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LARAMIE MONITOR WELL PROJECT
PHASE I - INTERIM TECHNICAL MEMORANDUM

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I. Introduction / Background

This report provides a systematic program for the initial construction of groundwater monitoring wells in the portion of the Casper Aquifer potentially contributing to the Laramie municipal Turner No. 1 and Turner No. 2 wells (see Fig. 1).

We first provide a cursory review of the history of concern with the aquifer and the associated reports, beginning in approximately 1993. This is followed by articulation of the objectives of this study and explanation of the hydrogeologic setting for the Turner Wells, with particular reference to those elements relevant to a program for long-term monitoring of water levels and groundwater quality. Individual monitoring well locations, first existing, then potential, are then examined with respect to project objectives and specific recommendations are presented to maximize the utility of well construction at each of three sites.

Approximately 50% of the municipal water supply for the City of Laramie currently comes from a series of wellfields developed in the Casper Aquifer. This aquifer is recharged over the hillside immediately east of the city. The municipal wells are located at the toe of that recharge area and are thus subject to whatever contamination may enter the aquifer across its exposed outcrop. The hydraulics of this aquifer have been studied for many years. Key references are included in the bibliography at the end of this memorandum.

The Casper aquifer is the source of City Springs, historically a critical source of water for steam locomotives and one reason Laramie was founded here in the first place. These and similar springs at Pope and Soldier were the initial water supply for the City. A surface-water treatment plant on the Laramie River was added in 1946. In 1982, in order to better manage the groundwater resource, the city began a program of well construction with completion of the Turner No.1 and Turner No.2 wells. Together these comprise the present Turner Wellfield, which is the focus of the present investigation.

Given the historical interest in the hydraulics of the aquifer (i.e. how water moves into, through, and out of the aquifer), there have been many measurements of groundwater levels. The most systematic of these in the project area is from the Huntoon #1 monitor well, for which measurements started in 1979 and continue to date (see Fig. 2).

Concern with the quality of groundwater in the Casper Aquifer is a more recent development. The first wellhead protection plan was produced by Western Water Consultants (WWC) in 1993. Following general EPA guidelines, that report focused on groundwater travel times to specific city wells. The report focused strongly on the role of faults as avenues of enhanced permeability guiding groundwater to the natural discharge areas subsequently targeted by municipal wells.

In the late 1990s, the focus of groundwater quality concern shifted from a wellhead focus to a more comprehensive view of the aquifer - recharge areas, groundwater flows, and identified and potential sources of contamination. A broad-based group of citizens and local hydrogeologists began creation of a Casper Aquifer Protection Plan (CAPP), the first version of which was finalized in 2002.

The 2002 plan included theoretical calculations suggesting groundwater nitrate levels[1] were likely to be substantially exceeding the EPA Primary Drinking Water standard ("maximum contaminant level" (MCL)) of 10 mg/l in the oldest of the subdivisions along East Grand Ave. (i.e. Laramie Plains) that still have individual septic systems. However, there were no comprehensive measurements of groundwater quality from the aquifer available to directly address contamination concerns. (Although there are a great many potential groundwater contaminants associated with septic systems, nitrates is the most common indicator due its ease of measurement and high concentration in septic system effluent relative to natural background levels.)

This continued to be the case through the 2008 update of the City of Laramie CAPP, for which the Contaminant Management Plan noted:

> "To date, there has not been a systematic, aquifer-wide, long-term groundwater monitoring program to assess water quality in the Casper Aquifer." (p. 91)

and concluded:

> "It is recommended that the City and County develop a program to routinely collect groundwater samples and water levels throughout the CAPA to establish baseline water quality data and to evaluate changes in groundwater quality over time. The baseline data collected from this program should be used to set standards for quantifying contamination in the Casper Aquifer. A systematic monitoring program has a secondary benefit of increasing understanding of the Casper Aquifer. The City of Laramie should

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[1]By convention, nitrate concentrations are typically reported as equivalent nitrogen, properly termed "Nitrate as N". That is the basis for the EPA standard of 10 mg/l. The difference is a factor of 4.45, i.e. actual nitrate = "Nitrate as N" X 4.45. "Nitrate" references throughout this report are all "Nitrate as N" values to allow ready comparison with EPA standards and other reports.

continue to evaluate water-quality at the City wells in the current manner of comparing current results to historical concentrations and initiating additional sampling when results show increased concentrations.

"A good monitoring program can provide an 'early warning' to the arrival of contaminated groundwater at a municipal supply well. The monitoring wells should be located throughout Zones 2 and 3 such that detection would provide enough lead time to either mitigate the in-coming contamination before it can reach a municipal well or to arrange for an alternate drinking water supply or treatment." p. 91)

The 2008 CAPP identified specific locations for monitor well construction, and recommended that "establishing a routine groundwater monitoring program be one of the City of Laramie's highest priorities for implementation." (Fig. F-1 and p. 60).

In 2009, with limited re-sampling in 2010, the City collected samples from 115 domestic wells across the Casper Aquifer recharge area. These data were analyzed by WWC Engineering (2013), who concluded that in the Laramie Plains and Sherman Hills Subdivision areas (their "Clusters" A and B) 100% and 45% respectively of the wells had been "impacted" by nitrate contamination[2], with 52% and 27% of those wells "significantly impacted" or "unsafe" (p. 8). They characterized the "risk to county residents" as "significant", but the "risk to city wells" as "low" (Laramie City Council presentation slides, July 13, 2010). A "statistically significant" trend of "slightly" increasing nitrate concentrations was cited for the Turner wells, but even very long-term projection of that trend fell well short of the EPA MCL.

In 2009, the City and County jointly began an investigation of possible mitigation measures for the aquifer contamination that could result from a hazardous materials spill on Interstate 80 where it traverses the recharge area in Telephone Canyon. The first report from the program (Trihydro, 2011) surveyed the vulnerability of the aquifer to this mode of contamination and outlined a series of potential monitoring, containment, and mitigation alternatives. As of this writing, additional feasibility studies and evaluation of possible I-80 monitor wells are on-going under that investigation.

As of January 2012, the City accounted their "investment in aquifer protection over the past two biennium" at $1,316,150 (1/25/12 letter to Gov. Mead from City Manager). The monitor well project is a continuation of that investment.

II. Project Area / Project Objectives

Because the density of potential and known sources of contamination is higher in the area east of the Turner Wells than potentially up-gradient of the other municipal wellfields, and because its

[2]The "impacted" designation was applied to all samples with nitrate concentrations over the natural background level of "less than 2 mg/L".

proximity to the city provides continuing development pressure, the Turner area was selected for this initial development of a focused monitor well program.

The project area for this report is the City of Laramie Turner Wellfield, consisting of the Turner No.1 and Turner No.2 municipal wells, and the portion of the Casper Aquifer potentially contributing groundwater to those wells. The 1993 WWC report suggested the "zone of contribution" for the Turner Wells is entirely north of the Sherman Hills Fault, i.e. something of a groundwater collection network via the Quarry, City Springs, and Jackrabbit fault zones. Review comments on the 1993 report by long-time U.Wyo geology professor Peter Huntoon disagreed, opining that the "major contributing zone for City Springs" extends up to 2 miles south of that fault. (The role of the Sherman Hills Fault in groundwater movement related to the East Grand Avenue subdivisions continues to be a major point of discussion.)

The previous identification of "potential and known sources of contamination" in the 2008 CAPP clustered along East Grand contrasts markedly with the mostly undeveloped area north of the Quarry Fault (see Fig. 1). Future development pressure based on land ownership and simple developability (topography, access, utilities, etc.) is also greatest in and around the area of existing development. Thus, attention is focused on the southern portion of the potential recharge area for the Turner Wells. This encompasses the area from the Turner wells east to the point where no further development is present on the aquifer and south from the Turner wells to the vicinity of the East Grand Ave. / Interstate-80 interchange.

As discussed further below, contamination above background levels is widespread in the developed portion of the project area, but groundwater quality is in nearly all cases well within EPA standards for public water supplies[3]. This project is not predicated on acceptance of "legal" as the threshold of concern, but rather on an objective of the Laramie municipal water supply remaining as free of contaminants as practically possible. Thus, the presence of contaminants at concentrations below regulatory levels, but above natural background, and of contaminants for which no specific health thresholds have been established are of interest.

The objective of this project is to start a program of consistent, focused groundwater monitoring to better understand the occurrence and movement of potential contaminants in the Casper aquifer tributary to the City of Laramie municipal water supply wells.

III. Hydrogeologic Setting

The project area aquifer consists of the saturated sandstones and limestones of the Casper Formation, which receives recharge across its outcrop area east of the city (see Fig. 1). Absent disruption by faulting and folding, which are understood to provide locally enhanced permeability, the Casper consists of a series of sandstone subaquifers (members designated epsilon, delta, gamma, beta, alpha, from top to bottom) sandwiched between low-permeability limestone layers (see Fig. 3). Faults and folds with substantial surface expression are included

[3]EPA regulations do not apply to domestic wells.

on Figure 1, the geologic mapping for which was performed by the Wyoming Geological Survey (VerPloeg, 2009).

Stratigraphy: Table 1 summarizes the stratigraphy of the project area. Lithologic descriptions are condensed from VerPloeg (2009) with modifications to reflect local conditions and thicknesses as reported in local wells and observed in downhole video (e.g. Turner No. 1, Turner No. 2, 41T2). The overall thickness of the Casper Fm. is approximately 700 ft. With the exception of the uppermost member (epsilon), each member is capped with a continuous limestone bed.

Table 1 - Summary of Turner Wells Area Stratigraphy

Unit	Approximate Thickness (ft)	Description
Quaternary deposits	0 - 20	Unconsolidated and poorly consolidated clay, silt, sand, and gravel. (Qa, Qac, Qs, Qf, Qt units of VerPloeg, 2009.)
Chugwater Formation	650 - 800	Red shale and siltstone with interbedded red to salmon to buff, fine-grained sandstone.
Forelle Limestone	10 - 30	Gray to purple, thin bedded limestone locally interbedded with red siltstone and thin gypsum laminations.
Satanka Shale	295 - 310	Red siltstone and soft sandstone, thin limestone beds, and local gypsum beds, especially near the top. Buff to orange to red, fine-grained sandstone with ripple marks common near base.
Casper Fm. - epsilon	62 - 64	Red to pink , medium- to fine-grained sandstone. Grades into the overlying Satanka Shale. Porous sandstone that is poorly to moderately cemented.
Casper Fm. - delta	106	Top is a 10-13-foot-thick , white-gray to pink , massive, fractured limestone. Underlying strata are: reddish-brown to buff, thinly laminated, 19 - 24 ft. thick sandstone; 15-19-ft pink to light-gray , massive, fractured limestone; and 50-ft. light-tan to red, calcareous, cross-laminated, porous sandstone.
Casper Fm. - gamma	73 - 86	Top is 7 ft thick sandy grayish limestone. Underlying strata are 50 to 60 feet thick pink to red, fine- to medium-grained, friable, calcareous sandstone with interbedded limestone units (not extensive).
Casper Fm. - beta	141 - 158	Top is 8 to 12 feet thick finely crystalline, purple to pink , dense, highly fractured limestone. Underlying strata are red to buff, moderately resistive, extremely calcareous, thick , moderately sorted sandstone layer with an interbedded dense, ridge-forming limestone, 18 to 26 feet thick .

Casper Fm. - alpha	266 - 375	Top is 29- to 40- foot thick limestone. Remainder of formation includes light-brown to reddish-brown, poorly sorted, fine-grained sandstone unit, 75 to 80 feet thick, an 8 to 12 feet thick, pink to purple, sandy limestone, a pink to brown, calcareous, cross-laminated, medium sorted, fine-grained sandstone, 65 to 80 feet thick, and a basal sandstone unit, 80 to 150 feet thick, that is slightly arkosic as it grades into the Fountain Formation.
Fountain Formation	0 - 30	Coarse-grained pink to red to purple sandstone and arkose, with some conglomerates, siltstones and shales.
Precambrian		Sherman Granite

The Satanka is generally recognized as a "confining" bed due to the low permeability of its shale and siltstone units. The Satanka outcrop is used, in various forms, to mark the western edge of the Casper aquifer recharge area. The 1993 wellhead protection study (WWC) recognized that the overlying Satanka Shale "is a good confining layer", but included "except where the confining integrity is lost due to fractures". Noting the occurrence of Casper-sourced springs issuing from the Satanka, the authors extended the suggested wellhead protection plan up to 0.5 miles west of the Satanka - Casper contact, "where a local reversal in the vertical gradient in the area of the Turner and Pope Well Fields may induce leakage from the Satanka" (p. 45).

The role of the Satanka is discussed in the various versions of the CAPP. The 2002 CAPP concluded that a thickness of 75 ft. of Satanka overlying the Casper was sufficient to preclude surface-based contaminants from entering the aquifer, and established land use protections accordingly. For ease of application and in recognition of uncertainties in where the desired 75 ft. is present, the 2008 CAPP revised the aquifer-protection boundary westward to conform with established survey lines. The 2011 Albany County version of the CAPP[4] did not make this adjustment, leaving two different western boundaries for the formal aquifer protection area. For the present project, the relevant difference is primarily the western 2/3 of the Laramie Plains subdivision. We have adopted the City CAPP boundary and included the entirety of this subdivision in the area of potential contaminant sources due to uncertainty in the integrity of the Satanka Shale as a sealing unit.

The character of the individual members of the Casper is important to our project to the extent they control the flow of groundwater and potential contaminants. While it is commonly understood that the limestone strata separating these members are relatively impermeable where they are unfractured, there are many zones of fracturing in the Casper, e.g. commonly associated with faults and folds. Such zones have been identified as "vulnerable features" since the first wellhead protection plans and CAPPs were developed due to their expected role as conduits for groundwater flow into and through the Casper aquifer. While previous investigators have widely

[4]Prior to 2008, there was a single City and County CAPP developed jointly. In 2008, differences of opinion led to creation of separate CAPPs. Unless otherwise specified, the "CAPP" referred to in this report is that approved by the City in 2008.

acknowledged the likely locally confining nature of the limestone strata, their interpretations of water table (or head) surfaces have not suggested anything but a single integrated water table. Detailed video logs of the Turner No. 1 and No. 2 wells documented significant horizontal fractures within the sandstone strata of both the epsilon and delta members, e.g. "large open horizontal fracture" (epsilon, Turner No. 1), "very large horizontal openings and bedding plane fractures in sandstone (delta, Turner No. 2); (Wyoming Groundwater, 2004 and 2011). Thus, the concept of fracture-enhanced permeability in the Casper should be extended beyond the conventional focus on fault / fold / fracture systems to include more horizontal features.

Subject to further investigation (see below) our working hypothesis is that fracturing is sufficient to largely homogenize water levels beyond the local level.

The epsilon member of the Casper is commonly identified by as having the greatest intrinsic (i.e. absent fracturing) permeability of the five members of the Casper (e.g. Thompson, 1979; WWC, 1995) and the upper Casper (epsilon and delta members) is "the primary water producing zone" (WWC, 1995; p. 6-1). The epsilon has been the most developed member for groundwater, both because it is generally productive (where saturated) and simply because it is the first unit encountered in most areas. Careful testing of the 41T2 well suggested that production declined once productive fractures in the delta member were dewatered at that location (WWC, 1996).

Subject to further investigation, our working hypothesis is that the epsilon and delta members form the most productive portion of the Casper aquifer, with the gamma, beta, and alpha members being generally less productive. However, isolated testing of the alpha member at the 41T2 well along the Quarry Fault found a specific capacity[5] of 6.8 gpm/ft (WWC, 1996), a value as high as the better epsilon and delta member wells in the east Grand Ave. subdivisions.

The Turner No. 1 well is completed in the epsilon and delta members; the Turner No. 2 well is completed in the epsilon, delta, gamma, and beta members (WWC, 1996). However, pump testing of the alpha member at 41T2 well (WWC, 1996) demonstrated that both Turner wells are in hydraulic connection with the entire Casper Fm., presumably as a result of the hydraulic homogenization in this area of intersecting faults, fractures, and the Quarry Anticline.

<u>Structure</u>: Figure 1 presents the most detailed published geology of the project area (VerPloeg, 2009), modified as follows for the present report:

- The contact between the epsilon and delta members of the Casper Fm. has been refined in the vicinity of the Sherman Hills Fault based on direct field inspection. Specifically, the limestone bed at the top of the delta member can be observed in the drainage along the south side of the Imperial Heights subdivision.

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[5]Specific capacity is the production rate divided by the drawdown, e.g. a well than produces 20 gpm with only 2 ft of drawdown has a specific capacity of 20 gpm/ft, and is much more productive than a well with a specific capacity of 2 gpm/ft.

- The contact between the Satanka Shale and the epsilon member north of the fault has been taken from Lundy (1978) to project through the area for which VerPloeg (2009) mapped only the surficial deposits (rather than interpreting the underlying bedrock).

- South of the Sherman Hills Fault, the Satanka/epsilon, epsilon/delta, and delta/gamma contacts have been projected beneath the cover of unconsolidated material (alluvial fan, terrace, and eolian deposits) based on well logs and the westward dip of the strata.

The magnitude of the westward dip of the Casper and overlying formations is calculated from pairs of wells in which a specific stratum is identifiable from the available logs. For example, the Huntoon #1 (P35758) well hit the limestone at the top of the delta member at 40 ft. The Honken (P99001) well hit the top of the epsilon member at 102 ft., addition of the epsilon thickness of 63 ft. puts the top of the delta at 165 ft. (The Honken well stopped at 150 ft., in the epsilon.) These two wells are 3,000 ft. apart, perpendicular to strike, and 80 ft. different in surface elevation. Thus, the indicated formation dip is 3.9°. Similar geometry from other well pairs indicates similar dips, i.e. around 4°. This compares with dips of 3° and 4° mapped by VerPloeg on outcrops of the Forelle Limestone on both sides of the fault and with 3° on the Casper just east of Imperial Heights.

The effect of displacement of these westward-dipping strata along the Sherman Hills Fault is readily apparent in the "jog" in the Forelle Limestone ridge running south from the Turner Wells. This ridge is approximately 1600 ft. further west on the north side of the fault than on the south side. At the dip calculated above, an equivalent vertical displacement of approximately 100 ft. is indicated. Lundy estimated a displacement of 65 ft. at a point with Casper Fm. exposure on both sides of the fault one mile east of the Imperial Heights Park, consistent with displacement decreasing eastward and subsequent attenuation of the mapped fault in that direction.

Due to the cover of unconsolidated material, the exact character and location of the Sherman Hills Fault is uncertain. (It is consistently mapped as "covered" through most of our project area.) Recent geophysical investigations by the University of Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) on the University property along East Grand Avenue and on the City's Imperial Heights Park found the main fault trace beneath the northern portion of the park, with an indicated displacement of approximately 60 ft. and a steep northward dip (approx. 77°). The fault is a high angle reverse fault, up on the north and down on the south. North of the fault, a coherent bedrock block is indicated by the geophysics, which is consistent with the observable outcrop. South of the fault, the geophysical characteristics suggest a zone of disrupted strata, e.g. subsidiary faults or associated fracturing.

Figure 6 presents a schematic cross-section from the Turner Wells to the middle of the Sherman Hills subdivision. Particularly north of the Sherman Hills Fault, the geometry is not well constrained by wells or outcrop data. The intersection of various folds and faults may create complex permeability distributions and groundwater flow patterns.

Groundwater Flow: Once recharge from the surface reaches the water table, it will flow horizontally along with the groundwater to which it is added, in response to groundwater gradients. Groundwater, like surface water, runs "downhill", although the groundwater "hill" is defined by the water table (or potentiometric head surface). Figure 4 provides an approximate contour map of groundwater head for the project area based on measured depths-to-water in various wells. Although limited to carefully-measured values, mostly from November, 2005 (WWC Engineering, 2006) some other sources and dates are included. (Consideration of Figure 2 demonstrates the potential scale of the approximation created by combining water levels from different times. A synoptic set of measurements of all available data points should be provided at some point.)

The contouring of Figure 4 was done without regard for the potential influence of zones of higher or lower permeability created by confining layers, fractures, fault offsets, etc. The focus on November data is intended to minimize the impact of domestic and municipal well pumping. At this basic level, the groundwater flow directions indicate a potential natural contribution to the area of the Turner wells from the area of the east-Grand subdivisions. In addition, when the Turner wells are being aggressively pumped, a "cone of depression" will extend outward from each well, creating much steeper local groundwater gradients and drawing groundwater toward the well discharge. The operating drawdown at the Turner No. 1 well is approximately 30 ft.; the pumping drawdown at the Turner No. 2 well is approximately 20 ft. (WWC Engineering, 2006).

A cursory review of reported static water levels from the domestic wells in the Sherman Hills and Laramie Plains areas was made to obtain additional data on groundwater gradients in those specific areas. These are plentiful, but generally low-quality data, subject to measurement errors by untrained personnel, variations due to seasonal and long-term fluctuations, and errors due to incomplete well recovery from construction and testing operations. However, in both areas the reported static water levels suggest somewhat more northwesterly flow components than the contouring of Figure 4.

North of the Sherman Hills Fault, water level data are insufficient to discern gradients in detail. More importantly, in the presence of preferential permeability pathways, groundwater may not flow perpendicular to the gradient contours. Comparable to a ditch cutting across a hillside and thus re-directing "downhill" flow, groundwater will take the path of least resistance which may mean flowing into and along, rather than across, a fractured fault system.

There is wide agreement that the convergence of several fault systems (City Springs, Quarry) and a sharp fold (Quarry Anticline) on the City Springs is the source of the spring's abundant flow and of the highly productive nature of the Turner wells (e.g. Lundy, 1979, WWC 1993). The role of the Sherman Hills Fault is less clear. As noted above, there have been divergent interpretations of whether groundwater flow from the area south of the fault simply proceeds westward to eventually discharge up through the overlying Satanka, Forelle, and Chugwater formations (e.g. at Huck Finn Pond), or moves northwestward out of the fault zone to discharge at City Springs / Turner Wells.

Cursory review of specific capacity information supplied by drillers on well Statements of Completion indicates the productivity of Casper Fm. wells within the subdivisions vary substantially, but are mostly less than the Turner wells. This is reasonable in that the location of a domestic well is constrained to the owner's lot, whereas the City wells were deliberately located for maximum production. Whereas the Turner No. 1 and No. 2 wells have high specific capacities (90 and 35 gpm/ft., respectively (WWC, 1995), a sampling of wells in the Sherman Hills and Laramie Plains subdivisions reported specific capacities from 0.3 to 5.0 (still a 17-fold range). Exceptions include a well just south of the Sherman Hills Fault, for which a specific capacity of 36 gpm/ft was carefully measured (Weston Engineering, 1995). (This may indicate a zone of fracturing extending southward from the main fault, as discussed above.)

The nature of faulting beneath the subdivisions is unknown, although the density of faults mapped in the surrounding areas of Casper outcrop suggests the Casper is not a monolithic block beneath the mapped Quaternary deposits. Similarly, as noted above, although the Sherman Hills Fault is conceptualized as a discrete linear feature, comparison with the mapped Quarry, City Springs, and Red Hill Faults (and the Sherman Hills Fault where it has been mapped at the surface) indicates splinters and bifurcations and offshoots are likely (see Fig. 1).

Groundwater Contamination

The known and potential contaminant sources of interest to this project are at the surface (or, in the case of septic system leach fields, in the shallow subsurface). Septic systems and specific potential sources of contamination were identified in the project area on Figure 4-2c of the 2008 CAPP and are included on our Figure 1[6]. The routine activities in the Imperial Heights subdivision likely involve opportunities for the introduction of contaminants into the subsurface, e.g. over-application of fertilizers, pesticides, herbicides; inappropriate waste disposal. Finally, the "urban runoff" from Imperial Heights and East Grand Ave. development that enters the drainage north of Imperial Heights and along the Quarry Fault is an obvious source of groundwater recharge to the exposed epsilon member (see Fig. 1).

The "potential sources of contamination" identified in the CAPP were based on certain types of activities known to generate hazardous wastes. There was no evaluation of the actual waste-disposal practices of these operations, nor was any investigation made of whether local groundwater had been in any way impacted. These sources and others like them are simply "potential" in that they are located in areas which, if wastes were released onto or into the ground, could contaminate the Casper aquifer.

The "existing" sources of contamination identified in the CAPP were the septic systems associated with residences in and adjacent to the Casper aquifer recharge area. As noted above, no direct measurements of impact were made, but aquifer "loading" in terms of nitrates entering the groundwater system was estimated using standard rates and concentrations promulgated by

[6]This coverage is a combination of GIS files received from Albany County 8/2014 and the printed figure in the 2008 CAPP.

the Wyoming DEQ (e.g. Chapter 23) (2008 CAPP, App. K). At the assigned factors of 300 gallons of septic system discharge to groundwater per household per day, with a nitrate concentration of 40 mg/l, the 2001 Environmental Advisory Committee estimated a nitrate loading rate of 16.1 kilograms/yr per household[7]. (These calculations were adopted in the 2008 CAPP as App. K.) Long-time University of Wyoming hydrogeology professor and Sherman Hills subdivision resident Peter Huntoon observed, "I have been anticipating [nitrate] hits in Sherman Hills for years" (pers. comm. 2/7/2010).

Nitrates are perhaps the most commonly assessed indicator of groundwater contamination. This is because natural background concentrations are consistently low (0 - 2 mg/l) (e.g. WWC Engineering, 2013), they are a common result of human activity (feedlots, crop fertilization, septic systems), they dissolve into and travel with ambient groundwater, are generally "conservative"[8], and they are inexpensive to analyze. However, and particularly when associated with the broad range of activities and waste disposal associated with rural residential properties, of course, nitrate is but one of many potential contaminants.

For example, Godfrey et al (2007) found various pharmaceuticals in an aquifer beneath septic systems in Missoula, Montana; Seiler et al. (1999) found pharmaceuticals and caffeine in wells in a septic-system served subdivision in Reno, Nevada; Miller et al (2006) found 22 different PPCPs (pharmaceuticals and personal care products) in domestic wells drawing from an aquifer with septic systems in Helena, Montana, concluding, "Low levels of various PPCPs in ground water provide clear evidence that domestic wastewater is a source of contamination." Although it is our understanding that private parties in the subdivisions area have been sampling wells for chlorides, we are aware of no publically-available groundwater analyses beyond nitrates and bacteria that have been made to assess potential contamination of the Casper aquifer in the project area.

Our cursory review of the literature on this topic suggests the conclusion of Seiler et al (1999) has not changed substantially over the subsequent decade's investigations: "The usefulness of caffeine as an indicator of recharge from septic systems is limited because it apparently is not conservative. The usefulness of human pharmaceuticals as indicators also is limited because the presence of pharmaceuticals is unpredictable." (By "not conservative", the authors mean that caffeine, although obviously common in domestic wastewater, is metabolized by bacteria in the septic system and leach field, so only proceeds into the groundwater system in much-reduced concentration.)

The primary value of PPCP testing for this project is the unambiguous association with human activity. Whereas nitrate concentrations as high as 2 mg/l can arguably be assigned to natural

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[7]300 gal/d * 3.79 l/gal * 40 mg/l * 365.25 d/yr = 16.6 million mg/yr

[8]In this context, "conservative" is used to describe chemical constituents that do not react within the aquifer.

sources (some suggest even higher), the natural threshold for PPCPs is zero. Thus, limited analysis of samples from monitor wells most likely to see septic-system impact is suggested.

Nitrate and chlorides remain the most consistently used indicators of septic system input to groundwater. Chlorides are the more conservative of the two, in that there are few natural processes that remove chloride from groundwater, i.e. the concentration is a reasonably straightforward function of input and dilution. Under certain aquifer conditions, nitrates in groundwater are "denitrified" and the nitrogen released as a gas. These conditions only occur when oxygen has been depleted from the system, however, which is unlikely to occur up-gradient from the Turner Wells. Hinkle et al (2009) describe water with 3 - 8 mg/l dissolved oxygen as "well oxygenated" and not subject to denitrification processes. Phelps (2004) found dissolved oxygen concentrations of 1 - 3 mg/l too high to allow denitrification. For comparison, dissolved oxygen concentrations routinely measured in the LCCC monitor well are approximately 10 mg/l. Denitrification is unlikely to play a significant role in the fate of nitrate contamination up-gradient of the Turner Wells.

Nitrogen isotope analysis has been suggested as a way to differentiate the potential sources of higher-than-background nitrate concentrations in groundwater. In situations where there is ambiguity among various potential sources - agricultural operations applying nitrogen fertilizers, animal feedlots, land application of municipal wastewater treatment solids, domestic septic systems, etc. – this may have value, but the sources of nitrates in the Turner Wells recharge area are obvious and limited. Isotopic analysis is not recommended for the initial sampling under this program.

At this point, the primary source of attenuation of contaminants reaching the groundwater in the Casper aquifer appears to be simple dilution.

The 2004 - 2013 average annual production from the Turner Wells was approximately 250 million gallons. Addition of the nitrate loading calculated above, i.e. without other dilution or attenuation, would produce a concentration of 0.02 mg/l per contributing household. As compiled below, there could be as many as 177 septic systems in the Turner Wells contributing area, for a combined nitrate concentration impact of 3 - 4 mg/l. Thus, it is virtually impossible for the routine operation of the current septic systems in the Turner Wells recharge area to increase nitrate concentrations at the wellfield to values approaching the EPA Maximum Contaminant Level. This calculation is consistent with the conclusion of the WWC Engineering report (2013, p. i) that, "Private septic systems east of Laramie do not pose a significant risk of nitrate contamination to the City of Laramie public drinking water supply wells at this time."

The locations of the epsilon and delta subcrops on Figure 1 are based on projection of formation dips discussed above into the area beneath the mantle of Quaternary-age deposits in the Laramie Plains / Sherman Hills subdivisions area. Static water levels are deeper than the alluvial mantle is thick, so septic system effluent is expected to migrate vertically downward until encountering flow-controlling strata in the bedrock formations and/or the water table.

Comparison of the CAPP-mapped locations of domestic septic systems (CAPP Fig. 4-2c) to the projected subcrops in the area provides the following estimation of the receiving strata for septic system effluent[9]:

Satanka Shale	61 systems	e.g. Laramie Plains Subdivision
Casper - epsilon	25 systems	e.g. western Sherman Hills
Casper - delta	70 systems	e.g. eastern Sherman Hills
Casper - gamma	21 systems	e.g. Pilot Peak Estates?

The 12 "potential contaminant sources" identified in the 2008 CAPP (Fig. 4-2c) are along and east of East Grand Avenue, placing them all on or above the Satanka Shale.

Recharge from surface sources will continue approximately downward until either the water table or a relatively low-permeability stratum is encountered. Where the limestone beds separating the various members of the Casper Fm. are intact, they may serve to divert recharge westward, i.e. infiltrating water may travel down dip along the top of the bed. Where those potentially confining limestone beds are broken by fracturing and faulting, however, the opportunity for continued downward migration is provided and deeper members of the Casper may be impacted. Similarly, in areas beneath the water table groundwater locally "trapped" beneath a confining limestone may move upward once a break in that layer is encountered.

Similar pathways through confining beds are provided by unsealed wellbores. The Statements of Completion filed with domestic wells in the project area were reviewed to investigate this situation. For many wells, insufficient information was reported to assess the well seal. For the others, a minority of wells had casings sealed to the water table, many were only sealed for the first 10 - 20 ft., and some are interpreted as having no significant seal at all (i.e. having an open or gravel-filled annulus around the well casing). This included Casper wells that penetrated portions of the Satanka Shale, providing the unsealed annulus as a potential pathway for migration of water from surface sources down into the Casper even in the areas west of Casper outcrop or subcrop.

Two wells reported from just south of the intersection of the Sherman Hills Fault and East Grand Avenue provide an example. An older well (P12798) was reportedly sealed to 50 ft., leaving another 60 ft. of Satanka open to the annulus, as well as the 20 ft. of underlying Casper assumed to be the main source of water. 30 years later, a new well (P99001) was constructed on the same lot, but was properly sealed to the top of the Casper Fm. In the latter well, a nitrate concentration of 9.4 mg/l was measured (Weston, 1995). The authors suggested contamination from the many septic systems to the east of this location may have been to blame for the high nitrates, but an alternate contaminant pathway may have been provided by the older well on the site allowing communication between local surface sources and the underlying Casper.

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[9]The area for this count is east of Vista Drive and north of a line projecting eastward from the I-80 / Grand Avenue interchange.

Consideration of subsurface fracturing and faults and the known commonly poor sealing of domestic wells in the area, indicates that septic systems and surface contaminant sources within the area of the Laramie Plains subdivision are potential contributors to the Casper aquifer despite occurring in the Satanka Shale.

Once contaminants enter the groundwater flow system, dilution occurs through dispersion. This occurs mechanically, as a "mixing" process under groundwater hydraulic gradients, and chemically, as contaminants move in response to concentration gradients. Given that the contaminants of interest enter the groundwater from above, it is reasonable to assume concentrations will be highest (to the extent they vary) in the uppermost saturated portion of the aquifer. Conveniently, vertical groundwater flow is likely naturally upward through most of the area of interest (the westernmost outcrop area) due to the higher elevation of the recharge areas of the lower members of the Casper and the migration of groundwater to the natural discharge points (springs) at the top of the formation.

This suggests that groundwater quality sampling focus on the uppermost portions of the aquifer. As per Figure 2, water levels may vary as much as 25 ft., which should be taken into account to ensure monitor wells are completed with sufficient depth to ensure continuous access to saturated material.

The 2008 CAPP recommended, "that the contaminants listed in the National Primary Drinking Water Standards and National Secondary Drinking Water Standards be monitored for all wells on a yearly basis. The quarterly sampling should include all inorganic compounds and microorganisms on the National Primary and Secondary Drinking Water Standards, petroleum hydrocarbons, conductivity, and temperature. The petroleum hydrocarbons will be used as a surrogate for organic compounds. If a petroleum hydrocarbon is detected, the City should initiate additional organic parameter testing at the impacted well."

We concur with the recommendation that the inorganics on the standards list be included in the initial sampling of the wells to be completed under this project, but believe that analysis for all listed organics may be excessive given the extremely low likelihood of occurrence (e.g. industrial solvents). The recommended broad-spectrum hydrocarbon parameter (e.g. TPH - total petroleum hydrocarbons) is sufficient for initial sampling, with follow-up analyses as indicated.

In addition to analysis for recognized contaminants, we recommend analysis for major cations and anions and Total Dissolved Solids as a basic geochemical signature, and of dissolved oxygen and Total Organic Carbon (TOC) as inexpensive parameters to address denitrification potential.

IV. Monitor Well Evaluation

This section lists the existing monitor wells available to the City potentially in the Turner wells' recharge area and evaluates opportunities for construction of additional wells on property currently under City ownership. For each of the latter wells, specific objectives and recommendations for a construction/testing approach are presented. The final section provides general recommendations for Phase II refinement of well designs and preparation of contract specifications.

A. Existing Wells

Figure 1 includes the existing groundwater monitor wells to which the City has routine access. Table 2 provides summary information. Water levels are consistently measured in the Turner production wells, LCCC MW#1, and Huntoon #1 and #2. Water quality is monitored for EPA Public Water Supply compliance at the Turner wells and for WDEQ compliance at the LCCC well, although in both cases the specific analytes may or may not fully address aquifer contamination concerns. Other wells on the table are available for monitoring, but have not been routinely sampled.

Table 2 - Permanent Casper-Formation Monitor Wells (including production wells)

well	depth (ft)	SWL (ft)	open interval		sources
			ft	strata	
Turner No.1	240	6	98 - 240	epsilon, delta	WWC, 1993; WWC, 1996
Turner No.2	351	flowing	100 - 351	epsilon - gamma	WWC, 1993; WWC, 1996
Huntoon #1	182	105 - 130	142 - 180	gamma	Lundy, 1979
41T2	554	30	90 -	delta - alpha	WWC, 1996
LCCC MW#1	210	15	140 - 210	epsilon, delta	Wyoming Groundwater, 2006
41T3	240	68	30 - 240	Satanka, epsilon	WWC Eng., 2006; Wyoming Groundwater, 2014
SHFCA-1	360	20	308 - 360	epsilon, delta	WWC, 1997
LAPCA - 1	475	+44	403 - 475	epsilon, delta	WWC, 1997
LaPrele No. 1	880	+46	400 - 880	epsilon - beta	WWC, 1997

Figure 4 included points for which water levels have been carefully measured in association with past studies. The 2009/2010 nitrate sampling involved 115 wells in the recharge area for the various city wellfields. (Exact locations for those wells is confidential.) Finally, there are some 233 water wells of record for the project area. With the exception of the wells on Figure 1, all of these potential groundwater monitoring points are in private ownership and may or may not be available for future use at the discretion of the owners.

The following paragraphs discuss specific existing wells relevant to the citing of additional monitor wells for this project. All of the wells on Figure 1 remain of interest and should be considered in future monitoring programs.

41T2. This well was drilled in 1941, but was never used due to anticipated interference with flows from City Springs. The well is cased and sealed to a depth of 90 ft. and completed open-hole through the small remaining thickness of the delta member and the underlying gamma, beta, and most of the alpha members of the Casper. The reported static water level of 30 ft. indicates approximately 70% saturation of the delta and of all lower members. (The sealing of the casing to 90 ft. precludes sampling directly at the water table.)

The well has a reported specific capacity of 52 gpm/ft (WWC, 1995). This is relatively high, particularly for the lower members of the Casper Fm. to which it is open, likely reflecting the enhanced permeability of its location along the fracture system associated with the Quarry Fault.

A five-day pump test of the Turner No. 1 well (1600 ft away) at 2100 gpm, produced 9.4 ft. of drawdown in the 41T2 well, over 1/3 of the drawdown of the test well itself (WWC, 1993). High permeability and ready communication along the Quarry Fault was demonstrated. Most interesting is that when the alpha member of the Casper Fm. was isolated for pumping in the 41T2 well (WWC, 1996), drawdown was observed at the Turner wells, but not in the upper members of the Casper Fm. at the 41T2 well itself.

Video logging of 41T2 in 1994 observed "abundant borehole fractures from 55 - 64 feet with a large vertical facture intersecting the wellbore from 56 - 63 ft.", i.e in the delta member. But the video also observed "large fractures" in the "sandstone intervals" of the alpha member at 411-419 feet and 488 - 504 feet (WWC, 1996; p. 4).

With respect to groundwater flow, the location of the 41T2 well in or just north of the Quarry Fault system should provide opportunity for sampling the head in the aquifer along the fault. With respect to groundwater quality, the well is exposed to recharge from a broad area of undeveloped land to the east and northeast, but also to recharge directly to the epsilon member along a drainage that receives surface runoff from the Imperial Heights subdivision, East Grand Avenue, and the Staples parking lot. Although unlikely to experience input from the area of septic systems to the southeast, this well may be a candidate for analysis of "urban runoff" components of potential contamination.

This location is similar to the "Turner MW-1" monitor well suggested in the 2008 CAPP, which was placed 0.5 miles farther east along the fault zone and thought to be within an approximately 1-year travel time of the Turner wells to "provide an early warning if contamination occurred". This location ideally fits the recommendation from the 2013 WWC Engineering study (p. 10), "For monitoring related to the Turner Wellfield, at least one well should be sited along or immediately south of the Quarry Fault and between 1/4 and ½ mile east of the Turner wells. ... Given the density of existing development near the City, this monitoring location would be the highest priority."

LCCC. There are four Casper Fm. wells on the Albany County campus of Laramie County Community College (LCCC). These were drilled in 2005 as part of a geothermal heating system for the facility (Wyoming Groundwater, 2006). The wells vary between 210 and 263 ft. in depth; all are completed open-hole through the epsilon member and into the delta member of the formation. Groundwater is withdrawn from one of two withdrawal wells, run though a heat exchanger, and injected into an injection well approximately 250 ft. away. Because the system is closed (all water returned to aquifer) no significant impacts on aquifer hydraulic relationships beyond the immediate area are likely, nor is the extraction of low-temperature heat anticipated to significantly impact groundwater chemistry.

The fourth well, LCCC MW#1, is used to monitor groundwater quality under the terms of the Wyoming DEQ permit for the system. Initial contacts with LCCC indicate this well could be made available for permanent monitoring as part of the City of Laramie monitor well network.

With respect to groundwater flow, this well is in a location that would monitor water levels along potential flow lines converging on the Turner Wells from the southeast, i.e. south of the Quarry Fault system and in the direction of the sources of potential contamination associated with development along East Grand Avenue Similarly, the well taps the upper members of the Casper Fm., the members most vulnerable to contamination from surface sources and the members through which the bulk of Casper Fm. water is thought to travel.

B. Additional Monitor Wells

In order to move forward with the Casper aquifer monitoring program with minimum delay, the utility of new monitor wells constructed on city-owned property is evaluated below. This will eliminate the time and expense associated with negotiation of purchase or access agreements and will ensure long-term continuity of water level and water-quality data.

Figure 7 presents September 2014 ownership status for the area of interest. City-owned property consists of: 1) Gateway Park; 2) the area immediately north across Grand Avenue; 3) an area informally termed the "triangle" at the intersection of Vista Drive and Grand Avenue; 4) the Imperial Heights Park just northeast of the Sherman Hills subdivision; and 5) a number of lots slated for development in the Turner Tract. The last of these is not available for permanent occupancy by city facilities. The others are likely to remain in city ownership indefinitely and are discussed here. Figure 7 includes recommended locations for three new monitor wells.

Fine-tuning of locations in consideration of drill rig access, utility lines, test discharge geometry, etc. will be accomplished along with construction specifications in Phase II of this project.

1. Imperial Heights Park

This location is of interest for two reasons: 1) it is the southeastern-most location within the City of Laramie boundary that is projected to remain undeveloped (due to being dedicated as a public park); and 2) it potentially spans the important Sherman Hills Fault.

The 2013 WWC Engineering study repeated the suggestion of their 1993 work that, "groundwater flow patterns near the Sherman Hills Fault restrict northward movement of groundwater from areas of highest septic system density and instead carry the groundwater generally west ...". This interpretation is of obvious interest to the City and to the residents of those "areas". A focused data collection effort is appropriate.

The nearest existing monitoring opportunity (beyond periodically available measurements from private wells) is the Huntoon #1 well, 1500 ft. to the east, on the south side of the fault. This land is not on public property, nor is there opportunity for a public-property companion well on the north side of the fault at this location.

Placement of monitor wells on both sides of the fault provides opportunity for testing the important issue of the hydraulic connection between the two sides.

North Well. A north-side well would encounter the top of the delta member immediately beneath shallow unconsolidated deposits. There is no existing well that is representative of this location. Based on the mapped geology, the delta member of the Casper would be fully penetrated within approximately 100 ft, and the gamma member at approximately 180 ft. Assuming hydraulic equilibrium across the fault, the water level would be approximately the same as in the south side well, i.e. around 90 ft. For this well, that would place first saturation near the top of the gamma member.

By imposing significant drawdown on the north side of the Sherman Hills Fault, this well would represent an extreme form of the Turner Wells, i.e. a sort of bringing of the wellfield up to the fault. The only historical precedent for such a test is that reported by Banner (1978). In that test, the 41T1 well was pumped at a rate of 1250 gpm for 51 days. The Huntoon #1 well was monitored for drawdown. The authors concluded that "the observation well was affected" (approximately 1 ft. is suggested by the provided data), but found the impacts to have been obscured by the larger drawdown cycles created by nearby domestic wells. They also observed, "this could be due to boundary effects from the Sherman Hills fault" (p. 20).

At the northward dip discussed above, the fault plane would be encountered 40 ft. further north for each 100 ft. in depth. Thus, to achieve the objective of completing this well entirely on the north side of the main fault, a location as far north on the park property as possible is recommended. There appears to be sufficient room for well construction on the north side of the small drainage bounding the Imperial Heights subdivision, and this is projected to be sufficiently far north to avoid intersection of the plane of the fault.

As the Sherman Hills Fault is projected to juxtapose saturated delta member (south side) against saturated gamma member (north side), the expected lower permeability of the gamma may inhibit cross-fault migration of groundwater. If the fault itself provides the expected high-permeability pathway, groundwater flow may be diverted westward down the fault until the saturated delta and epsilon members become available on the north side to accept groundwater moving northwestward out of the fault zone. This would occur west of Grand Avenue.

The objectives for the north-side well would be: 1) long-term water-level measurement; 2) pumping at sufficient rate and duration to generate a response in the companion well across the fault; 3) long-term assessment of groundwater quality in a portion of the aquifer which may be isolated from significant sources of contamination; and 4) evaluation of the permeability of the gamma member of the Casper in isolation.

Construction / Sampling Recommendations:

- This well should be drilled first (of the north-south pair at this site) to clarify local stratigraphy. Unlike the south well, the north well will start at a point certain, i.e. the top limestone of the delta member, and thus provide a detailed log of Casper Fm. layering in the immediate area.

- Borehole and casing size should accommodate a 6-inch pump to allow discharge of 200+ gpm during testing to adequately stress the aquifer and cross-fault permeability characteristics. This will require a minimum finished diameter of 8 inches, e.g. 9-7/8 inch borehole drilling.

- 12-inch surface casing should be installed and cemented in place to a depth of 20 ft. (more if conditions warrant) to preclude concern with contamination from the immediate surroundings

- The well should be drilled with air / foam circulation if possible to facilitate examination of water levels and water quality as drilling proceeds. The surface casing recommendation is oversized somewhat to accommodate the possibility of needing to telescope multiple casings to control caving conditions without having to resort to mud drilling.

- A tentative depth of approximately 200 ft. is recommended to verify local stratigraphy and to allow evaluation of potential water level and water quality differences between the delta, gamma, and beta members. Additional depth may be required to achieve a production goal of 200+ gpm.

- "First water" should be discretely sampled, and an equilibrated water level measured before drilling continues. Similarly, composite water quality and level should be sampled beneath each potentially confining bed penetrated.

- Provision should be made for geophysical investigations (e.g. by WyCEHG) prior to well completion, e.g. video and "spinner" logging to assess borehole conditions.

- Testing would follow construction of the "south" well of this pair, and should allow for a potential 2-phase approach (delay in between) depending on the response monitored in the "south" well.

- Test water disposal will be an issue for this site, in that rapid infiltration through the surficial deposits and underlying epsilon member could provide recharge within the period of testing. Transmission of test discharge westward far enough to overlie a significant thickness of Satanka Shale is strongly recommended. (There are four culverts under East Grand Avenue where it intersects drainages from the Imperial Heights Park.)

- Final well completion should be based on the results of drilling, water-quality analysis, geophysical logging, and pump testing. It may be desirable to seal the lower portion of the hole to establish long-term monitoring focused on the uppermost water-bearing strata. It may be desirable to complete the well open to the water table to provide sampling of the top of the groundwater column, with adequate provision for seasonal and long-term variations in depth-to-water.

South Well. A south-side well should be exposed to groundwater recharge from the northern portion of the Sherman Hills subdivision and, when paired with the existing Huntoon #1 well, a valid assessment of the east-west component of the groundwater gradient along the south side of the fault. A well at this location is anticipated to penetrate 10 - 20 ft. of unconsolidated material before hitting either the bottom-most strata of the Satanka Shale or the top of the epsilon member of the Casper. Full penetration of the epsilon member should occur within 80 ft. of the surface, and of the delta member within 180 ft. A static water level of 90 ft is indicated by the experience of domestic wells in the area, i.e. groundwater would be first encountered near the top of the delta member.

This location is comparable to the "Turner MW-5" monitor well suggested in the 2008 CAPP, which was placed in the northwest corner of the Imperial Heights neighborhood and thought to be within an approximately 1-year travel time of the Turner wells to "provide an early warning if contamination occurred".

The objectives for the south-side well would be: 1) long-term water-level measurement; 2) monitoring response to pumping of the companion well across the fault; 3) long-term assessment of groundwater quality at the periphery of a cluster of potential contaminant sources; 4) assessment of the locally confining character of the top-of-delta limestone with potential implications for contaminant transport.

Construction / Sampling Recommendations:

- Borehole and casing size need only accommodate a sampling pump. To maintain flexibility in drilling, a conventional "domestic" well is recommended, i.e. 5-inch casing.

- 10-inch surface casing should be installed and cemented in place to a depth of 20 ft. (more if conditions warrant) to preclude concern with contamination from the immediate surroundings

- The well should be drilled with air / foam circulation if possible to facilitate examination of water levels and water quality as drilling proceeds. The surface casing recommendation is oversized somewhat to accommodate the possibility of needing to telescope multiple casings to control caving conditions without having to resort to mud drilling. The relatively open cementation of the epsilon member is locally observed in problematic sand production in the construction of some wells.

- A tentative depth of approximately 280 ft. is recommended to allow evaluation of potential water level and water quality differences between the epsilon, delta, gamma, and beta members.

- "First water" should be discretely sampled, and an equilibrated water level measured before drilling continues. Particular attention should be paid to the bottom strata of the epsilon member, as local recharge may be accumulated on top of the uppermost delta-member limestone. Similarly, composite water quality and level should be sampled beneath each potentially confining bed penetrated.

- Provision should be made for geophysical investigations (e.g. by WyCEHG) prior to well completion, e.g. video and "spinner" logging to assess borehole conditions. "Spinner" logging during pumping of the "north" well should be considered to assist identification of the most active groundwater flow strata.

- Provision should be made for possible partial completion to provide monitoring response to test pumping of the "north" well before and after sealing lower members open to the well.

- Final well completion should be based on the results of drilling, water-quality analysis, geophysical logging, and pump testing. It may be desirable to seal the lower portion of the hole to establish long-term monitoring focused on the uppermost water-bearing strata. It may be desirable to complete the well open to the water table to provide sampling of the top of the groundwater column, with adequate provision for seasonal and long-term variations in depth-to-water. Such a limited completion may also serve to reduce purging needs for future sampling and to avoid deeper strata dominating the sampled groundwater quality.

2. Gateway Park

This location is of interest primarily because of its proximity to the Turner wells. Groundwater moving into the production-well area from the east, e.g. along the Quarry Fault, could be monitored for water-quality parameters to detect changes before impacting the city wells.

A well at this location would be expected to experience approximately the same conditions (geology, water level) as the LCCC wells discussed above. Midway between the 41T2 well and the LCCC MW#1, however, a Gateway Park location is more ambiguous than either one in that it could receive groundwater both from the east, associated with flow controlled by the Quarry Fault system, and from the southeast, associated with inflow controlled by the Sherman Hills Fault and potentially exposed to contamination from south of that fault.

In the absence of the 41T2 and LCCC alternatives, the objectives for a well at this location would be: 1) long-term water-level measurement, and 2) long-term assessment of groundwater quality in an area likely contributory to the Turner Wells. This could best be accomplished by locating a well in the far southeast corner of the property, in order to provide separation from the Quarry Fault and sufficient distance from the Turner Wells to provide something of an "early warning system". The most useful completion would be in the uppermost Casper Fm, i.e. the epsilon member at this location, as the zone most likely to carry surface-sourced contaminants.

However, the location potentially in a relatively undisturbed block of the aquifer may provide opportunity during drilling to investigate head and water-quality differences between members.

3. "Triangle"

This location is of interest as intermediate between the potential sources of contamination in the east Grand subdivisions and the Turner wells. It should encounter groundwater flow components from the undeveloped areas to the east, between the Sherman Hills and Quarry faults, and, depending on the hydraulic effects of the Sherman Hills Fault, from the long-developed area to the southeast. It should also provide valuable data on local groundwater gradients for comparison to those estimated for the more well-rich area south of the Sherman Hills Fault.

Geologic structure in this area is obscure. The only nearby well of record is that for the Premier Bone & Joint Clinic, for which the following log was submitted:

0 - 25 ft.	sand & limestond; cementing pieces
25 - 30 ft.	red shale
30 - 36 ft.	sandstone
36 - 140 ft.	lost circulation - waterbearing perforated

The groundwater level reported for the well was 64 ft., so there was no description provided for the water-bearing portion of this hole. The occurrence of lost circulation is generally indicative of productive aquifer material, although the loss may have occurred in the unsaturated portion of the hole.

Based on the location of the well with respect to our Figure 6 schematic, it would first encounter a small thickness (<20 ft.) of Satanka Shale, then a full section of the Casper Formation. A static water level comparable to the Premier Bone & Joint well would provide saturation of the lowest portion of the epsilon member and of all lower members.

The reported specific capacity for the well was a modest 40 gpm/30 ft. (i.e. 1.3 gpm/ft), which is consistent with the projected strata and a location relatively undisturbed by fracturing associated with area faults and folds. If so, this location may provide opportunity to assess the confining nature of the member-separating limestone strata through careful observations of water levels during drilling.

Construction / Sampling Recommendations:

- Given the restricted character of this site, careful utility locates should be a part of final well siting to preclude conflicts during construction and long-term monitoring.

- Borehole and casing size need only accommodate a sampling pump. To maintain flexibility in drilling, a conventional "domestic" well is recommended, i.e. 5-inch casing.

- 10-inch surface casing should be installed and cemented in place to a depth of 20 ft. or completely through the Satanka Shale, whichever is greater, to preclude entry of Satanka water during subsequent drilling and to preclude concern with contamination from the immediate surroundings.

- The well should be drilled with air / foam circulation if possible to facilitate examination of water levels and water quality as drilling proceeds. The surface casing recommendation is oversized somewhat to accommodate the possibility of needing to telescope multiple casings to control caving conditions without having to resort to mud drilling.

- A tentative depth of approximately 200 ft. is recommended to provide observation of local stratigraphy and evaluation of potential water level and water quality differences between the epsilon, delta, and gamma members.

- "First water" should be discretely sampled, and an equilibrated water level measured before drilling continues. Particular attention should be paid to the bottom strata of the epsilon member, as local recharge may be accumulated on top of the uppermost delta-member limestone. Similarly, composite water quality and level should be sampled beneath each potentially confining bed penetrated.

- Provision should be made for geophysical investigations (e.g. by WyCEHG) prior to well completion, e.g. video and "spinner" logging to assess borehole conditions. "Spinner" logging during pumping of the "north" well or the municipal Turner wells should be considered to assist identification of the most active groundwater flow strata.

- Provision should be made for possible partial completion to provide monitoring response to test pumping of the "north" well before and after sealing lower members open to the well.

- Final well completion should be based on the results of drilling, water-quality analysis, geophysical logging, and pump testing. It may be desirable to seal the lower portion of the hole to establish long-term monitoring focused on the uppermost water-bearing strata. It may be desirable to complete the well open to the water table to provide sampling of the top of the groundwater column, with adequate provision for seasonal and long-term variations in depth-to-water. Such a limited completion may also serve to reduce purging needs for future sampling and to avoid deeper strata dominating the sampled groundwater quality.

4. "Background"

Although not part of the immediate monitor well construction program, a well specifically sited to provide "background" water quality should be considered. Despite the clear association of the frequency of elevated nitrate values with areas of higher septic system density, there remains controversy about Casper aquifer contaminant levels (e.g. nitrates) in the absence of any significant development. With respect to the Turner wells, locations along major fracture systems converging from the east and northeast are suggested. The entirety of Section 36, directly east of the Turner wells, is State of Wyoming property, perhaps facilitating permanent access. That Section includes the Quarry Anticline and the City Springs Fault (see Fig. 1), neither of which has significant up-gradient development to source contaminant input to recharge.

The objectives for such a well would be: 1) long-term water-level measurement; and 2) long-term assessment of "background" water quality.

C. General Construction and Testing Recommendations

Our recommendation for Phase II of this project is to proceed with construction of two monitor wells at the Imperial Heights Park site, and one monitor well at the "Triangle" site. In addition to the well-specific criteria presented above, we recommend Phase II include:

1. Provision for a combined "lump sum" and "time and materials" well construction and testing contract. This will require flexibility on the part of the contractor, but will allow an adaptive response to maximize the information obtained from the well-construction program. To be refined in Phase II, our initial view is the following contract items are appropriately offered on a "lump sum" basis:

- overall mobilization / demobilization
- mobilization between sites
- furnish and install test pumping equipment
- furnish and install pump discharge piping

and the following items are appropriately priced on a unit basis:

- hourly rate for borehole drilling
- hourly rate for well construction and misc. work
- hourly rate for air-lifting / well development
- hourly rate for standby time, e.g. waiting on water-level equilibration

2. Provision for construction pauses to accommodate laboratory analyses (local lab can provide 1-day turnaround for nitrates) and geophysical logging (e.g. WyCEHG) to inform final well completion design.

3. Provision for full-time monitoring of well construction by a professional geologist thoroughly familiar with project objectives and concerns.

4. Provision for field testing of nitrates to assist ongoing decisions on construction and sampling.

5. The Phase II construction and testing program should include detailed documentation and sufficient written analysis of "lessons learned" regarding such issues as fault and stratigraphic control of groundwater flow and of contaminant distribution to guide future monitor well siting and construction. The Phase II program should also include recommendations for the appropriate degree of long-term monitoring/sampling of all available wells. For example,

periodic synoptic measurement of water levels should be undertaken to better define flow gradients and directions.

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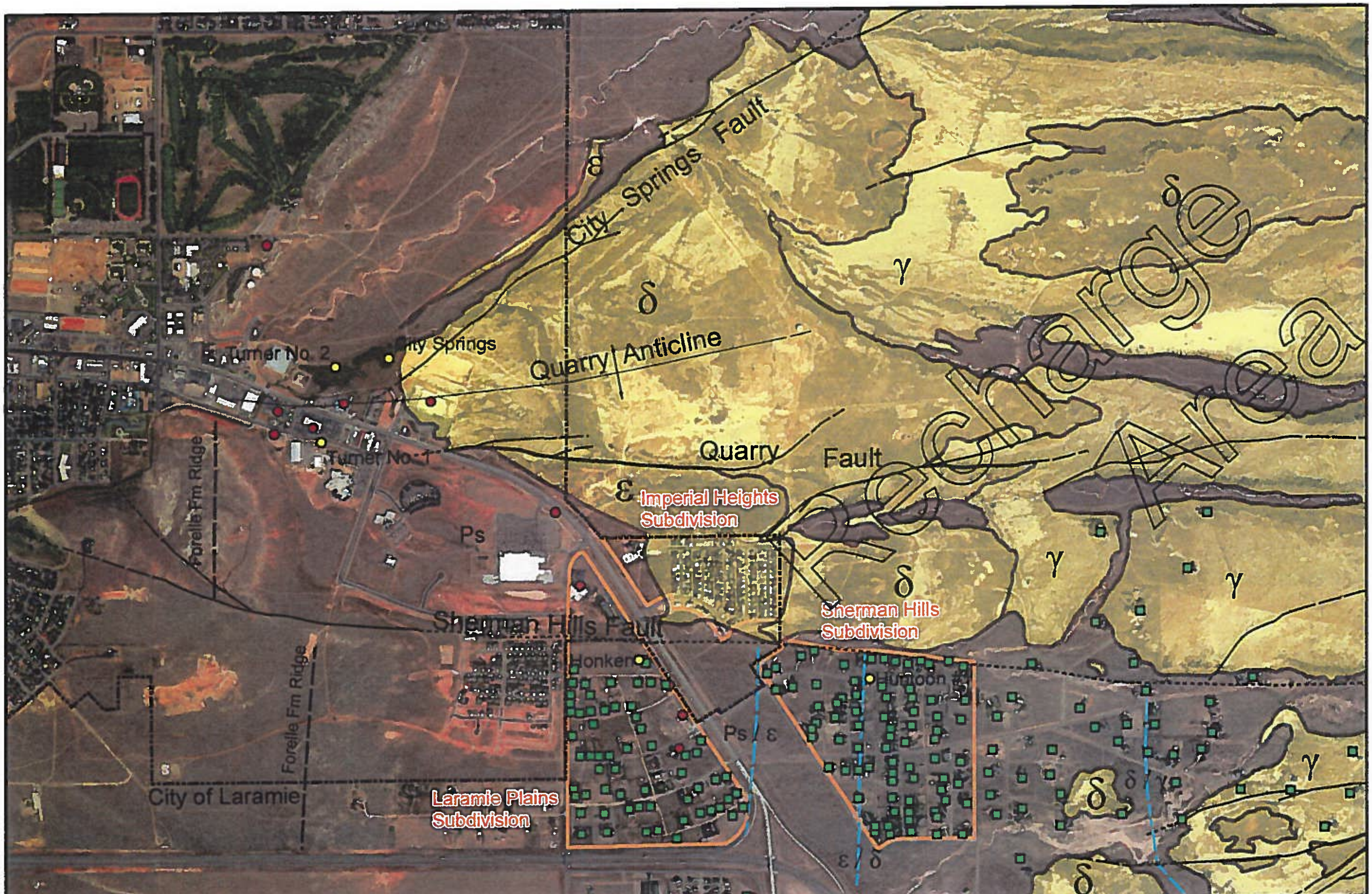


■ Septic Systems (2008 CAPP)
● Potential Contamination Sources (2008 CAPP)
-- Buried Contact

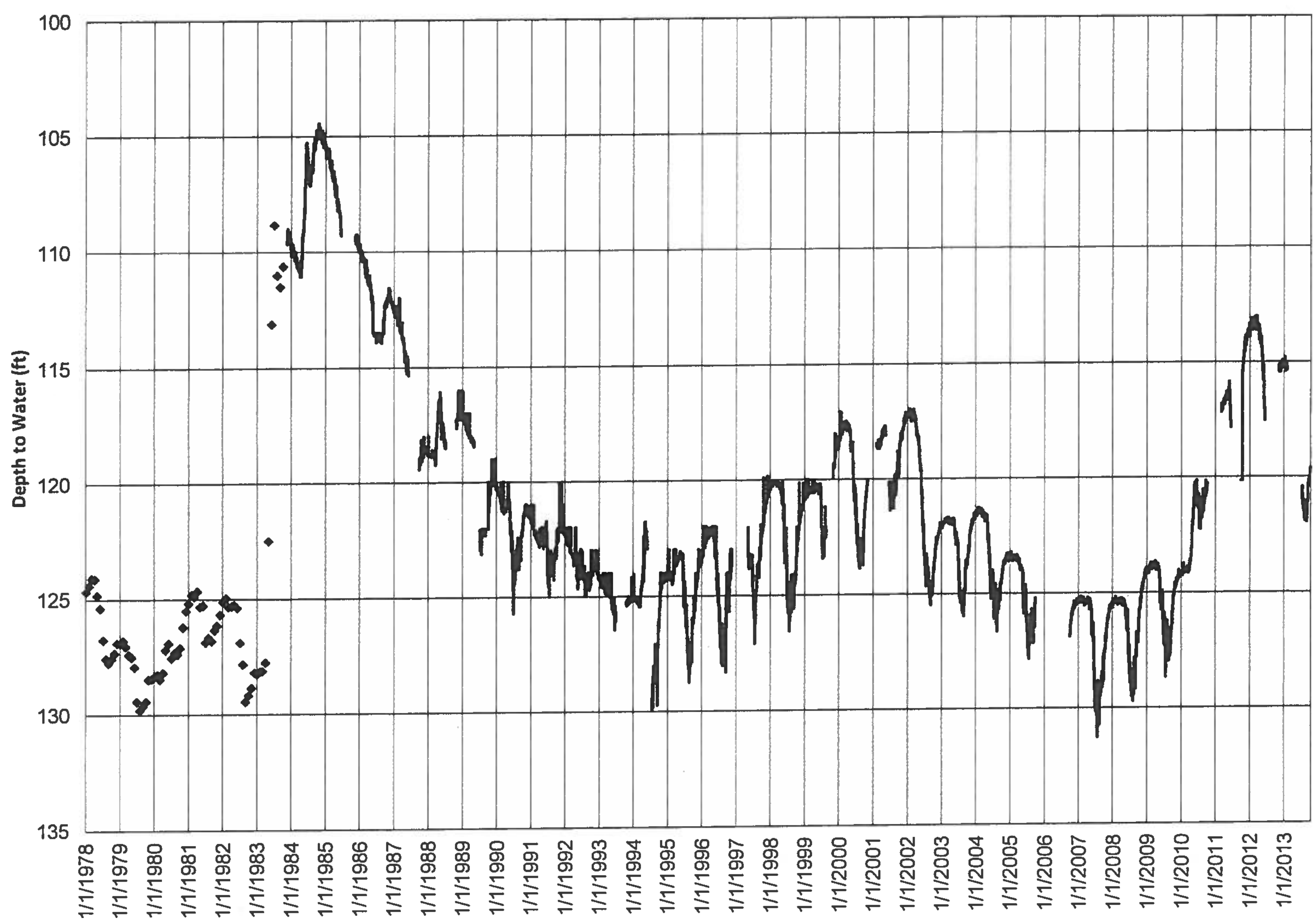
Ps - Satanka Shale
Casper Formation Members:
ε - Epsilon
δ - Delta
γ - Gamma

(Geology modified after VerPloeg, 2009)

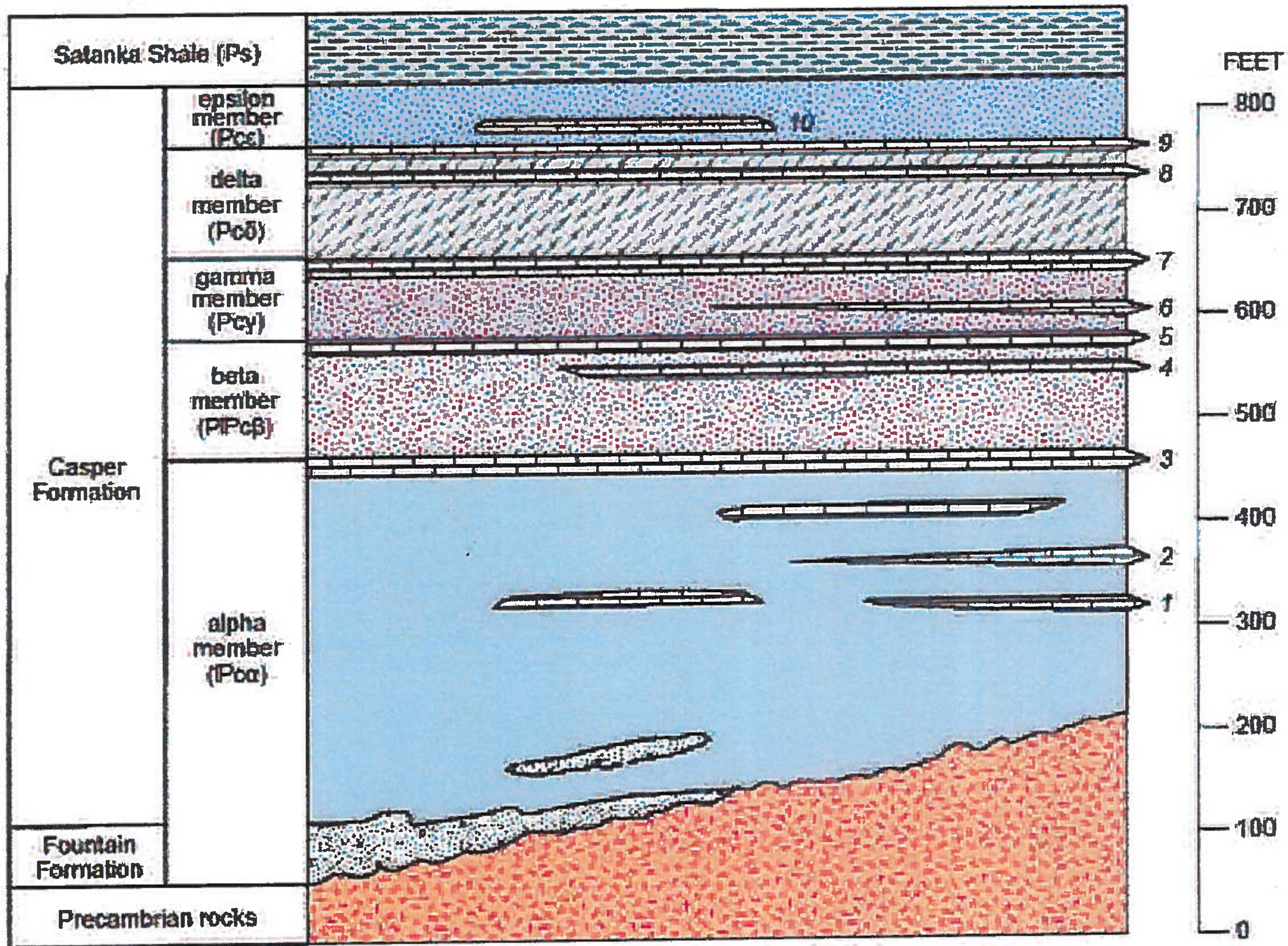
0 1,000 2,000 Feet

Figure 1 - Location Map
City of Laramie
Casper Aquifer Monitoring Program

Figure 2 - Huntoon No. 1 Water Levels



Schematic relationship between Lundy's (1978) informal members of the Casper Formation and the Casper limestones (1-10) as defined by Benniran (1970) in the vicinity of Laramie, Wyoming. Map area falls within diagram, but not all units crop out in the map area.



Source: VerPloeg, 2009

Figure 3 - Casper Formation Stratigraphy

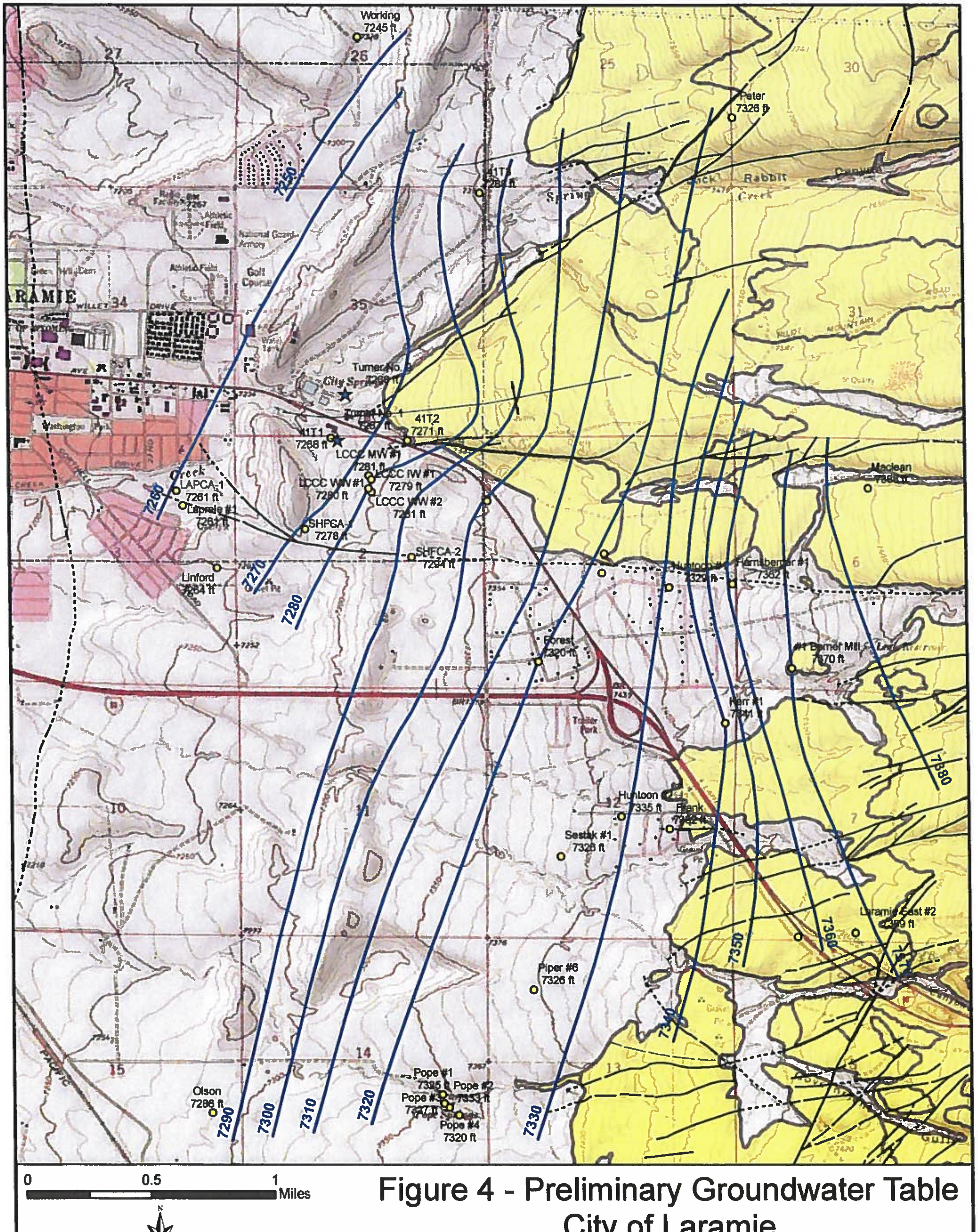


Figure 4 - Preliminary Groundwater Table
City of Laramie
Casper Aquifer Monitoring Program

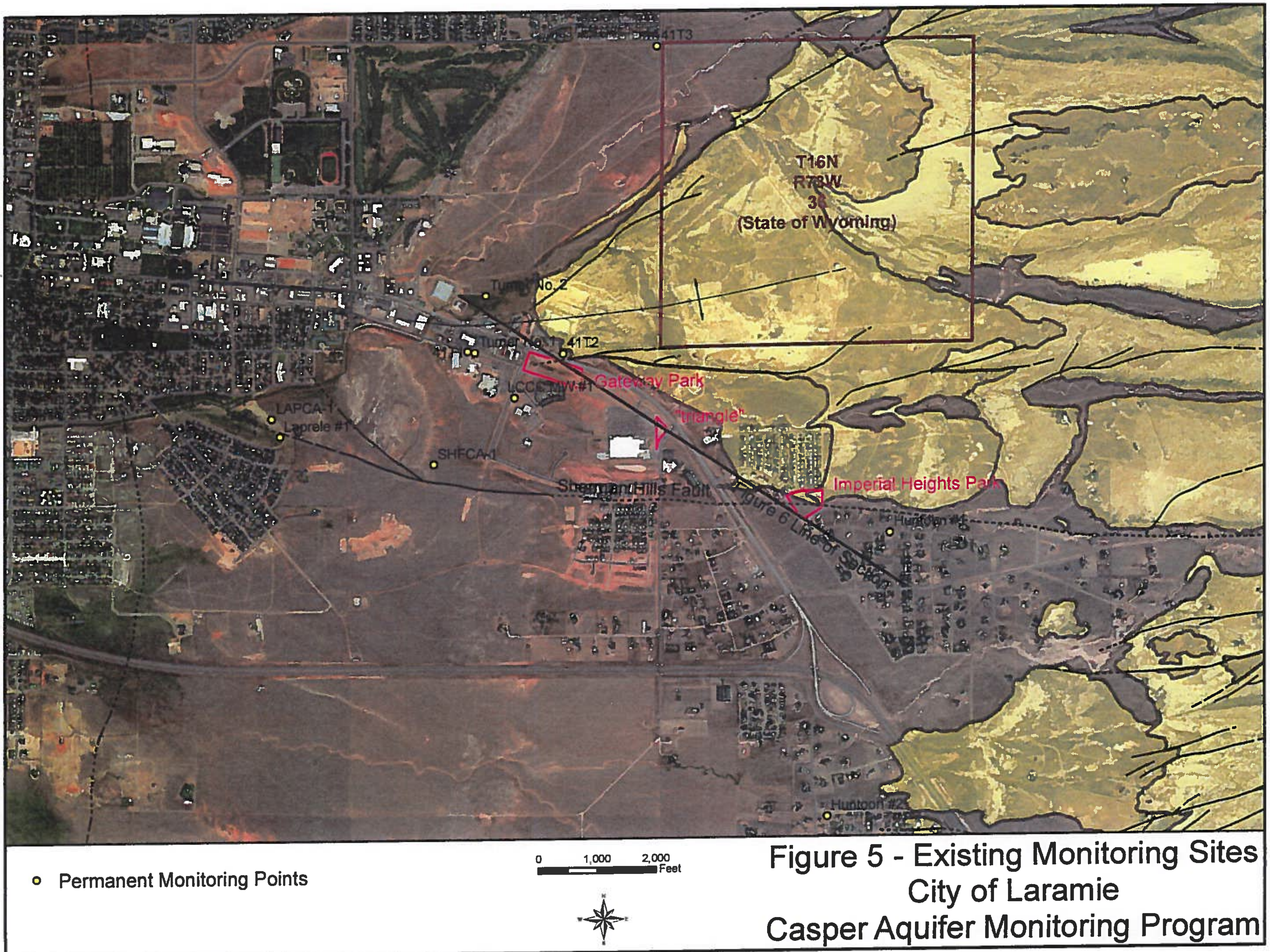


Figure 5 - Existing Monitoring Sites
City of Laramie
Casper Aquifer Monitoring Program

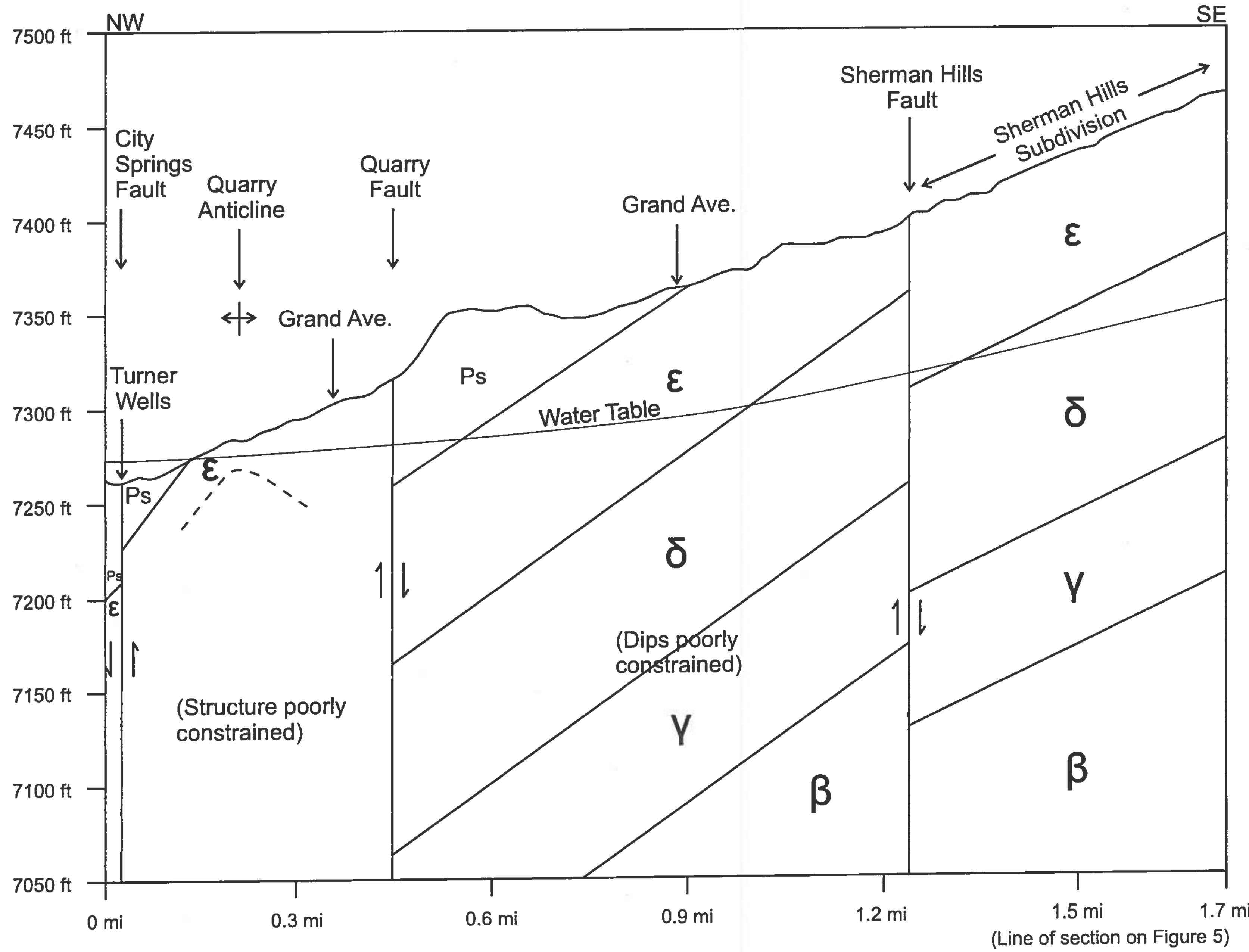


Figure 6 - Schematic Geologic Cross-Section

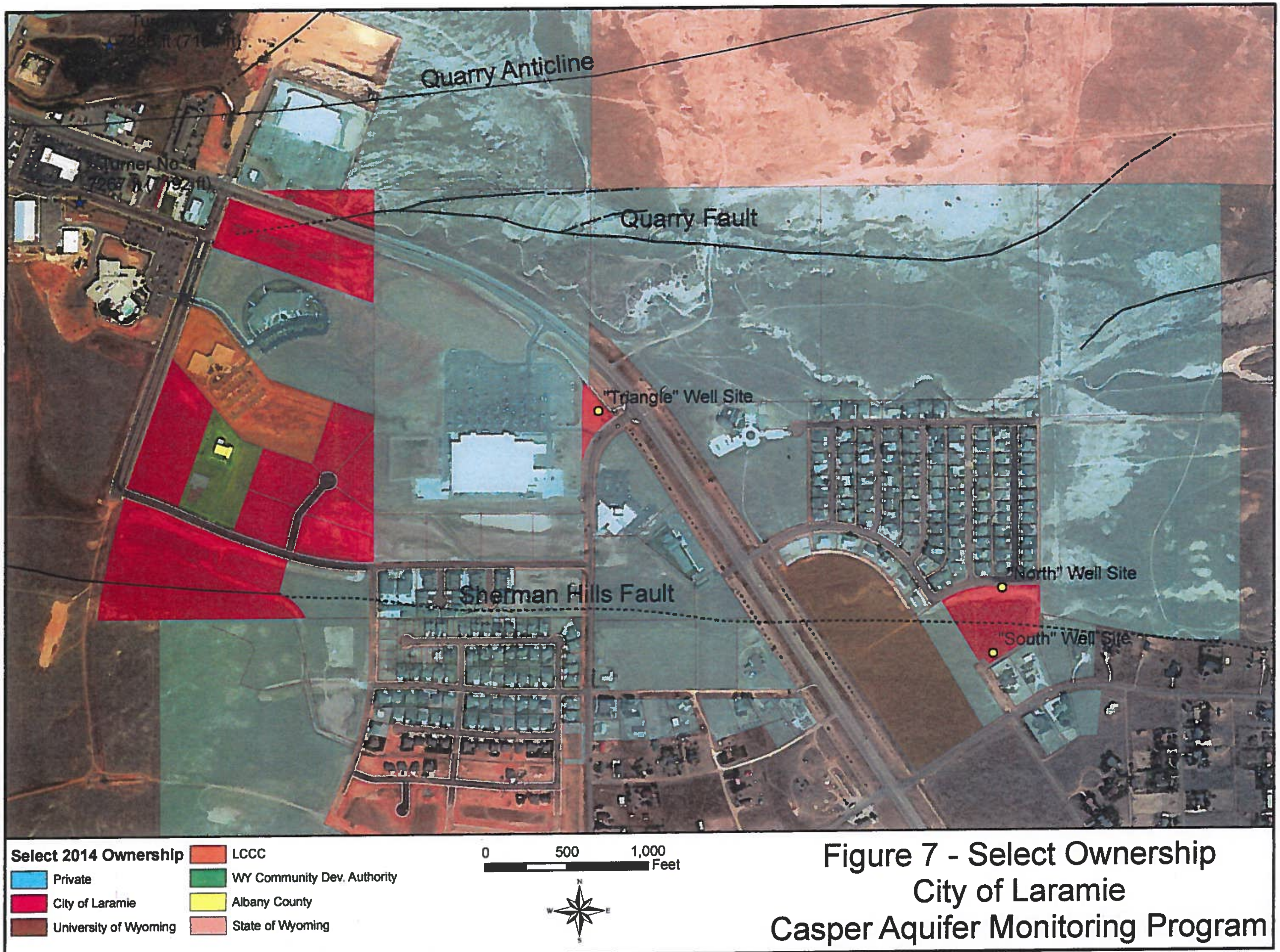


Figure 7 - Select Ownership
City of Laramie
Casper Aquifer Monitoring Program

Wyoming Center for Environmental
Hydrology and Geophysics

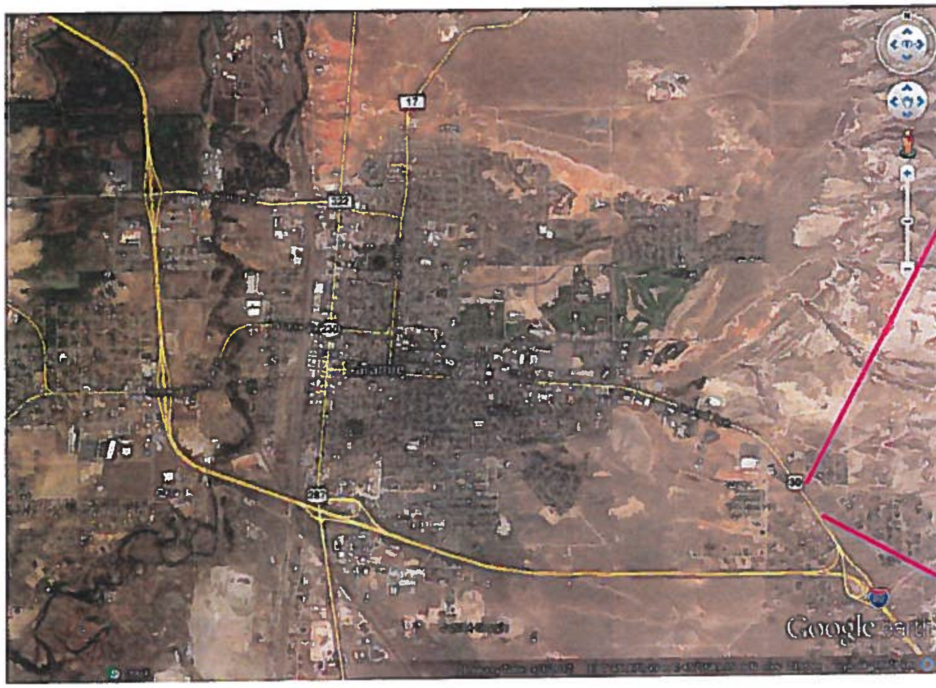
Geophysical Site Characterization of the Sherman Hills Fault zone Laramie, Wyoming

October, 2014

Brad Carr, Ph.D. – WyCEHG

Purpose:

To geophysically image the E-W oriented Sherman Hills Fault zone near the Imperial Heights neighborhood of Laramie, Wyoming.

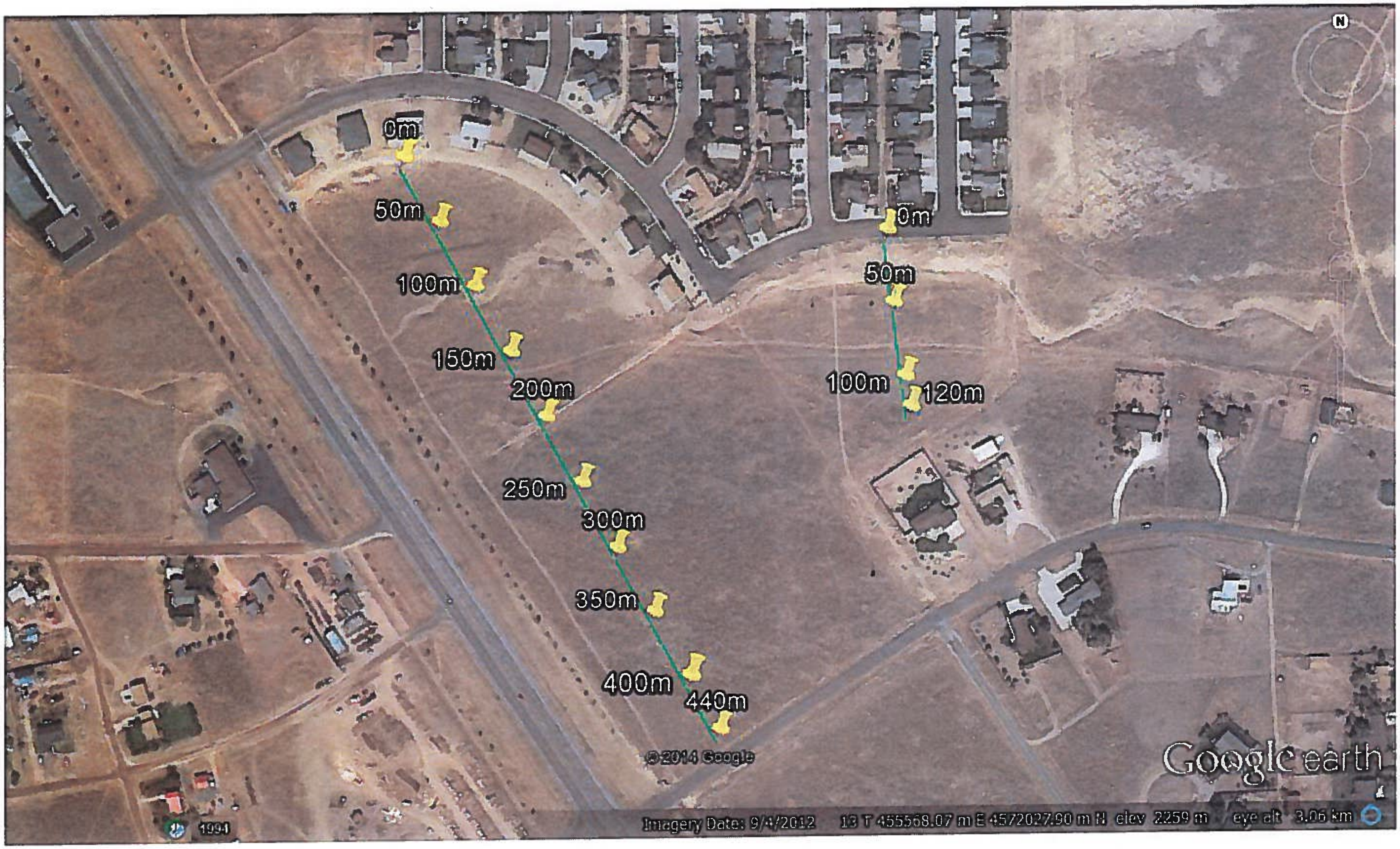


Site Profiles:

– Line 1 Acquired Oct. 2, 2014
– Line 2 Acquired Oct. 7th, 2014

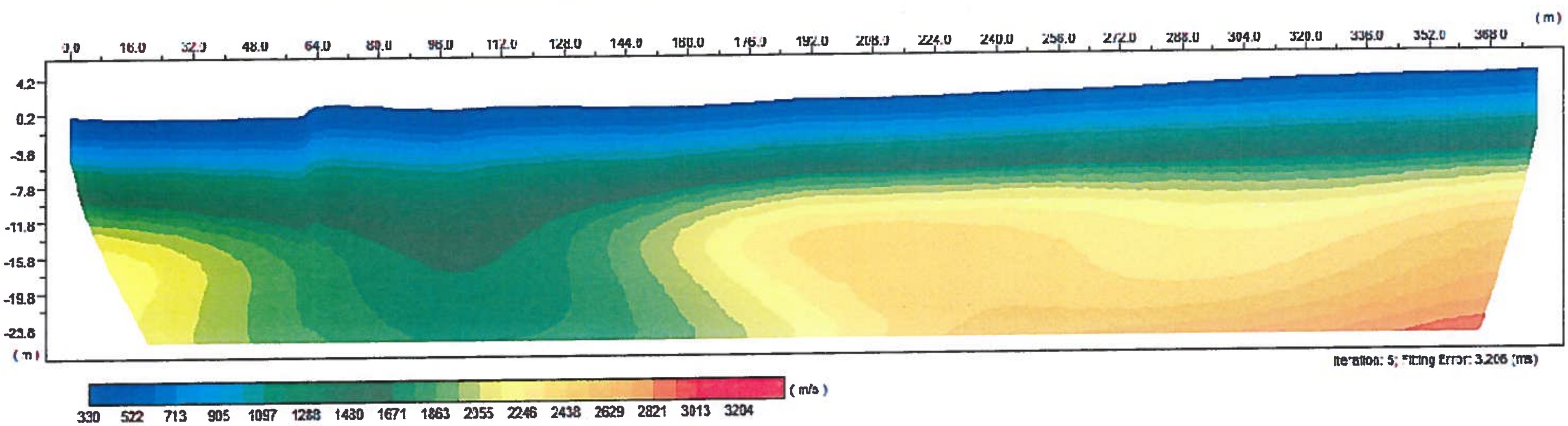
Line 1 data acquired on UW Foundation property
Line 2 data to be acquired on City of Laramie property

Line 1 & Line 2 locations and distances along profile (m) from differential GPS



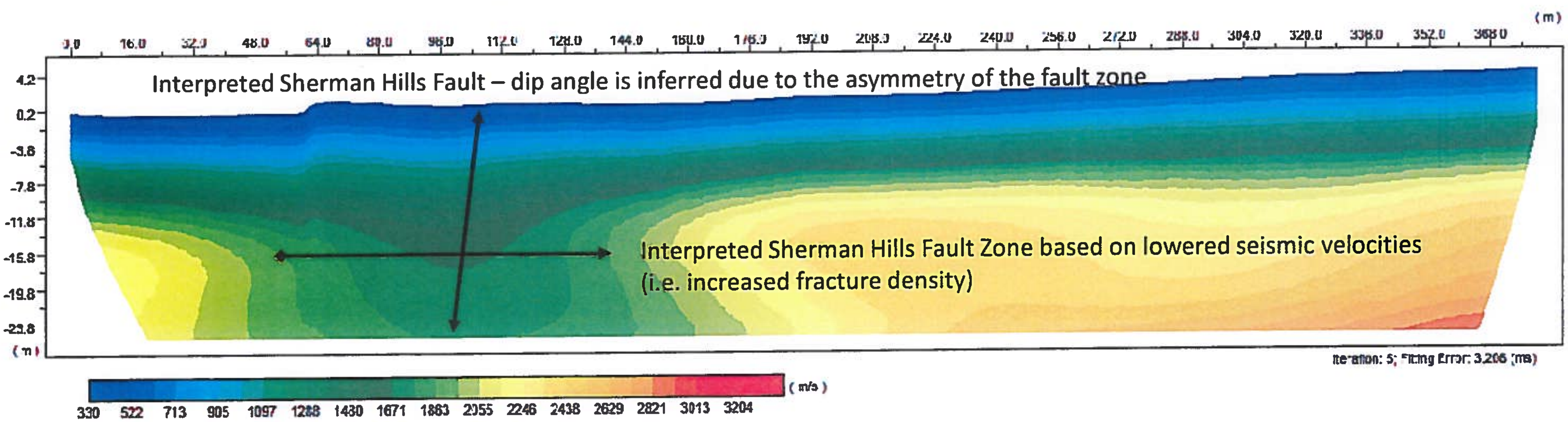
Line 1 Seismic Refraction Data w/out Interpretation

Sherman Hills_Line 1_Oct. 2_2014 Inverted Refraction Section (North to South)



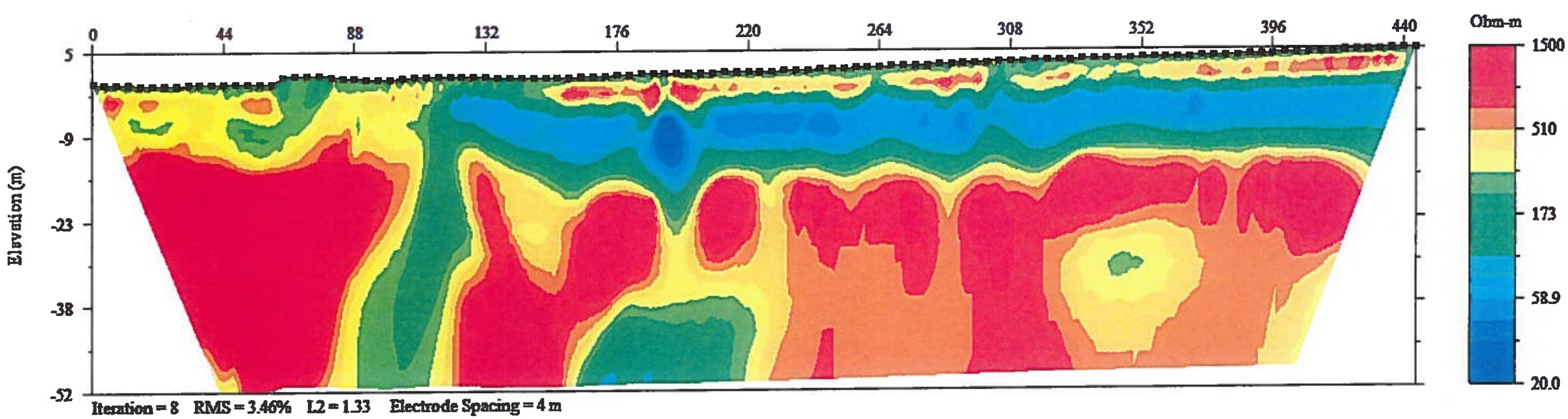
Line 1 Seismic Refraction Data with Sherman Hills Fault Zone Interpretation

Sherman Hills_Line 1_Oct. 2_2014 Inverted Refraction Section (North to South)

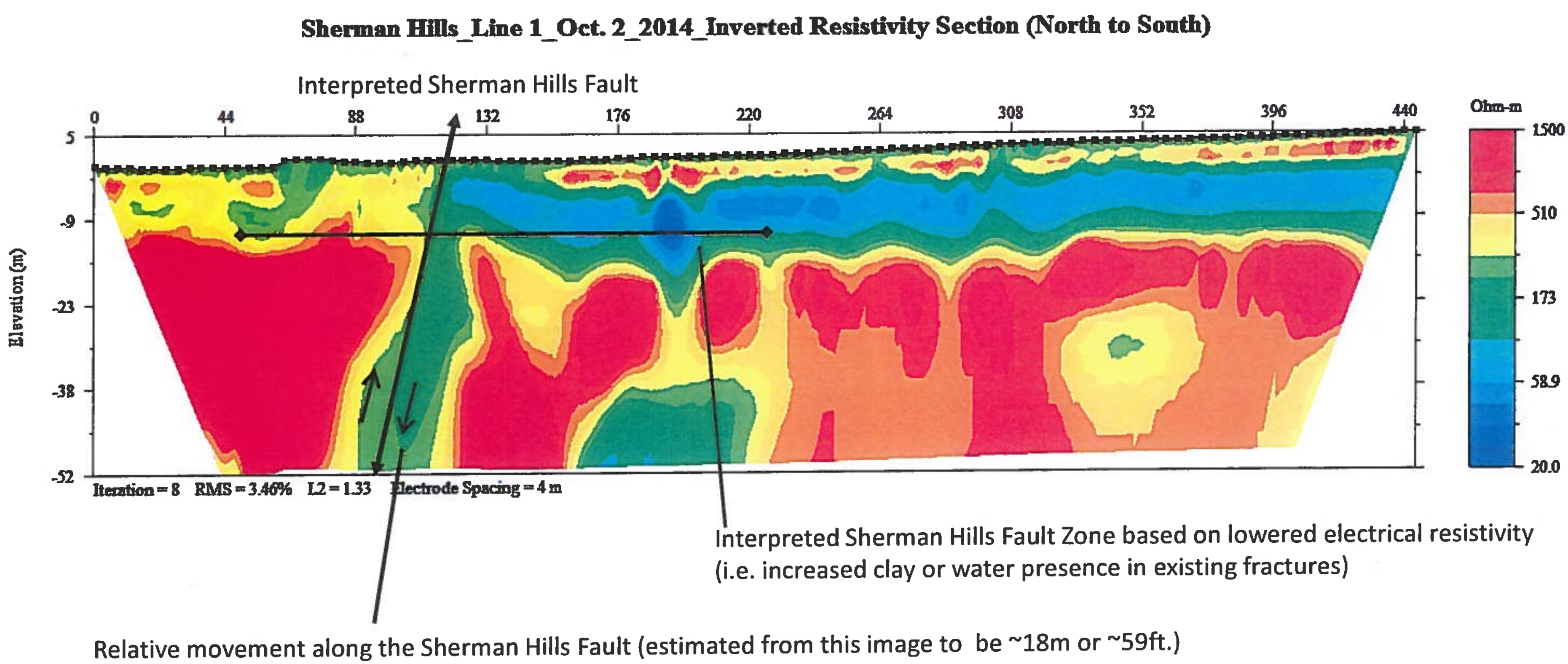


Line 1 Resistivity Data w/out Interpretation

Sherman Hills_Line 1_Oct. 2_2014_Inverted Resistivity Section (North to South)

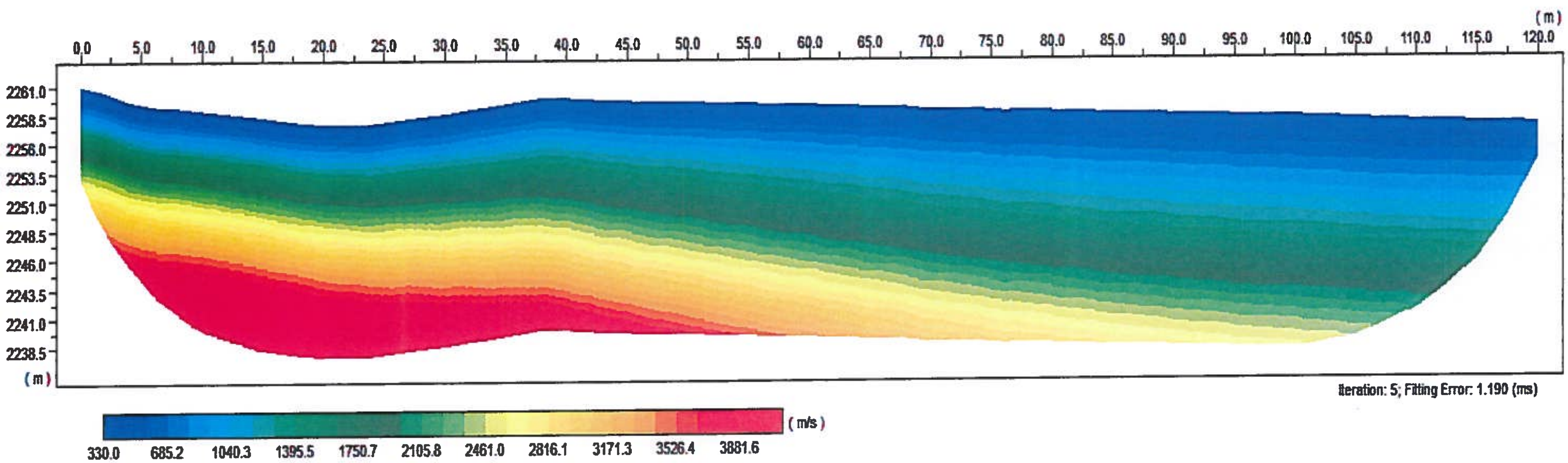


Line 1 Resistivity Data with Sherman Hills Fault Zone Interpretation



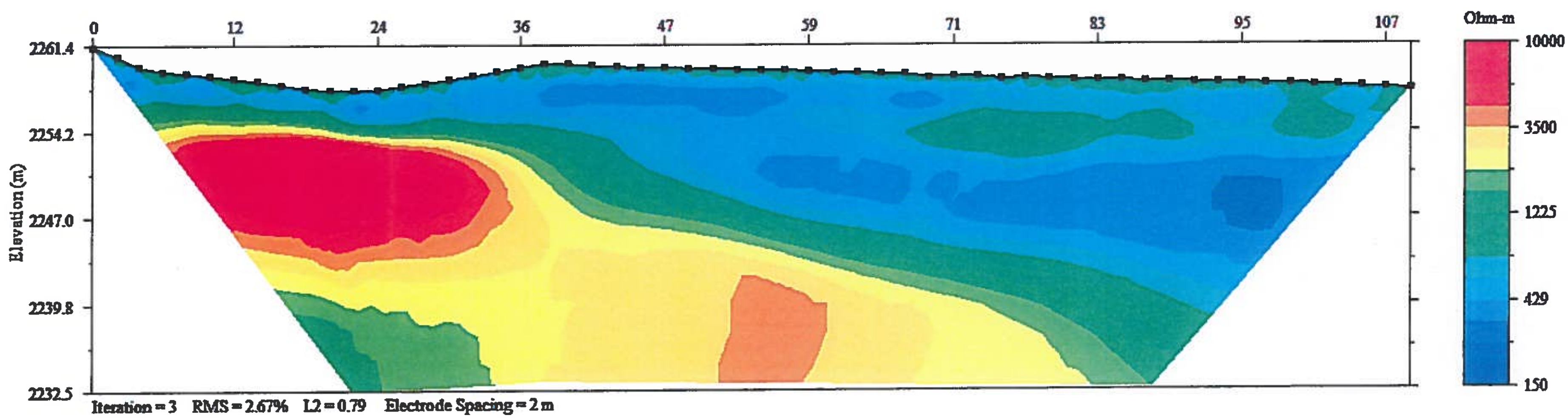
Line 2 Seismic Refraction Data w/out Interpretation
-No defined low velocity zone to interpret SH Fault trace-

Sherman Hills_Line 2_Oct.7_2014 Inverted Refraction Section (North to South)

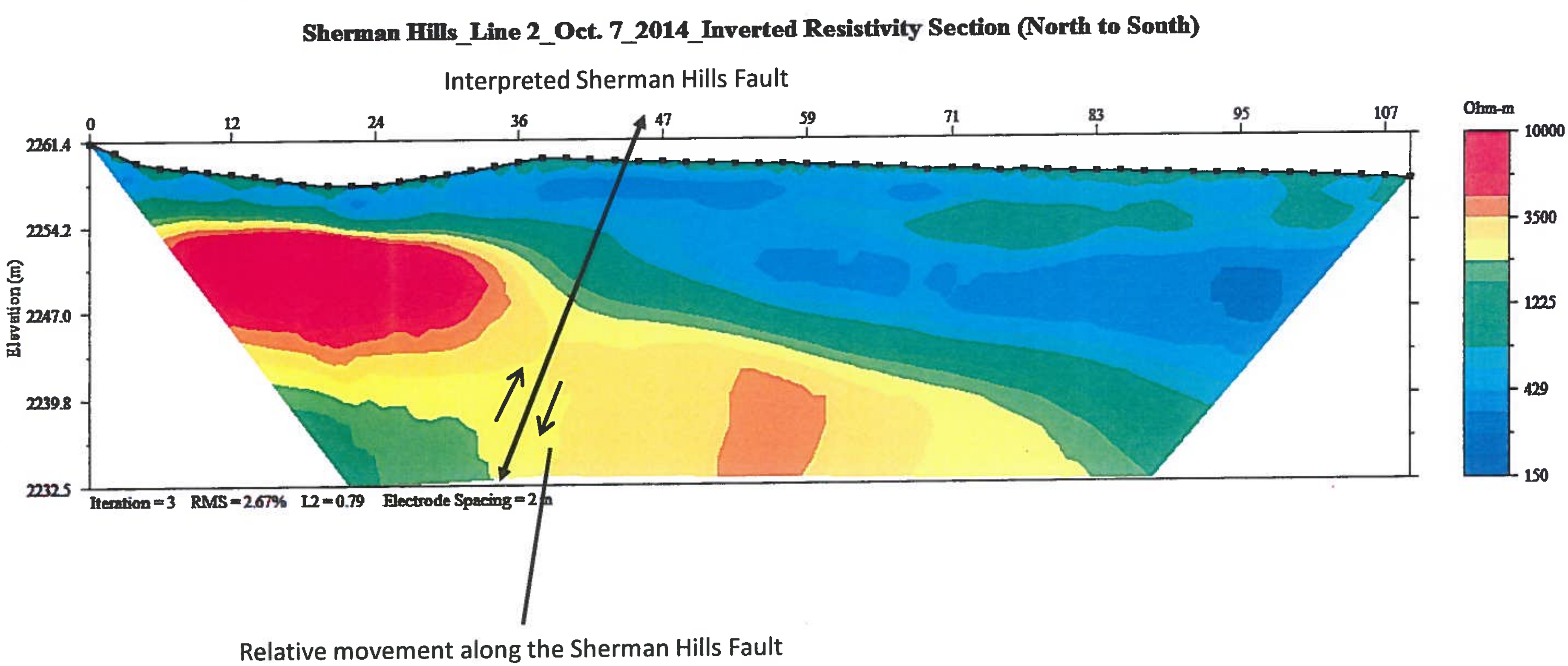


Line 2 Resistivity Data w/out Interpretation

Sherman Hills_Line 2_Oct. 7_2014_Inverted Resistivity Section (North to South)



Line 2 Resistivity Data with Sherman Hills Fault Zone Interpretation



Line 1 and Line 2 Interpreted location of the Sherman Hills Fault and projected extent of the fault zone (to the south)