Groundwater Research Report
WR15R004

THE WONEWOC AND TUNNEL CITY: A POTENTIAL NATURAL SOURCE OF GROUNDWATER CONTAMINATION IN WEST-CENTRAL WISCONSIN

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The Wonewoc and Tunnel City: A Potential Natural Source of Groundwater Contamination in West-Central Wisconsin

Project: WR15R004

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PROJECT SUMMARY

Title:
The Wonewoc and Tunnel City: A Potential Natural Source of Groundwater Contamination in West-Central Wisconsin

Project I.D.: WR15R004

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Period of Contract:
July 1st 2015 to June 30th 2016

Background/Need:
Preliminary data suggests that the rocks of the Wonewoc Formation and the overlying Tunnel City Group are a potential natural source for groundwater contamination across west and central Wisconsin, contributing high levels of aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, vanadium, and zinc that are above the advised levels for consumption, and additionally, lowering groundwater pH.

Objectives:
This research compiled geochemical and mineralogical data for the Wonewoc-Tunnel City contact interval that will provides a baseline for future research and regulations focused on mitigating this potential regional health hazard. More specifically, we characterized the elemental composition and mineralogy of rocks comprising the Wonewoc-Tunnel City contact interval from throughout Wisconsin using samples from drill core, outcrops, and well cuttings.

Methods:
Elemental, mineralogical, and isotopic data were collected from drill core, outcrops, and well cuttings using a variety of techniques including portable x-ray fluorescence (pXRF) and inductively coupled plasma mass spectrometry (ICP-MS) for elemental analysis, x-ray diffraction (XRD) for mineralogical analysis, and a Finnigan MAT 251 triple-collector gas source mass spectrometer coupled to a Finnigan Kiel automated preparation device for carbonate carbon isotopic analysis ($\delta^{13}C_{carbonate}$). Geophysical logs of wells (including a suite of tools such as natural gamma radiation, spontaneous potential, fluid conductivity, rock resistivity, borehole diameter (caliper), temperature, optical borehole imaging, and flow meter) were collected by the Wisconsin Geological and Natural History Survey (WGNHS) and/or compiled from their subsurface database and were used to reconstruct the relationship between water table, water conductivity, and groundwater flow to the stratigraphy of the Wonewoc-Tunnel City contact interval.

Results and Discussion:
Regional differences exist in the presence of sulfide minerals and their potential for surface and groundwater contamination. Sulfides in the Wonewoc and Tunnel City are relatively more common, and found at higher concentrations, in west-central and southwestern Wisconsin compared to the south-central portion of the state. Arsenic, lead, and zinc concentrations are variable but tend to be higher in southwest

and west-central Wisconsin and are highest in the west-central region. Local (kilometer-scale) concentration differences were observed between outcrop and subsurface samples. Surface (outcrop) materials were weathered and had lower, but still detectable, occurrences of sulfide minerals and in general lower concentrations of trace metals compared to subsurface samples.

At the uppermost end, we found Tunnel City rocks with relatively high levels of arsenic (547 ppm), cadmium (3.7 ppm), cobalt (100 ppm), chromium (90.6 ppm), copper (269 ppm), manganese (2630 ppm), molybdenum (5.47 ppm), nickel (158 ppm), lead (49.6 ppm), uranium (4.01 ppm), vanadium (113 ppm), and zinc (4860 ppm). Wonewoc samples also showed enrichments, including some at levels higher than seen in the Tunnel City, such as copper (645 ppm) and manganese (3790 ppm); elevated Wonewoc elemental concentrations also include cobalt (94.6 ppm), chromium (38.9 ppm), molybdenum (3.18 ppm), lead (42.5 ppm), uranium (2.21 ppm), and vanadium (62.6 ppm). The mineralogical analysis undertaken confirmed that the majority of these rocks are (glauconitic) dolomite-cemented quartz sandstones. Pyrite was confidently identified in two samples from Granddad Bluff. Other unidentified sulfide mineral samples that were analyzed for mineralogy yielded uncertain results; while a variety of sulfide minerals are possible, the XRD data obtained had to be interpreted with caution because the signal for abundant minerals, such as quartz, 'swamped out' the signals for less abundant minerals, i.e., the sulfides analyzed.

Conclusions/Implications/Recommendations:

- West-central Wisconsin has a higher potential for surface and groundwater contamination associated with naturally-occurring sulfide minerals in the Tunnel City Group and Wonewoc Formation than the southwestern and south-central regions of the study area.
- Local (site-specific) patterns in sulfide presence and composition are hypothesized to be related to weathering, preferential groundwater pathways, and water table fluctuation history; however, more work is necessary to confirm this conceptual model.
- Future work should focus on isolating sulfide materials for geochemical and mineralogical analysis. An important step would be to undertake sulfur isotopic analysis to determine the source of the sulfides; with a better understanding of sulfide origin, we would better be able to predict where they will be encountered as well as their trace metal composition.

The data presented herein will be submitted shortly for publication as a peer-reviewed scientific publication through the Wisconsin Geological and Natural History Survey. While we do not anticipate changes to the results or conclusions, policy and regulation decisions based on this study should be based on the anticipated peer-reviewed publication rather than this report to the funding agency.

Key Words:
sulfide, pyrite, oxidation, trace metal

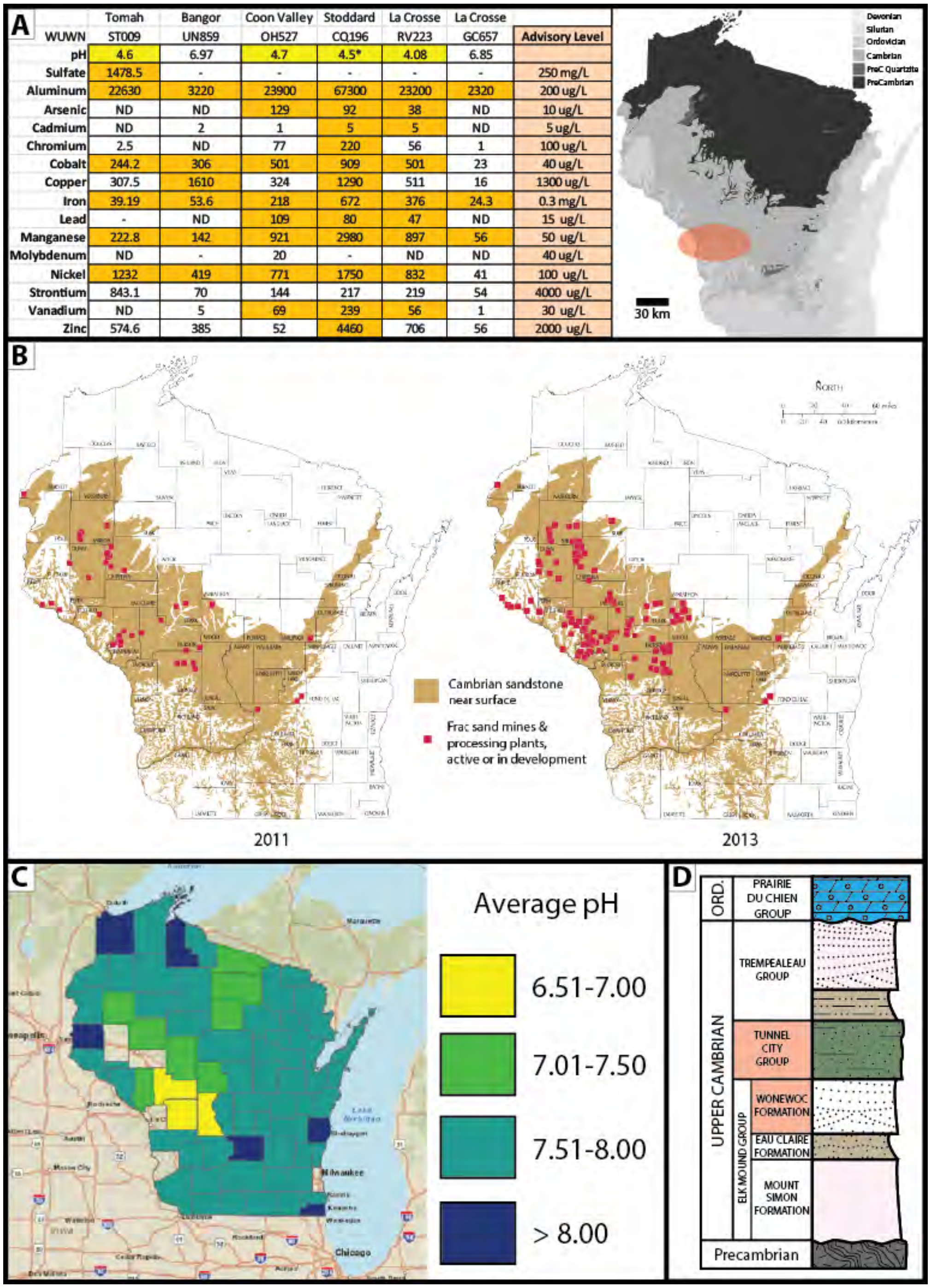
Funding:
This project was submitted to the State of Wisconsin Groundwater Research & Monitoring Program for State FY 2016, and funded by the University of Wisconsin System and the UW Water Resources Institute under award WR15R004. Additional funding was provided by the Wisconsin Geological and Natural History Survey, University of Wisconsin – Extension. Many of the cores studied were collected with support from the National Cooperative Geologic Mapping Program, under assistance of award numbers G13AC00138, G14AC00142, G15AC0016.

INTRODUCTION

Wisconsin faces a variety of groundwater quality issues that include both natural sources, such as arsenic from sulfide minerals, as well as human-induced sources, for example phosphorus from agricultural land-use practices. We hypothesize that the Cambrian age (~500 million year old) rocks of the Wonewoc-Tunnel City contact interval (lower Tunnel City Group and upper Wonewoc Formation) are a potential natural source of groundwater contamination in west and central Wisconsin. In this study, we collected and compiled a geochemical and mineralogical dataset for these rocks on a regional scale and assessed where this potential contamination, which can represent a health risk, is most likely to occur. Additionally, this study is timely because this same stratigraphic interval is now excavated, crushed, and exposed to surface weathering in many of the recently opened industrial (frac) sand mines throughout the state; this is potentially a new industrial source for surface and groundwater contamination in Wisconsin. Remaining questions include the origin of trace metal-bearing sulfides observed in the Tunnel City Group and Wonewoc Formation strata of western Wisconsin, and the degree, and spatial variability, of oxidation that these strata have undergone over possibly tens (maybe hundreds) of millions of years due to surface exposure in the Driftless Region of Wisconsin.

The impetus for this project was 1) prevalent water quality issues near La Crosse, and, 2) the rapid onset of large scale industrial (frac) sand mines in west-central Wisconsin. Over the past decade, western and central Wisconsin has undergone rapid land-use change related to suburban sprawl and an increase in industrial (frac) sand mines and processing facilities. As population increases and new homes are built in traditionally rural areas, new private drinking water wells are being constructed and their water quality tested. In the vicinity of La Crosse, WI, some private well water has been shown to contain enrichments of aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, vanadium, and zinc above advisory levels, as well as low pH (Fig. 1A). The same rocks that are serving as the aquifer also meet the specifications for use as a proppant (frac sand) in hydraulic fracturing, and therefore where these rocks outcrop at the surface they are currently mined (Fig. 1B). Finally, county-level analysis of groundwater pH indicates that the western Wisconsin region has relatively low groundwater pH (Fig. 1C).

Preliminary and published data suggests that there is a correspondence between the presence of these contaminants in wells that draw water from, and/or the water table occurs, near the stratigraphic contact between the Wonewoc Formation and the Tunnel City Group (Figure 1D, 2; Gotkowitz et al. 2012). For example, Figure 2 highlights the geophysical profile for one of the wells (GC657) used to construct Figure 1A. In this well, cased to ~315 ft, the Wonewoc-Tunnel City contact interval is found at a depth of ~450 ft. The water table in this well apparently fluctuates around the contact interval; the water table was measured at 434 ft when the well was drilled in 1993 and at 475 ft when it was logged in 2012 (however, 40 feet of water table fluctuation is doubtful and may be a result of measurement error or well equilibration following drilling, especially since there is not a high-capacity well nearby this private well). Fluctuating water levels would expose the rock to variable oxidizing and reducing conditions which could increase the rate at which minerals chemically weather and elements go into solution. A similar model has been proposed for arsenic-bearing sulfide minerals in the St. Peter sandstone in eastern Wisconsin (Schreiber et al. 2000; Gotkowitz et al. 2004).



WUWN	Tomah ST009	Bangor UN859	Coon Valley OH527	Stoddard CQ196	La Crosse RV223	La Crosse GC657	Advisory Level
pH	4.6	6.97	4.7	4.5*	4.08	6.85	
Sulfate	1478.5	-	-	-	-	-	250 mg/L
Aluminum	22630	3220	23900	67300	23200	2320	200 ug/L
Arsenic	ND	ND	129	92	38	ND	10 ug/L
Cadmium	ND	2	1	5	5	ND	5 ug/L
Chromium	2.5	ND	77	220	56	1	100 ug/L
Cobalt	244.2	306	501	909	501	23	40 ug/L
Copper	307.5	1610	324	1290	511	16	1300 ug/L
Iron	39.19	53.6	218	672	376	24.3	0.3 mg/L
Lead	-	ND	109	80	47	ND	15 ug/L
Manganese	222.8	142	921	2980	897	56	50 ug/L
Molybdenum	ND	-	20	-	ND	ND	40 ug/L
Nickel	1232	419	771	1750	832	41	100 ug/L
Strontium	843.1	70	144	217	219	54	4000 ug/L
Vanadium	ND	5	69	239	56	1	30 ug/L
Zinc	574.6	385	52	4460	706	56	2000 ug/L

Figure 1: A) Concentrations of elements that are known health risks and pH measurements from private wells near La Crosse, WI (concentration are in units that are the same as corresponding advisory levels; see area highlighted in inset geological map for well locations). Concentrations highlighted in orange exceed advised levels (http://dnr.wi.gov/topic/drinkingwater/documents/haltable.pdf); low pH measurements are highlighted in yellow. Asterisk denotes pH measured at time separate from when elemental concentrations were determined; ND is no detection; - is not measured. Water quality data provided by D. Johnson (WDNR) and the WI State Lab. of Hygiene. B) The location of Wisconsin's frac sand mines and processing plants, active and proposed, and the distribution of near surface Cambrian sandstone (Zambito and Parsen, 2014). C) Average pH measurements for Wisconsin counties (http://www.uwsp.edu/cnr-ap/watershed/pages/wellwaterviewer.aspx downloaded Sept. 2014). Transparent counties indicate that not enough data was available for analysis. D) Generalized stratigraphic column for the rocks for west-central Wisconsin. The study interval is colored pink.

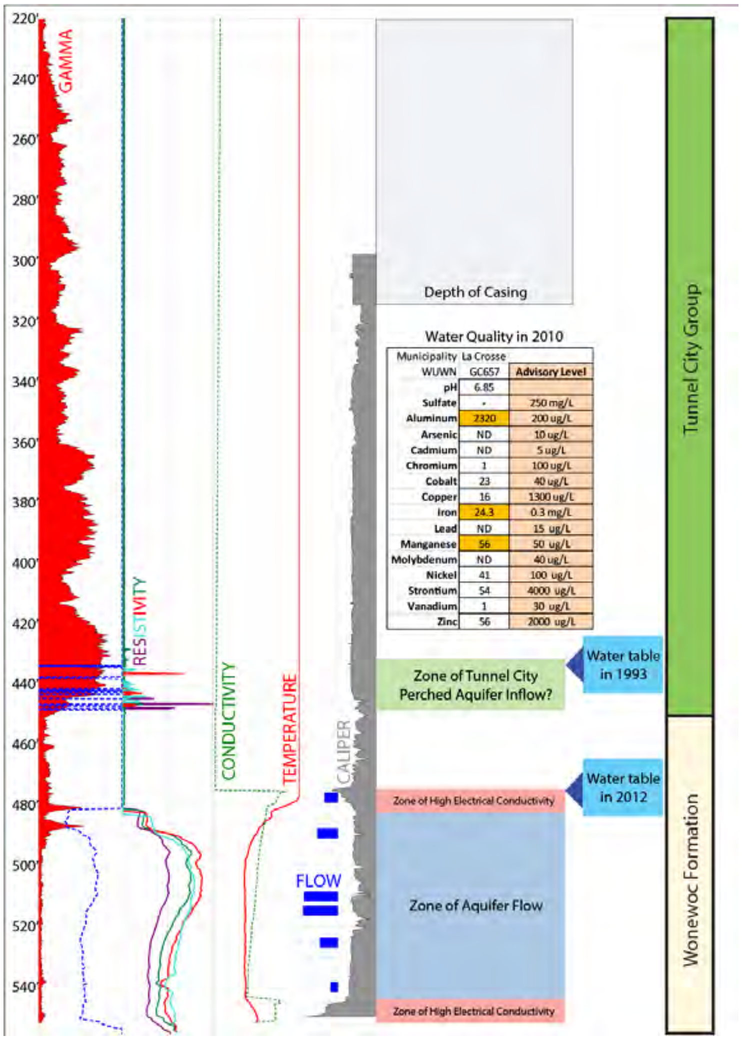


Figure 2: Geophysical log and water test results from well GC657 near La Crosse, WI. See text for explanation.

Variable oxidizing and reducing conditions could also occur if there is preferential flow along horizontal conduits. The geophysical log shown in Figure 2 suggests that there may be a perched water table within, and water flow through, the lower portion of the Tunnel City Group, as well as preferential fluid flow within the Wonewoc aquifer. Noise in the resistivity logs near the base of the Tunnel City Group may suggest that water was flowing through this interval and dripping onto the down-hole geophysical probes as they were being lowered in the well. This interpretation is in agreement with previous hydrostratigraphic studies in the Wonewoc-Tunnel City sandstone aquifer of the upper Midwest that have demonstrated that regionally extensive horizontal conduits within the Tunnel City and near the contact with the Wonewoc are highly hydraulically conductive (Runkel et al. 2006; Swanson 2007; Swanson et al. 2006). In addition, two instances of elevated electrical conductivity of the water suggests a high concentration of dissolved material near the water table and below a zone of flowing water within the Wonewoc aquifer (Fig. 2). Presumably, the electrical conductivity of the water decreased as a result of mixing with the water flowing through the intergranular Wonewoc aquifer. Furthermore, data obtained from the UW-Stevens Point Center for Watershed Science and Education suggested that this groundwater quality issue may be of regional concern (Fig. 1C). According to their database in 2014, private wells with low pH tend to be concentrated in west-central Wisconsin, where the Wonewoc-Tunnel City contact is found near or just below the land surface.

The recent expansion of frac sand mines in west-central Wisconsin (Fig. 1B) coincides with this area of observed low pH in groundwater (Fig. 1C). To be clear, we are not proposing that the frac sand mines are causing the low pH, but are pointing out that the hypothesized bedrock control for this low pH may have implications for the mining process. Sandstone of the Wonewoc Formation is the primary target for frac sand in this region and is often capped by the overburden (uneconomic) Tunnel City Group. Due to the presence of accessory minerals such as glauconite and more abundant cements, the overlying Tunnel City Group sandstone typically does not meet frac sand specifications without extensive processing. For example, during the typical frac sand mining process, rock from the Tunnel City is removed as overburden, set aside, and then later used as fill during reclamation. Preliminary data shows that stormwater runoff ponds at industrial sand mines can have fluctuating pH and are enriched in elements such as arsenic, lead, manganese, and vanadium (D. Johnson, personal communication, 2014). A potential source for these elements and the pH fluctuations in stormwater runoff ponds are the minerals present in the Tunnel City overburden piles waiting for use in reclamation. Initial removal and processing of overburden material increases the surface area of unweathered rock faces which are then exposed to precipitation and, similar to well GC657 described above, variably oxidizing conditions while awaiting use for reclamation. Through breaching of stormwater runoff ponds or by infiltration, these leached elements may eventually enter the groundwater system.

The preliminary data presented above suggests that there is a strong relationship between areas of Wisconsin with groundwater with low pH and enriched in elements of known health risk, and the chemical weathering of rocks of the Wonewoc-Tunnel City contact interval. In order to better understand the potential for surface and groundwater contamination by the rocks of the Wonewoc-Tunnel City contact interval, we collected and compiled an elemental and mineralogical database of the composition of these rocks in the west-central, southwestern, and south-central portions of the state using drill core, outcrop, and well cutting material. Such a database did not previously exist, which limited our understanding of the source of contamination observed. It is important to note that the mineralogy of any rock, regardless of its trace metal concentration, is the most important factor when determining the potential for these rocks to weather and their constituent trace metals released into surface and groundwater. As mentioned above, sulfide minerals are especially prone to weathering under near- and at-surface oxidizing conditions. If these trace metals are present in clay minerals, they may be relatively immobile due to higher earth surface stability. Regardless, in low pH waters, some clay minerals will breakdown (Jozefaciuk and Bowanko 2002), and this may be the potential pathway for aluminum and other trace metals to go into solution.

In this study, we focused on identifying the presence of sulfide minerals near the Wonewoc-Tunnel City contact interval because 1) sulfides are common hosts for trace metals, 2) they have been shown to cause water quality problems in other Wisconsin sandstone aquifers, 3) they are extremely unstable under oxygenated conditions, and 4) the oxidation of sulfides will lower water pH. In addition, we reconstructed the relationship between the position of the Wonewoc-Tunnel City contact interval in wells to the water table, electrical conductivity, and groundwater flow using geophysical logs for areas where the bedrock is enriched in elements that are potential health risks.

PROCEDURES AND METHODS

The distribution of the boreholes and outcrops studied is shown in Figure 3. In addition to studying geologic materials that were available from the research collections at the WGNHS, we also drilled a borehole in Trempealeau County, Wisconsin, just south of the City of Arcadia (WGNHS Arcadia Quarry 62000166) in order to collect drill core, and investigated and sampled six outcrops in the study area, of the Tunnel City – Wonewoc succession. Based on regional geologic features including bedrock geology, glacial history, and geomorphology we divided the counties of this study into three areas: south-central, southwest, and west-central Wisconsin.

Elemental, mineralogical, and isotopic data were collected from drill core, outcrops, and well cuttings using a variety of techniques including portable x-ray fluorescence (pXRF) and inductively coupled plasma mass spectrometry (ICP-MS) for elemental analysis, x-ray diffraction (XRD) for mineralogical analysis, and a Finnigan MAT 251 triple-collector gas source mass spectrometer coupled to a Finnigan Kiel automated preparation device for carbonate carbon isotopic analysis ($\delta^{13}C_{carbonate}$). Geophysical logs of wells (including a suite of tools such as natural gamma radiation, spontaneous potential, fluid conductivity, rock resistivity, borehole diameter (caliper), temperature, optical borehole imaging, and flow meter) were collected by the WGNHS or complied from their subsurface database and were used to reconstruct the relationship between water table, water conductivity, and groundwater flow to the stratigraphy of the Wonewoc-Tunnel City contact interval.

Our workflow began with identifying drill core and borehole cuttings samples available in the WGNHS research collections as well as any corresponding geophysical data. From this dataset we identified a drill site (WGNHS Arcadia Quarry 62000166) and six outcrops that would improve the spatial resolution of geological materials to be studied, and undertook fieldwork and drilling in June through August of 2015. In the laboratory, we collected pXRF elemental data for a ‘first look’ at the composition of the geological materials studied with a focus on sulfide minerals (Appendix B). Fresh cut, rock saw slabbed core and hand sample faces were analyzed when possible. Rock core that had not been slabbed was cleaned, using sand paper if necessary, and analyzed on the outer surface. Cuttings and unconsolidated hand samples were analyzed in a sample holder using polypropylene XRF film (details of sample preparation with different sample types are available in Zambito et al., 2016). Because we were analyzing different sample types in this study (core, cuttings, and hand samples), we undertook a case study of the effects of sample type and preparation on pXRF analysis (Zambito et al., 2016).

Using pXRF data, we were able to identify major rock forming elements that could be a proxy for lithology (silicon, calcium, and aluminum for quartz sandstone, carbonate cement, and clay minerals, respectively), elements indicative of pyrite (iron and sulfur), and trace metals at the Wonewoc-Tunnel City contact interval. If sulfur is associated with a specific suite of elements, it could provide an indication of one of two major sulfide mineralization processes: Mississippi Valley Type (MVT; lead and zinc for galena and sphalerite, respectively) or an early diagenetic (pyrite formed from Cambrian seawater) source for sulfides. Additionally, we looked for the presence of arsenic, a trace metal that not only poses health risks, but is also associated with sulfides in northeastern Wisconsin in the Ordovician St. Peter sandstone (Schreiber et al. 2000; Gotkowitz et al. 2004). For a given sample or core depth, we often performed multiple pXRF analyses in order to capture any lithological/mineralogic variability observed.

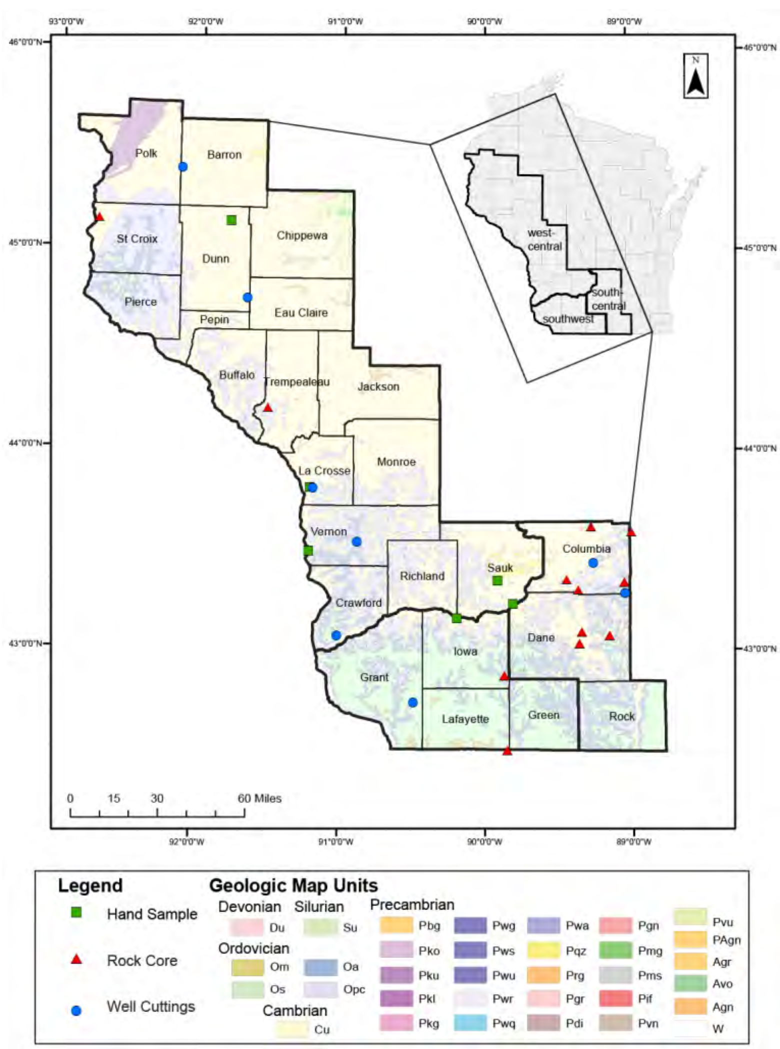


Figure 3: Location and sample type for the materials analyzed in this study (see Appendix B for more details).

The pXRF data was then used to select a subset of samples that represented the elemental variability observed in the studied successions to be further analyzed for elemental composition (ICP-MS) and mineralogical composition (XRD). Samples powders were drilled from rock material using a tungsten carbide drill bit, or powdered using a mortar and pestle for poorly lithified materials. This subset came mostly from drill core (62000166 WGNHS Arcadia Quarry, 56000829 WGNHS Belisle Quarry, and 11005900 WGNHS Triemstra Quarry), as well as outcrop (32outcrop Granddad Bluff La Crosse) and cuttings (32000107 Arbor Hills Addition Well). We also used the pXRF dataset to identify samples in the succession that had enough carbonate for $\delta^{13}C_{carbonate}$ analysis. Similarly, sample powders were drilled from rock material using a tungsten carbide drill bit, or powdered using a mortar and pestle for poorly lithified materials. Finally, we compiled and graphically depicted down-hole geophysical data available from the WGNHS subsurface database to understand hydrogeologic conditions at the studied Wonewoc-Tunnel City contact interval. Combined lithostratigraphic, geochemical, and applicable geophysical data for each borehole and outcrop is presented in Appendix B. We then identified and interpreted any regional and stratigraphic patterns in the data that may provide insight into mitigating water quality issues due to natural sources of contamination.

RESULTS

Elemental analysis by pXRF and geophysical data are summarized below for each borehole or outcrop studied, and separated into the following regions: south-central, west-central, and north-central Wisconsin (denoted in Figure 3 and presented in detail in Appendix B; WGNHS identification numbers – WIDs and county codes are used for internal WGNHS sample and data management). Since we used the pXRF analysis to obtain relative elemental composition (and sample type is variable, i.e., core, hand samples, and cuttings, along with variable lithologies) we did not calibrate the pXRF data presented herein (see Zambito et al., 2016 for further details on calibration) but instead used it as a 'first look'. Elemental data collected using ICP-MS and mineralogical data is presented below (Fig. 4, see also Appendix B for details). At the time of writing this report, the results of $\delta^{13}C_{carbonate}$ analysis are still being interpreted; the relatively low carbonate content of the rocks studies, and the possibility of MVT diagenesis, complicates a straightforward interpretation of this data. The $\delta^{13}C_{carbonate}$ results will be presented in a future report.

Southwest Wisconsin

<u>22000143 Platteville City Well 4 cuttings</u>

Elemental Geochemistry:

Enrichment patterns for arsenic, lead, and zinc are similar to aluminum, calcium, and sulfur.

Element	Presence	Max Concentration (pXRF)
sulfur	mostly near contact	~ 0.8%
arsenic	mostly near contact	~ 20ppm
lead	mostly near contact	~ 20ppm
zinc	mostly near contact	~ 40ppm

Subsurface Geophysics:

The water table is located at the Prairie du Chien Group – Ancell Group contact; well is cased to just below the water table.

<u>25000529 WGNHS Hwy A 2 core</u>

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near contact	~ 8.0%
arsenic	near contact	~ 40ppm
lead	near contact	~ 20ppm
zinc	throughout	~ 60ppm

Subsurface Geophysics:

The water table is located in the Prairie du Chien Group; well is cased ~50' lower, in the Prairie du Chien. Decreased water conductivity observed at the Tunnel City – Wonewoc contact interval.

<u>25outcrop Lone Rock Type Area</u>

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near contact	~ 0.2%
arsenic	near contact	~ 15ppm
lead	---	---
zinc	near contact	~ 20ppm

33000331 Commonwealth Edison UPH-1 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 5.0%
arsenic	near and above contact	~ 50ppm
lead	near and above contact	~ 40 ppm
zinc	throughout	~ 40ppm

South-Central Wisconsin

11000782 WGNHS Columbus 2 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	mostly near contact	~ 1.0%
arsenic	near contact	~ 100ppm
lead	near contact	~ 80ppm
zinc	mostly near contact	~ 100ppm

Subsurface Geophysics:

The water table is located near the Prairie du Chien Group – Ancell Group contact; no well casing. Slightly increased water conductivity observed just above the Tunnel City – Wonewoc contact interval, but log stops shortly thereafter.

11000783 WGNHS Rio 1 cuttings

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.05%
arsenic	---	---
lead	near contact	~ 5ppm
zinc	throughout	~ 70ppm

Subsurface Geophysics:

The water table is located near the St. Lawrence (Black Earth) – Tunnel City contact; well has shallow casing far above water table. Water conductivity shows some variation near the Tunnel City – Wonewoc contact interval.

11000784 WGNHS Manke Farm Test Hole cuttings

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	mostly near contact	< 0.05%
arsenic	rare	~ 5ppm
lead	above contact	~ 5ppm
zinc	throughout	~ 20ppm

Subsurface Geophysics:

The water table is located near the Ancell Group – Sinnipee (Platteville – Galena) Group contact; well is cased to just above water table. No change in water conductivity observed at the Tunnel City – Wonewoc contact interval.

11005900 WGNHS Triemstra Quarry core

Elemental Geochemistry (See also Appendix B):

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.6%
arsenic	rare	~ 10ppm
lead	near contact	~ 15ppm
zinc	throughout	~ 50ppm

Subsurface Geophysics:

The water table is located near the Tunnel City - Wonewoc contact; well has shallow casing far above water table. Water conductivity is highest at the water table, decreasing but elevated through the Tunnel City and Wonewoc, and lowest at and below the Wonewoc equivalent, where an interval of increased borehole flow is observed.

11005901 WGNHS Arlington Quarry core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.5%
arsenic	---	---
lead	---	---
zinc	throughout	~ 20ppm

Subsurface Geophysics:

The water table is located near the St. Lawrence (Black Earth) – Tunnel City contact; well has shallow casing far above water table. Water conductivity increases downhole, with a marked increase in the Tunnel City, but log stops shortly thereafter.

11005908 WGNHS Stevenson 2 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.3%
arsenic	rare	~ 5ppm
lead	uncommon	~ 15ppm
zinc	throughout	~ 175ppm

Subsurface Geophysics:

The water table is located within the Tunnel City; well has shallow casing far above water table. Water conductivity increases slightly downhole, with a marked increase near the bottom of the hole; since log stops shortly thereafter it is possible that this increase is an artifact.

13001216 Cottage Grove Hydrite MP-18 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.3%
arsenic	rare	~ 10ppm
lead	near contact	~ 10ppm
zinc	throughout	~ 50ppm

Subsurface Geophysics:

The water table is located above the base of the Prairie du Chien Group; well is cased to water table.

13001466 Nine Springs Core Hole 2 (NS-2) core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.8%
arsenic	uncommon	~ 10ppm
lead	near contact, else uncommon	~ 30ppm
zinc	throughout	~ 50ppm

Subsurface Geophysics:

Water table located within the Tunnel City Group; well is cased to water table. Water conductivity elevated throughout. Log ends near Tunnel City – Wonewoc contact interval.

13005716 Arcadis Madison Kipp MW-5D3 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	above contact	~ 8%
arsenic	rare	~ 10 ppm
lead	rare	~ 100ppm
zinc	throughout	~ 80ppm

14001384 WGNHS Alsum 4 core

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.6%
arsenic	---	---
lead	near contact	~ 60ppm
zinc	throughout	~ 80ppm

Subsurface Geophysics:

Water table is located within the Prairie du Chien Group; well is cased to water table. No change in water conductivity at the Tunnel City – Wonewoc contact interval. Increased borehole flow throughout the Tunnel City.

West-Central Wisconsin

3000192 Village of Turtle Lake 2 cuttings

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 1.2%
arsenic	near contact	~ 15ppm
lead	near and above contact	~ 15ppm
zinc	throughout	~ 30ppm

Subsurface Geophysics:

Water table in unlithified material above the Prairie du Chien Group; well is cased to ~100’ below water table, in the Trempealeau Group. Water conductivity elevated in the upper Tunnel City, above a zone of enhanced borehole flow; below this flow zone, relatively uniform low conductivity.

12000001 Aherns Bros. Farm cuttings

Elemental Geochemistry:

Enrichment patterns for arsenic, lead, and zinc similar to aluminum; zinc similar to calcium.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.4%
arsenic	above contact	~ 10ppm
lead	above contact	~ 15ppm
zinc	throughout	~ 20ppm

17000274 Duane Welch Well cuttings

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	below contact	~ 0.7%
arsenic	above contact	~ 10ppm
lead	rare	~ 5ppm
zinc	above contact	~ 60ppm

17outcrop Hwy W Hay Creek

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 0.02%
arsenic	near and above contact	~ 10ppm
lead	above contact	~ 15ppm
zinc	throughout	~ 90ppm

32000107 Arbor Hills Addition Well (S.D. 2) cuttings

Elemental Geochemistry (See also Appendix B):

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout, especially Wonewoc	~ 0.8%
arsenic	near and above contact	~ 30ppm
lead	near and above contact	~ 15ppm
zinc	throughout	~ 40ppm

Subsurface Geophysics:

Water table is located in the lower Wonewoc; well is cased more than 100' lower into the bottom of the Eau Claire Formation.

32outcrop Granddad Bluff La Crosse

Elemental Geochemistry (See also Appendix B):

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 6.0%; nodule is 33%
arsenic	near and above contact	~ 40ppm
lead	near and above contact	~ 30ppm
zinc	near and above contact	~ 200ppm

56000829 WGNHS Belisle Quarry core

Elemental Geochemistry (See also Appendix B):

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout, especially Wonewoc	~ 3.0%
arsenic	throughout	~ 60ppm
lead	throughout	~ 15ppm
zinc	throughout	~ 950ppm

57outcrop Ferry Bluff West

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	above contact	~ 0.2%
arsenic	above contact	~ 5ppm
lead	---	---
zinc	above contact	~ 40ppm

57outcrop Hwy C Leland

Elemental Geochemistry:

Overall, there are weak relationships between elements.

Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 0.8%
arsenic	near and above contact	~ 8ppm
lead	---	---
zinc	near and above contact	~ 15ppm

62000166 WGNHS Arcadia Quarry core

Elemental Geochemistry (See also Appendix B):

Overall, there are weak relationships between elements. However, iron and sulfur patterns are extremely similar in the Wonewoc, and iron and aluminum patterns are similar in the Tunnel City.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 30.0%
arsenic	above contact	~ 600ppm
lead	throughout	~ 50ppm
zinc	throughout	~ 40ppm; one value of 2686ppm

Subsurface Geophysics:

Water table located in the St. Lawrence Formation, above the Tunnel City; the well is cased more than 100’ above that in the Prairie du Chien. Water conductivity increases downhole, with inflections toward increasing values at the top of the Tunnel City, at the Tunnel City – Wonewoc contact, and the highest readings occurring within the Wonewoc.

63000165 Viroqua City Well #6 cuttings

Elemental Geochemistry:

Overall, there are weak relationships between elements. However, aluminum, sulfur, and arsenic have similar enrichment patterns.

Element	Presence	Max Concentration (pXRF)
sulfur	throughout	~ 0.5%
arsenic	near and above contact	~ 10ppm
lead	near and above contact	~ 10ppm
zinc	throughout	~ 50ppm

Subsurface Geophysics:

The water table is located just above the Tunnel City Wonewoc contact, but the well is cased ~400’ lower into the Elk Mound Group. Water conductivity increases at the contact.

63outcrop Victory North

Elemental Geochemistry:

Enrichment patterns for lead, aluminum, and sulfur are similar.

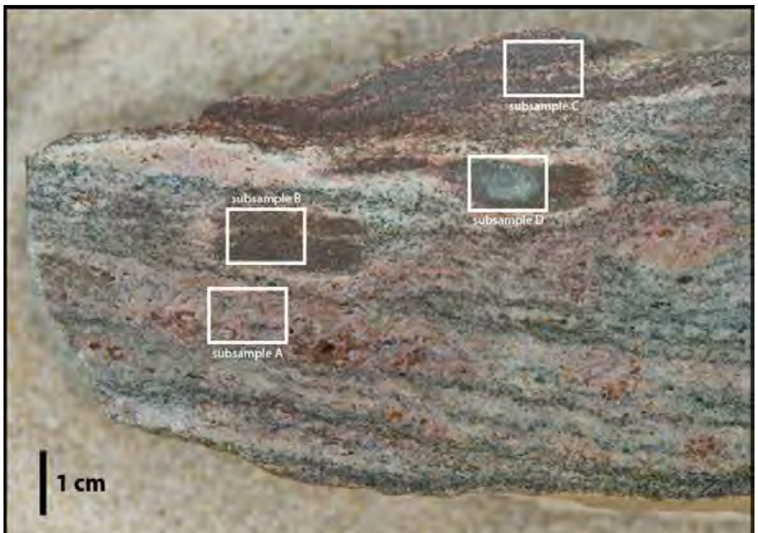
Element	Presence	Max Concentration (pXRF)
sulfur	near and above contact	~ 0.5%
arsenic	near and above contact	~ 100ppm
lead	near and above contact	~ 100ppm
zinc	near and above contact	~ 150ppm

Elemental and Mineralogical Analysis

The results of elemental analysis for trace metals using ICP-MS, and mineralogical analysis using XRD are presented in Appendix B, with select results highlighted in Figure 4. Lithologic, trace metal, and mineralogical variability over the scale of centimeters is clearly shown in Figure 4. This slabbed surface (cut with a rock saw) is a window inside the rock, collected from an outcrop at Granddad Bluff, La Crosse. Subsample A is a dolomite-cemented quartz-dominated sandstone. Subsample B is an interval of oxidized pyritic, glauconitic, dolomite-cemented quartz sandstone with elevated concentrations of arsenic, cobalt, chromium, molybdenum, nickel, lead, uranium, and vanadium. Subsample C is a glauconitic dolomite-cemented quartz sandstone. Subsample D is a pyrite nodule within a dolomite-cemented quartz sandstone with an iron-oxide and sulfate (gypsum) rim with elevated concentrations of arsenic, cobalt, copper, nickel, lead, and zinc. Also notable in Figure 4 is that some of the glauconite is also oxidized, represented by a change from green to red/orange/yellow in color. Although we focus on sulfides in this study because they are more readily oxidized and have been shown to be poor groundwater quality culprits in previous studies, it is also possible that trace metals in glauconite can be released during oxidation. Furthermore, sulfides are the most likely reason for the reports of low pH in groundwater wells and fluctuating pH in runoff ponds at industrial sand mines.

At the uppermost end, we found Tunnel City rocks with relatively high levels of arsenic (547 ppm), cadmium (3.7 ppm), cobalt (100 ppm), chromium (90.6 ppm), copper (269 ppm), manganese (2630 ppm), molybdenum (5.47 ppm), nickel (158 ppm), lead (49.6 ppm), uranium (4.01 ppm), vanadium (113 ppm), and zinc (4860 ppm). Wonewoc samples also showed enrichments, including some at levels higher than seen in the Tunnel City, such as copper (645 ppm) and manganese (3790 ppm); elevated Wonewoc elemental concentrations also include cobalt (94.6 ppm), chromium (38.9 ppm), molybdenum (3.18 ppm), lead (42.5 ppm), uranium (2.21 ppm), and vanadium (62.6 ppm).

The mineralogical analysis undertaken confirmed that the majority of these rocks are (glauconitic) dolomite-cemented quartz sandstones. Pyrite was confidently identified in two samples (Figure 4; Appendix B). Other sulfide samples that were analyzed for mineralogy came back with uncertain results; while a variety of sulfide minerals are possible (for example sphalerite, chalcopyrite, and covellite, the latter being extremely unlikely), the XRD data obtained had be interpreted with caution because the signal for abundant minerals, such as quartz, 'swamped out' the signals for less abundant minerals; this may be mitigated in future work by micro-sampling sulfide materials and limiting the incorporation of rock matrix into the sample (H. Xu, pers. comm. 2016).



Tunnel City Group, Sample +3.95m, Granddad Bluff, La Crosse, Wisconsin

	subsample A	subsample B	subsample C	subsample D
As	1.72 ppm	13.4 ppm	5.65 ppm	7.82 ppm
Cd	<0.005 ppm	<0.005 ppm	0.01 ppm	0.01 ppm
Co	9.6 ppm	30.6 ppm	16.5 ppm	19.3 ppm
Cr	3.5 ppm	10.6 ppm	8.2 ppm	5.1 ppm
Cu	19.1 ppm	13.6 ppm	2.6 ppm	45.1 ppm
Mn	2160.0 ppm	1140.0 ppm	1765.0 ppm	1185.0 ppm
Mo	1.11 ppm	5.47 ppm	2.45 ppm	2.40 ppm
Ni	14.8 ppm	123.5 ppm	34.7 ppm	73.3 ppm
Pb	4.5 ppm	21.2 ppm	11.2 ppm	15.3 ppm
U	0.7 ppm	2.07 ppm	1.07 ppm	0.78 ppm
V	6.7 ppm	12.5 ppm	8.3 ppm	6.0 ppm
Zn	2.6 ppm	9.4 ppm	4.0 ppm	13.1 ppm
	Quartz Dolomite	Quartz Glauconite Dolomite Pyrite	Quartz Glauconite Dolomite	Quartz Dolomite Pyrite Gypsum

Figure 4: A hand sample (slabbed surface using rock saw is shown) from Granddad Bluff, La Crosse, showing trace metal and mineralogical variation over the scale of centimeters. (see Appendix B for more details).

Figure 5: Piece of core from WGNHS Arcadia Quarry (62000166) showing large 'blebs' of pyrite, possibly worm burrow fillings, within quartz sandstone of the Wonewoc, just below the contact with the overlying Tunnel City.

DISCUSSION

Direct comparison between the different data types is difficult because of the scale of sampling: analyses of core were directed at discrete ~1 cm^2 spots and undertaken at a resolution of 0.1-1.0’, hand samples were collected at the decimeter to meter scale, and cuttings represent 0-5 feet of strata. Higher concentrations for trace metals were observed in core and hand samples than in cuttings; this is most likely an artifact of the sampling resolution inherent to sample type. Another complication is that outcrops were clearly weathered relative to subsurface samples; this was most obvious in the Wonewoc which in most cases could be removed from the outcrop with your bare hand, but was cemented in core. This suggests that some cements, including sulfide minerals, have been removed by weathering and oxidation at earth’s surface. Furthermore, uncertainty in where the Tunnel City-Wonewoc contact should be placed in some successions (for example, 62000166 WGNHS Arcadia Quarry) complicates our ability to treat these units separately in some cases; regardless, our observations, geochemical, and mineralogical data confirm that both geologic units contain sulfides that host a variety of trace metals.

Overall, enrichment patterns for different elements were unique, or in other words, cross-plots of elements presented in Appendix B did not show strong correlation. This is likely because these elements are present in multiple mineral forms, and the mineralogical composition of the rocks varies. For example, in WGNHS Arcadia Quarry (62000166) the stratigraphic pattern of iron is most similar to sulfur in the Wonewoc, but more similar to the aluminum and calcium patterns in the Tunnel City. We interpret this to suggest that iron is predominantly present in pyrite in the Wonewoc, and is predominantly found in glauconite in the Tunnel City. For successions in which the Tunnel City – Wonewoc contact was clear, we undertook preliminary analysis to cross-plot these elements separately for the Tunnel City and Wonewoc, and obtained higher correlations; future work should explore this further.

Regardless of region, we observed a common, though not universal trend, that groundwater near or in the Tunnel City and Wonewoc has an inflection in, or elevated, conductivity where data was available (Appendix B, Figure 2). More work is needed to investigate this pattern, which we attribute to a high concentration of dissolved material. We hypothesize that this would be most pronounced in wells where the water table is at or close to the Tunnel – City Wonewoc contact. If substantiated, the location of the water table would be a key piece of information for adequate well construction. A water table that fluctuates at or near the Tunnel City Wonewoc contact interval would likely oxidize any sulfides or other reduced minerals present which may be trace metal-bearing. Furthermore, as shown in Figure 2, a well with a water table below the contact interval may also be problematic: horizontal groundwater flow along conduits above the water table or within perched aquifers may also enhance oxidation and mobilize any trace metals present and transport them into the aquifer. Correspondingly, industrial sand mining above the water table is more likely to encounter rocks that have already undergone some oxidation. However, the observation of pyrite in the Tunnel City at Granddad Bluff outcrop indicates that these rocks may still contain sulfide minerals and high concentrations of trace metals (Fig. 4). If the Tunnel City is processed as overburden material at a mine site, any sulfide minerals present may undergo oxidation; of course, the abundance of sulfide minerals in the Tunnel City – Wonewoc contact interval is site specific (see Appendix B).

Regional differences exist in the presence of sulfides and their potential for surface and groundwater contamination. Sulfides in the Wonewoc and Tunnel City are relatively more common, and found at higher concentrations, in west-central and southwestern Wisconsin compared to the south-central portion of the state, and, arsenic, lead, and zinc concentrations are variable but tend to be higher in southwest and west-central Wisconsin and are highest in the west-central region (Appendix 3, Fig. 5,6). The Wonewoc and Tunnel City strata in the south-central portion of the state were deposited in a shallower water depositional environment during the Cambrian, and sulfides precipitating from Cambrian seawater may have been less common in these settings relative to offshore areas (west-central and southwestern Wisconsin; see Figure 6 inset); correspondingly, the Tunnel City Group rocks in south-central Wisconsin (Mazomanie Formation) are much less glauconitic than the Tunnel City rocks in western Wisconsin (Lone Rock Formation). In southwestern Wisconsin, sulfides found near the Tunnel City – Wonewoc contact interval are deeply buried below the regional presence of a Galena-Platteville caprock, in the Driftless Region, and in most cases well below the water table; all of these factors likely mean that the sulfides observed will remain in a reduced form. In contrast, sulfides observed at the Tunnel City – Wonewoc contact interval in west-central Wisconsin appear to currently be at a regional redox boundary. The heavily dissected topography of the region, related to being in the Driftless Region, along with a near absence of Galena-Platteville caprock, have resulted in a setting in which the water table and the Tunnel City - Wonewoc contact interval are more likely to, though not always, be at the same depth. An outstanding question is whether the sulfides observed in west-central Wisconsin are a result of Cambrian seawater, MVT mineralization with mineralizing fluids sourced from the Illinois and/or Michigan basins, or both.

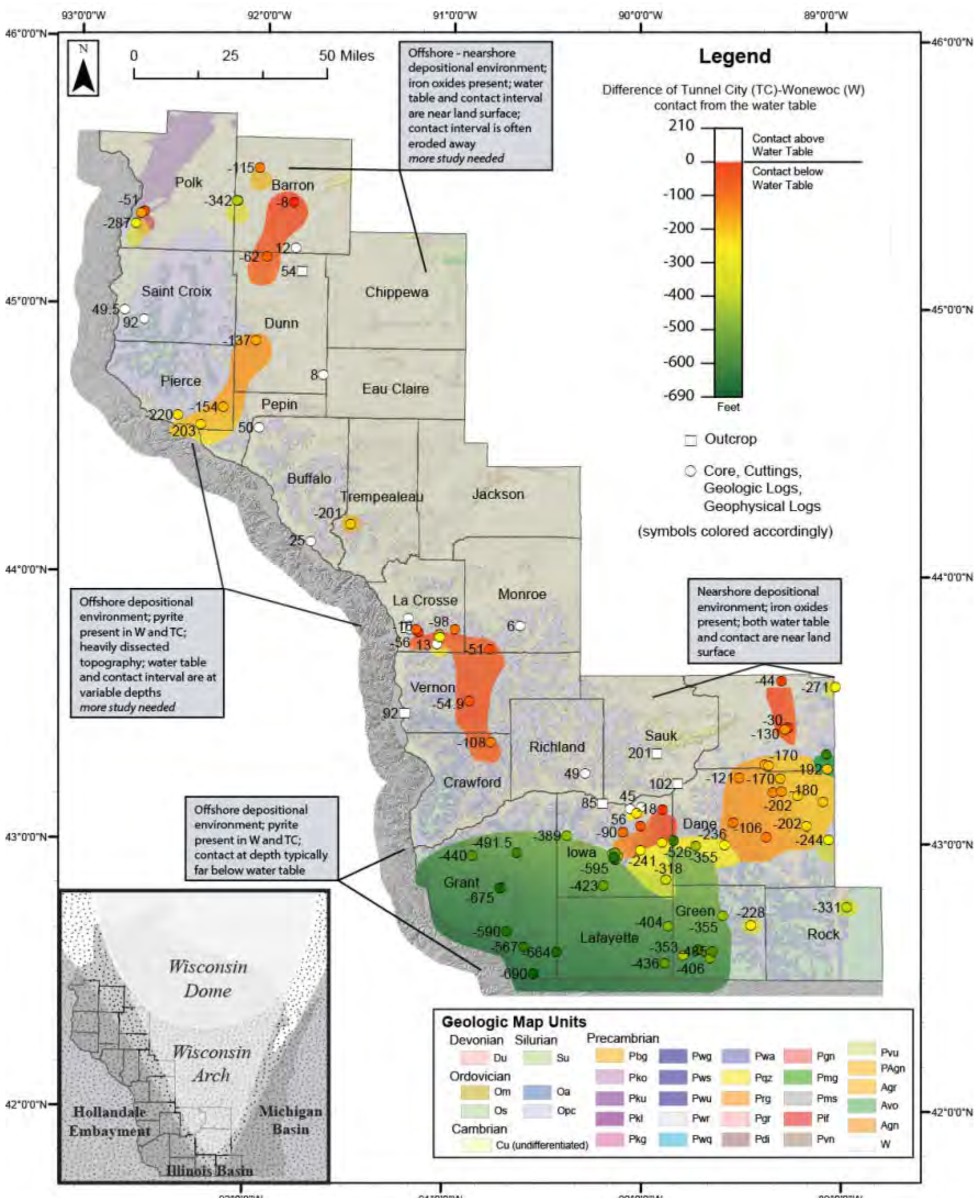


Figure 6: Preliminary compilation of borehole and outcrop data in which we could determine the relationship between the water table and the Tunnel City – Wonewoc contact. Inset figure in lower left denotes onshore (Wisconsin Arch and Dome) versus offshore (Hollandale Embayment, Illinois and Michigan basins) depositional settings. 'Cooler' colors signify the contact is >200 feet below the water table, and there is limited potential for the water table surface to come into contact with the Tunnel City – Wonewoc contact interval. 'Hotter' colors signify the water table is above, but close to the contact. White points indicate that the water table is below the contact, for example an outcrop, or where the Tunnel City-Wonewoc contact is above the water table in the subsurface. Uncolored areas either indicate that the contact is above the water table (near white dots) and/or more data is needed. While hotter colors mean there is a higher potential for redox changes at the Tunnel City – Wonewoc contact interval due to water table fluctuations, it is important to note that if sulfide minerals are not present or common, such as in the south-central region where the rocks studied were deposited in shallow water depositional settings on the Wisconsin Arch, there is limited potential for natural groundwater contamination due to this process. Based on this preliminary compilation, the west-central region has a higher potential for natural groundwater contamination from trace metal-bearing sulfides in the Tunnel City and Wonewoc. The data used to make this preliminary figure and a more detailed version of this figure will be presented in a subsequent report.

CONCLUSIONS AND RECOMMENDATIONS

Trace metal-bearing sulfide minerals have been documented in both the Tunnel City and Wonewoc. Regional patterns in sulfide presence and composition are a result of depositional environment and post-depositional history, such as presence/absence of overlying rock units or the depositional setting (water depth) during the Cambrian; west-central Wisconsin has a higher potential for surface and groundwater contamination associated with the composition of the Tunnel City and Wonewoc than the southwestern an south-central regions of the study area. Local (site-specific) patterns over the scale of a few kilometers in sulfide presence and composition are hypothesized to be related to weathering, preferential groundwater pathways, and water table fluctuation history; however, more work is necessary to confirm this conceptual model. This has important implications for industrial (frac) sand mining in Wisconsin. For example, is there a volume-to-surface area ratio threshold for hills comprised of Wonewoc sandstone that can be used to infer whether the resource has already been oxidized? Correspondingly, how far into a large hill of Wonewoc sandstone or ridge in west-central Wisconsin do you have to mine before you should expect to encounter sulfides?

Future work could also focus on isolating sulfide materials for geochemical and mineralogical analysis. In the XRD mineralogical analysis performed in this study, the mineralogy of sulfides could not be confidently identified if the sample was so quartz-dominated (sandstone) that the quartz signal swamped out the pattern for the sulfides (Appendix B). Once sulfide minerals are isolated for mineralogical and analysis, an additional step would be to undertake sulfur isotopic analysis to determine the source of the sulfides (MVT versus Cambrian seawater); with a better understanding of sulfide origin, we would better be able to predict where they will be encountered. In addition to sulfide origin, systematic differences in sulfide trace metal composition related to origin should also be investigated; for example, should we only worry about arsenic in MVT sulfides, or Cambrian seawater-derived sulfides also?

The data presented herein will be submitted shortly for publication as a peer-reviewed scientific publication through the Wisconsin Geological and Natural History Survey. While we do not anticipate changes to the results or conclusions, policy decisions based on this study should be based on the anticipated peer-reviewed publication rather than this report to the funding agency.

ACKNOWLEDGEMENTS

Dave Johnson (WDNR) suggested this project to us, and provided critical insight as this project has developed. Ken Bradbury (WGNHS) reviewed a draft of this report and provided his insight.

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APPENDIX A:

Awards

Haas, L. American Water Resources Association Wisconsin Chapter, Best Undergraduate Poster Presentation, Spring 2016

Publications

Zambito, J., P.I. McLaughlin, L.D. Haas, E.K. Stewart, S.E. Bremmer, and M.J. Hurth, 2016, Sampling methodologies and data analysis techniques for geologic materials using portable x-ray fluorescence (pXRF) elemental analysis: Wisconsin Geological and Natural History Survey Open-File Report 2016-02, 12 p., 5 appendices.

Presentations

Zambito, J., Parsen, M., and Haas, L., 2016, A new predictive model for understanding groundwater quality issues in west-central Wisconsin, American Water Resources Association Wisconsin Chapter.

Haas, L., Zambito, J., and Parsen, M. 2016, Wonewoc Formation and Tunnel City Group Rocks: Potential Natural Sources of Groundwater Contaminants in Wisconsin?, American Water Resources Association Wisconsin Chapter.

Haas, L., Zambito, J., and Parsen, M. 2016, Wonewoc Formation and Tunnel City Group Rocks: Potential Natural Sources of Groundwater Contaminants in Wisconsin?, UW-Madison Undergraduate Research Forum.

Haas, L., Zambito, J., and Parsen, M. 2016, Wonewoc Formation and Tunnel City Group Rocks: Potential Natural Sources of Groundwater Contaminants in Wisconsin?, UW-Madison, Department of Geoscience, Student Research Symposium.

Students

Lisa Haas, Undergraduate Senior, UW-Madison

The Wonewoc and Tunnel City: A Potential Natural Source of Groundwater Contamination in West-Central Wisconsin

Project: WR15R004

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APPENDIX B

West-Central

Site Name	Wid	County	Region	Sample Interval*	Has Geophysical Data	Sample Type	Type of Geochemical Analysis	Photos	Latitude	Longitude
Village of Turtle Lake #2	3000192	Barron	West-Central	350 to 550 (ft)	Yes; 3000515- Village of Turtle Lake 4	Well Cutting	XRF	No	45.3981	-92.1436
Aherns Bros. Farm	12000001	Crawford	West-Central	250 to 445 (ft)	No	Well Cutting	XRF	No	43.0750	-91.0150
Duane Welch Well	17000274	Dunn	West-Central	20 to 125 (ft)	No	Well Cutting	XRF	No	44.7556	-91.6667
Hwy W Hay Creek	17outcrop	Dunn	West-Central	1.0 to -1.0 (m)	No	Hand Sample	XRF	Yes	45.1395	-91.7892
Arbor Hills Addition Well (S.D. 2)	32000107	La Crosse	West-Central	250 to 450 (ft)	Yes	Well Cutting	XRF, XRD, ICP-MS	No	43.8103	-91.1919
Granddad Bluff La Crosse	32outcrop	La Crosse	West-Central	4.6 m to -3.8 (m)	No	Hand Sample	XRF, $\delta^{13}C$	Yes	43.8140	-91.2127
WGNHS Belisle Quarry	56000829	St. Croix	West-Central	140 to 200 (ft)	No	Core	XRF, XRD, ICP-MS, $\delta^{13}C$	Yes	45.1400	-92.7210
Ferry Bluff West	57outcrop	Sauk	West-Central	2.3 to -2.6 (m)	No	Hand Sample	XRF	Yes	43.2362	-89.8130
Hwy C Leland	57outcrop	Sauk	West-Central	1.4 to 1.5 (m)	No	Hand Sample	XRF	Yes	43.3516	-89.9183
WGNHS Arcadia Quarry	62000166	Trempealeau	West-Central	288.5 to 450 (ft)	Yes	Core	XRF, $\delta^{13}C$	Yes	44.2020	-91.4580
Viroqua City Well #6	63000165	Vernon	West-Central	405 to 635 (ft)	Yes	Well Cutting	XRF	No	43.5444	-90.8823
Victory North	63outcrop	Vernon	West-Central	1.9 to -1.1 (ft)	No	Hand Sample	XRF	Yes	43.4956	-91.2159

Southwest

Site Name	Wid	County	Region	Sample Interval*	Has Geophysical Data	Sample Type	Type of Geochemical Analysis	Photos	Latitude	Longitude
Platteville City Well 4	22000143	Grant	Southwest	650 to 955 (ft)	Yes	Well Cutting	XRF	No	42.7422	-90.4911
WGNHS Hwy A 2	25000529	Iowa	Southwest	292 to 357 (ft)	Yes; 25000512 WGNHS Hwy A	Core	XRF	Yes	42.8780	-89.8720
Lone Rock Type Area	25outcrop	Iowa	Southwest	0.3 to -1.0 (ft)	No	Hand Sample	XRF	Yes	43.1640	-90.1960
Commonwealth Edison UPH-1	33000331	Illinois	Southwest	667 to 735 (ft)	No	Core	XRF	Yes	42.5050	-89.8520

South-Central

Site Name	Wid	County	Region	Sample Interval*	Has Geophysical Data	Sample Type	Type of Geochemical Analysis	Photos	Latitude	Longitude
WGNHS Columbus 2	11000782	Columbia	South-Central	150 to 258.5 (ft)	Yes	Core	XRF, $\delta^{13}C$	Yes	43.3423	-89.0497
WGNHS Rio 1	11000783	Columbia	South-Central	100 to 305 (ft)	Yes	Well Cutting	XRF	No	43.4374	-89.2605
WGNHS Manke Farm Test Hole	11000784	Columbia	South-Central	221 to 400 (ft)	Yes	Well Cutting	XRF	No	43.2882	-89.0447
WGNHS Triemstra Quarry	11005900	Columbia	South-Central	133 to 209.0 (ft)	Yes	Core	XRF, XRD, ICP-MS, $\delta^{13}C$	Yes	43.6206	-89.2749
WGNHS Arlington Quarry	11005901	Columbia	South-Central	181.5 to 238.5 (ft)	Yes	Core	XRF	Yes	43.3050	-89.3650
WGNHS Stevenson 2	11005908	Columbia	South-Central	160 to 238.5 (ft)	Yes	Core	XRF	Yes	43.3574	-89.4443
Cottage Grove Hydrite MP-18	13001216	Dane	South-Central	200 to 300 (ft)	Yes	Core	XRF	Yes	43.0770	-89.1540
Nine Springs Core Hole 2 (NS-2)	13001466	Dane	South-Central	109 to 158 (ft)	Yes	Core	XRF, $\delta^{13}C$	Yes	43.0364	-89.3597
Arcadis Madison Kipp MW-5D3	13005716	Dane	South-Central	38 to 151.5 (ft)	No	Core	XRF	Yes	43.0950	-89.3420
WGNHS Alsum 4	14001384	Dodge	South-Central	232 to 325.2	Yes	Core	XRF	Yes	43.5939	-88.9977

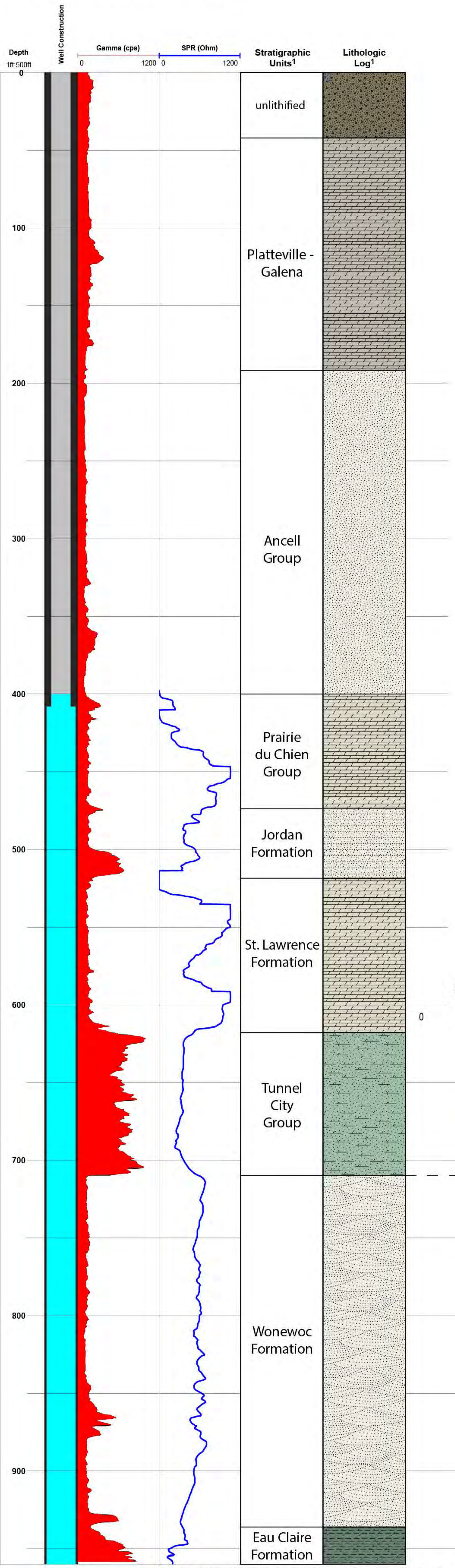
*Sample interval for subsurface data is given as depth below surface in feet. Sample interval for hand samples is given as a datum relative to the Tunnel City-Wonewoc contact in meters.

Region	Location	Horizon	Unit	As (ppm)	Cd (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	Mn (ppm)	Mo (ppm)	Ni (ppm)	Pb (ppm)	U (ppm)	V (ppm)	Zn (ppm)
south-central	110005900 WGNHS Triemstra Quarry	165.00	Tunnel City	0.81	0.02	11.4	48.6	2.2	248.0	0.12	5.3	7.1	1.82	28.5	9.4
south-central	110005900 WGNHS Triemstra Quarry	166.00	Tunnel City	1.00	0.09	4.0	4.9	2.3	799.0	0.06	2.6	0.8	0.35	5.4	5.8
south-central	110005900 WGNHS Triemstra Quarry	171.00	Wonewoc	0.15	0.01	57.8	3.2	1.5	43.5	0.13	1.1	0.9	0.30	1.5	1.5
south-central	110005900 WGNHS Triemstra Quarry	176.00	Wonewoc	0.82	0.03	12.5	19.8	3.1	337.0	0.08	3.1	5.0	0.79	13.2	5.6
south-central	110005900 WGNHS Triemstra Quarry	180.00	Wonewoc	0.08	<0.005	26.7	1.6	4.8	2.1	0.06	1.0	0.4	0.25	2.0	1.4
south-central	110005900 WGNHS Triemstra Quarry	202.90	Wonewoc	0.15	<0.005	41.0	3.1	4.9	8.7	0.12	1.0	1.2	1.38	1.6	2.4
west-central	56000829 WGNHS Belisle Quarry	132.00	Tunnel City	4.06	0.05	12.0	37.3	7.6	1940.0	0.38	13.0	8.2	1.35	40.2	15.5
west-central	56000829 WGNHS Belisle Quarry	146.00	Tunnel City	3.73	0.01	5.6	19.3	1.0	87.9	0.08	4.5	4.1	0.51	18.7	5.7
west-central	56000829 WGNHS Belisle Quarry	182.00	Wonewoc	0.49	0.03	32.0	11.6	22.2	16.0	0.12	5.2	2.2	0.65	15.0	13.5
west-central	56000829 WGNHS Belisle Quarry	199.00	Wonewoc	1.42	0.01	2.5	3.0	4.4	14.4	0.14	3.7	2.0	2.64	3.4	2.9
west-central	32000107 Arbor Hills Addition Well	257.50	Tunnel City	10.35	0.02	11.4	31.4	8.0	337.0	0.40	15.2	7.7	1.25	34.5	11.7
west-central	32000107 Arbor Hills Addition Well	402.50	Wonewoc	0.33	0.01	0.5	3.2	1.8	6.5	0.18	1.0	1.1	0.62	2.0	2.6
west-central	32outcrop Granddad Bluff La Crosse	3.95a	Tunnel City	1.72	<0.005	9.6	3.5	19.1	2160.0	1.11	14.8	4.5	0.70	6.7	2.6
west-central	32outcrop Granddad Bluff La Crosse	3.95b	Tunnel City	13.40	<0.005	30.6	10.6	13.6	1140.0	5.47	123.5	21.2	2.07	12.5	9.4
west-central	32outcrop Granddad Bluff La Crosse	3.95c	Tunnel City	5.65	0.01	16.5	8.2	2.6	1765.0	2.45	34.7	11.2	1.07	8.3	4.0
west-central	32outcrop Granddad Bluff La Crosse	3.95d	Tunnel City	7.82	0.01	19.3	5.1	45.1	1185.0	2.40	73.3	15.3	0.78	6.0	13.1
west-central	32outcrop Granddad Bluff La Crosse	3.25a	Tunnel City	1.33	0.04	5.1	4.4	3.5	1860.0	0.13	5.6	2.3	0.55	8.1	31.4
west-central	32outcrop Granddad Bluff La Crosse	0.95	Tunnel City	4.97	0.01	21.5	2.9	25.3	24.7	0.43	6.6	11.7	1.21	2.4	5.1
west-central	32outcrop Granddad Bluff La Crosse	-0.65	Wonewoc	0.71	0.01	3.0	4.7	3.9	24.4	0.14	0.8	5.8	1.34	3.7	1.0
west-central	32outcrop Granddad Bluff La Crosse	-3.55	Wonewoc	0.60	0.01	0.4	2.3	0.9	7.8	0.07	0.5	8.8	0.38	2.1	1.3
west-central	62000166 WGNHS Arcadia Quarry	290.00	Tunnel City	2.48	<0.005	13.1	29.7	3.6	212.0	0.04	12.3	4.6	1.35	34.0	10.1
west-central	62000166 WGNHS Arcadia Quarry	293.70	Tunnel City	2.23	0.01	27.5	4.7	64.2	83.9	0.30	8.3	5.9	0.63	7.4	1.5
west-central	62000166 WGNHS Arcadia Quarry	296.60	Tunnel City	43.80	3.70	100.0	41.4	269.0	167.5	1.10	149.0	22.8	1.72	31.9	4860.0
west-central	62000166 WGNHS Arcadia Quarry	309.40	Tunnel City	547.00	<0.005	19.6	34.0	21.5	151.5	2.38	42.3	17.3	1.80	34.1	9.0
west-central	62000166 WGNHS Arcadia Quarry	309.50	Tunnel City	5.56	<0.005	10.2	44.0	4.7	179.0	0.17	11.7	10.3	1.95	47.2	11.7
west-central	62000166 WGNHS Arcadia Quarry	310.50	Tunnel City	4.71	<0.005	8.3	40.5	2.9	128.0	0.11	9.7	10.9	2.29	42.1	8.7
west-central	62000166 WGNHS Arcadia Quarry	313.50	Tunnel City	3.03	<0.005	4.1	28.2	3.2	318.0	0.07	4.9	9.8	1.45	22.4	7.7
west-central	62000166 WGNHS Arcadia Quarry	313.70	Tunnel City	30.40	0.01	62.2	32.0	174.5	1700.0	0.31	158.0	11.5	0.56	107.5	16.7
west-central	62000166 WGNHS Arcadia Quarry	313.80	Tunnel City	42.70	<0.005	14.2	17.8	4.7	1885.0	0.47	20.7	13.0	0.49	51.9	17.0
west-central	62000166 WGNHS Arcadia Quarry	313.90	Tunnel City	5.93	<0.005	3.5	4.2	1.3	2630.0	0.14	5.9	2.1	0.19	7.7	8.6
west-central	62000166 WGNHS Arcadia Quarry	314.00	Tunnel City	23.60	<0.005	15.2	17.0	25.1	1935.0	0.27	12.8	8.6	0.82	23.2	11.5
west-central	62000166 WGNHS Arcadia Quarry	314.10	Tunnel City	4.53	<0.005	4.1	5.8	1.2	1150.0	0.73	4.3	8.5	0.66	16.6	9.5
west-central	62000166 WGNHS Arcadia Quarry	314.20	Tunnel City	5.03	0.01	9.0	7.1	12.5	1075.0	0.72	4.6	8.9	0.65	18.1	10.7
west-central	62000166 WGNHS Arcadia Quarry	314.30	Tunnel City	19.60	<0.005	12.2	28.5	2.0	1610.0	0.18	16.7	7.2	0.65	41.2	17.0
west-central	62000166 WGNHS Arcadia Quarry	314.40	Tunnel City	7.62	<0.005	10.9	38.1	3.5	1190.0	0.08	12.3	4.5	1.39	23.2	16.0
west-central	62000166 WGNHS Arcadia Quarry	320.00	Tunnel City	4.61	<0.005	9.8	31.5	8.4	1100.0	0.08	10.5	5.1	0.85	21.8	10.6
west-central	62000166 WGNHS Arcadia Quarry	323.90	Tunnel City	5.18	<0.005	9.1	23.3	5.1	1680.0	0.25	10.4	6.0	1.14	21.9	5.7
west-central	62000166 WGNHS Arcadia Quarry	325.80	Tunnel City	4.85	0.01	19.9	21.5	15.7	931.0	0.75	17.4	17.8	1.39	17.4	10.9
west-central	62000166 WGNHS Arcadia Quarry	334.90	Tunnel City	3.65	<0.005	7.0	8.7	3.0	29.2	0.05	5.5	5.3	0.66	9.0	5.3
west-central	62000166 WGNHS Arcadia Quarry	338.40	Tunnel City	139.50	<0.005	17.6	8.4	88.1	31.9	1.30	17.3	14.7	0.59	12.0	5.5
west-central	62000166 WGNHS Arcadia Quarry	339.70	Tunnel City	19.55	0.01	25.3	2.4	11.1	142.0	1.54	15.5	49.6	3.34	3.4	2.5
west-central	62000166 WGNHS Arcadia Quarry	345.50	Tunnel City	1.58	0.01	10.7	9.2	11.9	44.4	0.26	4.8	11.6	0.97	8.2	1.4
west-central	62000166 WGNHS Arcadia Quarry	346.50	Tunnel City	3.51	0.01	9.4	90.6	26.5	100.5	0.64	16.4	29.9	4.01	113.0	11.6
west-central	62000166 WGNHS Arcadia Quarry	347.70	Tunnel City	2.74	<0.005	5.8	2.5	5.1	423.0	0.57	5.7	9.8	0.39	3.7	1.6
west-central	62000166 WGNHS Arcadia Quarry	350.90	Tunnel City	3.96	<0.005	10.6	54.0	19.7	83.4	0.63	13.8	33.1	2.28	53.3	8.0
west-central	62000166 WGNHS Arcadia Quarry	353.20	Wonewoc	0.42	<0.005	1.6	2.8	3.7	4.0	0.07	2.9	5.2	0.38	2.8	0.7
west-central	62000166 WGNHS Arcadia Quarry	357.10	Wonewoc	0.71	<0.005	5.0	1.5	9.7	4.3	0.29	2.9	3.2	0.44	1.9	1.5
west-central	62000166 WGNHS Arcadia Quarry	375.70	Wonewoc	0.90	<0.005	21.5	16.0	37.2	30.9	0.30	9.6	7.3	1.30	15.9	2.6
west-central	62000166 WGNHS Arcadia Quarry	359.80	Wonewoc	3.90	0.03	94.6	14.3	645.0	13.4	1.44	7.1	9.0	0.40	2.0	1.7
west-central	62000166 WGNHS Arcadia Quarry	376.50	Wonewoc	1.61	<0.005	18.7	38.9	31.5	38.7	0.57	12.2	15.6	2.21	48.9	7.9
west-central	62000166 WGNHS Arcadia Quarry	383.10	Wonewoc	1.44	0.01	10.6	2.9	5.1	17.2	0.19	4.5	16.2	0.67	2.5	1.1
west-central	62000166 WGNHS Arcadia Quarry	384.50	Wonewoc	2.70	0.01	11.0	18.1	12.1	75.4	0.75	10.9	30.1	1.13	16.7	2.7
west-central	62000166 WGNHS Arcadia Quarry	394.00	Wonewoc	0.70	0.01	4.3	1.7	3.7	36.2	0.15	3.5	6.1	0.26	1.8	0.6
west-central	62000166 WGNHS Arcadia Quarry	395.50	Wonewoc	8.21	0.01	13.6	26.3	21.5	39.0	3.18	16.5	42.5	1.94	62.6	2.9
west-central	62000166 WGNHS Arcadia Quarry	398.00	Wonewoc	0.17	<0.005	0.6	0.9	1.6	1.4	0.11	2.0	1.7	0.30	0.8	0.9
west-central	62000166 WGNHS Arcadia Quarry	405.50	Wonewoc	3.98	0.01	9.5	14.2	16.4	78.1	0.41	9.3	23.7	1.47	13.1	2.2
west-central	62000166 WGNHS Arcadia Quarry	430.50	Wonewoc	1.77	0.01	5.0	13.5	6.4	74.2	0.76	8.8	15.7	1.20	13.8	3.7
west-central	62000166 WGNHS Arcadia Quarry	442.50	Wonewoc	2.65	0.01	4.1	9.4	6.0	3790.0	0.41	8.5	20.5	0.54	8.4	6.3
west-central	62000166 WGNHS Arcadia Quarry	445.00	Wonewoc	1.42	0.01	1.8	7.4	3.7	48.2	0.22	5.9	11.2	0.51	4.6	2.3

Region	Type	Sample	Unit	Quartz SiO_2	K-Spar $KAlSi_3O_8$	Glauconite $K(Fe,Al)_2(Si,Al)_4OH_2$	Dolomite $CaMg(CO_3)_2$	Calcite $CaCO_3$	Pyrite FeS_2	Sphalerite ZnS_2	Chalcopyrite $CuFeS_2$	Covellite CuS	Gypsum $CaSO_4{\cdot}2H_2O$
south-central	core	110005900 WGNHS Triemstra Quarry 165.0'	Tunnel City										
south-central	core	110005900 WGNHS Triemstra Quarry 166.0'	Tunnel City								?		
south-central	core	110005900 WGNHS Triemstra Quarry 171.0'	Wonewoc		?			?					
south-central	core	110005900 WGNHS Triemstra Quarry 180.0'	Wonewoc										
south-central	core	110005900 WGNHS Triemstra Quarry 180.0'	Wonewoc										
south-central	core	110005900 WGNHS Triemstra Quarry 202.9'	Wonewoc										
west-central	outcrop	32outcrop Granddad Bluff La Crosse -3.55m	Wonewoc										
west-central	outcrop	32outcrop Granddad Bluff La Crosse -0.65m	Wonewoc										
west-central	outcrop	32outcrop Granddad Bluff La Crosse 0.95m	Tunnel City										
west-central	outcrop	32outcrop Granddad Bluff La Crosse 3.25(a)m	Tunnel City										
west-central	outcrop	32outcrop Granddad Bluff La Crosse 3.95(a)m	Tunnel City			?							
west-central	outcrop	32outcrop Granddad Bluff La Crosse 3.95(b)m	Tunnel City										?
west-central	outcrop	32outcrop Granddad Bluff La Crosse 3.95(c)m	Tunnel City										?
west-central	outcrop	32outcrop Granddad Bluff La Crosse 3.95(d)m	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 290.0'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 296.6'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 313.7'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 313.8'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 313.9'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 314.1'	Tunnel City										
west-central	core	62000166 WGNHS Arcadia Quarry 323.9'	Tunnel City						?				
west-central	core	62000166 WGNHS Arcadia Quarry 338.4'	Tunnel City							?			
west-central	core	62000166 WGNHS Arcadia Quarry 339.7'	Tunnel City							?		?	
west-central	core	62000166 WGNHS Arcadia Quarry 383.1'	Wonewoc						?				
west-central	core	62000166 WGNHS Arcadia Quarry 395.5'	Wonewoc					?	?	?			
west-central	core	62000166 WGNHS Arcadia Quarry 405.5'	Wonewoc						?	?			
west-central	core	56000829 WGNHS Belisle Quarry 132.0'	Tunnel City		?								
west-central	core	56000829 WGNHS Belisle Quarry 146.0'	Tunnel City										
west-central	core	56000829 WGNHS Belisle Quarry 182.0'	Wonewoc										
west-central	core	56000829 WGNHS Belisle Quarry 199.0'	Wonewoc										
west-central	cuttings	32000107 Arbor Hills Addition Well 255-260'	Tunnel City						?				
west-central	cuttings	32000107 Arbor Hills Addition Well 400-405'	Wonewoc										

? = XRD pattern was suggestive of mineral, but it could not be identified for certain.

22000143 Platteville City Well 4



1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log

WGNHS Well ID 22000143

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY — WGNHS

DATE 8/8/1968 WELL NAME Platteville Municipal Well #4

LOCATION SE1/4, SE1/4, Sect 9, T3N, R1W

COUNTY Grant LOGGED BY PO & FR

LATITUDE - LONGITUDE -

LOCATION METHOD: GPS ☐ AIR PHOTO/TOPO ☐ PLSS ☐ OTHER Unknown

ELEVATION 965 ELEVATION METHOD: DEM ☐ TOPO ☐ OTHER

WELL DEPTH 960 CASING DEPTH 408 DEPTH TO WATER 400 estimate

CASING STICK UP Unknown File Created on: 8/12/2016 by: MJP

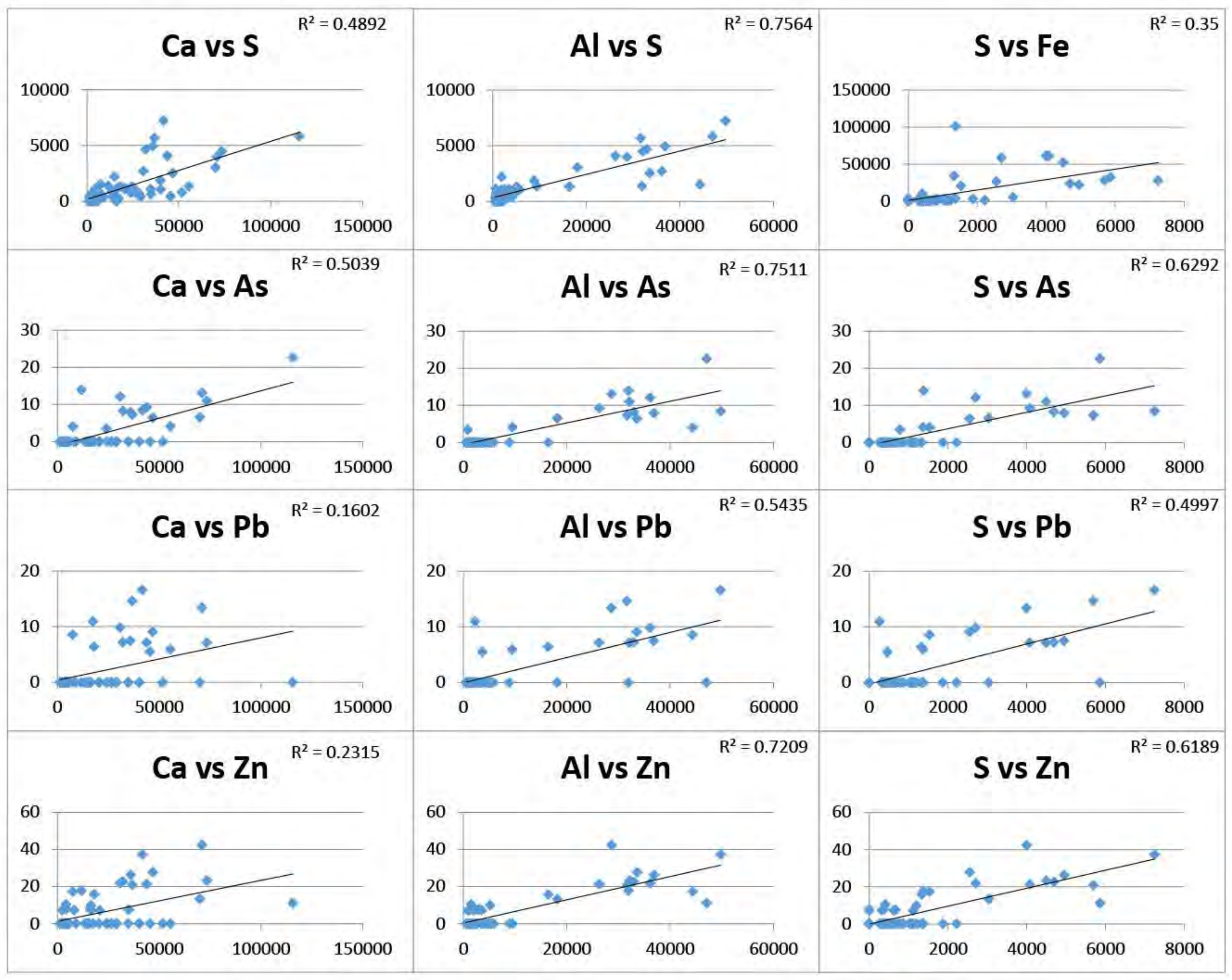
Comments: The Gamma and SPR data included in this log were measured in 1968 using methods of the day. Values shown should only be considered as relative estimates, not quantitative measures. SPR and SP profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging.

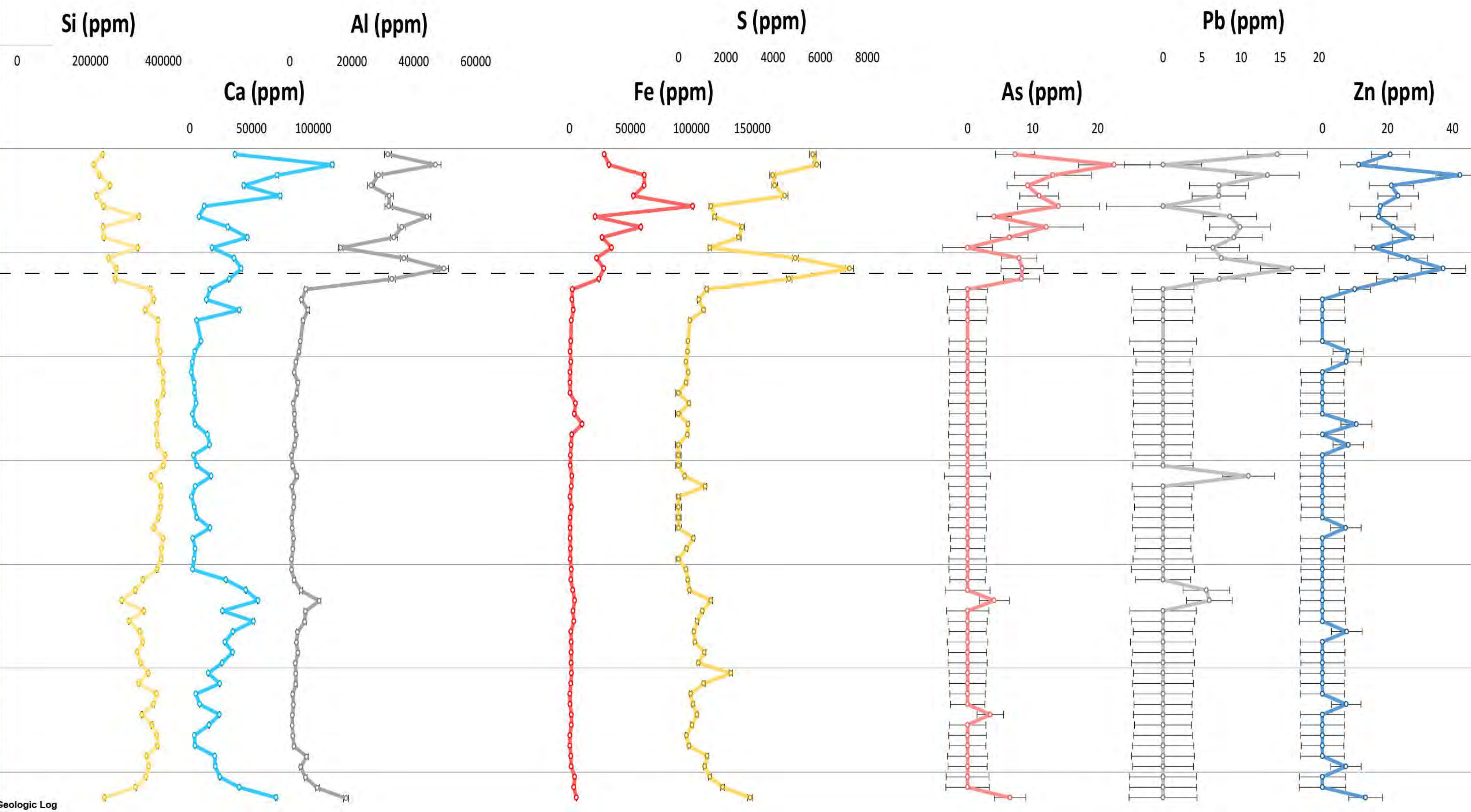
LOGS COLLECTED:

Gamma	x	Fluid Conductivity	
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature		OTHER:	

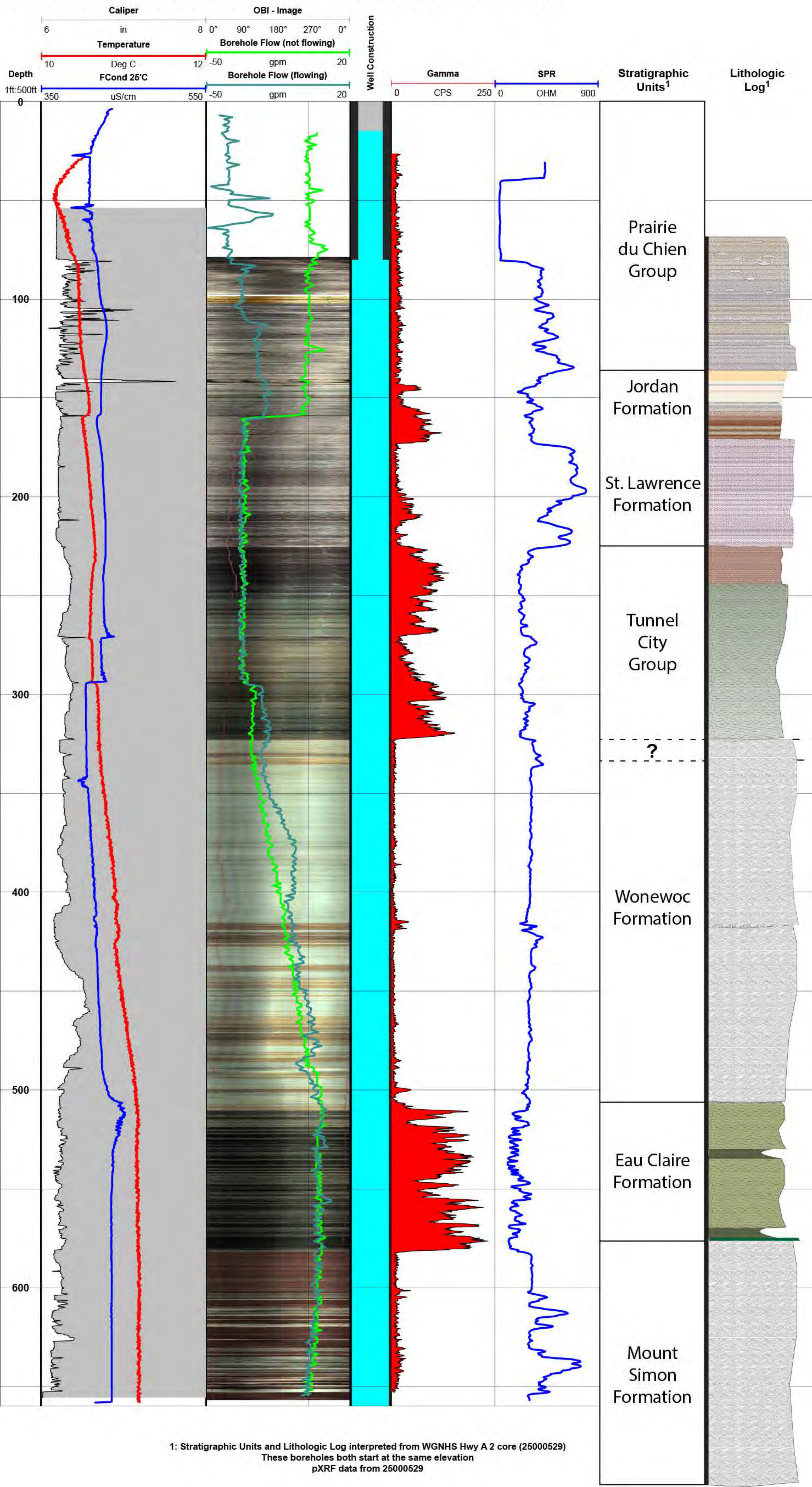
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu





25000512 WGNHS HWY A & 25000529 WGNHS HWY A 2



1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Hwy A 2 core (25000529)
These boreholes both start at the same elevation
pXRF data from 25000529

WGNHS Well ID 25000512

DATE 8/6-8/10/2009 WELL NAME Highway A Quarry Test Hole

LOCATION NW 1/4, SW 1/4, Sec 26 T5 R5 E

COUNTY Iowa LOGGED BY Chase, Batten, Gotkowitz, Hart

LATITUDE 267209.91 (wtm-m) LONGITUDE 530209.31 (wtm-m)

LOCATION METHOD: GPS ☐ AIR PHOTO/TOPO ☐ PLSS ☐ OTHER

ELEVATION 850 ELEVATION METHOD: DEM ☐ TOPO x OTHER

WELL DEPTH 660 CASING DEPTH 80 DEPTH TO WATER 15

CASING STICK UP 0 File Created on: 8/12/2016 by: MJP

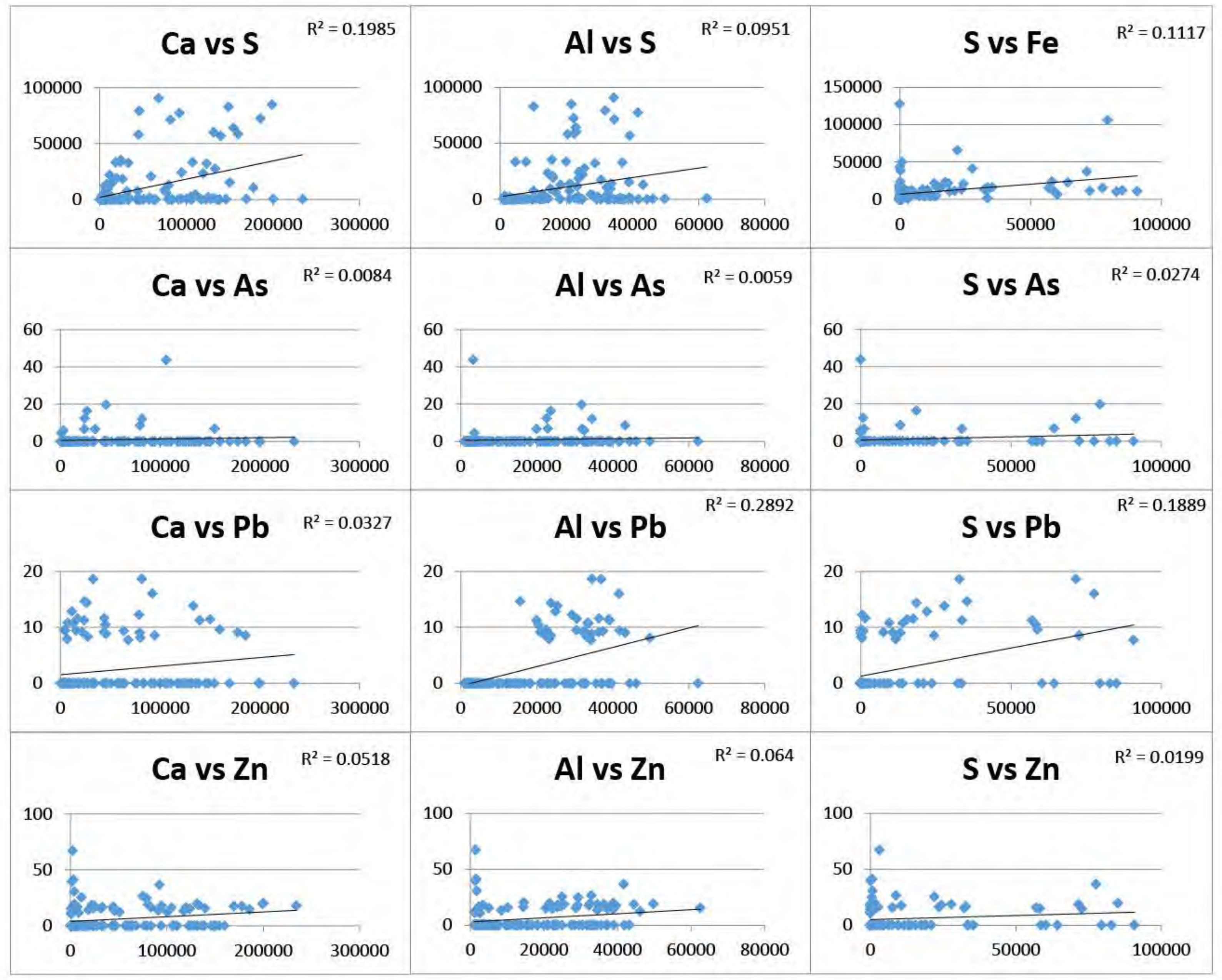
Comments: SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well and casing as measured on the day of logging. The water-level depth of of 15' was recorded on the day the well was not flowing (8/6/2009). Water-level when the well was flowing (8/10/2009), was above ground (artesian conditions)

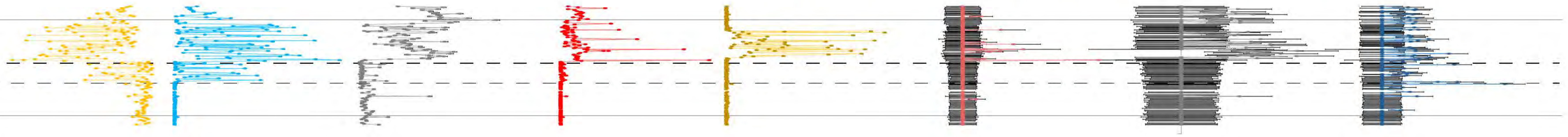
LOGS COLLECTED:

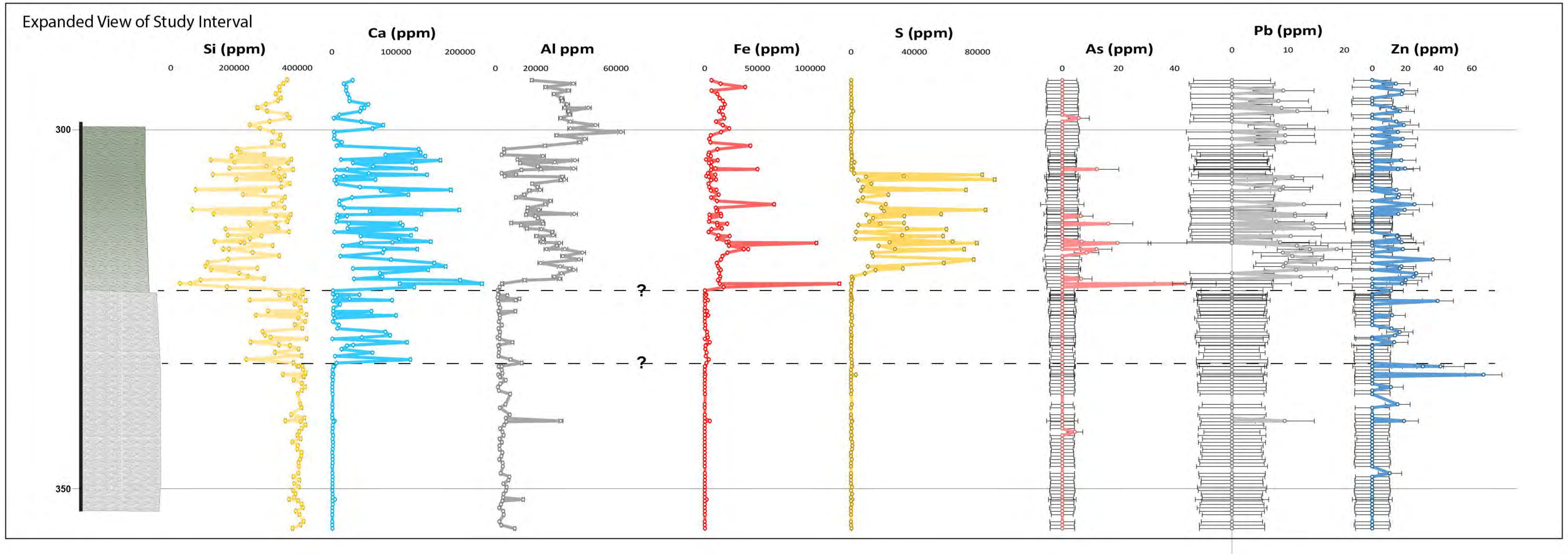
Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	x
Self Potential		Optical Borehole Imager	x
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER:	

Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

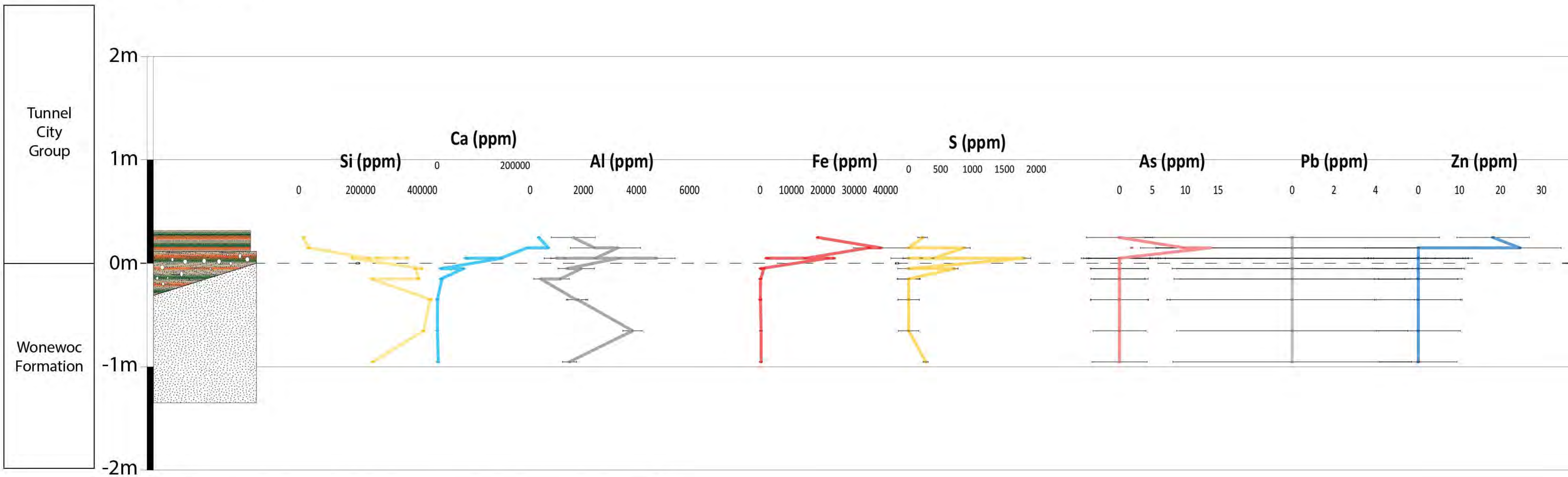
For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

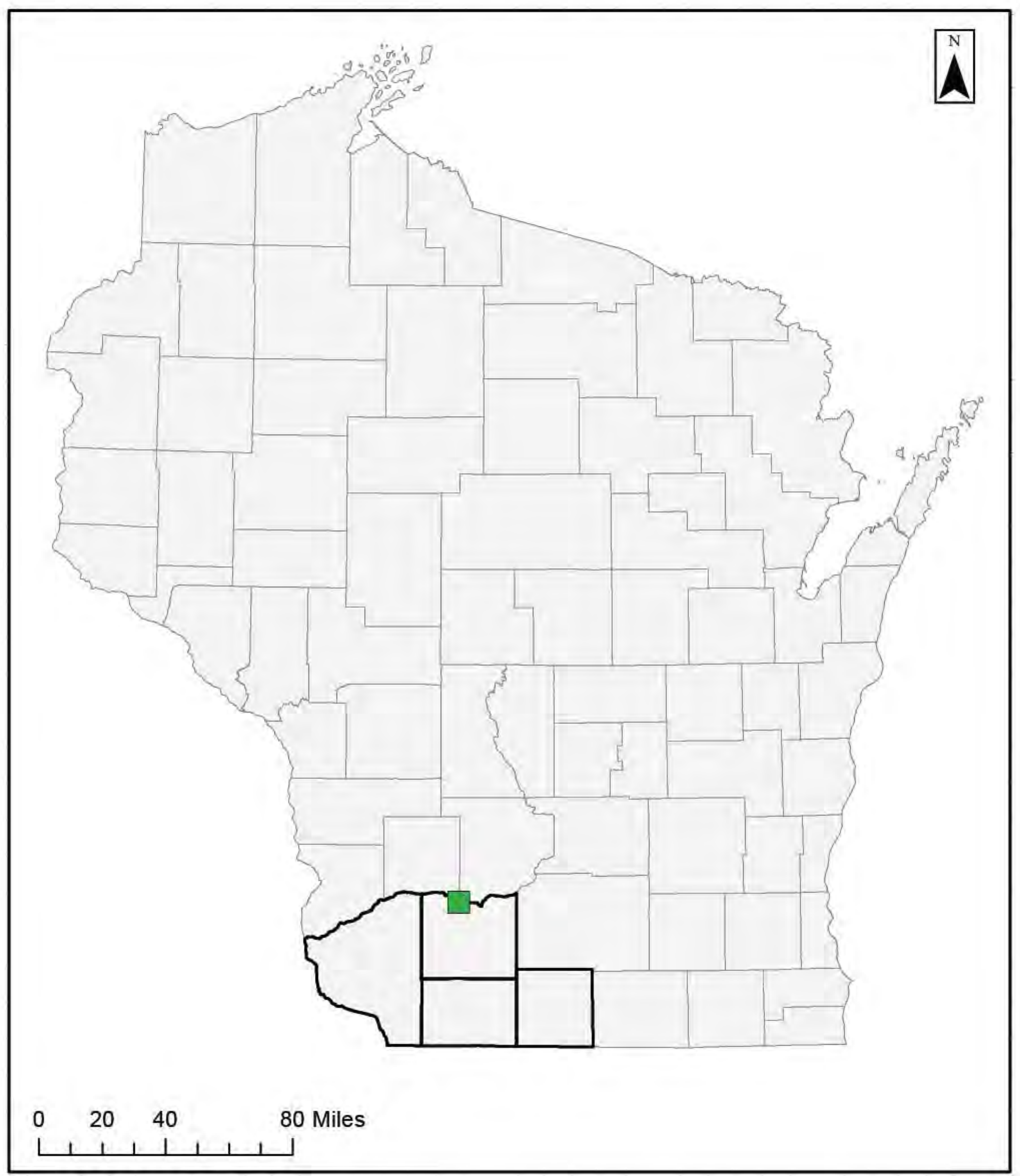


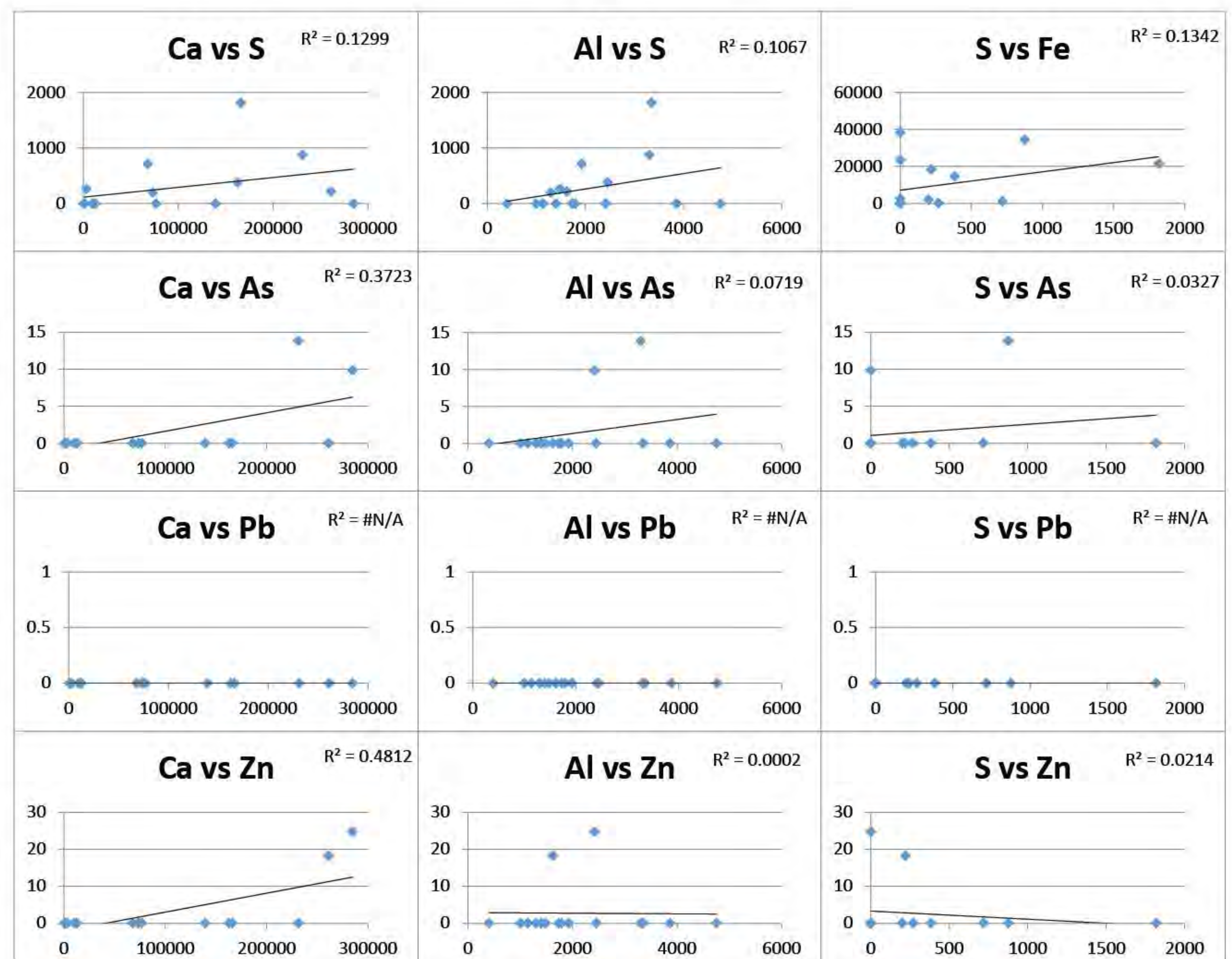




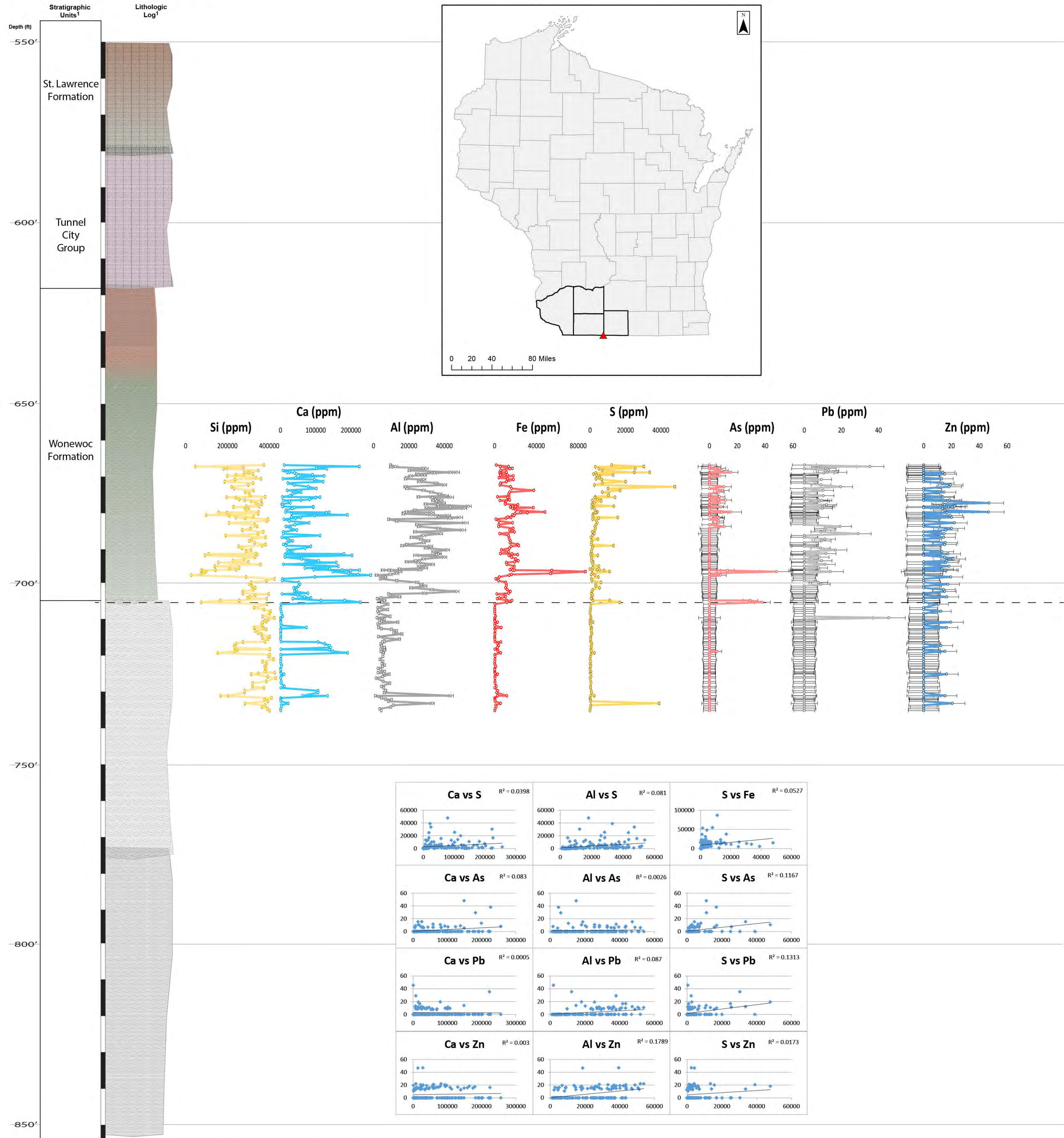
25outcrop Lone Rock Type Area





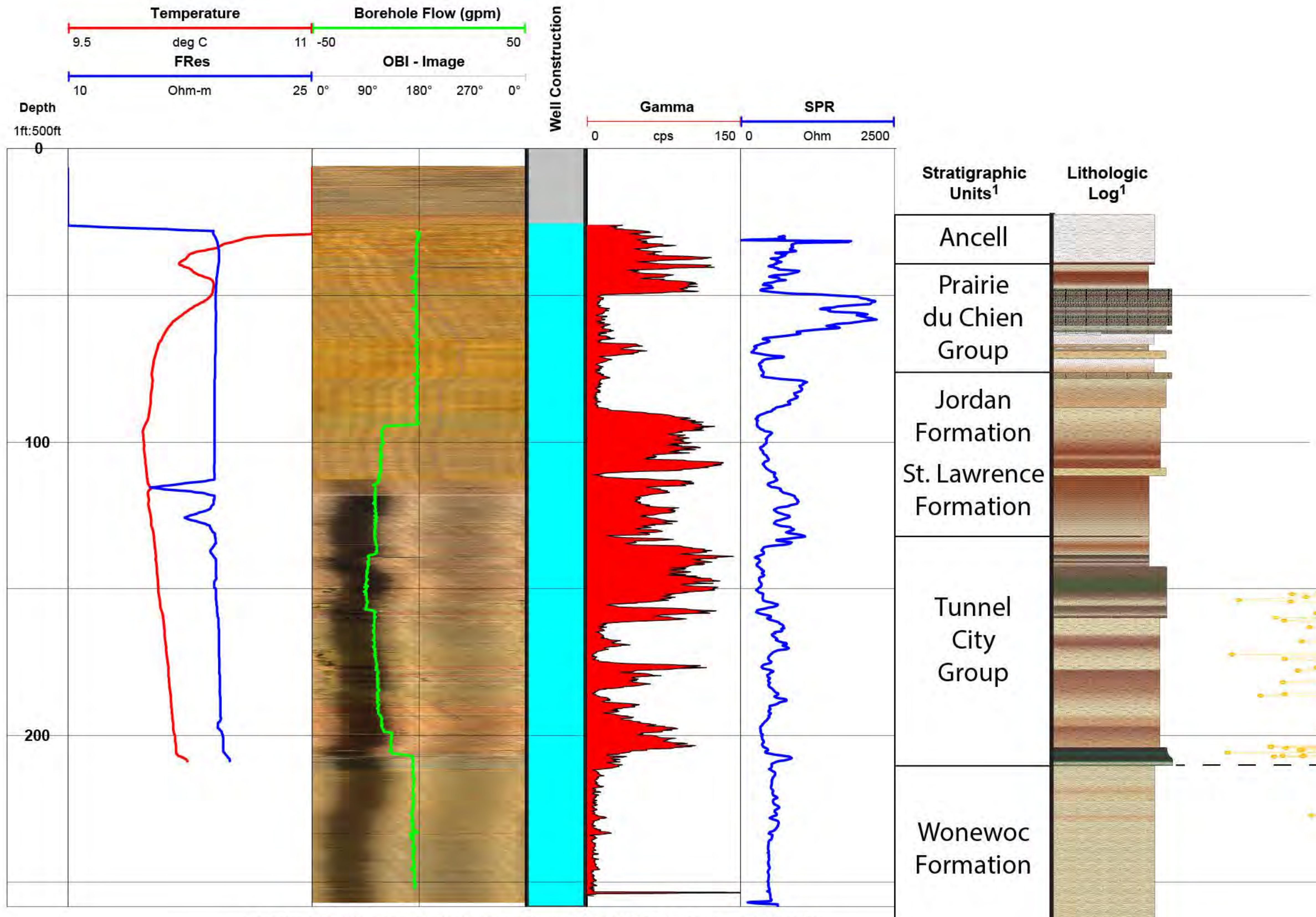


33000331 Commonwealth Edison UPH-1



1: Stratigraphic Units and Lithologic Log interpreted from Commonwealth Edison UPH-1 33000331

11000782 WGNHS Columbus 2



1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Columbus 2 (11000782)

WGNHS Well ID 11000782

DATE 6/25/2012 WELL NAME Columbus 2

LOCATION on top of a Quarry on highway 16 NW of Columbus, WI

COUNTY Columbia LOGGED BY M. Gotkowitz and S Sellwood

LATITUDE 43 deg 20' 32.44" N LONGITUDE 89 deg 2' 58.97" W

LOCATION METHOD: GPS [ ] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION 880 ELEVATION METHOD: DEM [ ] TOPO [X] OTHER +/- 5 feet

WELL DEPTH 258 CASING DEPTH None DEPTH TO WATER 25.4 feet

CASING STICK UP 1.4 File Created on: 8/10/2016 by: MJP

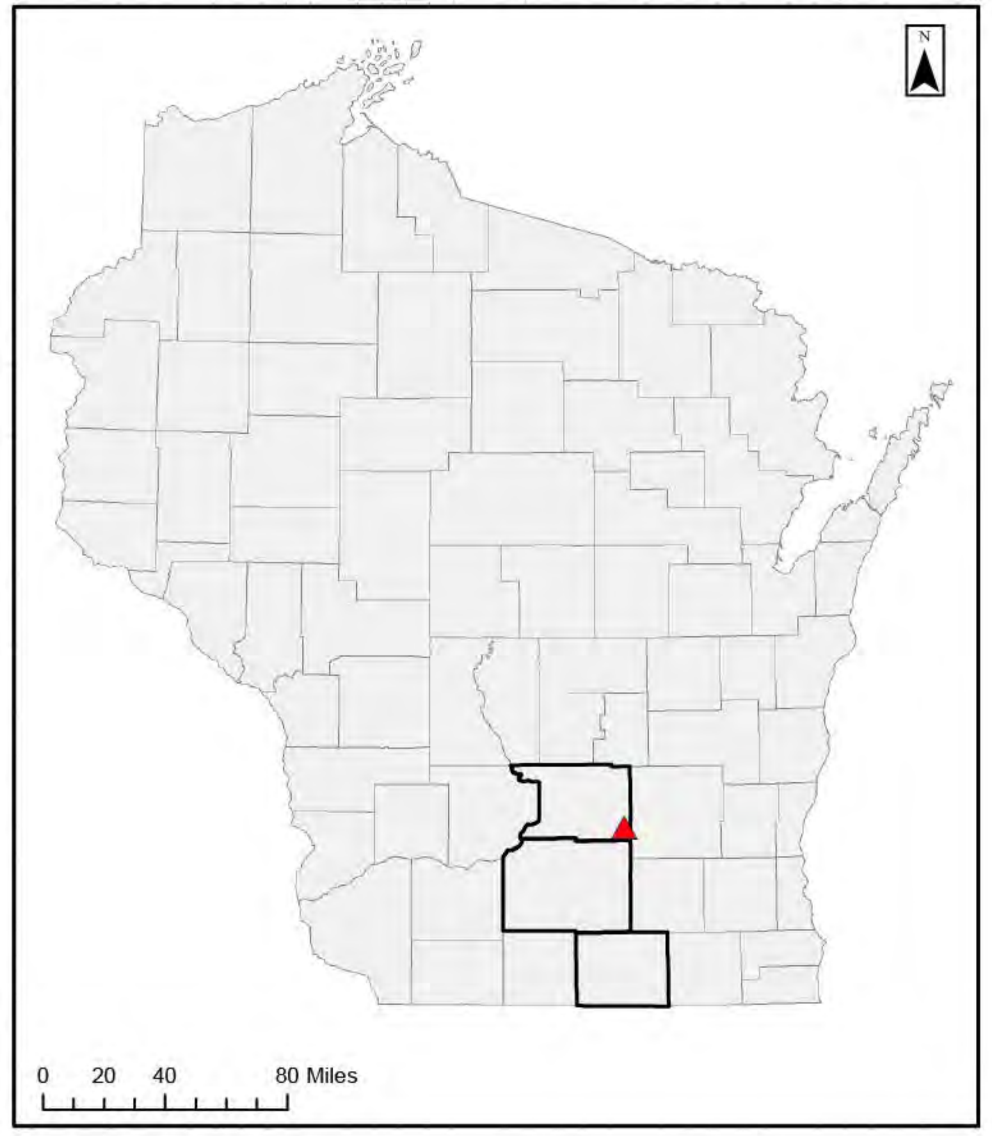
Comments: No casing placed since bedrock was near at land surface. Spinner flow measurement taken under ambient conditions. Spectral gamma, self potential, and normal resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well and water-level as measured on the day of logging.

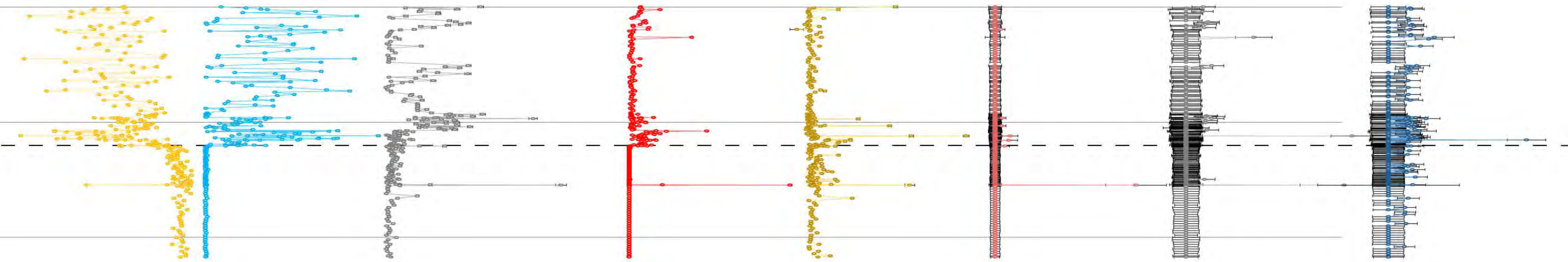
LOGS COLLECTED:

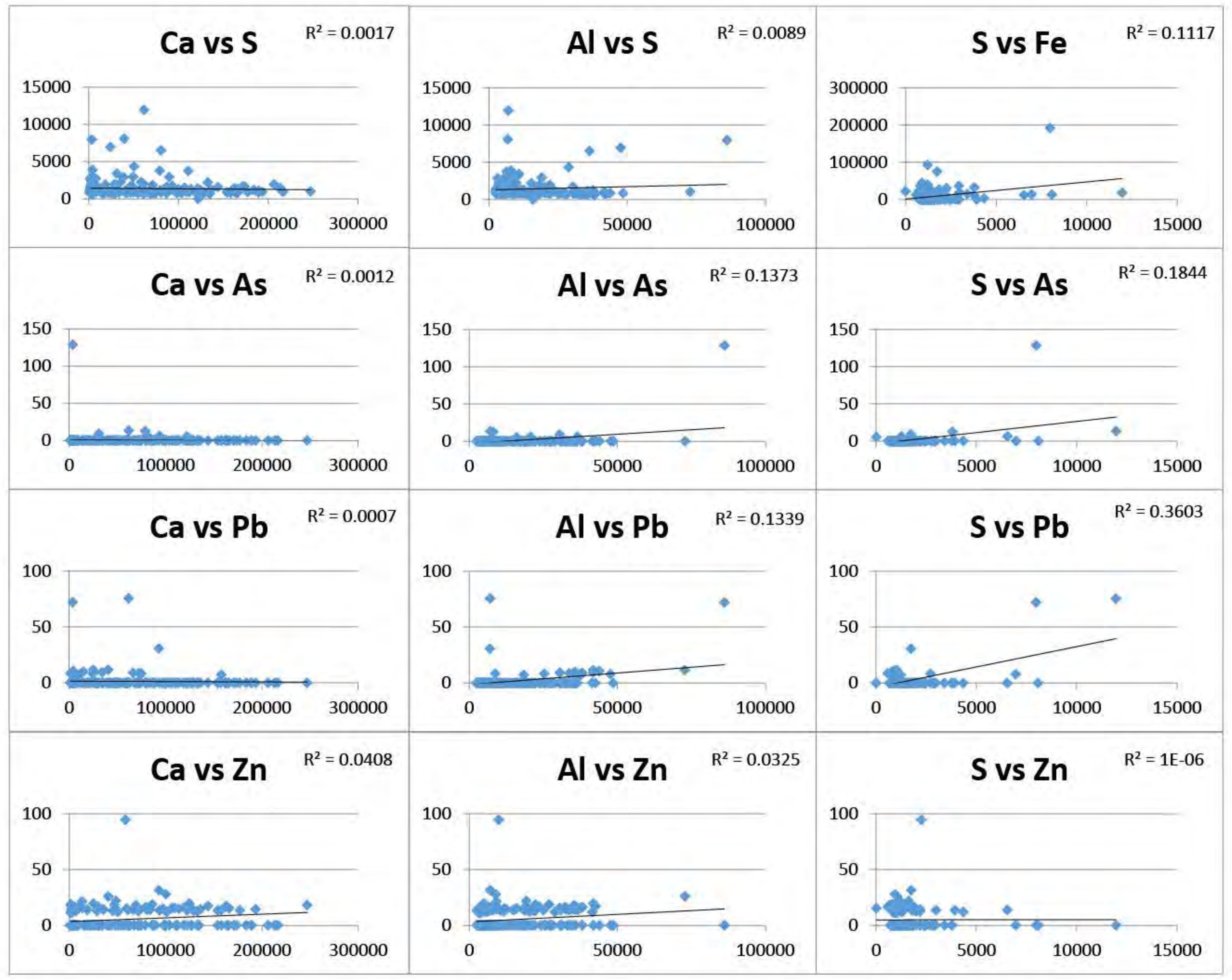
Gamma	X	Fluid Conductivity	
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner - flow up is negative, flow down is positive	X
Self Potential		Optical Borehole Imager	X
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER: Fluid Resistivity	X

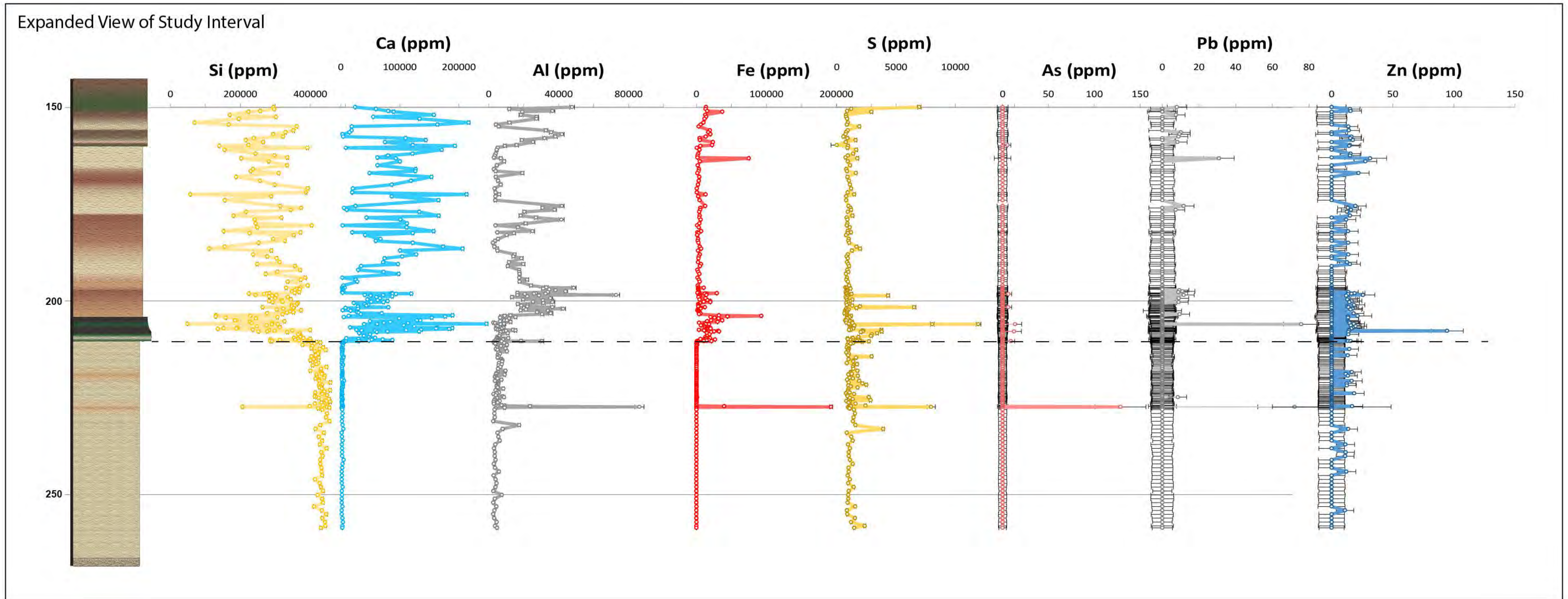
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

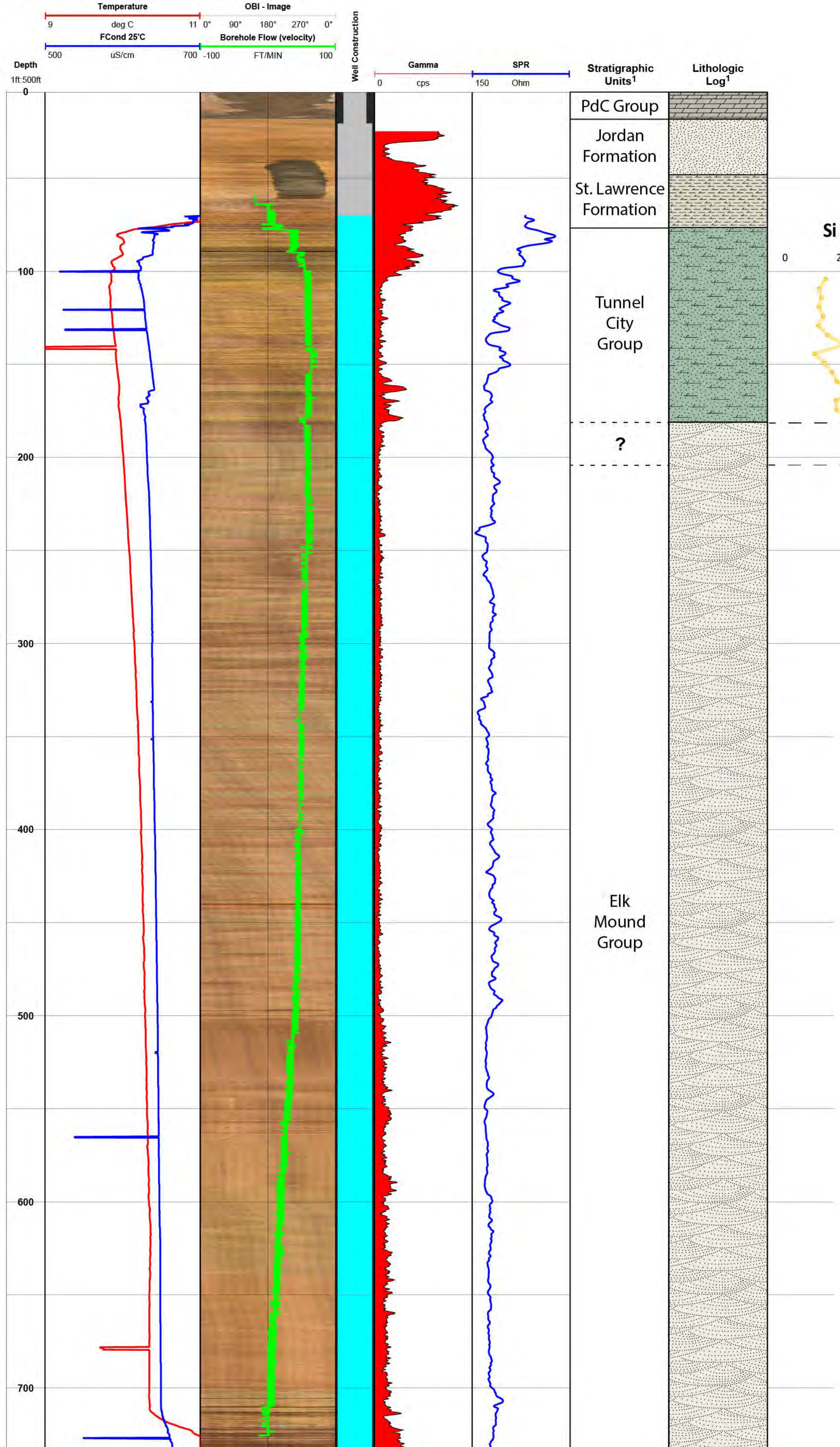


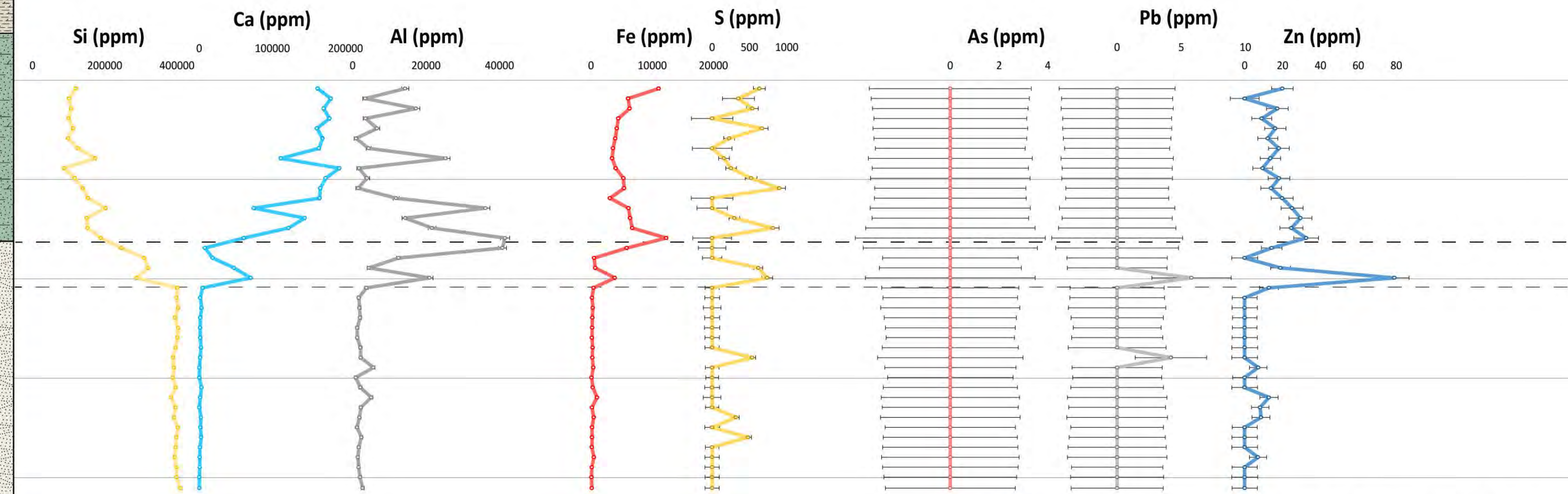


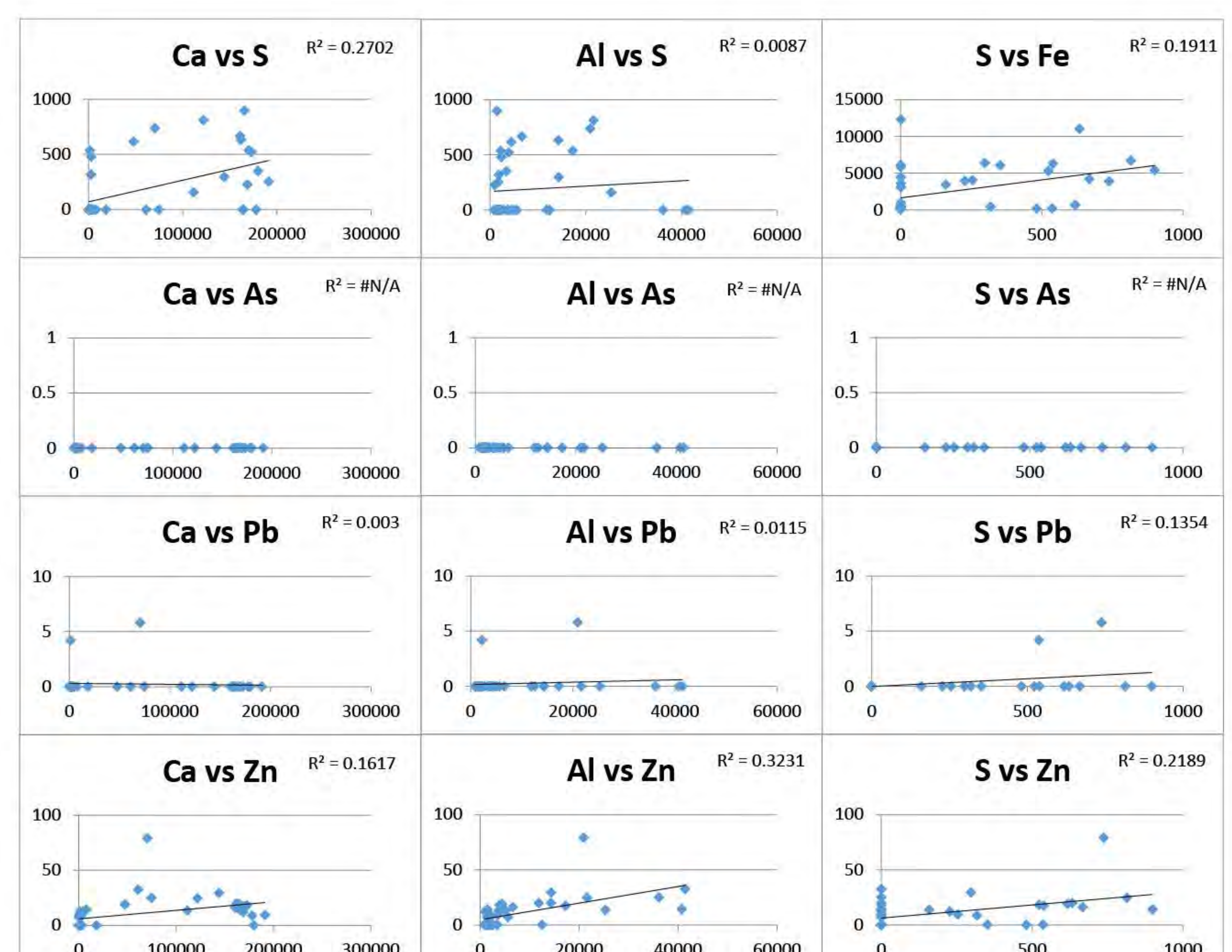




11000783 WGNHS Rio 1







1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log

WGNHS Well ID 11000783

DATE 9/25/2012 WELL NAME Rio 1
LOCATION Rio, WI
COUNTY Columbia LOGGED BY PMC
LATITUDE 43.43739 LONGITUDE -89.26045
LOCATION METHOD: GPS [X] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER
ELEVATION 1030.06 ELEVATION METHOD: DEM [X] TOPO [ ] OTHER
WELL DEPTH 738 feet CASING DEPTH 20.5 DEPTH TO WATER 70
CASING STICK UP 1 File Created on: 8/12/2016 by: MJP

Comments: Spinner flow measurement taken under ambient conditions. Borehole flow is reported as a velocity since the borehole diameter, which is needed for conversion to a flowrate, is not available. SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging.

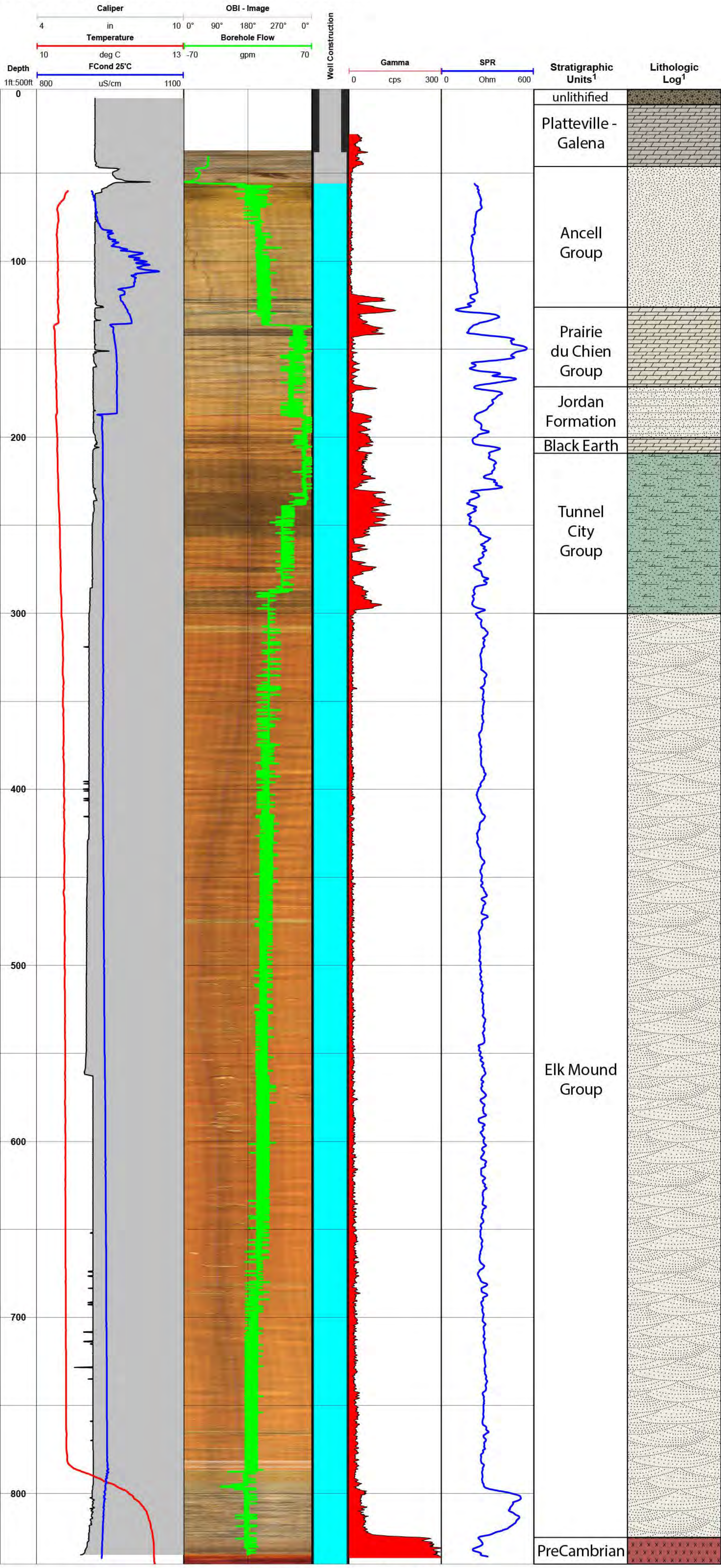
LOGS COLLECTED:

Gamma	X	Fluid Conductivity	X
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner - flow up is negative, flow down is positive	X
Self Potential		Optical Borehole Imager	X
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER:	

Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

11000784 WGNHS Manke Farm Test Hole



1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log

WGNHS Well ID 11000784

DATE *Oct - Nov 2012* WELL NAME *Manke Farm*

LOCATION *Manke Rd. South of Wiener Rd.*

COUNTY *Columbia* LOGGED BY *PMC*

LATITUDE *43.288229* LONGITUDE *-89.04474*

LOCATION METHOD: GPS [x] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION *941* ELEVATION METHOD: DEM [x] TOPO [ ] OTHER

WELL DEPTH *840* CASING DEPTH *38* DEPTH TO WATER *56*

CASING STICK UP *1.3* File Created on: *8/10/2016* by: *MJP*

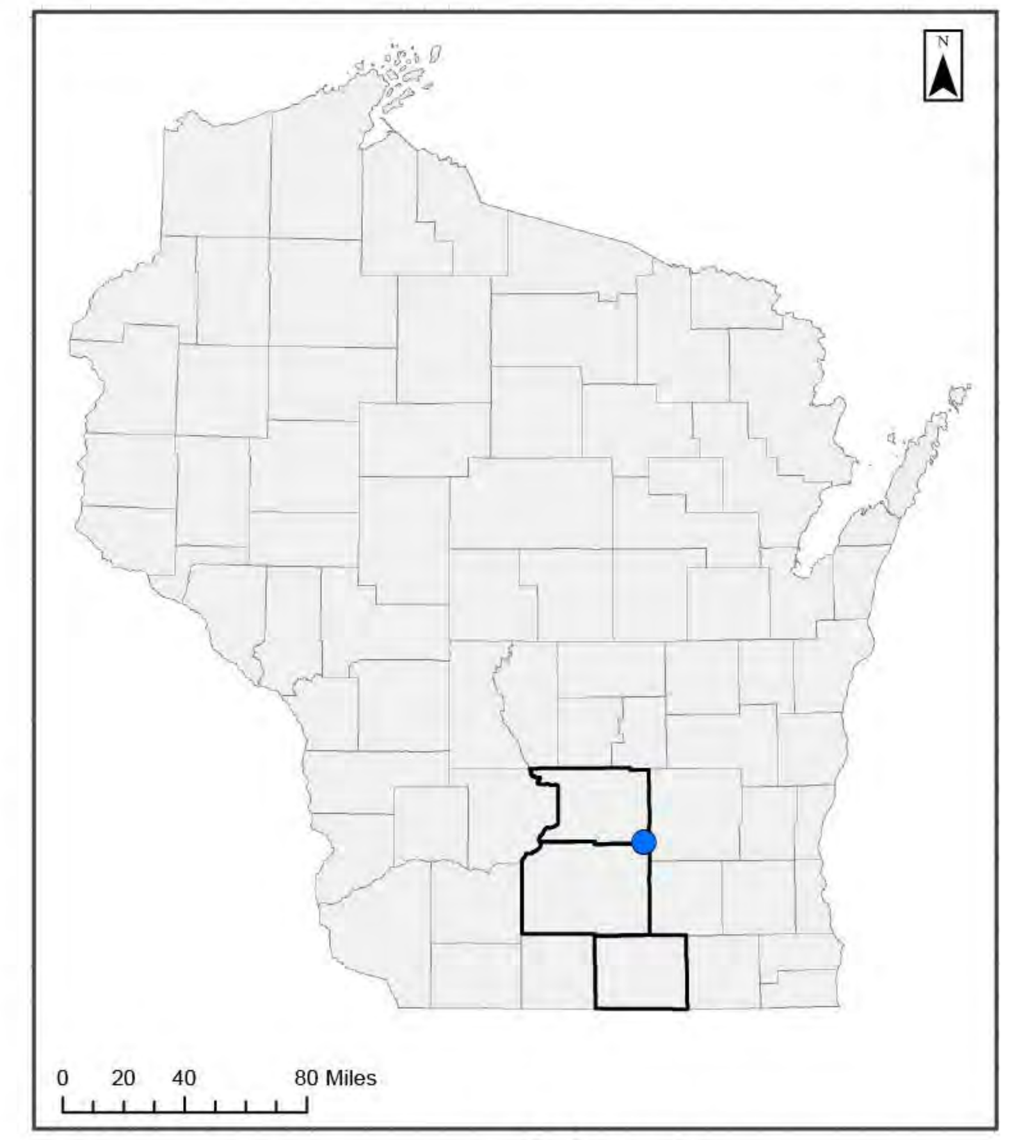
Comments: *SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. Flow logs taken in May 2013. Cascading water in well. Lots of iron bacteria settled to bottom. Spinner flow measurements taken under ambient conditions. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging.*

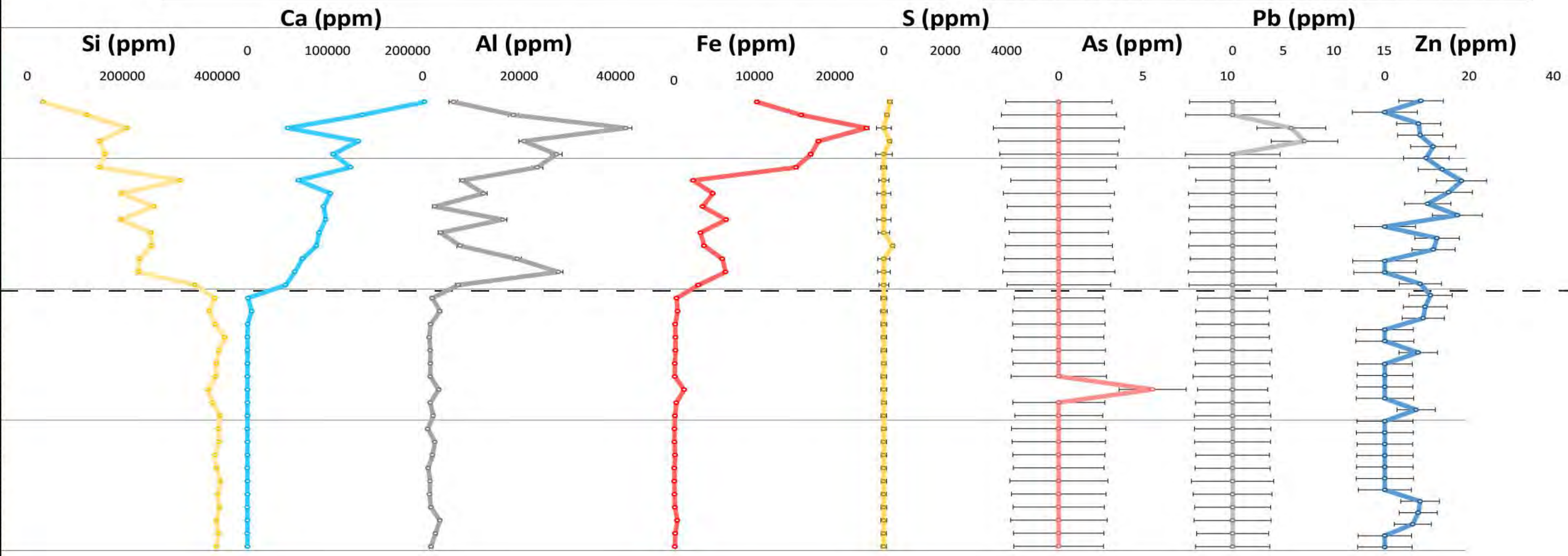
LOGS COLLECTED:

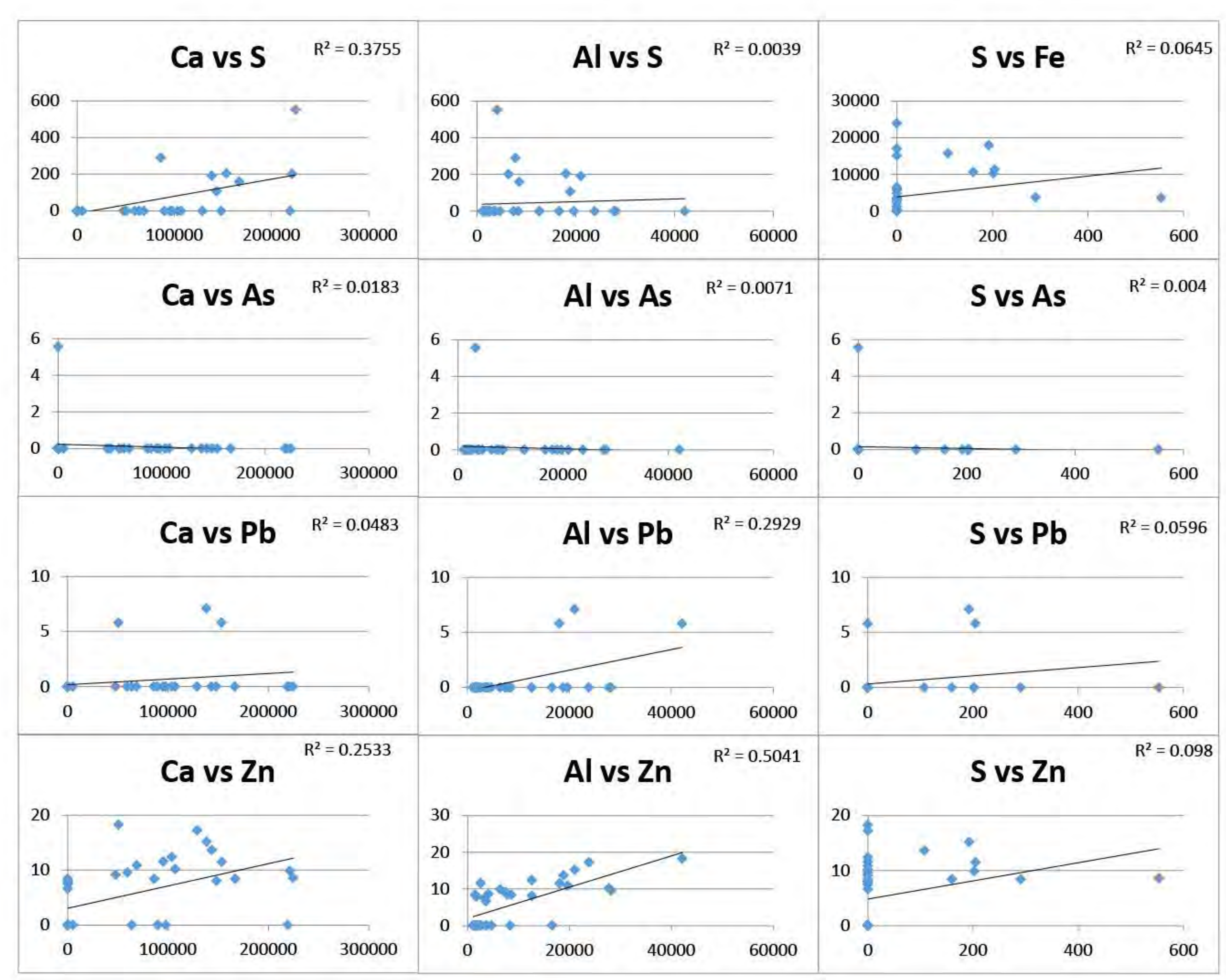
Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	x
Self Potential		Optical Borehole Imager	x
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER:	

Unless Noted:
- *all depths are in feet*
- *well depth, casing depth and depth to water are interpreted from geophysical log*
- *datum is the top of casing*

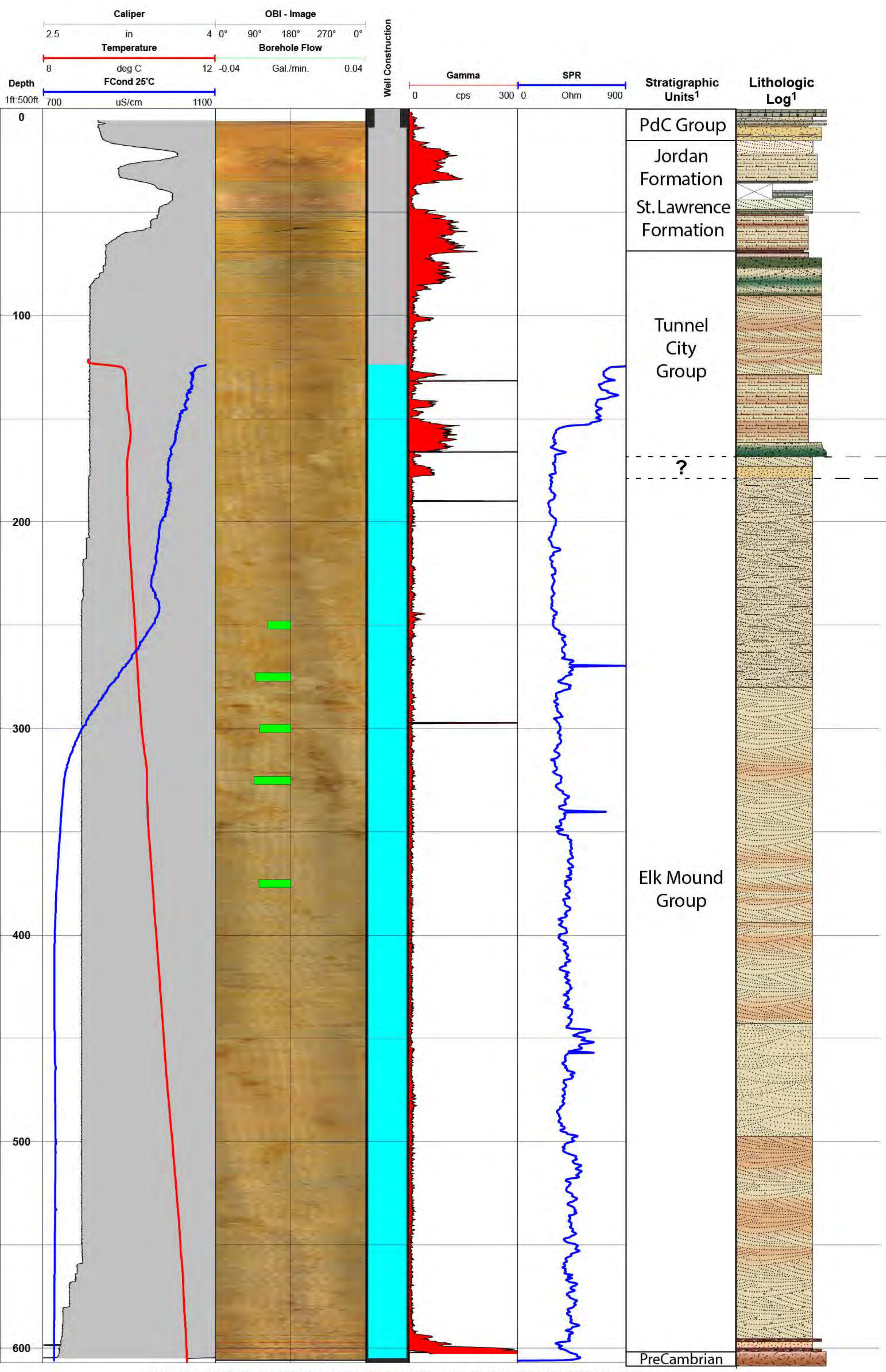
For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

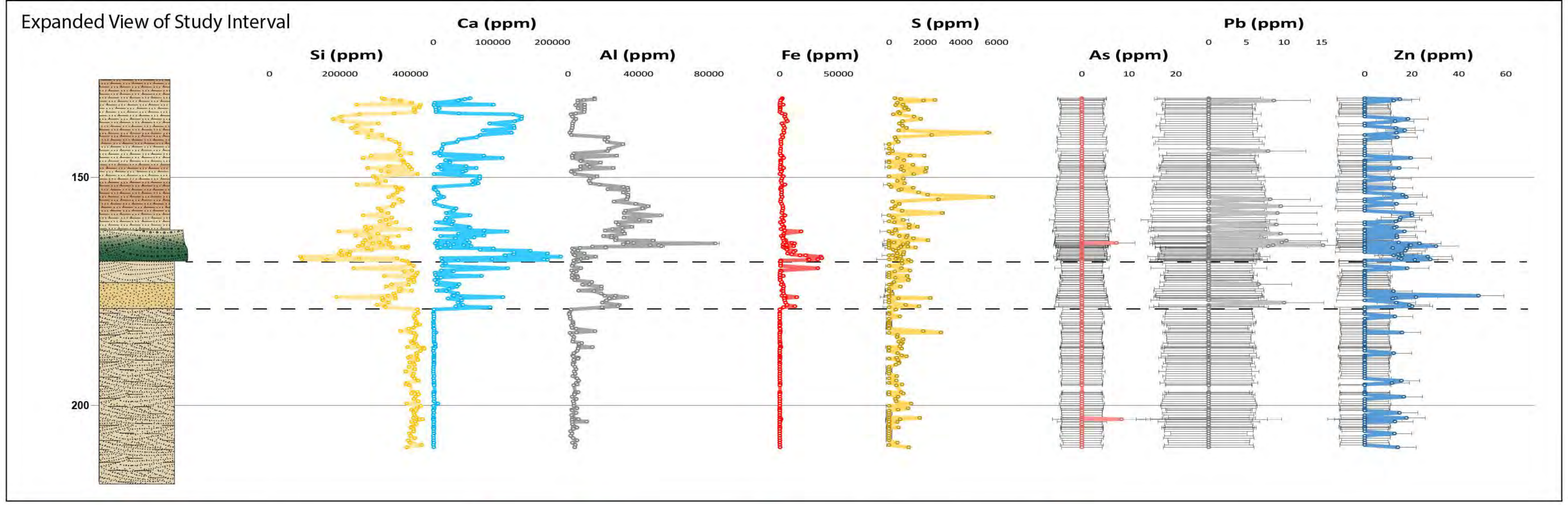


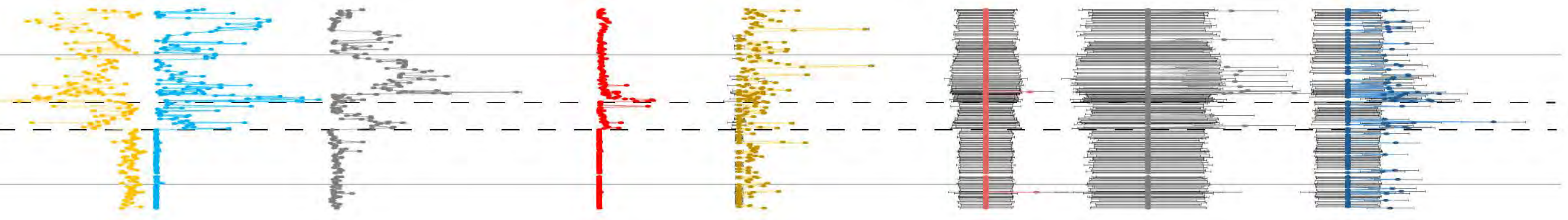


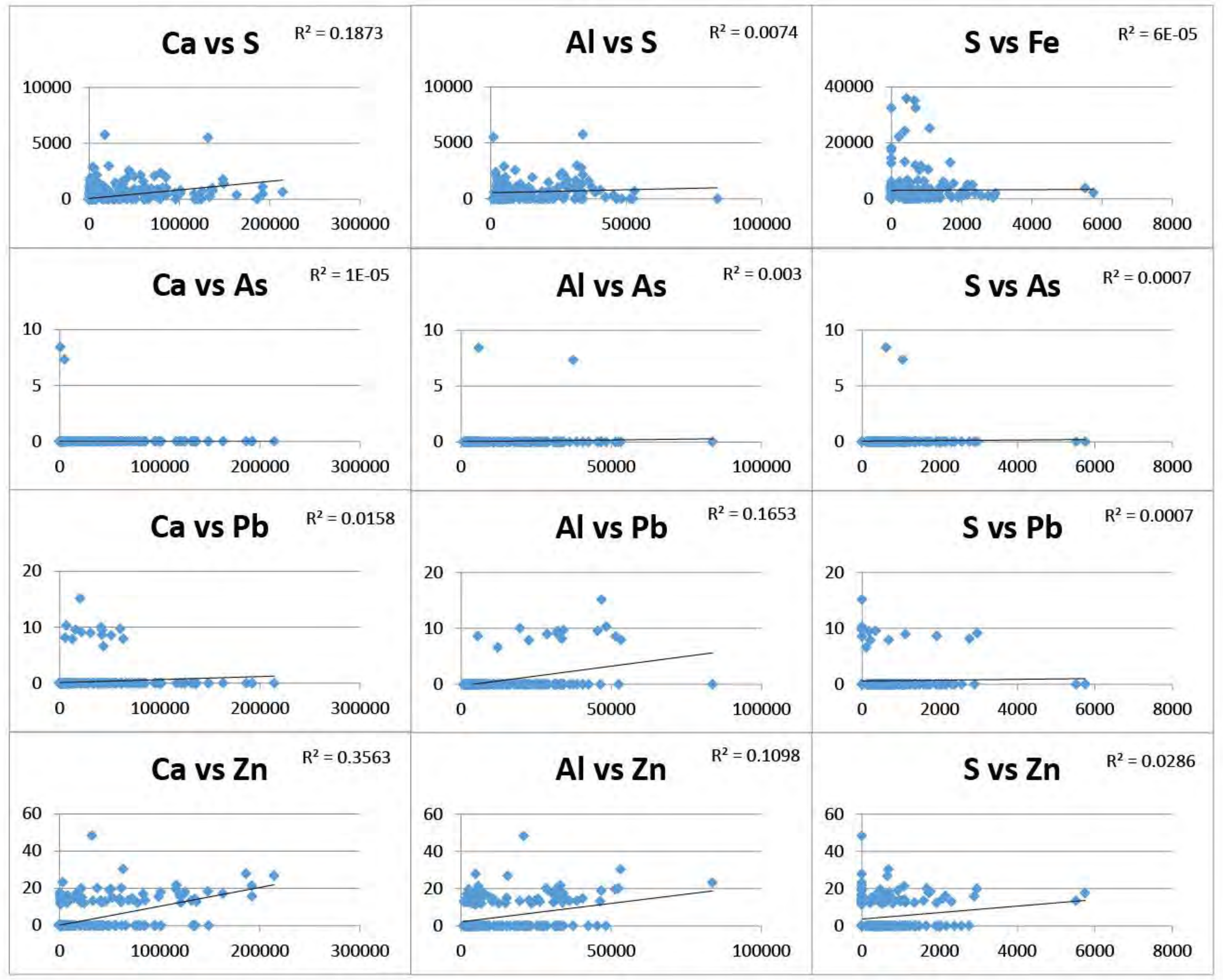


11005900 WGNHS Triemstra Quarry









WGNHS Well ID ***11005900***

DATE *11/1-11/4/13* WELL NAME *Triemstra Quarry*

LOCATION *NW corner of quarry 1km W, .75km Nof intersection of CTH EE & E*

COUNTY *Columbia* LOGGED BY *P. Chase*

LATITUDE *43.620585* LONGITUDE *-89.274949*

LOCATION METHOD: GPS [x] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION *920* ELEVATION METHOD: DEM [ ] TOPO [ ] OTHER *10M DEM*

WELL DEPTH *605* CASING DEPTH *9* DEPTH TO WATER *123.8*

CASING STICK UP *0.4* File Created on: *8/10/2016* by: *MJP*

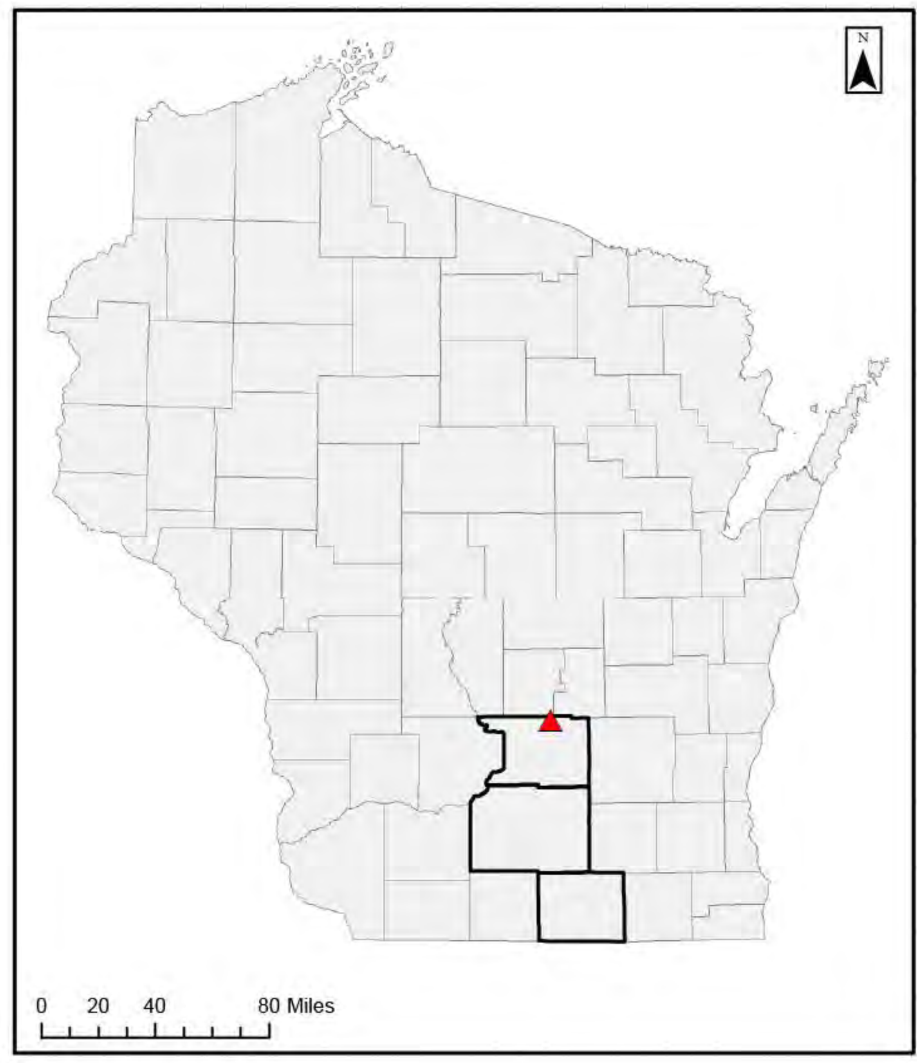
Comments: *SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. For the heat pulse flow meter, flow up is negative, flow down is positive.*

LOGS COLLECTED:

Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	x
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	x
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER:	

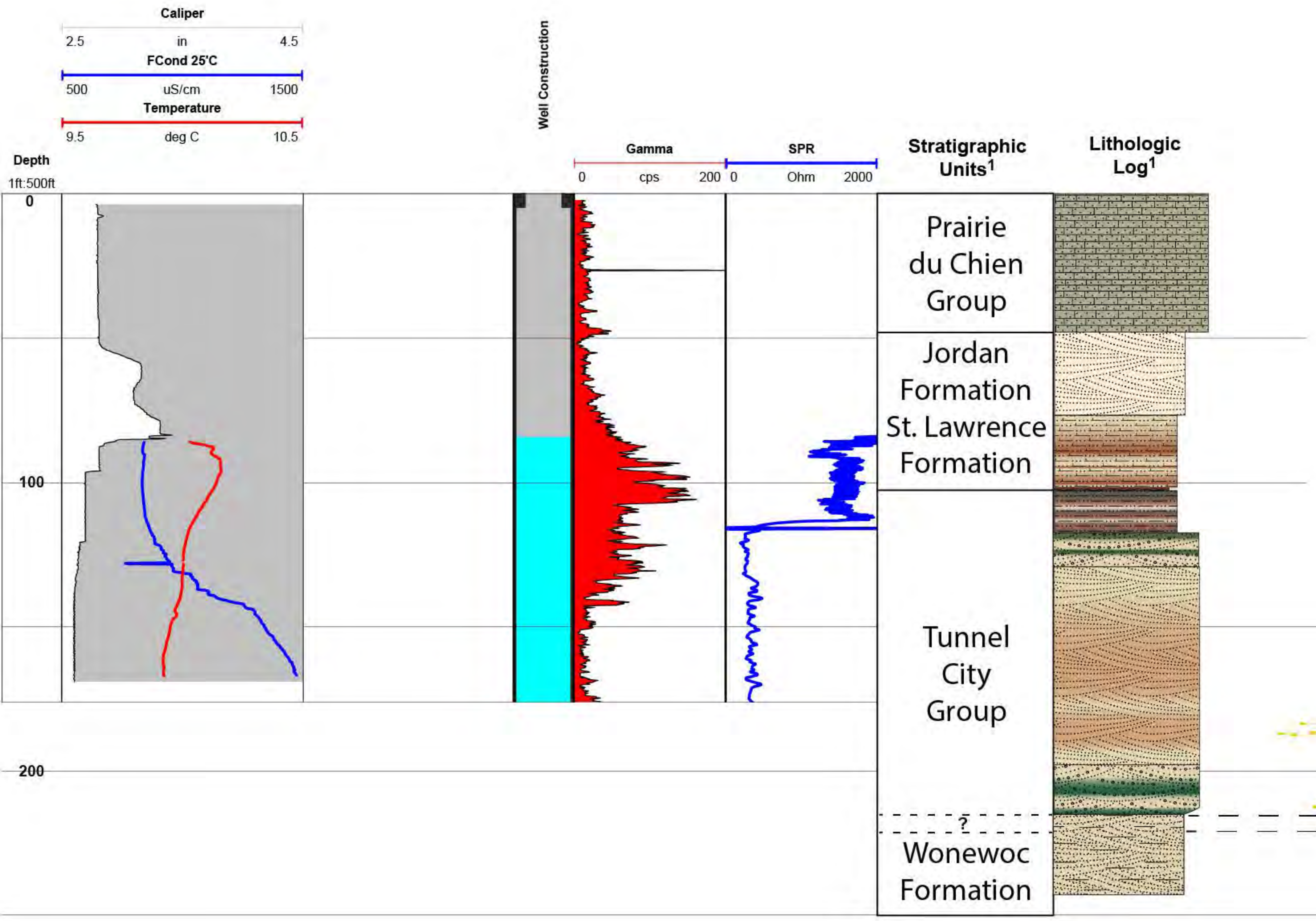
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu



1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Triemstra Quarry (11005900)

11005901 WGNHS Arlington Quarry



WGNHS Well ID 11005901

DATE 11/7/2013 WELL NAME Arlington Quarry

LOCATION NE 1/4 Sec 36 R10E T10N

COUNTY Columbia LOGGED BY PMC

LATITUDE 43.30479 LONGITUDE -89.364459

LOCATION METHOD: GPS [x] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION 1031.4 ELEVATION METHOD: DEM [ ] TOPO [ ] OTHER

WELL DEPTH 176 CASING DEPTH 5 DEPTH TO WATER 84.36

CASING STICK UP 1.1 File Created on: 8/10/2016 by: MJP

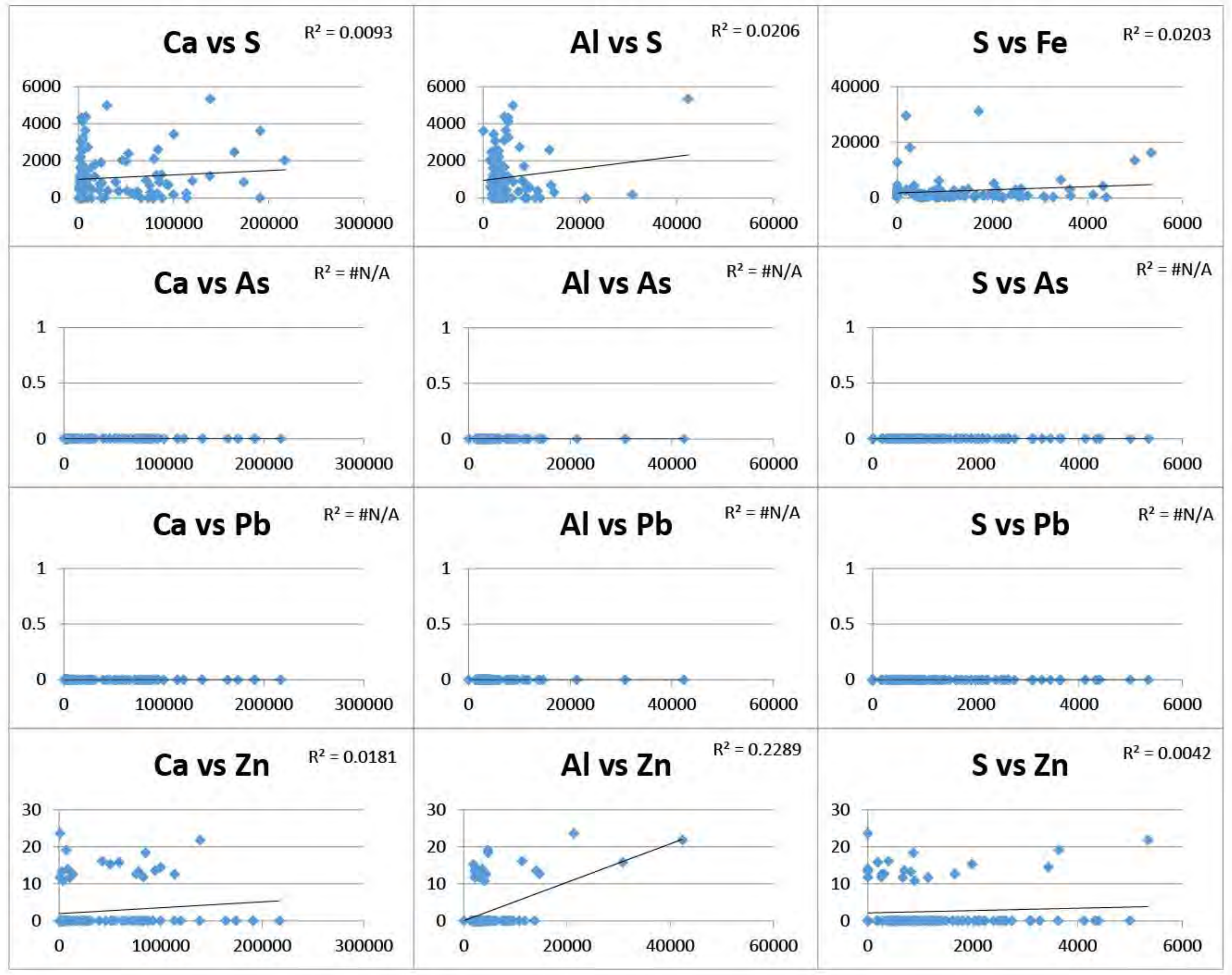
Comments: SPR, SP, and Normal resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. Erroneous temperature anomaly near 128-ft depth was removed from profile.

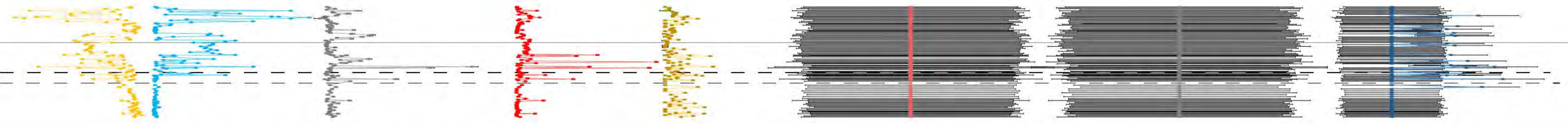
LOGS COLLECTED:

Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER:	

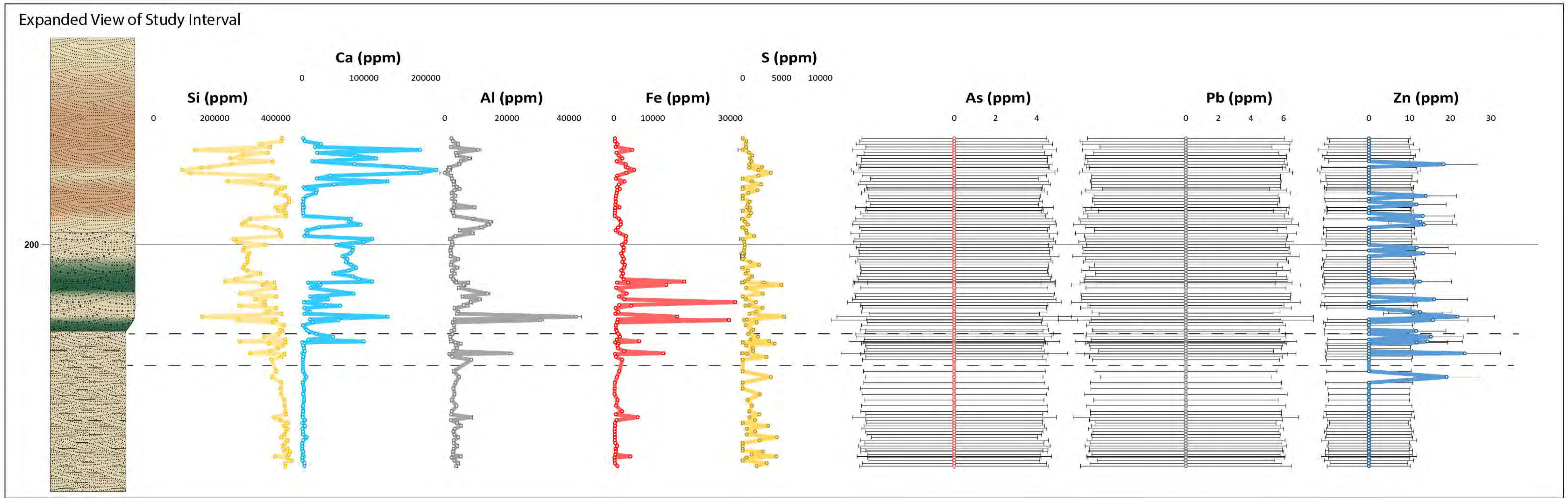
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu





1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Arlington Quarry (11005901)



11005908 WGNHS Stevenson 2

WGNHS Well ID 11005908

DATE 10/3/14 **WELL NAME** Stevenson Quarry #2 core

LOCATION 1900' N of Richards Rd, 450' W of Pine Holllow Rd, Arlington, WI

COUNTY Columbia **LOGGED BY** P. Chase

LATITUDE 43.357446 **LONGITUDE** -89.444337

LOCATION METHOD: GPS [X] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION 1091 **ELEVATION METHOD:** DEM [X] TOPO [ ] OTHER

WELL DEPTH 203 **CASING DEPTH** 4.7 **DEPTH TO WATER** 149.6

CASING STICK UP 1.2 File Created on: 8/11/2016 by: MJP

Comments: SPR and SP profiles were collected for this well but only SPR is presetned in this log. The Well Construction field depicts the well, casing , and water-level as measured on the day of logging.

LOGS COLLECTED:

Gamma	X	Fluid Conductivity	X
Caliper	X	Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner (- flow up is negative, flow down is positive)	
Self Potential		Optical Borehole Imager	X
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER:	

Unless Noted:
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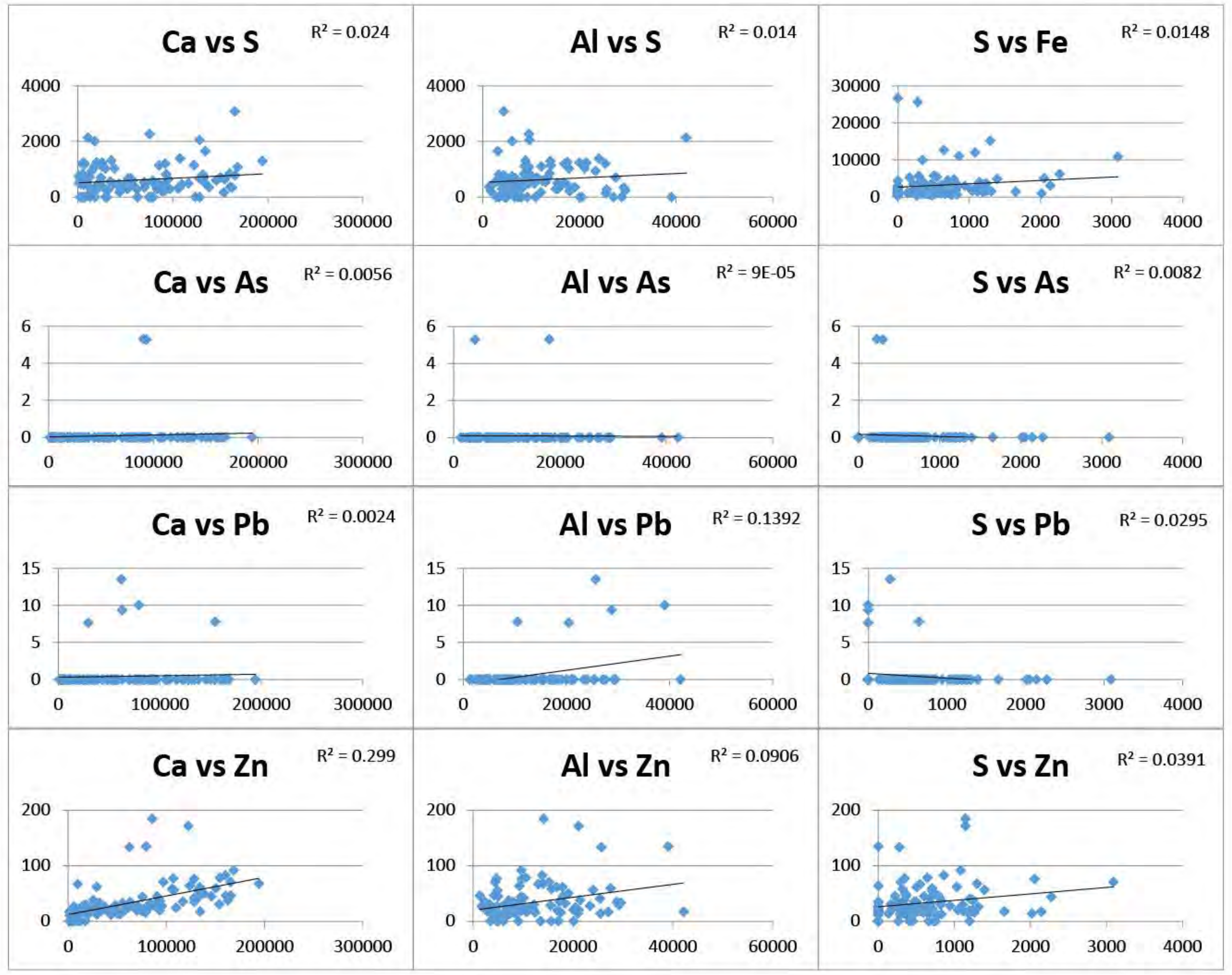
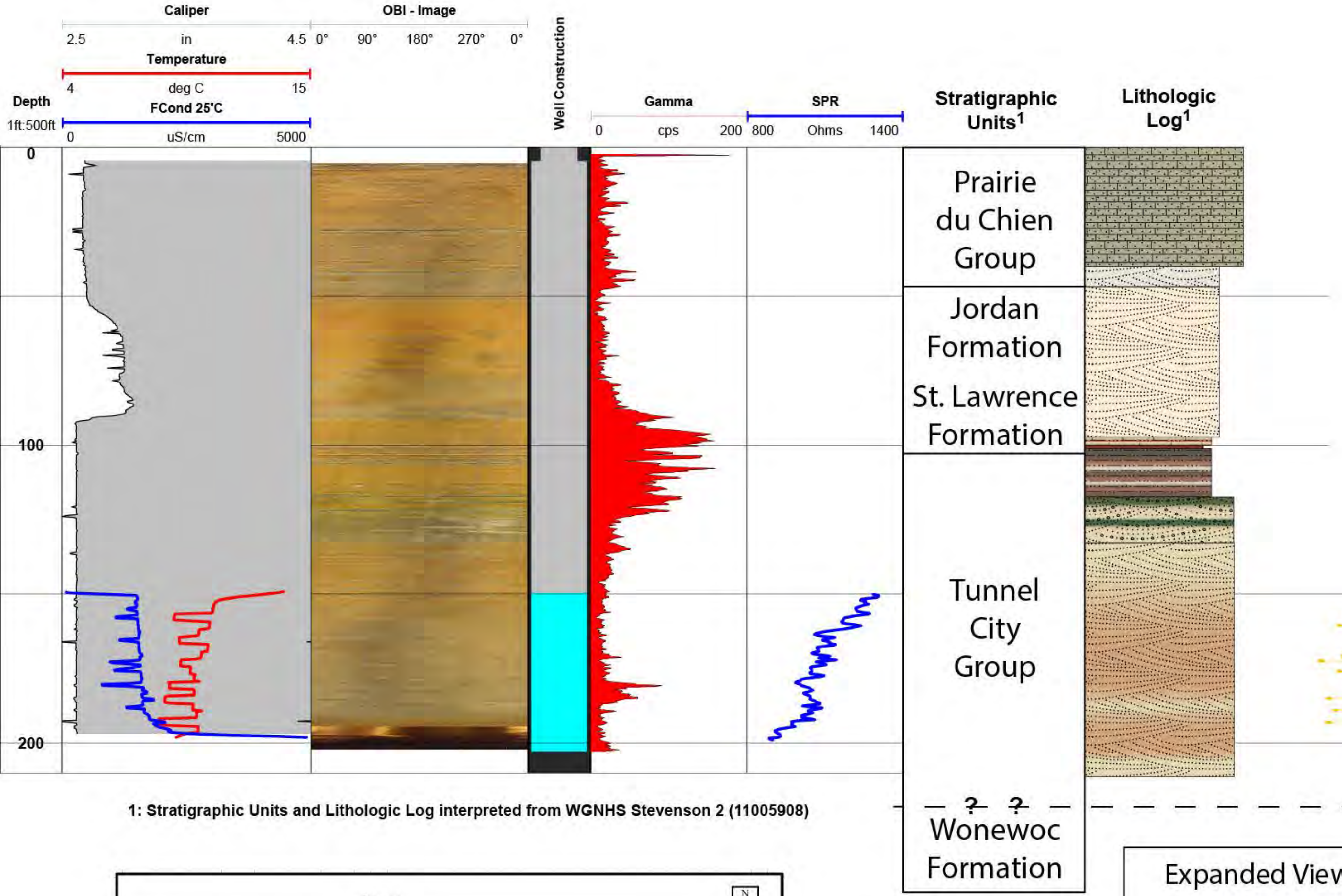
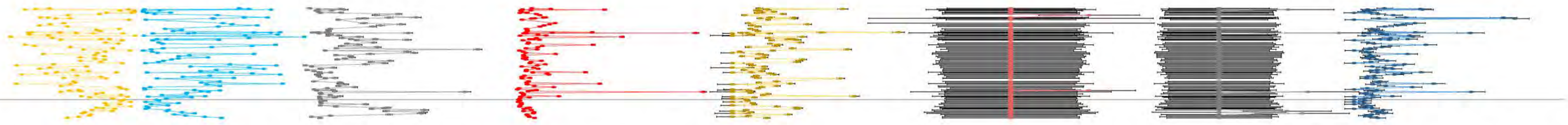
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

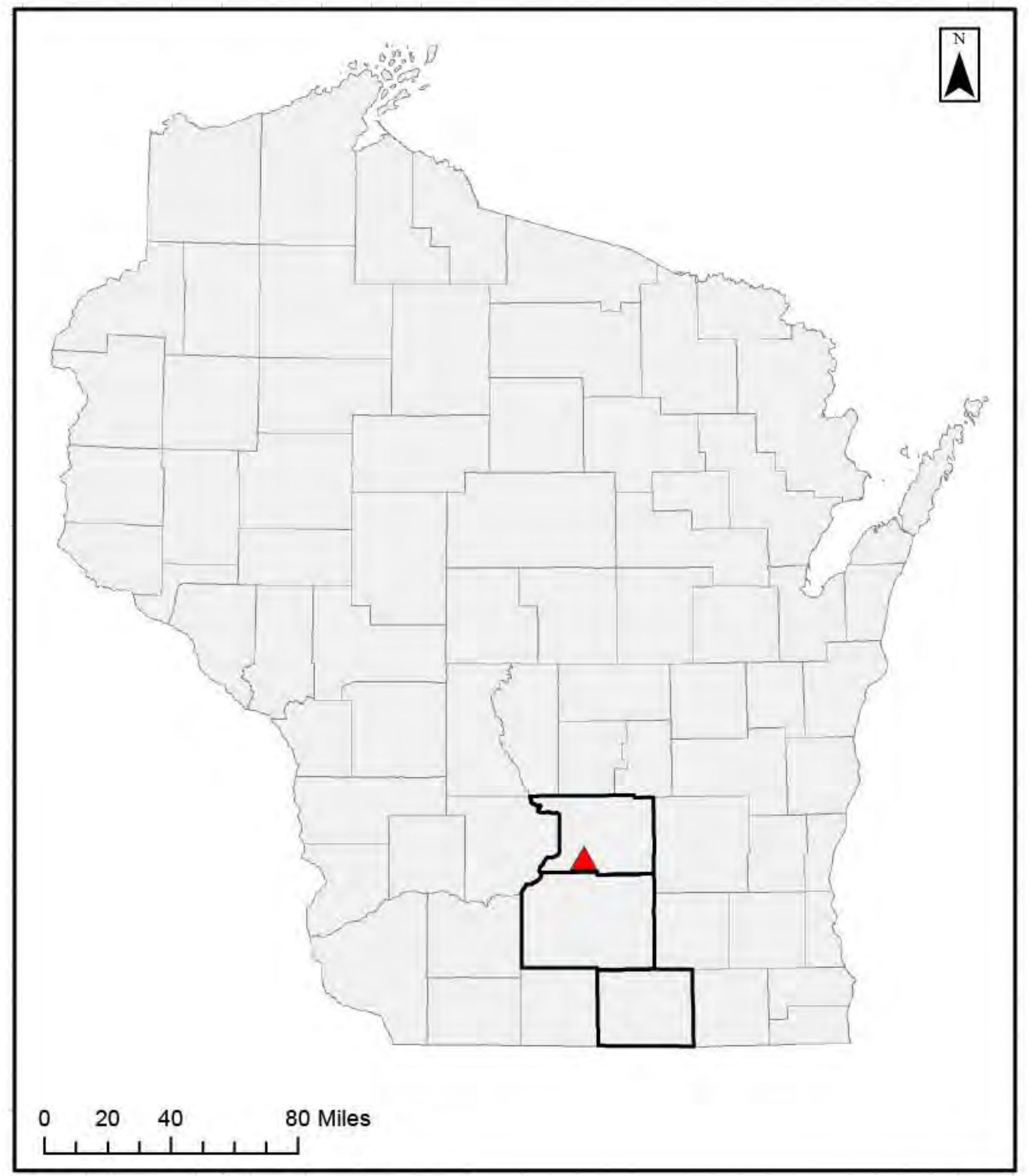
For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

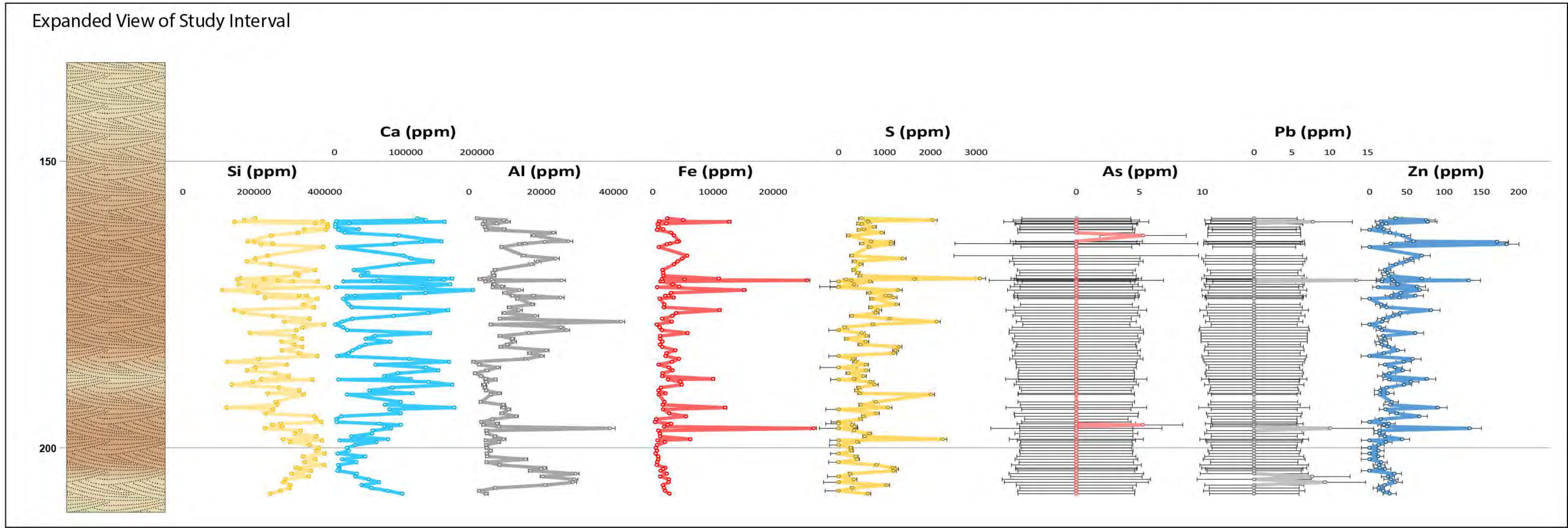




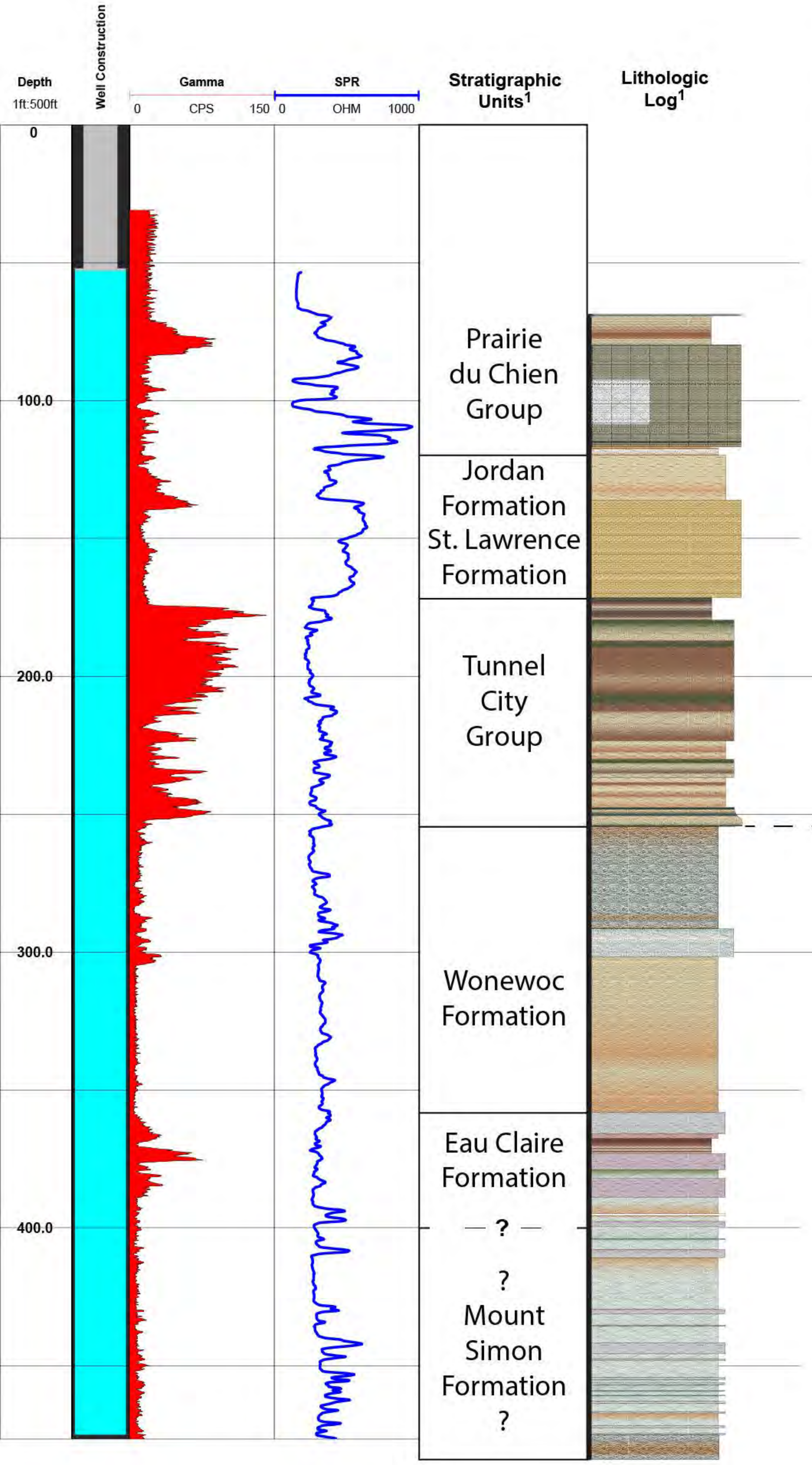


1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Stevenson 2 (11005908)





13001216 Cottage Grove Hydrite MP-18



WGNHS Well ID 13001216

DATE	9/18/2007
WELL NAME	Cottage Grove - Hydrite MP18
LOCATION	NE, NE Sec. 14 T7N R11E
COUNTY	Dane
LOGGED BY	Unknown
LATITUDE	289,742 (wtm-meters)
LONGITUDE	588,870 (wtm-meters)
LOCATION METHOD:	GPS ☐ AIR PHOTO/TOPO ☐ PLSS ☐ OTHER
ELEVATION	912.28
ELEVATION METHOD:	DEM ☐ TOPO ☐ OTHER Unknown
WELL DEPTH	475
CASING DEPTH	52
DEPTH TO WATER	53 (estimate)
CASING STICK UP	
File Created on:	8/12/2016
by:	MJP

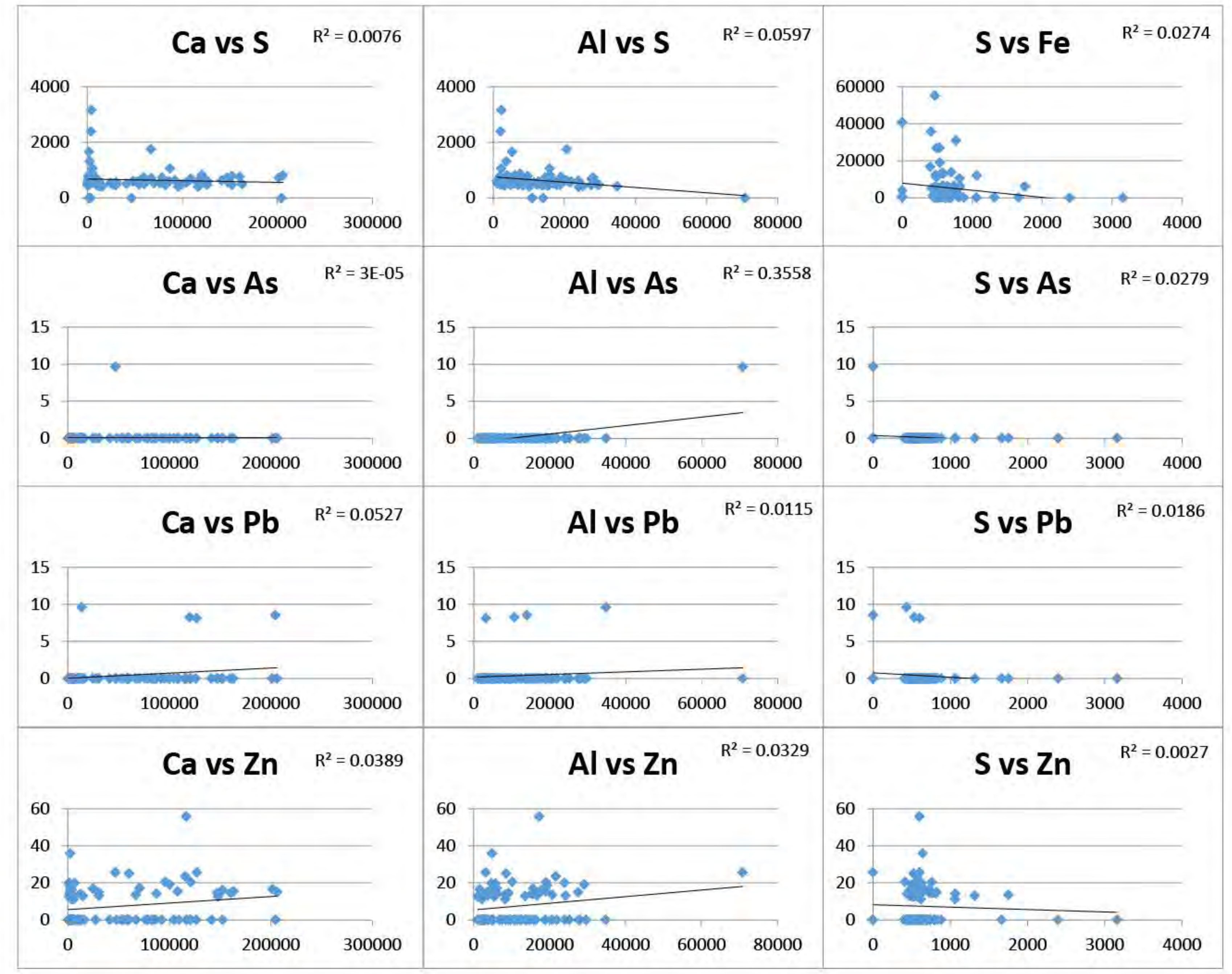
Comments: SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well and water-level as measured on the day of logging.

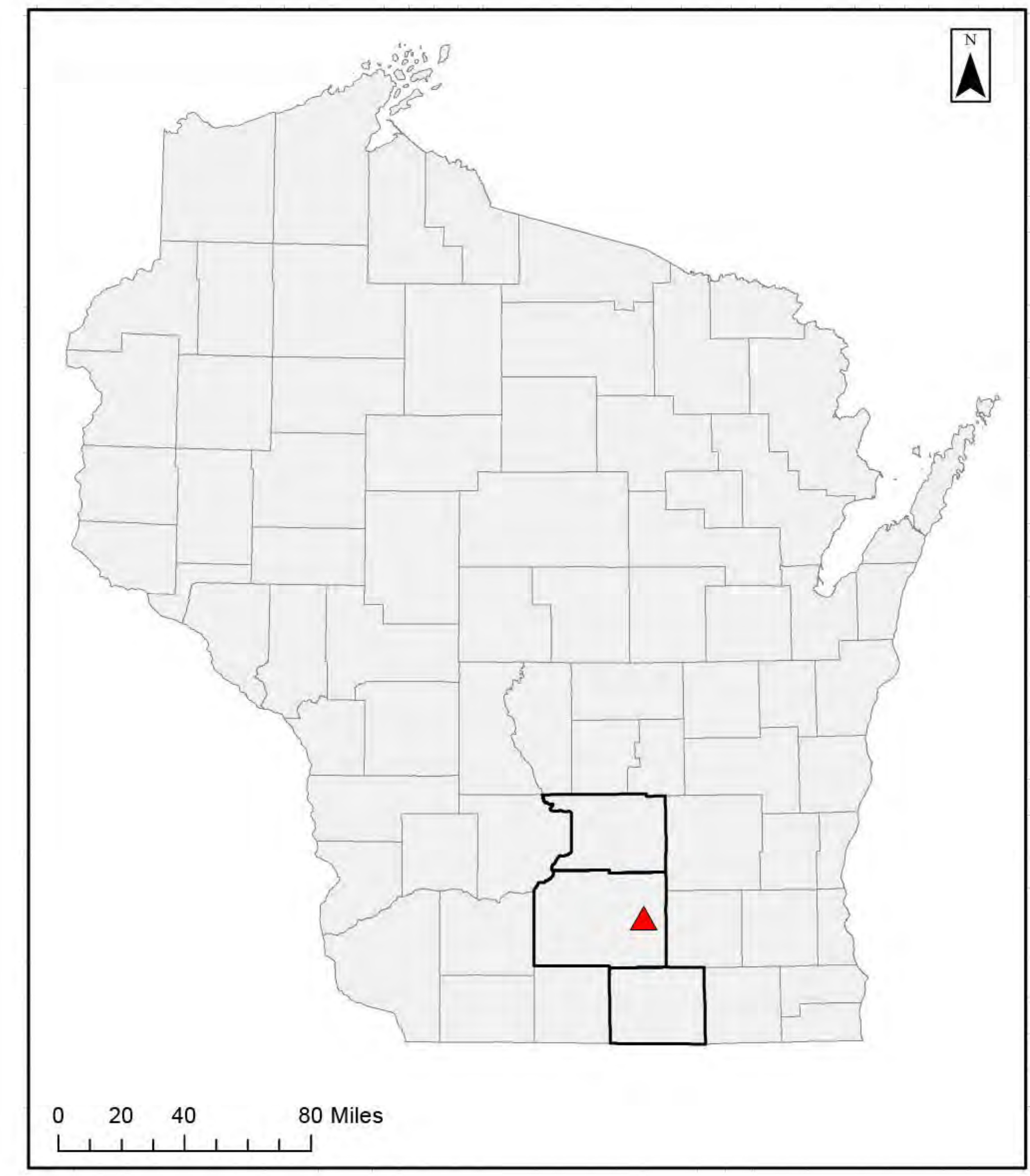
LOGS COLLECTED:

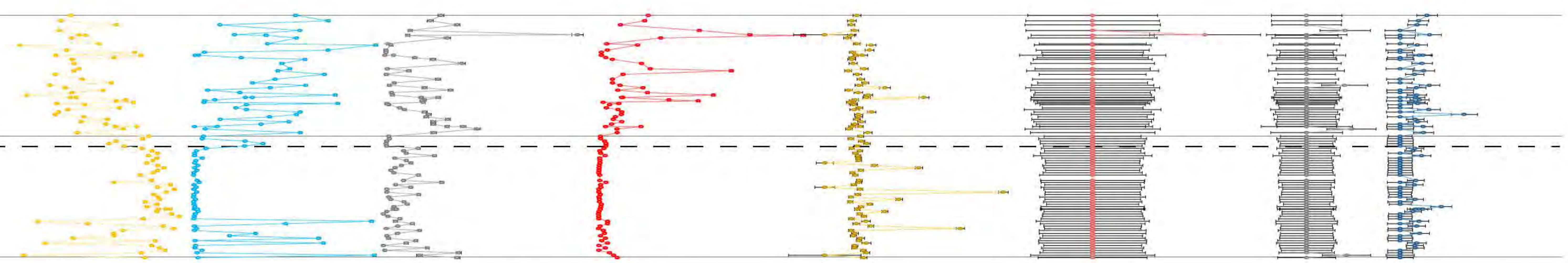
Gamma	X	Fluid Conductivity	
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature		OTHER:	

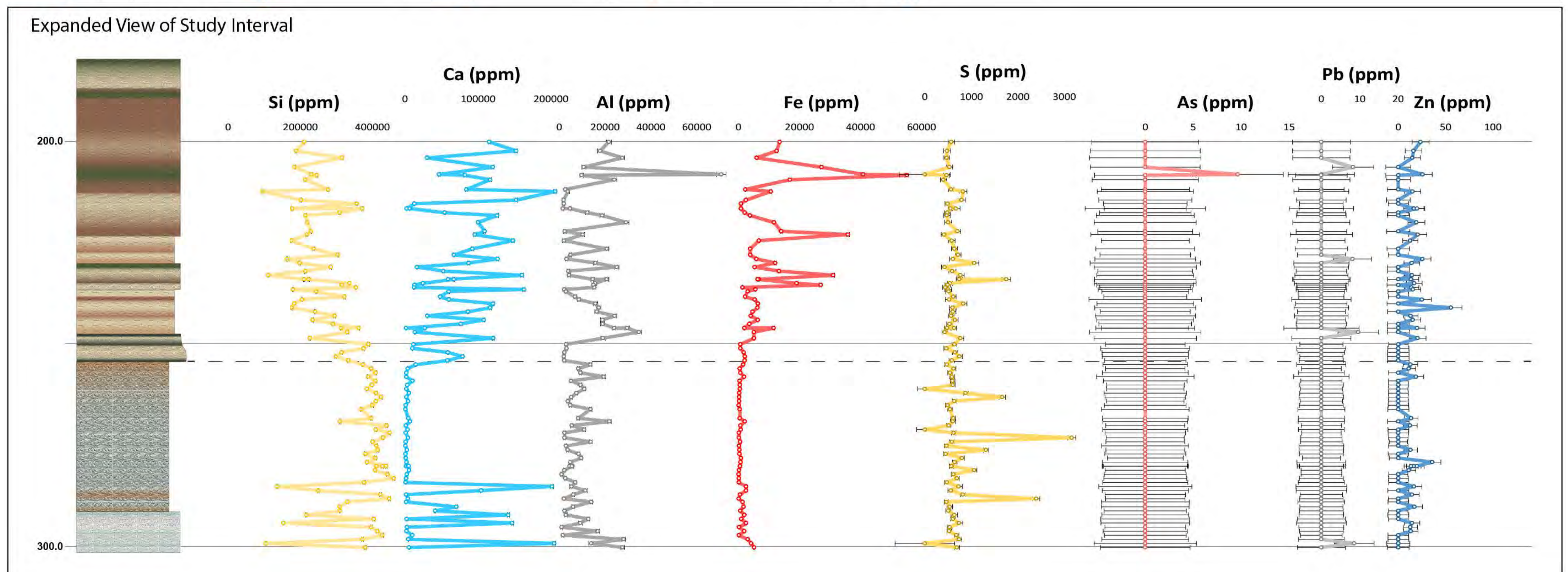
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu



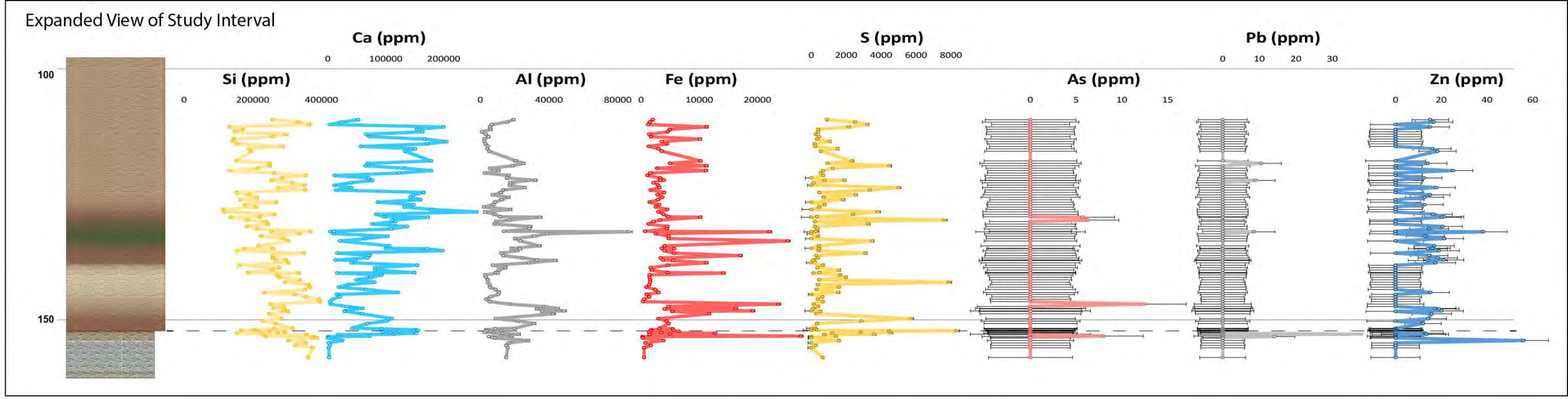






1: Stratigraphic Units and Lithologic Log interpreted from Cottage Grove Hydrite MP-18 (13001216)

13001466 Nine Springs Core Hole (NS-2)



1: Stratigraphic Units and Lithologic Log interpreted from Nine Springs Core Hole (NS-2) (13001466)

WGNHS Well ID 13001466

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY WGNHS

DATE *4/2012* WELL NAME *Nine Springs 2*

LOCATION *Nine Springs - MMSD Facility*

COUNTY *Dane* LOGGED BY *D. Hart*

LATITUDE *43.03639* LONGITUDE *-89.35967*

LOCATION METHOD: GPS *x* AIR PHOTO/TOPO PLSS OTHER

ELEVATION *863* ELEVATION METHOD: DEM *x* TOPO OTHER

WELL DEPTH *158* CASING DEPTH *58* DEPTH TO WATER *47*

CASING STICK UP *2* File Created on: *8/11/2016* by: *MJP*

Comments: *SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of the logging. Acoustic Borehole Imaging (ABI) was also performed in this well but is not included in this log.*

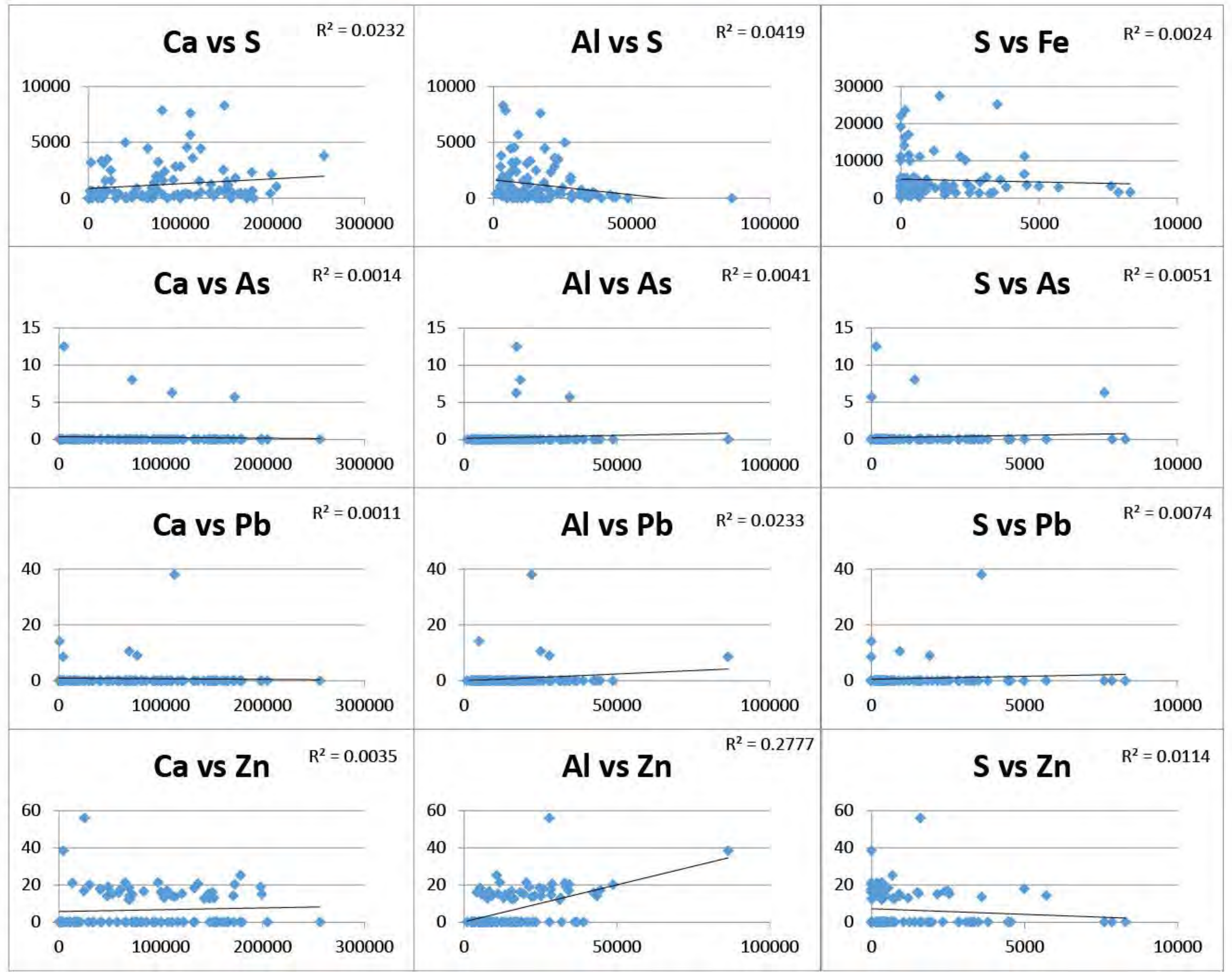
LOGS COLLECTED:

Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	x
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER:	

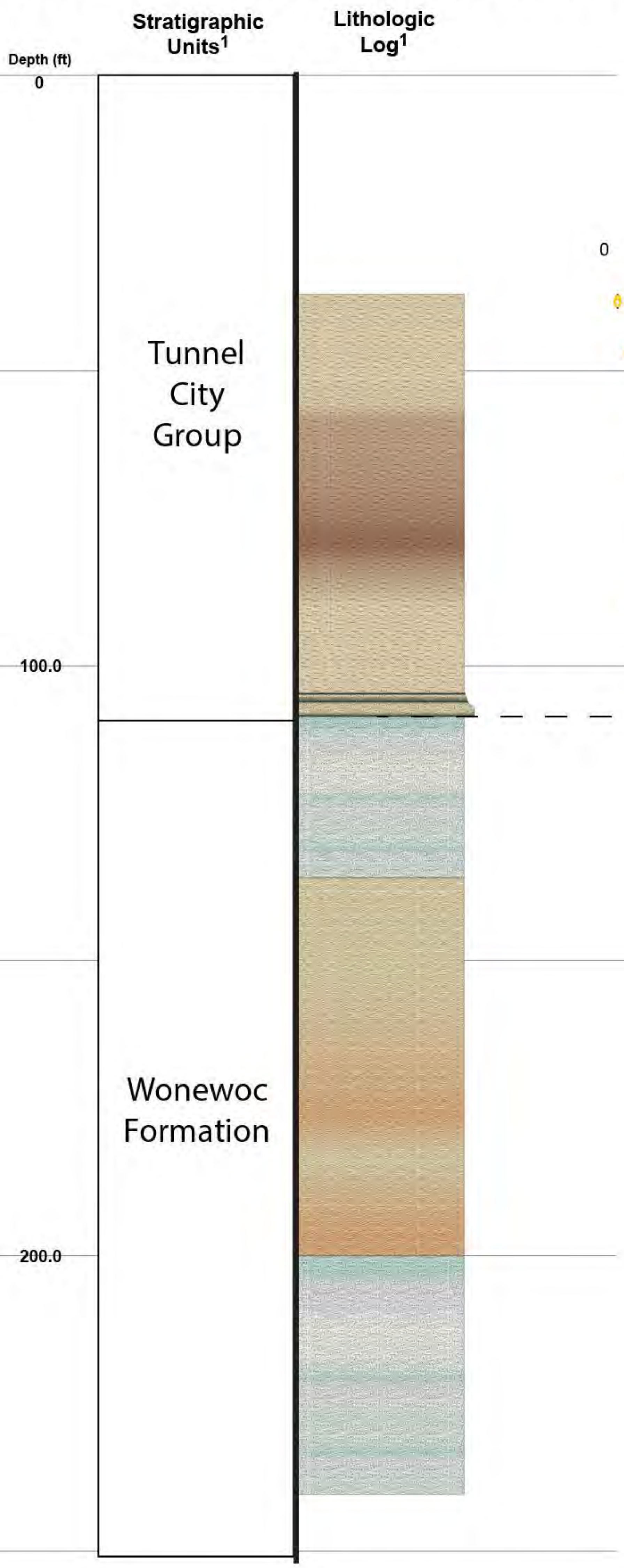
Unless Noted:

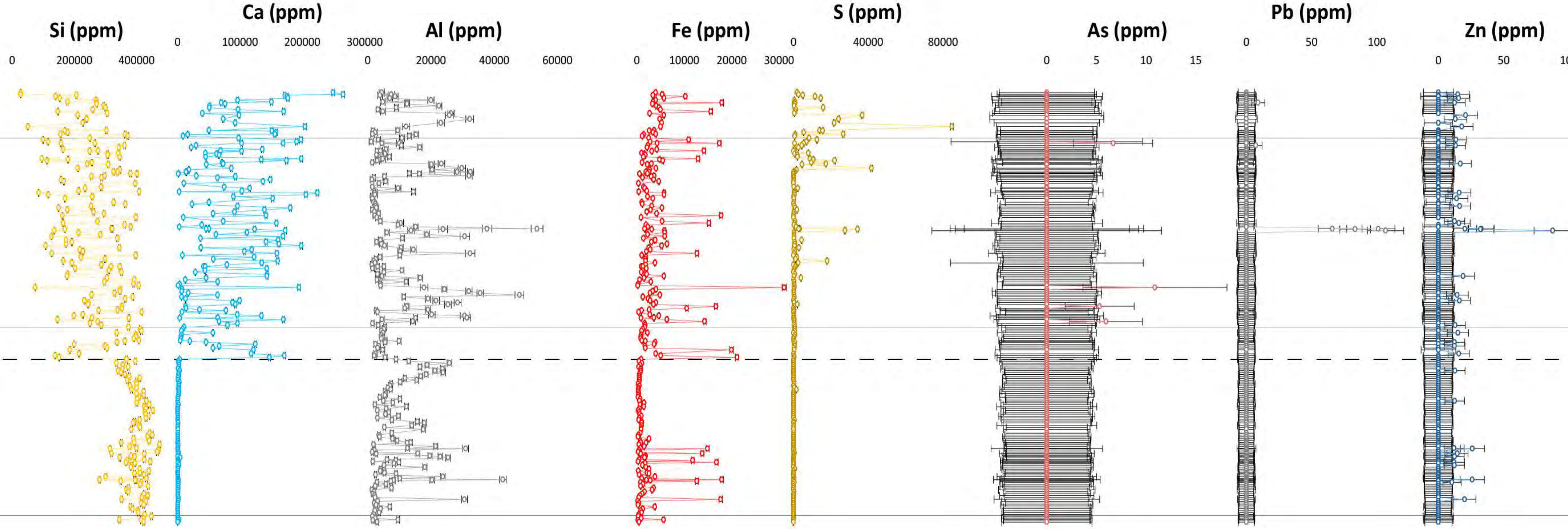
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

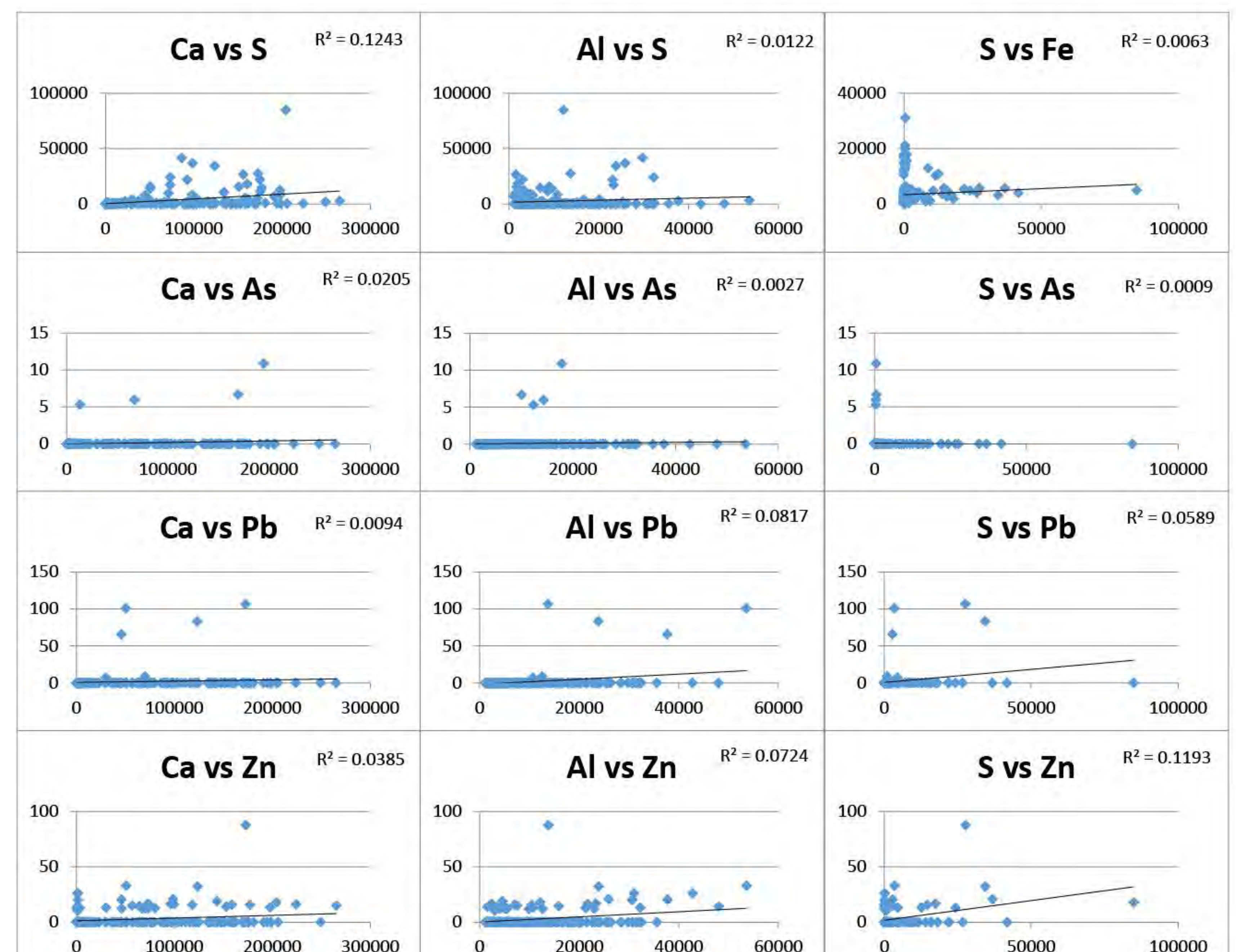


13005716 Arcadis Madison Kipp MW-5D3

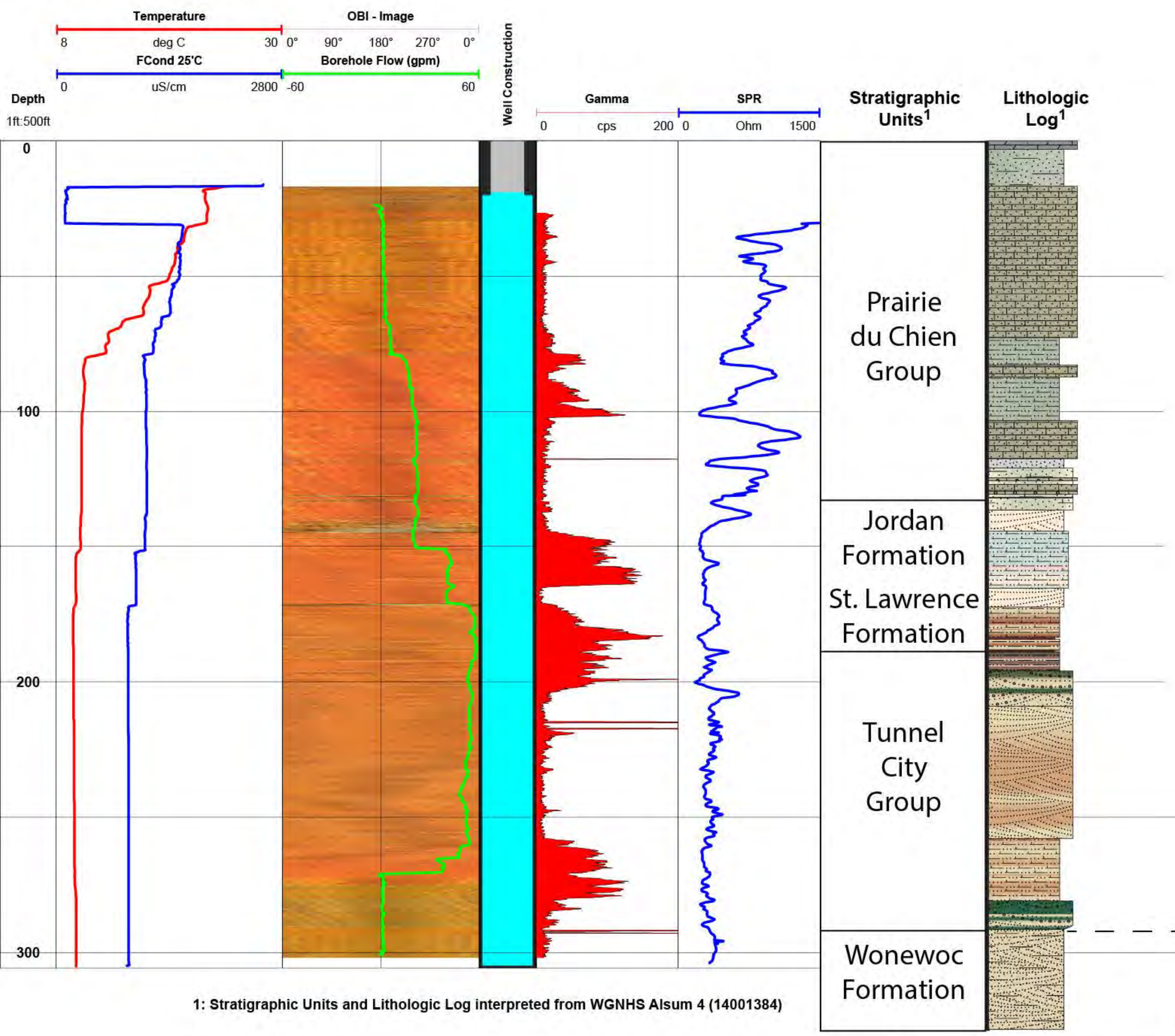




1: Stratigraphic Units and Lithologic Log interpreted from Arcadis Madison Kipp MW-5D3 13005716



14001384 WGNHS Alsum 4



1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Alsum 4 (14001384)

WGNHS Well ID 14001384

DATE 8/15/2012 WELL NAME Alsum Quarry Corehole 4
LOCATION Randolph, WI
COUNTY Dodge LOGGED BY P. Chase, S. Sellwood
LATITUDE 43.593864 LONGITUDE -88.997651
LOCATION METHOD: GPS ☐ AIR PHOTO/TOPO ☐ PLSS ☐ OTHER
ELEVATION 970 ELEVATION METHOD: DEM ☐ TOPO ☒ OTHER
WELL DEPTH 305 CASING DEPTH 20 DEPTH TO WATER 19
CASING STICK UP 0 File Created on: 8/11/2016 by: MJP

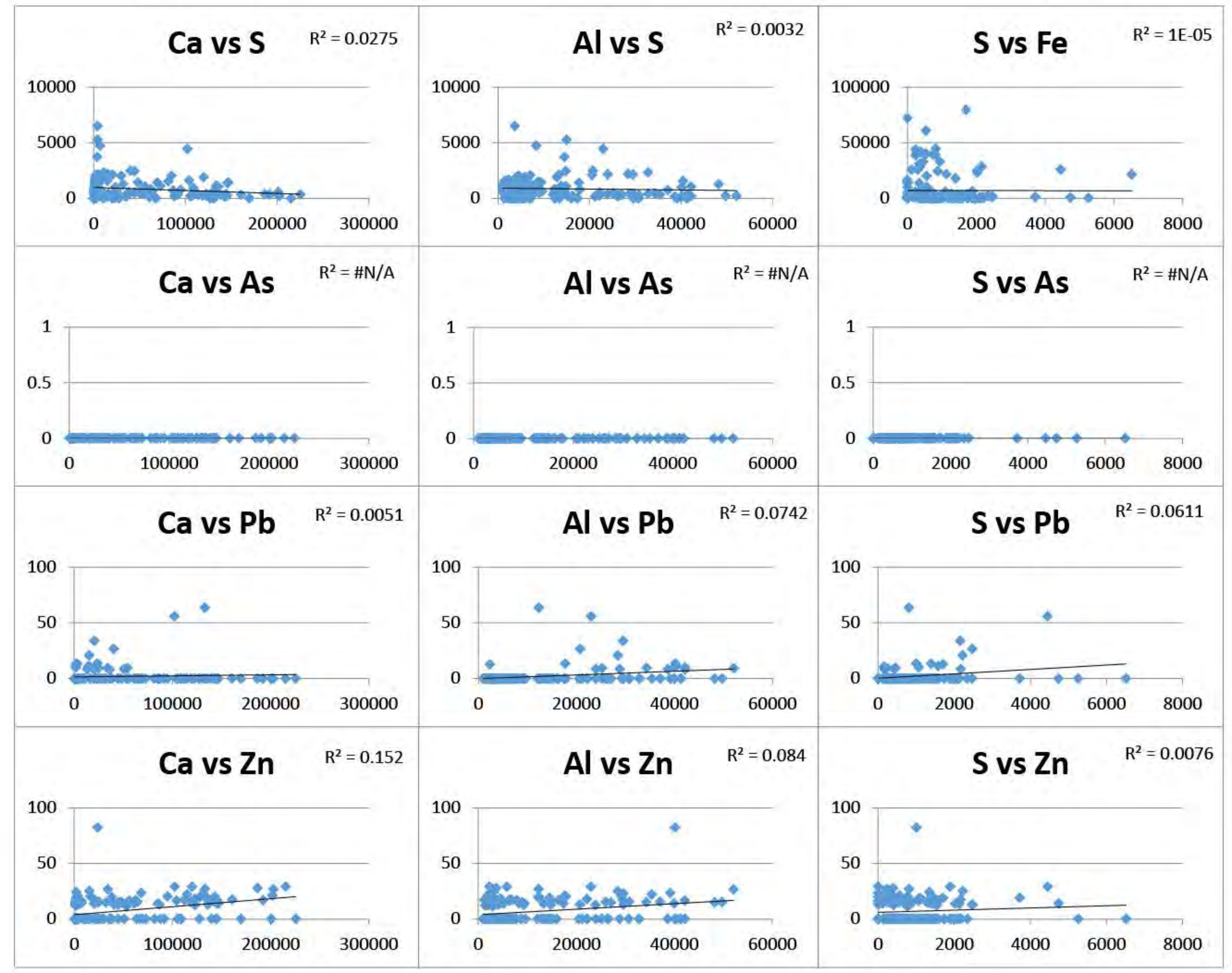
Comments: SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. Spinner flow collected under ambient conditions. Cascading water observed at approx. 30' during drilling, water-level rose by the time the well was logged. ABI also collected but not included.

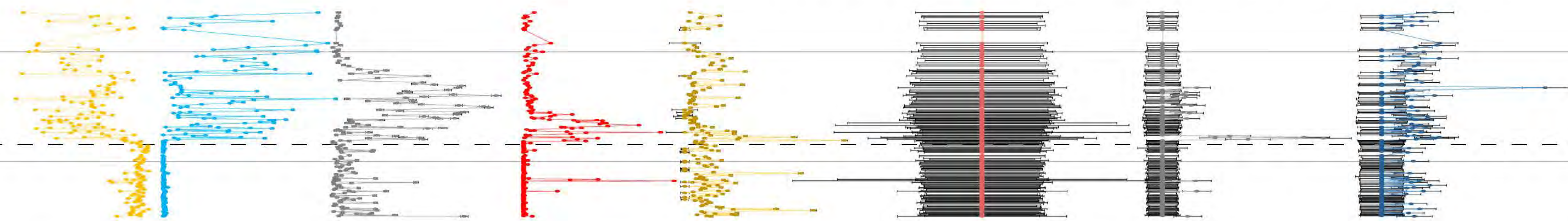
LOGS COLLECTED:

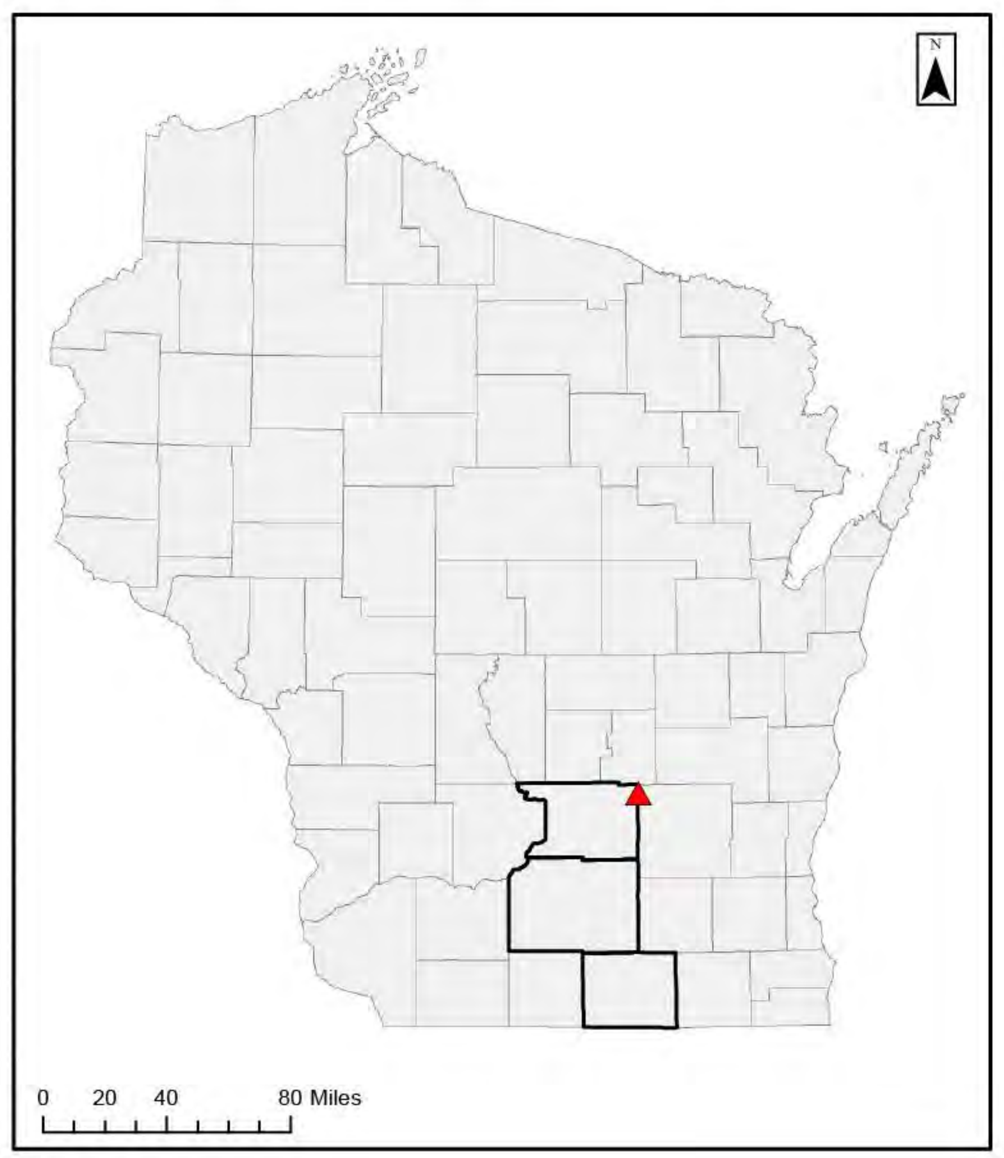
Gamma	X	Fluid Conductivity	X
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner (- flow up is negative, flow down is positive)	X
Self Potential		Optical Borehole Imager	X
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER:	

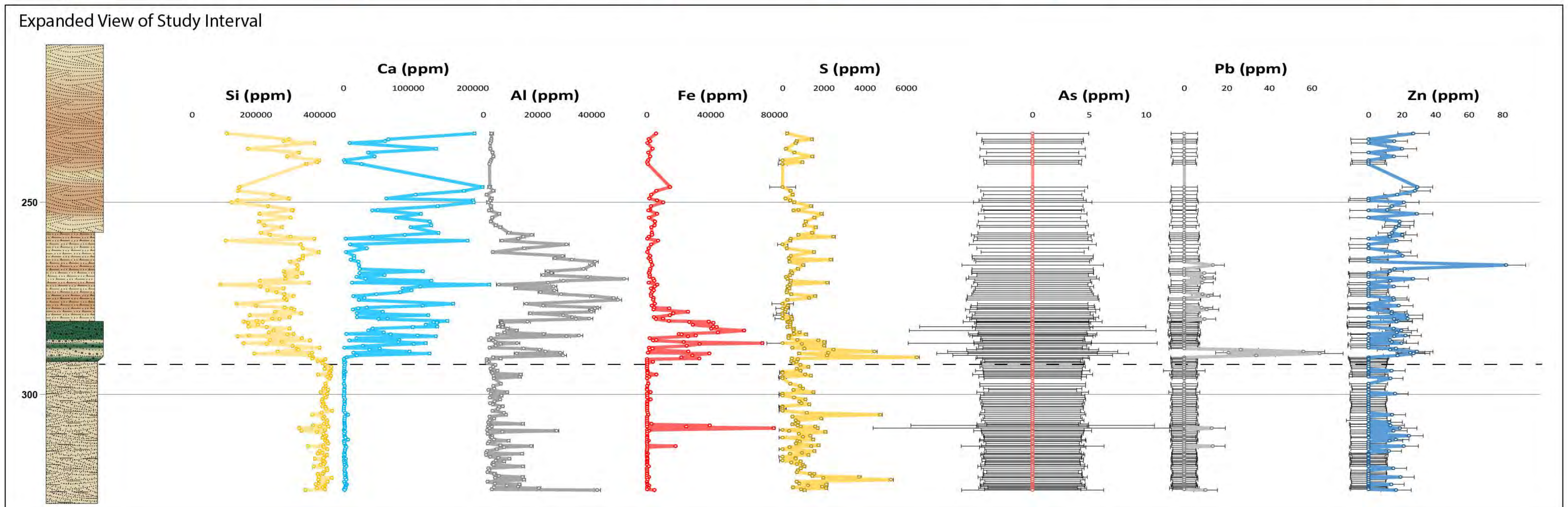
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

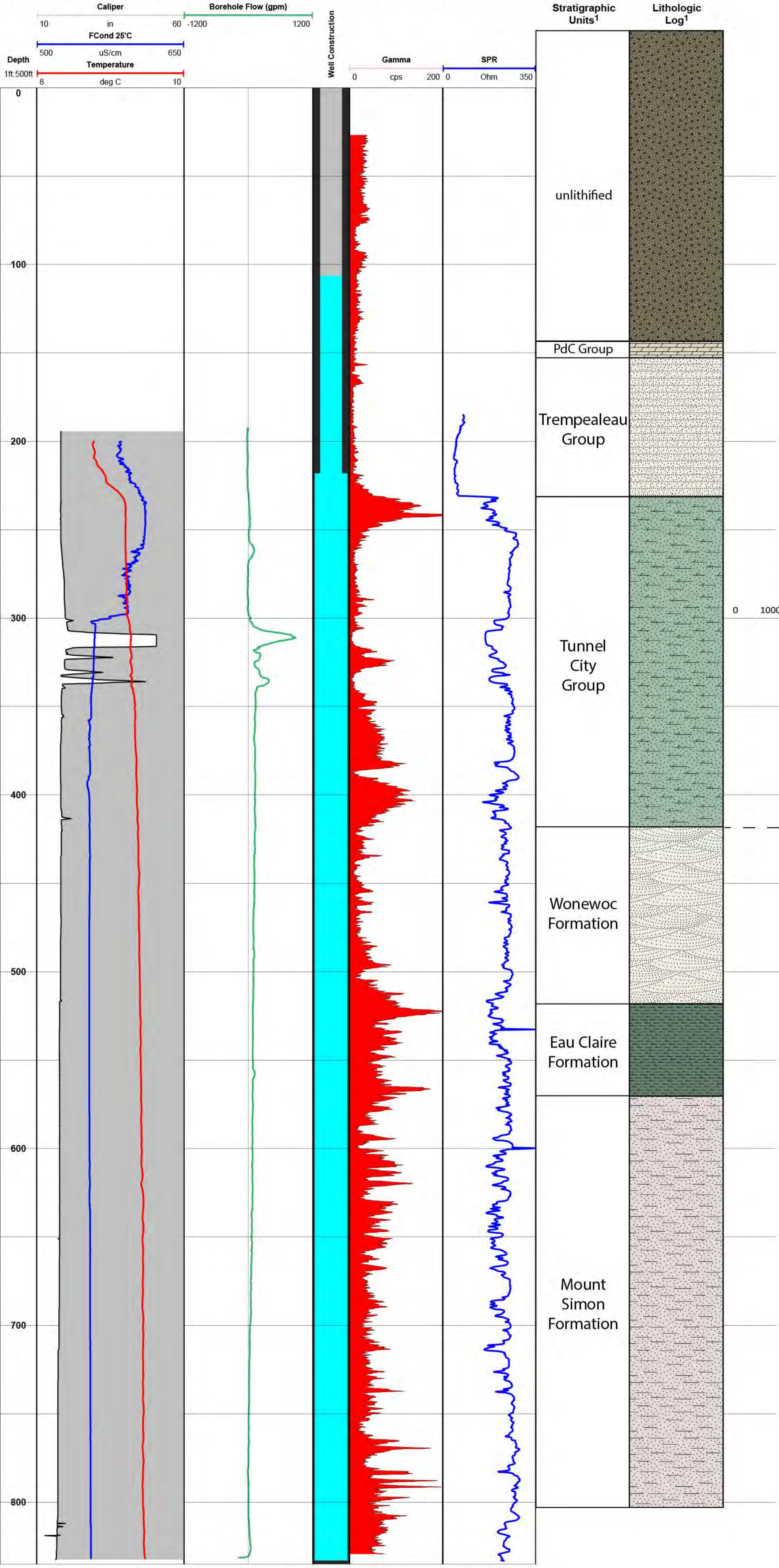








3000515 Village of Turtle Lake Test Well 4 & 3000192 Village of Turtle Lake Well 2



WGNHS Well ID 3000515

DATE 1/25/2013 WELL NAME Village of Turtle Lake - Test Well #4

LOCATION NE1/4SE1/4 Sec.30 T34N R14W

COUNTY Barron LOGGED BY PM Chase

LATITUDE 45.40077003 LONGITUDE -92.13724671

LOCATION METHOD: GPS [X] AIR PHOTO/TOPO [ ] PLSS [ ] OTHER

ELEVATION 1260 ELEVATION METHOD: DEM [ ] TOPO [X] OTHER

WELL DEPTH 833 CASING DEPTH 218 DEPTH TO WATER 106.3

CASING STICK UP 4.0 File Created on: 8/10/2016 by: MJP

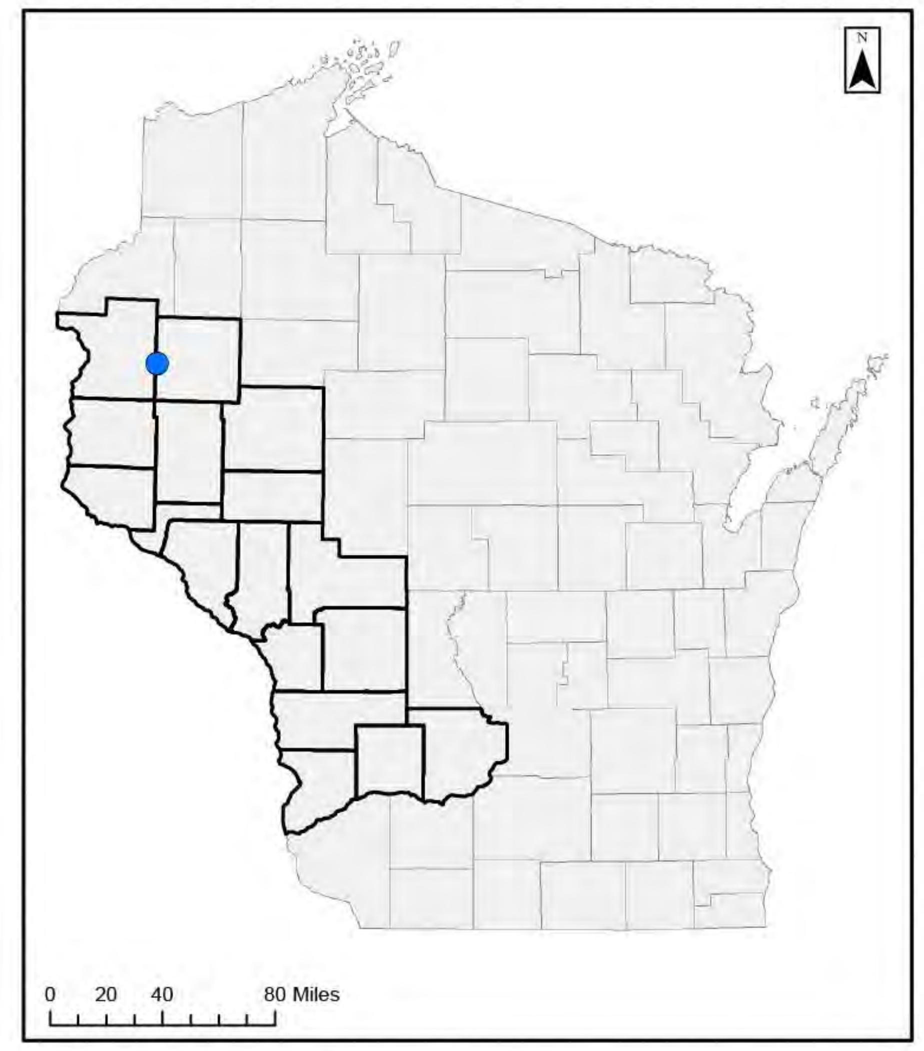
Comments: SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. Spinner flow measurements taken under ambient conditions.

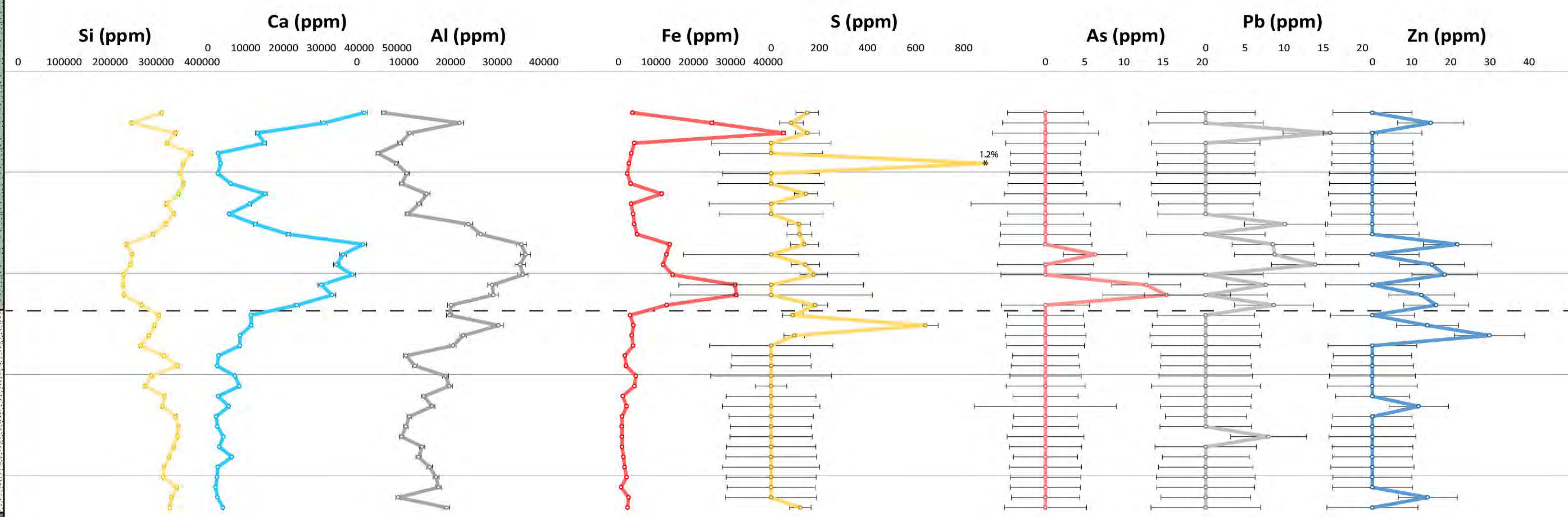
LOGS COLLECTED:

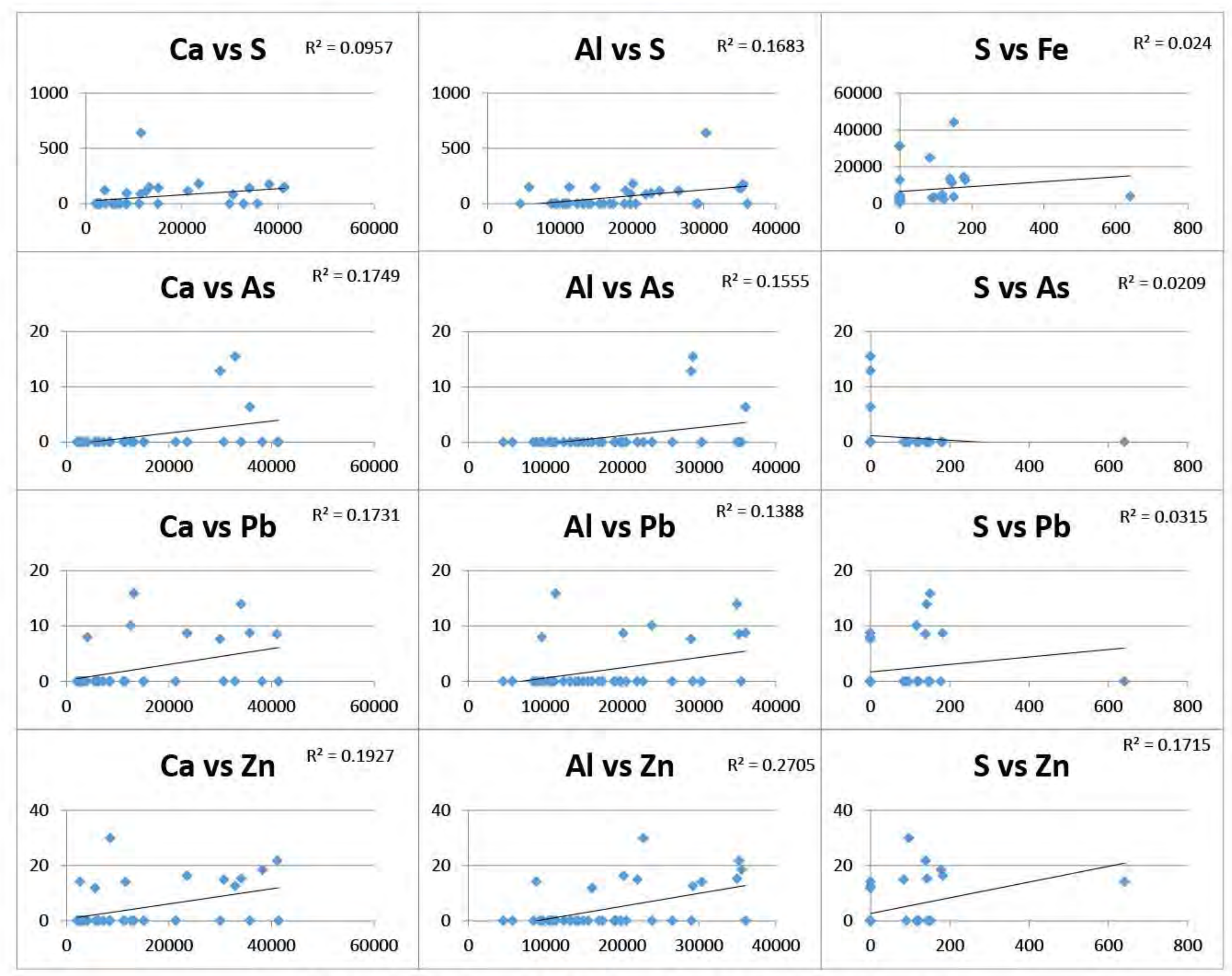
Gamma	X	Fluid Conductivity	X
Caliper	X	Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner (flow up is negative, flow down is positive)	X
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER:	

Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu



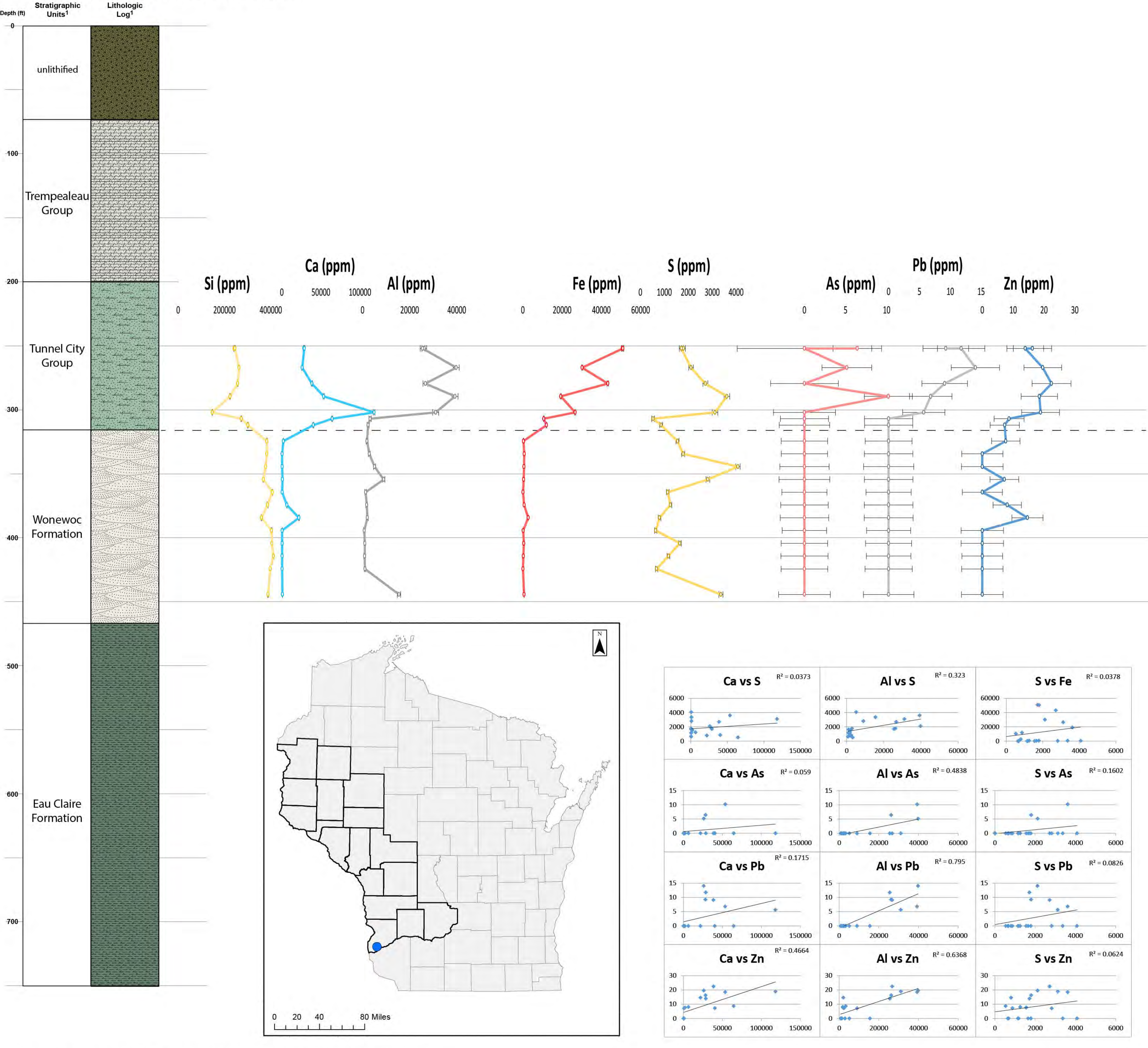




* Note that the outliers value of ~1.2% sulfir has been removed from cross-plots

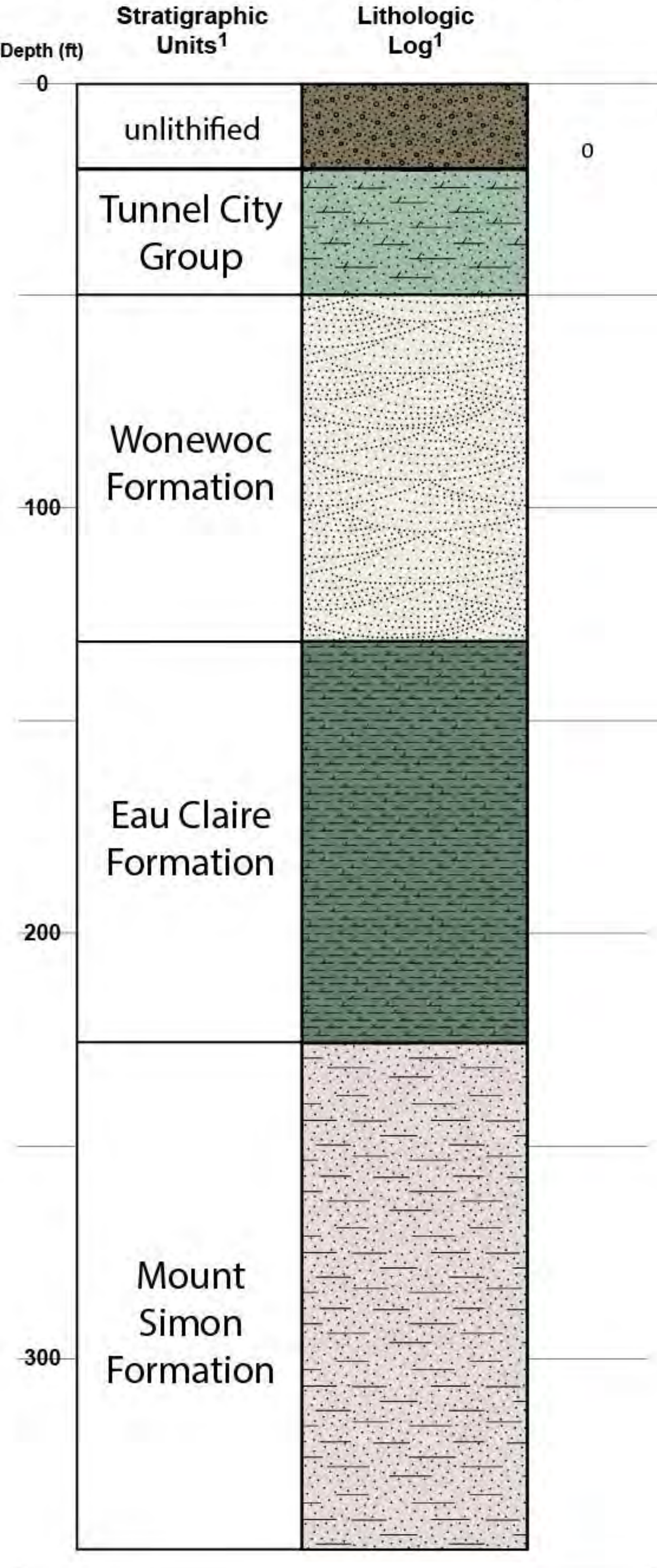
1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log of Village of Turtle lake Well 2 (3000192)
3000192 was estimated to start at 1270' elevation; a shift of ~25' made it comparable to 3000515 (gamma vs Al)
pXRF data collected from 3000192

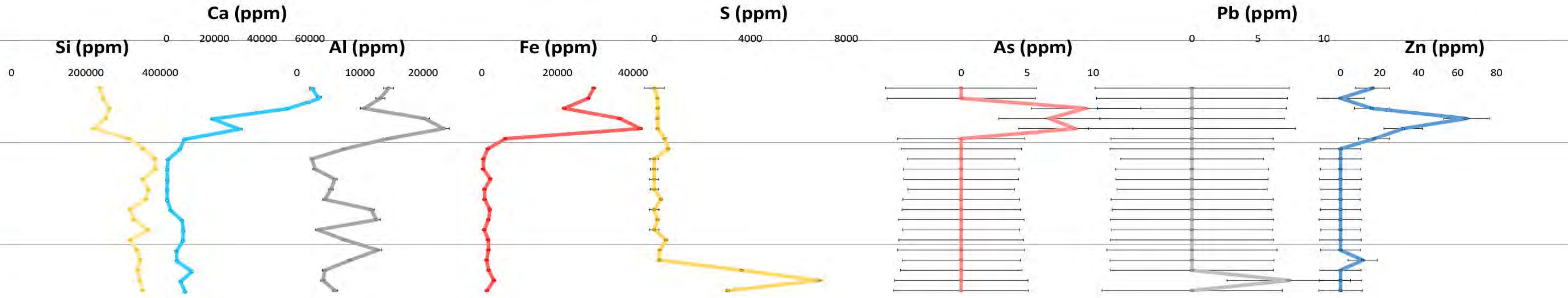
12000001 Aherns Bros. Farm Artesian Well

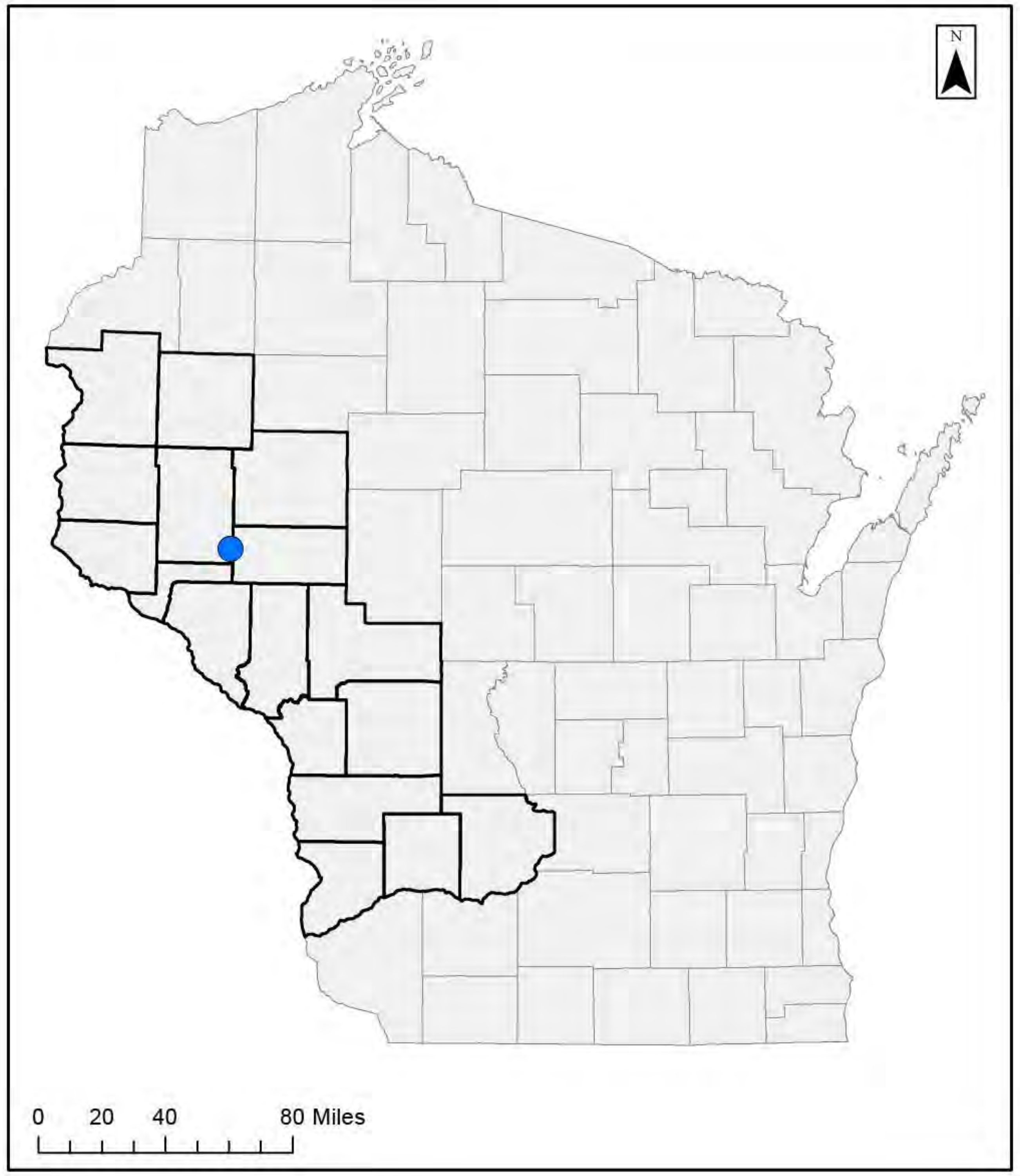


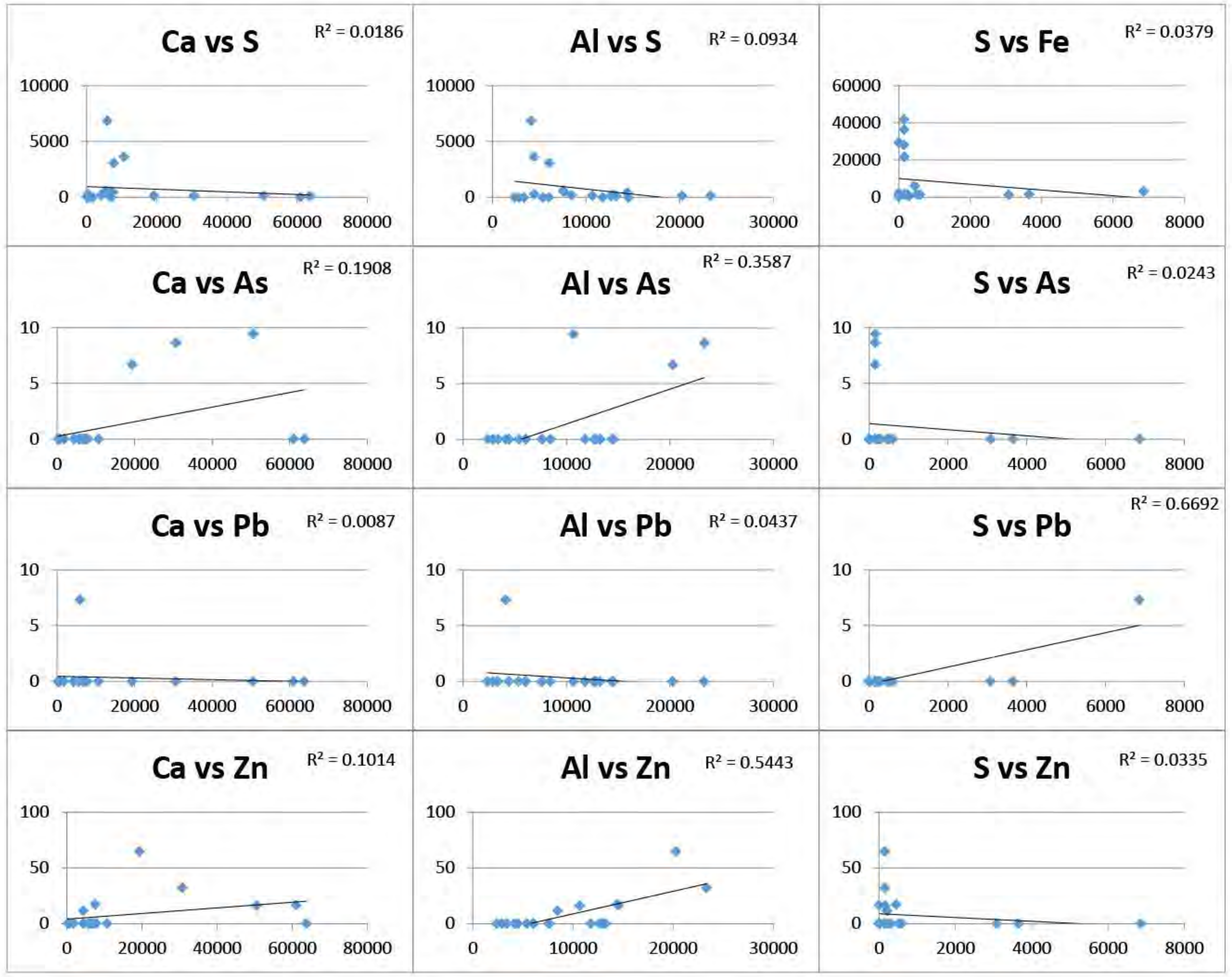
1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log of Aherns Bros. Farm Artesian Well (12000001)

17000274 Duane Welch Well



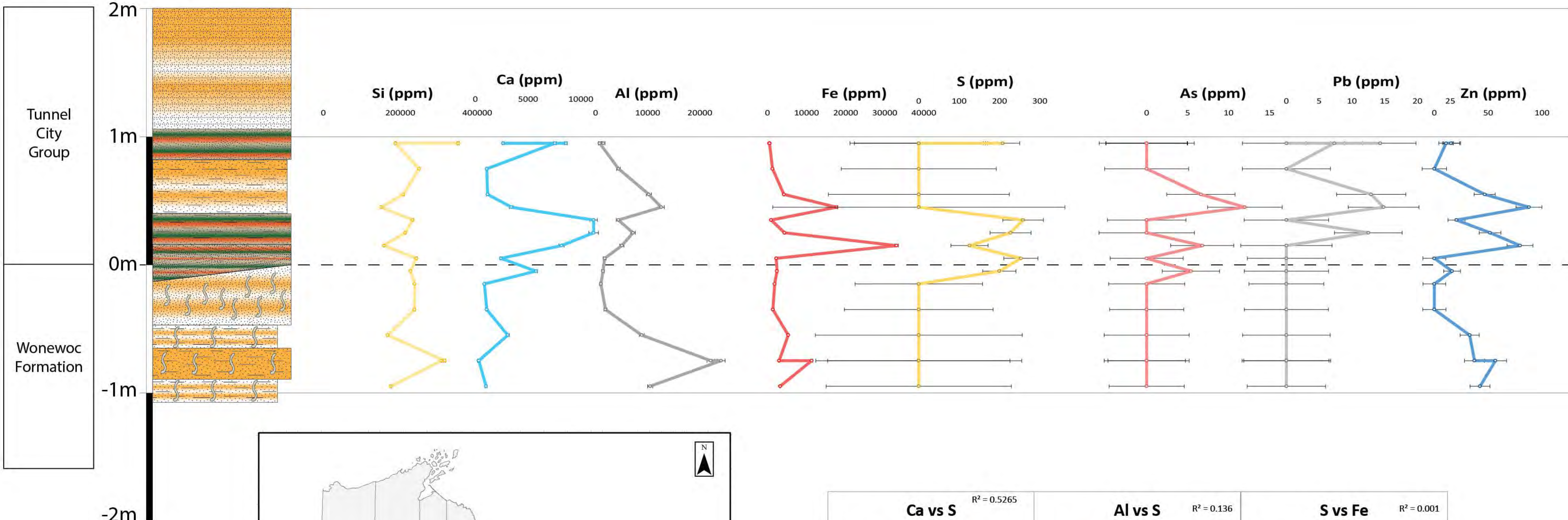


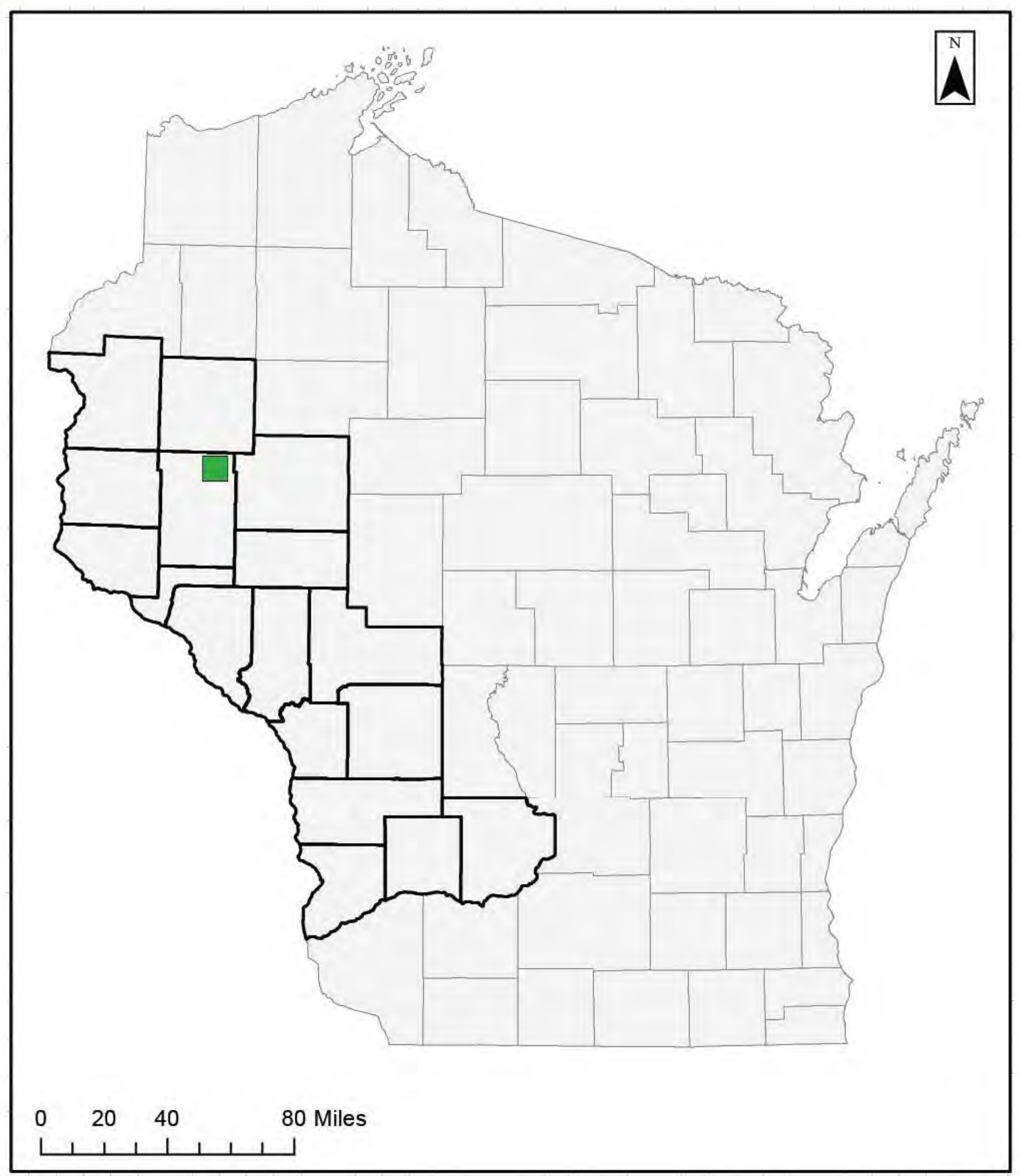


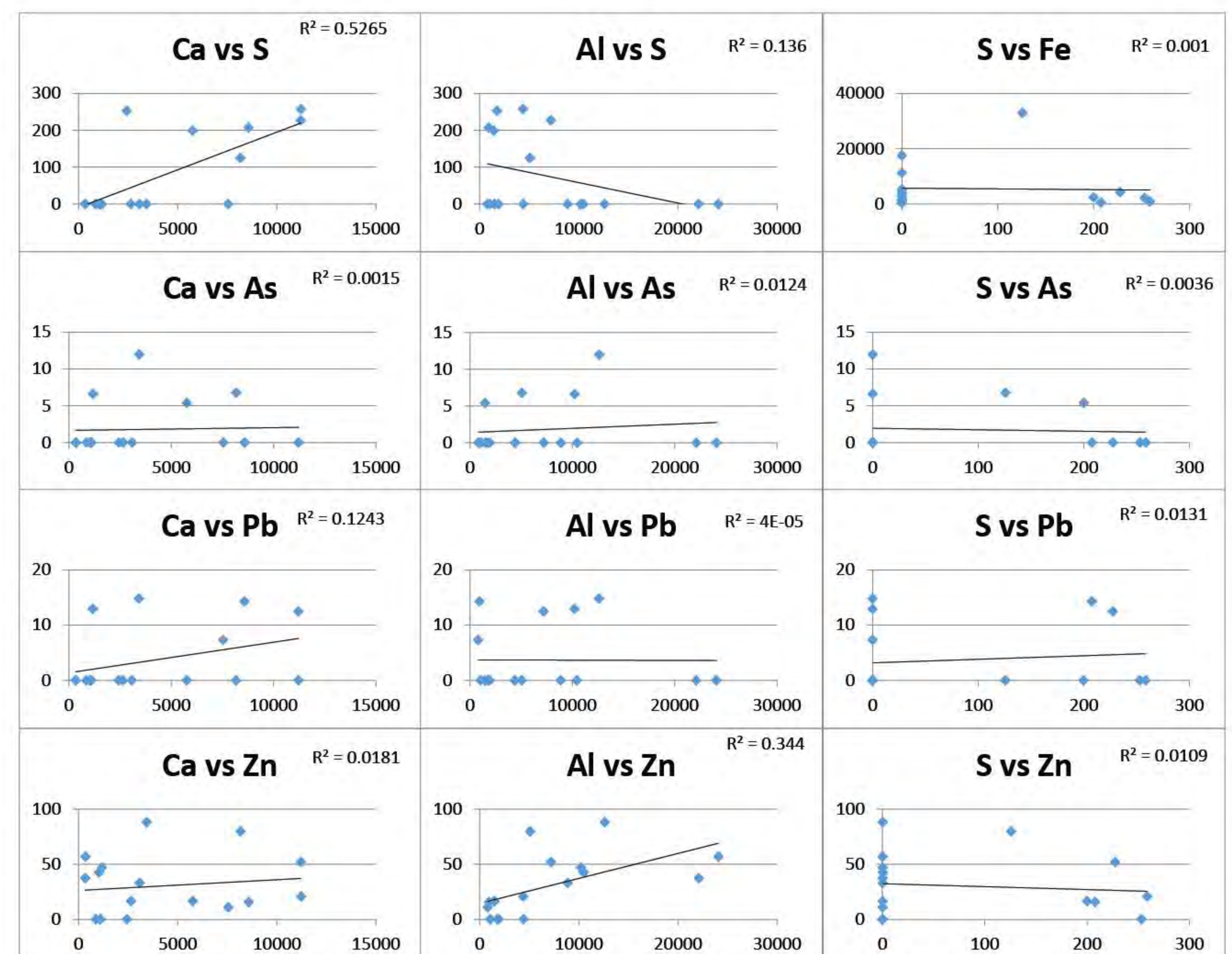


1: Stratigraphic Units and Lithologic Log adapted from WGNHS Geologic Log of Duane Welch Well (17000274)

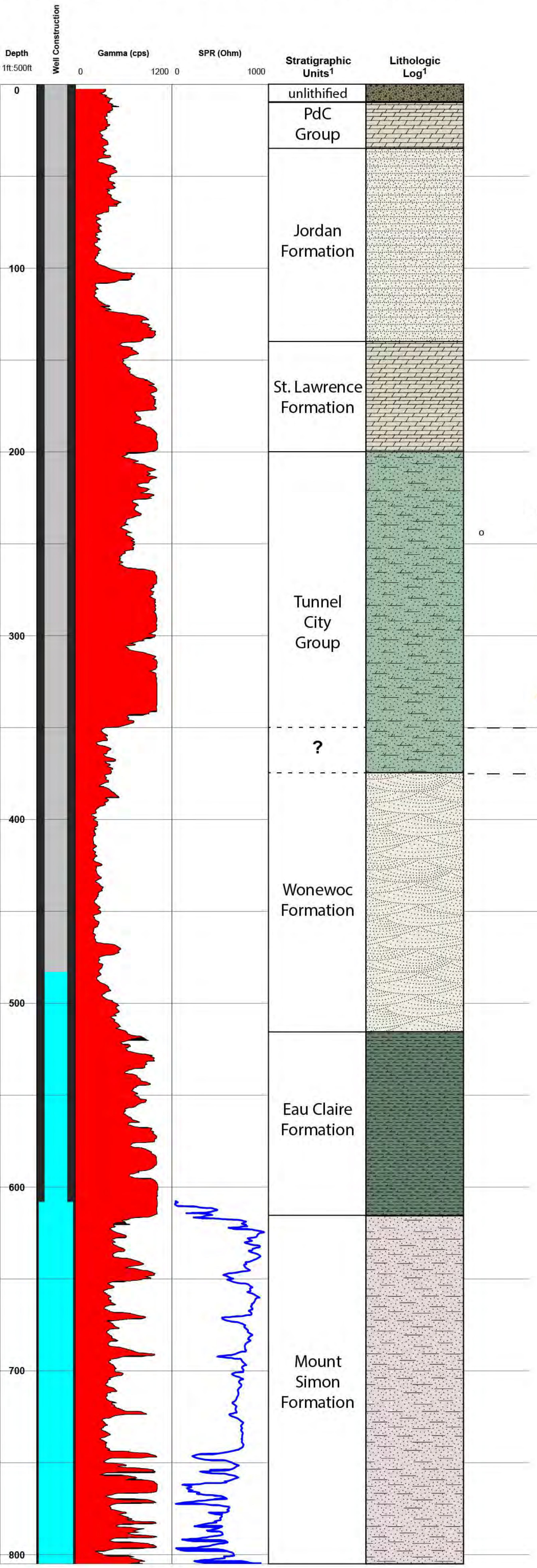
17outcrop Hwy W Hay Creek







32000107 Arbor Hills Addition Well (Shelby S.D. 2)



WGNHS Well ID ***32000107***

DATE *10/14/1970* **WELL NAME** *Arbor Hills*

LOCATION *NE1/4, NE1/4, NW1/4, Section 12, T2N, R22E*

COUNTY *LaCrosse* **LOGGED BY** *R.M. Peters*

LATITUDE *-* **LONGITUDE** *-*

LOCATION METHOD: ***GPS*** ☐ ***AIR PHOTO/TOPO*** ☐ ***PLSS*** ☐ ***OTHER*** *Unknown*

ELEVATION *1135.5* **ELEVATION METHOD:** ***DEM*** ☐ ***TOPO*** ☐ ***OTHER***

WELL DEPTH *805* **CASING DEPTH** *608* **DEPTH TO WATER** *483*

CASING STICK UP *Unknown* ***File Created on:*** *8/12/2016* ***by:*** *MJP*

Comments: *The Gamma and SPR data included in this log were measured in 1968 using methods of the day. Values shown should only be considered as relative estimates, not quantitative measures. SPR and SP profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging.*

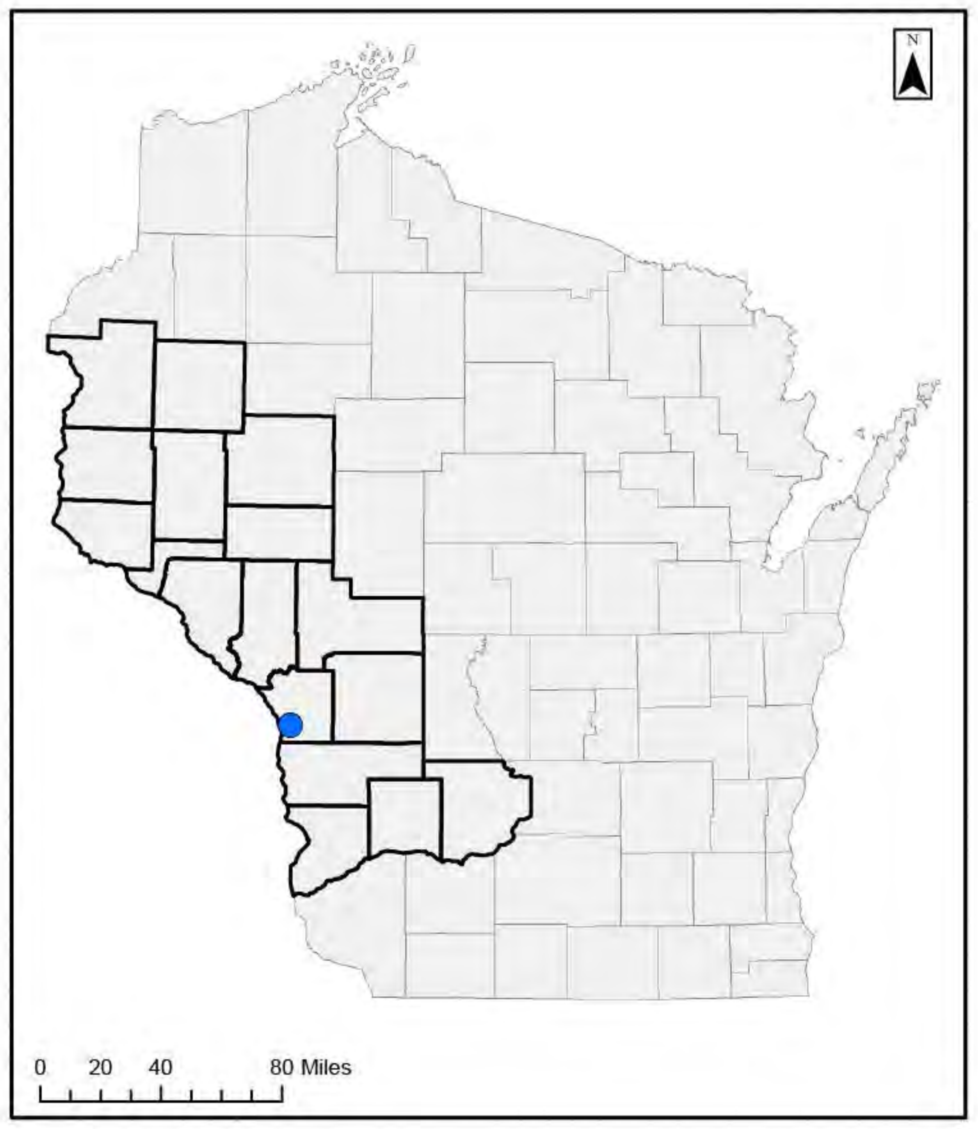
LOGS COLLECTED:

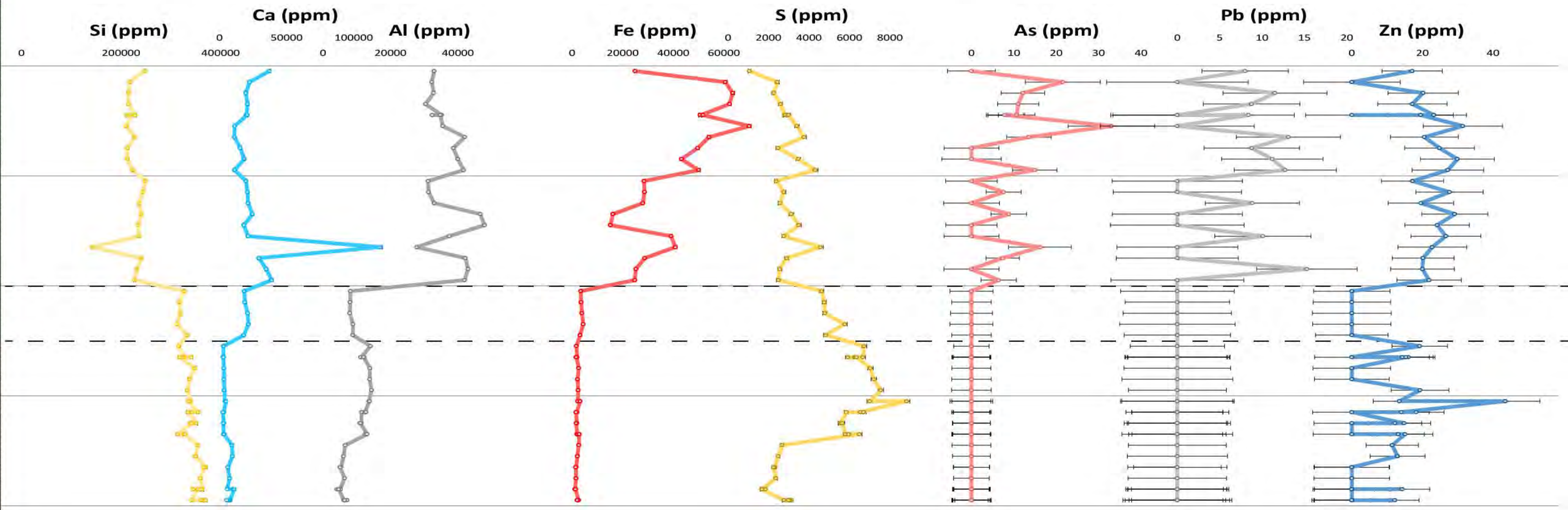
Gamma	x	Fluid Conductivity	
Caliper		Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner *- flow up is negative, flow down is positive*	
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature		OTHER:	

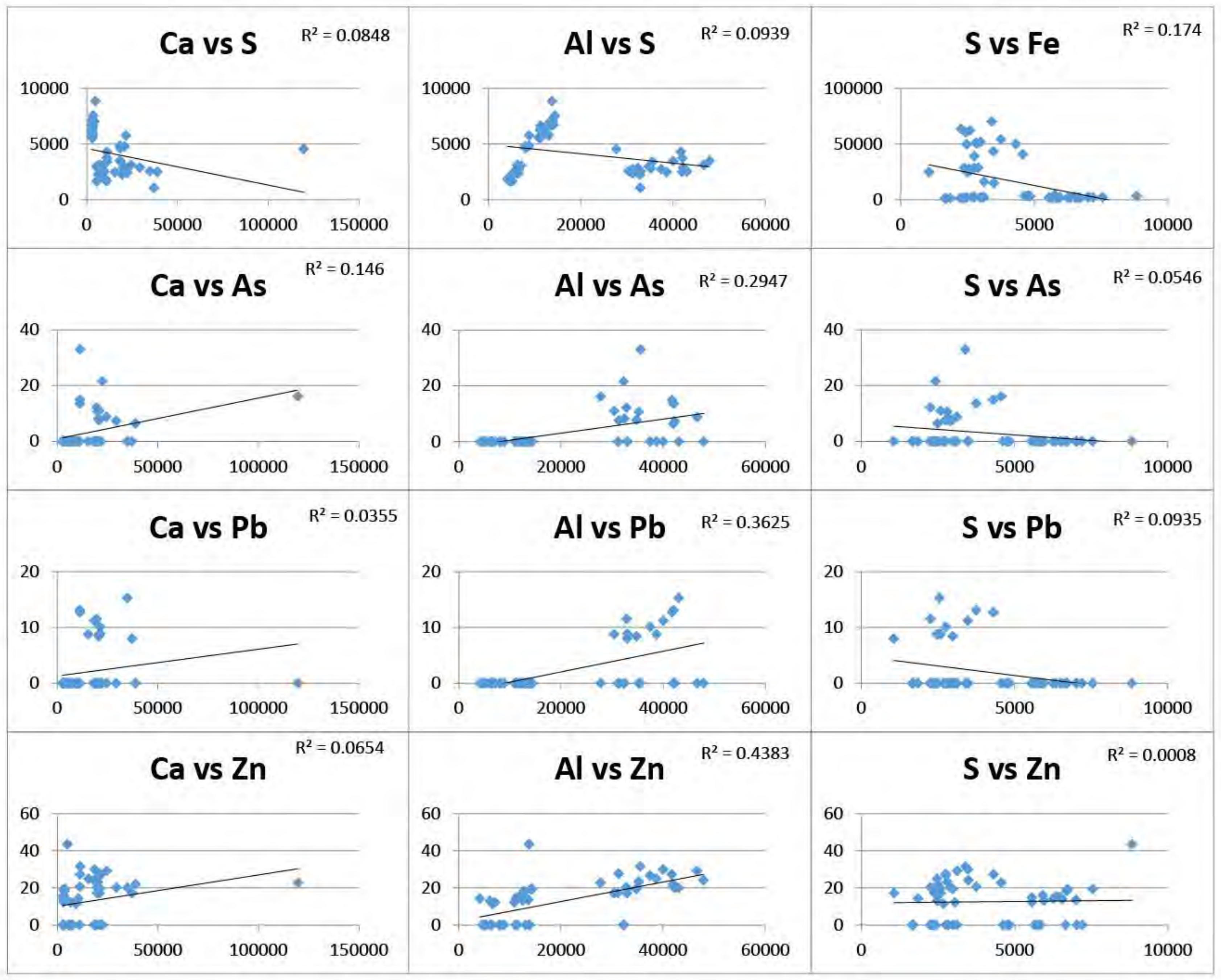
Unless Noted:

- *all depths are in feet*
- *well depth, casing depth and depth to water are interpreted from geophysical log*
- *datum is the top of casing*

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu

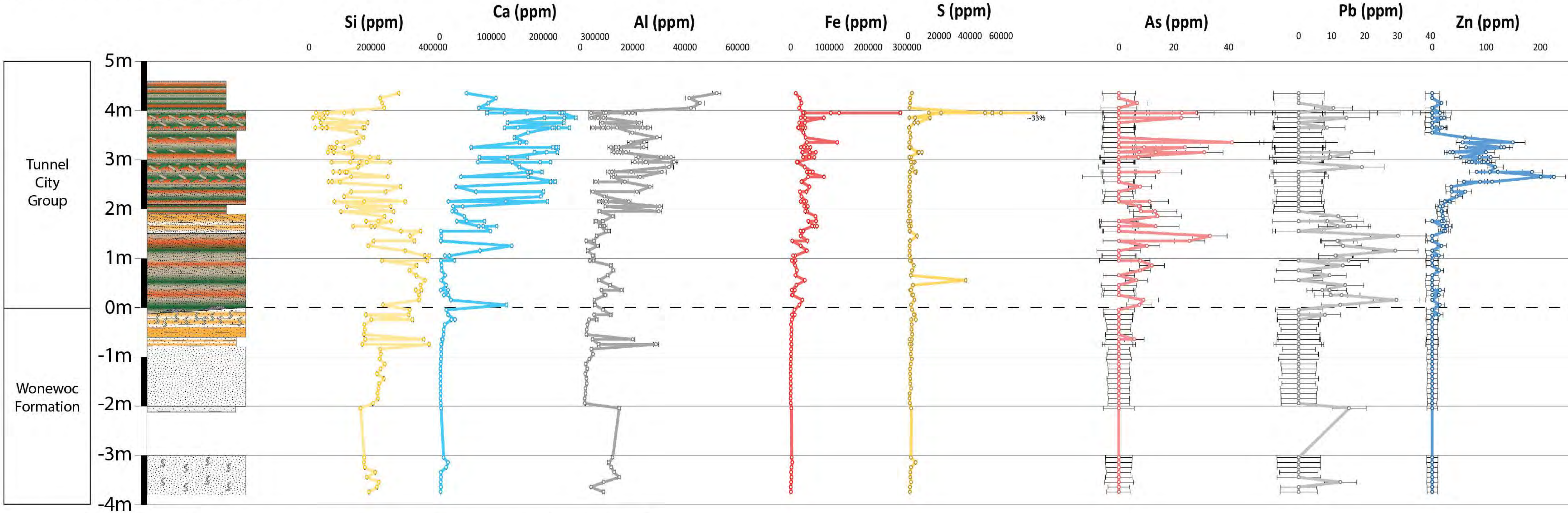


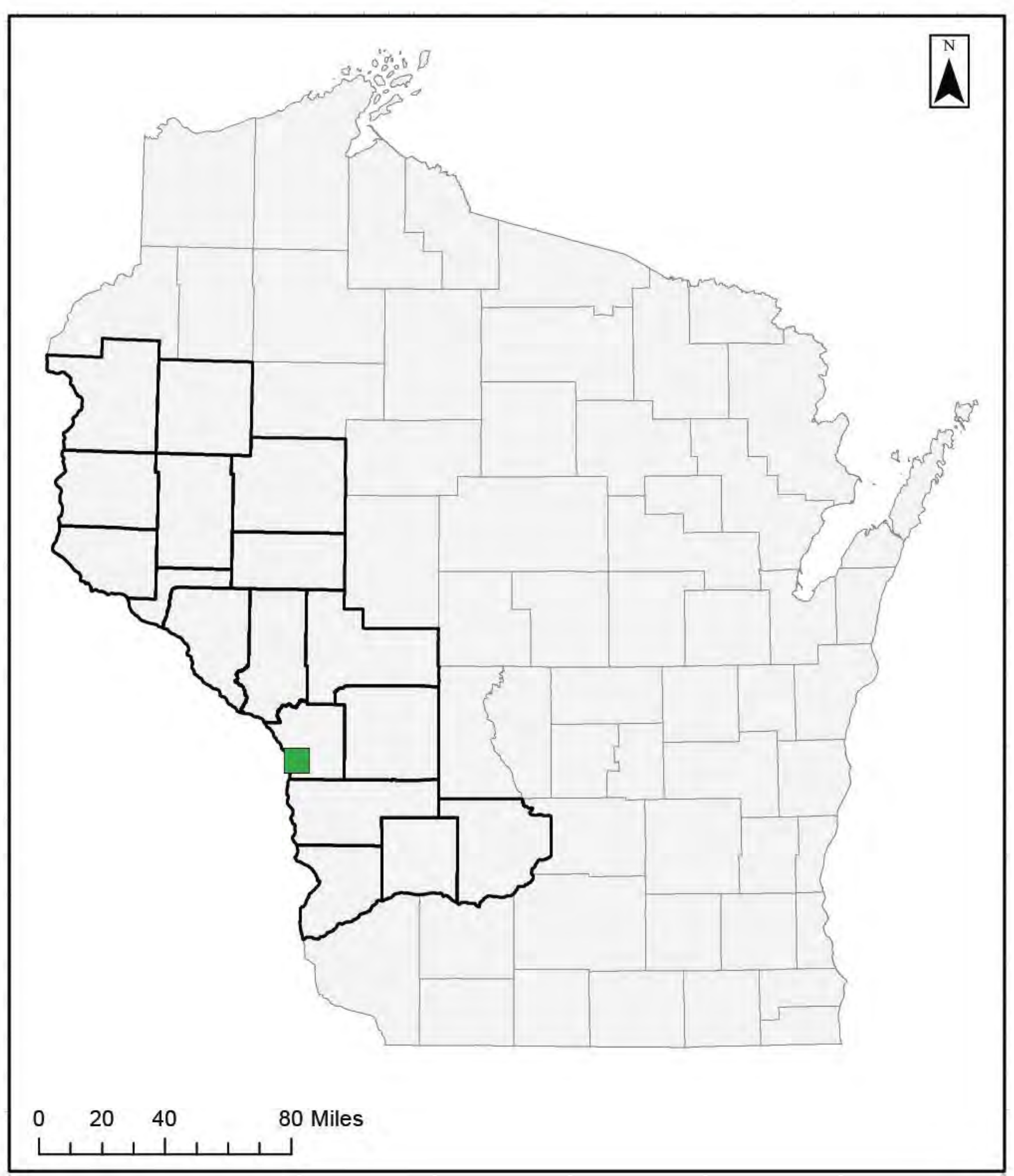


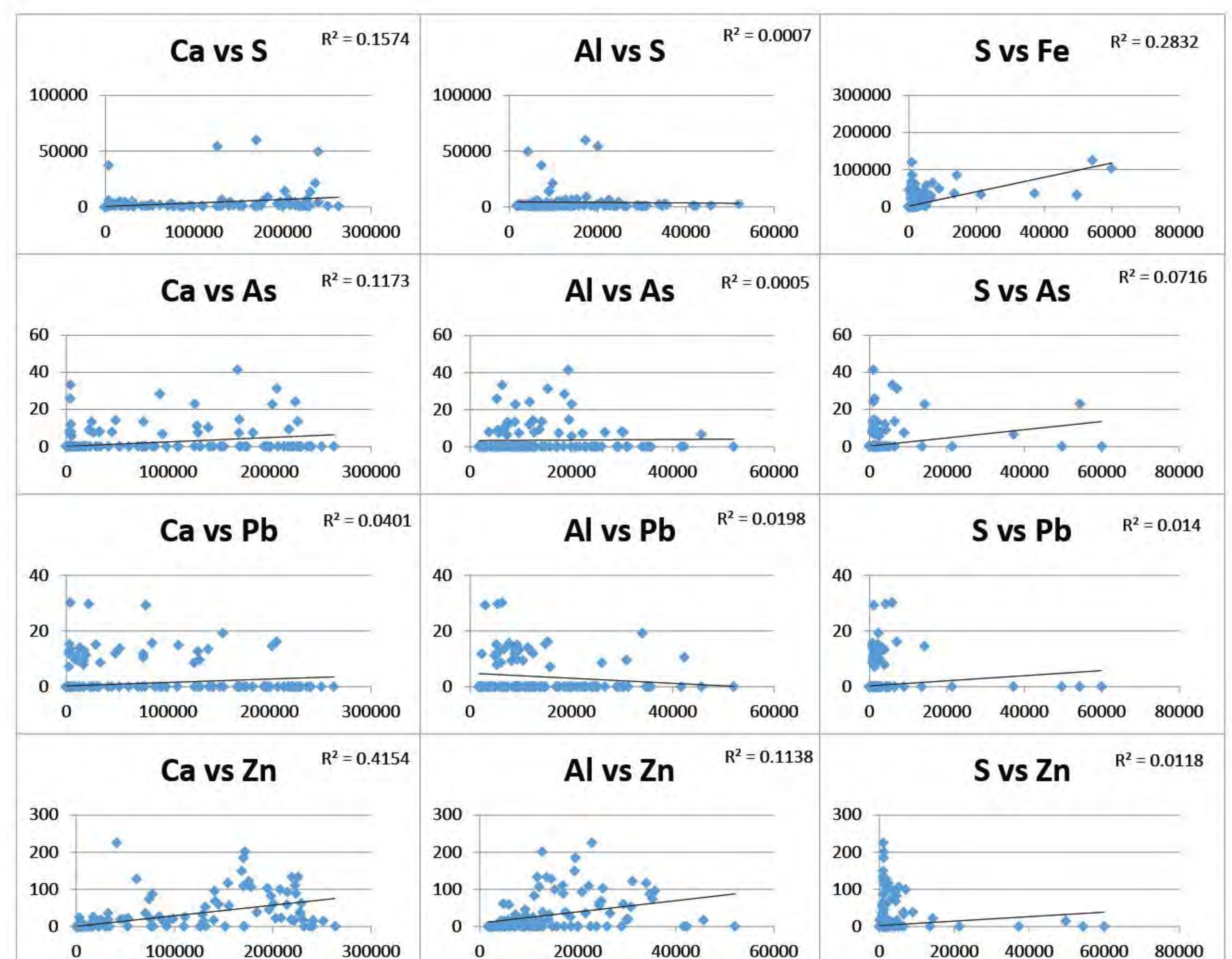


1: Stratigraphic Units and Lithologic Log adapted from WGHS Geologic Log of Arbor Hills Addition Well (32000107)

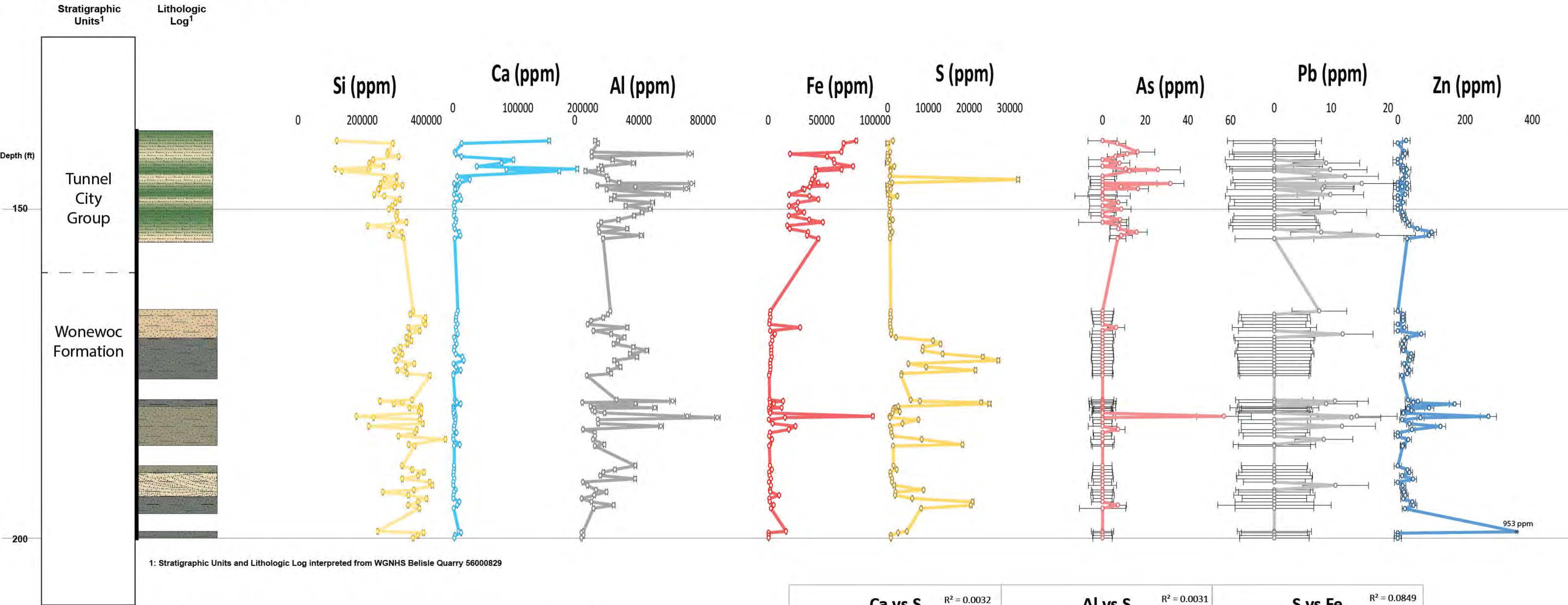
32outcrop Granddad Bluff La Crosse



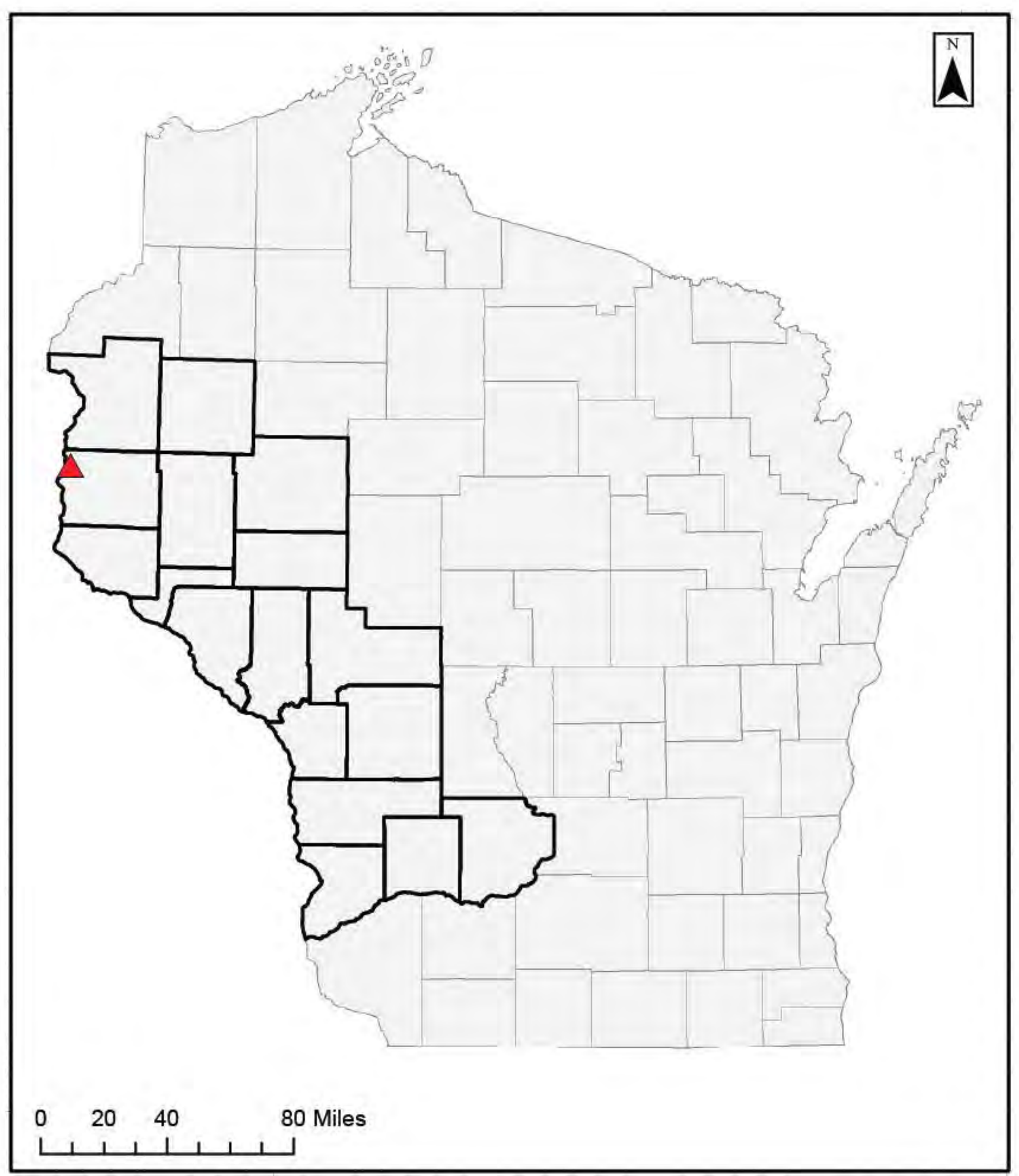


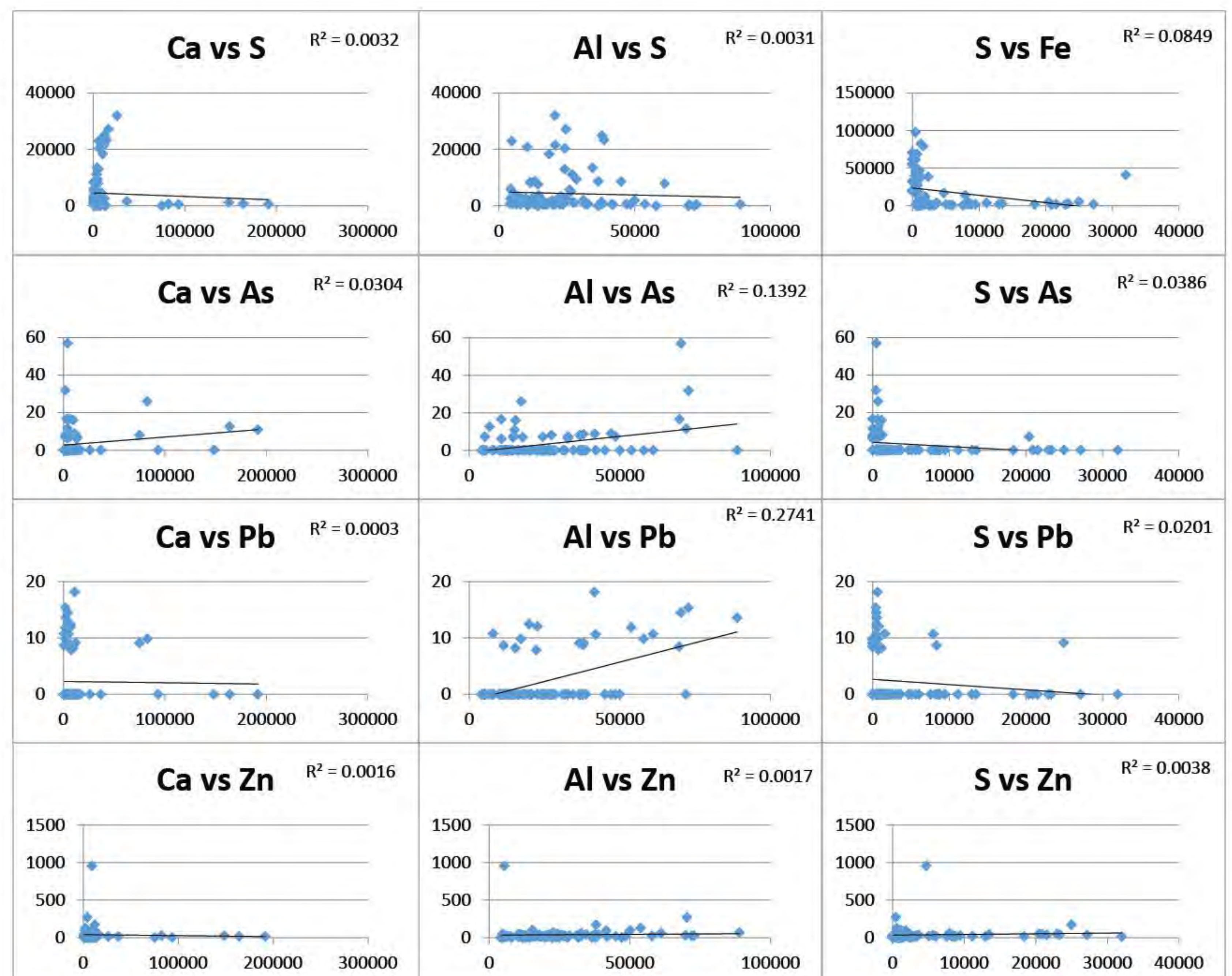


56000829 WGNHS Belisle Quarry

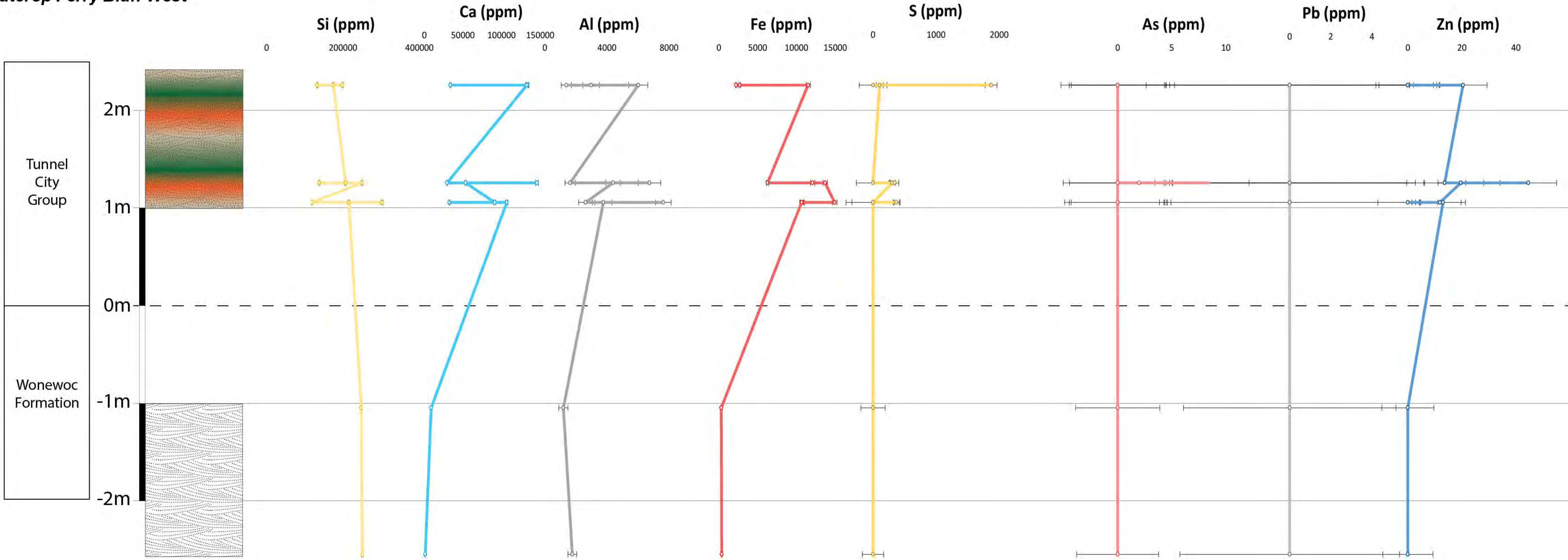


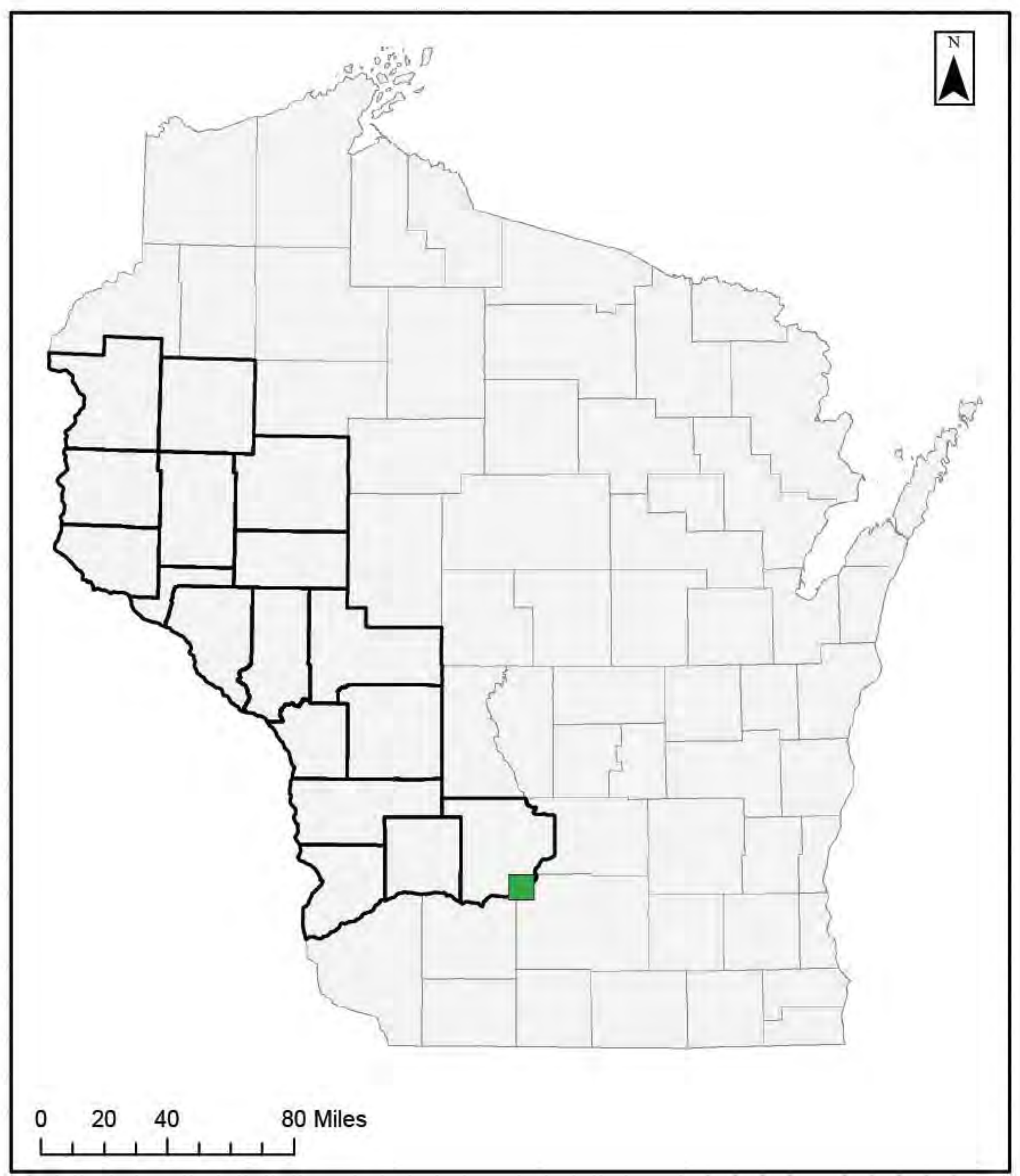
1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Belisle Quarry 56000829

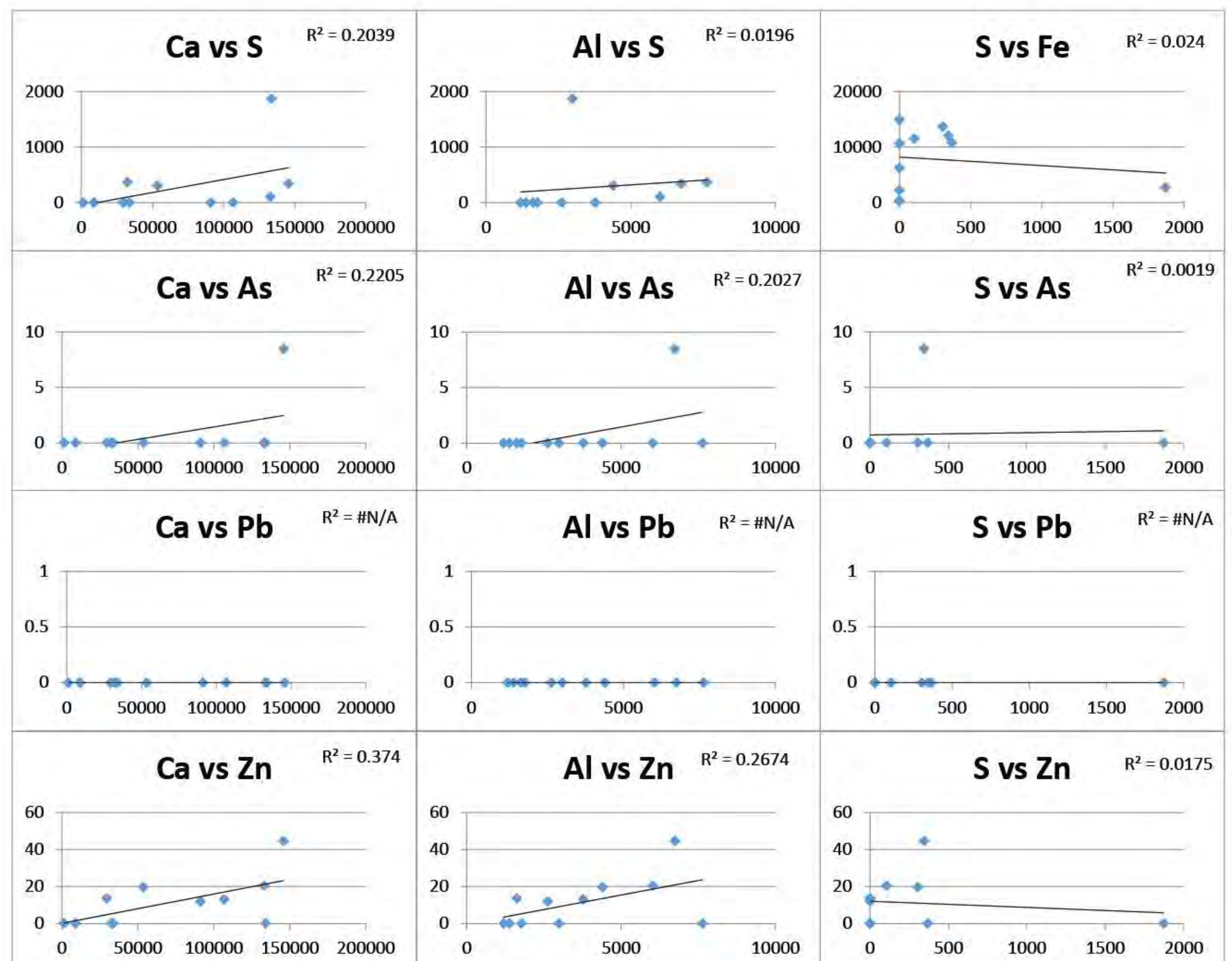




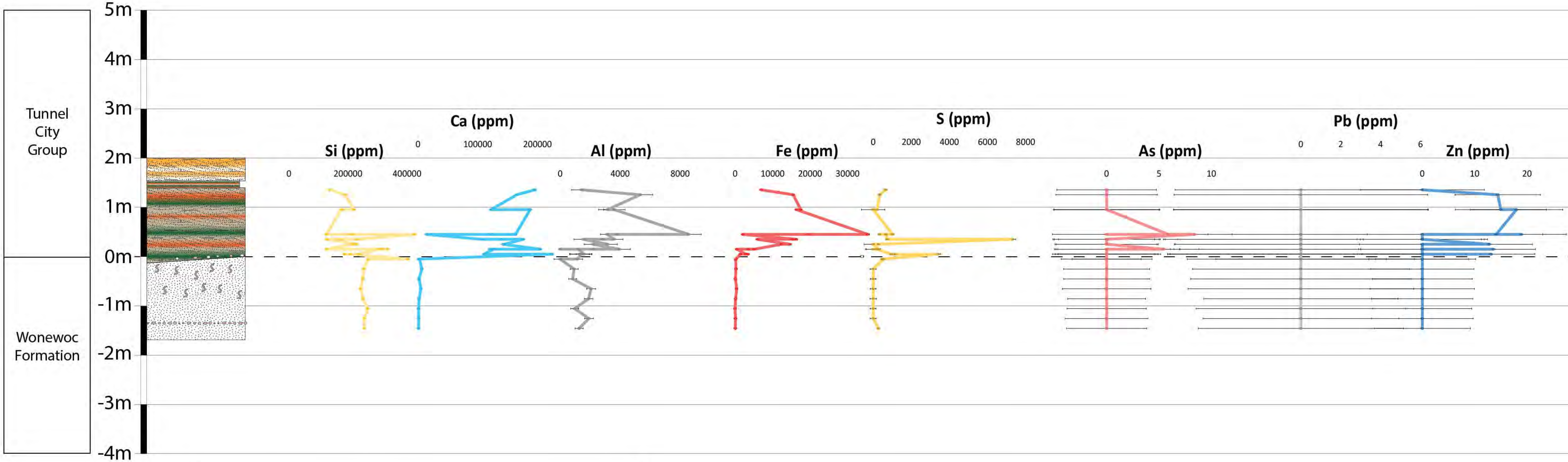
57outcrop Ferry Bluff West

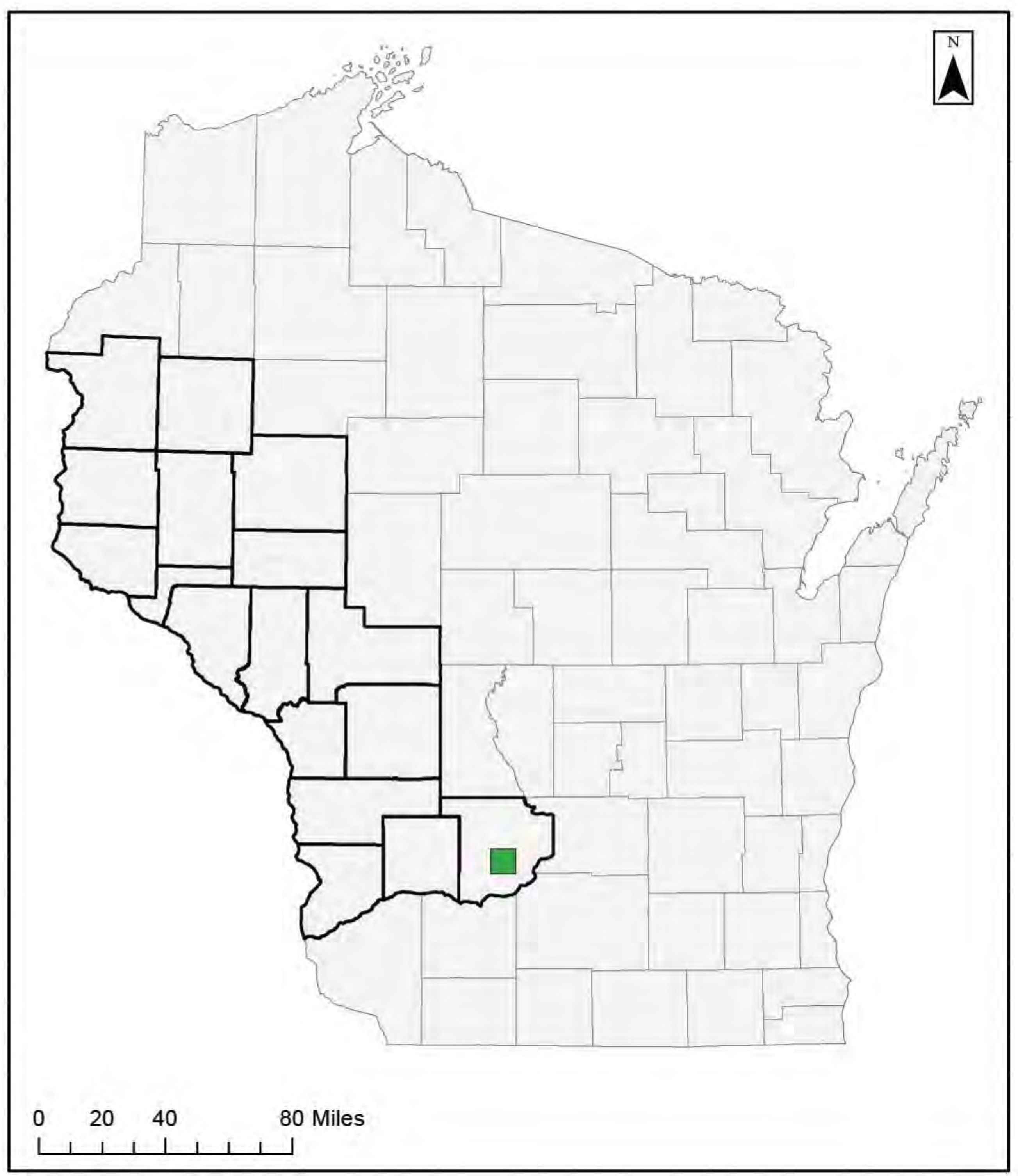


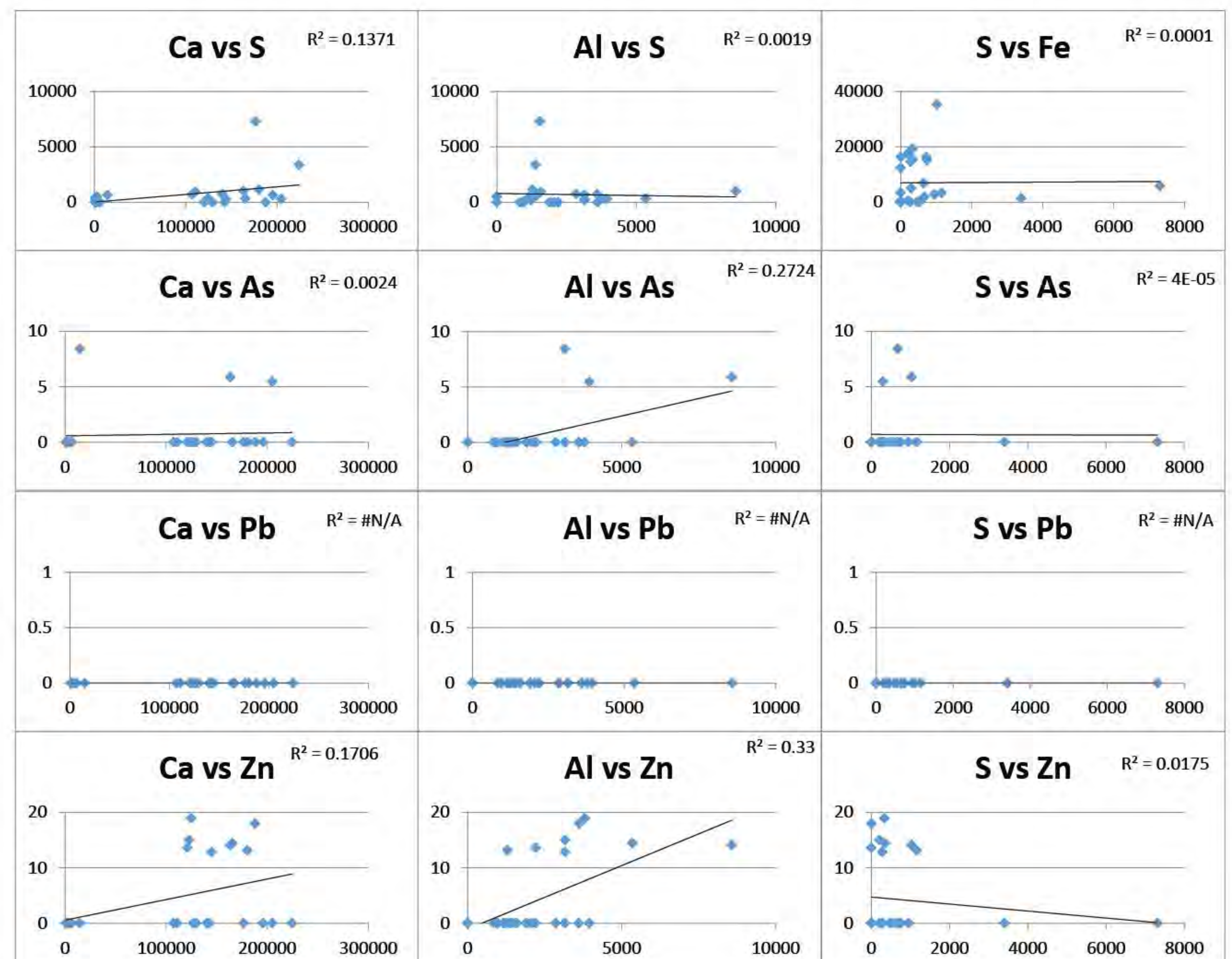




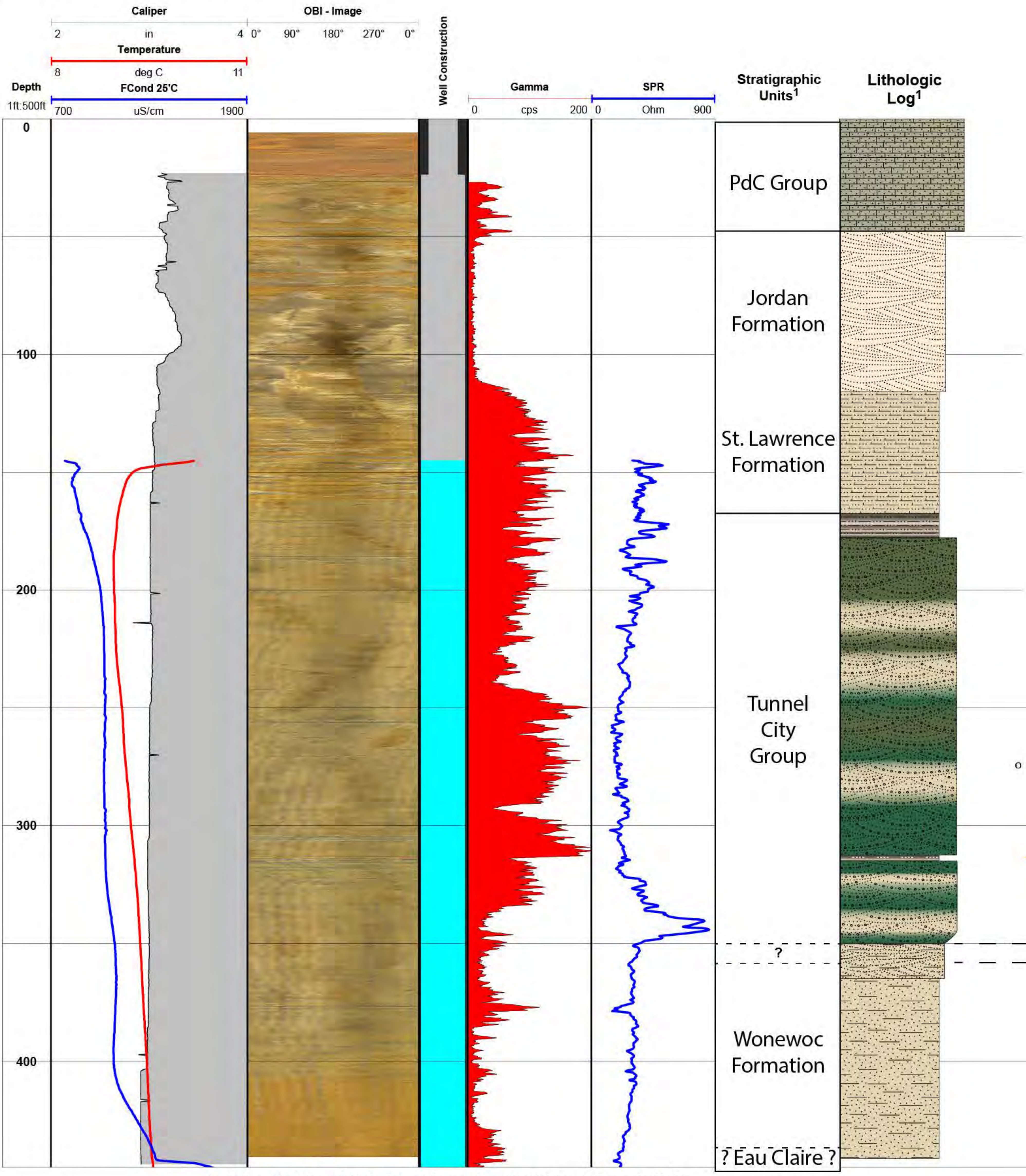
57outcrop Hwy C Leland







62000166 WGNHS Arcadia Quarry



1: Stratigraphic Units and Lithologic Log interpreted from WGNHS Arcadia Quarry 62000166

WGNHS Well ID 62000166

DATE 8/4/15 WELL NAME WGNHS Arcadia Quarry

LOCATION The Kramer Company Quarry SE of Acadia

COUNTY Trempealeau LOGGED BY Bill Batten

LATITUDE 44.202276 LONGITUDE -91.459189

LOCATION METHOD: GPS ☐ AIR PHOTO/TOPO ☐ PLSS ☐ OTHER DEM

ELEVATION 1200 ELEVATION METHOD: DEM X TOPO ☐ OTHER

WELL DEPTH 445 CASING DEPTH 23.6 DEPTH TO WATER 145

CASING STICK UP 1.2 File Created on: 8/12/2016 by: MJP

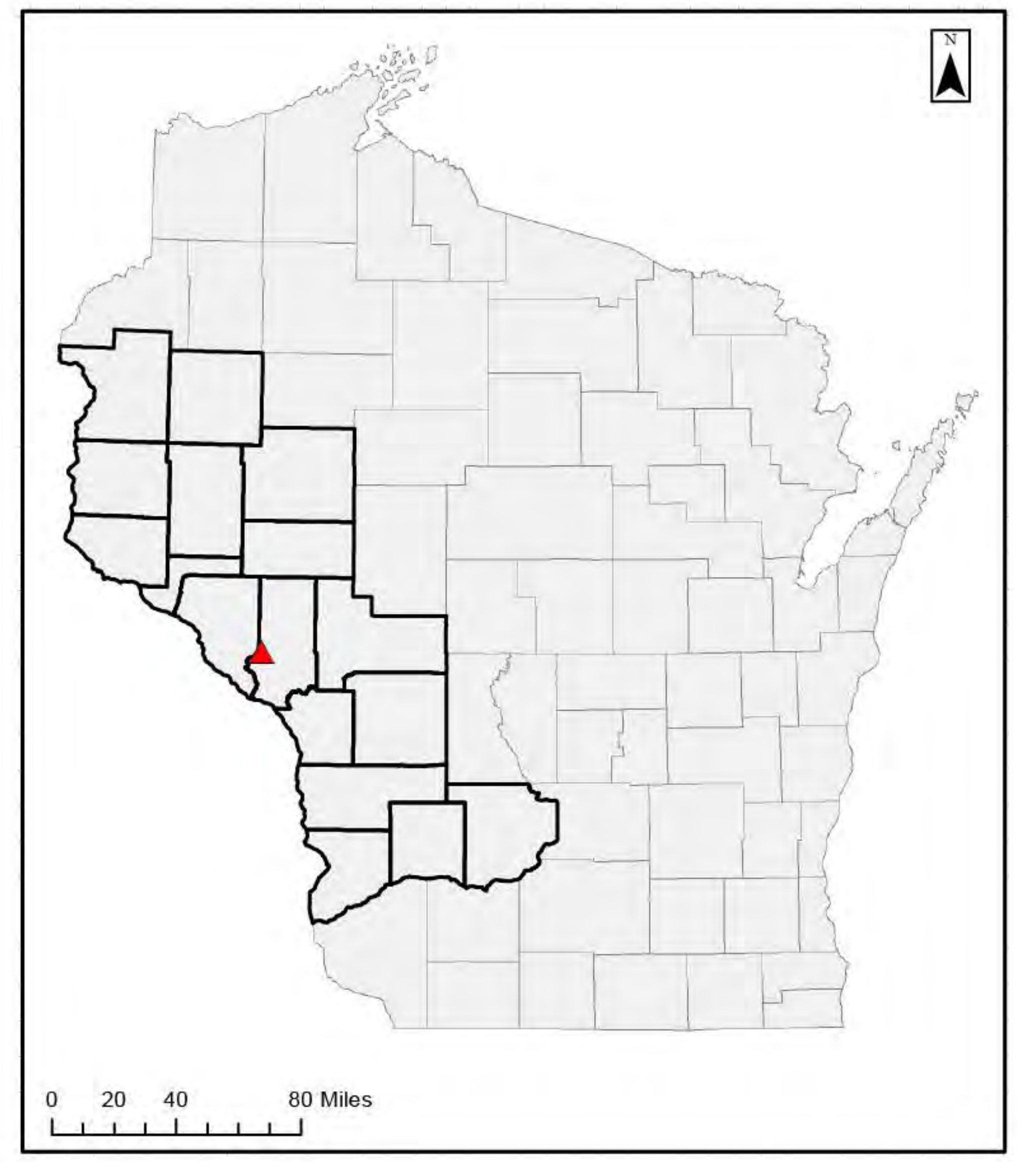
Comments: SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. Spinner flow measurements taken under ambient conditions

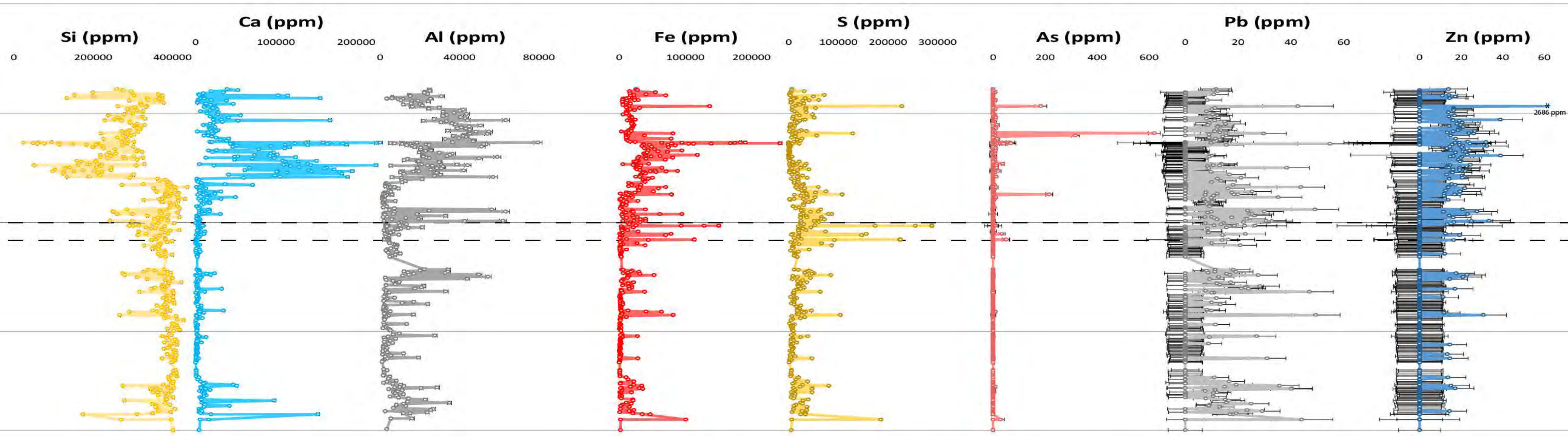
LOGS COLLECTED:

Gamma	X	Fluid Conductivity	X
Caliper	X	Flow Meter- HeatPulse	
Single Point Resistivity	X	Flow Meter- Spinner - flow up is negative, flow down is positive	
Self Potential		Optical Borehole Imager	X
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	X	OTHER:	

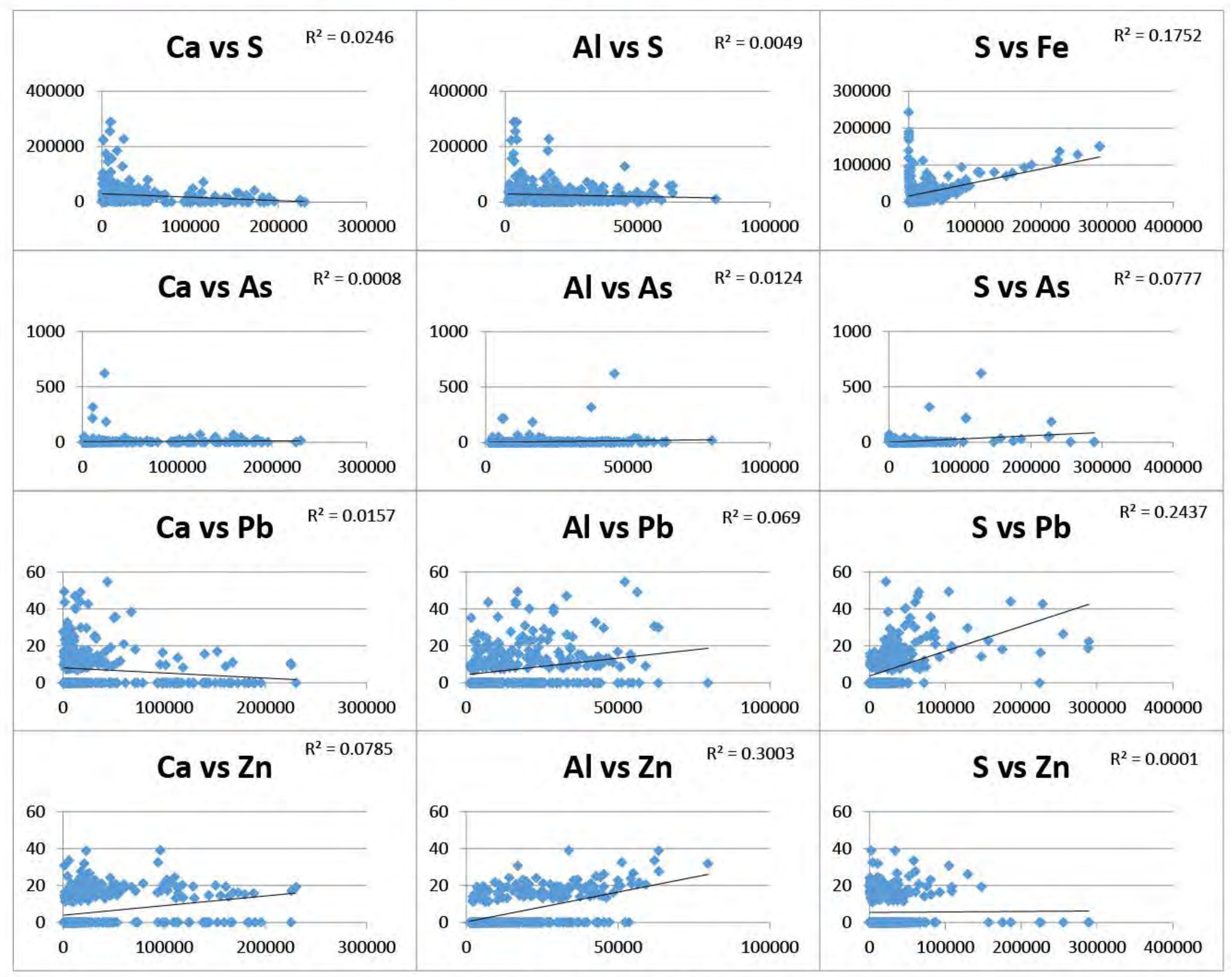
Unless Noted:
- all depths are in feet
- well depth, casing depth and depth to water are interpreted from geophysical log
- datum is the top of casing

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu



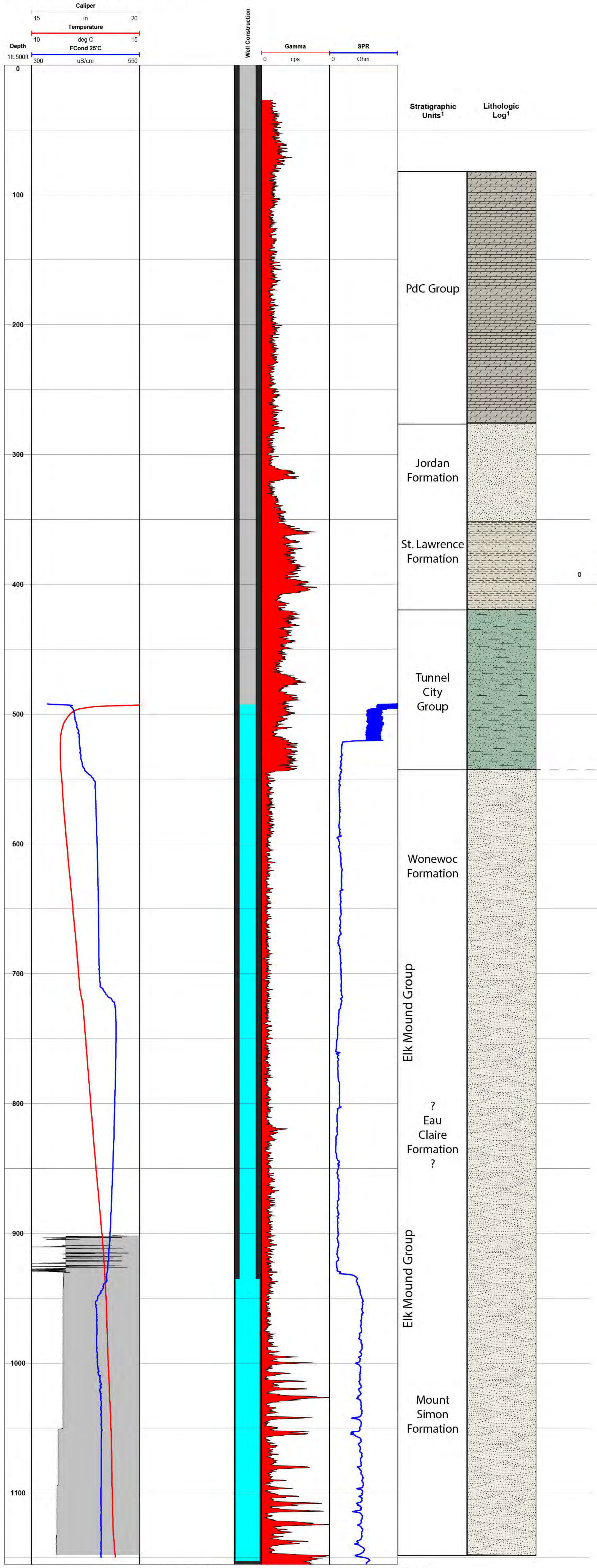


WGNHS Arcadia Quarry 62000166 showing no clear contact between the Tunnel City Group and Wonewoc Formation



* Outlier zinc Value of 2686 ppm removed from linear regression

63000165 Viroqua City Well 6



WGNHS Well ID	*63000165*
DATE *8/19/13*	**WELL NAME** *Viroqua Municipal Well #6*
LOCATION *S. Washington Ave. Viroqua*	
COUNTY *Vernon*	**LOGGED BY** *PMC*
LATITUDE *43.544424*	**LONGITUDE** *-90.882292*

LOCATION METHOD: *GPS* [x] *AIR PHOTO/TOPO* [ ] *PLSS* [ ] *OTHER* ____

ELEVATION *1275.6* **ELEVATION METHOD:** *DEM* [ ] *TOPO* [ ] *OTHER* *5ft LiDAR DEM*

WELL DEPTH *1152.5* **CASING DEPTH** *935* **DEPTH TO WATER** *492.6*

CASING STICK UP *1.4* ***File Created on:*** *8/12/2016* ***by:*** *MJP*

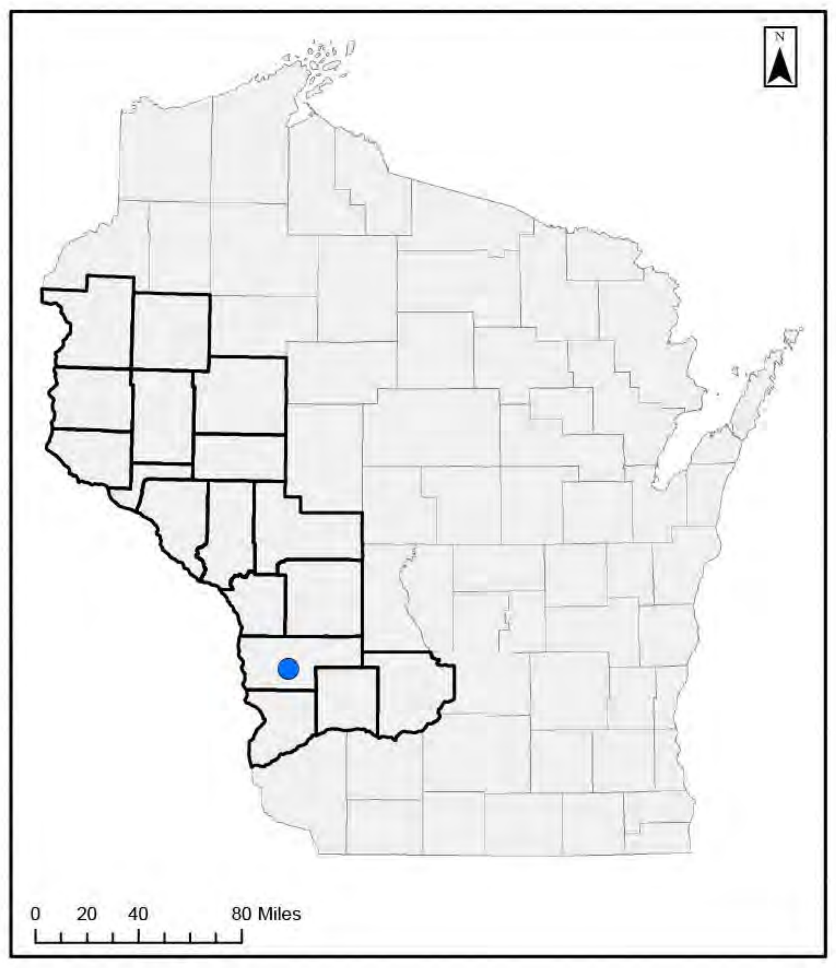
Comments: *SPR, SP, and Normal Resistivity profiles were collected for this well but only SPR is presented in this log. ABI profiles were also collected but not presented here. The Well Construction field depicts the well, casing, and water-level as measured on the day of logging. Caliper tool was recalibrated with long arms for large diameter hole.*

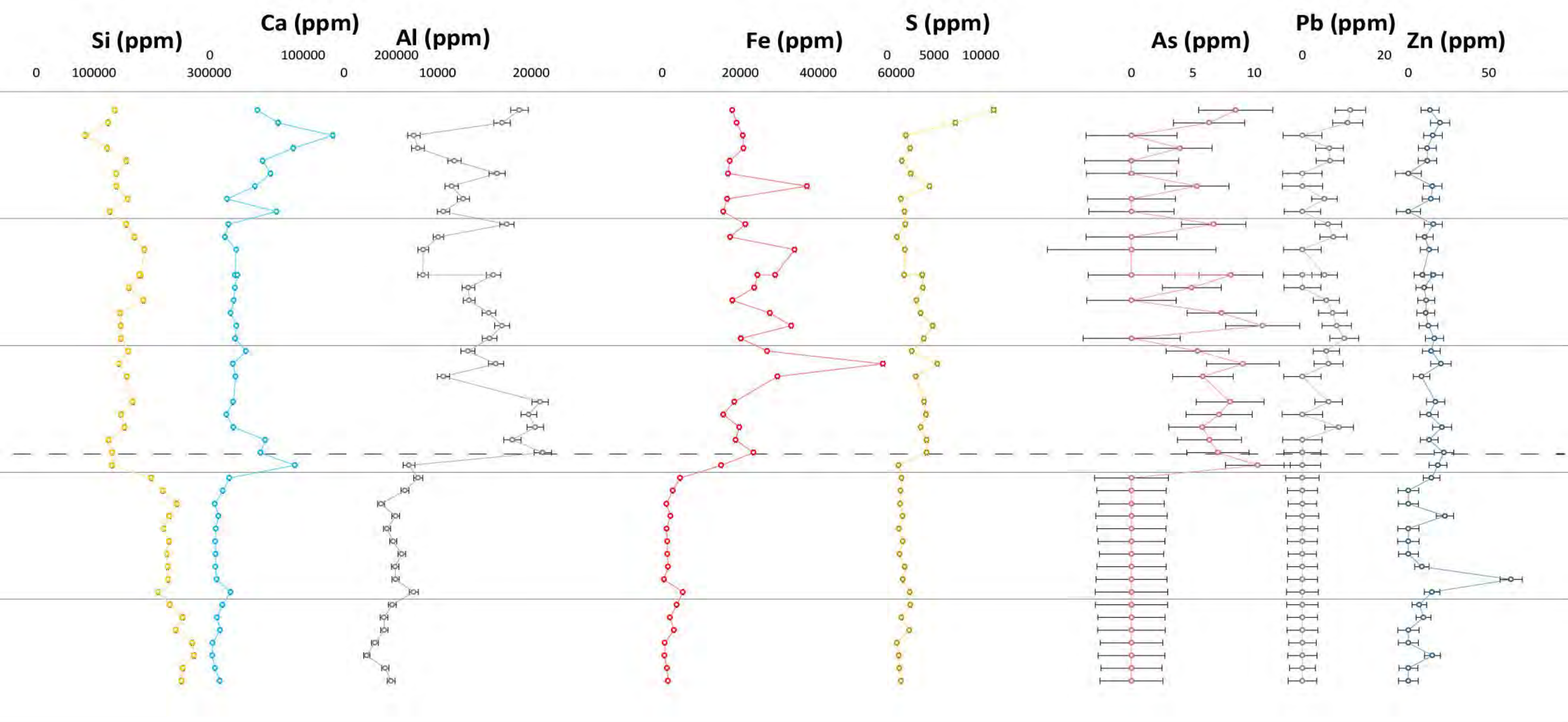
LOGS COLLECTED:

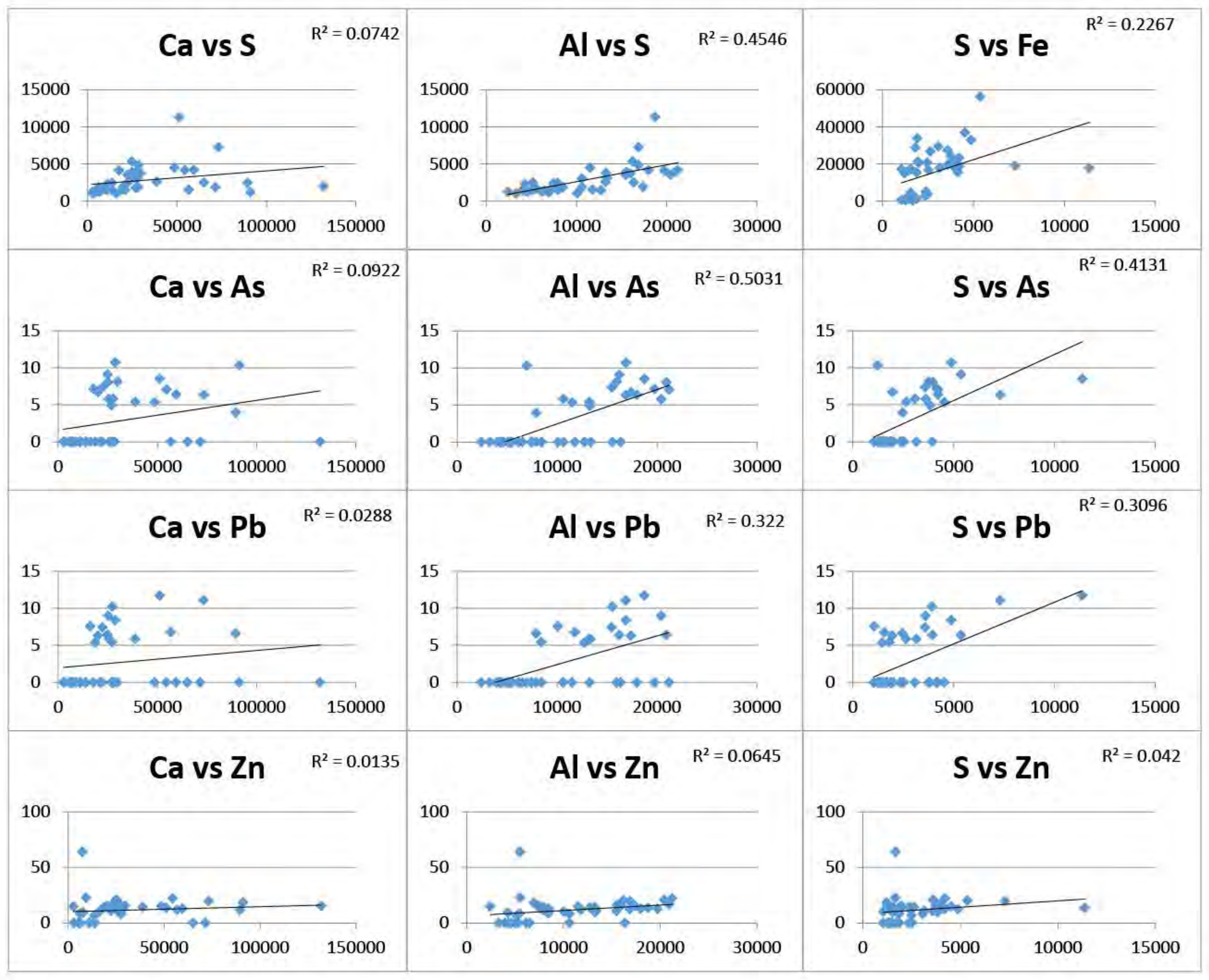
Gamma	x	Fluid Conductivity	x
Caliper	x	Flow Meter- HeatPulse	
Single Point Resistivity	x	Flow Meter- Spinner - *flow up is negative, flow down is positive*	
Self Potential		Optical Borehole Imager	
Normal Resistivity		Acoustic Borehole Imager	
Fluid Temperature	x	OTHER: ____	

Unless Noted:
- *all depths are in feet*
- *well depth, casing depth and depth to water are interpreted from geophysical log*
- *datum is the top of casing*

For more information or to obtain collected data not shown please contact us at geodata@uwex.edu







1: Stratigraphic Units and Lithologic Log interpreted from nearby Geologic Log Viroqua Well 4 63000053

63outcrop Victory North