may have been more easily eroded (pre-Neogene) to form paleovalleys. Unpublished geophysical surveys indicate possible basins and thicker CRBGs, which could potentially act as hydrogeological conduits.

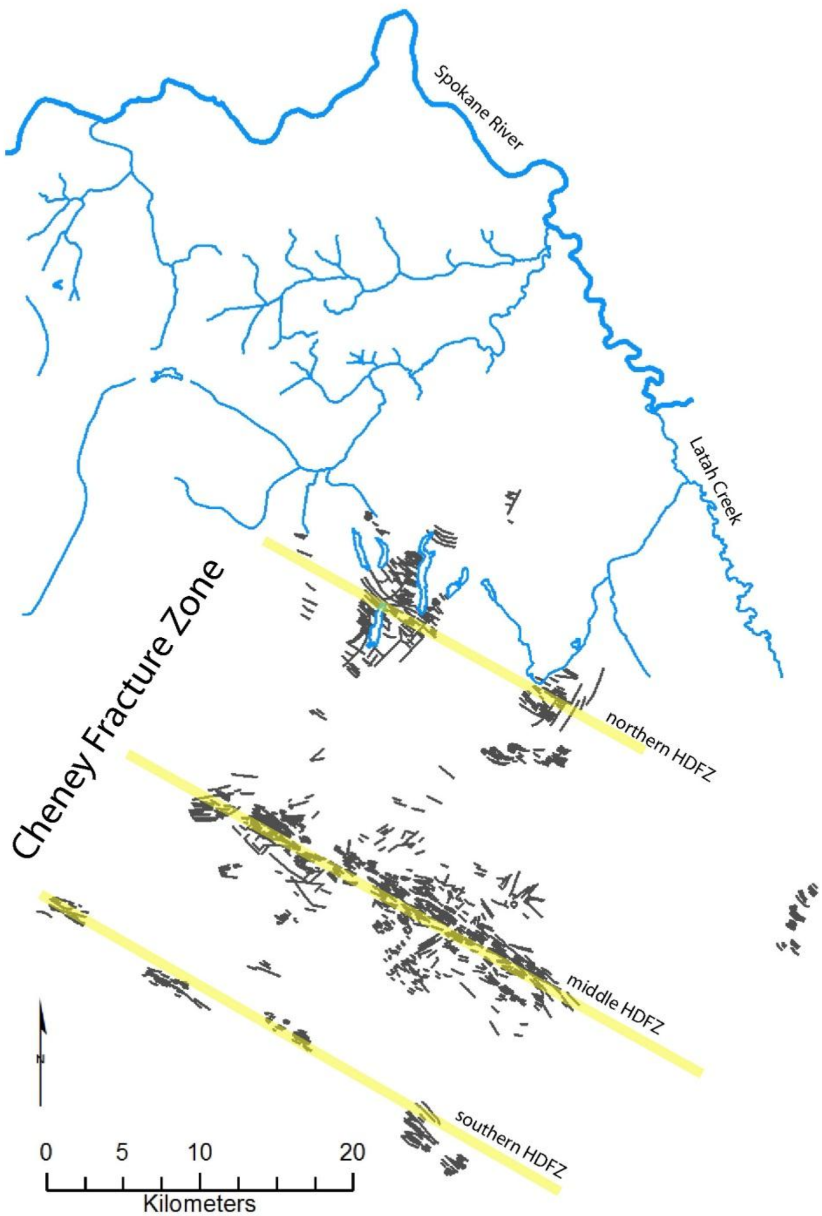

Figure 8. *Distribution map of the Cheney Fracture Zone in the West Plains region.*

Figure 9. *Example of conjugate fractures in the western portion of the Cheney Fracture Zone. The angle between fractures is approximately 30°, with a fracture trending N57°W (303)° and 0.48 miles (775 m) long and a second N85°W (275°) and 0.59 miles (950 m) long.*

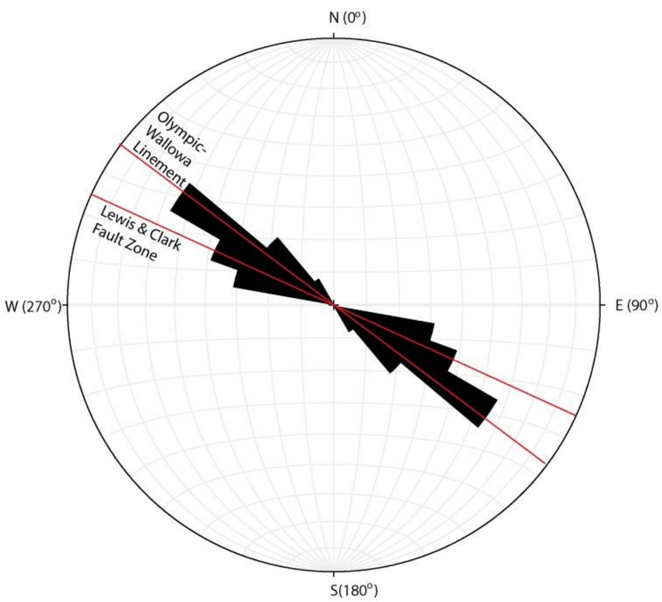

Figure 10. *A percentage scale or rose diagram (in black) of relative number of fractures in the given orientation, from the Bonnie Lake area. The general orientation is approximately N60°W (300° azimuth). Also presented are the general orientations of the Olympic-Wallowa lineament N50°W (~310°) and the Lewis & Clark fault zone N65°W (~295°).*

VIII. SURFACE DELINATION OF THE BASEMENT & HYDRO-STRUCTURAL-GEOLOGY

The northern CRBG have a regional dip to the south and southwest toward the basin center located in the central portion of the Columbia Plateau and the conventional wisdom is that this dictated the aquifer flow direction. This portion of the WIRA 54 project was initiated based upon past mapping of the area by Derkey and others (2004) that depicted a large and very gentle fold that may have influenced the direction of groundwater flow in the West Plains. The suspect fold would have had an axial plane paralleling Highway 2 in the Airway Heights area with long limbs directing groundwater to the north and south of the axis, and groundwater would be expected to follow flow contacts. In other parts of eastern Washington such folds are common, and generally associated with geologic structures and tectonic processes (Watkinson and Hooper, 2000; Reidel, 1984). However, from recent mapping directly associated with this study, it appears that the Wanapum Basalt in the Airway Heights area most likely dip gently to the north due to either paleo-topography during emplacement or subsequent differential compaction of the Latah Formation, which thickens substantially to the north. The abbreviated field research, due to contract limitations of time, disallowed any attempt to trace the previously documented folding found in the Miocene flood basalts from the southeast into the West Plains, although this project has identified multiple structural features that may influence groundwater flow and have not been addressed in past geologic literature.

The just completed geologic mapping of this region by Linda and Mike McCollum (EWU) has also revealed that a ridge of pre-CRBG basement runs contiguously from Edwall through Reardan and north to the Spokane River. Therefore, the Spokane West Plains aquifer system is a virtually isolated CRBG basin surrounded by basement on the south and west and by the Spokane River and Latah Creek on the north and east (Figure 11). Groundwater replenishment is therefore dependant on local surface recharge areas that are being reduced by increasing development in the eastern West Plains.

Furthermore, zones of infiltration and increased mixing between CRBG aquifers are expected in the northern HDFZ, Cheney Fracture Zone. We expect that other HDFZ may be present north of the mapped fractures, but are covered by Quaternary glacial flood deposits and alluvium and therefore not visible in aerial photo-interpretations. Certainly, the Craig Road corridor of municipal wells may be in a high fracture zone which would explain the high permeability between the basalt flows.

Other factors also modify or impede the aquifer flow in the West Plains. Creeks and paleochannels (older channels that have been infilled with Quaternary flood deposits and alluvium) deeply dissect the CRBG and buried basement ridges have also disrupted the CRBG aquifer system (Figure 11). In addition, the large scale structures mentioned above may have an important role in sculpting the pre-basalt landscape, most notably the formation of paleovalleys now filled with basalt or quaternary sediments. Finally, structures affecting the CRBG, such as joints, lineaments and gentle warping, can also enhance or inhibit ground water flow in discreet portions of the West Plains.

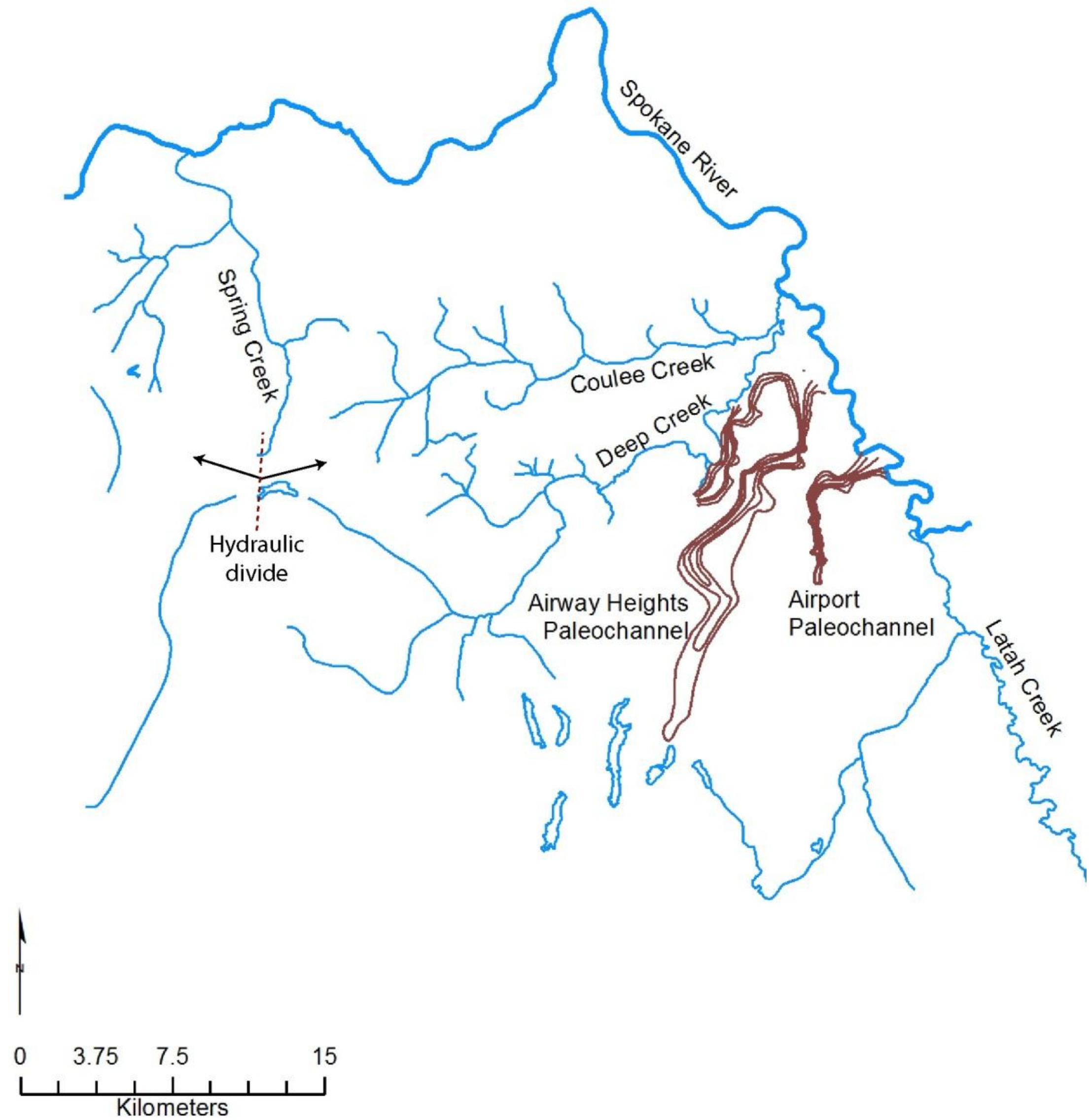

Figure 11. *Major drainages and paleochannels in the West Plains region. Red dashed line indicates a hydraulic divide due to shallow basement, discovered during the mapping of the McCollums (EWU), arrows indicate general direction of flow away from the basement divide. Paleochannels were modified from Derkey et al. (2004).*

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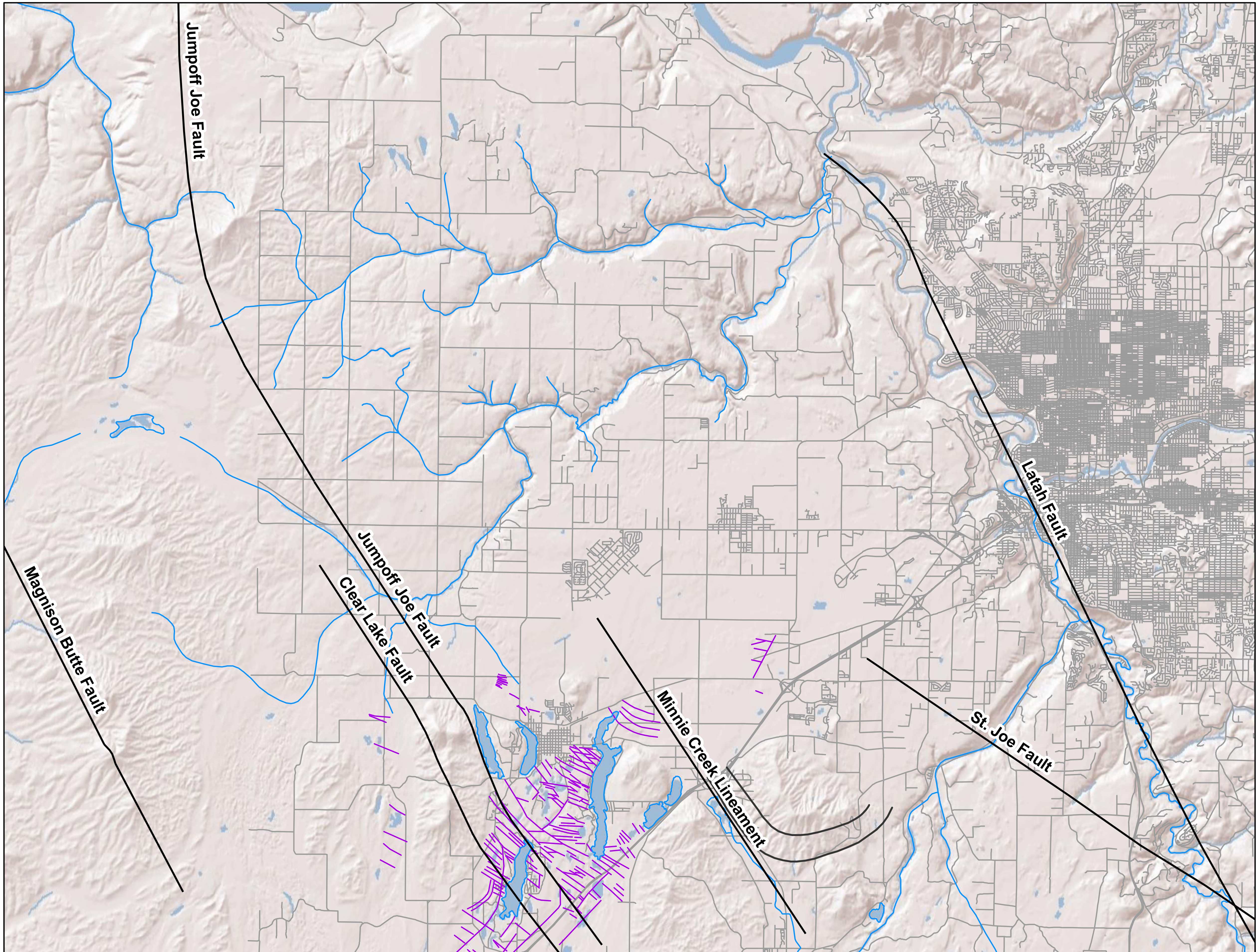
FIGURES



West Plains Geologic Structures

This map depicts geologic structures that may affect groundwater flow patterns in the West Plains area of Spokane County.

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Legend

- Faults
- Fractures

1 0.5 0 1 2 Miles

N