Appendix B
Basalt Aquifer Characterization

Grain Handling Facility at Freeman, Freeman, Washington

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Draft

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Union Pacific Railroad

Grain Handling Facility at Freeman, Freeman, Washington

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Executive Summary

This report documents field investigations primarily focusing on the properties of the basalt aquifer and distribution of carbon tetrachloride (CT) within fractures of the basalt and potentially underlying basement rock at the Grain Handling Facility at Freeman, Washington and areas downgradient of the facility. Specifically, these field investigations involve a transect of four boreholes (RC-01 through RC-04) from the source area (grain handling facility) to the current Freeman School District Well approximately 1/3 mile to the south. The field investigations included a 2018 investigation focused on the shallow basalt, determining the degree of weathering and fracturing at the contact with the overlying loess deposits, and a 2019 investigation focused on the interior and deeper basalt flows and underlying basement rocks.

The 2018 investigation focused on coring boreholes at the four locations until competent, or relatively unfractured basalt was encountered, describing the core, conducting borehole geophysics in the open borehole interval at each location, and collecting groundwater grab samples at flowing fracture intervals for volatile organic constituents (VOC) analysis. Results from this investigation indicated the upper basalt near the contact with the loess is highly fractured in locations RC-01 through RC-03 and unfractured with little/no fracture flow at RC-04, the location closest to the Freeman School District Well. Location RC-01 encountered repeated borehole collapse because of intense fracturing, and the borehole was abandoned with no subsequent work performed at this location. Borehole geophysics determined fracture density and orientation and flowing fractures in RC-02 and RC-03 and groundwater grab samples from one interval in RC-02 and two intervals in RC-03. All interval samples contained CT above regulatory criteria with concentrations ranging from 293 micrograms per liter (µg/L) in RC-02 at approximately 100 feet below ground surface (bgs) to 184 µg/L in RC-03 at 62 feet bgs.

The 2019 investigation continued to drill down into boreholes RC-02, RC-03, and RC-04 with considerable variation in rock texture and presence of alteration zones and weathering horizons indicating multiple basalt flows. The most notable features being tagging a granitic gneiss bedrock at all locations from 225 feet bgs at RC-02 to 372 feet bgs at RC-04, the presence of an altered basalt known as palagonite at RC-03 from 170 feet bgs to approximately 245 feet bgs, and a distinct clay and organics (wood) weathering horizon, or paleosol, from 275 to 288 feet bgs at RC-04 indicating at least two discrete basalt flows in this borehole. After borehole completion and a groundwater grab sample collected from the granitic gneiss interval at the bottom of RC-04, borehole geophysics and hydrophysics were completed to document fracture features and determine precise locations of inflow and outflow at each location under ambient and pumping (stressed) conditions. Hydrophysical logging indicated flowing intervals suitable for subsequent packer testing and determined that a downward hydraulic gradient exists in RC-02, a downward gradient in the shallow portions at RC-03 before outflowing at 160 to 168 feet bgs, and a downward gradient is absent at RC-04. Upward gradients are present from below the outflow interval at RC-03 and throughout the entire flowing fracture interval at RC-04 (142.5 to 288 feet bgs). Packer testing and groundwater sampling within packer intervals were conducted at RC-02 and RC-04 with all intervals detecting CT at RC-02 and no detections of CT in RC-04.

Subsequent monitoring well installations at varying intervals at RC-02, RC-03, and RC-04 indicate vertical distribution of CT in this transect. Monitoring wells at RC-02 are all impacted by CT with concentrations up to 399 µg/L; at RC-03, the deepest well set at 215 to 225 feet bgs had no detectable concentrations of CT with ongoing monitoring well installation above this interval, and RC-04 had detections of CT up to 13.1 µg/L in all wells except the lowermost well screened below the paleosol. Subsequent monitoring well installations at this locations indicate the upper basalt flow at RC-04 is impacted by CT but underneath the clay paleosol at 275 feet bgs, groundwater has a strong upward gradient has no detections of CT.

Contents

Appendixes

Figures

Acronyms and Abbreviations

µg/L	microgram(s) per liter
bgs	below ground surface
COC	constituent of concern
CHS	Cenex Harvest States, Inc.
CSM	conceptual site model
CT	carbon tetrachloride
DI	deionized
Ecology	Washington State Department of Ecology
ft^2/day	square foot (feet) per day
FS	feasibility study
GAC	granular activated carbon
GHFF	Grain Handling Facility at Freeman
gpm	gallon(s) per minute
MTCA	Model Toxics Control Act
NAPL	nonaqueous phase liquid
Order	Enforcement Order No. DE 12863
ORP	oxidation-reduction potential
PVC	polyvinyl chloride
RC	rock core
RI	remedial investigation
RQD	rock quality designation
SWL	static water level
UPRR	Union Pacific Railroad
VI	vapor intrusion
VOC	volatile organic compound

1. Introduction

This report documents activities performed to collect bedrock data from fall 2018 through summer 2019 at the Grain Handling Facility at Freeman (GHFF) in Washington. The GHFF is under investigation from a 2015 Enforcement Order No. DE 12863 (Order) issued to Union Pacific Railroad (UPRR) and Cenex Harvest States, Inc. (CHS) by the Washington State Department of Ecology (Ecology) in full compliance with the requirements of the Order and the Model Toxics Control Act (Revised Code of Washington Chapter 70.105D and its implementing regulations) (MTCA). The Order requires performance of the remedial investigation (RI) and a feasibility study (FS) to assess remedial actions at the site. This report describes the characterization of the basalt aquifer to provide meaningful data for the FS.

1.1 Purpose

The primary objective of performing the 2018-2019 rock coring and borehole geophysical/hydrophysical logging is to quantify fracture characterization and groundwater flow in both the upper and lower basalt intervals and underlying crystalline basement rock. These data will be used to refine the existing conceptual site model (CSM) and select appropriate remedial response alternatives for the FS. Specific objectives of this report are as follows:

- Determining the distribution of the onsite chemical of concern (COC) and carbon tetrachloride (CT) within the fractures of the local basalt aquifer and underlying basement rock.
- Characterizing the groundwater flowpaths and fractures within the basalt aquifer along the CT plume axis using borehole geophysical and hydrophysical logging and packer testing.
- Characterizing the occurrence and vertical distribution of CT within the basalt aquifer by analytical groundwater sampling at multiple intervals during both static and stressed pumping conditions.

1.2 Site Description and Background

The GHFF is located at 14603 Highway 27 on the eastern side of State Highway 27 in the town of Freeman, Washington, approximately 20 miles southeast of Spokane, Washington. The property is owned by UPRR, currently leased to CHS, and used as a seasonally active grain handling facility. The facility consists of 11 steel grain silos, 1 steel grain elevator, and 1 subterranean receiving pit. UPRR owns and operates a railway line that parallels State Highway 27 and traverses the property from the southeast to the northwest (Figure 1). The grain handling facility is leased by CHS d/b/a Primeland Cooperatives (CHS/Primeland) from UPRR under a 99-year lease agreement. CHS/Primeland purchased Rockford Grain Growers in 1993. Rockford Grain Growers, an agricultural cooperative, was the original operator of the facility, which was constructed in 1955. The GHFF is believed to have been operated as a grain handling facility since 1955.

The Freeman School District is immediately across State Highway 27 from the GHFF. The Freeman School District covers approximately 56 acres of land and includes an elementary school, a middle school, and a high school. There are three water supply wells in the Freeman School District. The well (Primary Freeman School District Well [WS5]) that supplies drinking water to the school was installed in 1980 and, as of the 2018 RI report, is the sole source of water for the Freeman School District. In late August 2013, a treatment system consisting of an air stripper was put into operation to treat CT in groundwater extracted from the Primary Freeman School District Well (WS5). After the air stripping process and before entering the water distributions system, the water is treated with chlorine for disinfection. The Freeman School District monitors the water quality on a routine basis.

The water supply for surrounding residences is provided by privately owned domestic and agricultural wells. Granular activated carbon (GAC) point-of-entry treatment systems were installed in September 2016 to treat the water supply at two residences (Marlow and Randall). The treatment systems have been performing as designed (that is, removing CT and chloroform) based on routine weekly sampling since September 2016.

1.3 Previous Investigations

From May 2016 through June 2018, RI activities were conducted at the site and surrounding area to supplement previous RI data and fully delineate the presence and extent of COCs in soil, groundwater, surface water, air, and soil vapor (Jacobs, 2018). Soil and groundwater at the GHFF and groundwater downgradient of the GHFF contain elevated concentrations of selected volatile organic compounds (VOCs), primarily CT and chloroform. Based on previous correspondence with Ecology, CT and chloroform have been designated the COCs for the site.

Descriptions of RI activities and results are presented in this section consistent with these categories.

1.3.1 Source Area Delineation

Previous investigation activities indicated the presence of COCs in soil at and surrounding the GHFF. The results of those previous investigation activities could indicate the presence of nonaqueous phase liquid (NAPL) that could be an ongoing contribution of dissolved-phase COCs in downgradient groundwater. Therefore, between May 2016 and June 2018, additional investigation was conducted to evaluate the potential presence and extent of COCs in soil and NAPL at and surrounding the GHFF. Extensive soil sampling has been conducted at the site, including beneath the grain handing infrastructure. The combination of soil, sub-slab soil vapor, and passive/active soil vapor results indicate that low levels of residual COCs remain beneath the GHFF and extend slightly downgradient. The results do not indicate the presence of any NAPL that would function as a long-term source. The distribution of COCs in soil and groundwater at and downgradient of the site suggest that COCs have migrated offsite as a dissolved, rather than nonaqueous, phase in groundwater.

1.3.2 Groundwater Characterization

Previous domestic well sampling indicated the presence of COCs in groundwater downgradient of the GHFF. Therefore, between May 2016 and July 2018, additional investigation was conducted to evaluate the presence and extent of COCs in groundwater downgradient of the GHFF. Soil boring and sampling, groundwater grab sampling, monitoring well installation and sampling, aquifer testing, and surface water sampling were all undertaken as part of the characterization.

A summary of findings from groundwater characterization conducted are as follows:

- Groundwater flow direction and gradients are influenced by domestic pumping and heterogenous flow paths within the basalt unit.
- CT concentrations above screening levels have been detected at the highest concentrations at the GHFF and extend with decreasing concentrations approximately 2,700 feet south of the GHFF.
- CT concentrations in groundwater have been detected at up to 222 feet below ground surface (bgs) (monitoring well MW-6D), and vertical migration of COCs is likely influenced by pumping at the Primary Freeman School District Well (WS5) and open borehole wells associated with the domestic wells.
- Impacted groundwater largely resides within the basalt unit.
- The highest concentrations of COCs in groundwater appear to be stable.
- Surface water bodies (Little Cottonwood Creek) do not appear to be affected by impacted groundwater.

1.3.3 Exposure Assessment

Investigation activities were conducted to evaluate the potential exposure of COCs at the Freeman School District and residences. Residential and commercial soil sampling and potable groundwater sampling were all evaluated under the assessment. In addition, air (background, indoor, outdoor, and crawl space) and sub-slab vapor sampling results were used to conduct a comprehensive vapor intrusion (VI) assessment consistent with MTCA guidelines developed by Ecology.

A summary of findings from the exposure assessment conducted are as follows:

- There are no COCs in surface soil samples collected in the residential area.
- Commercial soil sample analytical results at the GHFF are significantly below screening levels.
- Groundwater (drinking water) sampling identified COCs at levels above screening levels in drinking water sources.
- Comprehensive air and VI assessment, including background, indoor, and outdoor air, was completed in April 2017 and presented to Ecology. The evaluation concluded that based on the comparison with background levels and the monitoring of indoor emissions sources, CT and chloroform concentrations detected in indoor air in the Freeman School District buildings are unrelated to COCs detected in groundwater. Ecology concurred with this conclusion.

1.4 Conceptual Site Model

CT has historically been used at grain handling facilities to control pests. Although there are no records indicating CT was used at the GHFF, soil and groundwater sampling conducted at and surrounding the site indicate that CT was likely used at the site and migrated through the subsurface to groundwater. CT was detected at relatively low concentrations in several soil samples collected at the site. However, most soil samples where CT was detected at concentrations above the reporting limits were at depths greater than 15 feet bgs. The extent of CT detected in soil samples is relatively small and generally limited to the GHFF boundaries. These and other 2018 RI results suggest limited residual sources that could further dissolve into groundwater. It is likely that over time CT that may have been present in the vadose zone has volatilized and/or dissolved into infiltrating precipitation and migrated to groundwater.

Once CT has migrated to groundwater, contaminant transport via groundwater at the site and surrounding area is affected by soil/groundwater interactions and biotic/abiotic reactions. Dissolved CT will move with groundwater but at a different velocity because of continuing solute-soil interactions. The highest CT concentrations have been detected in the shallow unconsolidated soils and fractured upper basalt at the southeastern corner of the GHFF facility in the water table zone (within the capillary fringe of the water table). Over time, the groundwater plume has extended downgradient from the site following preferential flow paths driven by hydraulic gradients. Some mass adsorb to soils, some diffuse into less permeable soils, and some migrate with groundwater. Abiotic and biotic transformation processes can reduce COC concentrations over time and distance. Groundwater flow, and thus COC transport, within basalt rock can be accelerated by fractures and well connected pore spaces. Basalt rock has considerable pore space at the tops and bottoms of lava flows. Numerous basalt flows commonly overlap, and the flows are separated by soil zones or alluvial material that form permeable zones. Columnar joints that develop in the central parts of basalt flows create passages that allow water to move vertically through the basalt. Contaminant transport can also be accelerated through domestic wells constructed using long open boreholes that connect multiple permeable zones, such as the Primary Freeman School District Well (WS5). Lateral and vertical contaminant transport can also be accelerated by pumping at domestic wells.

CT can volatize from the groundwater table into the vadose zone and migrate into crawl spaces and indoor spaces in structures above impacted groundwater. If the water is not treated, CT can also volatize from tap water from domestic wells screened within the CT plume. It is noteworthy that CT is being removed using point-of-entry treatment systems at the Freeman School District and two surrounding residences. An extensive air assessment has indicated that there is no significant VI associated with the groundwater and drinking water.

2. Field Activities

The following subsections describe the drilling, geophysical/hydrophysical logging, packer testing, monitoring well installation, and any groundwater sampling activities conducted as part of the rock coring investigation. Boring locations were screened for subsurface utilities by a third-party subcontractor, and the One-Call of Washington was used to notify the utility companies in the areas.

2.1 Summary of Tasks

The 2018-2019 rock coring investigation tasks completed are as follows:

2.1.1 2018 Upper Basalt Investigation

- Drilled four borings to collect continuous core within the upper basalt with total depths ranging from 55 to 110 feet bgs.
- Conducted borehole geophysics in three borings within the upper basalt.
- Collected five groundwater samples from fracture intervals within three borings.

2.1.2 2019 Lower Basalt and Basement Rock Investigation

- Continued drilling with air-rotary methods at three of the existing boreholes to depths ranging from 230 to 390 feet bgs.
- Conducted borehole geophysical logging in the open borehole interval at each boring location.
- Conducted hydrophysical logging within the same intervals to determine groundwater flow zones at each boring location.
- Based upon the geophysical and hydrophysical logging, packer testing was performed at selected intervals in all three boring locations for sample collection and hydraulic parameters measurement.
- Provided recommendations on screen intervals for the installation of 11 monitoring well clusters at varying depths at each boring location as part of the upcoming FS.

Summaries of each borehole for both the upper and lower basalt investigations are provided on Figures 2 through 5.

2.2 2018 Upper Basalt Investigation

2.2.1 Drilling and Rock Coring

Drilling and rock coring of the upper basalt began on November 8, 2018, and was performed using a combination of sonic, wireline coring, and air-hammer techniques by Environmental West Exploration of Spokane Valley, Washington, under the supervision of a driller and geologist licensed in Washington State. Four locations designated Rock Core (RC) boreholes one through four (RC-01 through RC-04) were selected for the investigation (Figure 1). The objective of the rock coring was to determine the depth from top of basalt to intervals where weathering and fracturing had decreased and rock quality designation (RQD) values indicated that competent rock, that may separate groundwater from the weathered zone to deeper fracture intervals, had been reached.

Following subsurface utility screening, the drilling at each location began with the installation of an 8-inch steel conductor casing via sonic drilling through the loess and keyed several feet into the upper basalt to prevent downward migration of groundwater in the loess and weathered top of basalt to the more competent basalt aquifer below. Depths of the conductor casing ranged from 43 feet bgs at RC-01 to 94 feet bgs at RC-02. Following drilling, the casing was sealed with a bentonite grout from total depth to the ground surface at each location and allowed to set before wireline coring began.

Wireline coring was conducted using a diamond NQ size (1.88-inch core diameter, 2.98-inch hole diameter) coring bit to collect rock core in 5-foot sections. Once a core was retrieved to the surface, a Jacobs geologist recorded rock type and composition, strength, texture, degree of fracturing, cementation/annealing, and any staining. In addition, RQD was determined for each core run to determine overall rock strength and degree of fracturing present, and photographs of the rock core were taken. Following wireline coring, the interval at each location was reamed out to 4-inch diameter in advance of borehole geophysical logging. Hole collapse at location RC-01 occurred at numerous intervals because of the intensely fractured nature of the basalt. The driller stated that they would not be able to maintain borehole integrity without the addition of polymers. Because of the uncertainty of the composition of the polymers and possible addition of VOCs, it was decided to abandon RC-01 by installing a bentonite grout via tremie pipe from the total depth to the surface.

2.2.2 Borehole Geophysical Logging

Borehole geophysical logging of the upper basalt was conducted at RC-02 through RC-04 on November 29 and 30 by Global Geophysics of Redmond, Washington. The list of geophysical logs and their objective are as follows:

- **Fluid temperature and conductivity:** Monitors borehole water quality with depth. Changes in temperature and conductivity may be indicative of zones of groundwater entering or exiting the borehole.
- **Natural Gamma:** Picks up radioactive isotopes (primarily Potassium 40) contained in minerals often present in clays (such as fracture infilling).
- **Caliper:** Measures borehole diameter and roughness – can identify casing bottom and large fractures.
- **Televiewers:** Both optical (above and below water in clear conditions) and acoustic (under water only in turbid conditions) used to identify fracture location, attitude, aperture size, and degree of cementation.
- **Heat pulse flow meter:** Measures the magnitude and direction of vertical flow at discrete locations selected from the other logs. The flow meter can detect intervals where groundwater in the borehole is traveling vertically (up and down).

Logging was completed in the open borehole interval at each hole within the upper basalt, from the bottom of the conductor casing to the total depth. Results are discussed in Section 3.1.2. The report from Global Geophysics is included in Appendix A

2.2.3 Aquifer Testing and Groundwater Sampling

Based on the results of the borehole geophysics, groundwater sample locations were collected on December 19 and 20, 2019, at intervals where fracture flow was believed to be occurring. Sampling only occurred at RC-02 at one interval (100 to 101.5 feet bgs) and two intervals at RC-03 (60 to 62 and 72 to 73 feet bgs). No flowing fractures were detected at RC-04, and the water in the borehole was from drilling activities with no change in head from borehole geophysics to sampling; therefore, no samples were collected from this borehole. Groundwater sampling at intervals within RC-02 and RC-03 were collected at low-flow rates and then a single sample for the entire open borehole immediately following a higher flow stressed rate that acted as a short aquifer test concurrent with sampling. In-Situ Troll transducers were placed in each borehole prior to sampling to measure changes in head over time for mini aquifer testing prior to the higher flow sampling. Low flow sampling purged groundwater until parameters including temperature, conductivity, turbidity, oxidation-reduction potential (ORP), and pH had stabilized before groundwater was collected for VOC analysis. Following the low-flow sampling, the aquifer test was conducted where the borehole was stressed to measure the highest pumping rate the borehole could maintain with stabilized drawdown. Following the testing, a post-test sample from each borehole was collected to determine if concentrations of VOCs had changed from the samples collected under low-flow conditions.

2.3 2019 Lower Basalt and Basement Rock Investigation

Following the collection of field data for the upper basalt, additional work resumed to investigate the lower basalt section and potentially the underlying basement rock at three boreholes (RC-02, RC-03, and RC-04) on March 12, 2019.

2.3.1 Drilling

Drilling resumed through the 5.5-inch conductor casing and the open borehole section of the upper basalt at three remaining boreholes using air-rotary drilling techniques. Logging was conducted by a Jacobs geologist who collected rock chips from the cyclone separator at 5-foot intervals. Rock type, degree of decomposition/altering, any sudden drops of the air hammer bit, and increases and decreases of water production were documented along with photographs of the rock chips at selected intervals. Boreholes reached a total depth of 230 feet bgs at RC-02, 250 feet bgs at RC-03, and 390 feet bgs at RC-04.

Hole collapse resulting from highly fragmented rock occurred at all borings and drilling through clay zones that likely represented paleosol surfaces of discrete basalt flows or intensely altered intervals occurred in RC-03 and RC-04. RC-04 encountered the basement rock (weathered granite) while drilling below 372 feet bgs, but clay and weathered material within this interval (372 to 390 feet bgs) repeatedly collapsed the borehole. Because of the borehole being unable to remain open for subsequent borehole geophysical/hydrophysical logging at this depth, a temporary 2-inch Schedule 40 polyvinyl chloride (PVC) well was installed with a 5-foot 0.020-inch slot screen set at 383.5 to 389.5 feet bgs for groundwater sample collection of VOCs in low-flow and post-aquifer test conditions using procedures outlined in Section 2.2.3. Following sampling, the temporary well was removed, and a bentonite seal up to approximately 360 feet bgs was installed to allow for geophysical/hydrophysical logging above the collapsed interval.

2.3.2 Borehole Geophysical Logging

Borehole geophysical and hydrophysical logging services were provided by Colog, Inc. of Lakewood, Colorado, over several mobilizations from April 22 through May 25, 2019. Geophysical logging at RC-02, RC-03, and RC-04 was conducted prior to hydrophysical logging to ascertain borehole conditions prior to injection of deionized (DI) water and pumping equipment. Three-arm caliper, temperature and conductivity, and acoustic and optical televiewer logs were all run and are located in the *Geophysical & Hydrophysical Logging Results, Jacobs, Union Pacific, Spokane, WA Final Report* included in Appendix B. Logging runs were completed through the entire open borehole length at RC-02 (123 to 225 feet bgs) and RC-04 (81 to 360 feet bgs). At RC-03, the interval from the bottom of the conductor casing at 83 feet bgs to 196 feet bgs was logged. However, a soft, intensely altered zone from approximately 196 to 210 feet bgs would not allow the geophysical instrumentation to penetrate to total depth at RC-03.

2.3.3 Hydrophysical Logging

Following borehole geophysical logging, Colog performed hydrophysical logging at RC-02, RC-03, and RC-04 in the same intervals as the geophysical logging. Hydrophysical logging is a two-stage process that quantifies groundwater movement through the borehole in terms of rate and direction:

1) **Ambient Flow Logging:** This test is performed first at the borehole and involves emplacing a column of DI water into the open borehole interval. This was accomplished by injecting DI water at the bottom of the borehole while simultaneously removing existing formation water at the same rate from the top of the water column. Injection and pumping are stopped, and a temperature and conductivity probe is constantly moved up and down the water column to determine intervals where higher-conductivity formation water is entering the borehole and displacing the low conductivity DI water. The inverse is also true where DI water can be tracked leaving the water column at intervals of groundwater outflow. Modeling software then quantifies the rate of inflow and outflow at differing intervals. Ambient flow logs for RC-02, RC-03, and RC-04 are located on Figures 3 through 5.

2) **Stressed Flow Logging:** Following the ambient flow log (normally the following day), the borehole is pumped under stressed conditions where DI water is injected at a slower rate than the formation water is extracted, and a steady-state drawdown is achieved. As the temperature and conductivity probe travels through the water column, the inflowing formation water is detected, and rate quantified by modeling software. The subsequent profile can determine the total transmissivity of all flowing fractures in the borehole. Stressed flow logs for RC-02, RC-03, and RC-04 are located on Figures 3 through 5.

2.3.4 Packer Testing and Groundwater Grab Sampling

Following analysis of the borehole geophysical and hydrophysical logs by Colog and Jacobs technical teams, packer testing of selected flowing intervals were chosen. Permeability (transmissivity) testing of selected fracture zones was performed by Colog with subsequent sampling for VOCs at the same intervals during low-flow and post-aquifer test performed by Jacobs staff. These activities were conducted interbedded with other site activities at boreholes RC-02 and RC-04 from May 3 to 25, 2019. No packer testing was conducted at boring RC-03 because of the unstable hole conditions below 200 feet bgs and the need to install a monitoring well to screen below this interface. MW-26 was installed as a 2-inch Schedule 40 PVC well screened from 215 to 225 feet bgs.

A wireline packer assembly that utilized both single and dual (straddle) packer configurations were used for testing selected test intervals at RC-02 and RC-04. Pressure transducers were placed within the tested intervals to measure the hydraulic head during testing and above and below (if applicable) the assembly to measure for potential leakage or water bypass.

Four intervals were tested at RC-02 (static water level (SWL) to 142, 145.5 to 156, 156 to 225, and 192 to 225 feet bgs) and four intervals at RC-04 (SWL to 48, 254 to 264.5, 265.5 to 276, and 282.2 to 292.5 feet bgs). Groundwater samples for VOC analysis were collected from each interval following the purge of at least one straddle interval volume (24 gallons for a standard 10.5-foot interval. In addition to the low-flow purge and sampling, the packer test intervals at RC-02 also underwent aquifer testing under stressed conditions to potentially collect water from further out into the formation. Following completion of the test, a sample was collected for VOC analysis. The provided pump from Colog was unable to create stressed conditions at the packer intervals at RC-04; therefore, no testing to stress the aquifer and subsequent groundwater sampling was conducted.

3. Results

3.1 2018 Shallow Basalt Investigation

3.1.1 Rock Core Analysis

Analysis of rock core collected from borings at RC-01, RC-02, and RC-04 was conducted concurrent with drilling operations. All core collected were tholeiitic basalts from the Columbia River Group. The state of weathering and fracturing for core samples varied considerably across the three boreholes. Because of the many problems experienced by the driller with borehole collapse, core barrel seizure, and inability to lift fine-grained cuttings out of the borehole, the Jacobs technical team determined that coring at the RC-03 location (logistically, the final borehole to be drilled) could be omitted. Borehole geophysical logging could estimate fracture density and orientation at RC-03 but only after the cessation of drilling, so estimating depth to competent basalt would need to be determined by less precise drilling data such as water gain/loss and drill rate.

RC-01: Basalt from this location was strong, mainly aphanitic texture with some porphyritic intervals and slight vesiculation (air bubbles) with plagioclase feldspar crystals visible with a moderate degree of weathering (iron staining on surfaces). Fracturing was intense with RQD values ranging from 0 percent (very poor) to 28 percent (poor) per 5-foot run. Only three runs were collected at RC-01 from 43 to 55 feet bgs because the core barrel became trapped numerous times by borehole collapse, and the drillers were unable to maintain borehole integrity.

RC-02: Basalt at this location was very strong to strong, aphanitic in texture with deeper core runs extremely vesicular with vesicles up to 3 millimeters in diameter. Oxidation and iron staining were common, and some silica cementation was present within some vesicles. Degree of fracturing varied from moderate in the upper core run to intensely fractured in the deeper intervals with RQD values ranging from 0 percent (very poor) to 35 percent (poor) per 5-foot run. Only three runs were collected at RC-02 from 97.7 to 110.7 feet bgs as the driller experienced similar problems of core barrel seizure and borehole integrity.

RC-04: Basalt at RC-04 was overall strong, aphanitic with some vesicular intervals. As opposed to the first two borings, the RC-04 core was unweathered and unfractured for the entire length of the coring interval (61.1 to 80.1 feet bgs), with 100 percent RQD (excellent) recorded in four 5-foot coring runs. At this depth it was determined that the basalt was competent and a barrier between the overlying loess deposits and deeper fracture intervals was present.

3.1.2 Borehole Geophysical Results

Borehole geophysics for the shallow basalt were logged by Global Geophysics from RC-02, RC-03, and RC-04. The report is included in Appendix A.

RC-02: Basalt was logged from 95 (the bottom of the conductor casing for upper basalt investigation) to 110 feet bgs. No deviations were noted for temperature and conductivity logs, and the natural gamma log did not display much correlation with increases in gamma ray count and magnitude with degree of cementation at fracture intervals. The caliper log displayed increases in borehole diameter just below the conductor casing at 95 feet bgs, and fracture zones at 100 to 102 feet bgs and 104 to 106 feet bgs. The optical and acoustic televiewer logs revealed fracture zones with significant aperture size and steeply dipping orientation at 100 to 101 feet bgs (0.21 inch) and 104.5 to 105.5 feet bgs (0.26 inch). The heat pulse flowmeter detected downward flow within the borehole from 96 to 109 feet bgs up to 4.92 feet per minute. Based on the available fracture data, the mean fracture aperture and spacing are 0.117 and 6.144 inches, respectively. The portion of the entire bedrock volume that is occupied by fractures for this interval (fracture porosity) is 0.019 percent.

RC-03: Basalt was logged from the bottom of the conductor casing for the upper basalt investigation at 53.5 feet bgs to 83 feet bgs. No deviations were noted for temperature and conductivity logs, and the natural gamma log did not produce any meaningful data. The caliper log correlated well with the televiewer data in identifying increases in borehole diameter with associated fracture zones. The televiewer data revealed fracture zones with shallow to steeply dipping fracture planes and significant aperture sizes at 56.5 feet bgs (0.86 inch), 60 to 66.5 feet bgs (0.49 inch), and 72.5 feet bgs (1.04 inches). The heat pulse flowmeter detected downward flow within the borehole from 54 to 80 feet bgs at 6.89 to 4.85 feet per minute, respectively. The mean fracture aperture and spacing are 0.177 and 8.876 inches, respectively. The fracture porosity for this interval (fracture porosity) is 0.02 percent.

RC-04: Basalt was logged from the bottom of the conductor casing for the upper basalt investigation at 59.5 to 78.5 feet bgs. No deviations were noted for temperature and conductivity logs and similar to the previous borehole logs, the natural gamma log did not produce any data of significance. In addition, no fractures with aperture thicknesses greater than 0.01 inch were identified in the interval, and no flow was detected using the heat-pulse flowmeter suggesting that water inside the borehole was a remnant from drilling. These data imply that the interval logged at RC-04 was completely separated from groundwater in the overlying loess and underlying fracture zones deeper in the basalt. The mean fracture spacing is 57 inches, and no fractures with measurable aperture thicknesses were documented. Therefore, the fracture porosity for this interval is 0 percent.

3.1.3 Shallow Basalt Groundwater Results

Groundwater samples collected from RC-02 and RC-03 were placed on ice and shipped to Pace Analytical of Minneapolis, Minnesota, for laboratory analysis. Samples were run for site COCs (CT and chloroform) using Method US260B.

Results for sampled boreholes are the following:

RC-02: The borehole was sampled from low-flow and post-aquifer test (stressed) conditions from a fracture zone between 100 and 101.5 feet bgs identified from the borehole geophysical logging. The low-flow sample was collected at 0.2 gallon per minute (gpm), and the stressed sample was collected after the aquifer had been pumped at approximately 2.5 gpm for 90 minutes. CT concentrations for the low-flow sample were 190 micrograms per liter (µg/L) and 293 µg/L for the sample taken after the mini-aquifer test. Hydraulic conductivity was measured at 4.64 feet per day and transmissivity at 188 feet per day. The increase in CT concentration between the two samples are probably because of the aquifer test pulling in contaminated groundwater along secondary porosity features further out from the borehole.

RC-03: The borehole was sampled at two intervals within the open borehole section of the shallow borehole investigation. Fracture intervals identified from borehole geophysical logging at 60 to 62 feet bgs and the large fracture at 72 to 73 feet bgs were targeted for analysis. The two low-flow samples were collected first with pumps lowered to their specified intervals and pumped at 0.3 gpm (60 to 62 feet bgs) and 0.4 gpm (72 to 73 feet bgs), respectively. An aquifer step test was conducted for the entire open borehole length from 3.2 up to 10.4 gpm for approximately 3.5 hours prior to sample collection at the 72 to 73 feet bgs interval. CT concentrations from the low-flow samples were 184 µg/L at 60 to 62 feet bgs and 202 µg/L at 72 to 73 feet bgs. Hydraulic conductivity and transmissivity values could not be assessed as the pumping level could not keep enough hydraulic head above the transducer for the entire test. The post-aquifer step test groundwater sample had a concentration of 193 µg/L, suggesting that no significant CT concentrations were pulled in from further out in the formation by the aquifer test, and the sample was a mix of the upper and lower intervals.

3.2 2019 Lower Basalt and Basement Rock Investigation

3.2.1 Drilling and Rock Logging

Drilling for the deep basalt investigation was conducted using the air-hammer drilling method provided by Environmental West Drilling. Because of the logistical and technical challenges Environmental West were encountering with rock coring, the team determined that the three boreholes, RC-02 through RC-04, could identify the goal of the top of the basement rock using this drilling method with the Jacobs geologist collecting and photographing rock cuttings from the cyclone hopper at 5-foot intervals. In addition, the geologist would document rock type, strength, color, texture and degree of decomposition. Drilling rate, any gain or loss of drilling fluid, and any sudden drops in drill string or excessive rig chatter were also noted.

RC-02: Following completion of the shallow basalt investigation, a 6-inch conductor casing was installed to a depth of 123 feet bgs. A 5.5-inch hammer bit was telescoped through the conductor casing and drilled the open borehole section for the deep basalt investigation from 123 feet bgs to a total depth of 230 feet bgs. Tholeiitic Columbia River Basalt in various stages of decomposition from unweathered to heavily oxidized was recorded from 111 feet bgs (during conductor casing installation) to 205 feet bgs. At this depth, a soft brown clay interbedded with weathered basalt was encountered to 225 feet bgs. This assemblage appears to be a heavily altered volcanic rock known as palagonite; palagonite occurs where volcanic rocks such as flood basalts are quenched rapidly from contact with standing water and are common features on the edge of basalt flows. The last rock cuttings collected at 230 feet bgs before borehole collapse appeared to be a highly weathered granitoid rock indicating contact with the underlying basement rock. For subsequent borehole geophysical logging, the total depth these instruments reached was 225 feet bgs suggesting the palagonite interval collapsed.

RC-03: The 6-inch conductor casing was installed down to 83 feet bgs and the 5.5 hammer bit telescoped through to drill the open borehole section below to a total depth of 250 feet bgs. The basalt encountered was moderately to heavily decomposed for its entirety with a minor clay alteration component throughout and likely palagonite cuttings from 200 feet onwards. The drilling log notes an increase in clay content at 230 feet bgs, signifying an intensification of weathering, and the drill cuttings taken from the 245 and 250 feet bgs intervals indicated a rock primarily composed of quartz and muscovite mica – likely the same basement rock encountered at RC-02. Subsequent hole collapse and borehole heave left the total depth at 240.5 feet bgs.

RC-04: The 6-inch conductor casing was placed at 81 feet bgs, and the 5.5-inch hammer bit drilled the open borehole section from this depth to a total depth of 390 feet bgs. Basalt from the conductor casing (81 feet bgs) to approximately 160 feet bgs was unweathered with no soft drilling conditions or altered rock cuttings noted. From 160 to approximately 270 feet bgs, the basalt was fractured with soft drilling, lots of water produced, and altered texture and composition. From 270 to approximately 290 to 295 feet bgs, the borehole encountered a soft gray clay with weathered basalt fragments with occasional well preserved wood pieces. The clay interval likely represents a paleosol at the top of a basalt flow that was exposed to the surface for an indeterminant amount of time before the overlying basalt flow covered it up. This paleosol layer is the first evidence noted of multiple basalt flows being present at the site. Underneath the clay layer at 290 to 372 feet bgs, the underlying basalt flow was strong, with no evidence of increased water flow, weathering, or alteration. A change in drilling to very soft conditions and the presence of a dark gray, soft clay was encountered from 272 to 381 feet bgs. This clay interval ended at 381 feet bgs where weathered fragments of quartz and muscovite interpreted as the basement rock were documented to the total depth of the boring at 390 feet bgs.

Subsequent collapse of the borehole immediately after drilling into the basement rock prompted the technical team to install a temporary well screened within the basement rock to be installed and is described in detail in Section 2.3.1. Summaries of the borehole drilling with photographs are located on Figures 2 through 5, and a cross section with updated lithological data is provided on Figure 6.

3.2.2 Borehole Geophysical Logging Results

Borehole geophysical logging for the deep basalt investigation was completed by Colog for boreholes RC-02, RC-03, and RC-04. A summary of logging results is described below and on Figures 3 through 5, and orientation data at each borehole are displayed on Figure 10.

RC-02: The borehole was logged in the deep basalt interval from the bottom of the conductor casing at 123 feet bgs to 225 feet bgs. The conductivity log had activity at 150 feet bgs and approximately 175 to 200 feet bgs. The caliper log registered a notable increase in borehole diameter at 182 feet bgs. The televiewer data documented high-angle fractures from 146 to 155 feet bgs and weathered basalt and palagonite with associated low- and high-angle fractures from 176 to 215 feet bgs. Aperture sizes corresponded to open cracks in the 146- to 155-foot-bgs interval and up to distinct, interconnected large fractures in the 176- to 215-foot bgs interval. A totalizing of all large fractures in the open borehole section of RC-02 had a predominant orientation of northwest to southeast with generally steep to moderate dips toward the north. Based on the available fracture data, the mean fracture aperture and spacing in the lower basalt are 0.775 and 67.95 inches, respectively. The portion of the entire bedrock volume that is occupied by fractures for this interval (fracture porosity) is 0.0114 percent. The entire logged borehole interval comprising the upper and lower basalt investigations yield a total fracture porosity of 0.0125 percent for RC-02.

RC-03: The borehole was logged in the deep basalt interval from the bottom of conductor casing at 83 feet bgs to 210 feet bgs. The conductivity log had significant deviation from background values at 125 feet bgs with minor changes from this depth down to 180 feet bgs. The caliper log encountered a large opening at 172 feet bgs and cavities greater than the full extent of the caliper tool (diameter of 14 inches within a 5.5-inch borehole) at 195 feet bgs. These logs were confirmed by the televiewer data with large, open fractures at both shallow and steeply dipping angles from 157 to 184 feet bgs and large, vug-like cavities and pillow basalt with ellipsoidal fracturing in an interpreted palagonite sequence beginning at 172 feet bgs and continuing to at least 196 feet bgs. Quantifying the fracture orientation of the larger fractures within the RC-03 borehole displayed a dominant northeast to southwest direction with both shallow and steep dips to the northwest and southeast. Mean fracture aperture and spacing in the lower basalt at RC-03 are 0.91 and 38.33 inches, respectively. Fracture porosity for the lower basalt at RC-03 is 0.0237 percent and for the combined upper and lower basalt units logged is 0.023 percent.

RC-04: The borehole was logged from the bottom of the conductor casing at 81 feet bgs to 360 feet bgs. The conductivity log had deviations at 130 and 140 feet bgs with the largest increase between 300 and 320 feet bgs. The caliper log noted increase in borehole diameter within the 170- to 184-foot-bgs interval, periodic openings between 218 and 240 feet bgs, and large fractures and cavities up to 8 inches in diameter from 276 to 286 feet bgs. Televiewer data for the logging interval noted unweathered, unfractured basalt from 81 feet bgs to approximately 163 feet bgs, where fractures and cavities containing orange (iron) staining and signs of cementation continued to the bottom of the first basalt flow at approximately 275 feet bgs. The clay paleosol with wood fragments is clearly visible from 275 to 282 feet bgs as wells as a large flow zone in weathered basalt directly underneath the paleosol from 283 to 285 feet bgs. Below this interval, the basalt of the second (deeper) flow is unweathered with an absence of large fractures down to the bottom of the logging interval at 360 feet bgs. Orientation data of large fractures in RC-04 display less preferential direction than the previous two borings, but there is a congregation of data striking north-northeast and northwest weighted toward steeply dipping fracture angles.

Fracture porosity in the lower basalt at RC-04 can be divided into three distinct intervals; the lower basalt from 82 to approximately 274 feet bgs, the paleosol and associated weathering features from 274 to 284 feet bgs, and the underlying basalt flow from 284 to 357 feet bgs. The lower basalt above the paleosol has a mean aperture of 0.67 inch and mean spacing of 57.35 inches giving a fracture porosity of 0.012 percent. The paleosol unit and associated erosional features both below Basalt Flow No. 1 and at the top of Basalt Flow No. 2 have a mean fracture aperture of 2.6 inches and mean spacing of 22.32 inches, giving a fracture porosity of 0.117 percent, an order of magnitude higher than the overlying basalt flow. Basalt Flow No. 2 had a mean fracture spacing of 6.55 inches, but similar to the upper basalt at RC-04, this interval did not contain any measurable fractions, and the fracture porosity is 0 percent.

3.2.3 Hydrophysical Logging Results

Hydrophysical logging was conducted by Colog for the deep basalt intervals at borings RC-02 through RC-04. The logging is used to determine inflow and outflow depth intervals, determine if groundwater was flowing in or out of the borehole, determine direction of groundwater flow up or down the borehole, and assess a flow rate to flowing fracture intervals. A summary of the logging results is presented below and on Figures 3 through 5, and a more detailed review can be found in the Colog report (Appendix B). To better understand the spatial relationships of the flows quantified from the hydrophysical logging, results have also been plotted on cross sections for both ambient and stress flow logging (Figures 7 and 8).

RC-02: Results of the ambient flow logging within the open borehole interval at RC-02 documented three intervals of inflow from 123 to 160 feet bgs at rates between 0.0004 and 0.042 gpm with all borehole water traveling downward and exiting from deeper fractures between 177 and 193 feet bgs at 0.070 gpm. No water movement was recorded below this interval to the total depth at 225 feet bgs. Static water level for the ambient flow log was at 57.07 feet bgs (within the conductor casing).

The stress test conducted the following day had a steady state pumping rate at 9.88 gpm. The steady state pumping rate was achieved with injection of DI water at the bottom of the borehole and pumping of formation water from a depth within the conductor casing. This allowed a steady column of DI water within the borehole to detect formation water inflow during stressed pumping conditions. Ten intervals of inflow were detected from this test ranging in depth from 123 to 225 feet bgs. Out of the ten intervals of inflow, three were considered major inflow intervals (rates over 1 gpm). Two upper intervals, 131.4 to 142.2 feet bgs at 2.02 gpm and 152.2 to 155.9 feet bgs at 2.52 gpm, both corresponded to an inflow zone during ambient testing. The dominant flow interval with the highest inflow rate of 4.88 gpm (approximately 47 percent of total inflow) was located at the same interval as the outflow zone during ambient testing (177 to 192 feet bgs).

RC-03: Hydrophysical flow logging occurred in a more limited interval than the geophysical logging, approximately 112 to 195 feet bgs because of additional borehole collapse. Ambient flow logging detected three intervals of inflow and one interval of outflow at RC-03. Minor inflow occurred in two intervals in the upper portion of the borehole, 113.1 to 118.9 feet bgs and 125.3 to 138.8 feet bgs, with downward flow rates of 0.004 and 0.011, gpm respectively. The dominant inflow interval was the deepest flow zone of the test at 194.1 feet bgs at 0.07 gpm (82 percent of total inflow) and flowing upward. The outflow zone for the ambient test was located at 160 to 168.4 feet bgs at 0.085 gpm. Static water level for the ambient flow log was 112.62 feet bgs, within the open borehole section.

The stress test conducted the day after the ambient test had a steady state pumping rate of 14.9 gpm. Seven intervals of inflow were detected with only two intervals above 1 gpm. The dominant inflow zone was between 125.3 and 138.8 feet bgs (one of the downward inflow zones from the ambient testing) at 10.33 gpm (77 percent of total inflow), with the second major flow zone at 144.2 to 152.8 feet bgs at a much lower 1.36 gpm (10 percent of total inflow).

RC-04: Hydrophysical logging at RC-04 occurred between 119.92 feet bgs (static water level) and approximately 360 feet bgs where bentonite from the temporary well abandonment (screened at 381 to 383 feet bgs) was encountered. The ambient logging picked up three inflow and two outflow zones at RC-04. All inflow was detected between 254 and 288 feet bgs in the fractured basalt just above the paleosol with upward flow between 0.12 and 0.35 gpm. The fractures just below the paleosol were the dominant interval contributing 58 percent of total inflow. Outflow occurred above the inflow zones in a broad interval from 142.5 to 240.5 feet bgs between 0.21 and 0.39 gpm. No inflow or outflow was recorded in the unweathered portion of the lower basalt flow below 288 feet bgs.

The stress test conducted the following day recorded a steady state pumping rate of 16.2 gpm. Eight intervals of inflow were recorded with four above the 1 gpm threshold. Three of these inflow zones were detected just below and within the paleosol and the fractured/weathered basalt at the base of the upper basalt flow from 254 to 288 feet bgs with inflows ranging from 1.11 to 4.37 gpm contributing 59 percent of total inflow. The singular largest inflow was measured at 5.14 gpm (35 percent of total inflow) along an interval with a multitude of smaller fractures from 142.5 to 211.3 feet bgs. Similar to the ambient logging, no flow was recorded in the unweathered portions of the lower basalt flow below 288 feet bgs.

3.2.4 Packer Test Results

The packer testing at boreholes RC-02 and RC-04 involved the aquifer testing and analytical sampling of groundwater at four intervals in each borehole. Interval-specific permeability was calculated using both the Thiem equation and Theis Recovery method using the software program AQTESOLV. A summary of the packer testing results is presented below and on Figures 3 through 5 and Figure 9, and a more detailed review can be found in the Colog report (Appendix B).

RC-02: Packer testing was conducted at four intervals from static water level at 57.1 feet bgs (at the time of testing) to 225 feet bgs (just above the weathered granite and interval of borehole collapse). A single packer was inflated for the shallow interval (SWL to 142 feet bgs) and two deeper intervals (156 and 192 feet bgs to total depth at 225 feet bgs), and a double packer assembly used to test a major inflow fracture from 145.5 to 156 feet bgs. Extraction rates for each interval ranged from 1.07 gpm at the double-packer interval (145.5 to 156 feet bgs) to 16.67 gpm at the wider single packer interval of 156 feet bgs to total depth. Fracture interval permeability or transmissivity ranged from 1.81 square feet per day (ft^2/day) at the deepest interval (192 feet bgs to total depth) to 42.9 ft^2/day from the 156 feet bgs to total depth.

RC-04 – packer testing at four intervals located between static water level at 120.27 feet bgs (at the time of testing) to the bottom of the paleosol between basalt flows at 288 feet bgs (with the bottom packer set at 292.5 feet bgs). A single packer was inflated for the water table test (SWL to 148 feet bgs) and a double packer assembly with a 10.5-foot spacing was used for the remaining, deeper test intervals at 254 to 264.5, 265.5 to 276, and 282 to 292.5 feet bgs. Extraction rates ranged from only 0.37 gpm at the single packered SWL to the 148-foot-bgs interval, to 20.5 gpm at the double packered 254- to 265.5-foot-bgs interval. Permeability testing yielded transmissivity values that ranged from 3.98 to 822 ft^2/day for the same intervals.

3.2.5 Groundwater Grab Sample Results

Groundwater grab samples were collected under several circumstances during the deep basalt investigation because of limitations from subcontractor equipment and unstable borehole conditions. Overall, the dominant COC encountered in this characterization (confirming previous site investigations) was CT with minor amounts of chloroform also detected. Acetone was also detected in samples but can be a common laboratory contaminant.

RC-02: Groundwater grab samples were collected at three of the four packer intervals using both low-flow methodology after at least one interval volume had been purged and following the constant rate aquifer test conducted at each interval during packer testing. The 156 feet bgs to total depth interval was not sampled because of nearby monitoring well MW-4D, which is part of the long-term monitoring network and is screened in the same interval. All samples collected from RC-02 over shallow and deep investigations had relatively uniform CT concentrations throughout the borehole and all within an order of magnitude. For the deep basalt portion of the investigation, CT concentrations ranged from 234 µg/L from the post-aquifer test sample at the deepest interval (192 to 225 feet bgs), up to 413 µg/L from the post-aquifer test sample at the shallowest interval (57.1 to 142 feet bgs).

RC-03: Groundwater grab samples in the deep basalt interval were not collected because of the lack of packer testing and earlier installation of monitoring well MW-26. Low-flow sampling of MW-26, screened from 215 to 225 feet bgs, had no detections of CT.

RC-04: Groundwater grab samples were collected from all four packer intervals and a temporary well installed for a groundwater grab sample within the granitic basement rock underlying the lower basalt flow. For the packer intervals, only low-flow samples were collected because of pump capacity limitations with Colog's equipment, but low-flow and post-stress test samples were collected from the deeper temporary well screened at 383.5 to 388.5 feet bgs. All samples collected had no detections of CT.

4. Conclusions and Recommendations

The primary focus of the 2018 and 2019 field investigations in the basalt aquifer at the site was to characterize CT distribution in groundwater within the fracture system and collect quantifiable data for groundwater flow modeling that will be used in the FS. In addition, the data were used to determine optimal depths for permanent monitoring well installations and to update the site CSM with a better vertical refinement of CT concentrations in groundwater.

4.1 Conclusions

The fieldwork was conducted in two stages; the upper basalt investigation in 2018 focused on the weathered top of the flow and to determine extent of fracturing, CT concentrations in groundwater, and any potential hydraulic connections in this zone with overlying loess deposits. Results and conclusions from the upper basalt investigation are as follows:

- Coring and RQD indicate the top of the basalt is highly weathered and fractured in at least the upper 15 to 20 feet bgs at the grain handling facility and south to RC-02 and RC-03. Although a core was not collected at RC-03, the geophysical televiewer logs indicate significant fracturing in at least the upper 30 feet of the basalt. Conversely, coring at RC-04 encountered an unfractured 20 feet of upper basalt with 100 percent RQD. Basalt is closer to the surface at RC-04 (43 feet bgs) than RC-02 and RC-03 (94 and 50 feet bgs, respectively) and may represent a more resistant basalt layer because of the lack of fracturing in the upper intervals.
- Based on geophysical flowmeter and televiewer logging, open flowing fractures were targeted for grab groundwater samples at RC-02 and RC-03. CT concentrations were within a factor of 2 at all sample intervals under low-flow and stressed conditions (184 to 293 µg/L). These values are relatively close to the most recent (June 2019) groundwater CT concentrations in two existing monitoring wells screened in the upper basalt between the two RC locations: the Randall well and Marlow No. 1 well had CT concentrations in groundwater at 191 and 109 µg/L, respectively. These groundwater concentrations indicate CT is present in fractures within the shallow basalt in a relatively uniform distribution over 1,000 feet south from the GHFF.

Fieldwork continued in 2019 drilling into deeper portions of the basalt and to the underlying basement rock using existing boreholes RC-02, RC-03, and RC-04 to determine CT distribution below the weathered top of the upper basalt. Results and conclusions from the upper basalt investigation are as follows:

- Considerable variability was encountered in the basalt at all borehole locations. Intervals of intense alteration within otherwise unaltered basalt were observed in rock cuttings and geophysical televiewer logs. Large (1-foot diameter) vug-like openings consistent with a palagonite texture were observed in RC-03 contributing to ambient inflow at depth in comparison to the more traditional fractures and vesicular textures located above. This palagonite alteration was most intense near the contact with the underlying basement rock and lessened to the south and higher up in the basalt flow. Evidence for discrete basalt flows, occurring with a significant time between flow events, was observed in RC-04 with wood fragments present in a paleosol of the older (lower) flow at 275 to 285 feet bgs. Basement rock was encountered in all three deep basalt borings and appears to be a granitic gneiss by the numerous muscovite, quartz, and feldspar crystals observed. This corresponds to the Precambrian-aged Gneiss near Chester Creek that comprises the basement rock exposed immediately northwest of the GHFF (Weis, 1968).
- Borehole geophysical logging revealed fracture orientation within the basalt having preferential direction (strike) in one or two directions for all three boreholes. However, dip direction had a more random distribution, and the differing strike directions at all three locations infer that the fracture network does not have a preferential pathway inside the discrete basalt flows. Fracture porosity was determined at all three deep basalt borings with multiple zones of porosity encountered, often in the same borehole. Fracture porosity ranged from 0 percent in the lower basalt flow under the clay paleosol at RC-04 to 0.117 percent in the broken-up basalt immediately above and below the same paleosol/borehole.

- Hydrophysical ambient flow logging at the boreholes indicated a downward hydraulic gradient in RC-02 within the logged interval, downward gradient in the shallow portions before outflowing at 160 to 168 feet bgs at RC-03, but no flow zones are found in the upper basalt at RC-04. Upward gradients are present from below the outflow interval at RC-03 and throughout the entire flowing fracture interval at RC-04 (142.5 to 288 feet bgs). CT was not detected in any packer interval that was sampled with an upward hydraulic gradient, indicating confining conditions, especially directly underneath the paleosol at RC-04. Recent monitoring well installations in and around RC-04 have observed strong upward gradients at the paleosol layer where MW-31, screened from 380 to 390 feet bgs, has a depth to water (100.5 feet bgs on July 19, 2019) over 20 feet higher than wells screened within the first basalt flow at the same location and date (for example, MW-33 screened from 254 to 274 feet bgs at 124.59 feet bgs). This upward gradient may be preventing CT-contaminated groundwater found in shallower intervals (above approximately the 2,400 feet above mean sea level elevation) from migrating deeper into the aquifer. However, the hydraulic head in the deep zones is similar to those in the overburden loess in the vicinity of RC-04. It is likely that the upward hydraulic gradient at RC-03 and RC-04 has been induced by groundwater extraction from the Freeman School District Well WS5, which creates a hydraulic sink in the middle of basalt in the vicinity of RC-04 and to a lesser degree at RC-03.
- CT grab samples collected during the investigation indicate the entire open borehole interval at RC-02 has CT-contaminated groundwater in groundwater fractures similar in magnitude to the shallow basalt investigation sample. No packer testing was completed at RC-03, and the vertical distribution is not well understood below the CT-contaminated groundwater intervals from the shallow basalt investigation. However, recently installed monitoring well MW-26 within the borehole and screened in the deeper interval with upward hydraulic gradient had no detections of CT.
- At RC-04, all packer test intervals sampled in the basement rock and immediately above and below the paleosol layer (up to 120 feet bgs) registered non-detects of CT. The Freeman School District Well (WS5) is screened from 52 to 215 feet bgs, is located less than 50 feet from RC-04 and has 5 µg/L of CT present in groundwater from the last round of quarterly sampling (June 2019). However, the recent (summer 2019) well installations at RC-04 have detections of CT in the upper intervals (13.1 µg/L at MW-34 screened from 165 to 185 feet bgs and 1.1 µg/L at MW-33 screened from 254 to 274 feet bgs). Further investigation as part of the FS is underway, but it appears that the upper basalt flow is impacted by CT but underneath the clay paleosol at 275 feet bgs, groundwater has no detections of CT, which may be attributable to the induced upward hydraulic gradient toward The Freeman School District Well at this location.

4.2 Recommendations

This report supplies site data and CSM updates that will be used in the FS. These recommendations have either been incorporated into the FS or may be addressed by future site field activities.

- Data available from this report should be used to update the existing site CSM and groundwater flow model. Emphasis should be taken to determine from exactly what interval(s) and elevation the CT is entering the Freeman School District Well.
- If barrier technology is considered at the source area, geotechnical borings that allow for accurate delineation of major flow zones and mass flux should be considered along the barrier transect prior to installation to assess the likelihood of CT contaminated–groundwater migrating underneath or around the proposed footprint. In addition, VOC sampling within the rock matrix could be assessed to determine the potential of back diffusion from the basalt into the fractures downgradient of the barrier and total organic carbon collected from rock samples to refine the aquifer cleanup timeframe.
- Before installation of groundwater extraction wells for groundwater recirculation remedy implementation, pilot test boring(s) should be drilled to identify preferential flow paths and zones so that the extraction wells can be installed to target extraction from the intervals contributing to the majority of plume mass flux.

5. References

Jacobs Engineering Group Inc. (Jacobs). 2018. *Remedial Investigation Report, Grain Handling Facility at Freeman, Freeman, Washington*. September.

Weis, P L. 1968. Geologic Map of the Greenacres Quadrangle, Washington and Idaho. U.S. Geological Survey.

Figures

LEGEND

- Proposed Rock Coring
- Monitoring Well
- Domestic Well
- Grain Handling Facility at Freeman

Notes:
Greyed out wells have been decomissioned.

Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS,

N

0 162.5 325 650 Feet

Figure 1
Site and Borehole Location Map
Basalt Aquifer Characterization
Grain Handling Facility at Freeman,
Freeman, Washington

JACOBS

ROOKSIDEFILES\GIS_SHARE\ENBG\00_PROJ\U\UPRR\UPRR_FREEMAN\MAPS\REPORT\2019\BASALT_AQUIFER_CHARACTERIZATION\FIG1_ROCKCORING.MXD GMOON 12/11/2019 9:49:32 AM

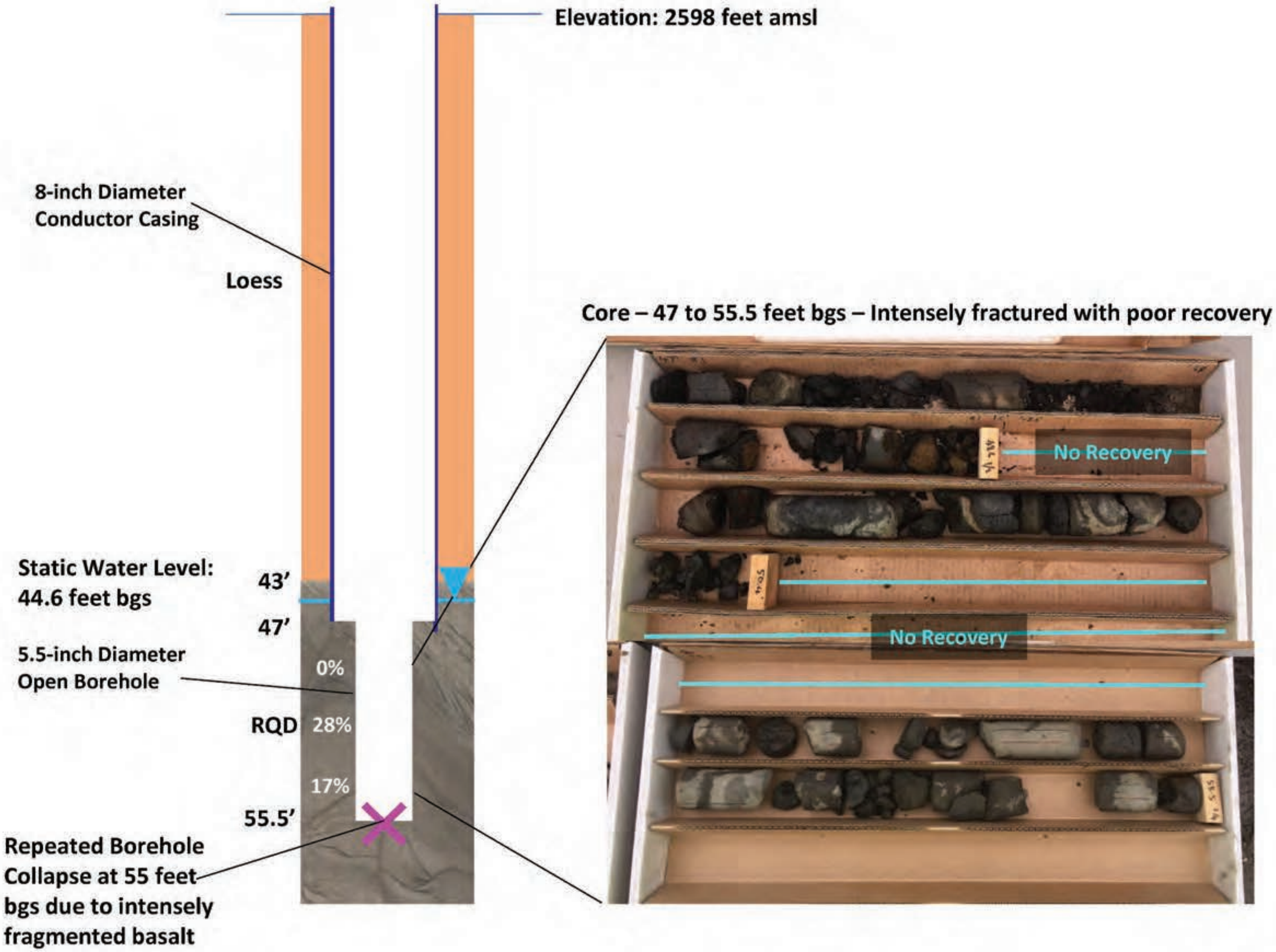

Figure 2. Borehole RC-01 Summary
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

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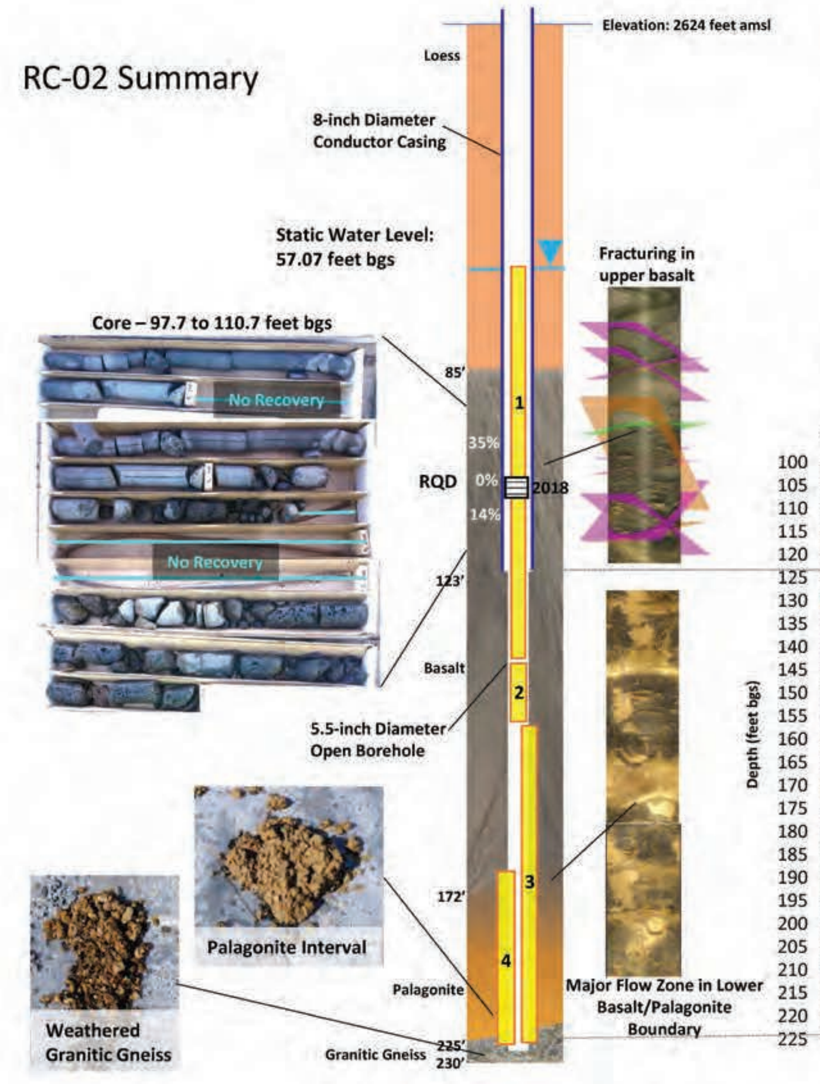
RC-02 Summary



Grab Sample / Packer Test Interval No.	Top of Interval (ft bgs)	Bottom of Interval (ft bgs)	Interval Specific Extraction Rate: WSP Stress Test (gpm)	Interval Specific Hydraulic Conductivity (ft/day)	AQTESOLV (Theis) Method Transmissivity (ft²/day)	Carbon Tetrachloride Concentration – Low Flow (µg/L)	Carbon Tetrachloride Concentration – Post Packer Test (µg/L)
2018	100	101.5	2.5	4.64 E+00	1.88 E+02	190	293 (Stress)
1	57.1	142.0	2.85	2.81 E-01	2.32 E+01	411	413
2	145.5	156.0	1.07	1.94 E+00	2.05 E+01	324	364
3	156.0	225.0	16.67	4.26 E-01	4.29 E+01	Not Sampled	Not Sampled
4	192.0	225.0	1.98	4.88 E-01	1.81 E+01	253	234

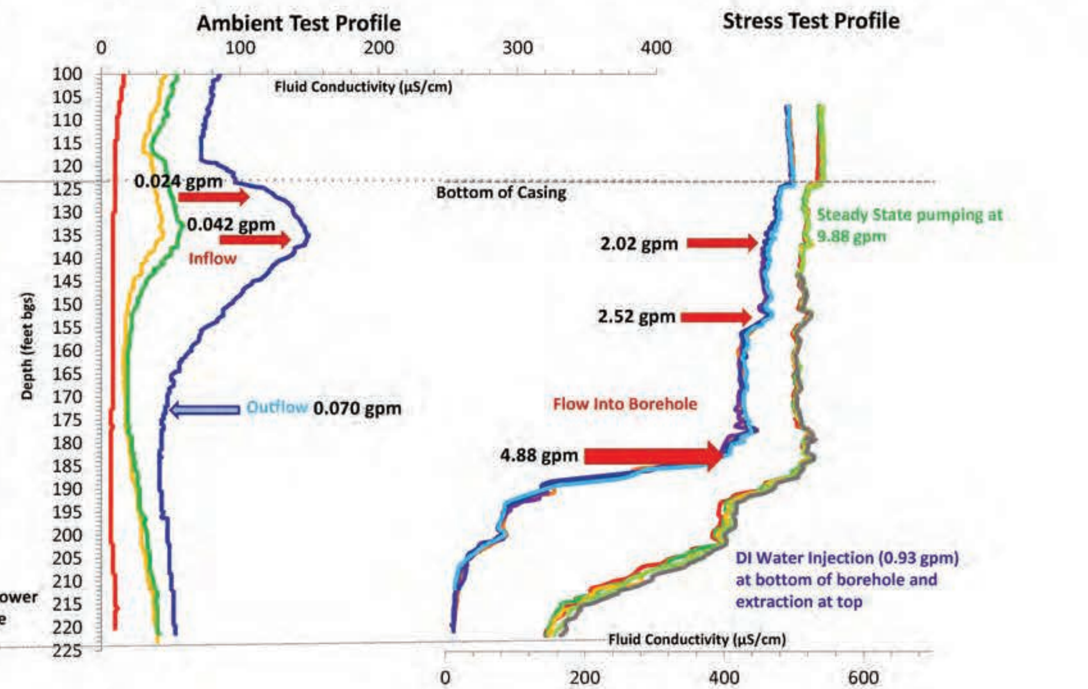


Figure 3. Borehole RC-02 Summary
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

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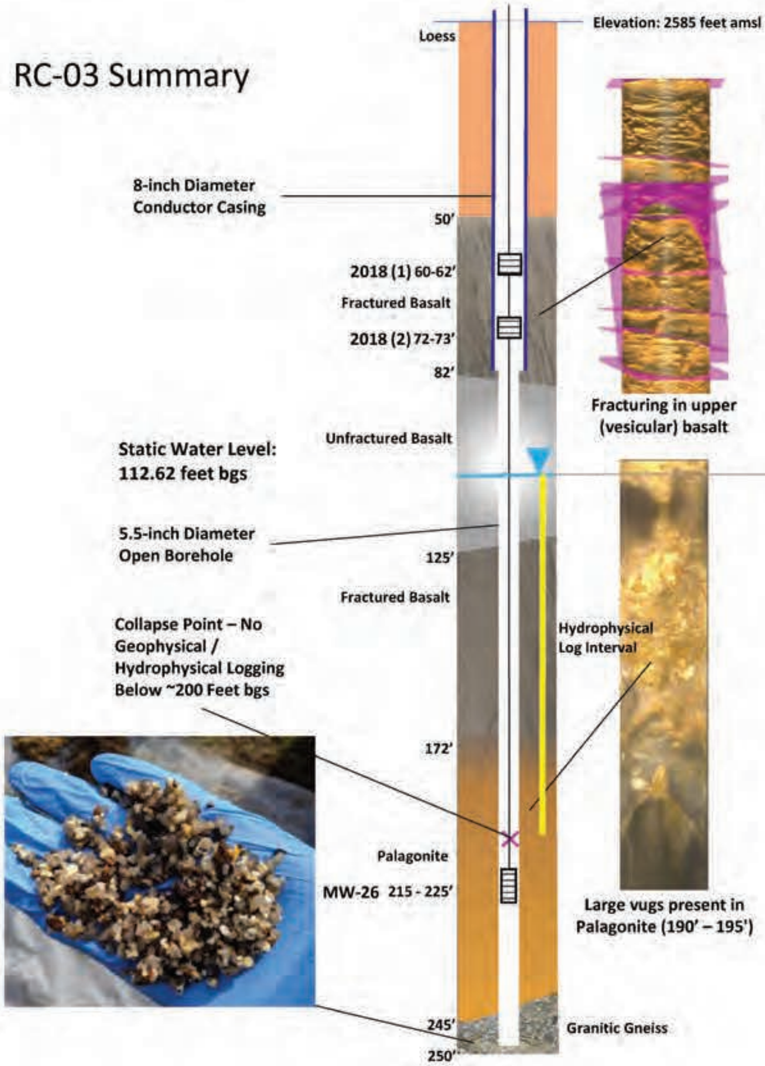
RC-03 Summary



Grab Sample / Monitoring Well	Top of Interval (ft bgs)	Bottom of Interval (ft bgs)	Interval Specific Extraction Rate: WSP Stress Test (gpm)	Interval Specific Hydraulic Conductivity (ft/day)	AQTESOLV (Theis) Method Transmissivity (ft^2/day)	Carbon Tetrachloride Concentration – Low Flow (µg/L)	Carbon Tetrachloride Concentration – Post Packer Test (µg/L)
2018 (1)	60	62	NA	--*	--*	184	NA
2018 (2)	72	73	10.4	--*	--*	202	193
MW-26	215	225	NA	NA	NA	Non -Detect	NA

* - Transducer data invalid due to lack of hydraulic head during test

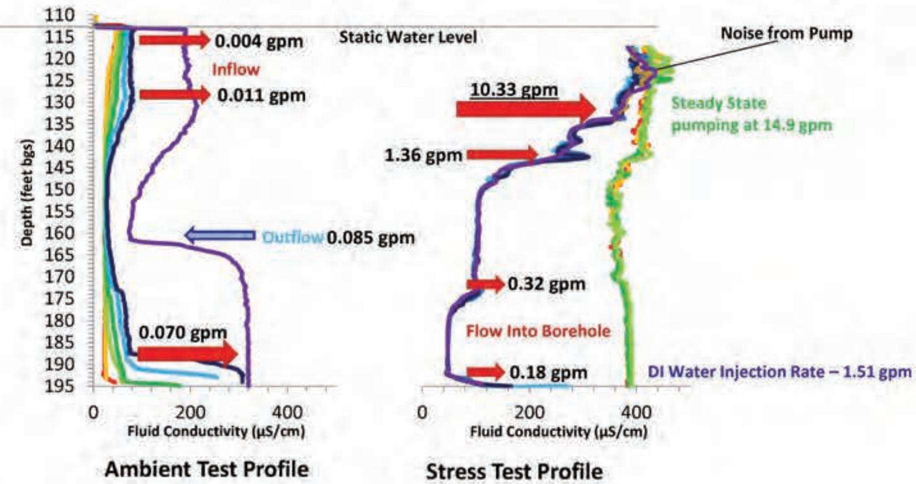
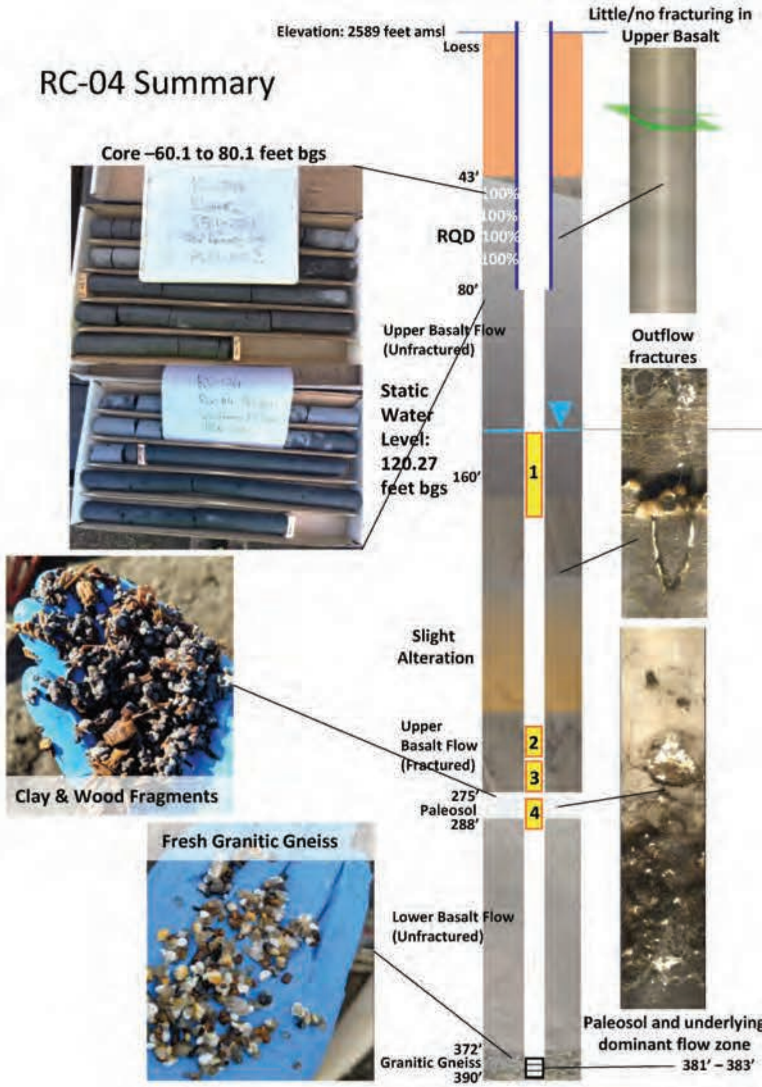


Figure 4. Borehole RC-03 Summary
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

RC-04 Summary

Grab Sample / Packer Test Interval No.	Top of Interval (ft bgs)	Bottom of Interval (ft bgs)	Interval Specific Extraction Rate: WSP Stress Test (gpm)	Interval Specific Hydraulic Conductivity (ft/day)	AQTESOLV (Theis) Method Transmissivity (ft^2/day)	Carbon Tetrachloride Concentration – Low Flow (µg/L)	Carbon Tetrachloride Concentration – Post Packer Test (µg/L)
1	120.3	148.0	0.37	1.19 E-01	3.98E+00	ND	NA
2	254.0	264.5	20.50	7.83 E+01	NA	ND	NA
3	265.5	276.0	10.50	4.52 E+00	NA	ND	NA
4	282.0	292.5	16.66	5.00 E+01	NA	ND	NA
381-383'	381'	383'	--	--	--	ND	ND



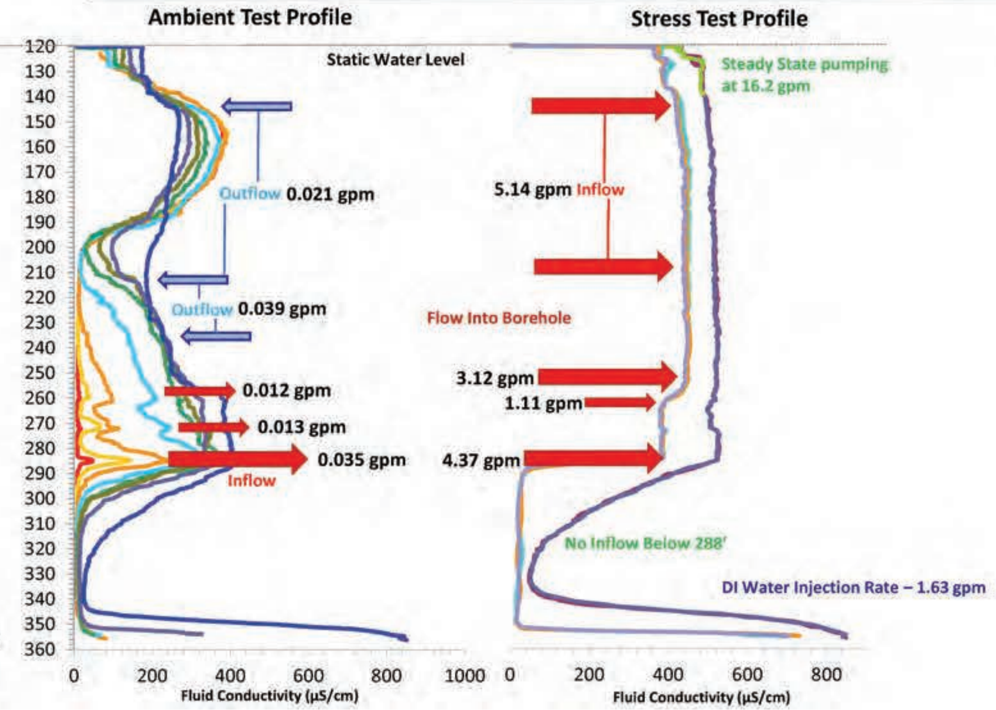


Figure 5. Borehole RC-04 Summary
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

JACOBS

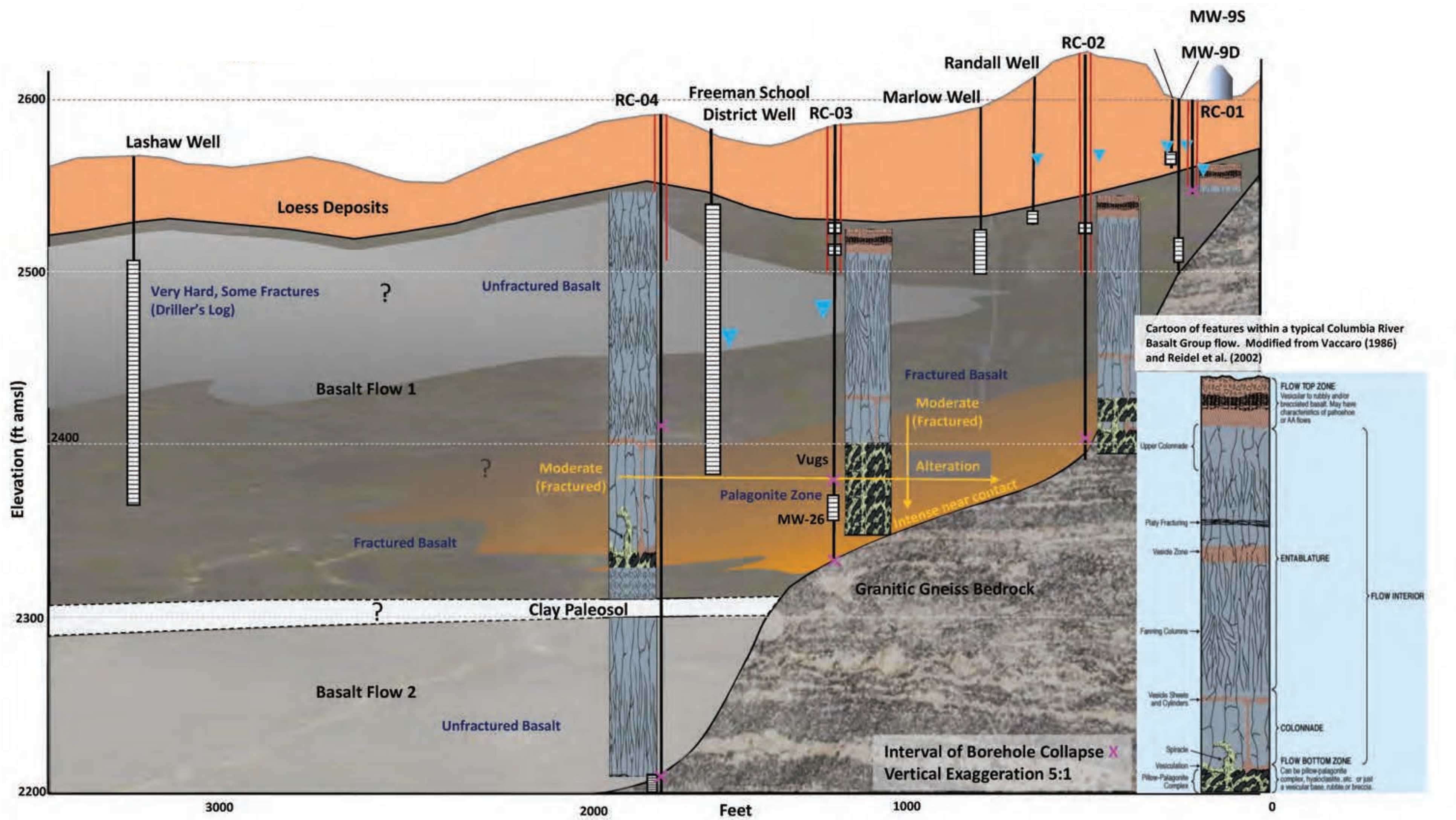


Figure 6. Lithological Results Cross Section
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

JACOBS

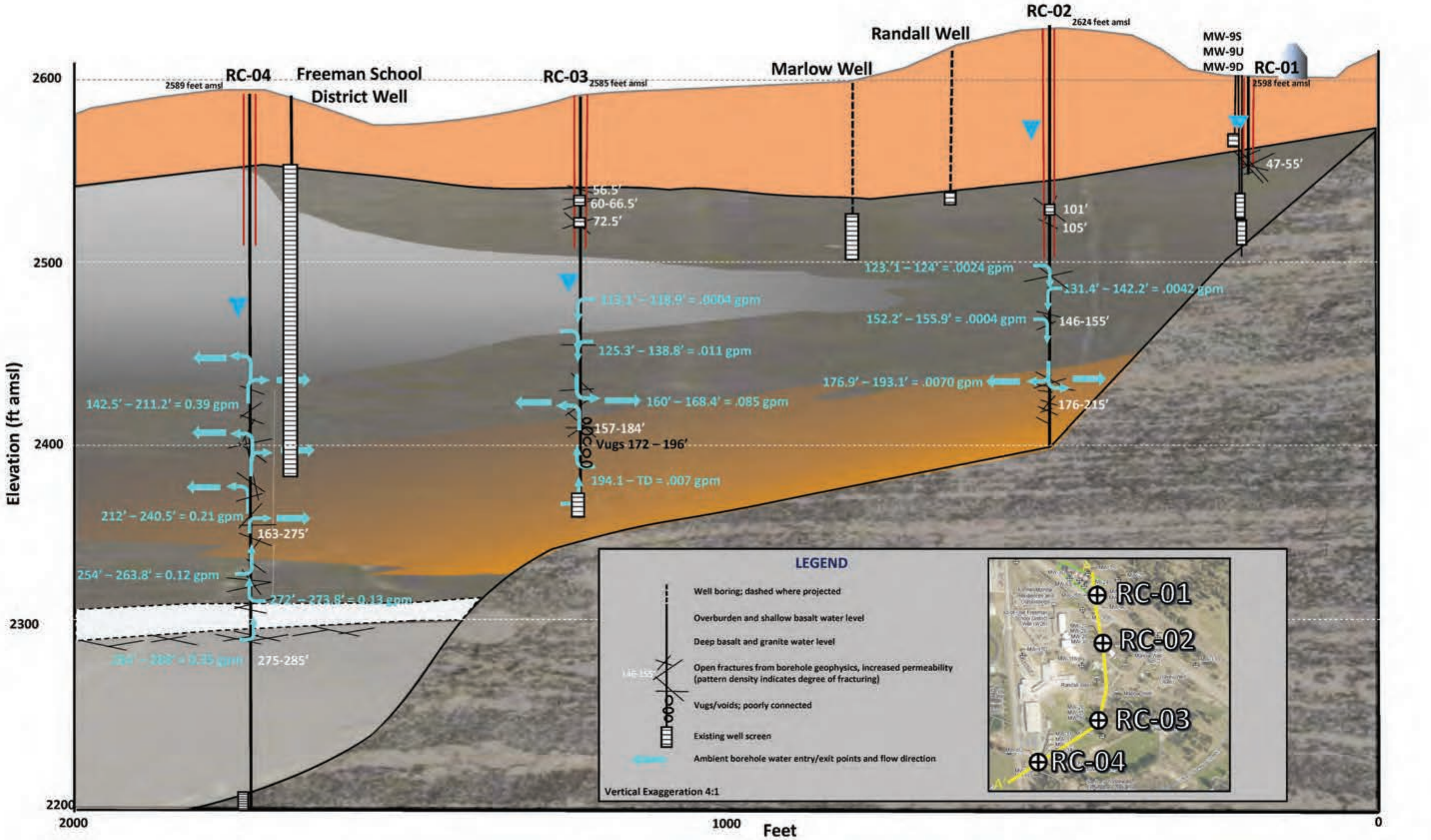


Figure 7. Hydrophysical Logging Cross Section – Ambient
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

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AX0530181205PDX Fig7_Hydrophysical_Logging_Cross_Section_Ambient

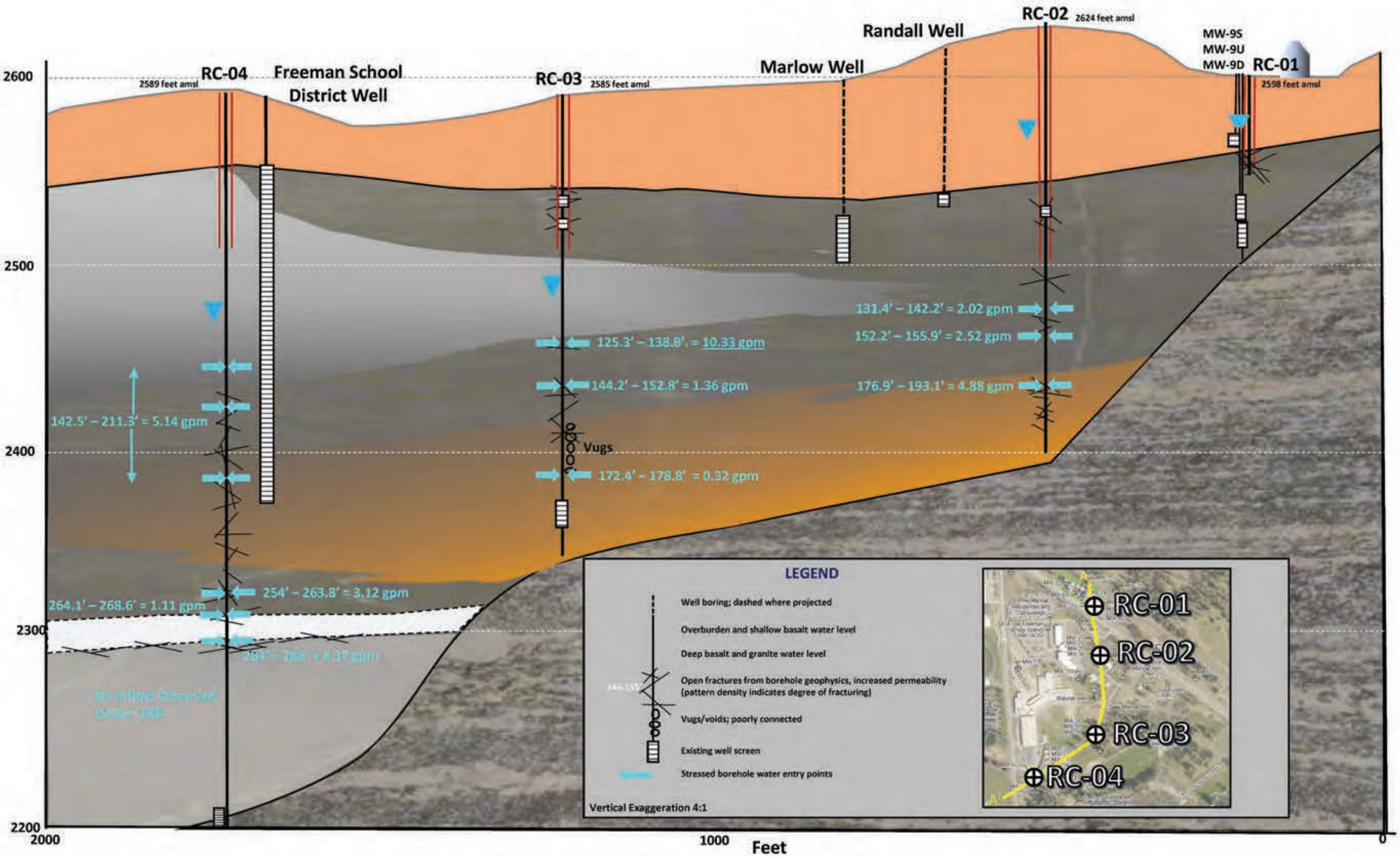

Figure 8. Hydrophysical Logging Cross Section – Stressed
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

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AX0530181205PDX Fig8_Hydrophysical_Logging_Cross_Section_Stressed

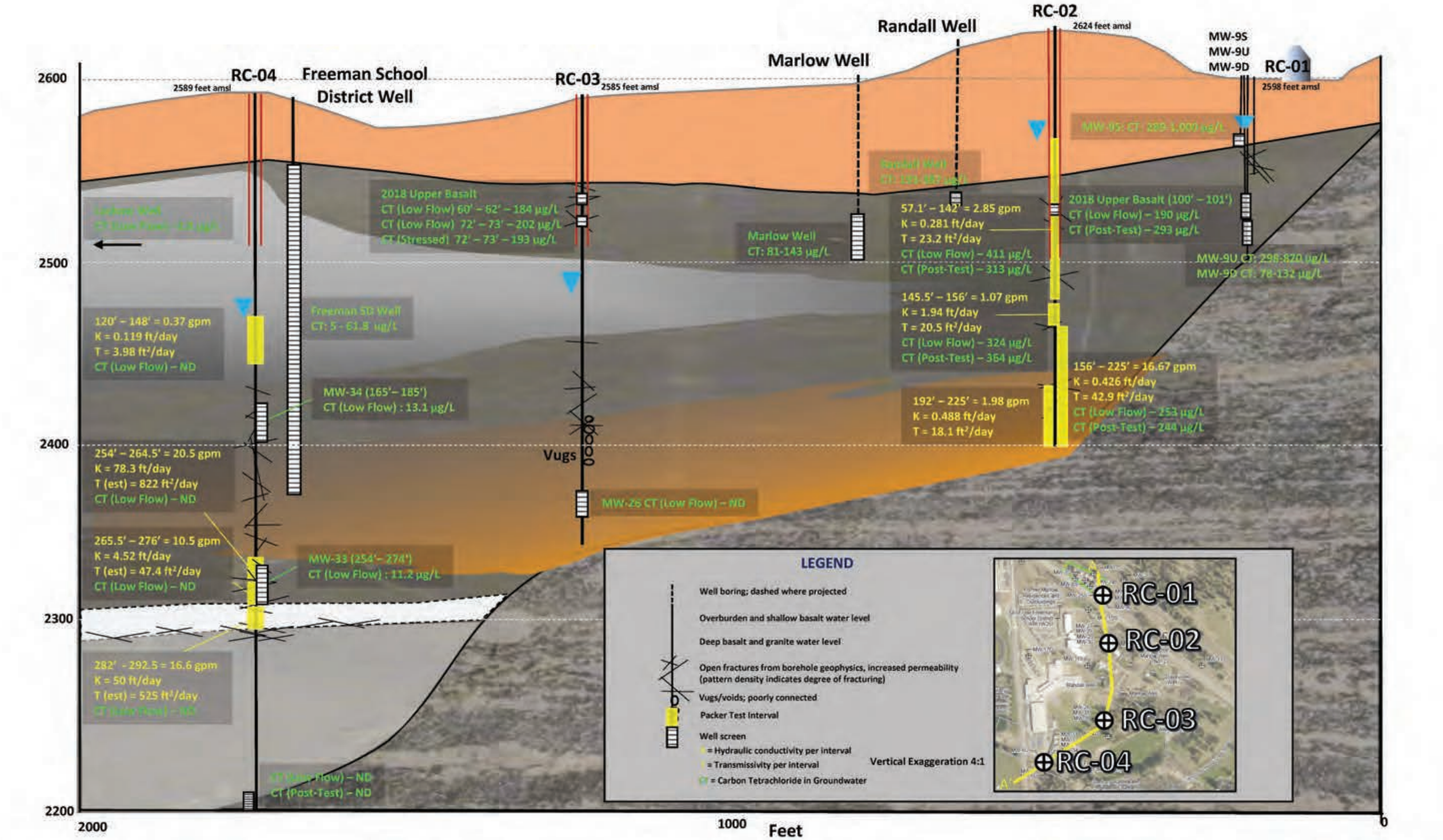

Figure 9. Packer Testing and Sampling Results
Basalt Aquifer Characterization
Grain Handling Facility at Freeman
Freeman, Washington

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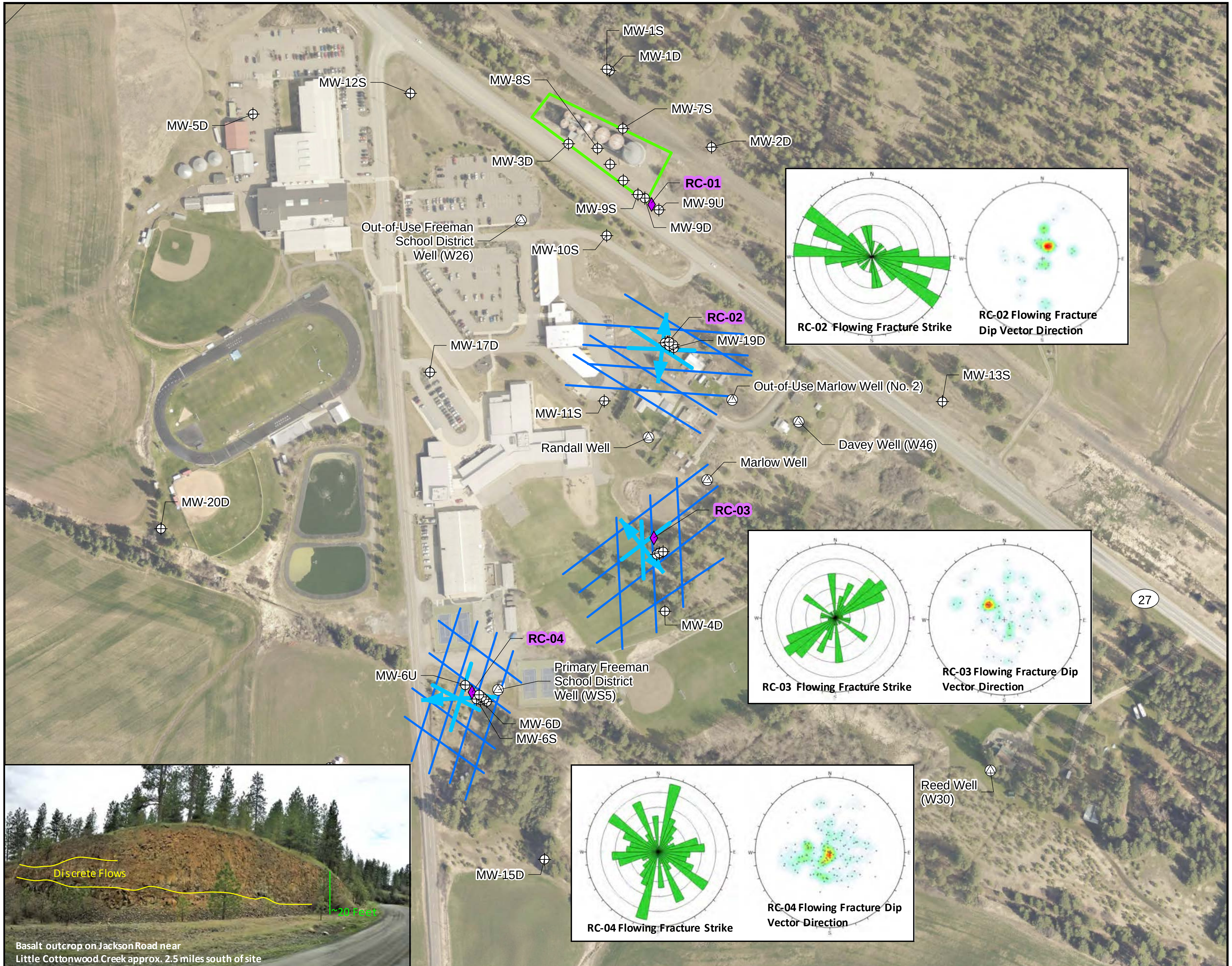
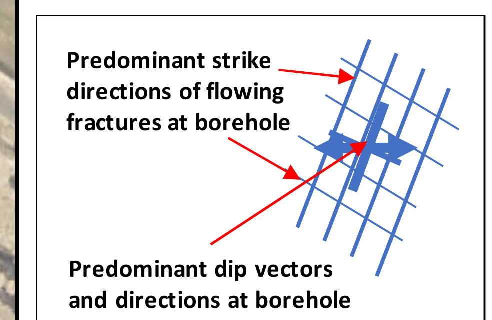
AX0530181205PDX Fig9_Packer_Testing_and_Sampling_Results



LEGEND

- Proposed Rock Coring
- Monitoring Well
- Domestic Well
- Grain Handling Facility at Freeman



Notes:
Greyed out wells have been decomissioned.

Service Layer Credits: Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS,

N

0 162.5 325 650 Feet

Figure 10
Fracture Orientation Map
Basalt Aquifer Characterization
Grain Handling Facility at Freeman,
Freeman, Washington

JACOBS

Appendix A
Shallow Basalt Investigation Borehole Geophysical Report

Global Geophysics
P. O. Box 2229
WA, 98073-2229
Tel: 425-890-4321
Fax: 206-582-0838

December 7, 2018 Our ref: 108-1031.000

Environmental West Exploration Inc.
1015 N Yardley Road
Spokane Valley, WA 98212

Attention: Mr. Zach Gourde

RE: REPORT FOR BOREHOLE LOGGING IN FREEMAN, WASHINGTON

This report presents the results of the geophysical surveys performed by Global Geophysics. The borehole logging were carried out in three vertical holes on November 29 and 30, 2018 at Freeman Elementary and High Schools, Freeman, WA. The objective of the geophysical survey was to characterize discontinuities and their orientations in the rock, to measure fluid temperature and conductivity, natural gamma, borehole diameter, and flow rates. The following loggings were completed:

- Fluid temperature/conductivity/natural gamma
- Optical and acoustic televiewer
- Flow logging using impeller and heat flow probes;
- Caliper

GEOPHYSICAL METHOD AND FIELD PROCEDURE

Fluid temperature/conductivity/natural gamma

This probe combination provides a continuous, depth-based measurement of fluid temperature and conductivity. Both parameters can be output in absolute and in differential forms. A natural-gamma detector is included for correlation purposes.

The temperature and conductivity sensors are located in an insulated housing at the base of the probe. During logging, borehole fluid flows freely through ports on the side and base of this housing and over the sensors.

The log was recorded downwards while running into the hole to minimize fluid disturbance.

Optical/Acoustic Televiewer

This instrument generates a continuous oriented 360° image of the borehole wall using an acoustic/optical imaging system. The tool includes a full orientation device consisting of a precision 3-axis magnetometer and two accelerometers. This arrangement provides a means to obtain accurate borehole deviation data during the logging run, and for determining precise orientation of the image during data processing. The video image will be continuously recorded and displayed on a laptop computer, as the probe is moved in the borehole. During post-processing the video image will be unwrapped and displayed as simulated core sample that could be rotated on the screen and analyzed for fractures.

Optical and acoustic televiewers made by Robertson Geologging were used for this project.

Flow logging

The impeller flowmeter provides a continuous log of vertical flow velocity within the borehole. The probes are equipped with lightweight helical impellers mounted on double sapphire bearings. The impellers contain magnets which actuate Hall-effect switches within the probe to detect impeller rotation. Separate log channels record the time of rotation according to fast and slow time-bases for improved resolution at high and low flow rates. Uphole and downhole rotations are distinguished within the sonde.

The heat-pulse flowmeter measure the flow in the range of 0.33 ft/min to 9.84 ft/min. The heat-pulse flowmeter sonde is used to detect low vertical flows within a borehole below the threshold limits of conventional impeller tools. The probe is designed for stationary measurements only. Normal logging practice involves measurements at a series of depths across the zone of interest (every 10 ft). The probe contains a horizontal wire-grid heating element and thermistors located above and below it. Apertures in the tool permit the free flow of well fluid through the assembly. Pulses of electric current are applied to the heating grid under surface command, warming fluid in the vicinity of the grid. The warm fluid front migrates towards the thermistors where it is detected. Depending on the direction of flow, either upper or lower thermistor detects the warm fluid front first. The time taken to reach the detector gives an indication of flow rate.

Caliper

The three-arm caliper probe provides a single continuous log of borehole diameter as recorded by three mechanically coupled arms in contact with the borehole wall. 38mm and 60mm models are available to suit a range of well diameters. The caliper is a useful first log to determine the borehole conditions before running more costly probes or those containing radioactive sources. Opening and closing of the motor-driver caliper arms is by surface command, allowing the probe to run into the borehole with the arms retracted. Once opened, the spring-loaded arms respond to borehole diameter variations as the probe is raised up the borehole.

ANALYSIS AND RESULTS

Borehole logging results

The televiewer, fluid temperature, fluid conductivity, natural gamma, and caliper data were imported and analyzed in WellCad. The interpreted depth, dipping direction and dip angle of each fracture/joint in the rock are presented in the tables below. The dipping direction is referenced to magnetic north. The images of the borehole walls are included in the Appendix A.

Table 1: RC-2 fracture/joint information

Depth (ft)	Azimuth (degree)	Dip (degree)	Aperture (in)	Type
95.71	156.97	14.97	0.11	2
96.48	272.18	28.37	0.03	2
96.98	174.07	33.02	0.10	4
97.63	299.02	22.22	0.15	2
97.97	192.26	14.04	0.11	4
98.16	158.28	18.19	0.07	2
99.16	230.55	51.15	0.10	2
99.37	107.62	27.36	0.21	2
99.44	243.84	53.01	0.09	2
100.03	144.49	16.08	0.00	5
100.28	83.87	17.22	0.19	2
100.28	215.21	70.71	0.06	3
100.43	99.94	18.49	0.19	2
100.88	30.93	56.41	0.09	2
101.04	235.39	57.02	0.11	2
101.12	66.02	27.69	0.17	3
101.69	112.94	15.43	0.11	2
104.24	100.44	44.58	0.11	5
104.59	319.53	53.75	0.14	2
104.62	129.68	19.25	0.26	2
105.01	97.05	47.7	0.19	2
105.3	291.36	67.87	0.07	2
105.77	148.21	36.45	0.16	2
106.18	130.42	33.27	0.07	5
108.01	121.05	41.35	0.06	4
108.51	17.22	41.08	0.09	5

Fracture/joint types: 1-major open joint/fracture; 2-minor open joint/fracture; 3-partially open joint/fracture; 4-sealed joint/fracture; 5-bedding/banding/foliation

Table 2: RC-3 fracture/joint information

Depth (ft)	Azimuth (degree)	Dip (degree)	Aperture (in)	Type
54.96	148.48	18	0.11	2
56.33	290.46	18.26	0.86	1
56.4	335.69	13.84	0.08	5
59.22	312.53	27.02	0.14	5
59.76	176.5	13.18	0.19	2
60.44	230.5	12.89	0.27	2
60.66	28.52	23.58	0.14	2
60.86	16.26	21.12	0.26	2
61.37	354.41	19.47	0.22	2
61.42	189.4	75.03	0.05	2
61.77	225.56	10.99	0.19	2
62.01	249.63	26.7	0.18	2
62.25	333.64	26.24	0.49	2
62.81	243.51	20.19	0.11	2
64.32	284.8	32.93	0.23	2
64.65	158.09	50.42	0.10	2
65.07	208.25	52.28	0.14	2
65.96	160.36	39.1	0.21	2
66.63	160.19	50.57	0.15	2
67.37	172.45	44.75	0.20	2
67.97	53.36	63.02	0.09	2
68.49	232.62	64.32	0.05	2
68.75	215.66	25.1	0.25	2
69.59	207.03	69.57	0.10	2
69.77	191.36	74.74	0.07	2
70.58	10.71	58.55	0.10	2
70.72	308.6	11.71	0.19	2
72.58	343.46	71.58	1.04	1
73.76	348.16	49.41	0.00	2
73.89	359.16	50.85	0.00	2
75.24	5.68	47.75	0.00	2
76.45	78.33	58.63	0.00	3
78.05	49.05	31.8	0.00	5
79.15	358.46	30.01	0.00	2
80.11	147.96	19.8	0.00	2

Fracture/joint types: 1-major open joint/fracture; 2-minor open joint/fracture;
3-partially open joint/fracture; 4-sealed joint/fracture; 5-bedding/banding/foliation

Table 3: RC-4 fracture/joint information

Depth (ft)	Azimuth (degree)	Dip (degree)	Aperture (in)	Type
66.19	126.23	14.08	0	5
69.32	222.61	17.35	0	5
69.42	325.19	54.46	0	5

Fracture/joint types: 1-major open joint/fracture; 2-minor open joint/fracture; 3-partially open joint/fracture; 4-sealed joint/fracture; 5-bedding/banding/foliation

The impeller data suggest the flow rates are within the limitations of the probe. The measured flow rates from heat-pulse are shown in the table below.

Table 4 RC-2 flow rates

Depth (ft)	Down flow rate (ft/min)
96	4.92
100	4.92
105	4.92
109	4.1

Table 5 RC-3 flow rates

Depth (ft)	Down flow rate (ft/min)
54	6.89
60	6.89
65	6.23
70	6.23
75	4.99
80	4.85

Table 6 RC-4 flow rates

Depth (ft)	Down flow rate (ft/min)
60	0.60
65	0.60
70	0.60
75	0.60

CLOSURE

Global Geophysics services will be conducted in a manner consistent with the level of care and skill ordinarily exercised by other members of the geophysical community currently practicing under similar conditions subject to the time limits and financial and physical constraints applicable to the services. However, borehole logging is a remote sensing geophysical method that may not detect all subsurface conditions.

We appreciate the opportunity to work with you on this project, and we hope that you find the results of the geophysical survey useful to your investigation. If you have any questions regarding this report, please call the undersigned at 425-890-4321. We look forward to providing you with additional geophysical services in the future.

Sincerely,

Global Geophysics.

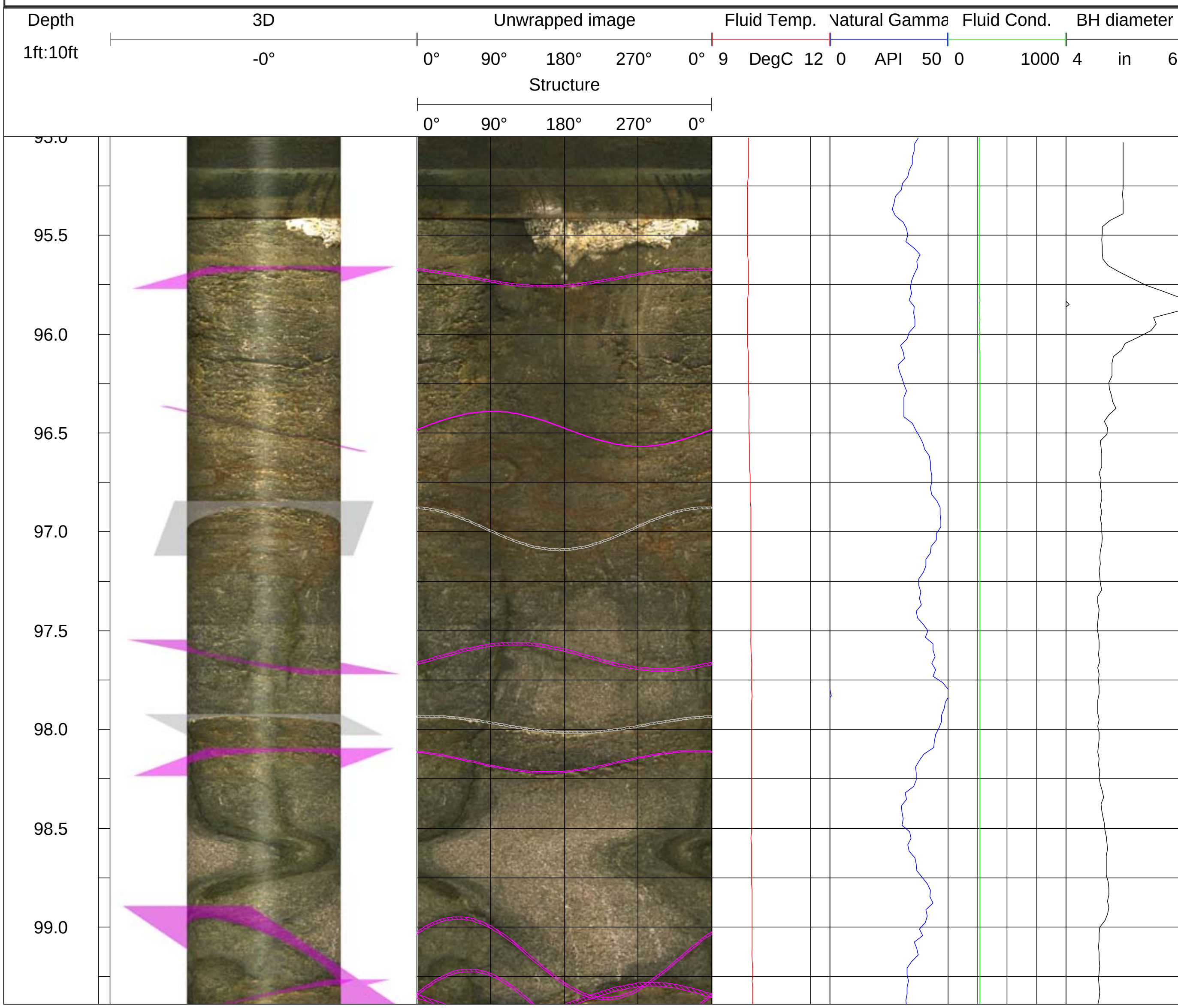
John Liu, Ph.D., R.G.
Principal Geophysicist

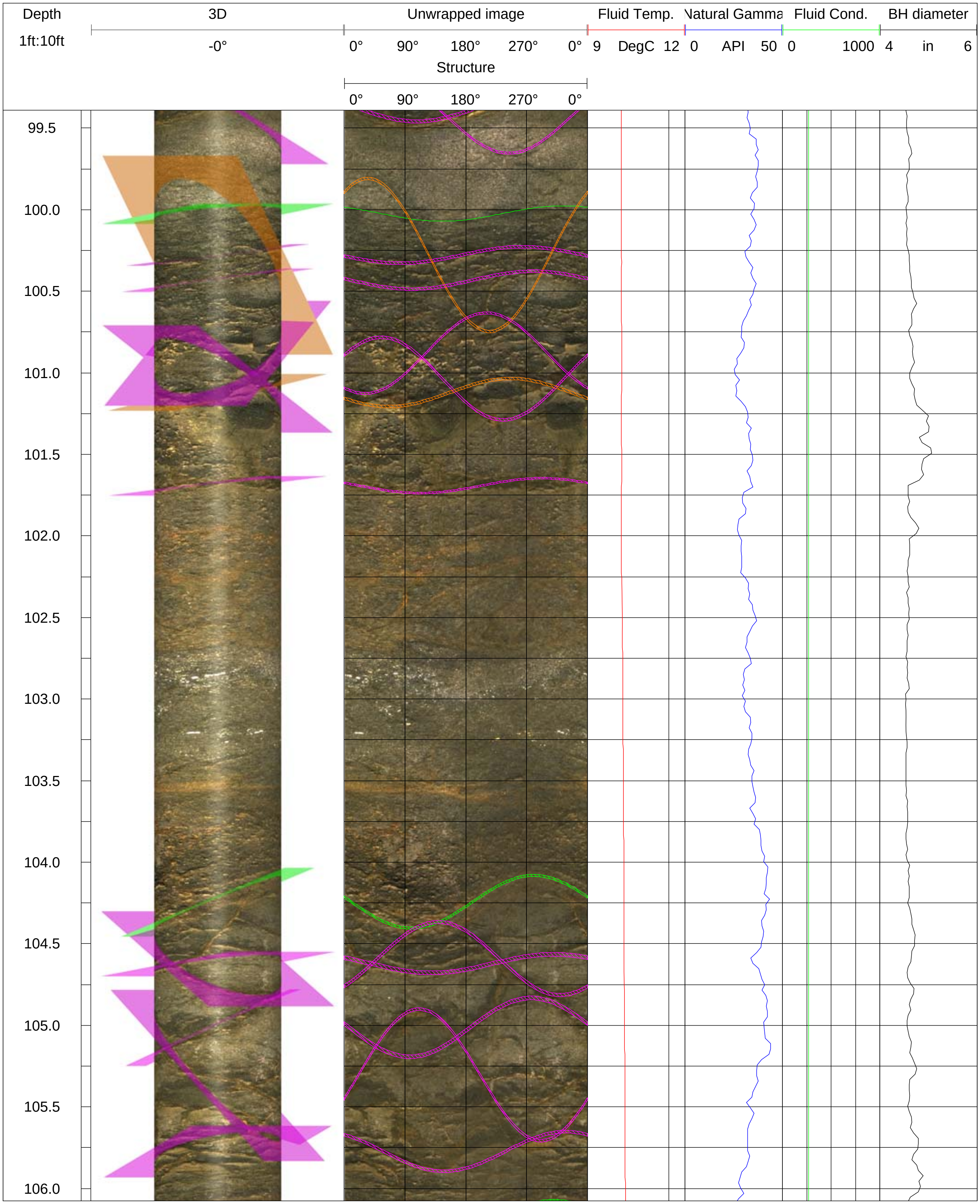
Appendix A

Global Geophysics

P.O. Box 2229
Redmond, WA, 98073-2229
Tel: 425-890-4321
Email: JLiu@GlobalGeophysics.com

CLIENT	*Environmental West Exploration, Inc.*	**DATE**	*December 3, 2018*
WELL	*RC-02*	**LOCATION**	*Freeman*
FIELD			
COUNTRY	*USA*	**STATE**	*WA*




Depth
1ft:10ft
3D
-0°
Unwrapped image
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
Fluid Temp.
9 DegC 12
Natural Gamma
0 API 50
Fluid Cond.
0 1000
BH diameter
4 in 6
99.5
100.0
100.5
101.0
101.5
102.0
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103.0
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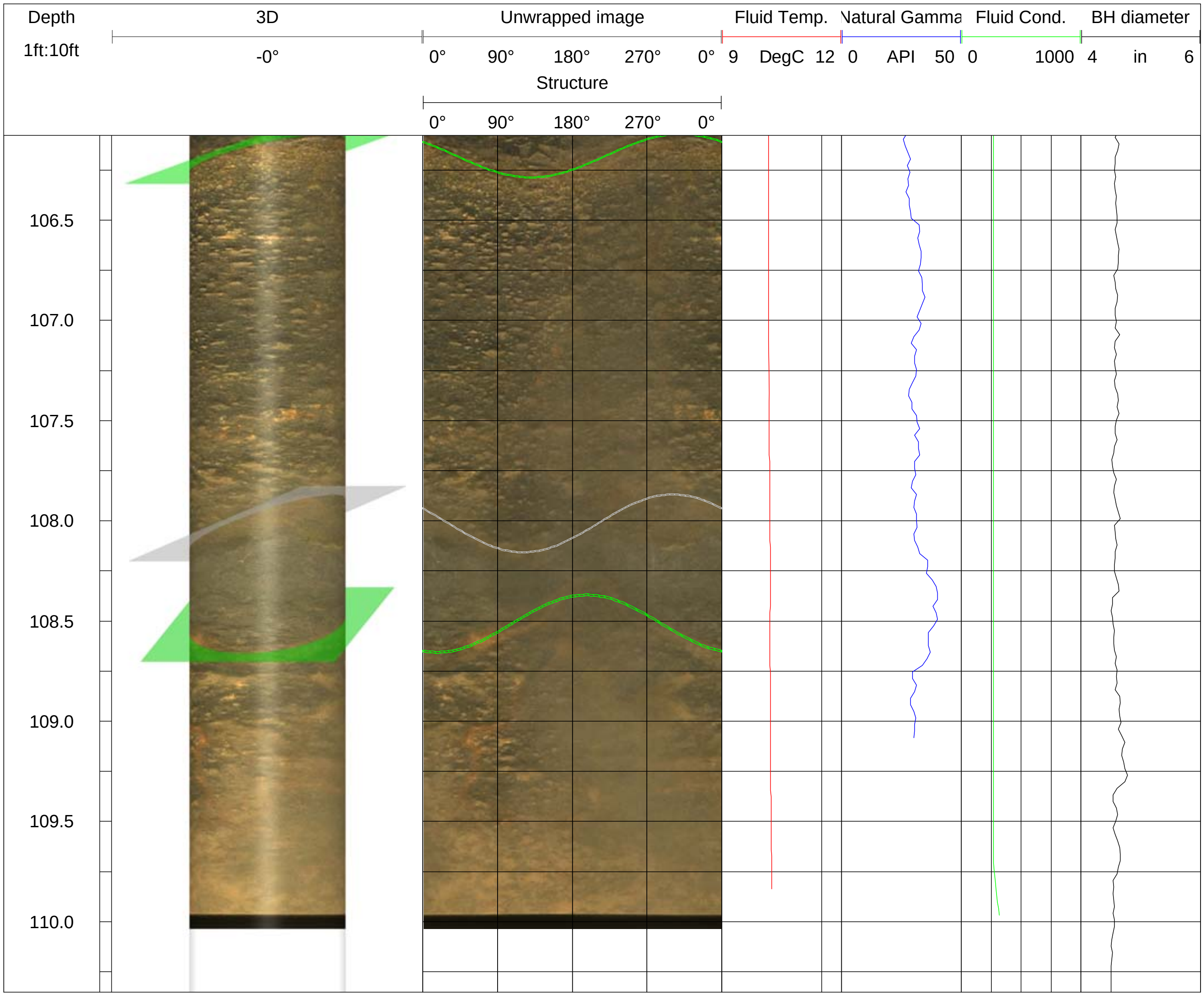
104.5
105.0
105.5
106.0



Depth
1ft:10ft
3D
-0°
Unwrapped image
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
Fluid Temp.
9 DegC 12
Natural Gamma
0 API 50
Fluid Cond.
0 1000
BH diameter
4 in 6
106.5
107.0
107.5
108.0
108.5
109.0
109.5
110.0

Global Geophysics

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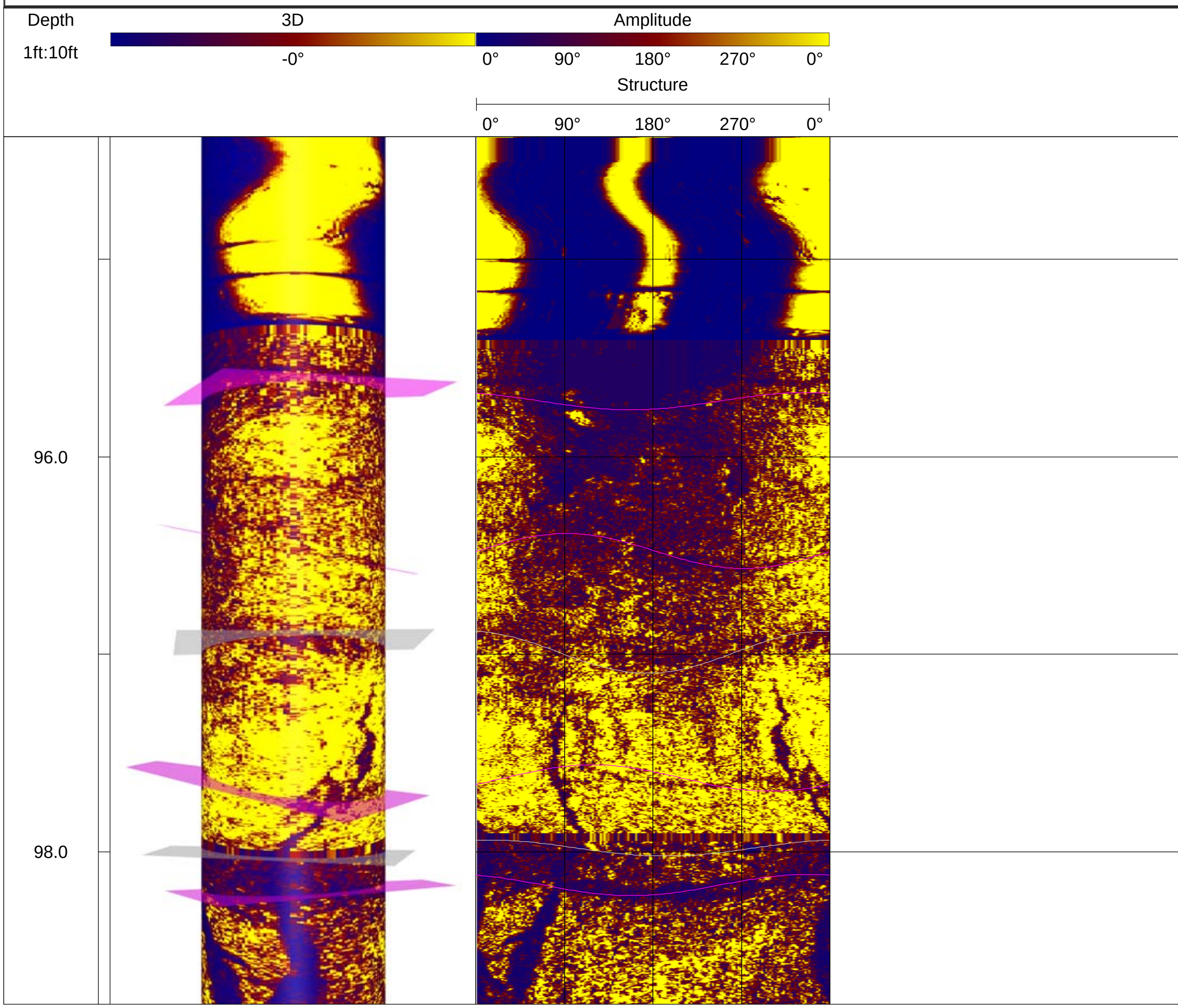
Email: JLiu@GlobalGeophysics.com

CLIENT	*Environmental West Exploration Inc.*	**DATE**	*30 Nov 2018*
WELL	*RC-2*	**LOCATION**	*Freeman*
FIELD	*Acoustic Televiewer*		
COUNTRY	*USA*	**STATE**	*WA*



Depth

1ft:10ft

3D

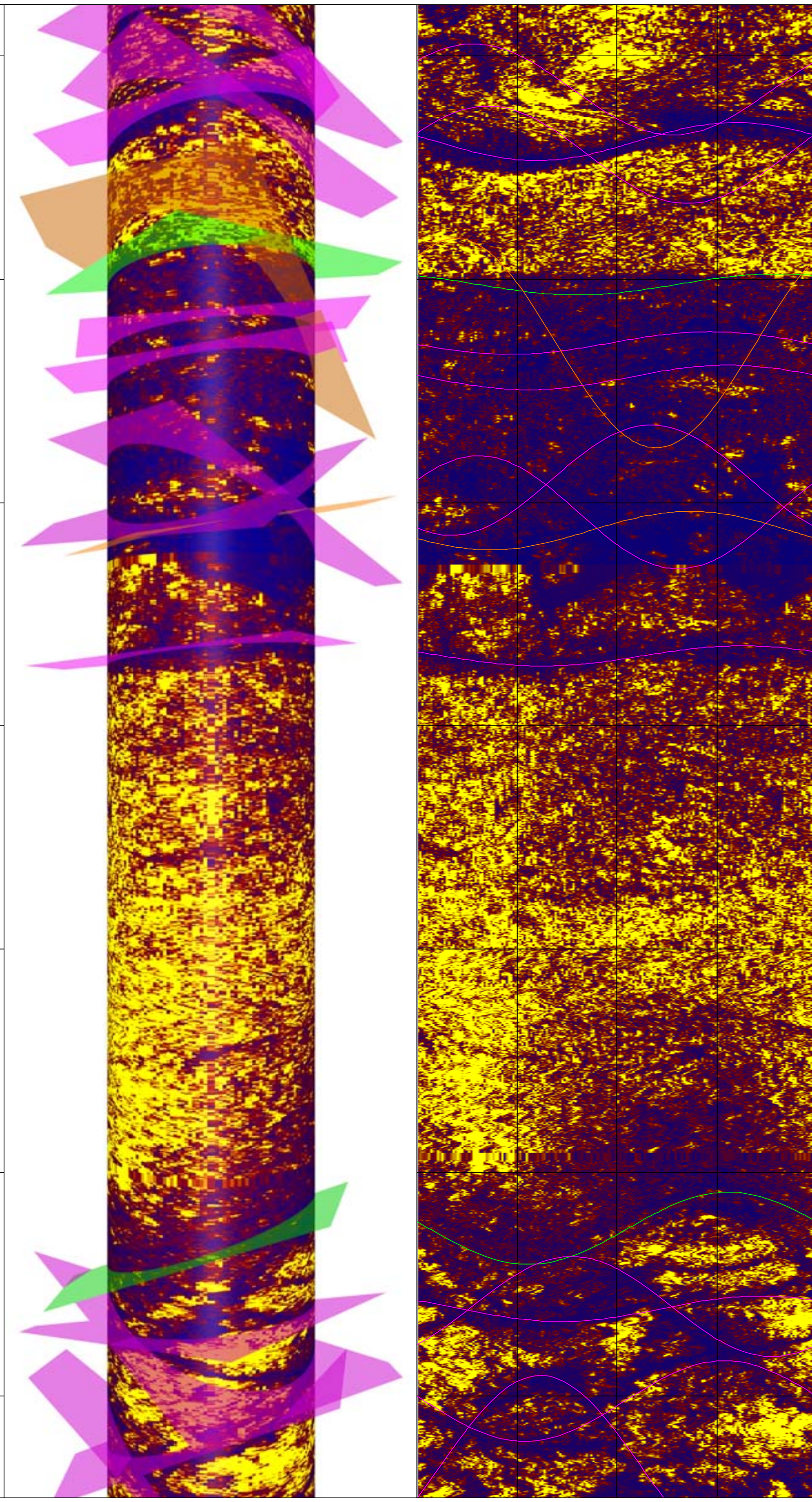
-0°

Amplitude

0° 90° 180° 270° 0°

Structure

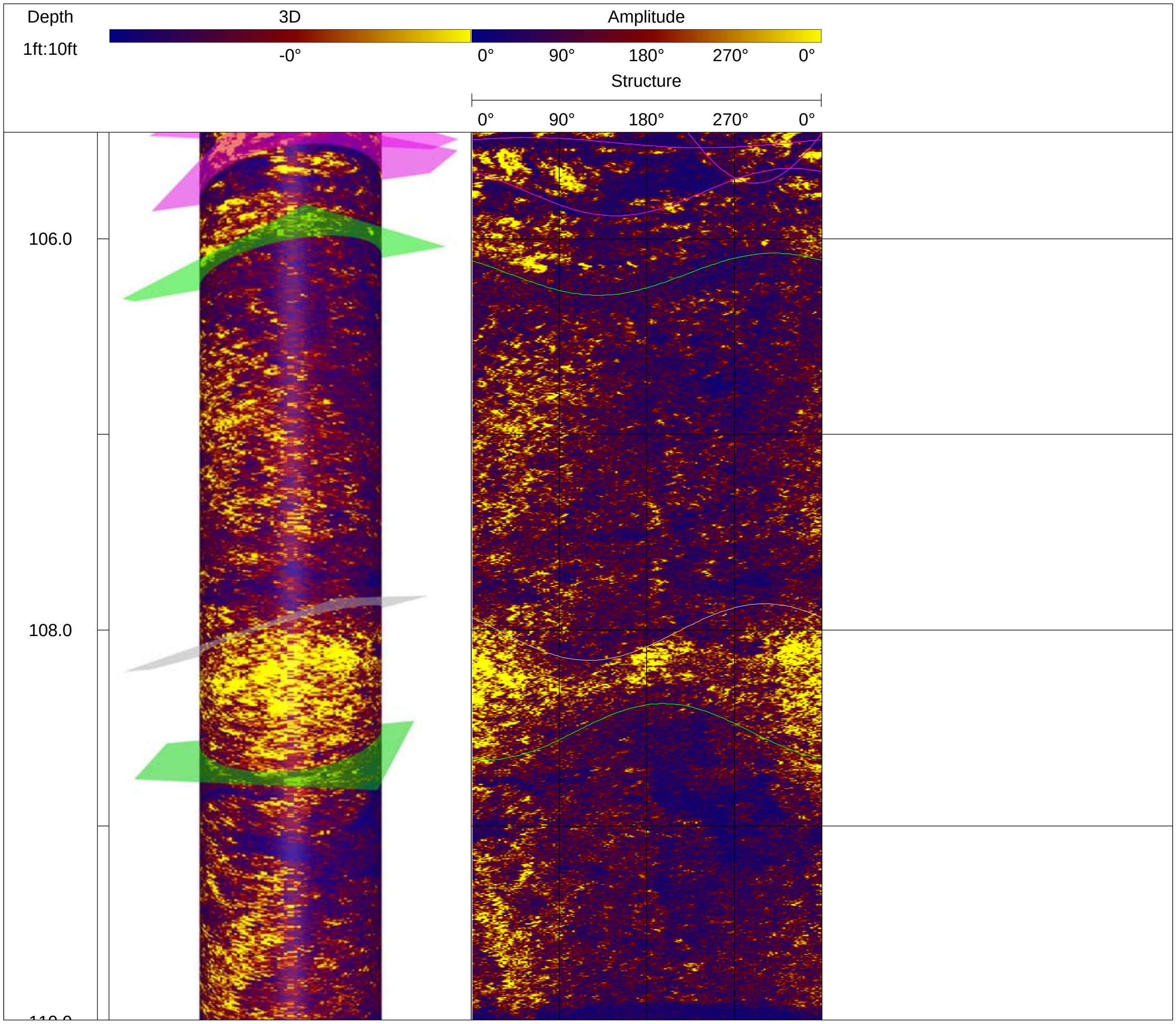
0° 90° 180° 270° 0°



100.0

102.0

104.0


Depth
1ft:10ft
3D
-0°
Amplitude
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
106.0
108.0

Global Geophysics

P.O. Box 2229
Redmond, WA, 98073-2229
Tel: 425-890-4321
Email: JLiu@GlobalGeophysics.com

CLIENT *Environmental West Exploration, Inc.*

DATE *November 29, 2018*

WELL *RC-3*

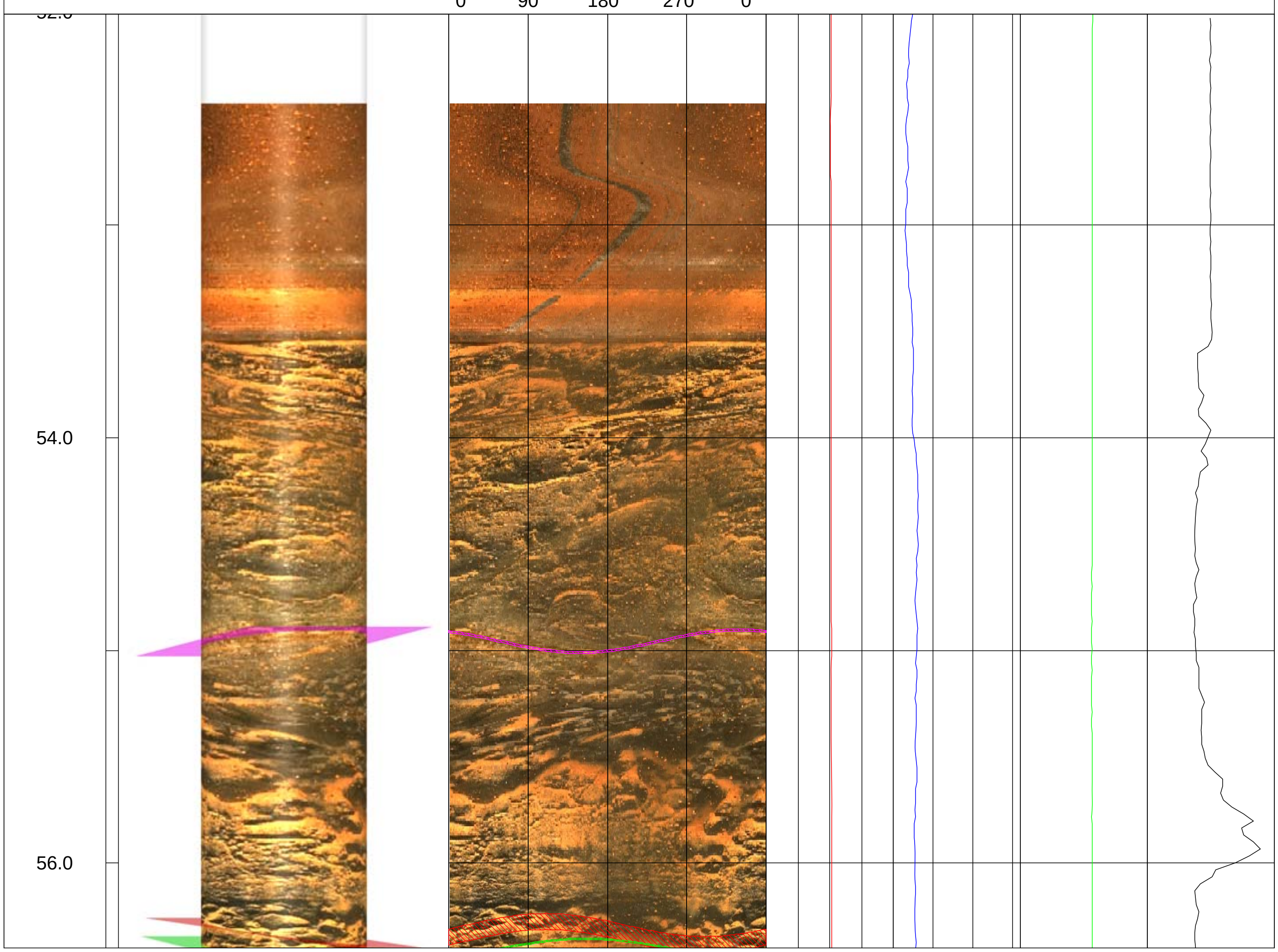
LOCATION *Freeman*

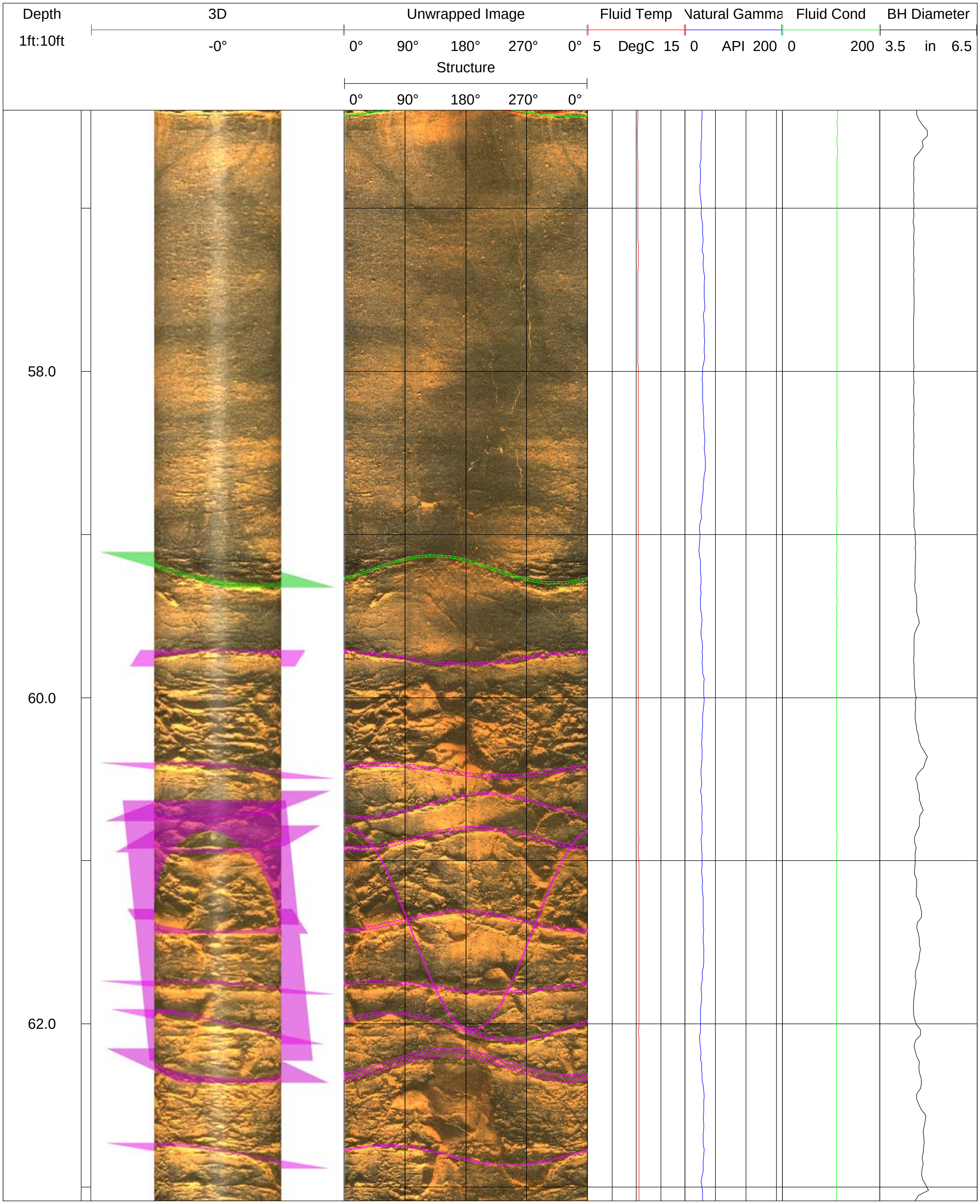
FIELD

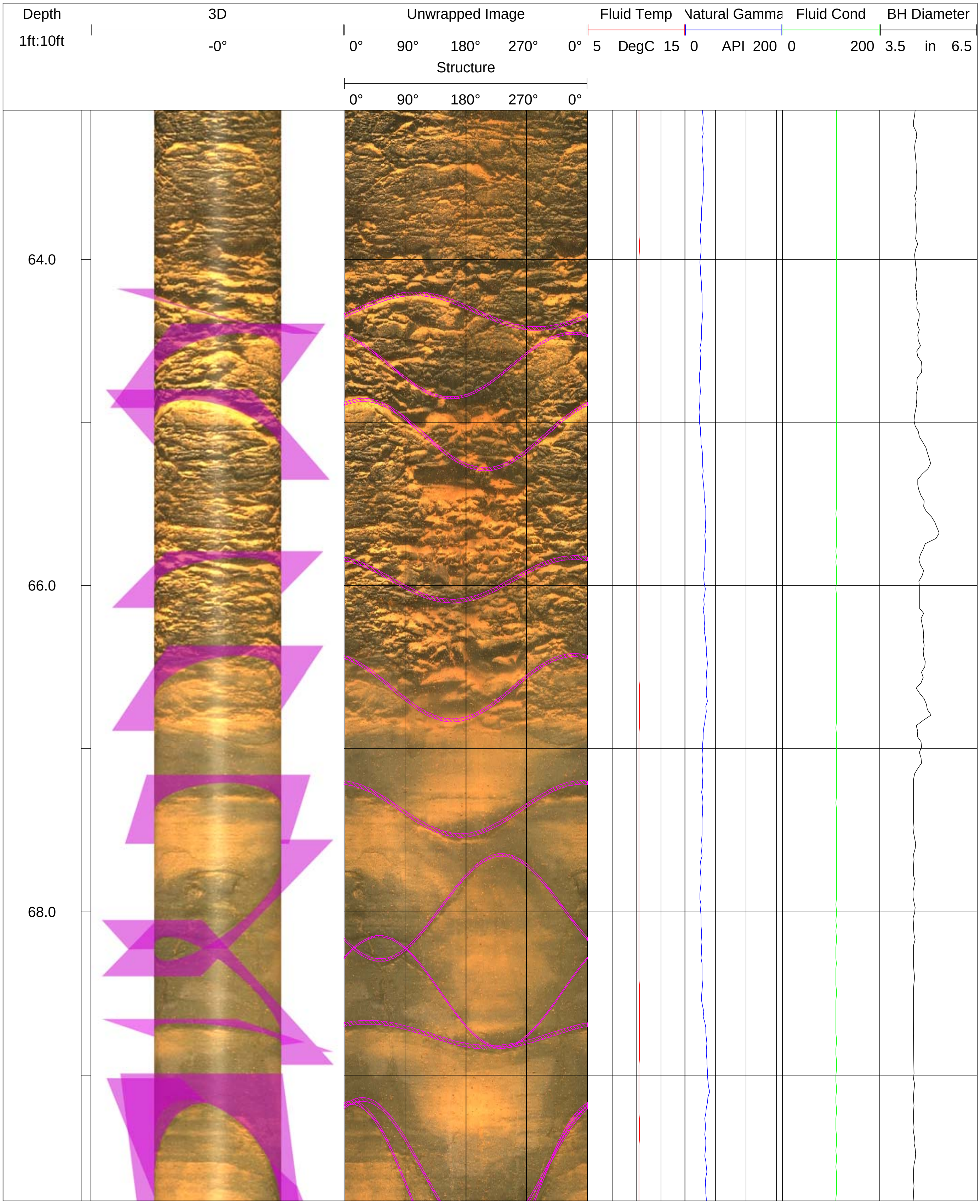
COUNTRY *USA*

STATE *WA*

Depth	3D	Unwrapped Image	Fluid Temp	Natural Gamma	Fluid Cond	BH Diameter
1ft:10ft	-0°	0° 90° 180° 270° 0°	5 DegC 15	0 API 200	0 200	3.5 in 6.5
		Structure				
		0° 90° 180° 270° 0°				




Depth
1ft:10ft
3D
-0°
Unwrapped Image
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
Fluid Temp
5 DegC 15
Natural Gamma
0 API 200
Fluid Cond
0 200
BH Diameter
3.5 in 6.5
58.0
60.0
62.0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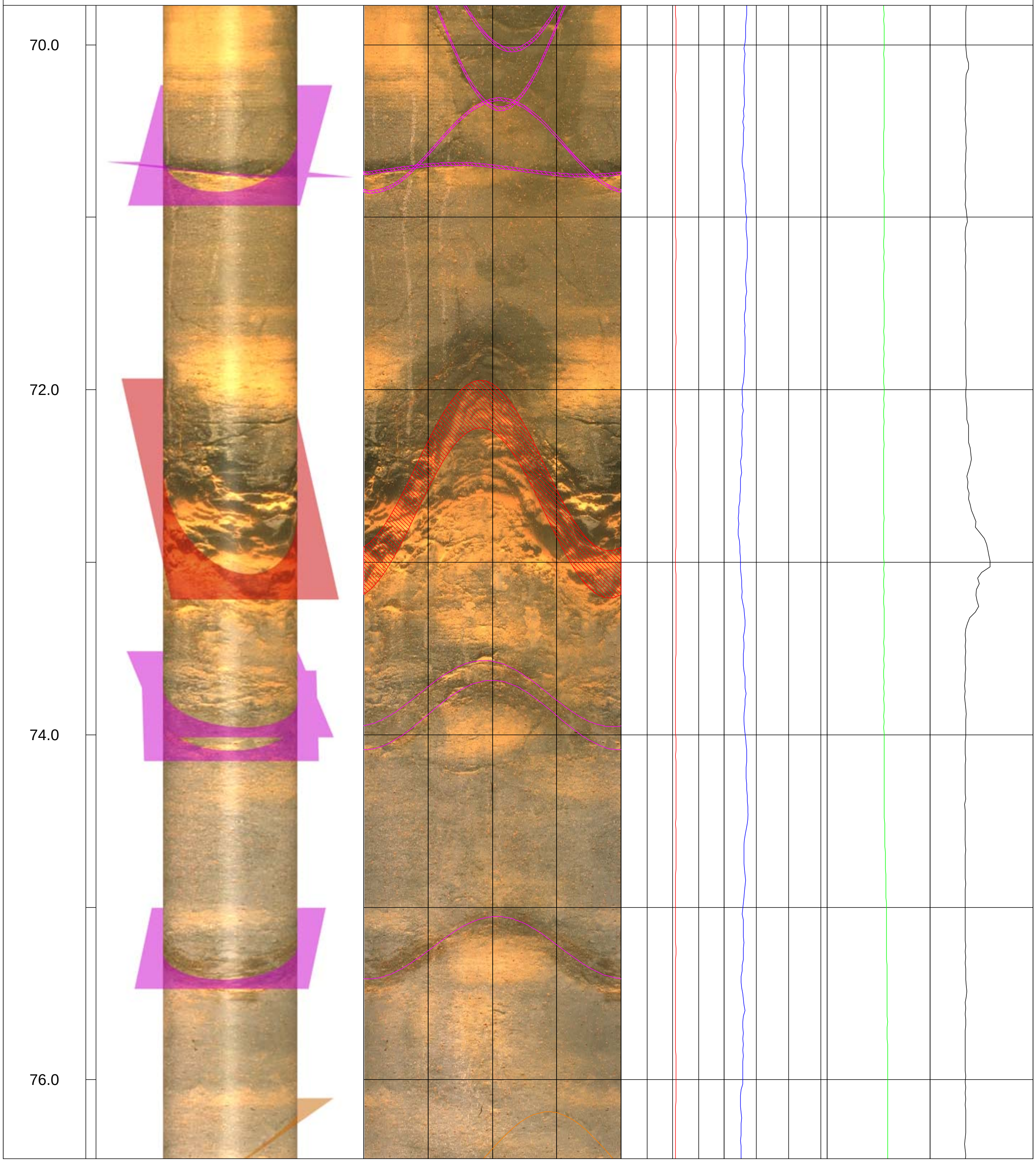
3D
-0°
Unwrapped Image
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
Fluid Temp
5 DegC 15
Natural Gamma
0 API 200
Fluid Cond
0 200
BH Diameter
3.5 in 6.5
64.0
66.0
68.0

Depth	3D	Unwrapped Image	Fluid Temp	Natural Gamma	Fluid Cond	BH Diameter
1ft:10ft	-0°	0° 90° 180° 270° 0°	5 DegC 15	0 API 200	0 200	3.5 in 6.5
		Structure				
		0° 90° 180° 270° 0°				



Depth	3D	Unwrapped Image	Fluid Temp	Natural Gamma	Fluid Cond	BH Diameter
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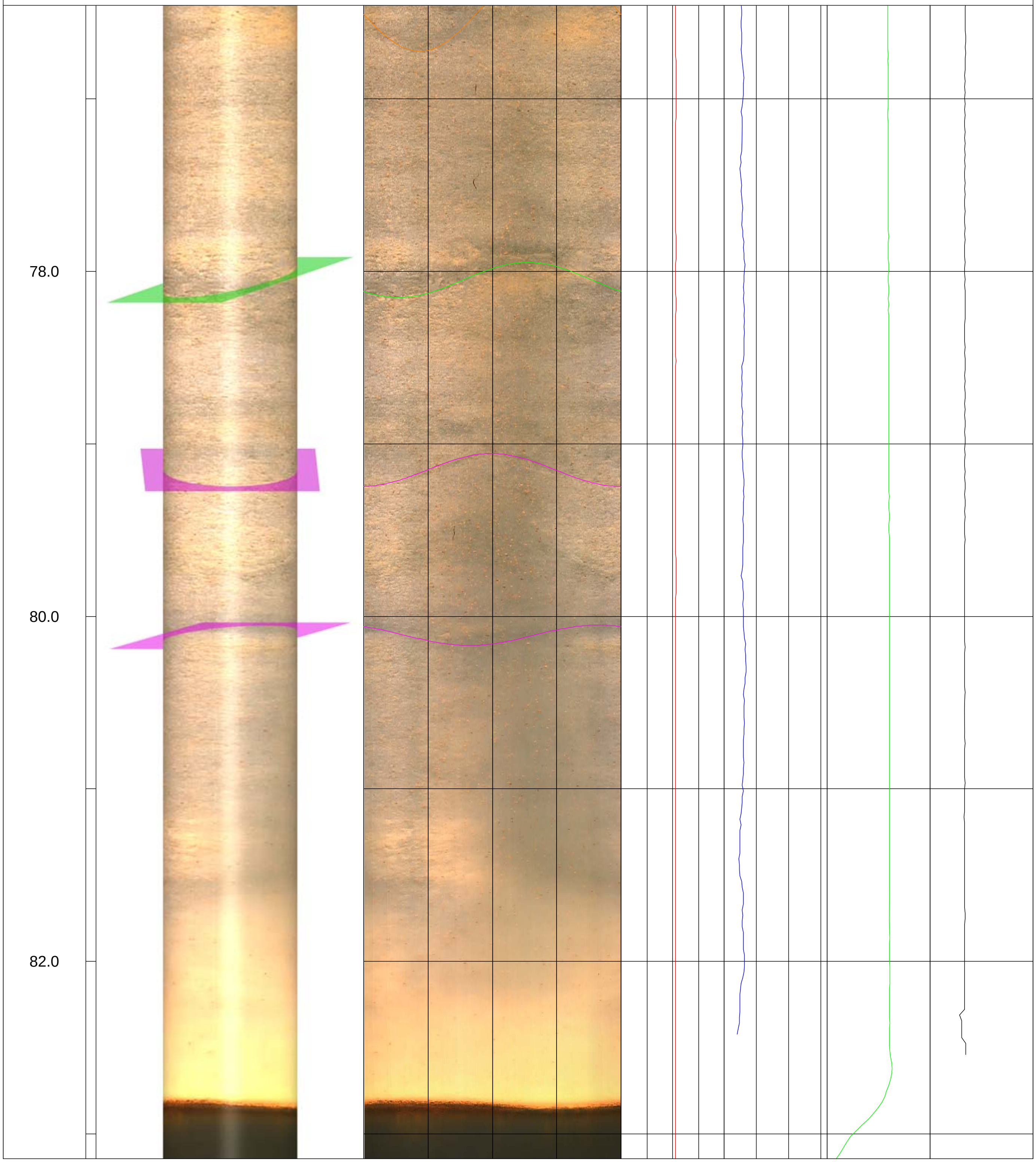
		Structure				
		0° 90° 180° 270° 0°				

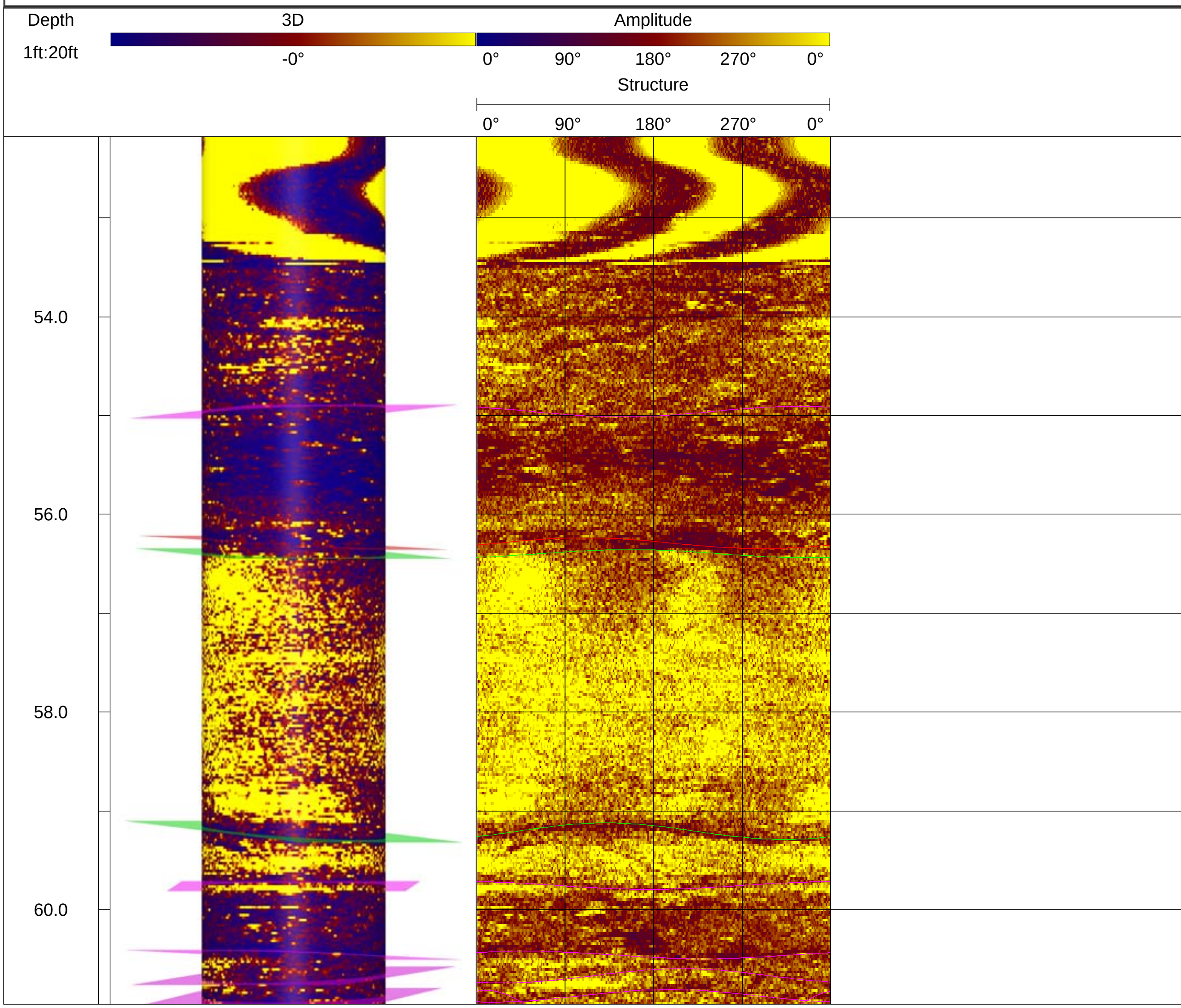


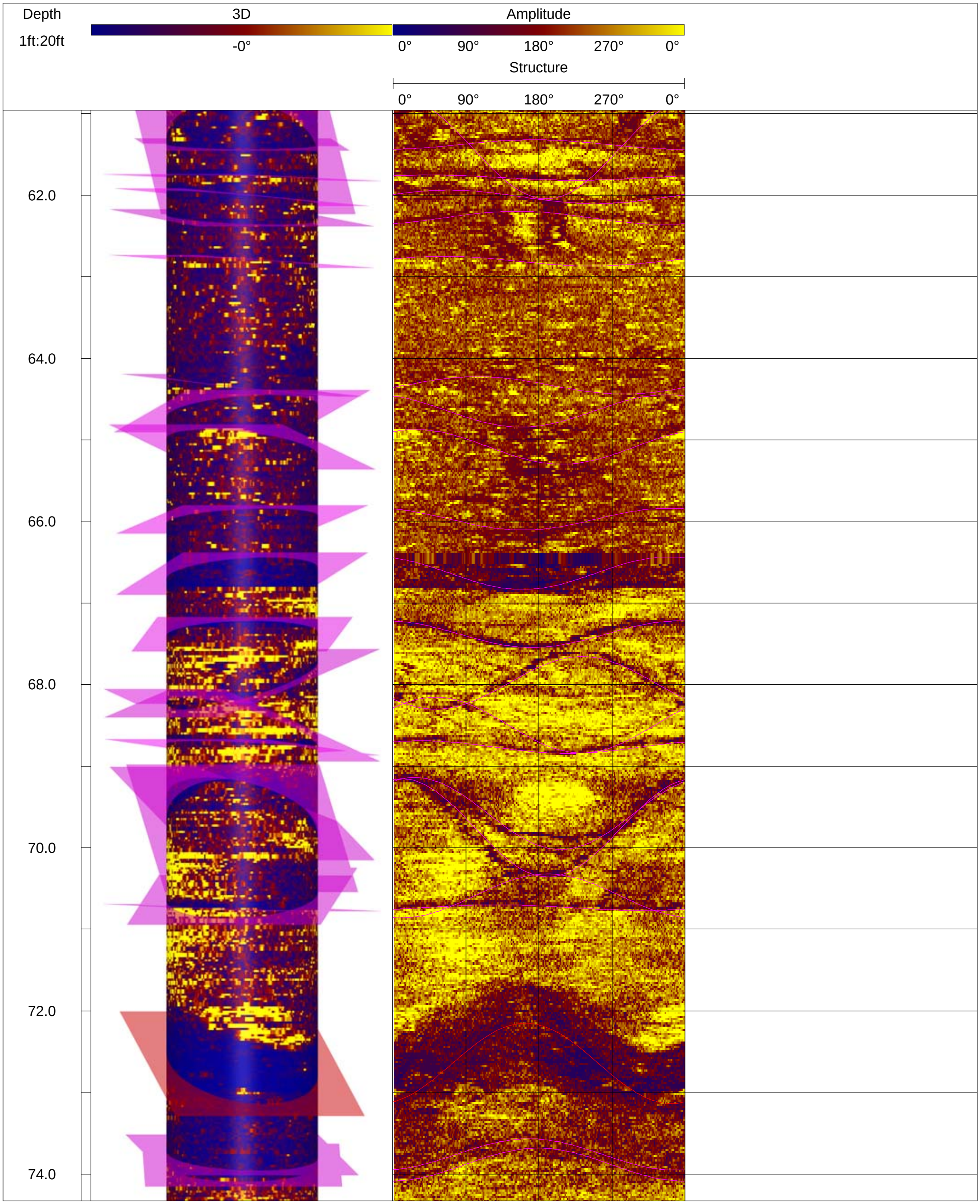
Depth	3D	Unwrapped Image	Fluid Temp	Natural Gamma	Fluid Cond	BH Diameter
1ft:10ft	-0°	0° 90° 180° 270° 0°	5 DegC 15	0 API 200	0 200	3.5 in 6.5
		Structure				
		0° 90° 180° 270° 0°				

Global Geophysics

P.O. Box 2229
Redmond, WA, 98073-2229
Tel: 425-890-4321
Email: JLiu@GlobalGeophysics.com

CLIENT	*Environmental West Exploration, Inc.*	**DATE**	*29 Nov 2018*
WELL	*RC-3*	**LOCATION**	*Freeman*
FIELD	*Acoustic Televiewer*		
COUNTRY	*USA*	**STATE**	*WA*




Depth
1ft:20ft
3D
-0°
Amplitude
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
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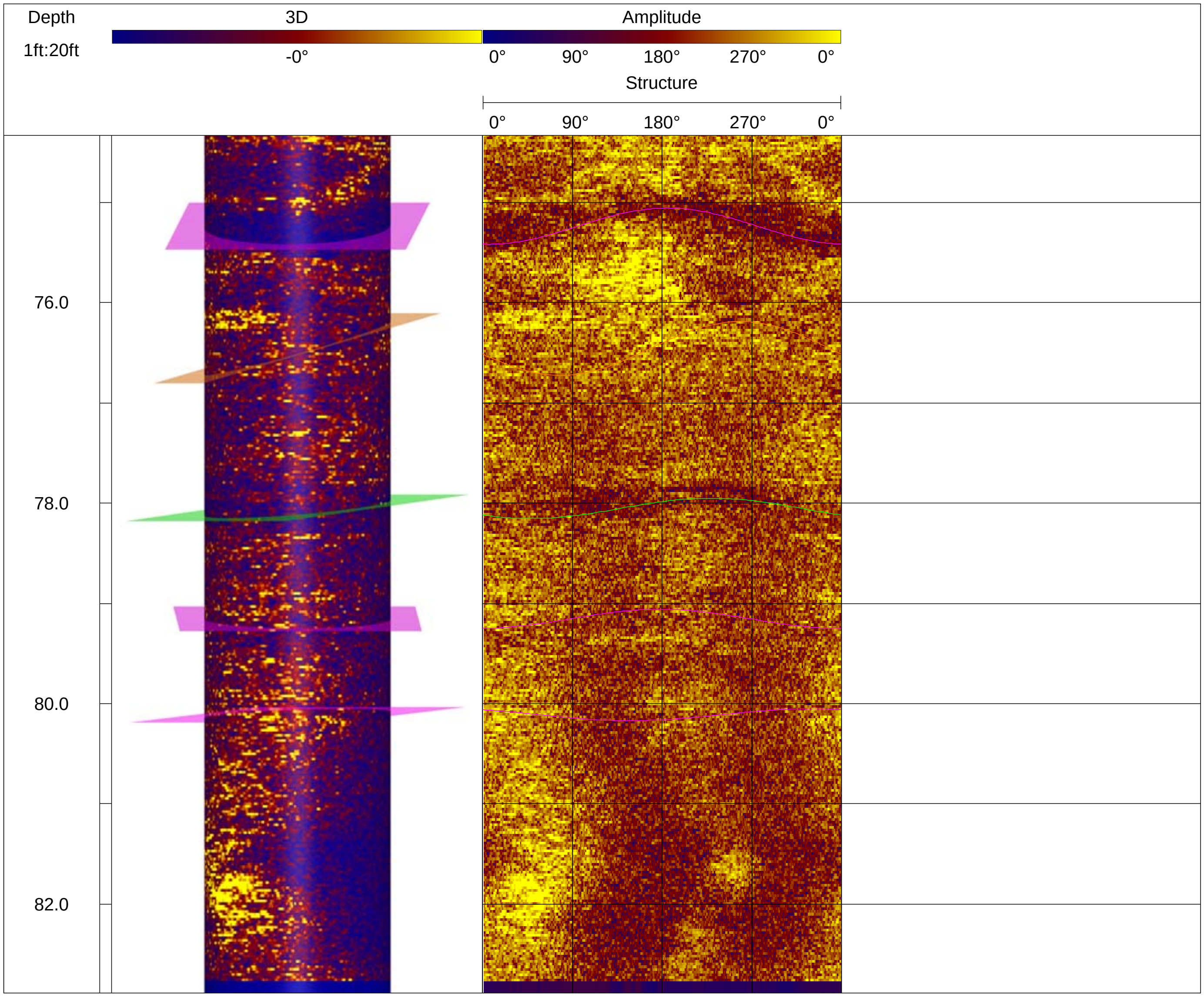
64.0
66.0
68.0
70.0
72.0
74.0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1ft:20ft
3D
-0°
Amplitude
0° 90° 180° 270° 0°
Structure
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78.0
80.0
82.0

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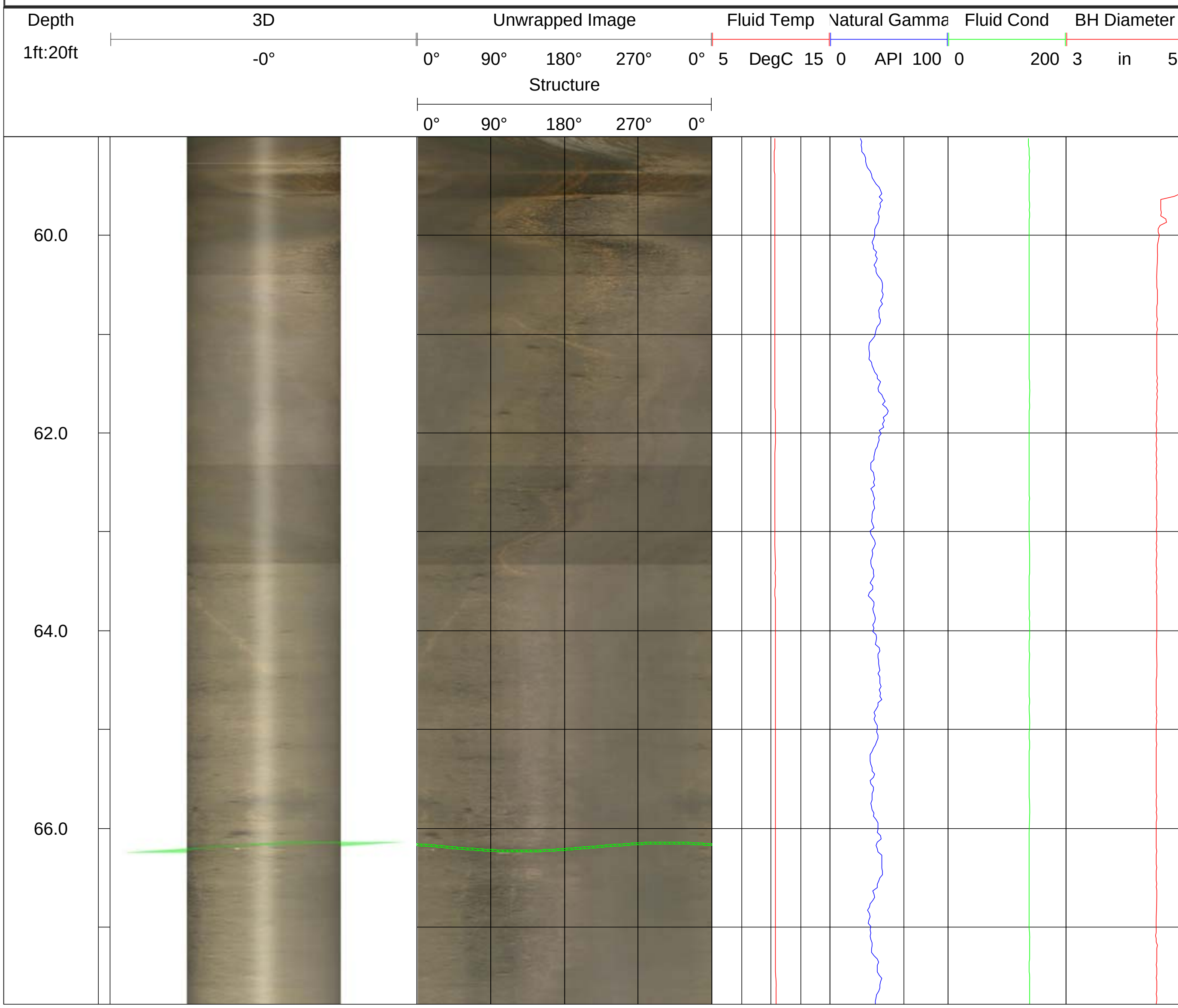
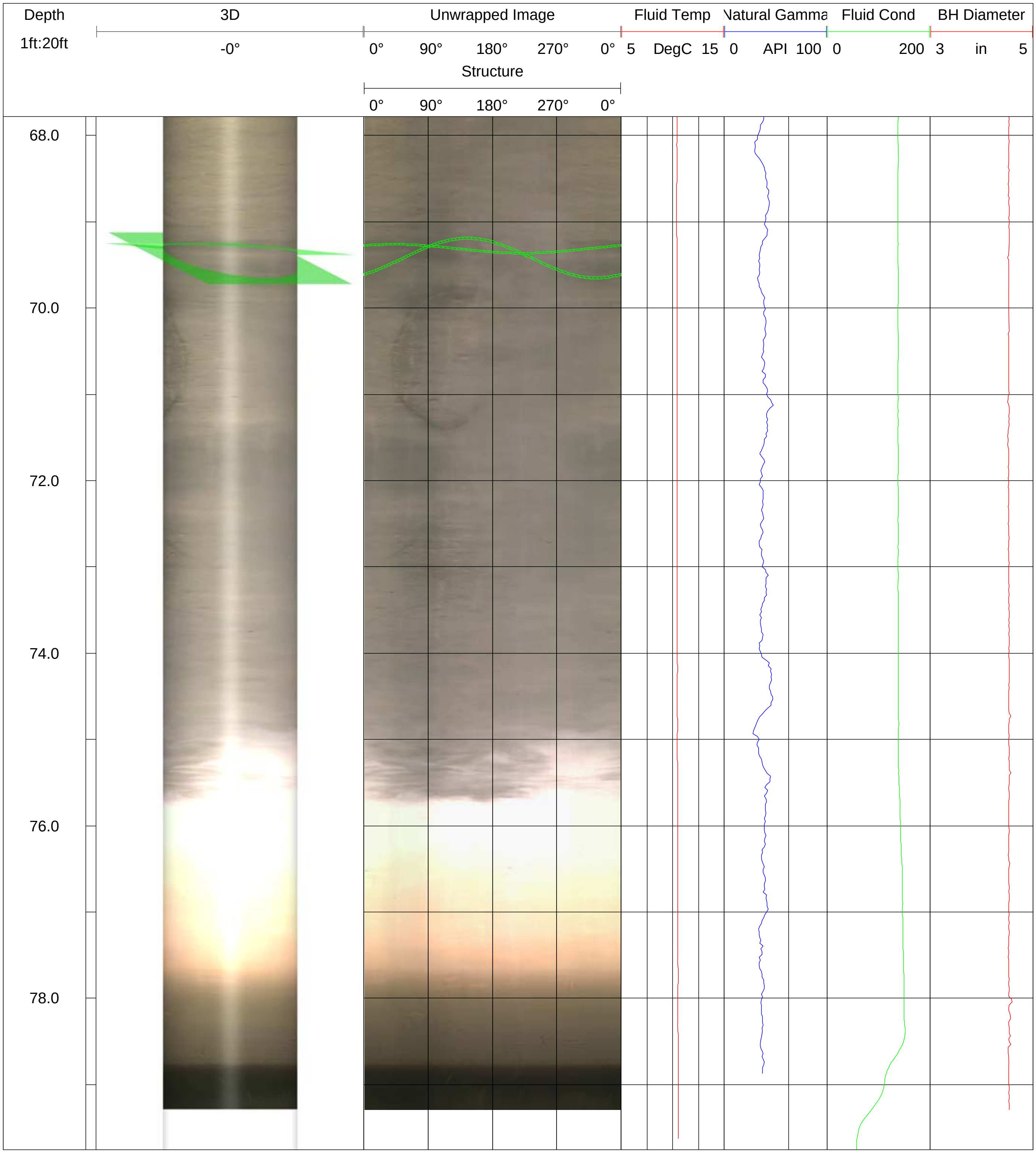
CLIENT	*Environmental West Exploration, Inc.*	**DATE**	*November 29, 2018*
WELL	*RC-4*	**LOCATION**	*Freeman*
FIELD			
COUNTRY	*USA*	**STATE**	*WA*

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0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
Fluid Temp
5 DegC 15
Natural Gamma
0 API 100
Fluid Cond
0 200
BH Diameter
3 in 5
68.0
70.0
72.0
74.0
76.0
78.0

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CLIENT	*Environmental West Exploration, Inc.*	**DATE**	*29 Nov 2018*
WELL	*RC-4*	**LOCATION**	*Freeman*
FIELD	*Acoustic Televiewer*		
COUNTRY	*USA*	**STATE**	*WA*

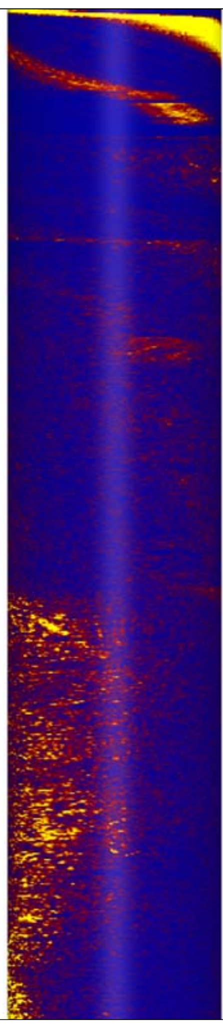
Depth 1ft:20ft	3D -0°	Amplitude 0° 90° 180° 270° 0° Structure 0° 90° 180° 270° 0°

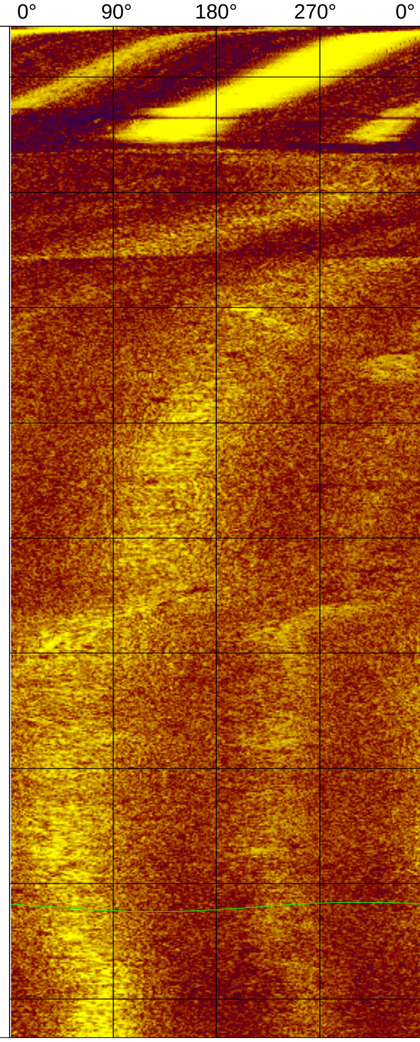
60.0

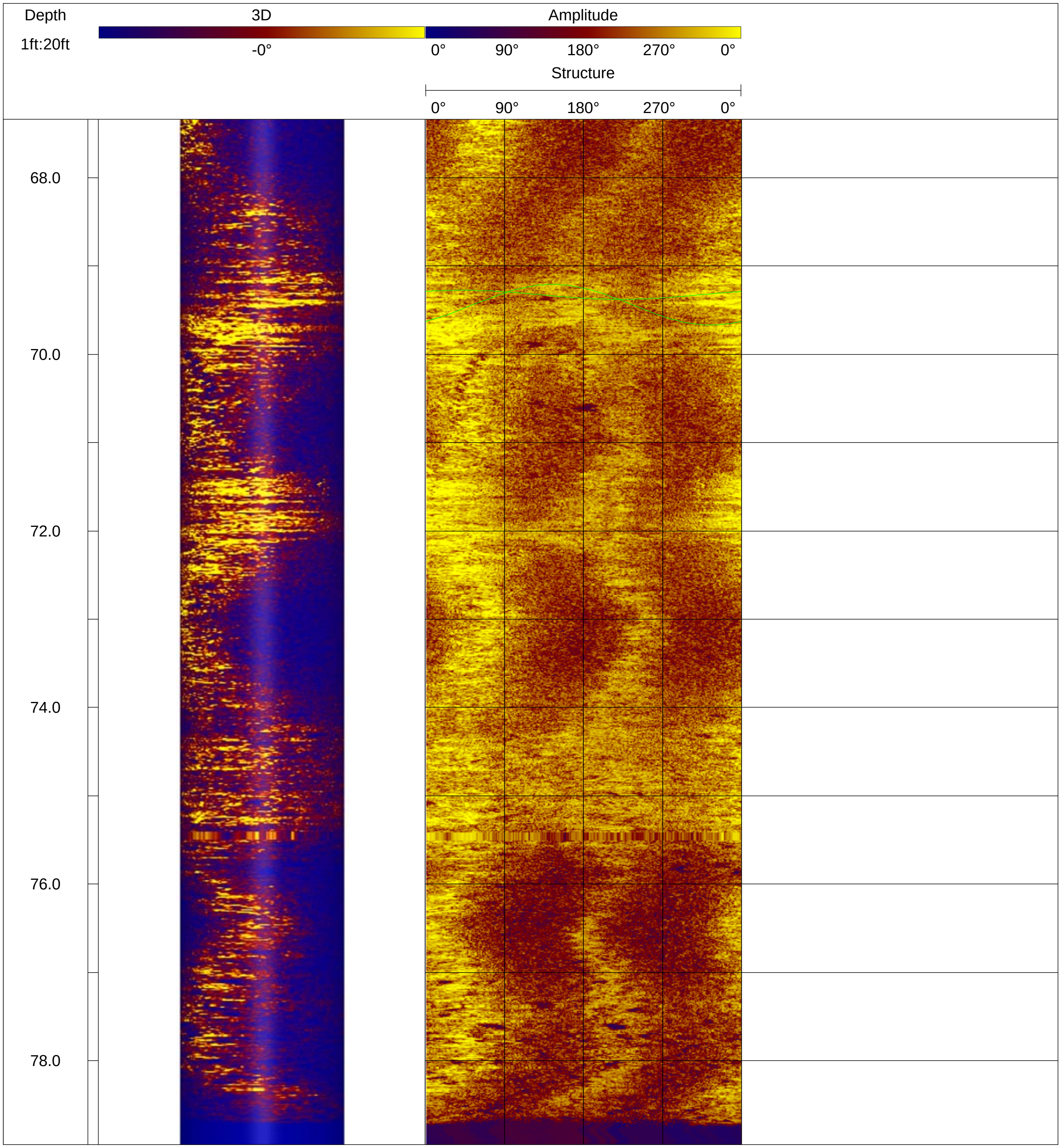
62.0

64.0

66.0






Depth
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3D
-0°
Amplitude
0° 90° 180° 270° 0°
Structure
0° 90° 180° 270° 0°
68.0
70.0
72.0
74.0
76.0
78.0

Appendix B
Lower Basalt Borehole Geophysical and Hydrophysical Report

Geophysical & Hydrophysical Logging Results
Jacobs
Union Pacific
Spokane, WA

Prepared for
Jacobs
July 9, 2019

Prepared by
COLOG, Inc.
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Table of Contents

Geophysical & Hydrophysical Logging Results
Jacobs; Union Pacific, Spokane, Washington

List of Acronyms

ft – feet
ftbtoc – feet below top of casing
ftbgs – feet below ground surface
min. – minute
sec – second
cps – counts per second
μS – micro Siemens
mS/m – milliSiemens per meter
FEC – Fluid Electrical Conductivity
BOC – Bottom of Casing
OBI – Optical Borehole Imager, or generically, optical televiewer
ABI – Acoustic Borehole Imager, or generically, acoustic televiewer
WSP – Wireline Straddle Packer
gpm – gallons per minute
HpL - Hydrophysical Logging
DI – De-ionized, e.g., DI water

Introduction

In accordance with the Contract NO.: 01947, executed between Union Pacific Railroad Company and COLOG, dated February 19, 2019, COLOG has applied geophysical and hydrophysical logging methods to characterize the borehole formation of three wellbores at the Union Pacific job site. The objectives of the investigation were to:

1) Evaluate temperature and fluid electrical conductivity under pre-testing conditions.
2) Identify fractures and features intersecting the borehole and evaluate their orientation.
3) Evaluate the vertical distribution of flow under stressed conditions.
4) Provide data to assist in the evaluation of the lithology intersecting the subject boreholes.
5) Obtain interval-specific or fracture-specific groundwater samples at major water-bearing zones.

Three subject wellbores were geophysically and hydrophysically logged at the Union Pacific job site in Freeman, Washington: RC-02, RC-03, and RC-04. The results of the geophysical investigations performed in the wellbores provides useful data for understanding the local lithology and fracture patterns, as well as the preferential flow-pathways. The geophysical logs also assisted in identifying potential water-bearing fractures or intervals for hydrophysical testing. The subject wellbores were tested under ambient and stressed conditions for a complete profile of the hydraulic conditions intersecting the subject wellbore. Wireline straddle packer testing intervals were determined using the televiewer images, identifying fractures with aperture, caliper anomalies and/or fluid electrical conductivity (FEC) and temperature anomalies, as well as any water-bearing zones identified by the hydrophysics. Minimal flow was identified under ambient conditions and significant flow identified under stressed conditions within all three boreholes at the Union Pacific project site.

COLOG's logging of the subject wellbores was performed over the period of April 22 through May 25, 2019. All depths reported herein are referenced to ground surface, unless stated otherwise.

Methodology

HydroPhysical Logging (HpL)

The HydroPhysical logging technique involves pumping the wellbore and then pumping while injecting into the Wellbore with deionized water (DI). During this process, profiles of the changes in fluid electrical conductivity of the fluid column are recorded. These changes occur when electrically contrasting formation water is drawn back into the borehole by pumping or by native formation pressures (for ambient flow characterization). A downhole wireline HydroPhysical tool, which simultaneously measures fluid electrical conductivity (FEC) and temperature is employed to log the physical/chemical changes of the emplaced fluid.

The computer programs FLOWCALC and/or BOREII (Hale and Tsang, 1988 and (Doughty and Tsang, 2000) can be utilized to evaluate the inflow quantities of the formation water for each specific inflow location. FLOWCALC is used to estimate the interval-specific flow rates for the production test results based on "hand-picked" values of FEC and depth. The values are determined from the "Pumping" and "Pumping During DI Injection logs". Numerical modeling of the reported data is performed using code BOREII. These methods accurately reflect the flow quantities for the identified water bearing intervals.

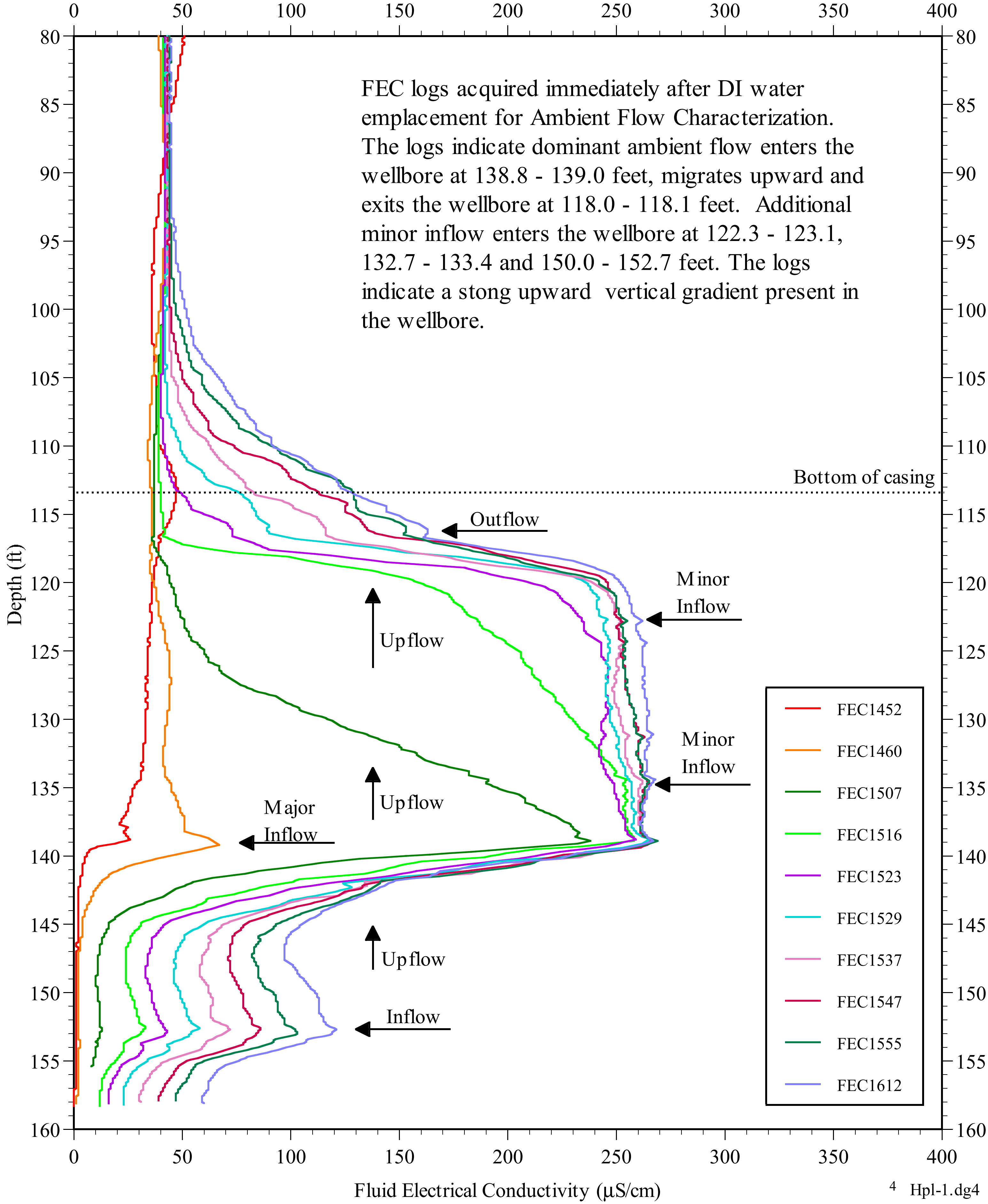
In addition to conducting HydroPhysical logging for identification of the hydraulically conductive intervals and quantification of the interval specific flow rates, additional logging runs are also typically performed. Prior to emplacement of DI, ambient fluid electrical conductivity and temperature (FEC/T) logs are acquired to assess the ambient fluid conditions within the borehole. During these runs, no pumping or DI emplacement is performed, and precautions are taken to preserve the existing ambient geohydrological and geochemical regime. These ambient water quality logs are performed to provide baseline values for the undisturbed borehole fluid conditions prior to testing.

For interval-specific permeability estimations, COLOG utilizes Hvorslev's 1951 porosity equation in conjunction with the HpL results. Several assumptions are made for estimating the permeability of secondary porosity. First, the type of production test COLOG performs in the field may significantly affect the accuracy of the transmissivity estimation. The permeability equation is relatively sensitive to overall observed drawdown. For a high yield wellbore, drawdown will usually stabilize and an accurate observed drawdown can be estimated. However, for a low yield wellbore, drawdown usually does not stabilize but instead, water level continues to drop until it reaches the pump inlet and the test is complete. In this case COLOG utilizes the maximum observed drawdown. The inaccuracy arises in the fact that overall observed drawdown does not stabilize and therefore is more an arbitrary value dependent on the placement of the pump downhole. Secondly, in an environment where flow originates from secondary porosity the length of the interval is derived from the either the thickness of the fracture down to 0.1 feet or the thickness of the fracture network producing water. This assumption of a fracture network producing water versus a porous media is not how the permeability equation was designed to be used. In lieu of a more appropriate equation unknown to COLOG at this time, COLOG utilizes Hvorslev's 1951 porosity equation based on its sensitivity to interval-specific flow which can be measured accurately, drawdown which can be measured accurately in the case of a high yield wellbore and its insensitivity to effective radius. The insensitivity to effective radius is critical when an observation well is not available to measure drawdown at a known distance from the subject wellbore.

How to Interpret HydroPhysical Logs

Figure HpL:1 below is an example data set acquired under ambient conditions. The data represents HpL logs acquired immediately after deionized (DI) water emplacement for ambient flow evaluation. For ambient flow evaluation the wellbore fluids are first replaced with DI water (termed "emplacement"), then a series of fluid electrical conductivity (FEC) logs are acquired over a period of a time to monitor ground water entering the wellbore under natural pressures and migrating either vertically or horizontally through the wellbore. The wellbore fluids are replaced with DI water without disturbing the ambient free-water level by injecting DI water at the bottom of the wellbore and extracting wellbore water at exactly the same rate at the free-water surface. However, at the beginning of the DI water emplacement, a slightly depressed free-water level (approximately one tenth of a foot below ambient free water-level) is achieved and maintained throughout the test. This procedure is implemented to ensure that little to no DI water is able to enter the surrounding formation during DI water emplacement. By acquiring FEC logs during the emplacement of DI water and by continuously measuring water level with a downhole pressure transducer the emplacement can be properly monitored and controlled to minimize the disturbance of the recorded ambient water. After the wellbore fluids are replaced with DI water, the injection and extraction pumps are turned off and in most cases the downhole plumbing is removed from the wellbore. A check valve is installed in the pump standpipe to ensure water in the standpipe does not drain back into the wellbore. While the plumbing is removed from the wellbore DI water is injected from the top of the wellbore to maintain ambient water level. Often a baseline FEC log is acquired during the final stages of the emplacement of DI water to provide baseline conditions just before the ceasing of pumping. Figure HpL:1 illustrates ambient flow entering the wellbore at depths of 150.0 to 152.7, 138.8 to 139.0, 132.7 to 133.4, 122.3 to 123.1 and 118.0 to 118.1 feet. The location of these intervals is illustrated by the sharp increases or "spikes" in FEC. The increase in FEC over time at these four intervals is characteristic of ambient inflow. The upward vertical trend in this inflow is also apparent from the FEC logs. For example, the dominant inflowing zone at 138.8 to 139.0 feet illustrates a major growth in FEC above the inflow "spike", and little growth below the "spike." The zone at 118.0 to 118.1 feet is the termination of all inflow into the well. The sum of the four inflow zones make up the outflow of this zone, and this value, along with the value of the four inflow zones is computed using code BOREII.

FIGURE HpL:1. EXAMPLE OF HYDROPHYSICAL LOGS DURING AMBIENT FLOW CHARACTERIZATION WITH EXAMPLE INTERPRETATION.



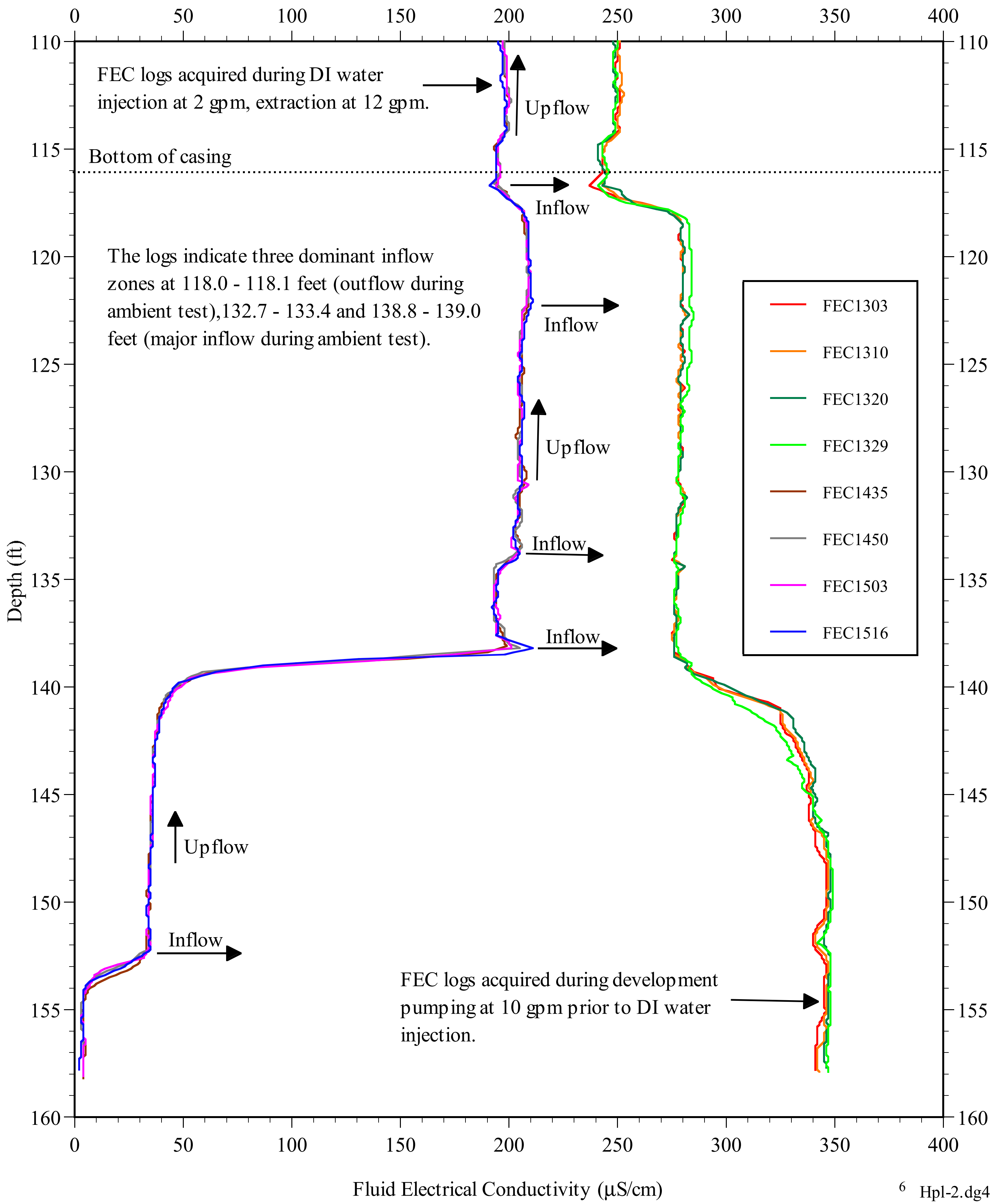
4 Hpl-1.dg4

COLOG uses three types of tests to identify the water-bearing intervals in a wellbore under stressed conditions. In the lowest yield environment (less than 0.5 gpm) a slug test approach is utilized. In a relatively low-yield wellbore environment a pump after emplacement (PAE) test is conducted, and in a relatively medium to high-yield wellbore environment a pump and inject (PNI) test is conducted. The decision on the type of test to perform on a specific wellbore is made in the field based on the ability of the wellbore to recover to ambient free-water level when a disturbance in water level is introduced into the well, i.e. inserting tools and/or pluming into the well.

In a low-yield wellbore environment a slug or PAE test is utilized to identify the water-bearing intervals under stressed conditions. These tests are similar in protocol and involve first a replacement of wellbore fluids with DI water in a manner identical to that of the emplacement during an ambient flow evaluation. Often a baseline FEC log is acquired during the final stages of the emplacement of DI water to provide baseline conditions just before the ceasing of injection pumping. Following the cessation of injection pumping, the extraction pump is left used to either pull an instantaneous slug (slug test) or is used to pump at a relatively steady low rate of flow in the wellbore (approximately 1-2 gpm). During this time numerous FEC logs are acquired over time. The location of water-bearing intervals is apparent by the sharp increases or "spikes" in FEC over time. The rate at which these intervals inflow is calculated using BOREII and is based on the rate of increase of mass (area under the curve using the FEC log as the curve). Flow direction is easily determined by tracking the center of mass of the area under the curve. In most cases, if pumping is being conducted flow is traveling up the wellbore towards the pump which is situated inside casing.

Figure HpL:2 is an example data set from the same wellbore as Figure HpL:1, acquired under stressed conditions. The data represents HpL logs acquired during a PNI test. The set of FEC logs on the right of this figure (FEC1303, FEC1310, FEC1320, and FEC1329) illustrate the condition of the wellbore during development pumping. In the case of this example, the wellbore was stressed at a rate of approximately 10 gpm until a relatively steady-state condition was achieved in the wellbore. A steady-state condition is apparent when the FEC logs begin to repeat as they do in figure HPL:2. Repeatable FEC logs indicate that the hydrochemistry of the water inflowing to the wellbore is not changing over time (steady-state) and that the flow rates of all inflow zones is also not changing over time. Additionally, the drawdown is monitored continuously to observe a "slowing down" in the rate of increase of drawdown. When drawdown (water level) is stable, the inflow rates of the various inflow zones are assumed to be steady. By contrast, if DI water injection is begun in the early stages of pumping when drawdown is still increasing, i.e. water level is dropping rapidly, the inflow rates of the various inflow zones would increase with time as less wellbore storage is used to maintain a particular pumping rate. The remaining FEC logs (FEC1435, FEC1450, FEC1503, and FEC1516) illustrate the conditions in the wellbore during pumping and injection procedures. Fluid was extracted from the wellbore at a rate of approximately twelve gpm while DI water was simultaneously injected at the bottom of the wellbore at a rate of approximately two gpm, until a relatively steady-state condition existed in the well. Water-bearing intervals in the wellbore are identified by changes or "steps" in FEC throughout the FEC logs. The flow rate of these intervals is computed using BOREII and/or Flowcalc software. Every location that the FEC increases in these logs is a zone of inflow. Similarly, where the logs decrease in FEC indicates a zone of inflow with water lower in FEC than the water in the wellbore. A zone exhibiting a decrease in FEC on the injection logs should also decrease at the same depth on the development (pre-DI water injection) logs. Please see Appendix B for a detailed discussion of code BOREII used to numerically model the reported field FEC logs.

FIGURE HpL:2. EXAMPLE OF HYDROPHYSICAL LOGS DURING A 10 GPM PRODUCTION TEST WITH EXAMPLE INTERPRETATION.



 Hpl-2.dg4

Sensitivity of Transmissivity to Effective Radius

An estimation of transmissivity (T) has be made for all identified water-bearing intervals using an equation after Hvorslev (1951) assuming steady-state radial flow in an unconfined aquifer:

$$T = KL = \frac{q_i}{2\pi\Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL™ results (or "Delta Flow" from the table which equals "Interval-Specific Flow Rate During Pumping Conditions" minus "Ambient Flow Rate" if any), r_w is the borehole radius, r_e is the effective pumping radius, Δh_w is the observed maximum drawdown and L is the thickness of the zone through which flow occurs. For this example the data for wellbore MW-655 is used. The thickness, or length of the interval is calculated using a combination of the HpL™ data and any other data set available. L can usually be estimated with a high degree of confidence based on both of those data sets. Q_i, or Delta Flow, can also be estimated accurately using code BOREII (see appendix B) for the HpL™ data sets. Δh_w is estimated with a high degree of confidence using Cologs' downhole pressure transducer and a laptop to record water-level data every 10 seconds. Additionally, the borehole radius is confirmed quite readily from the caliper data. For this example, r_w equals 0.20 feet, r_e has been assumed to be approximately 100 feet and the observed maximum drawdown was 9.98 feet. By applying L and q_i from the HpL™ results under the two pressure conditions, the interval specific transmissivity can be calculated for each identified water-producing interval.

Colog utilizes Hvorslevs' 1951 equation when an observation well a known distance away with measurable drawdown is not available. Essentially, Hvorslevs' 1951 equation is similar to the prevalent Theis equation minus the observation well drawdown information. In replace of the observation well drawdown data Hvorslevs' equation uses an assumed "effective radius" divided by the borehole radius. One benefit to using Hvorslevs' 1951 equation when observation well data is unavailable is the insensitivity of the equation to the assumed effective radius as this is the only "unknown" variable in the equation. All other variables are known or calculated with a high degree of confidence. Only the effective radius is unproven, or unsupported, but its value can be estimated with some degree of accuracy.

The following example will illustrate the insensitivity of Hvorslevs' 1951 equation to the assumed effective radius of an aquifer. The greatest magnitude of change in this example between r_e of 50 feet and r_e of 300 feet is 22.0 feet^2/day transmissivity.

Interval (feet)	**Length of Interval (feet)**	**Q_i - Delta Flow (gpm)**	**Borehole Radius (feet)**	**Transmissivity Using r_e of 50 Feet**	**Transmissivity Using r_e of 100 Feet**	**Transmissivity Using r_e of 300 Feet**
118.0 – 118.1	0.1	3.997	0.20	6.78 x E^{01}	7.63 x E^{01}	8.98 x E^{01}
122.3 – 123.1	0.8	0.335	0.20	5.68 x E^{00}	6.39 x E^{00}	7.53 x E^{00}
132.7 – 133.4	0.7	1.217	0.20	2.06 x E^{01}	2.32 x E^{01}	2.73 x E^{01}
138.8 – 139.0	0.2	3.961	0.20	6.72 x E^{01}	7.56 x E^{01}	8.90 x E^{01}
150.0 – 152.7	2.7	0.197	0.20	3.34 x E^{00}	3.76 x E^{00}	4.43 E^{00}

Optical and Acoustic Televiewers

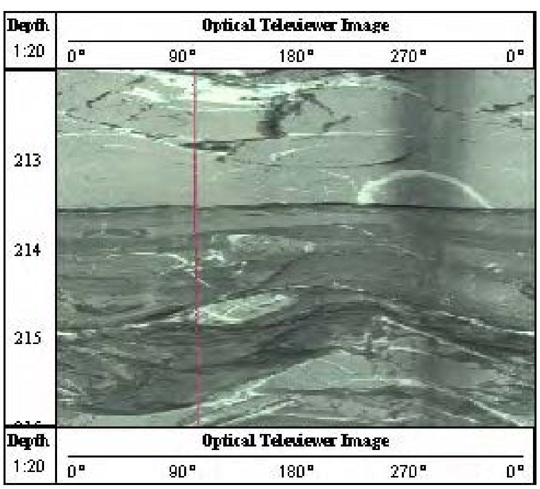
The OBI-40 optical televiewer and the ABI-40 acoustic televiewer (and its predecessor, the FAC40), from Advanced Logic Technologies (ALT), provide the highest resolution available for fracture and feature analysis in boreholes. Precise dip direction and angle measurements of bedding, fractures, and joint planes, along with other geological analyses, are possible.

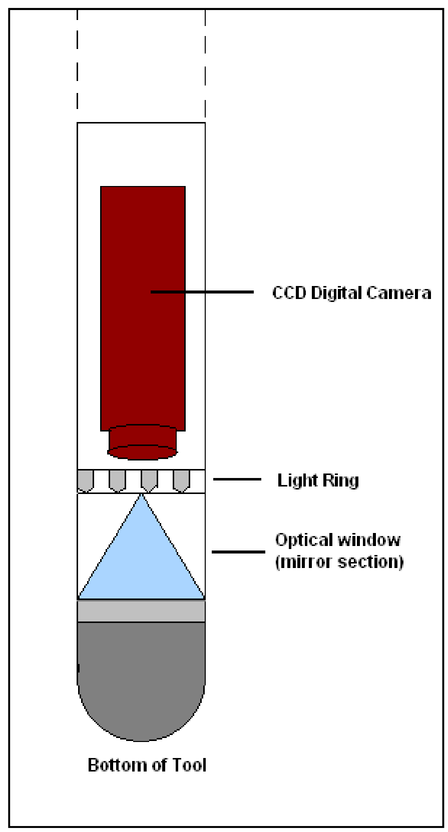
The optical televiewer technology is based on direct optical observation of the borehole wall face and can be utilized in both air and clear fluid filled boreholes. The acoustic televiewer technology is based on the return amplitude and time of an acoustic wave reflected off the borehole wall face; it can be utilized in clear or murky fluid-filled boreholes, but not in air.

Varying borehole conditions often exist which preclude the usage of one or the other tool; therefore, the optical televiewer and acoustic televiewer are often used in conjunction to image the entire borehole. When doing so, it must be kept in mind that optical and acoustic properties are not necessarily yielding the same data set. For example, a transition between two similarly-colored beds may not stand out visually, but it may stand out acoustically if the densities of the two materials are different.

<u>Optical Televiewer – Theory of Operation</u>

The OBI-40 optical televiewer provides a detailed, oriented optical image of the borehole wall. A small ring of lights illuminates the borehole wall allowing a camera to directly image the borehole wall face. A conical mirror housed in a clear cylindrical window focuses a 360° optical "slice" of the borehole wall onto the camera's lens. As the optical televiewer tool is lowered down the hole, the video signal from the camera is transmitted uphole via the wireline to the recording instrumentation.





Figures: Example of OBI40 optical Televiewer data (left) and sketch of OBI40 optical tool head (right).

The signal is digitized in real time by capturing up to 720 pixels from the conical optical image. A digital magnetometer and accelerometer package is used to determine the orientation of the probe, and thus the digital image, for each conical image capture. The conical image rings are stacked and unwrapped to a 2-D, oriented image of the borehole wall.

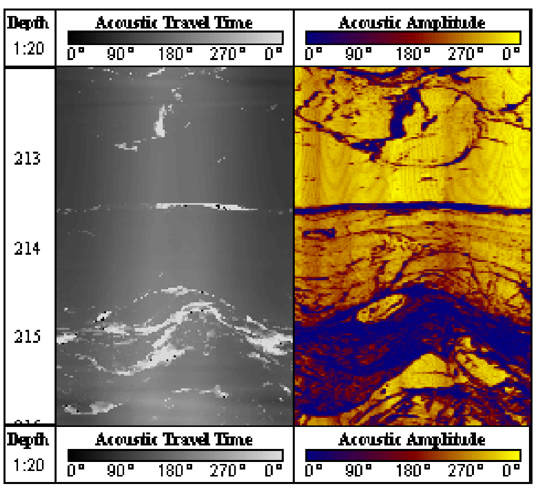
Precise borehole trajectory/deviation and image orientation are achieved using a 3-axis magnetometer and three accelerometers. When the tool is well-centralized, azimuthal accuracy is to ±1.0 degrees and inclination accuracy is to ±0.5 degrees. Deviated or rugous boreholes and outside magnetic interference can contribute to reduced orientation accuracy of the tool, and thus the oriented image. The pink line seen in the example data above represents a fixed point on the tool; it is used in orienting the data with respect to magnetic north.

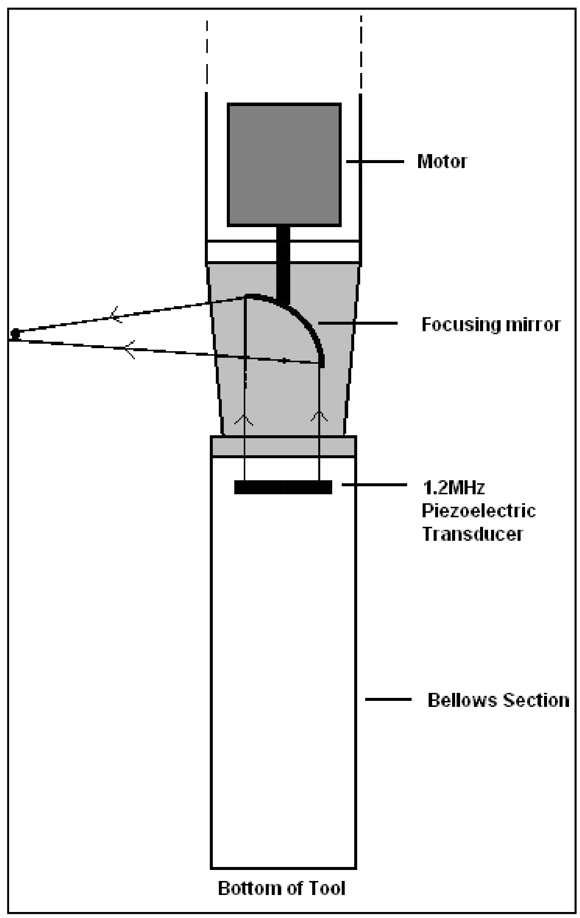
Tool image colors are calibrated in shop to true-color, however, varying light conditions downhole often lead to color images that are somewhat false-colored. This should be taken into account when reviewing images.

Main applications of the optical televiewer include: fracture detection and evaluation, detection of thin beds, determination of bedding dip, lithological characterization, and casing inspection.

Acoustic Televiewer (ATV) – Theory of Operation

The ABI-40 acoustic televiewer, from Advanced Logic Technologies (ALT), provides a detailed, oriented image of acoustic reflections from the borehole wall. A unique focusing system resolves bedding features as small as 2 mm and is capable of detecting fractures with apertures as small as 0.1 mm.





Figures: Example ABI40 acoustic televiewer data (left) and sketch of ABI40 acoustic head (right).

The acoustic televiewer transmits ultrasonic pulses from a rotating sensor (mirror) and records the signals reflected from the interface between the borehole fluid and the borehole wall. The amplitude of these reflections is representative of the hardness of the formation surrounding the borehole, while the travel time represents the borehole shape and diameter. As many as 288 reflections may be recorded per revolution at up to 10 revolutions per second. The conical image rings are stacked and unwrapped to a 2-D, oriented image of the borehole wall. The digital amplitude and travel time data are presented using a variety of color schemes.

Precise borehole trajectory/deviation and acoustic image orientation are achieved using a 3-axis magnetometer and three accelerometers. When the tool is well-centralized, azimuthal accuracy is to ±1.0 degrees and inclination accuracy is to ±0.5 degrees. Deviated or rugous boreholes and outside magnetic interference can contribute to reduced orientation accuracy of the tool, and thus the oriented image.

The high-resolution reflection images and the precise travel time measurements make the ABI-40 acoustic televiewer a versatile tool. Possible applications include: fracture detection and evaluation, detection of thin beds, determination of bedding dip, lithological characterization, casing inspection, and high-resolution caliper measurements.

Acoustic Televiewer Caliper Log

An unconventional caliper log may be generated from the travel time data acquired by the ABI-40 acoustic televiewer. Using WellCAD software, an estimation of the distance from the probe to the borehole wall can be made by incorporating the travel time of the acoustic signal with an estimation of the velocity of the borehole fluid. The time it takes the acoustic signal to travel through a known viscous medium and back to the probe is directly related to the distance between the signal generator and the borehole wall provided the borehole fluid viscosity remains constant and the probe is properly centralized. The distance from the probe to the borehole wall is then corrected for the radius of the probe, producing a borehole diameter value.

Understanding 2-D Televiewer Images

For both the optical and acoustic televiewer, the 2-D picture of the borehole wall is unwrapped from north to north. Planar features that intersect the borehole appear to be sinusoids on the unwrapped image. To calculate the dip angle of a fracture or bedding feature, the amplitude of the sinusoid (h) and the borehole diameter (d) are required. The angle of dip is equal to the arc tangent of h/d, and the dip direction is picked at the trough of the sinusoid.

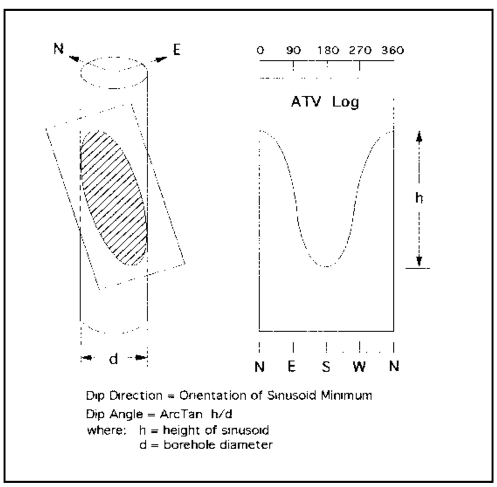


Figure: Geometric representation of a north-dipping fracture plane and corresponding log.

Interpreting Optical and/or Acoustic Televiewer Data

Sinusoidal features are picked throughout the boreholes by visual inspection of the digital optical and acoustic televiewer images using the interactive software WellCAD. These sinusoidal feature *projections* can directly overlay the televiewer images or be plotted alongside the televiewer images.

The features can also be represented by *tadpoles*. The tail of the tadpole points in the azimuthal direction of dip, where north is up, east is 90° to the right, etcetera. The head of the tadpole is located vertically on the plot, at the projection's inflection point, that is, halfway between the peak and the trough depth of the sinusoidal projection. The horizontal head location represents the dip angle, with shallow features near the left side of the plot and steeper features near the right side.

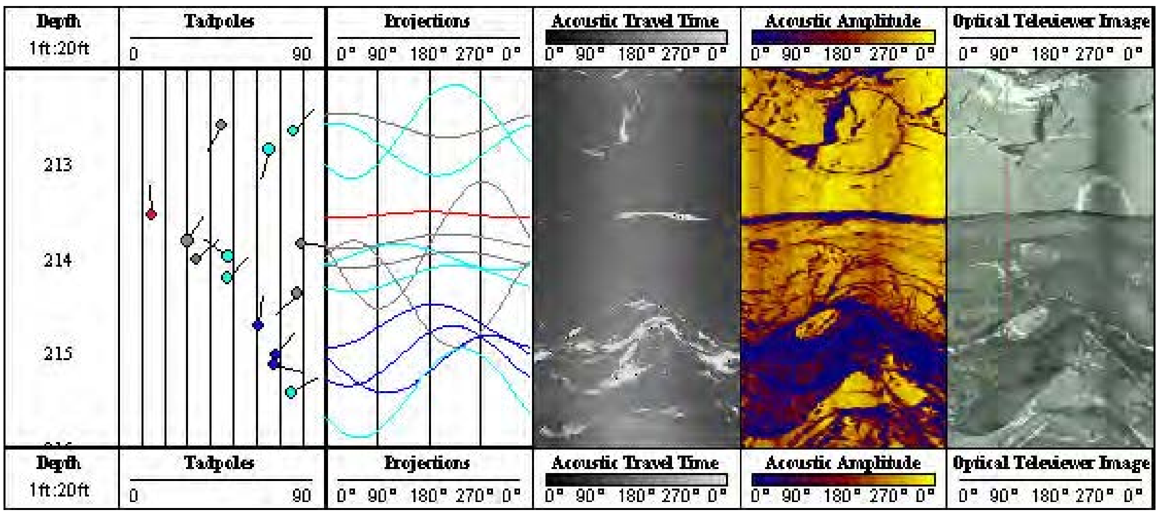


Figure: Example projections and tadpoles for corresponding optical and acoustic televiewer data sets.

The WellCAD software calculates the true feature orientation (dip direction and angle) in either deviated or vertical boreholes. Depths are assigned to the fractures or bedding features at the inflection points (middles) of the sinusoids. Features are subjectively ranked for flow potential using *COLOG's Ranking System for Optical Televiewer Features*, included in this report. The features picked, along with their assigned ranks, orientations and depths are exported and presented in tables for each well. Orientations are based on magnetic north and are not corrected for magnetic declination, unless specified.

From the feature data tables, stereonet plots and rose diagrams are generated, as necessary. Stereonet plots and rose diagrams provide useful information concerning the statistical distribution and possible patterns or trends that may exist from the optical and/or acoustic televiewer feature orientation data set.

Rose Diagrams

A rose diagram is a polar diagram in which radial length of the petals indicates the relative frequency (percentage) of observation of a particular angle or fracture dip direction or range of angles or dip directions. Rose diagrams are used to identify patterns (if any) in the frequency of dip angles or directions for a particular data set. The following rose diagrams and stereonet plots all come from the same data set to help illustrate the relationships between the plot types.

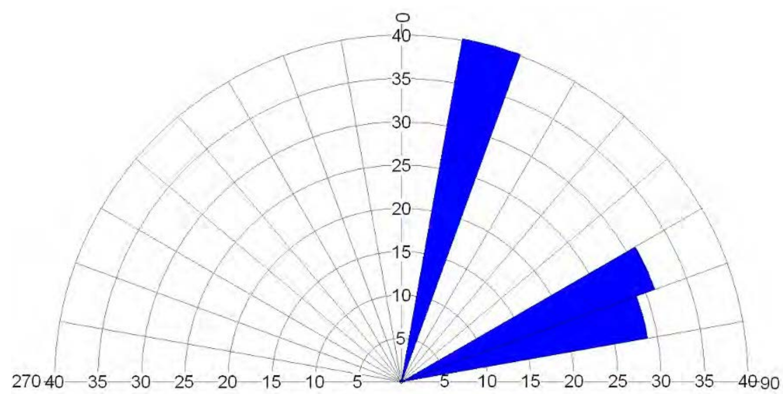


Figure: Example rose diagram from an optical televiewer data set illustrating the frequency (%) of dip angles.

With a quick glance at the above rose diagram of dip angle values, one can see two distinct sets of dip angles; one set with lower dip angles and one set with higher dip angles. Specifically, 40 percent of the features have a dip angle between 10^{o} and <20^{o}, and 60 percent of the features have a dip angle between 60^{o} and <80^{o}. The left-hand side of the above rose diagram will always be blank by convention of positive dip angle values only.

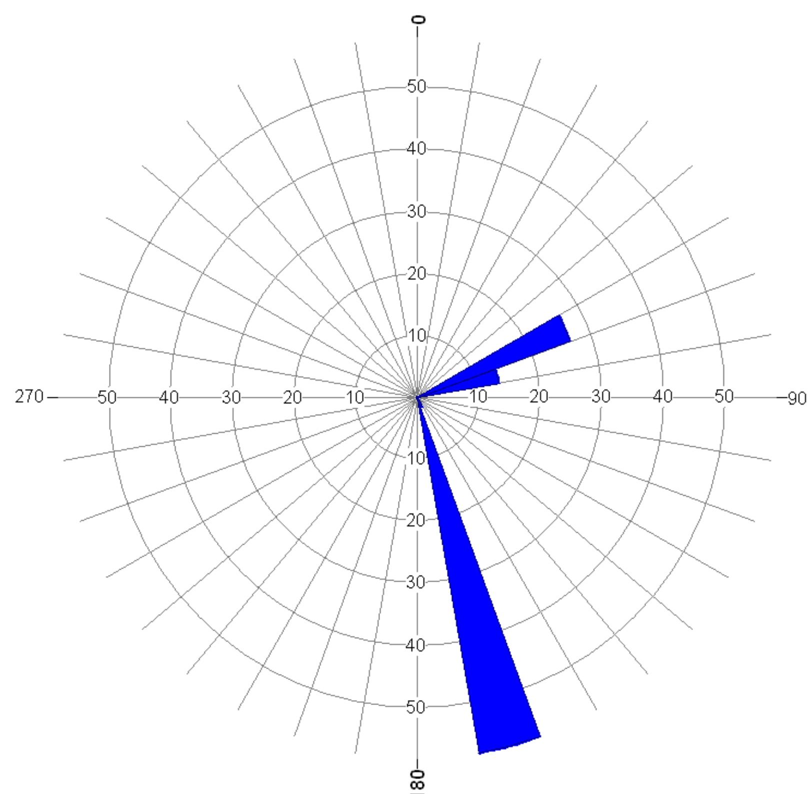


Figure: Example rose diagram from an optical televiewer data set illustrating the frequency (%) of dip direction (azimuth).

With a quick glance at the above rose diagram of dip direction values, one can see that the features (and/or fractures) in this data set have two primary dip directions. Specifically, 40 percent of the features dip to the east-northeast between 60^{o} degrees and <80^{o} in azimuth and 60 percent of the features dip to the south-southeast between 160^{o} and <170^{o} in azimuth.

Stereonets

For stereonets, Colog utilizes a southern-hemisphere projected, equal-area Schmidt net to plot the poles to the feature planes. These plots are often used in plotting geologic data such as the dips and orientations of structural features. Here, the azimuthal angle indicates dip direction of the plane's pole (which dips 180 degrees opposite in azimuth from the plane's dip direction at a complementary angle). The distance from the center indicates the dip magnitude. The further from the center the steeper the dip angle; the closer to the center the more horizontal the feature is.

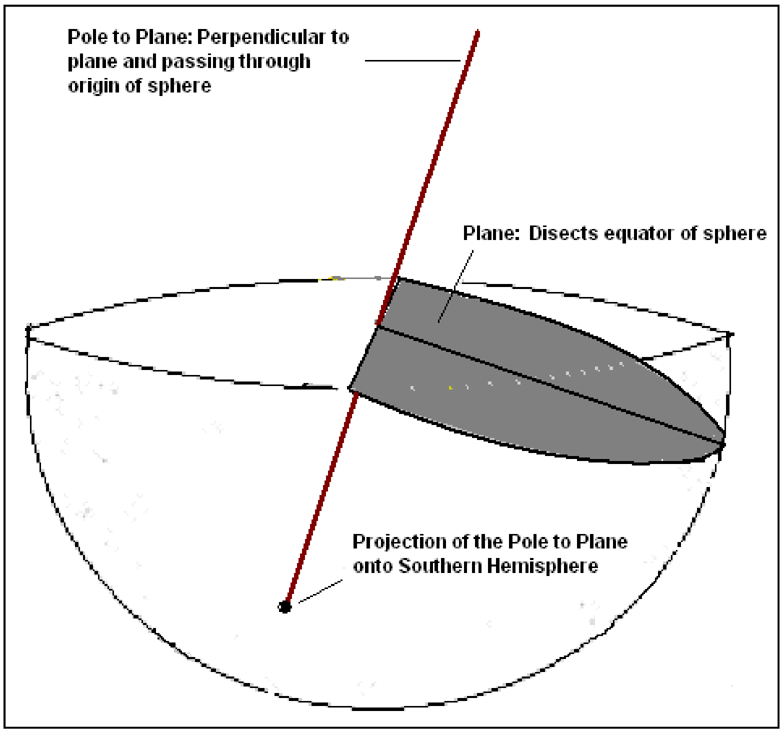


Figure: The above cartoon demonstrates the relationship between a plane and its pole, as projected onto the southern hemisphere of a sphere.

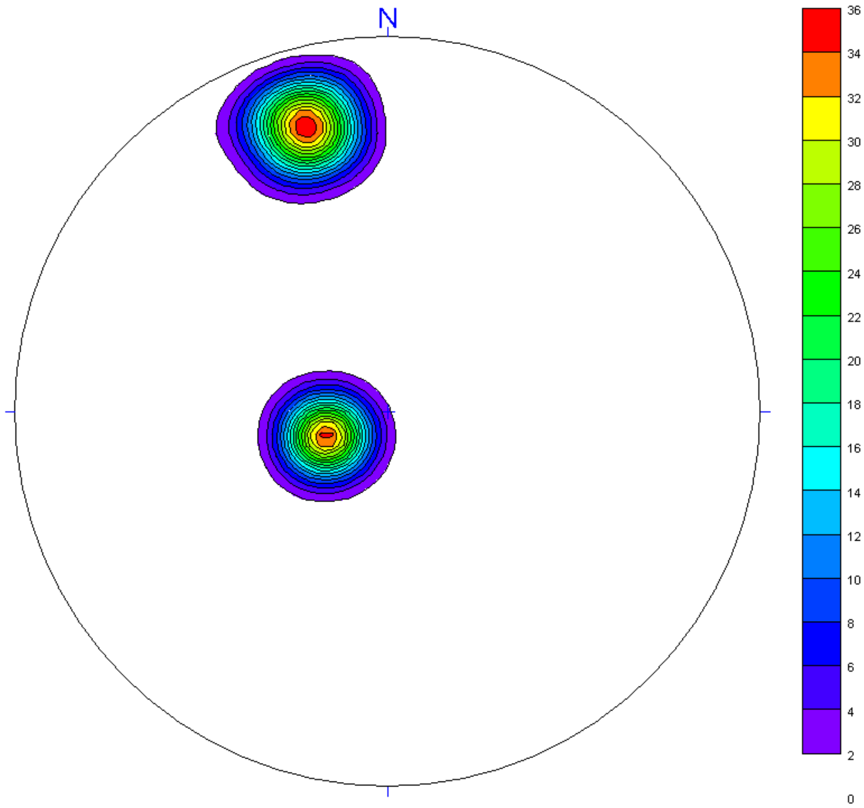
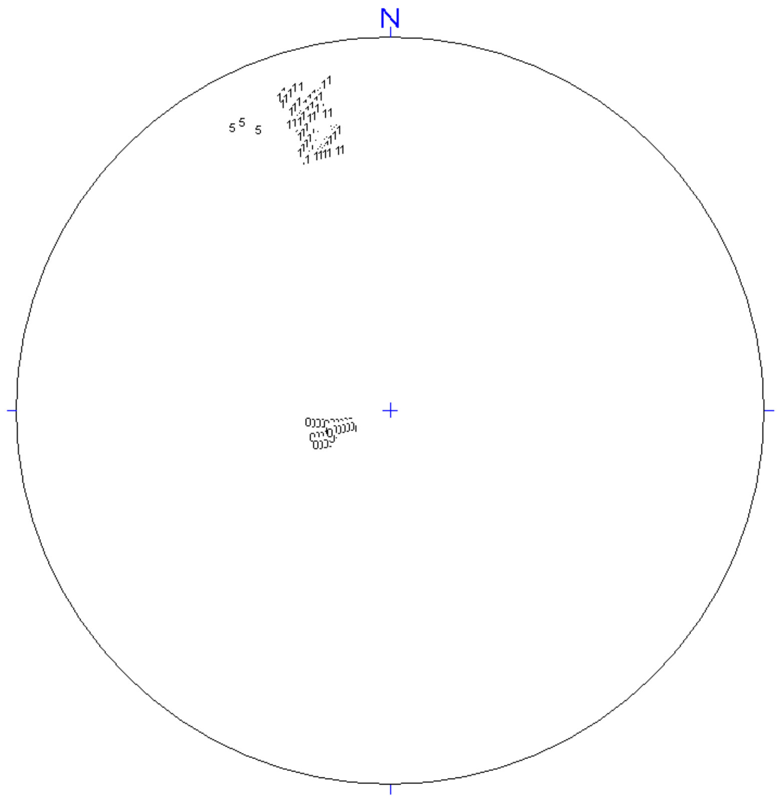


Figure: Example stereonet from an optical televiewer data set illustrating the frequency (%) of dip direction and dip angle.

The figure above is an example stereonet diagram from the same televiewer data set of fractures and features as used previously to describe rose diagrams. It was created by binning the density (frequency) of poles per area. The figure below indicates, with a quick glance, that two distinct patterns exist in the example data set. A cluster of fractures/features with similar dip directions of approximately 160-170 degrees with steep dip angles of around 60-80 degrees is apparent. A second cluster is apparent with similar dip directions of approximately 60-80 degrees with moderate dip angles of approximately 10-20 degrees. The white areas indicate low to zero density of poles.



Colog also often provides a Schmidt net with the qualitative rank of each fracture/feature plotted at the location of its planar pole. Please refer to the *Ranking System for Optical/Acoustic Televiewer Features,* included in the report, for an explanation of the qualitative ranks assigned each optical/acoustic televiewer feature identified.

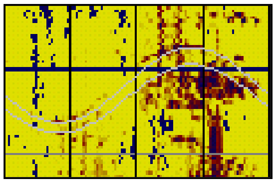
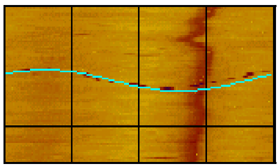
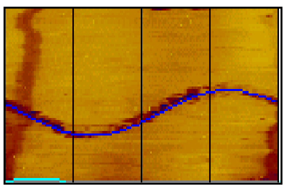
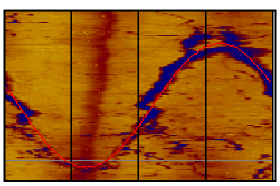
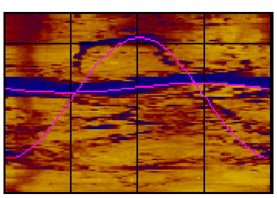
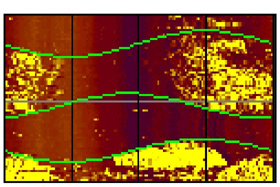
With a quick glance at the above Schmidt net, one can see that the low dip angle features which dip to the east-northeast are bedding features, ranked "0"; the high dip angle features dipping to the south-southeast are primarily weak or partial fractures, ranked "1"; and there are several major fracture zones, ranked "5", with strike/dip very similar to the majority of the partial/weak fractures in the well.

Ranking System for Optical Televiewer Features

	Rank	Color Code	Observation	Flow Rating System
	**0**	**Gray**	**Non-flow feature** **(bedding, healed fracture, staining, foliation, vein, etc.)**	**Sealed, no flow**
	**1**	**Cyan**	**Weak feature** **(not continuous around the borehole)**	**Partial open crack**
	**2**	**Blue**	**Clean, distinct feature**	**Continuous Open crack**
	**3**	**Red**	**Distinct feature with apparent aperture**	**Wide open crack Or cracks**
	**4**	**Magenta**	**Very distinct, wide possible interconnected fracture**	**Very wide crack or multiple interconnected fractures**
	**5**	**Green**	**Major fracture zone with large openings.**	**Major fracture with large openings or breakouts**

This ranking system is based on a system developed and applied by Paillet (USGS, WRD, Borehole Research Project) as a subjective evaluation of permeability potential. In general, the higher the rank, the greater the likelihood of fracture interconnection and subsequent increased permeability. Tadpoles represent individual features, where the tail points in the direction of dip (clockwise from the top, 0-359). The head is positioned vertically according to the median depth of the feature and positioned horizontally according to the feature dip angle (0-90 from horizontal).

Ranking System for Acoustic Televiewer Features

	Rank	Color Code	Observation	Flow Rating System
	0	Gray	Non-flow feature (bedding, healed fracture, vein, etc.)	Sealed, no flow
	1	Cyan	Weak feature (not continuous around the borehole)	Partial open crack
	2	Blue	Clean, distinct feature	Continuous Open crack
	3	Red	Distinct feature with apparent aperture (visible on travel-time image)	Wide open crack Or cracks
	4	Magenta	Very distinct, wide possible interconnected fracture	Very wide crack or multiple interconnected fractures
	5	Green	Major fracture zone, visible on both the amplitude and travel time images	Major fracture with large openings or breakouts

This ranking system is based on a system developed and applied by Paillet (USGS, WRD, Borehole Research Project) as a subjective evaluation of permeability potential. In general, the higher the rank, the greater the likelihood of fracture interconnection and subsequent increased permeability.

1-Arm and 3-Arm Caliper

The caliper log represents the average borehole diameter determined by the extension of 1 or 3 spring-loaded arms. The measurement of the borehole diameter is determined by the change in the variable pot resistors in the probe, which are internally connected to the caliper arms.

Caliper logs may show diameter increases in cavities and, depending on drilling techniques used, in weathered zones. An apparent decrease in borehole diameter may result from mud or drill-cutting accumulation along the sides of the borehole (mudcake), a swelled clay horizon or a planned change in drill bit size. The bottom of the boring can also induce a small diameter reading from the caliper due to the caliper leaning up against on side of the borehole. The caliper log is often a useful indicator of fracturing. The log anomalies do not directly represent the true in-situ fracture size or geometry. Rather, they represent areas of borehole wall breakage associated with the mechanical weakening at the borehole-fracture intersection. Caliper anomalies may represent fractures, bedding planes, lithologic changes or solution openings. Generally, in solid bedrock, caliper log anomalies indicate the intervals where fractures intersect boreholes.

Colog records the caliper log with either a single-arm caliper measurement using the decentralization arm of the density probe or a separate stand-alone three-arm caliper. Calibrations of the probe are done routinely on the bench and in the field directly before the tool is placed into the borehole. Calibration standards consist of rings of known diameters that are placed over the extended arms as the tool response at these diameters is recorded. Additionally, as with other geophysical measurements, a repeat section may be collected and compared with the original logs for consistency and accuracy.

Fundamental assumptions and limitations inherent in these procedures are as follows:

- Excessive borehole diameters (greater than 36 inches) may limit the range of borehole caliper measurements. Holes greater than 12 inches must be logged with extended arms for hole diameters up to 36 inches.

Since the caliper probe is an electro-mechanical device, a certain amount of error is inherent in the measurement. These errors are due to: 1) averaging hole diameter using three arms, 2) non-linearity of the measurement resistor, 3) tolerance in the mechanical movement of the caliper arms (mechanical hysteresis).

Wireline Straddle-Packer Methodology

Introduction

This Standard Operating Procedure (SOP) addresses particular activities associated with conducting oversight during operation of inflatable packers. The primary purpose of inflatable packers (packers) is to isolate a zone or interval of interest in a well or open borehole. The use of a packer is one of several methods used for this purpose. Other methods include the use of rubber drawdown seals, temporary bentonite seals placed above and below a perforated section of well casing or drill pipe, or the use of flow control (i.e., low-flow), to name a few. All of these methods may be considered a form of environmental profiling. With any of these methods, the objective is to isolate a particular zone of interest and to prevent hydraulic bypass in to, or out from, that interval. Packers may be used to obtain water samples for chemical analysis or hydraulic information. Testing zones are typically identified through the use of core samples (e.g., through identification of porous lithologies or fractures, drilling characteristics;

rate of penetration or loss of drilling fluid, geophysical logging; temperature, conductivity, flowmeter, or sonic logging), optical borehole imaging, and/or environmental sampling and analysis.

Packer Design

The packers are operated by a qualified subcontractor that understands the requirements and limitations of the packer assembly. A user's manual from the manufacturer should be provided with the packer assembly. The packer assembly may include the following major components:

- Eductor pipe (i.e., a drop pipe containing an airlift line) or Conductor pipe (i.e., a drop pipe to which a pump is directly connected and through which water is discharged)
- Inflatable packers which may be suspended on either a drop pipe or a wireline
- Centralizers to keep the packer assembly centered, especially in angled boreholes
- Supply lines to inflate the packers with inert gas (e.g., nitrogen) or fluid (e.g., water)
- Transfer tubes and ports for monitoring hydraulic pressure
- Ports for pressure transducers
- Calibration certified pressure transducers
- Pressure transducer cables that may be either vented (for barometric equilibration) or non- vented to read absolute pressure
- Submersible pump
- Centrifugal pump and water tank
- Pressure tank (nitrogen or argon) with tested and certified regulator, gauges and manifold

As a general rule, the designer and builder should work to minimize material types, diameter changes, and bends to simplify installation and to reduce frictional losses during testing.

The hydrostatic pressure of the packer test interval is dependent on the packer configuration and depth of submergence. For a single packer configuration, the hydrostatic pressure of the packer interval is represented by the pressure below the top packer. For a dual packer configuration, the hydrostatic pressure of the packer interval is represented by the interval between the packers.

Through custom design a dual packer configuration can be made modular, allowing for independent packer inflation. The advantage of a modular or independent packer configuration allows the user to switch between single or dual packer configurations. The primary advantage of this custom feature is that it enables test methodology to respond real-time to observed aquifer conditions. Packer configurations are discussed in more detail below.

Single Packer

The single packer configuration involves use of a single packer to test the underlying interval of open borehole. This configuration can be used to test relatively large borehole intervals, up to several hundred feet to determine the sensitivity of the formation to hydraulic stresses applied during the test. Based on these results the length of the test interval can be optimized to obtain valid results in a reasonable time frame. In the absence of supporting data (e.g., hydrophysical surveys) one approach is to conduct a single packer test in the entire borehole, then the bottom 2/3 of the borehole, and then the bottom 1/3 of the borehole. Ideally, test intervals can be established based on borehole specific information thereby developing a logical correlation between observed features (e.g., lithology, fractures, or flow zones) and test results representative of the test interval.

Dual Packer

The dual packer, or straddle packer, testing is used to test relatively small (i.e., several tens of feet) intervals of the borehole. In this configuration, the packer interval is represented by the portion of the borehole that is between the bottom and top packer. These tests target specific zones identified by supporting data (e.g., hydrophysical surveys). The number of zones selected for testing may be based on formation characteristics (e.g., the number of discrete flow zones identified by hydrophysical surveys and the hydraulic conductivity of these zones), but may also be constrained by the project scope including the number of boreholes to be tested and the overall project schedule and budget.

Inflation Principles

An individual packer is typically one to five feet long and is constructed with a high density rubber membrane. However, custom design and construction is not uncommon, and therefore membrane length and type can vary depending on specific applications and borehole chemistry. The membrane is inflated with air or fluid, depending on the submerged depth, to create a seal along the borehole wall. Inert compressed gas is recommended for relatively low inflation pressures; however, water is recommended for inflation pressures greater than 500 psi. The minimum inflation pressure of a packer is the sum of the hydrostatic pressure, stretch pressure of the packer, and seating pressure of the packer as follows:

- inflation pressure = hydrostatic + stretch + seating
- hydrostatic pressure = depth * density of water
- stretch pressure = manufacturer constant
- seating pressure = manufacturer constant * differential pressure
- differential pressure = hydrostatic pressure of packer interval - hydrostatic pressure above top packer

Since the inflation pressure is calculated prior to the packer test, the differential pressure is an estimate of the expected hydrostatic pressure of the packer interval. This may be logistically difficult to estimate depending on the type of test. Another approach is to calculate a multiplier based from the maximum allowable differential pressure.

Pressure Transducer Installations

The proper function of the packer assembly is to isolate an interval of interest. Pressure transducers (transducers) are used to verify that the packer assembly is functioning properly and to monitor the response of the formation to an applied stress.

During hydraulic testing, a transducer is installed within the test interval to record the hydraulic head (i.e., pressure) within the test interval. Thus the transducer will record pre-test static pressures, the magnitude and duration of any applied stress (e.g., resulting from the addition or withdrawal of water), and the response over time to the formation of the applied stress. Transducer data are then used to analyze the hydraulic properties of the test interval.

During groundwater sampling or hydraulic testing, one or two transducer(s) may also be installed outside of the test interval to monitor and verify that water bypass around the top and/or bottom packer is not occurring. Ideally, the data from these transducers should remain uniform before, during, and after the pressure test or sampling event. If a change in head is noted, the magnitude of the change should be evaluated to determine the cause and significance, which could indicate packer under inflation, insufficient packer seal, or bypass through the formation.

The maximum submergence allowed for a transducer is a function of the pressure rating. A pressure transducer with a rating of 6 pounds per square inch (psi) can be submerged no more than 13.86 feet below groundwater, based on the conversion 2.31 feet/psi. For deep applications the transducer ratings may be in units of Pascal (Pa) or Kilopascal (kPa), in which 6.8947 kPa is equal to 1 psi.

The transducer cables also need to be considered during pressure measurements. The transducer cable may be vented or non-vented. A vented cable is “open” to atmospheric pressure, and therefore, is not sensitive to barometric pressure. A non-vented cable allows a pressure transducer to measure all the pressure it is under, both water pressure (hydraulic head) and atmospheric pressure. If a non-vented cable is used, barometric changes will need to be subtracted from the data during post-processing. The barometric changes can be recorded with a separate transducer placed at the ground surface and operated on the same schedule as the subsurface transducers. If the sampling or testing is being conducted near a metropolitan area, a local airport may have a weather station that collects barometric pressure measurements on a regular interval.

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RC-02: Geophysical & Hydrophysical Logging Results

Overview

The hydrophysical logging performed in RC-02 consisted of fluid electrical conductivity (FEC) and temperature logs in a static condition in the wellbore and hydrophysical flow characterization under ambient and pumping conditions. The geophysical logs performed in RC-02 were: optical televiewer (OBI), acoustic televiewer (ABI), and three-arm caliper. At the conclusion of the hydrophysical and geophysical logging, the data was reviewed in the field and intervals were picked for permeability testing and sampling using the Wireline Straddle Packer (WSP) assembly. The data was collected in an approximately 5.5-inch open borehole with 6-inch steel surface casing installed to approximately the bedrock interface. Water-bearing flow zones were indicated during ambient and stressed hydrophysical testing that correlate well with the geophysical log anomalies. The data for the hydrophysical results are presented in Figures RC-02:1, 2, 3, 4A, 4B, Table RC-02:1. The Optical and Acoustic Televiewer data as well as the caliper data are presented in the RC-02 Optical and Acoustic Image Plots. The fracture orientation data, Stereonet and Rose plots derived from the televiewer data are presented in Figures RC-02:5-8 and Table RC-02:2. The wireline straddle packer test results are presented in Figures RC-02:9A through D and Table RC-02:3 as well as the AQTESOLV results in Figures RC-02:10A through D. All of the data results for RC-02 are presented in Appendix A.

Summary of Major Water-Bearing Zones During Hydrophysical Testing: RC-02

Individual Water-Bearing Zones				Wellbore Properties			
Major Water-Bearing Zones (feet)	Ambient Flow Rate (gpm)	Pumping Flow Rate (gpm)	Transport Mechanism	Ambient Depth to Water (ftbgs)	Formation Production Rate (gpm)	Observed Drawdown (feet)	Wellbore Specific Capacity (gpm/ft-dd)
131.4 – 142.2	0.0042	2.02	fractures & vesicles	57.18	10.39	23.21	0.45
152.2 – 155.9	0.0004	2.52	fracture network				
176.9 – 193.1	-0.0070	4.88	fractures				

Hydrophysical Logging

Ambient Fluid Electrical Conductivity and Temperature Log

At 07:07 hours on April 27th, 2019, after a calibration check of the fluid electrical conductivity (FEC) and temperature logging tool, the fluid column was logged for FEC and temperature profiles with COLOG's 1.5-inch diameter HpL probe. These logs were performed prior to the installation of any pumping equipment. Please refer to Figure RC-02:1. The ambient FEC profile is relatively featureless with a minor anomaly at 176 feet, which correlates with an outflow zone identified during the Ambient Flow Characterization discussed in the next section. The ambient FEC profile registers a nominal 515 µS/cm above 176 feet and a nominal 535 µS/cm below 176 feet. The ambient temperature profile is also relatively featureless, registering a minor increase in temperature with depth. The temperature log registers a minimum temperature of 10.64 degrees C at the base of casing at 123.1 feet and a maximum temperature of 12.56 degrees C at 220 feet near the bottom of the borehole.

Ambient Flow Characterization

On April 27th, 2019, an ambient flow characterization (AFC) was conducted in boring RC-02. For ambient flow assessment, the formation water in the borehole was replaced with de-ionized (DI) water and the boring left in an undisturbed state to allow any natural flow to occur. Prior to this period and throughout all HpL testing, water levels were monitored and recorded digitally every second. Ambient flow evaluation is reported for the period after the water surface returned to near pre-emplacement levels. A series of FEC and temperature logs were then conducted to identify changes in the fluid column associated with ambient flow. Ambient flow characterization is conducted to evaluate the presence of both vertical and horizontal ambient flow.

On April 27th, 2019, at 08:50 hours (t = 0 minutes, elapsed time of test), dilution of the fluid column was complete. During the 22.3 hours following the emplacement of DI water, multiple FEC logs were conducted. Of those logs, four are presented in Figure RC-02:2. The designation of each logging with the FEC tool is indicated in the figure legend by the time of logging (e.g., FEC0842 versus a subsequent logging at FEC1455), thus the progressing of curves to the right in this figure represents changes in FEC over the total logging period. The last four digits of each log ID correspond to the time at which that particular log was started. Only logs acquired during logging in the downward direction are presented as the design of the FEC/Temperature probe allows the most accurate data to be collected in the downward direction. The logs acquired in the upward logging direction are not representative of downhole conditions and are therefore omitted. These logs illustrate a change in FEC in the upper portion of the wellbore. These changes in the FEC profiles with respect to time are associated with ambient vertical flow occurring within the wellbore.

Formation water migration as a result of downward vertical flow through the fluid column is indicated by the increase in FEC over time at 123.1 to 124.0, 131.4 to 142.2 and 152.2 to 155.9 feet. Numerical modeling of the reported field data using code BOREII indicates these intervals contribute water to the wellbore at rates of 0.0024, 0.0042 and 0.0004 gpm, respectively. The modeling indicates the ambient inflow from this interval migrates down the borehole and exits as outflow at 176.9 - 193.1 feet, at -0.0070 gpm. This flow rate is based on the rate of increase of mass at these depths and migration of the center of mass of the area under the curves. Static Water Level (SWL) at the time of testing was recorded at 57.18 ftbgs.

Flow Characterization During 10 GPM Production Test

Pumping of borehole fluids and simultaneous DI injection was conducted at one pumping rate to establish the inflow locations and evaluate the interval-specific inflow rates during production testing. Development pumping at a given rate was conducted until reasonably constant drawdown and repeatable FEC logs downhole were observed. When these conditions were observed, DI injection was initiated at the bottom of the borehole at approximately 20% of the pumping rate while the extraction pumping rate was increased the same amount to maintain a constant total formation production rate (i.e. pumping rate prior to DI water injection). These procedures were conducted at a differential rate of 10.39 gpm.

On April 29, 2019 at 07:57 hours (t = 0 minutes elapsed time of testing), development pumping was initiated at approximately 10 gpm. Prior to initiating pumping, the ambient depth to water was recorded at 57.18 ftbgs. All drawdown values are referenced to this ambient water level. Time dependent depth to water, totals and flow rate information were recorded digitally every second and are presented in Figure RC-02:3. Pumping was maintained at a time-averaged rate of 9.88 gpm until 11:16 hours (t = 199 minutes, elapsed time of testing). During development pumping numerous FEC logs were acquired to monitor the development process and assist in identifying the depths of flow zones. Of these FEC logs, five (FEC0954, FEC1000, FEC1005, FEC1011 and FEC1018) are presented in Figure RC-02:4A. The FEC logs acquired during development pumping illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases or decreases in FEC. DI water injection from the bottom of the wellbore was initiated at 11:16 hours at a time-averaged rate of 0.93 gpm while the total extraction rate was increased to a time-averaged rate of 11.32 gpm, resulting in a total borehole formation time-averaged production rate of 10.39 gpm. These flow conditions were maintained until 12:36 hours (t = 278 minutes) during which time a relatively constant drawdown of approximately 23.21 feet was observed. The FEC logs acquired during dilution procedures illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases in FEC. Ten inflow intervals were identified from these logs with flow rates ranging from 0.009 to 4.88 gpm. The logs indicate the intervals 131.4 to 142.2, 152.2 to 155.9 and 176.9 to 193.1 feet dominated inflow during pumping, producing 2.02, 2.52 and 4.88 gpm, respectively, or 90.6 percent of the total inflow. Please refer to Table RC-02:1 for a summary of hydrophysical flow results and the depths of individual inflow zones.

At the conclusion of the dilution process, the DI water injection was shut off and the extraction pumping maintained at approximately 11.32 gpm, to try to induce additional drawdown and potentially identify any additional inflow zones not apparent during the dilution process. The presence of a highly diluted state in the lower portion of the borehole without the presence of DI water migrating up the borehole makes an ideal condition to identify very low-flow inflow zones. FEC logs were acquired during this re-development process and are presented in Figure RC-02:4B. This test, however, did not show any evidence of any additional inflow zones not already identified from logs presented in Figure RC-02:4A.

Estimation of Interval Specific Transmissivity

An estimation of transmissivity (T) can be made using an equation after Thiem (1906) assuming steady-state radial flow in a confined aquifer:

$$T = KL = \frac{q_i}{2\pi\Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL results, r_w is the wellbore radius (0.23 ft), r_e is the effective pumping radius, Δh_w is the observed maximum drawdown (23.21 feet) and L is the thickness of the zone through which flow occurs. For our calculations, COLOG used r_e of 100 feet (assumed). By applying L and q_i from the HpL results under the two pressure conditions, the interval-specific transmissivity can be calculated for each identified water-producing interval. These calculations were made at each identified interval and are presented in Table RC-02:1. In summary, the previously identified inflow zones during production testing at 131.4 to 142.2, 152.2 to 155.9 and 176.9 to 193.1 feet exhibited the highest transmissivities of approximately 16.2, 20.2 and 39.2 ft^2/day.

Geophysical Logging

Optical Televiewer (OBI) and Acoustic Televiewer (ABI)

On April 26, 2019, optical televiewer (OBI) and acoustic televiewer (ABI) logging was performed in RC-02. The OBI was logged from 56.4 feet to a depth of 225.0 feet and the ABI was logged from 121.3 feet to a depth of 225.0 feet. Fracture density and fracture orientation were evaluated over the entire OBI and ABI datasets.

The majority of the features identified in RC-02 were complete or open fractures, indicating potential for flow zones from within the borehole. The rose diagrams displayed in Appendix A indicate the majority of the fractures, approximately 19% of the features, dip less than 50° from horizontal and an additional 19% of features dip less than 70° from horizontal. The rose diagrams indicates approximately 22% of the identified features in RC-02 dip in the relatively dominant direction of 0° to 40° (Northeast). In borehole RC-02, 83 high-angle fractures or features (dip angles greater than 45°) were identified. Of these 83 high-angle features, 38 features are qualitatively ranked 2 to 4, suggesting possible flow potential from these features. The remaining high-angle features are qualitatively ranked 1 or 0, indicating minimal to no flow potential from these features.

Three-Arm Caliper

On April 26, 2019, three-arm caliper logging was performed in RC-02 to a depth of 225.4 feet and registered the bottom of casing (BOC) at 123.1feet, correlating well with the OBI and ABI images. Diameter inflections in the open borehole correlate well with features qualitatively ranked 2 or greater on the OBI and ABI logs, suggesting they are either fractures with aperture or a borehole enlargement due to washout of the borehole. The caliper log registers sixteen significant anomalies at: 176.9, 178.5 to 179.4, 181.5 to 183.0, 186.0 to 186.7, 188.8, 194.1, 197.3, 203.5, 206.6, 209.7 to 210.4, 212.1, 213.3, 215.2, 220.2, 220.9, and 222.8 feet, that register maximum enlargements between approximately 5.91 to 7.24 inches. Please refer to the Optical Televiewer and Acoustic Televiewer Plot. The caliper registered a nominal 5.8-inch diameter borehole.

Wireline Straddle Packer Testing

Discussion

On May 21st through 22nd and May 24th through 25th, 2019, wireline straddle packer (WSP) testing and sampling was conducted in RC-02 at four intervals:

142.0 feet to WL
145.5 to 156.0 feet
156.0 to 225.0 (TD) feet
192.0 to 225.0 (TD) feet

WSP testing was conducted to acquire an interval-specific groundwater sample from fracture/inflow zones identified during hydrophysical and geophysical logging investigations. In addition to collecting a representative groundwater sample from each interval, development pumping was conducted whenever possible to purge as much water from the sample interval as reasonably possible. During pumping and sampling, pressures in the zone of interest, above and below the zone of interest were recorded to monitor the pumping process and provide information on the relative fracture-interconnectiveness between intervals. For the standard configuration of the WSP assembly, one interval volume is assumed to be approximately 24 gallons with standard plumbing and equipment in the borehole. Discussion of contaminant concentrations derived from the sampling results is not part of the scope of Colog's involvement.

WSP testing was also conducted to estimate permeability within the packer intervals chosen. Extraction pump tests were conducted at the intervals believed to be potentially water-bearing with pressures within the interval of interest and surrounding the interval of interest recorded to estimate fracture-specific or interval-specific permeability for each interval tested using the Thiem equation method and/or the Theis Recovery method using the program AQTESOLV (Duffield, G.M., 2007. AQTESOLV for Windows Version 4.5 User's Guide, HydroSOLVE, Inc., Reston, VA.). Figures RC-02:9A through D and Table RC-02:3 located in Appendix A show a complete summary of the pressures wireline straddle packer sampling, and Figures RC-02:10A through D for the permeability estimations derived from AQTESOLV. SWL in RC-02 prior to testing was recorded at 57.07 ftbgs. All depths herein are referenced to ground surface unless otherwise noted.

Zone Specific Results:

Interval 142.0 feet to WL – On May 21st, 2019 the WSP was utilized in a modified configuration with only the upper packer inflated. This makes the upper pressure transducer the zone transducer and the lower transducer reading pressure below the zone of interest. The interval was pumped at approximately 2.85 gpm resulting in a differential pressure of approximately 9.64 psi (Figure RC-02:9A). The data does show a minor response in the lower transducer indicating that a hydraulic connection with the interval below is present, however, based on the significant drawdown observed in the interval, this hydraulic connection between intervals can be assumed to be relatively small. The estimated transmissivity is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 23.8 $feet^2$/day. Utilizing the AQTESOLV program and the Theis solution, the transmissivity of this interval is estimated to be approximately 23.2 $feet^2$/day, illustrating good correlation with the Thiem equation result.

Low-flow sampling was conducted at approximately 07:22 hours on May 21 after the interval was pumped overnight at a rate of approximately 0.28 gpm (approximately 251 gallons pumped). At 07:22 hours the pump rate was reduced to approximately 0.065 gpm and groundwater samples were collected. Please refer to Table RC-02:3 for a complete summary of the WSP data acquired and permeability results for this interval.

Interval 145.5 – 156.0 feet – On May 24th, 2019 the WSP was utilized in its standard configuration, both packers inflated, and all pressure transducers measuring pressure in their respective zones of interest. Low-rate pumping for sampling was initiated at 12:16 hours at a rate of 0.23 gpm. At approximately 14:44 hours, after 148 minutes of pumping, the pumping rate was reduced to approximately 0.065 gpm to acquired groundwater samples. During the 148 minutes of pumping prior to sampling, approximately 34 gallons was pumped from the interval.

At 15:26 hours on May 24th, 2019, the extraction rate was increased to approximately 1.07 gpm for stress testing. The interval was pumped at approximately 1.07 gpm for 44 minutes resulting in a differential pressure of approximately 4.24 psi (Figure RC-02:9B). The data does show a minor response in both the lower and upper transducers indicating that a hydraulic connection with the intervals below and above the test interval are present, however, based on the amount of drawdown observed in the interval, this hydraulic connection between intervals can be assumed to be relatively small, though clearly present. The estimated transmissivity of the interval is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 20.3 $feet^2$/day. Utilizing the AQTESOLV program and the Theis solution, the transmissivity of this interval is estimated to be approximately 20.5 $feet^2$/day, illustrating good correlation with the Thiem equation result. Please refer to Table RC-02:3 for a complete summary of the WSP data acquired and permeability results for this interval.

RC-03: Geophysical & Hydrophysical Logging Results

Overview

The hydrophysical logging performed in RC-03 consisted of fluid electrical conductivity (FEC) and temperature logs in a static condition in the wellbore and hydrophysical flow characterization under ambient and pumping conditions. The geophysical logs performed in RC-03 were: optical televiewer (OBI), acoustic televiewer (ABI), and three-arm caliper. The data was collected through 6-inch diameter casing, within an approximately 5.5-inch open borehole. Water-bearing flow zones were indicated during ambient and stressed Hydrophysical testing that correlate well with some of the geophysical log anomalies. The data for these and all of the logs acquired are presented in the RC-03 Optical and Acoustic Image Plots, Stereonets, Rose Diagrams and Fracture Table, and the hydrophysical results Figures RC-03:1, 2, 3, 4A, 4B and Table RC-03:1, located in Appendix B.

Summary Table of Hydrophysical and Geophysical Logging Results: RC-03

Individual Water-Bearing Zones				Wellbore Properties			
Major Water-Bearing Zones (feet)	Ambient Flow Rate (gpm)	Pumping Flow Rate (gpm)	Transport Mechanism	Ambient Depth to Water (ftbgs)	Pumping Rate (gpm)	Observed Drawdown (feet)	Wellbore Specific Capacity (gpm/ft-dd)
125.3 – 138.8	0.011	10.33	fractures	113.16	13.43	3.41	3.94
144.2 – 152.8	0.000	1.36	fractures & solution openings				

Hydrophysical Logging

Ambient Fluid Electrical Conductivity and Temperature Log

At 11:09 hours on May 14th, 2019, after a calibration check of the fluid electrical conductivity (FEC) and temperature logging tool, the fluid column was logged for FEC and temperature profiles with COLOG's 1.5-inch diameter HpL probe. These logs were performed prior to the installation of any pumping equipment. Please refer to Figure RC-03:1. The ambient FEC profile registers a minor conductivity anomaly at 115 feet and 125 feet. Below 125 feet the FEC profile remains relatively featureless to TD (196.5 feet). These conductivity anomalies correlate well with inflow zones identified during Hydrophysical Ambient Flow Characterization. The ambient FEC profile registers a maximum conductivity of 409 µS/cm just below water level, and minimum conductivity of 357 µS/cm at 124 feet – just above the conductivity anomaly at 125 feet. The ambient temperature profile registers an increasing temperature in the borehole fluids with depth, with two temperature log anomalies, or changes in the slope of the temperature, where water may be entering or exiting the borehole under ambient conditions. The two temperature anomalies are observed at approximately 130 feet and 172 feet. These changes in the ambient temperature profile correlate well with water-bearing zones identified during Hydrophysical Ambient Flow Characterization and production flow testing. The ambient temperature profile registers a maximum temperature of 12.50 degrees C at TD and a minimum temperature of 9.17 degrees C at water level.

Ambient Flow Characterization

On May 14th, 2019, an ambient flow characterization (AFC) was conducted in boring RC-03. For ambient flow assessment, the formation water in the borehole was replaced with de-ionized (DI) water and the boring left in an undisturbed state to allow any natural flow to occur. Prior to this period and throughout all HpL testing, water levels were monitored and recorded digitally every second. Ambient flow evaluation is reported for the period after the water surface returned to near pre-emplacement levels. A series of FEC and temperature logs were then conducted to identify changes in the fluid column associated with ambient flow. Ambient flow characterization is conducted to evaluate the presence of both vertical and horizontal ambient flow.

On May 14th, 2019, at 15:13 hours (t = 0 minutes, elapsed time of test), dilution of the fluid column was complete. During the 16.2 hours following the emplacement of DI water, multiple FEC logs were conducted. Of those logs, six FEC logs are presented in Figure RC-03:2 with the last log, FEC0723 occurring the following morning after the borehole sat undisturbed overnight. The designation of each logging with the FEC tool is indicated in the figure legend by the time of logging (e.g., FEC1518 versus a subsequent logging at FEC1622), thus the progressing of curves to the right in this figure represents changes in FEC over the total logging period. The last four digits of each log ID correspond to the time at which that particular log was started. Only logs acquired during logging in the downward direction are presented as the design of the FEC/Temperature probe allows the most accurate data to be collected in the downward direction. The logs acquired in the upward logging direction are not representative of downhole conditions and are therefore omitted. These logs illustrate change in FEC in two distinct portions of the wellbore. These changes in the FEC profile with respect to time are associated with ambient vertical flow occurring within the borehole.

Formation water migration as a result of downward vertical flow through the fluid column is indicated by the increase in FEC over time in the upper portion of the borehole from approximately water level to approximately 140 feet. Numerical modeling of the reported field data using code BOREII indicates groundwater is entering the borehole at 113.1 (WL) to 118.9 feet and 125.3 to 138.8 feet, at rates of 0.004 and 0.011 gpm, respectively. The modeling indicates the ambient inflow from this interval migrates down the borehole and exits as outflow at 160.0 to 168.4 feet. Additional vertical flow is observed to enter the borehole at 194.1 to 196.5 feet (TD) at a rate of 0.070 gpm, and migrate upward. This ambient upflow is observed to exit the borehole at the same outflow interval described above at 160.0 to 168.4 feet. These flow rates described above based on the rate of increase of mass at the depth intervals and the migration of the center of mass of the area under the curves. The ambient depth to water at the time of testing was 113.16 feet below ground surface (ftbgs).

Flow Characterization During 13 GPM Production Test

Pumping of borehole fluids and simultaneous DI injection was conducted at one pumping rate to establish the inflow locations and evaluate the interval-specific inflow rates during production testing. Development pumping at a given rate was conducted until reasonably constant drawdown and repeatable FEC logs downhole were observed. When these conditions were observed, DI injection was initiated at the bottom of the borehole at approximately 20% of the pumping rate while the extraction pumping rate was increased the same amount to maintain a constant total formation production rate (i.e. pumping rate prior to DI water injection). These procedures were conducted at a differential rate of 13.42 gpm.

On May 15th, 2019 at 09:15 hours (t = 0 minutes elapsed time of testing), development pumping was initiated at approximately 12.5 gpm. Prior to initiating pumping, the ambient depth to water was recorded at 113.16 ftbgs. All drawdown values are referenced to this ambient water level.

Time dependent depth to water, totals and flow rate information were recorded digitally every second and are presented in Figure RC-03:3. Pumping was maintained at a time-averaged rate of 12.50 gpm until 13:41 hours (t = 266 minutes, elapsed time of testing). During development pumping numerous FEC logs were acquired to monitor the development process and assist in identifying the depths of flow zones. Of these FEC logs, four (FEC1305 through FEC1332) are presented in Figure RC-03:4A. The FEC logs acquired during development pumping illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases or decreases in FEC. DI water injection from the bottom of the wellbore was initiated at 13:41 hours at a time-averaged rate of 1.51 gpm while the total extraction rate was increased to a time-averaged rate of 14.93 gpm, resulting in a total borehole formation time-averaged production rate of 13.42 gpm. These flow conditions were maintained until 16:51 hours (t = 278 minutes) during which time a relatively constant, maximum drawdown of approximately 3.41 feet was observed. The FEC logs acquired during dilution procedures illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases in FEC. Seven inflow intervals were identified from these logs with flow rates ranging from 0.18 to 10.33 gpm. The logs indicate the interval 125.3 to 138.8 feet dominated inflow during pumping, producing 10.33 gpm, or 77 percent of the total inflow. Please refer to Table RC-03:1 for a summary of hydrophysical flow results and the depths of individual inflow zones.

At the conclusion of the dilution process, the DI water injection was shut off and the extraction pumping maintained at approximately 14.93 gpm, to try to induce additional drawdown and potentially identify any additional inflow zones not apparent during the dilution process. The presence of a highly diluted state in the lower portion of the borehole without the presence of DI water migrating up the borehole makes an ideal condition to identify very low-flow inflow zones. FEC logging was conducted during this re-development process and are presented in Figure RC-03:4B. This test, however, did not show any evidence of any additional inflow zones not already identified from logs presented in Figure RC-03:4A.

Estimation of Interval Specific Transmissivity

An estimation of transmissivity (T) can be made using an equation after Thiem (1906) assuming steady-state radial flow in a confined aquifer:

$$T = KL = \frac{q_i}{2\pi \Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL results, r_w is the wellbore radius (0.23 ft), r_e is the effective pumping radius, Δh_w is the observed maximum drawdown (3.41 feet) and L is the thickness of the zone through which flow occurs. For our calculations, COLOG used r_e of 100 feet (assumed). By applying L and q_i from the HpL results under the two pressure conditions, the interval-specific transmissivity can be calculated for each identified water producing interval. These calculations were made at each identified interval and are presented in Table RC-03:1. In summary, the previously identified inflow zone during production testing at 125.3 to 138.8 feet exhibited the highest transmissivity of approximately 564 ft^2/day.

Geophysical Logging

Optical Televiewer (OBI) and Acoustic Televiewer (ABI)

On April 25, 2019, optical televiewer (OBI) and acoustic televiewer (ABI) logging was performed in RC-03. The OBI was logged from 79.1 feet to a depth of 209.4 feet and the ABI was logged from 110.8 feet to a depth of 194.9 feet. Fracture density and fracture orientation were evaluated over the entire OBI and ABI datasets.

The majority of the features identified in RC-03 were partial, complete or open fractures, indicating potential for flow zones from within the borehole. The rose diagrams displayed in Appendix B indicate the majority of the fractures, approximately 21% of the features, dip less than 40° from horizontal and an additional 22% of features dip less than 60° from horizontal. The rose diagrams in Appendix B indicates the RC-03 OBI and ABI fracture data does not indicate the presence of a dominant dip direction, or trend, suggesting the fracture dip direction data set to be heterogeneous. In borehole RC-03, 106 high-angle fractures or features (dip angles greater than 45°) were identified. Of these 106 high-angle features, 37 features are qualitatively ranked 2 to 5, suggesting possible flow potential from these features. The remaining high-angle features are qualitatively ranked 1, indicating minimal flow potential from these features.

Three-Arm Caliper

On April 25, 2019, three-arm caliper logging was performed in RC-03 to a depth of 196.2 feet and registered the bottom of casing (BOC) at 83.6 feet, correlating well with the OBI image identifying the bottom of casing.

Diameter inflections in the open borehole correlate well with features qualitatively ranked 2 or greater on the OBI and ABI logs, suggesting they are either fractures with aperture or a borehole enlargement due to washout of the borehole. The caliper log registers seventeen significant anomalies at: 95.2, 100.8, 107.4, 125.45, 129.6, 137.3, 157.2, 158.9, 159.9, 161.4 to 162.3, 165.6, 170.7 to 173.0, 178.9, 183.5 to 184.5, 186.21 to 186.8, 187.9 to 189.3, and a large washout beginning at approximately 192.9 feet, which register maximum enlargements between approximately 5.92 to 8.57 inches. Please refer to the Optical Televiewer and Acoustic Televiewer Plot. The caliper registered a nominal 5.8-inch diameter borehole.

RC-04: Geophysical & Hydrophysical Logging Results

Overview

The hydrophysical logging performed in RC-04 consisted of fluid electrical conductivity (FEC) and temperature logs in a static condition in the borehole and hydrophysical flow characterization under ambient and pumping conditions. The geophysical logs performed in RC-04 were: optical televiewer (OBI), acoustic televiewer (ABI), and three-arm caliper. At the conclusion of the hydrophysical and geophysical logging, the data was reviewed in the field and intervals were picked for permeability testing and sampling using the Wireline Straddle Packer (WSP) assembly. The data was collected in an approximately 5.5-inch open borehole with 6-inch steel surface casing installed to approximately the bedrock interface. Water-bearing flow zones were indicated during ambient and stressed hydrophysical testing that correlate well with the geophysical log anomalies. The data for the hydrophysical results are presented in Figures RC-04:1, 2, 3, 4A, 4B, Table RC-04:1. The Optical and Acoustic Televiewer data as well as the caliper data are presented in the RC-04 Optical and Acoustic Image Plots. The fracture orientation data, Stereonet and Rose plots derived from the televiewer data are presented in Figures RC-04:5-8 and Table RC-04:2. The wireline straddle packer test results are presented in Figures RC-04:9A through D and Table RC-04:3 as well as the AQTESOLV results in Figures RC-04:10A through D. All of the data results for RC-04 are presented in Appendix C.

Summary of Major Water-Bearing Zones During Hydrophysical Testing: RC-04

Individual Water-Bearing Zones				Wellbore Properties			
Major Water-Bearing Zones (feet)	Ambient Flow Rate (gpm)	Pumping Flow Rate (gpm)	Transport Mechanism	Ambient Depth to Water (ftbgs)	Formation Production Rate (gpm)	Observed Drawdown (feet)	Wellbore Specific Capacity (gpm/ft-dd)
142.5 – 211.2	-0.21	5.14	high-angle fractures & vesicles	119.92	14.49	1.60	9.06
254.0 – 263.8	0.12	3.12	fractures & possible vesicles				
284.0 – 288.0	0.35	4.37	fractures				

Hydrophysical Logging

Ambient Fluid Electrical Conductivity and Temperature Log

At 11:12 hours on April 22nd, 2019, after a calibration check of the fluid electrical conductivity (FEC) and temperature logging tool, the fluid column was logged for FEC and temperature profiles with COLOG's 1.5-inch diameter HpL probe. These logs were performed prior to the installation of any pumping equipment. Please refer to Figure RC-04:1. The ambient FEC profile indicates anomalies at 126, 142 and 303 feet. The anomaly at 303 feet may be the results of drilling activities or stratification as no water bearing zones are identified in this wellbore below 288 feet. The anomalies at 126 and 142 correlate well with water-bearing intervals identified during the Ambient Flow Characterization. The ambient FEC profile registers a nominal 375 µS/cm between 142 and 303 feet, with a minimum FEC of 229 µS/cm at 126 feet and a maximum of 762 µS/cm at TD (360.0 feet). The ambient temperature profile registers an increasing temperature with depth, with three anomalies, or changes in the slope of the temperature profile, which may indicate water-bearing zones at these changes, at 156, 211 – 215 and 303 feet. The temperature log registers a minimum temperature of 11.06 degrees C at water level and a maximum temperature of 15.09 degrees C at TD.

Ambient Flow Characterization

On April 22nd, 2019, an ambient flow characterization (AFC) was conducted in boring RC-04. For ambient flow assessment, the formation water in the borehole was replaced with de-ionized (DI) water and the boring left in an undisturbed state to allow any natural flow to occur. Prior to this period and throughout all HpL testing, water levels were monitored and recorded digitally every second. Ambient flow evaluation is reported for the period after the water surface returned to near pre-emplacement levels. A series of FEC and temperature logs were then conducted to identify changes in the fluid column associated with ambient flow. Ambient flow characterization is conducted to evaluate the presence of both vertical and horizontal ambient flow.

On April 22nd, 2019, at 16:23 hours (t = 0 minutes, elapsed time of test), dilution of the fluid column was complete. During the 14.7 hours following the emplacement of DI water, multiple FEC logs were conducted. Of those logs, eight are presented in Figure RC-04:2 with the last log, FEC0706, occurring the following morning after the borehole sat undisturbed overnight. The designation of each logging with the FEC tool is indicated in the figure legend by the time of logging (e.g., FEC1625 versus a subsequent logging at FEC1632), thus the progressing of curves to the right in this figure represents changes in FEC over the total logging period. The last four digits of each log ID correspond to the time at which that particular log was started. Only logs acquired during logging in the downward direction are presented as the design of the FEC/Temperature probe allows the most accurate data to be collected in the downward direction. The logs acquired in the upward logging direction are not representative of downhole conditions and are therefore omitted. These logs illustrate a change in FEC in the upper and middle-lower portions of the borehole. These changes in the FEC profiles with respect to time are associated with ambient vertical flow occurring within the wellbore.

Formation water migration as a result of upward vertical flow through the fluid column is indicated by the increase in FEC over time at 254.0 to 263.8, 272.0 to 273.8 and 284.0 to 288.0 feet. Numerical modeling of the reported field data using code BOREII indicates these intervals contribute water to the wellbore at rates of 0.12, 0.13 and 0.35 gpm, respectively. The modeling indicates the ambient inflow from this interval migrates up the borehole and exits as outflow at 142.5 to 211.2 and 212.2 to 240.5 feet, based on the change in slope and, more significantly, the truncation of the FEC logs in Figure RC-04:2 at these depths, indicating a slowing of the velocity of the water migrating up the borehole fluid column. These flow rates are based on the rate of increase of mass at these depths and the migration of the center of mass of the area under the curves. Static Water Level (SWL) at the time of testing was recorded at 119.92 ftbgs.

Flow Characterization During 15 GPM Production Test

Pumping of borehole fluids and simultaneous DI injection was conducted at one pumping rate to establish the inflow locations and evaluate the interval-specific inflow rates during production testing. Development pumping at a given rate was conducted until reasonably constant drawdown and repeatable FEC logs downhole were observed. When these conditions were observed, DI injection was initiated at the bottom of the borehole at approximately 20% of the pumping rate while the extraction pumping rate was increased the same amount to maintain a constant total formation production rate (i.e. pumping rate prior to DI water injection). These procedures were conducted at a differential rate of 14.49 gpm.

On April 24th, 2019 at 09:08 hours (t = 0 minutes elapsed time of testing), development pumping was initiated at approximately 15 gpm. Prior to initiating pumping, the ambient depth to water was recorded at 119.92 ftbgs. All drawdown values are referenced to this ambient water level.

Time dependent depth to water, totals and flow rate information were recorded digitally every second and are presented in Figure RC-04:3. Pumping was maintained at a time-averaged rate of 15.28 gpm until 12:07 hours (t = 179 minutes, elapsed time of testing). During development pumping numerous FEC logs were acquired to monitor the development process and assist in identifying the depths of flow zones. Of these FEC logs, three (FEC1116, FEC1143 and FEC1144) are presented in Figure RC-04:4A. The FEC logs acquired during development pumping illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases or decreases in FEC. DI water injection from the bottom of the wellbore was initiated at 12:07 hours at a time-averaged rate of 1.63 gpm while the total extraction rate was increased to a time-averaged rate of 16.12 gpm, resulting in a total borehole formation time-averaged production rate of 14.49 gpm. These flow conditions were maintained until 14:08 hours (t = 300 minutes) during which time a relatively constant drawdown of approximately 1.60 feet was observed. The FEC logs acquired during dilution procedures illustrate a reasonably stable condition of the fluid column with local inflow locations identified by spikes or incremental step increases in FEC. Eight inflow intervals were identified from these logs with flow rates ranging from 0.002 to 5.14 gpm. The logs indicate the intervals 142.5 to 211.2, 254.0 to 263.8 and 284.0 to 288.0 feet dominated inflow during pumping, producing 5.14, 3.12 and 4.37 gpm, respectively, or 87.2 percent of the total inflow. Please refer to Table RC-04:1 for a summary of hydrophysical flow results and the depths of individual inflow zones.

At the conclusion of the dilution process, the DI water injection was shut off and the extraction pumping maintained at approximately 16.12 gpm, to try to induce additional drawdown and potentially identify any additional inflow zones not apparent during the dilution process. The presence of a highly diluted state in the lower portion of the borehole without the presence of DI water migrating up the borehole makes an ideal condition to identify very low-flow inflow zones, if present. FEC logs were acquired during this re-development process and are presented in Figure RC-04:4B. This test, however, did not show any evidence of any additional inflow zones not already identified from logs presented in Figure RC-04:4A.

Estimation of Interval Specific Transmissivity

An estimation of transmissivity (T) can be made using an equation after Thiem (1906) assuming steady-state radial flow in a confined aquifer:

$$T = KL = \frac{q_i}{2\pi \Delta h_w} \ln\left(\frac{r_e}{r_w}\right)$$

where K is the hydraulic conductivity, q_i is the interval specific inflow rate calculated using HpL results, r_w is the wellbore radius (0.23 ft), r_e is the effective pumping radius, Δh_w is the observed maximum drawdown (1.60 feet) and L is the thickness of the zone through which flow occurs. For our calculations, COLOG used r_e of 100 feet (assumed). By applying L and q_i from the HpL results under the two pressure conditions, the interval-specific transmissivity can be calculated for each identified water-producing interval. These calculations were made at each identified interval and are presented in Table RC-04:1. In summary, the previously identified inflow zones during production testing at 142.5 to 211.2, 254.0 to 263.8 and 284.0 to 288.0 feet exhibited the highest transmissivities of approximately 623, 349 and 468 ft^2/day.

Geophysical Logging

Optical Televiewer (OBI) and Acoustic Televiewer (ABI)

On April 22 and 25, 2019, optical televiewer (OBI) and acoustic televiewer (ABI) logging was performed in RC-04. The OBI was logged from 3.3 feet to a depth of 341.9 feet and the ABI was logged from 115.9 feet to a depth of 359.7 feet. Fracture density and fracture orientation were evaluated over the entire OBI and ABI datasets.

The majority of the features identified in RC-04 were partial, complete or open fractures, indicating potential for flow zones from within the borehole. The rose diagrams displayed in Appendix C indicate the majority of the fractures, approximately 23% of the features, dip less than 90° from horizontal and an additional 18% of features dip less than 90° from horizontal. The rose diagrams indicates approximately 25% of the identified features in RC-04 dip in the relatively dominant direction of 240° to 3000° (Southwest to Northwest). In borehole RC-04, 265 high-angle fractures or features (dip angles greater than 45°) were identified. Of these 265 high-angle features, 64 features are qualitatively ranked 2 to 5, suggesting possible flow potential from these features. The remaining high-angle features are qualitatively ranked 1 or 0, indicating minimal to no flow potential from these features.

Three-Arm Caliper

On April 25, 2019, three-arm caliper logging was performed in RC-04 to a depth of 359.3 feet and registered the bottom of casing (BOC) at 81.1 feet, correlating well with the OBI image identifying the bottom of casing.

Diameter inflections in the open borehole correlate well with features qualitatively ranked 2 or greater on the OBI and ABI logs, suggesting they are either fractures with aperture or a borehole enlargement due to washout of the borehole. The caliper log registers 42 significant anomalies at: 99.3, 154.0, 158.7, 162.6 to 16.4, 164.1 to 164.9, 167.1, 168.9 to 170.1, 171.4 to 172.0, 173.9, 174.7 to 176.5, 178.1 to 179.0, 181.2, 182.7 to 184.5, 189.4, 196.7, 206.7, 212.5, 213.5, 214.7, 215.8, 218.1, 219.2, 222.0 to 223.4, 225.0 to 225.5. 226.7, 228.2, 229.8, 231.3, 232.8 to 234.5, 236.0, 237.0, 239.1, 239.6 to 240.5, 247.4, 254.3, 255.2, 258.0, 260.2, 273.1 to 274.3, 275.4 to 278.6, 280.1, and 281.0 to 285.7 feet, which register maximum enlargements between approximately 5.89 to 8.18 inches. Please refer to the Optical Televiewer and Acoustic Televiewer Plot. The caliper registered a nominal 5.8-inch diameter borehole.

Wireline Straddle Packer Testing

Discussion

On May 3rd and May 18th through 19th, 2019, wireline straddle packer (WSP) testing and sampling was conducted in RC-04 at four intervals:

148.0 feet to WL
254.0 to 264.5 feet
265.5 to 276.0 feet
282.2 to 292.5 feet

WSP testing was conducted to acquire an interval-specific groundwater sample from fracture/inflow zones identified during hydrophysical and geophysical logging investigations. In addition to collecting a representative groundwater sample from each interval, development pumping was conducted whenever possible to purge as much water from the sample interval as reasonably possible. During pumping and sampling, pressures in the zone of interest, above and below the zone of interest were recorded to monitor the pumping process and provide information on the relative fracture-interconnectiveness between intervals. For the standard configuration of the WSP assembly, one interval volume is assumed to be approximately 24 gallons with standard plumbing and equipment in the borehole. Discussion of contaminant concentrations derived from the sampling results is not part of the scope of Colog's involvement.

WSP testing was also conducted to estimate permeability within the packer intervals chosen. Extraction pump tests were conducted at the intervals believed to be potentially water-bearing with pressures within the interval of interest and surrounding the interval of interest recorded to estimate fracture-specific or interval-specific permeability for each interval tested using the Thiem equation method and/or the Theis Recovery method using the program AQTESOLV (Duffield, G.M., 2007. AQTESOLV for Windows Version 4.5 User's Guide, HydroSOLVE, Inc., Reston, VA.). Figures RC-04:9A through D and Table RC-04:3 located in Appendix A show a complete summary of the pressures wireline straddle packer sampling, and Figures RC-04:10A through D for the permeability estimations derived from AQTESOLV. SWL in RC-04 prior to testing was recorded at 120.27 ftbgs. All depths herein are referenced to ground surface unless otherwise noted.

Zone Specific Results:

Interval 148.0 feet to WL – On May 3rd, 2019 the WSP was utilized in a modified configuration with only the lower packer inflated. This makes the middle pressure transducer and the upper transducer both reading in the zone of interest. However, water level in the zone, once stressed, dropped below the upper transducer, therefore the middle transducer is the zone transducer for permeability estimations. The lower transducer, which was supposed to be reading in the isolated lower zone, did not function properly, therefore the data is omitted. Unfortunately there is no lower transducer reading for this test. The interval was pumped at approximately 0.37 gpm resulting in a differential pressure of approximately 9.01 psi (Figure RC-04:9A). The estimated transmissivity is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 3.31 $feet^2$/day. Utilizing the AQTESOLV program and the Theis solution, the transmissivity of this interval is estimated to be approximately 3.98 $feet^2$/day, illustrating good correlation with the Thiem equation result.

Low-flow sampling was conducted at approximately 07:27 hours on May 4th after the interval was observed for recovery overnight. At 07:37 hours the pump rate was reduced and groundwater samples were collected. A total of approximately 67 gallons was pumped prior to sampling, which includes the purge-pumping the previous day. Please refer to Table RC-04:3 for a complete summary of the WSP data acquired and permeability results for this interval.

Interval 254.0 – 264.5 feet – On May 12th, 2019 the WSP was utilized in its standard configuration, both packers inflated, and all pressure transducers measuring pressure in their respective zones of interest. Low-rate pumping for sampling was initiated at 08:04 hours at a rate of 0.25 gpm. At approximately 12:35 hours, after 70 minutes of pumping, the pumping rate was set to approximately 0.25 gpm to acquire groundwater samples. During the 70 minutes of pumping prior to sampling, approximately 17.5 gallons was pumped from the interval.

At 08:04 hours on May 19th, 2019, the extraction rate was increased to approximately 20.5 gpm for stress testing. The interval was pumped at approximately 20.5 gpm for 52 minutes resulting in a differential pressure of approximately 2.01 psi (Figure RC-04:9B). The data does show a minor response in both the lower and upper transducers indicating that a hydraulic connection with the intervals below and above the test interval are present, however, based on the amount of drawdown observed in the interval, this hydraulic connection between intervals can be assumed to be relatively small, though clearly present. The estimated transmissivity of the interval is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 822 $feet^2$/day. No AQTESOLV analysis was performed on this interval due to the rapid recovery of the interval. Please refer to Table RC-04:3 for a complete summary of the WSP data acquired and permeability results for this interval.

Interval 265.5 to 276.0 feet – On May 12th, 2019 the WSP was utilized in its standard configuration, both packers inflated, and all pressure transducers measuring pressure in their respective zones of interest. Low-rate pumping for sampling was initiated at 15:20 hours at a rate of 0.33 gpm. At approximately 18:16 hours, after 176 minutes of pumping, the pumping rate remained set to approximately 0.33 gpm to acquire groundwater samples. During the 176 minutes of pumping prior to sampling, approximately 58.1 gallons was pumped from the interval.

At 16:58 hours on May 18th, 2019, the interval was pumped at approximately 10.5 gpm resulting in a differential pressure of approximately 17.85 psi (Figure RC-04:9C). The data does show a minor response in both the lower and upper transducers indicating that a hydraulic connection with the intervals below and above the test interval are present, however, based on the amount of drawdown observed in the interval, this hydraulic connection between intervals can be assumed to be relatively small, though clearly present. The estimated transmissivity of the interval is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 47.4 $feet^2$/day. No AQTESOLV analysis was performed on this interval due to the rapid recovery of the interval. Please refer to Table RC-04:3 for a complete summary of the WSP data acquired and permeability results for this interval.

Interval 282.0 to 292.5 feet – On May 18th, 2019 the WSP was utilized in its standard configuration, both packers inflated, and all pressure transducers measuring pressure in their respective zones of interest. The interval was pumped at approximately 16.66 gpm resulting in a differential pressure of approximately 2.56 psi (Figure RC-04:9D). The data does show a minor response in both the lower and upper transducers indicating that a hydraulic connection with the intervals below and above the test interval are present, however, based on the amount of drawdown observed in the interval, this hydraulic connection between intervals can be assumed to be relatively small, though clearly present. The estimated transmissivity of the interval is based on the pumping rate and the resulting differential pressure at the end of the test. The transmissivity of this interval is estimated, using the Thiem equation, to be approximately 525 $feet^2$/day. No AQTESOLV analysis was performed on this interval due to the rapid recovery of the interval. Please refer to Table RC-04:3 for a complete summary of the WSP data acquired and permeability results for this interval.

Low-flow sampling was conducted and samples were collected at approximately 13:49 hours on May 18th before the interval pumping rate was increased to a rate of approximately 16.66 gpm at 14:19 hours and pumped on for approximately 85 minutes (approximately 1,416 gallons pumped). Please refer to Table RC-04:3 for a complete summary of the WSP data acquired and permeability results for this interval.

APPENDIX A

RC-02 GEOPHYSICAL & HYDROPHYSICAL DATA RESULTS

borehole geophysics / hydrophysics

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QTR **SEC** **TWP** **RGE**

OTHER SERVICES
Hydrophysical Logging
WSP Testing

PERMANENT DATUM **ELEVATION**
LOG MEAS. FROM Ground Surface **ABOVE PERMANENT DATUM**
DRILLING MEAS. FROM

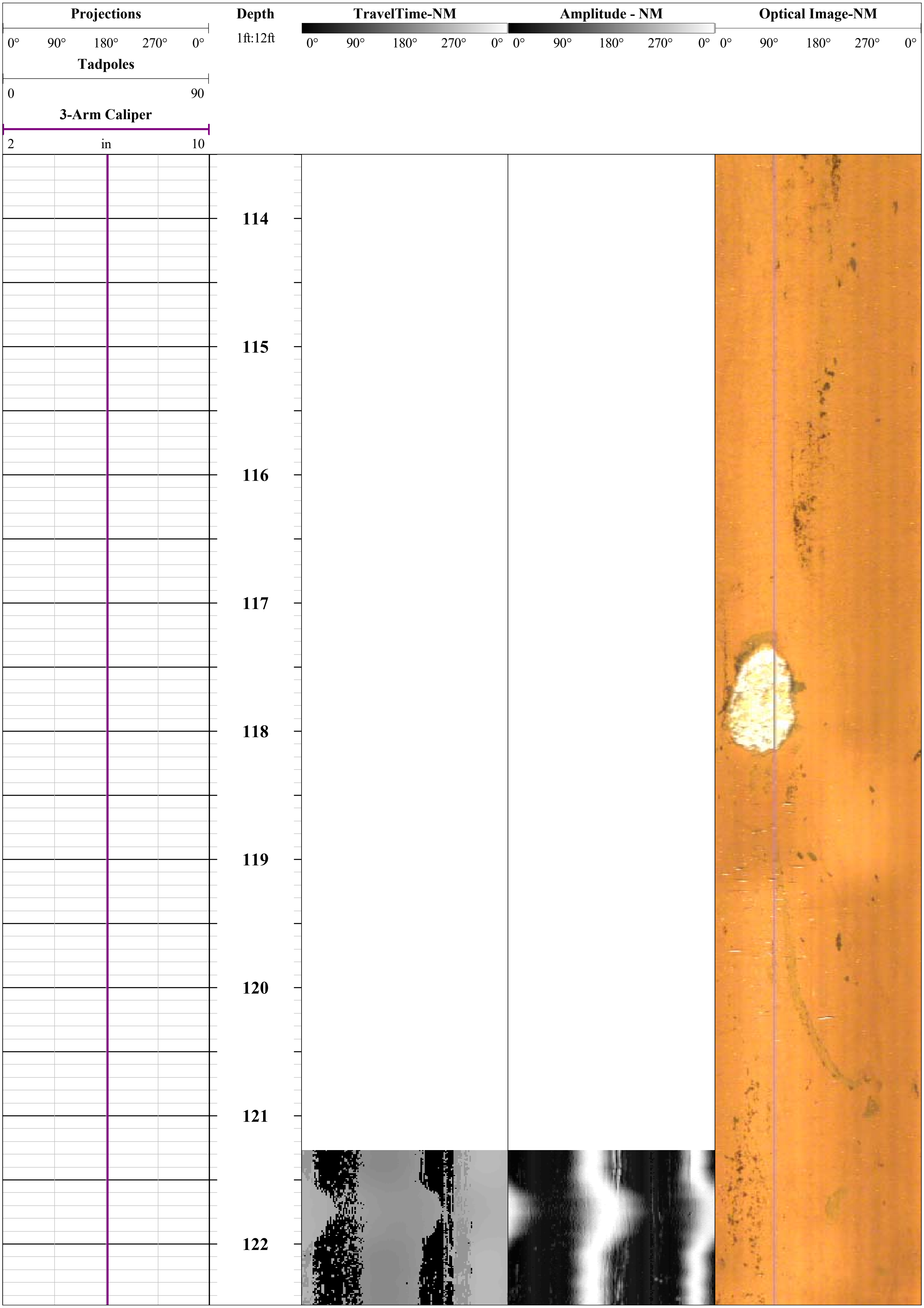
DATE ACQUIRED	4/26/2019	4/26/2019	4/26/2019	4/26/2019
RUN NUMBER	1	2	3	4,5
LOG TYPE	OBI	Fluid Temp. & Cond.	Caliper	ABI
DEPTH-DRILLER				
DEPTH-LOGGER	225.19 ftbgs			
BTM LOG INTERVAL	225.19	225.09	225.56	224.87
TOP LOG INTERVAL	56.35	2.45	113.24	121.11
RECORDED BY	BEH, KMG	KMG, BEH	KMG, BEH	KMG, BEH
WITNESSED BY				
PROBE TYPE, S/N	OBI40, 063702	HpL Tool	2CAA, 5837	ABI40, 121206
LOGGING SPEED	4 ft/min (down)	20 ft/min (down)	15 ft/min (up)	4 ft/min (up)
A.S.D.E. / Sample Interval	0.48 ft / 0.0075 ft	0.77 ft / NA	0.46 ft / 0.1 ft	0.18 ft / 0.0075 ft
Fluid Level / Fluid Type				

BOREHOLE RECORD				**CASING RECORD**			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**
				6 "		GS	123 ft

COMMENTS

NA - Not Available, N/A - Not Applicable

AWL = 57.212 ftbgs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TravelTime-NM
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Amplitude - NM
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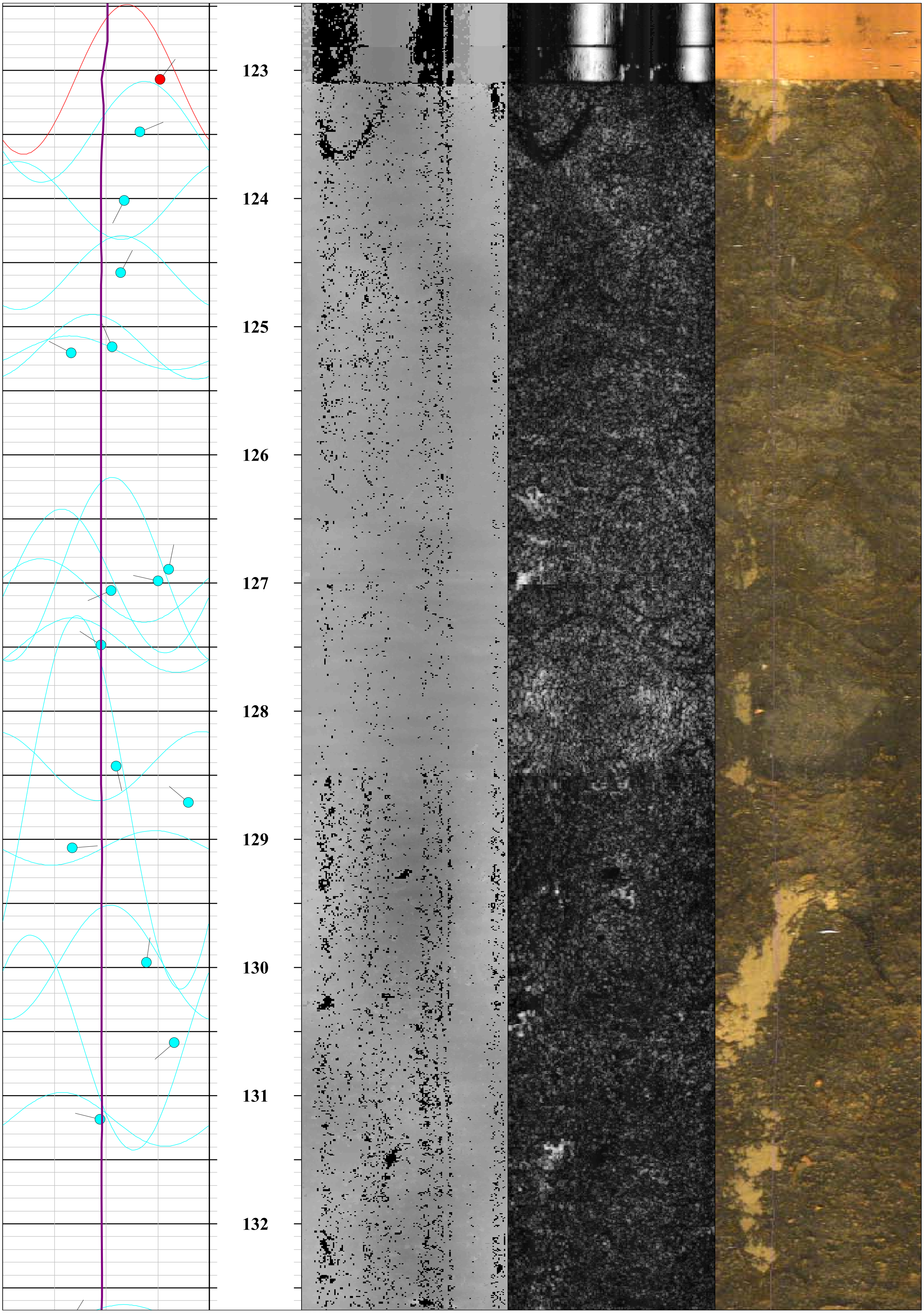
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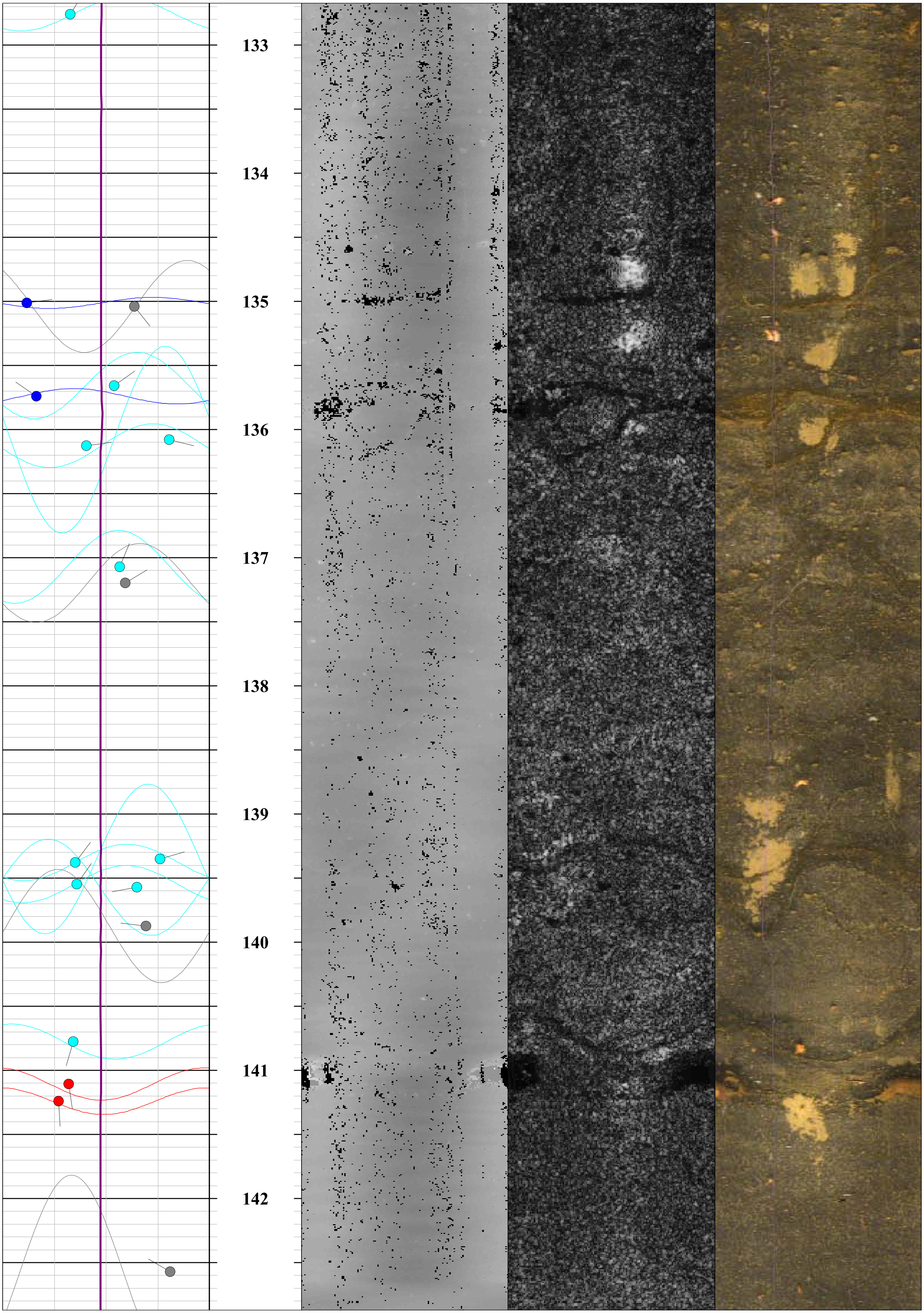
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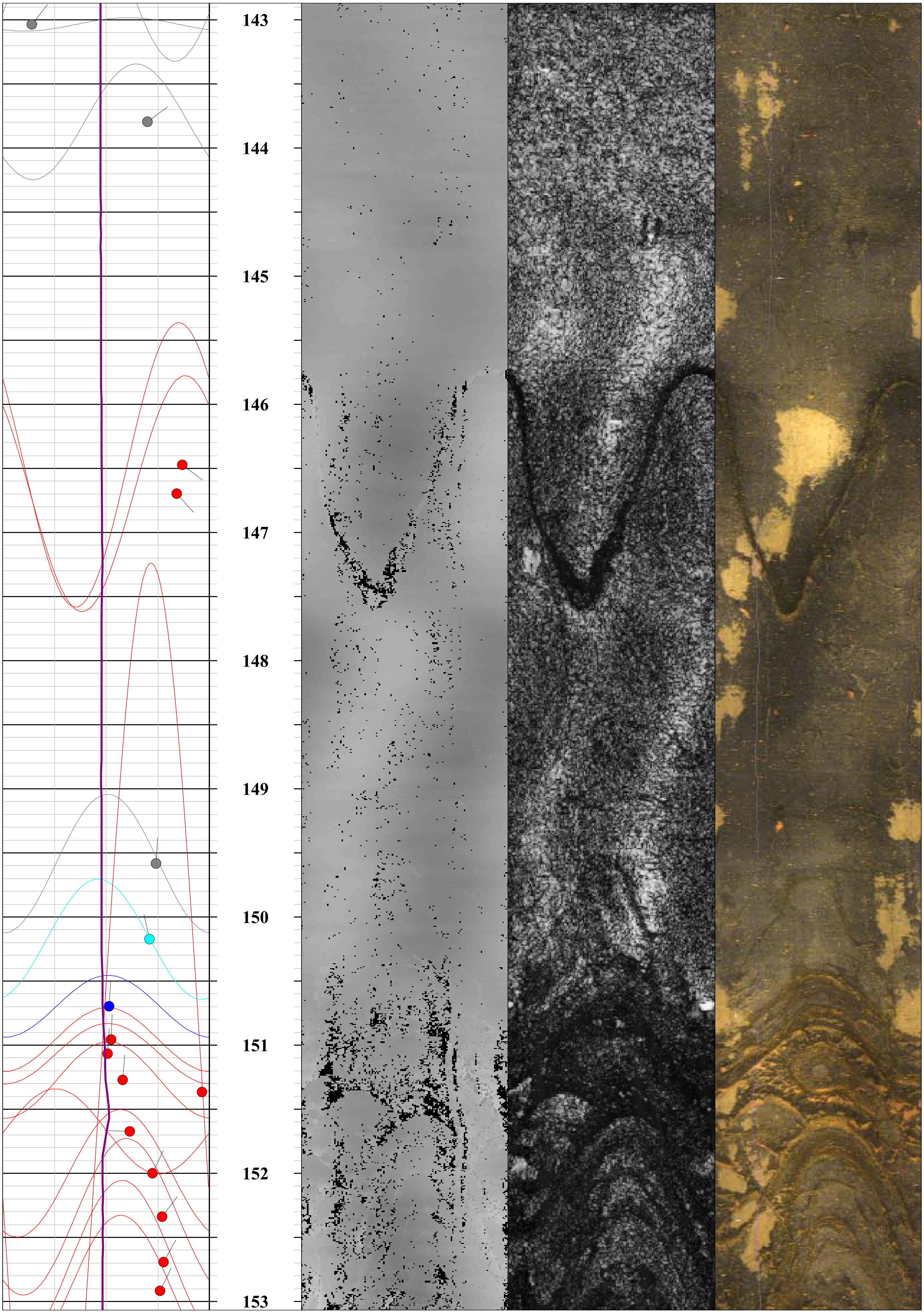
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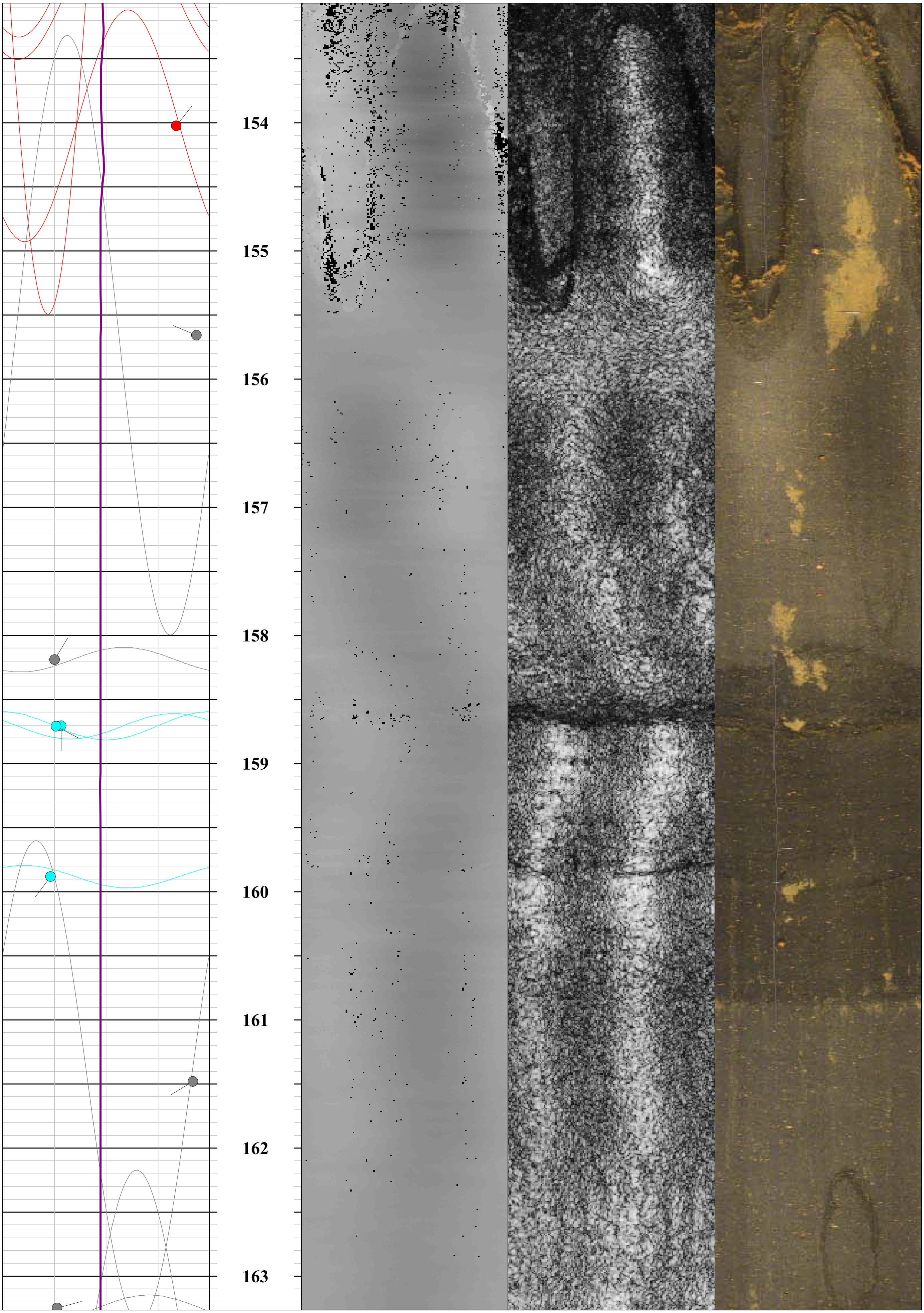
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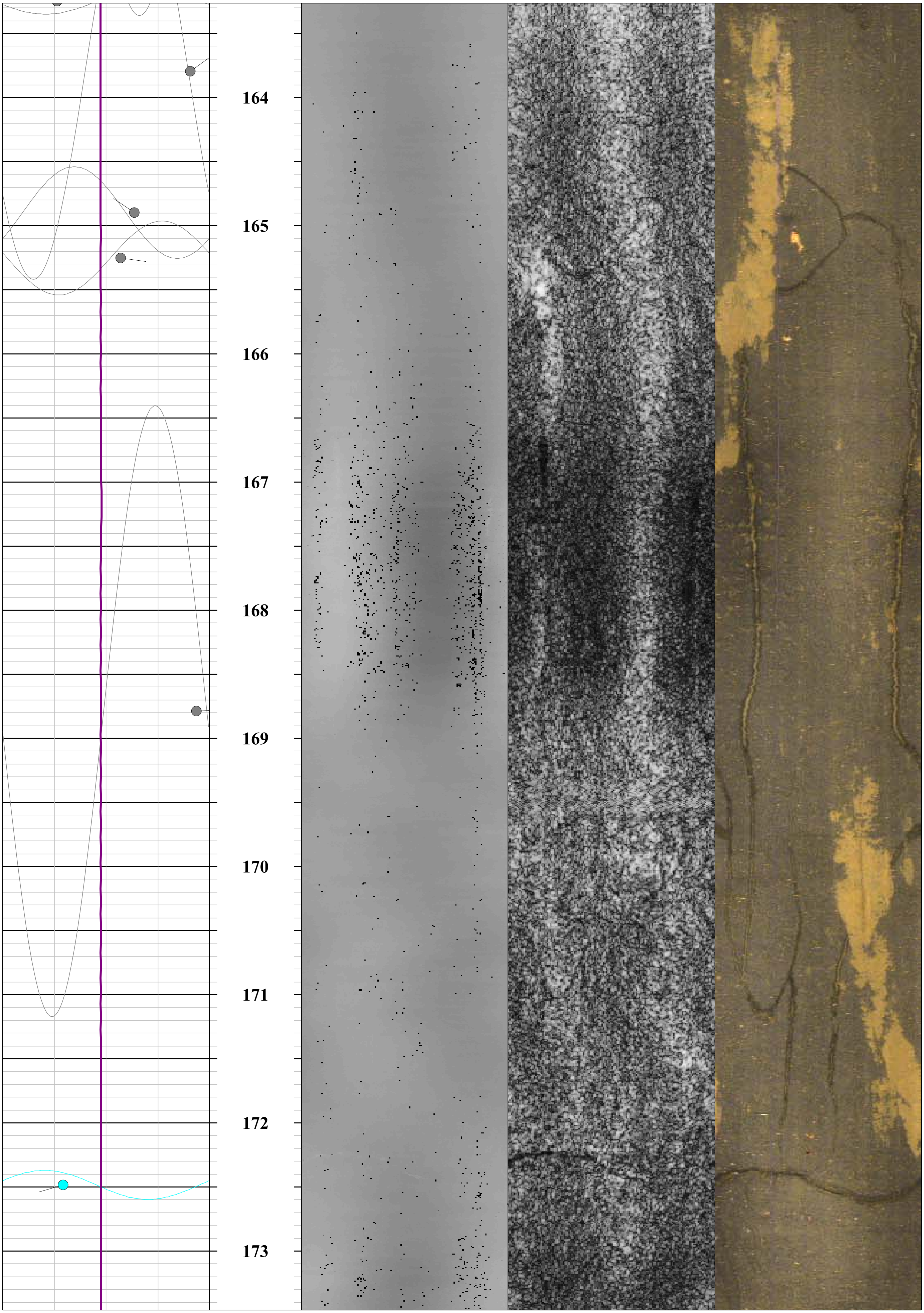
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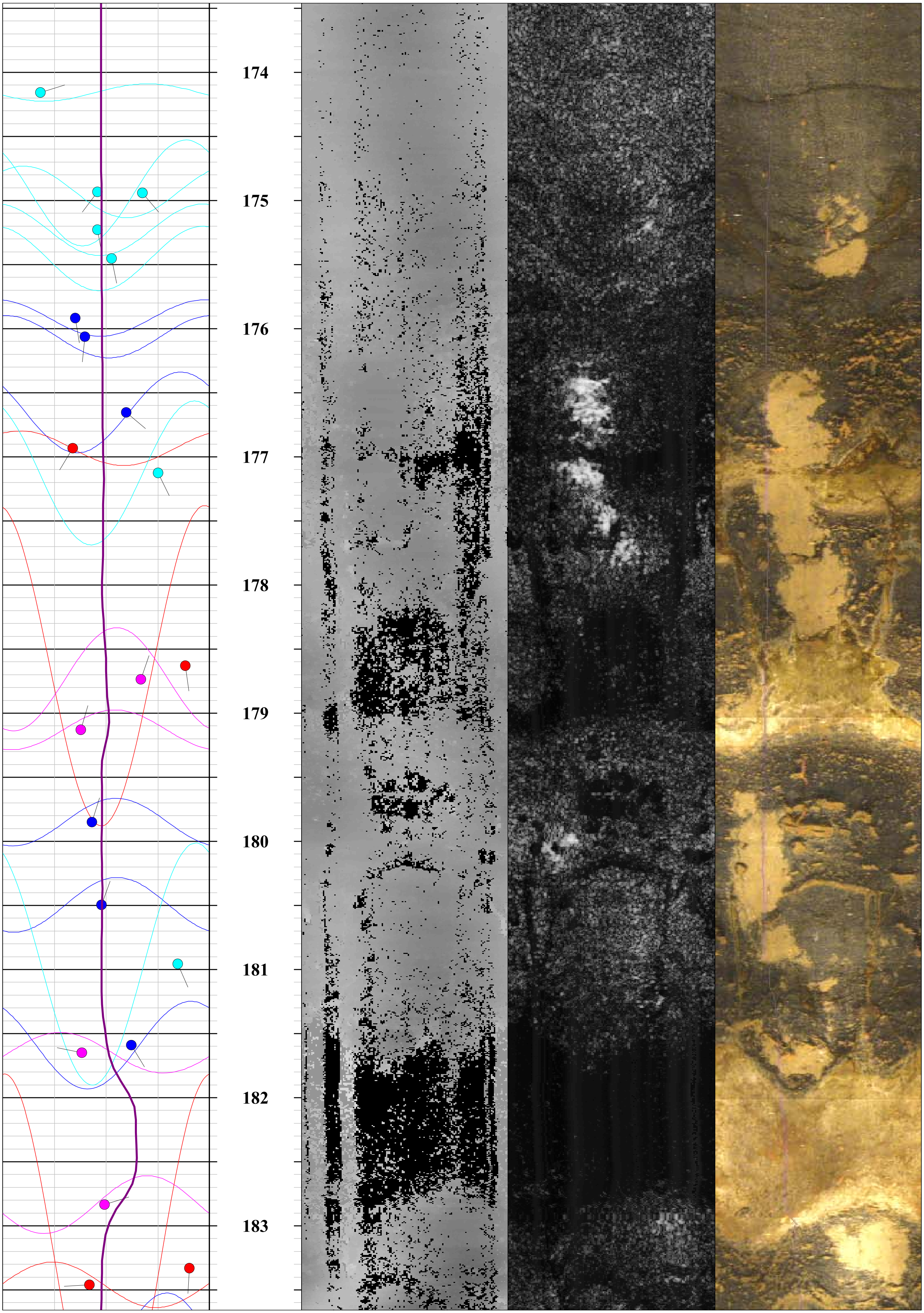
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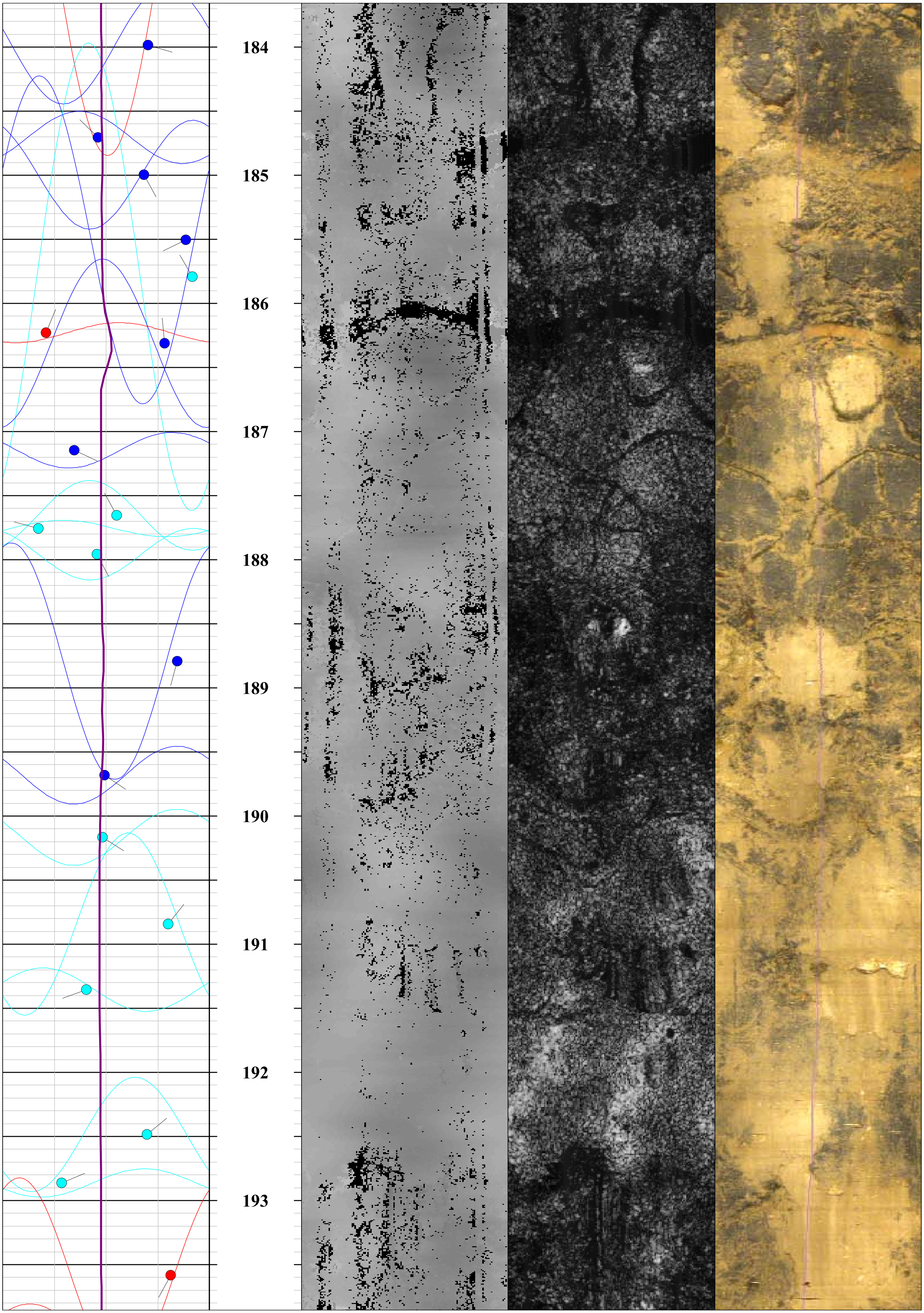
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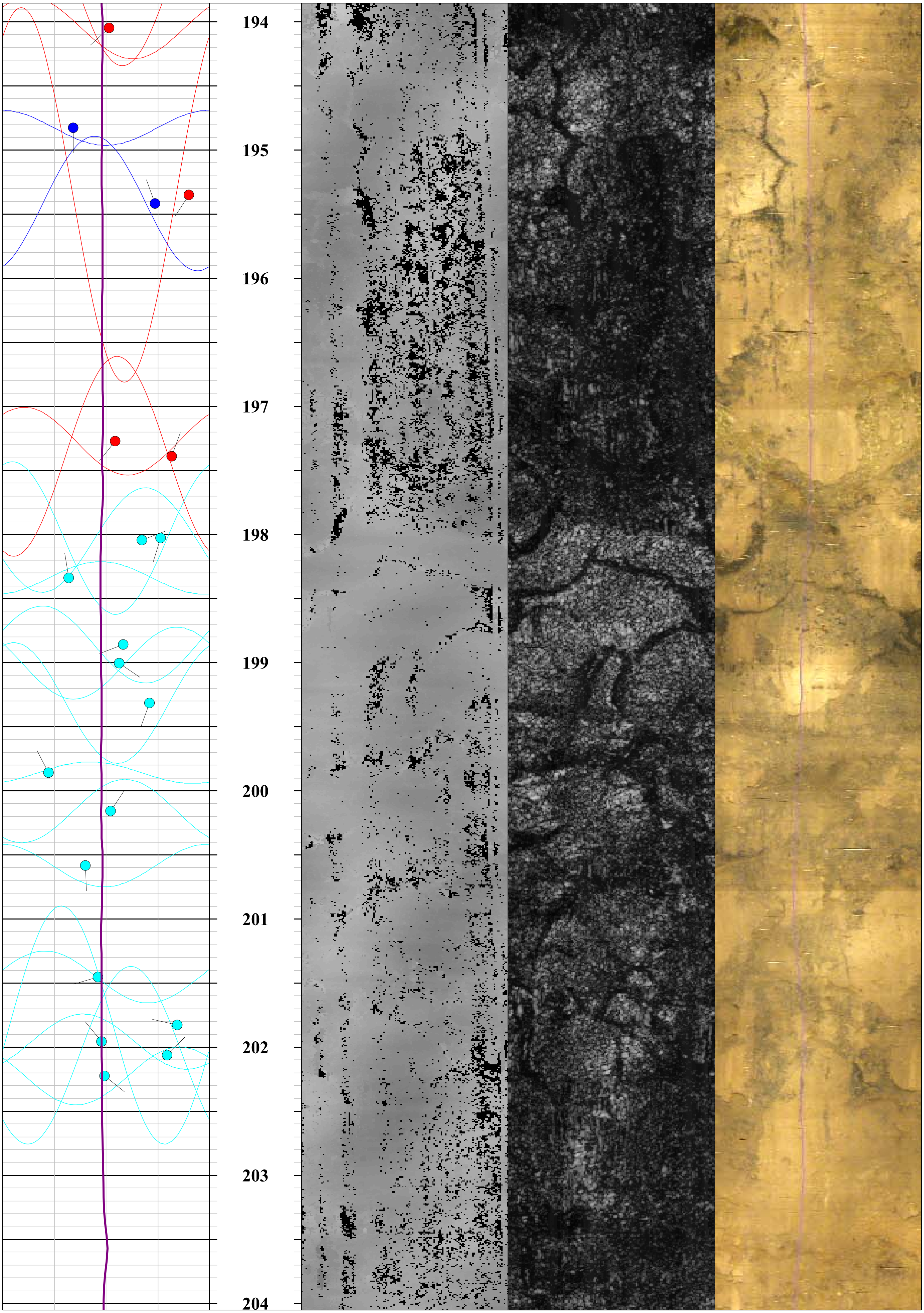
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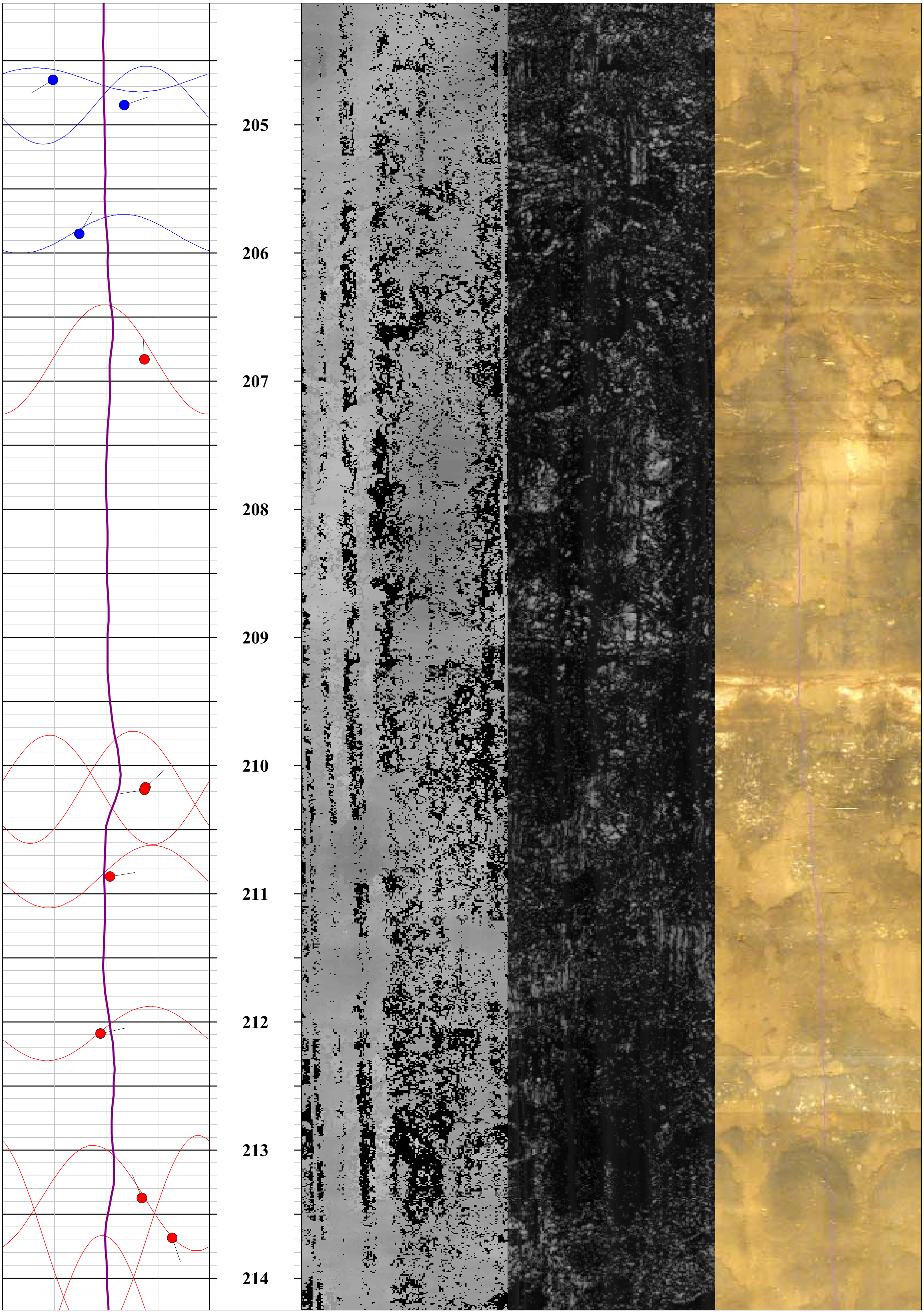
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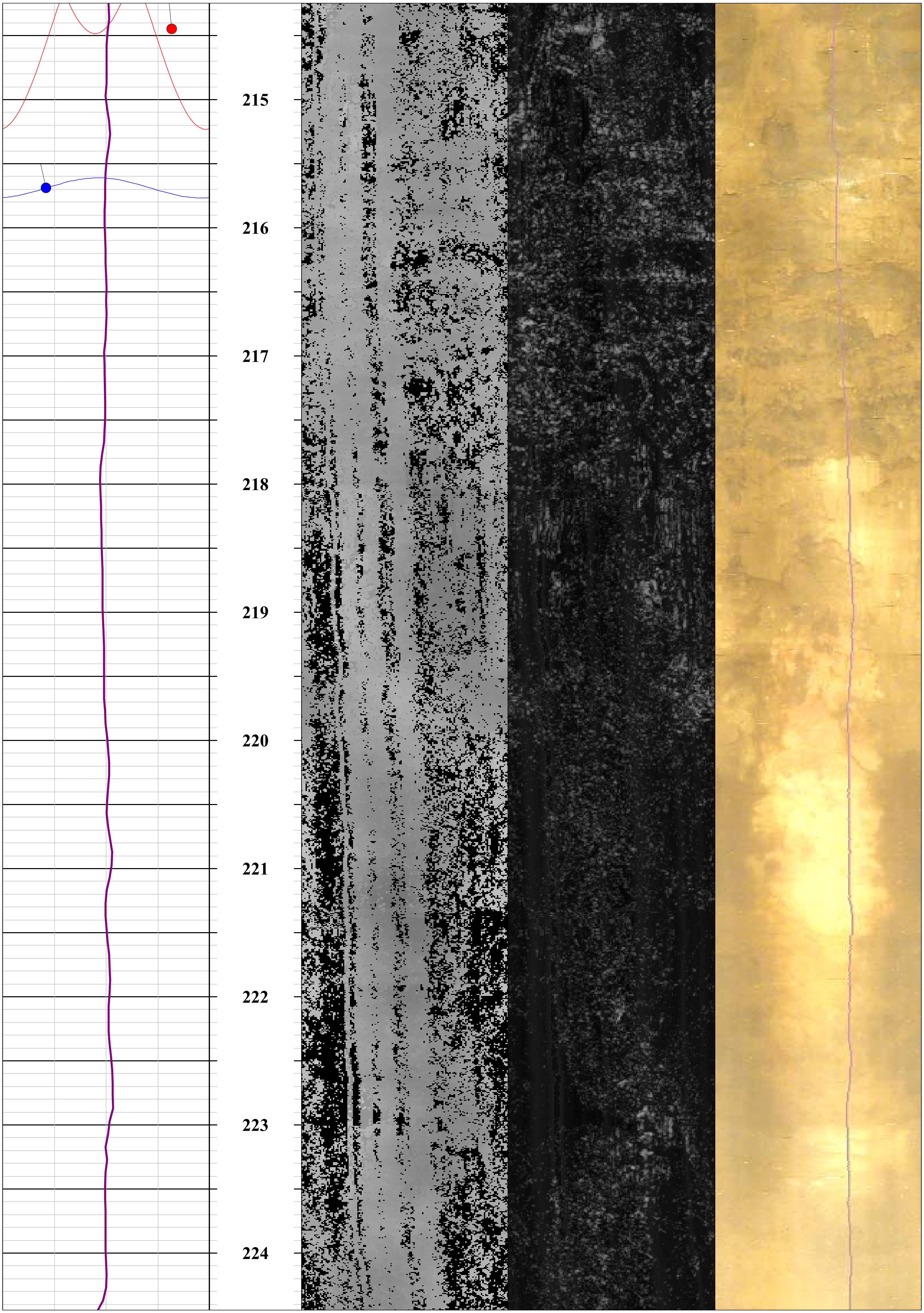

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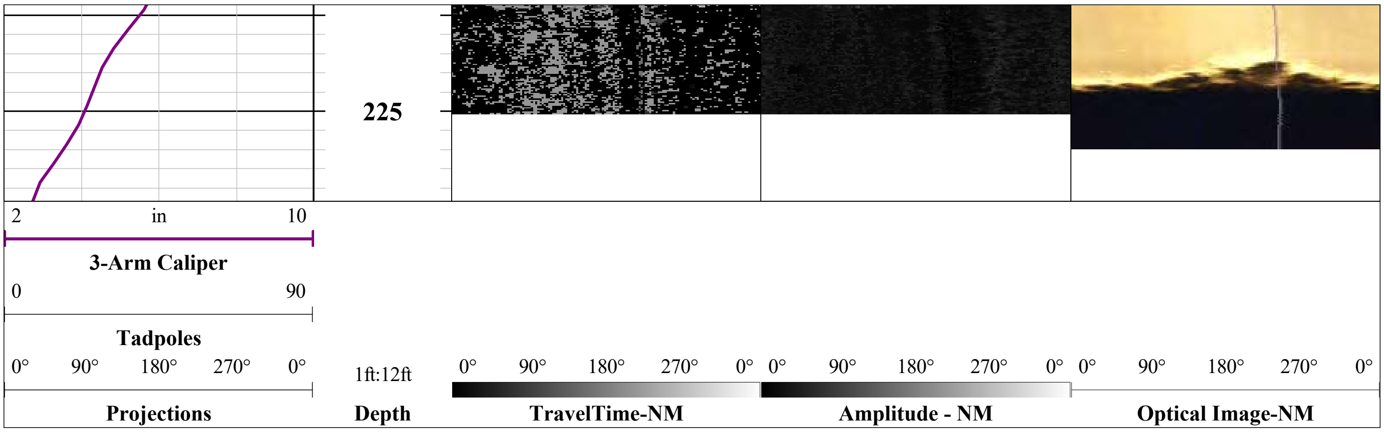
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2 in 10
3-Arm Caliper
0 90
Tadpoles
0° 90° 180° 270° 0°
Projections
1ft:12ft
Depth
0° 90° 180° 270° 0°
TravelTime-NM
0° 90° 180° 270° 0°
Amplitude - NM
0° 90° 180° 270° 0°
Optical Image-NM

Table RC-02:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
1	37.51	123.1	36	69	3
2	37.64	123.5	68	60	1
3	37.80	124.0	207	53	1
4	37.97	124.6	28	51	1
5	38.15	125.2	336	48	1
6	38.16	125.2	297	30	1
7	38.68	126.9	11	72	1
8	38.70	127.0	283	68	1
9	38.73	127.1	246	47	1
10	38.86	127.5	303	43	1
11	39.15	128.4	167	50	1
12	39.23	128.7	310	81	1
13	39.34	129.1	85	30	1
14	39.61	130.0	8	63	1
15	39.80	130.6	229	75	1
16	39.99	131.2	283	42	1
17	40.47	132.8	32	29	1
18	41.15	135.0	82	11	2
19	41.16	135.0	142	57	0
20	41.35	135.7	55	49	1
21	41.37	135.7	304	15	2
22	41.48	136.1	104	73	1
23	41.49	136.1	82	37	1
24	41.78	137.1	22	51	1
25	41.82	137.2	58	53	0
26	42.47	139.4	74	69	1
27	42.48	139.4	37	32	1
28	42.53	139.6	35	32	1
29	42.54	139.6	260	59	1
30	42.64	139.9	276	63	0
31	42.91	140.8	196	31	1
32	43.01	141.1	172	29	3
33	43.05	141.2	176	24	3
34	43.46	142.6	300	73	0
35	43.60	143.0	38	13	0
36	43.83	143.8	53	63	0
37	44.64	146.5	127	78	3
38	44.71	146.7	138	76	3
39	45.59	149.6	3	67	0
40	45.77	150.2	347	64	1
41	45.93	150.7	4	46	2
42	46.01	151.0	2	47	3
43	46.05	151.1	3	46	3
44	46.11	151.3	4	52	3
45	46.14	151.4	79	87	3

All directions are with respect to Magnetic North.

Table RC-02:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
46	46.23	151.7	273	55	3
47	46.33	152.0	25	65	3
48	46.43	152.3	36	69	3
49	46.54	152.7	28.4	70.2	3
50	46.61	152.9	26.2	68.8	3
51	46.95	154.0	38.6	75.8	3
52	47.45	155.7	292.7	84.4	0
53	48.22	158.2	31.2	22.7	0
54	48.37	158.7	180.3	25.5	1
55	48.37	158.7	117.9	23.3	1
56	48.73	159.9	217.2	20.9	1
57	49.22	161.5	238.4	83.1	0
58	49.76	163.3	75.0	23.8	0
59	49.92	163.8	53.9	82.0	0
60	50.26	164.9	304.7	57.4	0
61	50.37	165.3	97.9	51.5	0
62	51.45	168.8	86.2	84.5	0
63	52.57	172.5	253.5	26.3	1
64	53.08	174.2	72.8	16.5	1
65	53.32	174.9	216.7	41.3	1
66	53.32	174.9	139.5	61.0	1
67	53.41	175.2	169.6	41.3	1
68	53.48	175.5	168.3	47.6	1
69	53.62	175.9	171.2	31.7	2
70	53.66	176.1	185.2	35.8	2
71	53.84	176.7	130.2	54.0	2
72	53.93	176.9	210.8	30.6	3
73	53.99	177.1	154.5	67.8	1
74	54.45	178.6	172.3	79.6	3
75	54.48	178.7	18.7	60.4	4
76	54.60	179.1	15.7	34.2	4
77	54.82	179.9	17.9	39.0	2
78	55.01	180.5	19.5	43.0	2
79	55.16	181.0	156.7	76.4	1
80	55.35	181.6	148.2	56.2	2
81	55.37	181.7	281.0	34.7	4
82	55.73	182.8	72.4	44.6	4
83	55.88	183.3	183.4	81.4	3
84	55.92	183.5	266.9	37.8	3
85	56.08	184.0	105.9	63.5	2
86	56.30	184.7	313.7	41.6	2
87	56.39	185.0	151.8	61.6	2
88	56.54	185.5	244.4	79.8	2
89	56.63	185.8	329.8	82.8	1
90	56.76	186.2	22.5	18.9	3

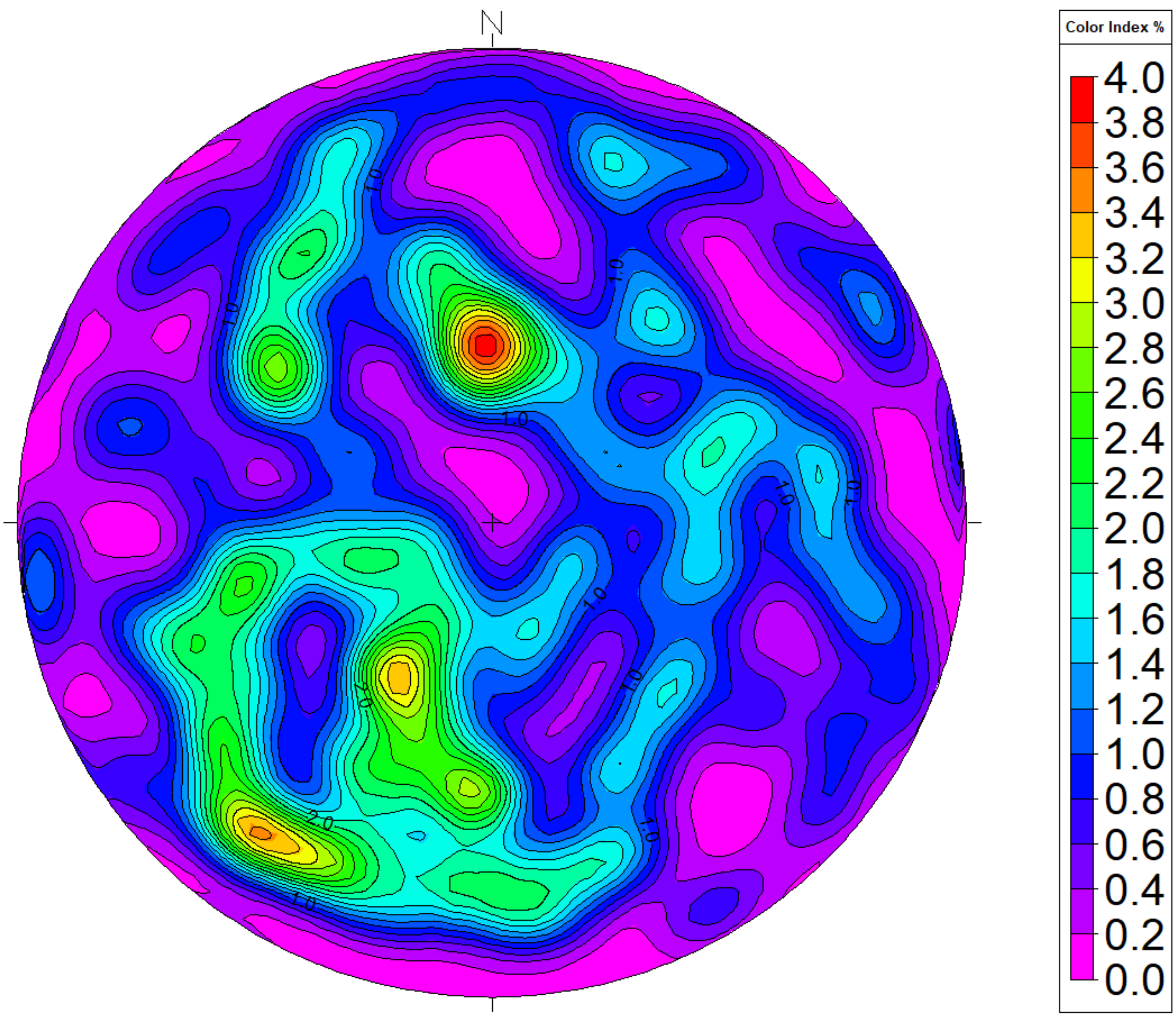
All directions are with respect to Magnetic North.

Table RC-02:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
91	56.79	186.3	354.4	70.8	2
92	57.04	187.1	114.9	31.2	2
93	57.20	187.7	331.3	49.8	1
94	57.23	187.8	285.1	15.7	1
95	57.29	188.0	152.1	41.2	1
96	57.54	188.8	195.5	76.1	2
97	57.81	189.7	123.9	44.6	2
98	57.96	190.2	123.4	43.6	1
99	58.17	190.8	38.4	72.1	1
100	58.32	191.4	250.2	36.5	1
101	58.67	192.5	50.8	62.8	1
102	58.78	192.9	67.4	25.6	1
103	59.00	193.6	209.0	73.2	3
104	59.15	194.1	227.3	46.4	3
105	59.38	194.8	179.8	30.8	2
106	59.54	195.4	212.6	81.1	3
107	59.56	195.4	340.1	66.4	2
108	60.13	197.3	217.9	49.1	3
109	60.16	197.4	19.3	73.6	3
110	60.36	198.0	197.1	68.9	1
111	60.36	198.0	68.9	60.7	1
112	60.45	198.3	350.7	28.8	1
113	60.61	198.9	249.1	52.7	1
114	60.66	199.0	124.1	50.8	1
115	60.75	199.3	200.1	64.1	1
116	60.92	199.9	332.1	20.1	1
117	61.01	200.2	33.4	47.1	1
118	61.14	200.6	177.2	36.0	1
119	61.40	201.5	253.8	41.5	1
120	61.52	201.8	282.5	76.1	1
121	61.56	202.0	320.4	43.2	1
122	61.59	202.1	43.8	71.7	1
123	61.64	202.2	128.8	44.5	1
124	62.38	204.7	238.7	22.1	2
125	62.44	204.9	70.8	53.0	2
126	62.74	205.9	30.6	33.5	2
127	63.04	206.8	357.1	61.8	3
128	64.06	210.2	48	62	3
129	64.07	210.2	261	62	3
130	64.27	210.9	80	47	3
131	64.65	212.1	77	43	3
132	65.04	213.4	338	61	3
133	65.13	213.7	161	74	3
134	65.36	214.5	354	74	3
135	65.74	215.7	347	19	2

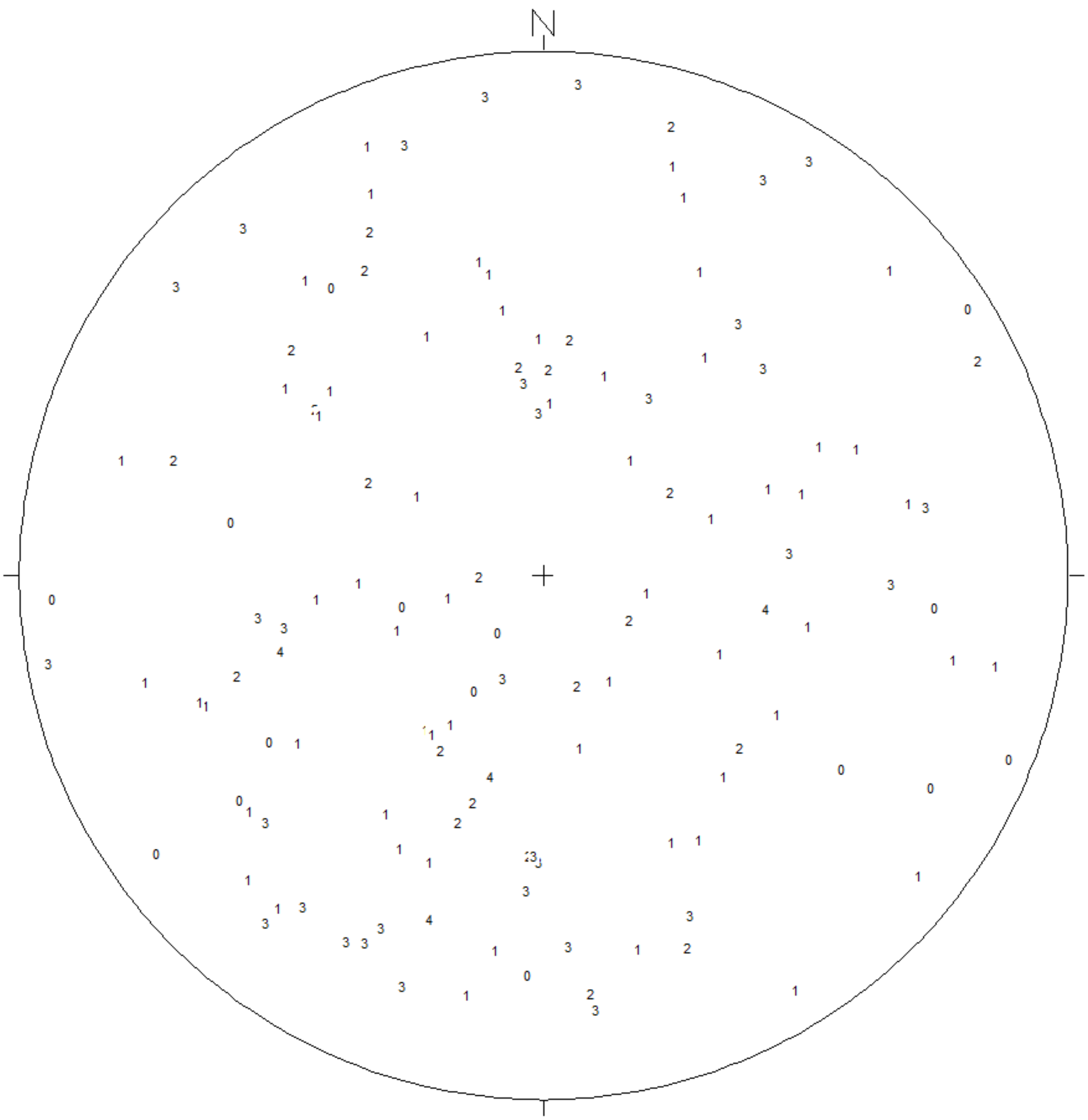
All directions are with respect to Magnetic North.

Figure RC-02:5. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019



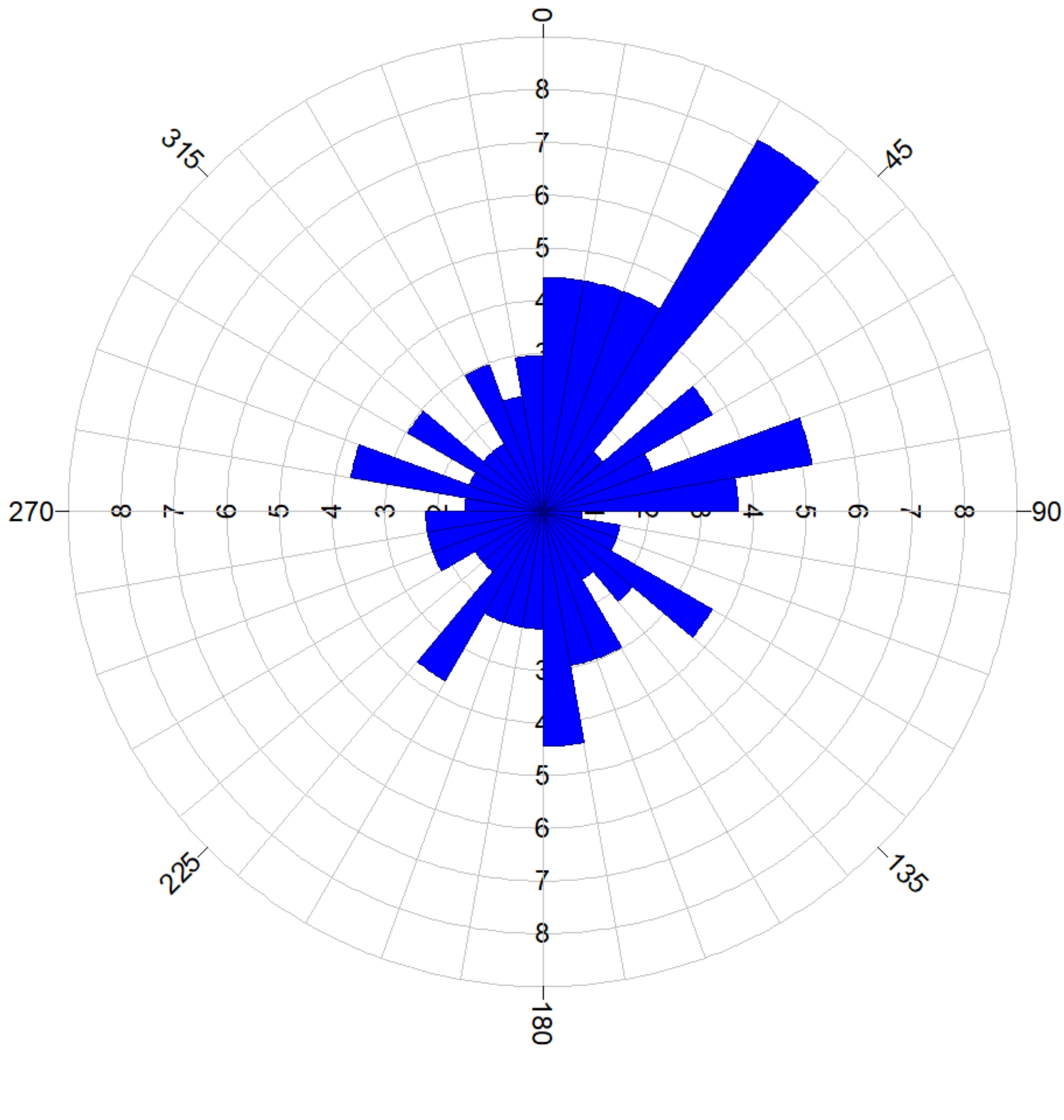
All directions are with respect to Magnetic North.

Figure RC-02:6. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019



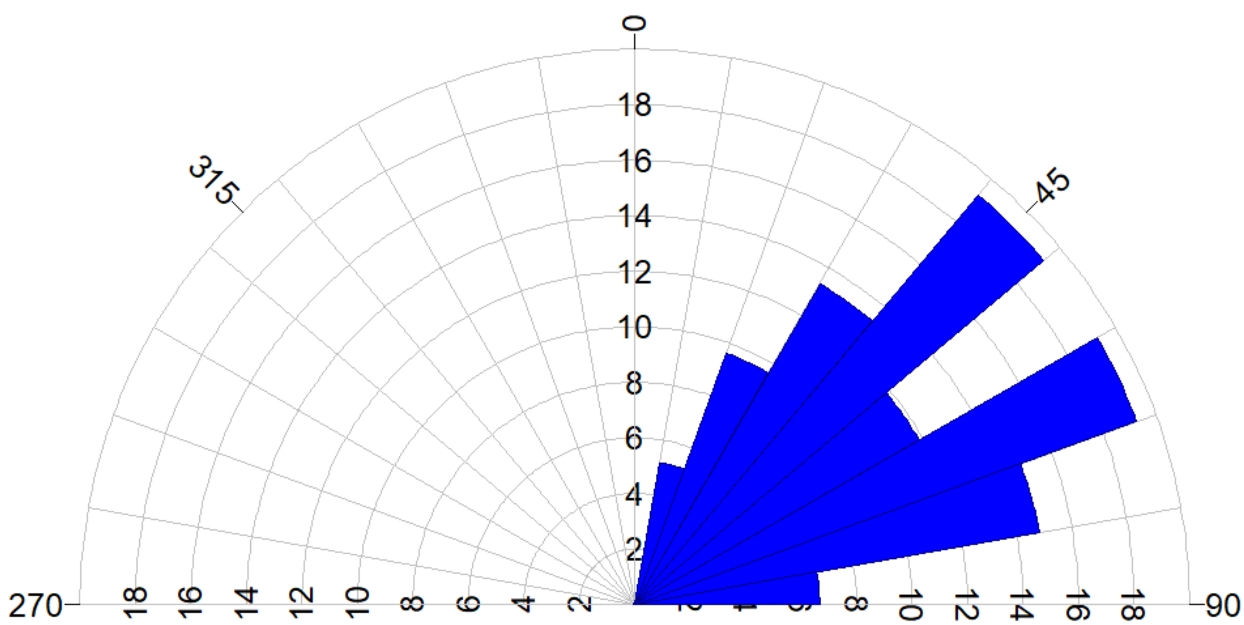
All directions are with respect to Magnetic North.

Figure RC-02:7. Rose Diagram – Dip Directions
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019



All directions are with respect to Magnetic North.

Figure RC-02:8. Rose Diagram – Dip Angles
Televiewer Image Features
Jacobs
Union Pacific
RC-02
26 April 2019



All directions are with respect to Magnetic North.

FIGURE RC-02:1. Ambient Temperature and Fluid Electrical Conductivity; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

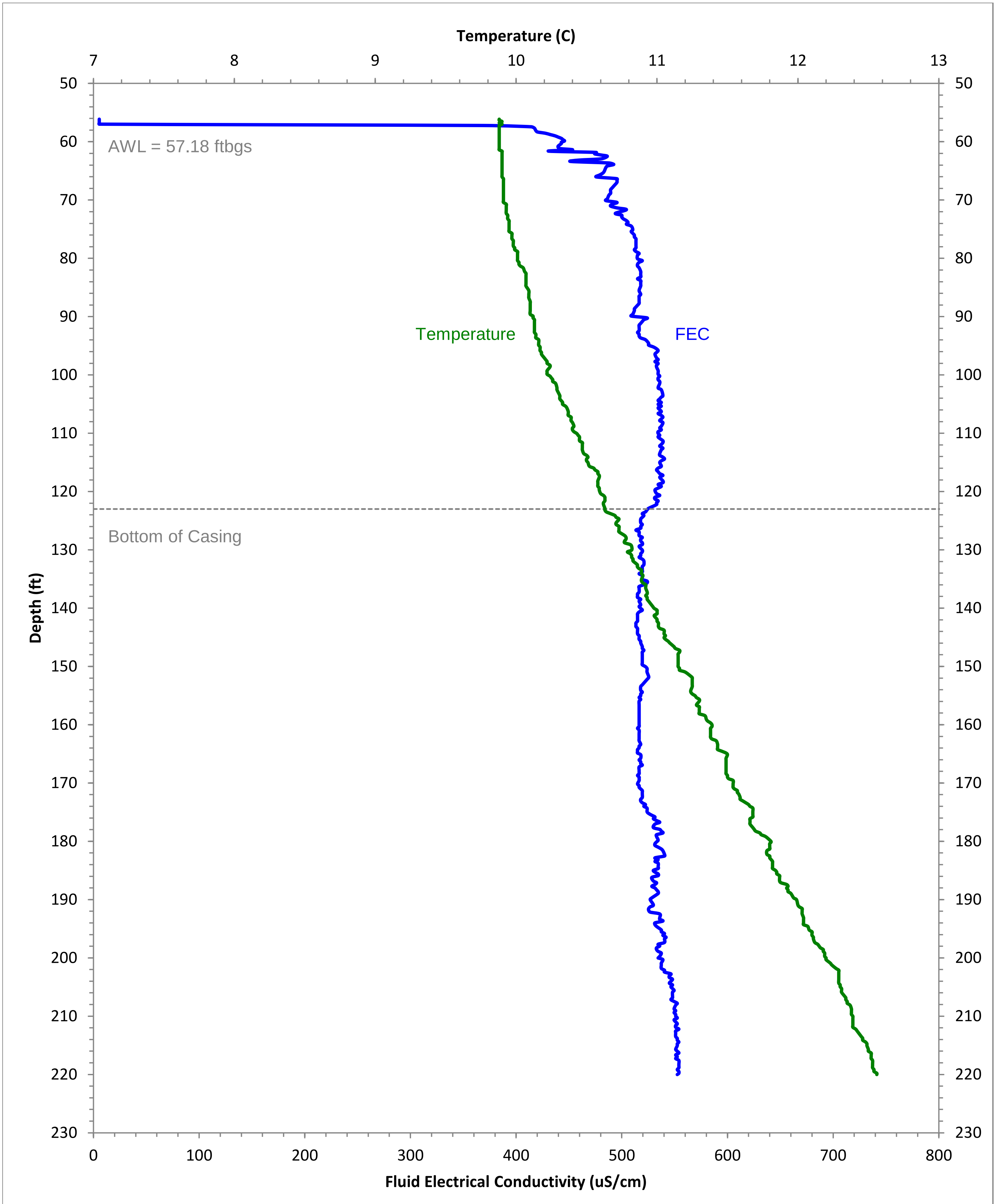


FIGURE RC-02:2. Summary of Hydrophysical Logs During Ambient Flow Characterization; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

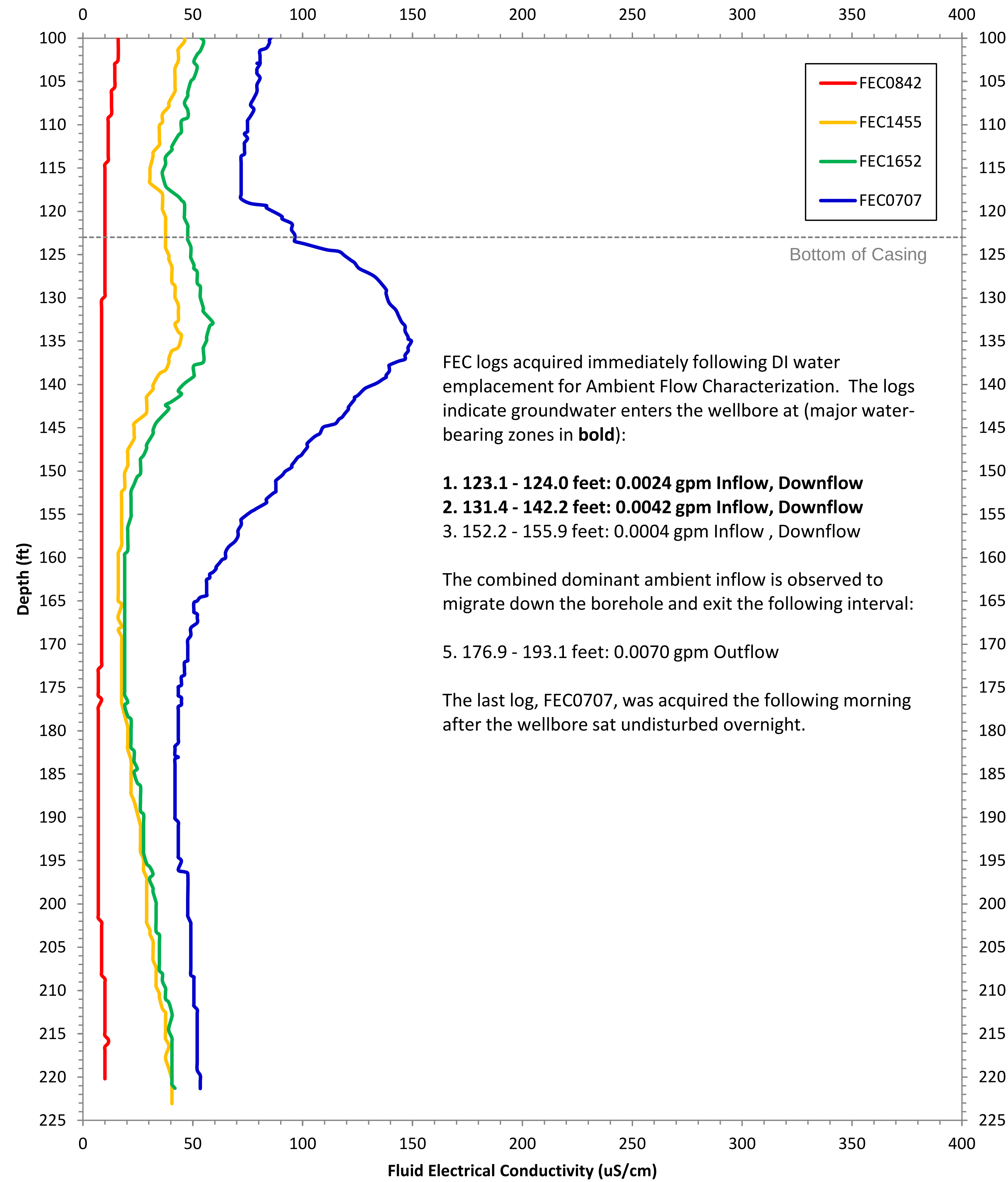


FIGURE RC-02:3. Pumping And Drawdown Data During 10 GPM Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

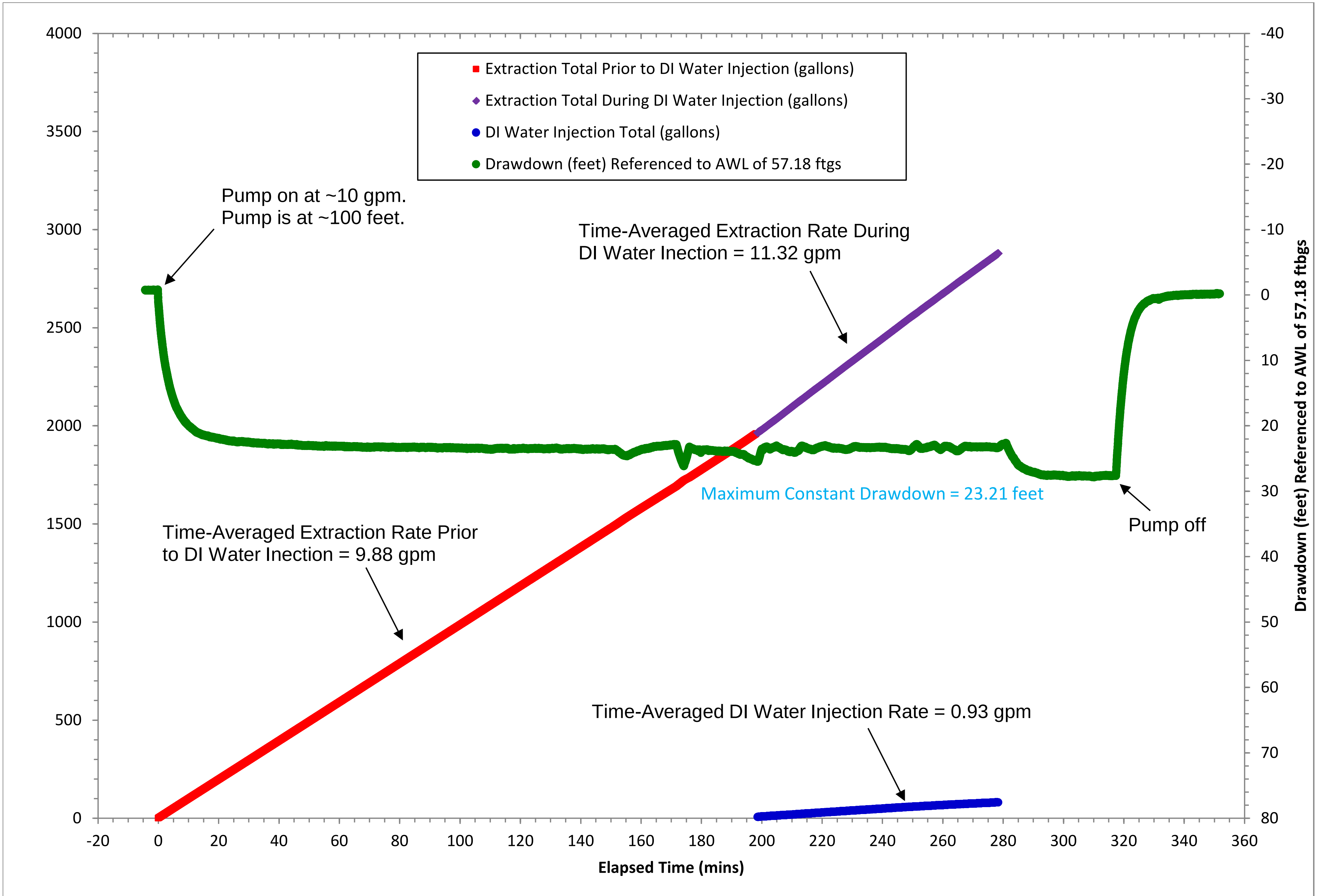


FIGURE RC-02:4A. Summary of Hydrophysical Logs During 10 GPM Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

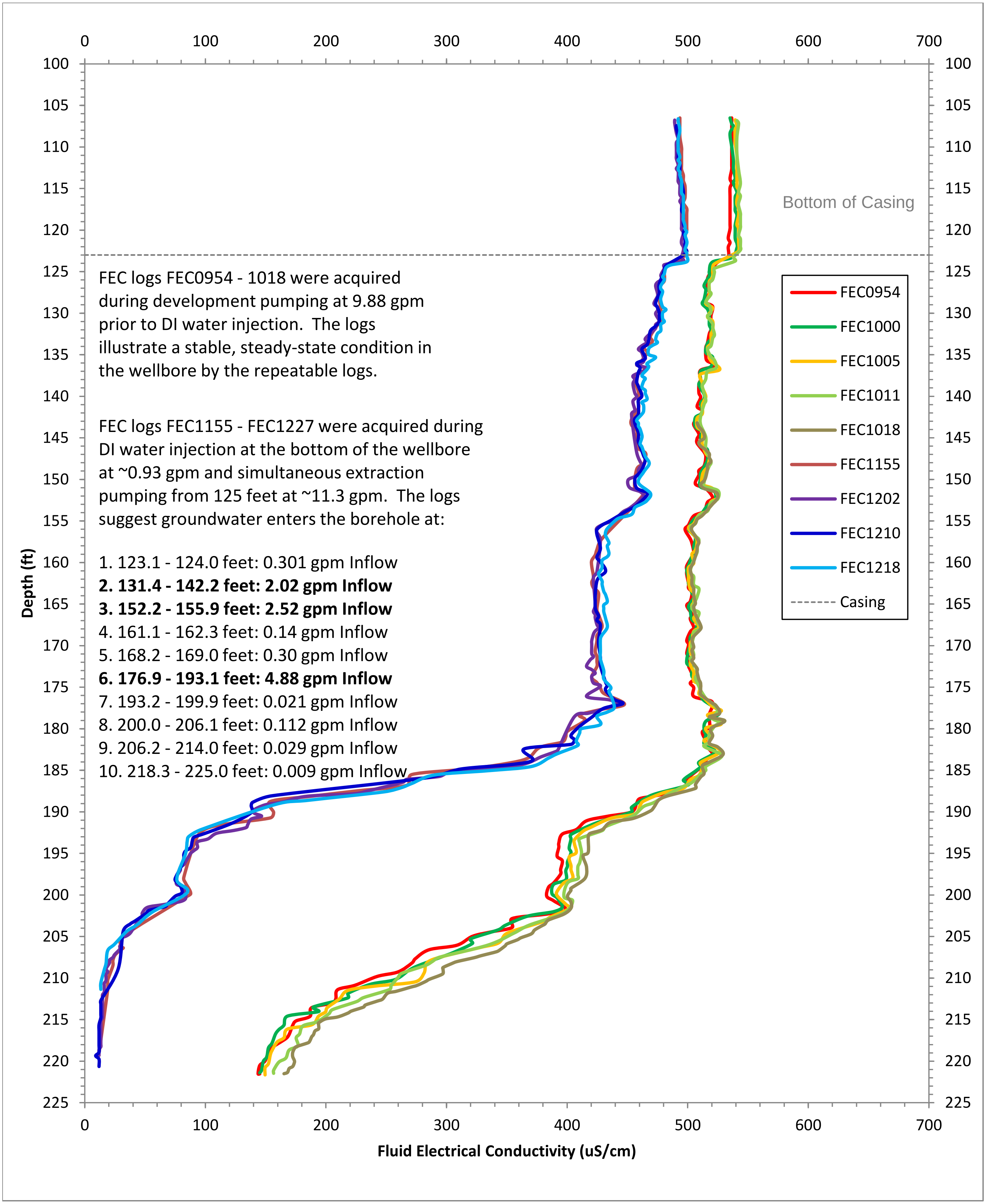


FIGURE RC-02:4B. Summary of Hydrophysical Logs During Re-Development Pumping at 11.3 gpm After the Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

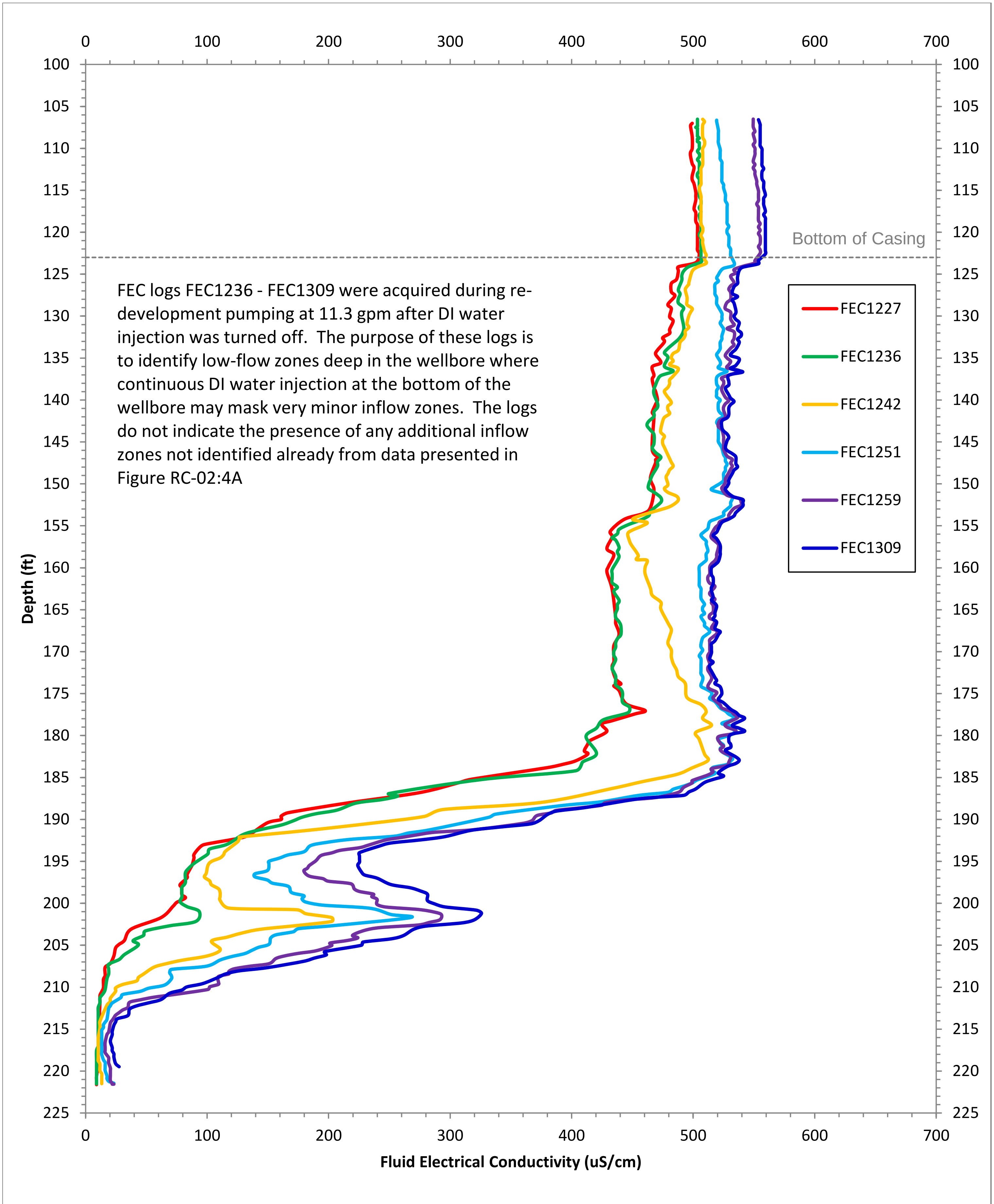


Table RC-02:1. Summary Of Hydrophysical Logging Results With Hydraulic Conductivity And Transmissivity Estimations; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

Well Name	RC-02
Ambient Depth to Water (ftbtoc)	57.93
Ambient Depth to Water (ftbgs)	57.18
Cased Interval (ftbgs)	0 - 123.1

Diameter of Well (ft)	0.46
Maximum Drawdown (ft)	23.21
Effective Radius (ft)	100
Well Specific Capacity (gpm/ft-dd)	0.45

Hydrophysical Logging Results - RC-02

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Length of Interval (ft)	Ambient Flow[1] (gpm)	Darcy Velocity in Aquifer[2] (ft/day)	Interval-Specific Flow Rate During Pumping (gpm)	Interval-Specific Hydraulic Conductivity[3] (ft/day)	Transmissivity (ft^2/day)	Interval-Specific Fluid Electrical Conductivity (uS/cm)
1*	123.1	124.0	0.9	0.0024	NA	0.301	2.66E+00	2.40E+00	595
2	131.4	142.2	10.8	0.0042	NA	2.02	1.50E+00	1.62E+01	584
3	152.2	155.9	3.7	0.0004	NA	2.52	5.46E+00	2.02E+01	519
4	161.1	162.3	1.2	0.0000	NA	0.140	9.36E-01	1.12E+00	504
5	168.2	169.0	0.8	0.0000	NA	0.300	3.01E+00	2.41E+00	497
6	176.9	193.1	16.2	-0.0070	NA	4.88	2.42E+00	3.92E+01	505
7	193.2	199.9	6.7	0.0000	NA	0.021	2.51E-02	1.68E-01	519
8	200.0	206.1	6.1	0.0000	NA	0.112	1.47E-01	8.99E-01	519
9	206.2	214.0	7.8	0.0000	NA	0.029	2.98E-02	2.33E-01	519
10	218.3	225.0	6.7	0.0000	NA	0.009	1.08E-02	7.22E-02	519
Borehole Transmissivity Using Thiem Equation (ft^2/day)								**8.29E+01**	
Borehole Hydraulic Conductivity (K=T/b; b=length of open interval of 123'-224.8' = 101.8') (ft/day)							**8.14E-01**		

Note: Negative flow, if any, is outflow from the borehole to the aquifer, positive flow is inflow to the borehole.

* The top of this interval is assumed to be the bottom of the casing.

[1] Downward vertical flow is identified in this borehole under ambient conditions.

[2] Darcy Velocity, or Specific Discharge in aquifer, is calculated using the observed volumetric flow rate, the cross-sectional area of the flow interval in the wellbore and a wellbore convergence factor of 3.0 (Drost, 1968). The Darcy Velocity is only applicable to ambient horizontal flow.

All depths reported herein are referenced to ground surface.

NA = Not Applicable

FIGURE RC-02:9A. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 142.0 Feet to WL; Jacobs; Union Pacific; Wellbore: RC-02

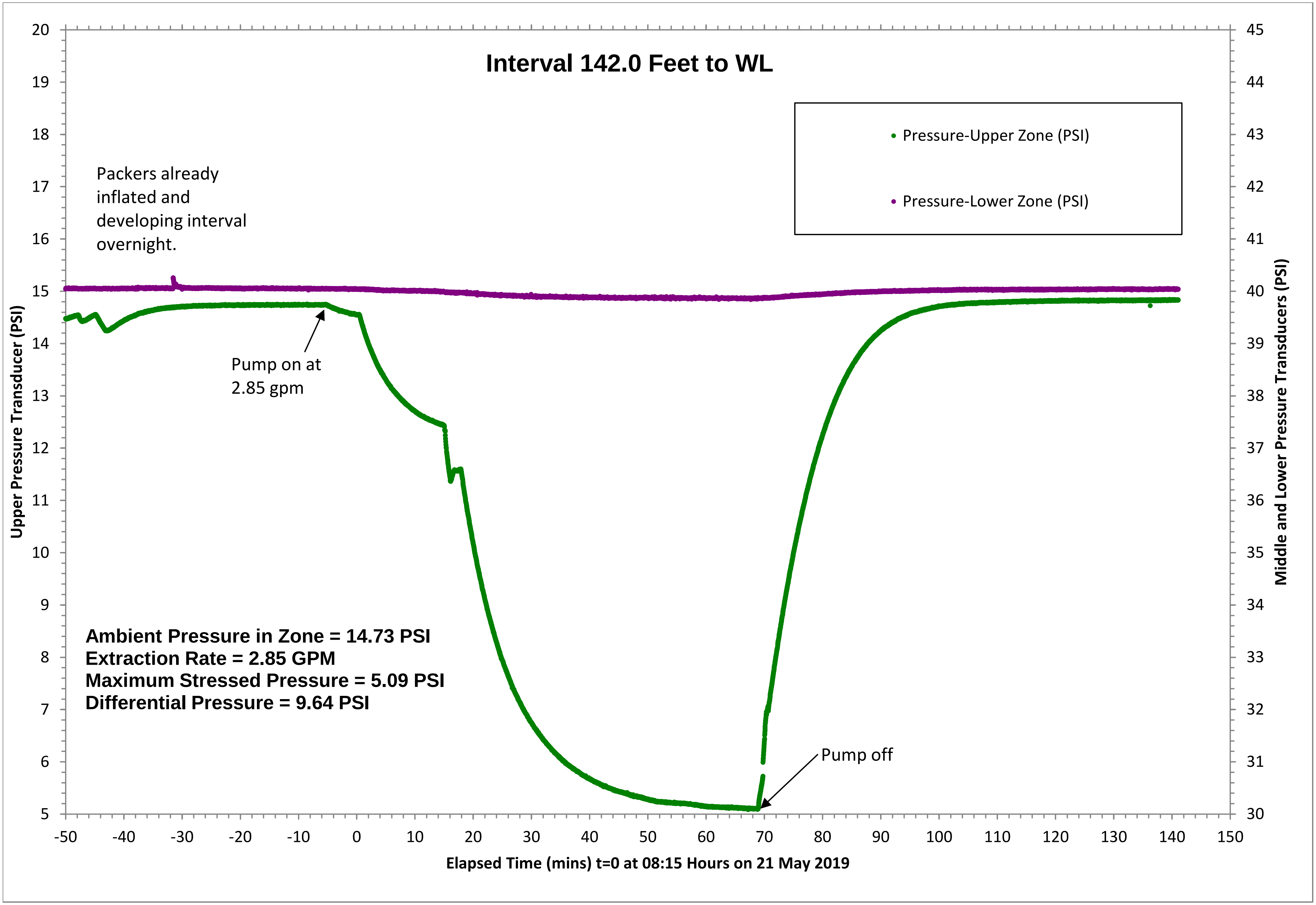


FIGURE RC-02:9B. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 145.5 to 156.0 Feet; Jacobs; Union Pacific; Wellbore: RC-02

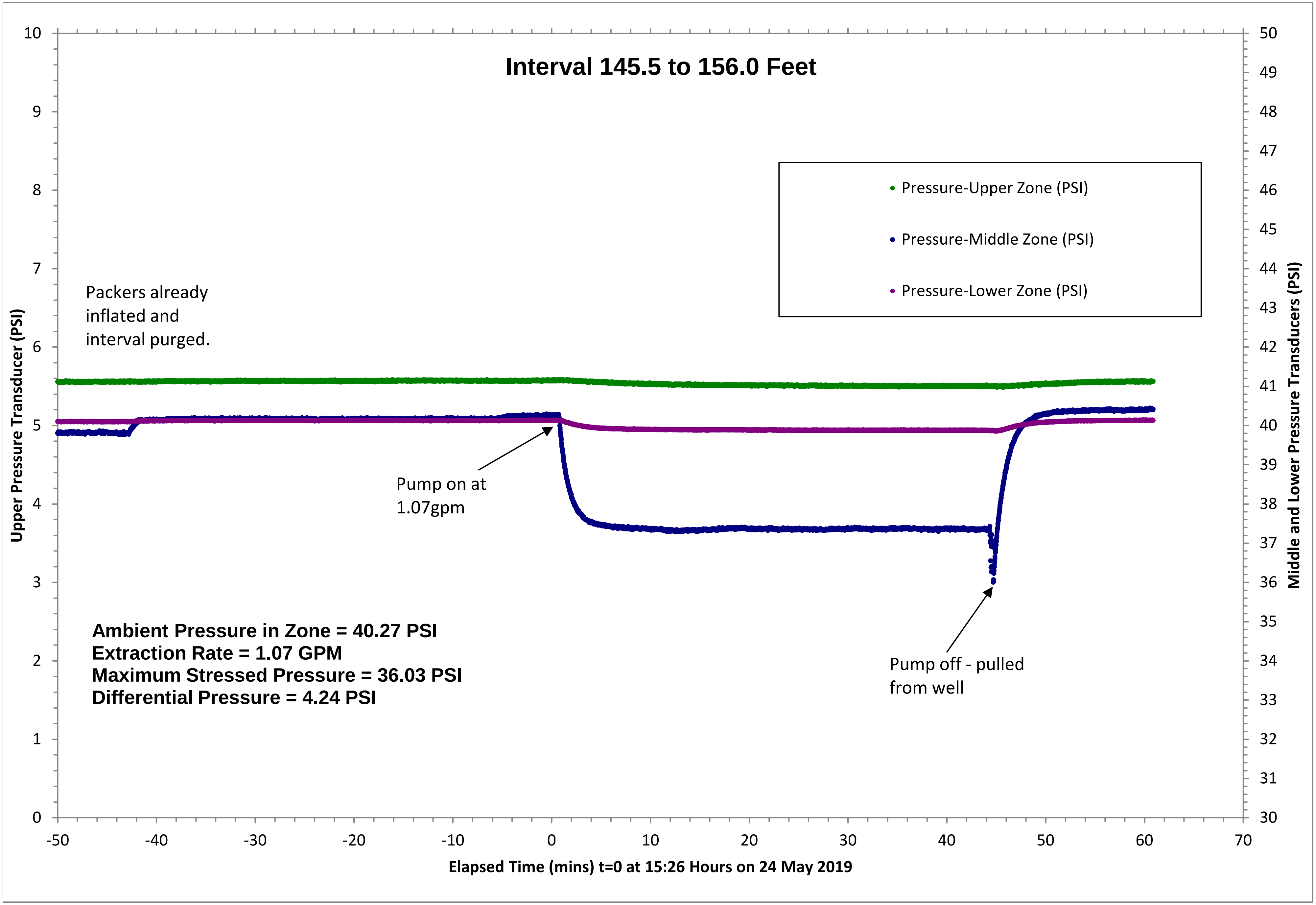


FIGURE RC-02:9C. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 156.0 Feet to TD; Jacobs; Union Pacific; Wellbore: RC-02

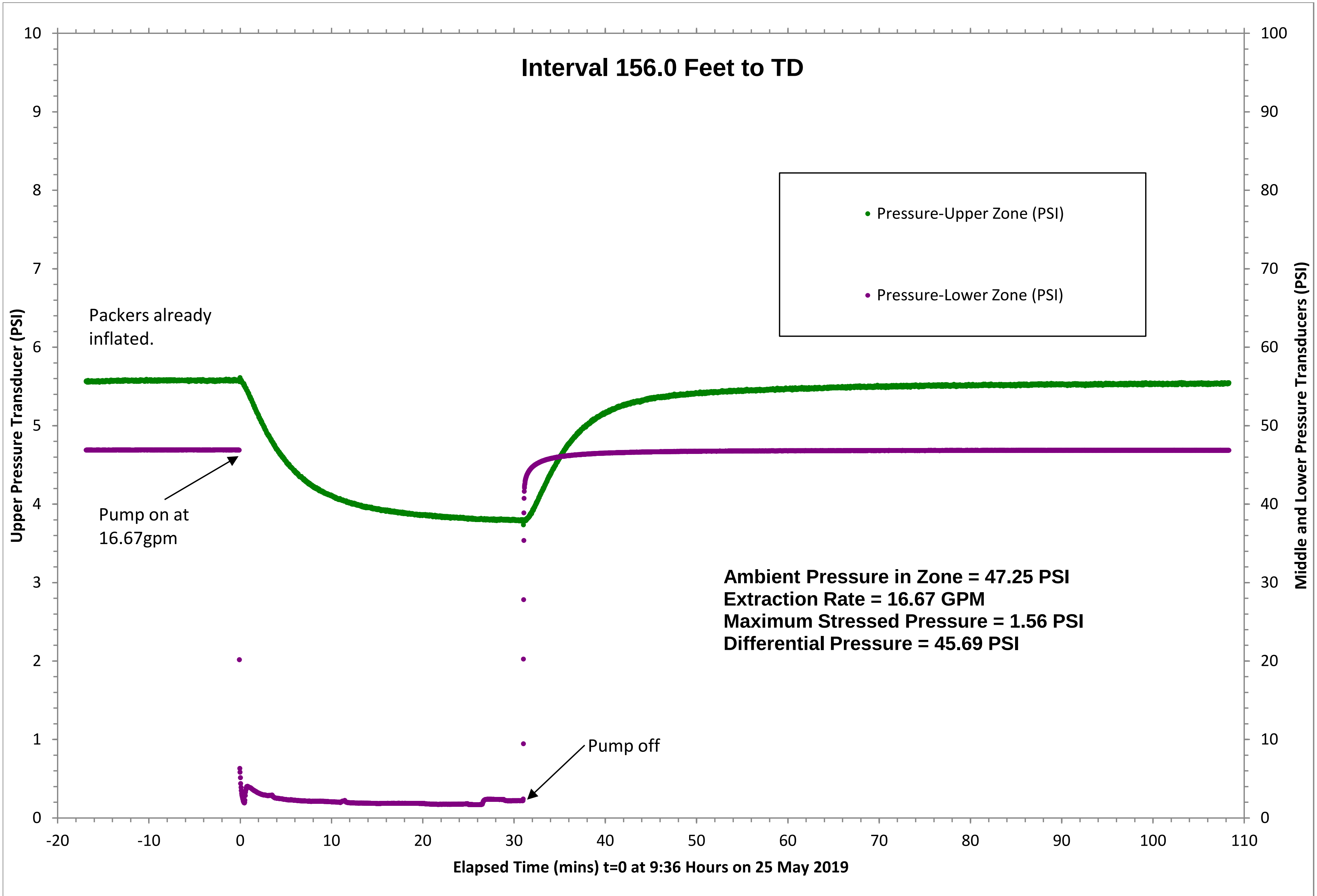


FIGURE RC-02:9D. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 192.0 Feet to TD; Jacobs; Union Pacific; Wellbore: RC-02

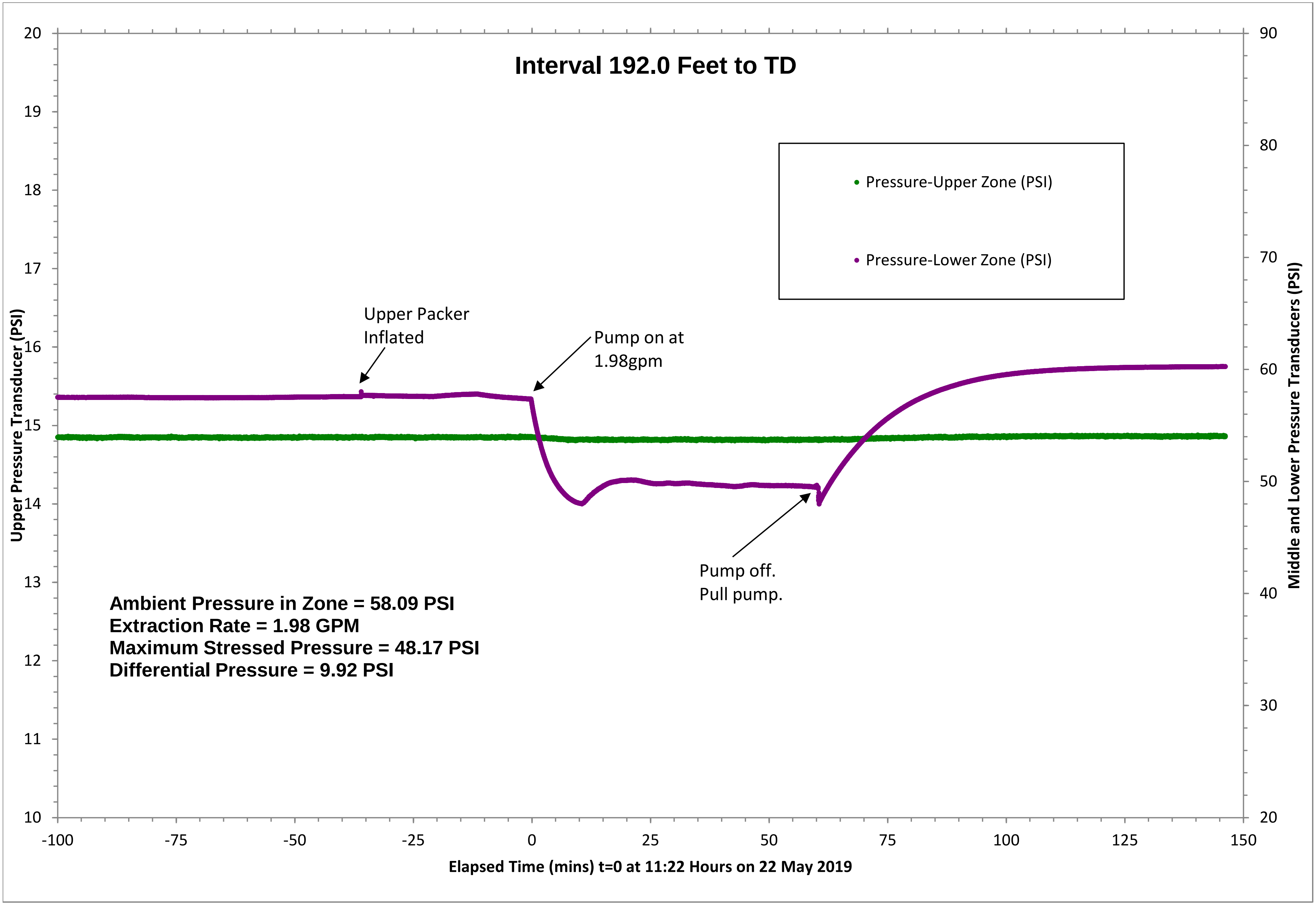


Table RC-02:3. Summary Of Wireline Straddle Packer Testing With Hydraulic Conductivity And Transmissivity Estimations; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-02

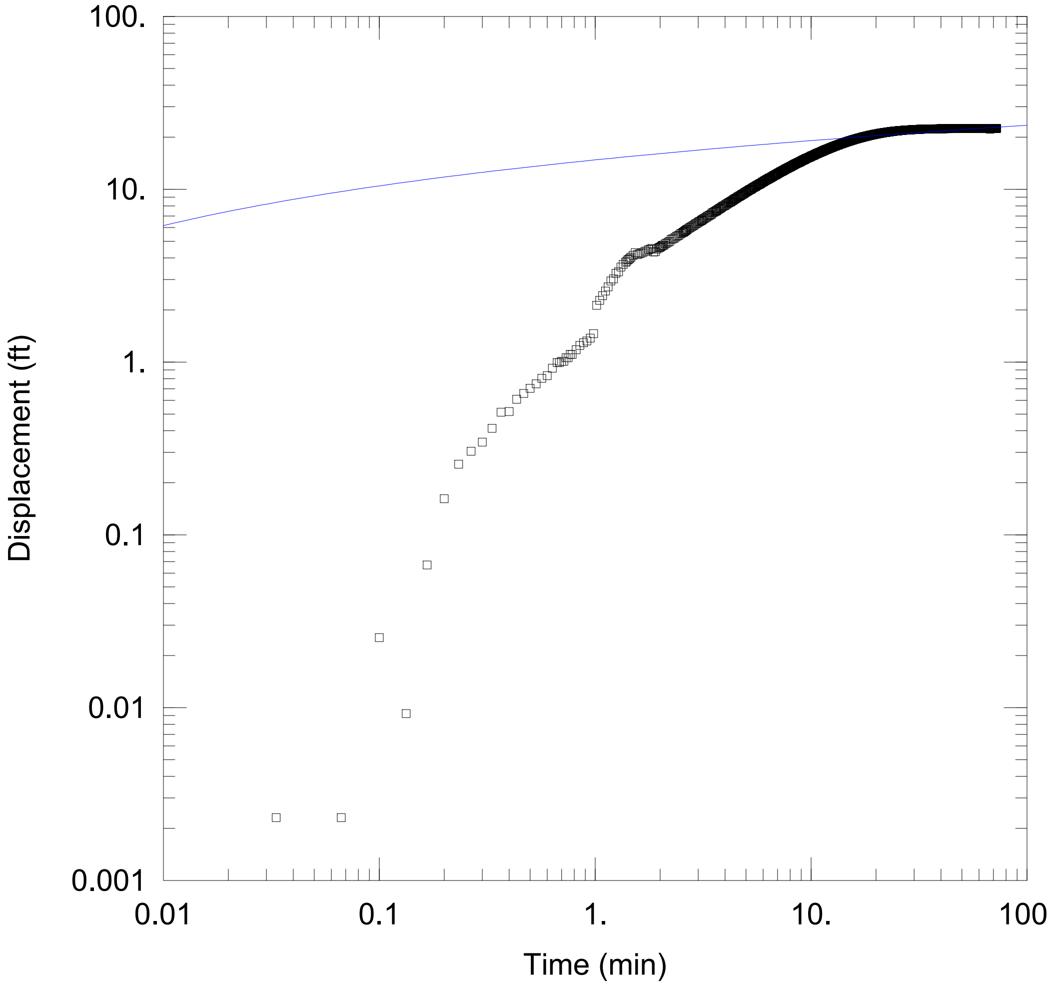
Well Name	RC-02
Ambient Depth to Water (ftbgs)	57.07
Diameter of Borehole (ft)	0.46
Effective Radius (ft)	100

Wireline Straddle Packer Testing Results - RC-02

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Length of Interval (ft)	Differential Pressure (psi)	Drawdown (feet)[1]	Interval Specific Extraction Rate: WSP Stress Test (gpm)	Interval Specific Extraction Rate: WSP Stress Test (ft^3/min)	Interval Specific Hydraulic Conductivity (ft/day)	Thiem Method Transmissivity (ft2/day)	AQTESOLV (Theis) Method Transmissivity (ft2/day)
1	57.1	142.0	84.9	9.64	22.26	2.85	0.381	2.81E-01	2.38E+01	2.32E+01
2	145.5	156.0	10.5	4.24	9.79	1.07	0.143	1.94E+00	2.03E+01	2.05E+01
3	156.0	225.0	69.0	45.69	105.52	16.67	2.229	4.26E-01	2.94E+01	4.29E+01
4	192.0	225.0	33.0	9.92	22.91	1.98	0.265	4.88E-01	1.61E+01	1.81E+01

[1] Drawdown is the difference between ambient pressure and stressed pressure, converted to feet.

Figure RC-02:10A. AQTESOLV Analysis Using Theis Solution: Interval 142ft to WL; Jacobs; Union Pacific; Spokane, WA; Wellbore: RC-02



WELL TEST ANALYSIS

Data Set: RC-02 - WSP 142ft to WL.aqt

Date: 06/07/19 Time: 14:32:53

PROJECT INFORMATION

Company: Colog, Inc.
Client: Jacobs
Project: Union Pacific
Location: Freeman, WA
Test Well: RC-02
Test Date: 21 May 2018

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RC-02	0	0

Observation Wells

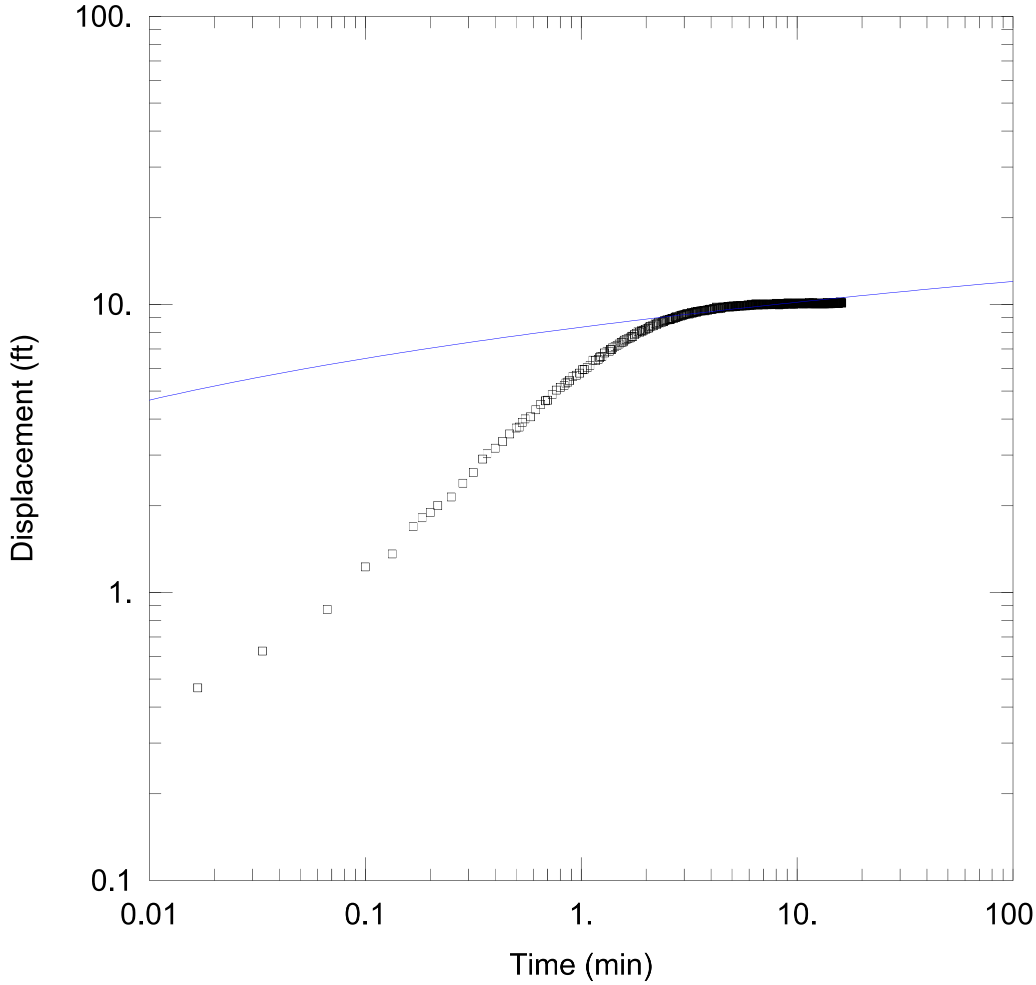
Well Name	X (ft)	Y (ft)
□ RC-02	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Theis

T = 23.22 ft^2/day S = 0.0002646
Kz/Kr = 1. b = 84.93 ft

Figure RC-02:10B. AQTESOLV Analysis Using Theis Solution: Interval 145.5 - 156.0 Feet; Jacobs; Union Pacific; Spokane, WA; Wellbore: RC-02



WELL TEST ANALYSIS

Data Set: RC-02 - WSP 145.5 to 156.0ft.aqt

Date: 06/07/19 Time: 15:30:48

PROJECT INFORMATION

Company: Colog, Inc.
Client: Jacobs
Project: Union Pacific
Location: Freeman, WA
Test Well: RC-02
Test Date: 21 May 2018

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RC-02	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ RC-02	0	0

SOLUTION

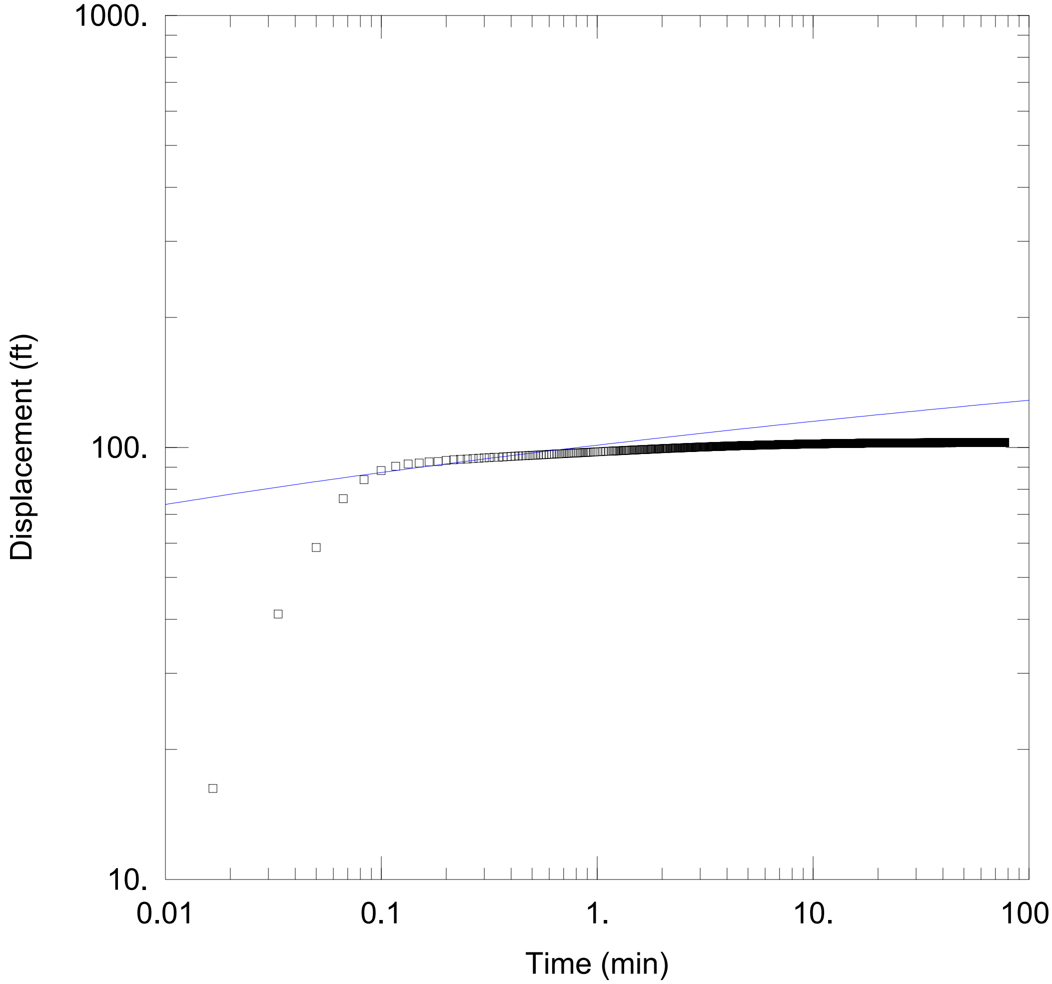
Aquifer Model: Confined

Solution Method: Theis

T = 20.49 ft^2/day
Kz/Kr = 1.

S = 1.803E-5
b = 10.5 ft

Figure RC-02:10C. AQTESOLV Analysis Using Theis Solution: Interval 156ft to TD; Jacobs; Union Pacific; Spokane, WA; Wellbore: RC-02



WELL TEST ANALYSIS

Data Set: RC-02 WSP 156ft to TD.aqt

Date: 06/07/19 Time: 15:30:29

PROJECT INFORMATION

Company: Colog, Inc.
Client: Jacobs
Project: Union Pacific
Location: Freeman, WA
Test Well: RC-02
Test Date: 21 May 2018

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RC-02	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ RC-02	0	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

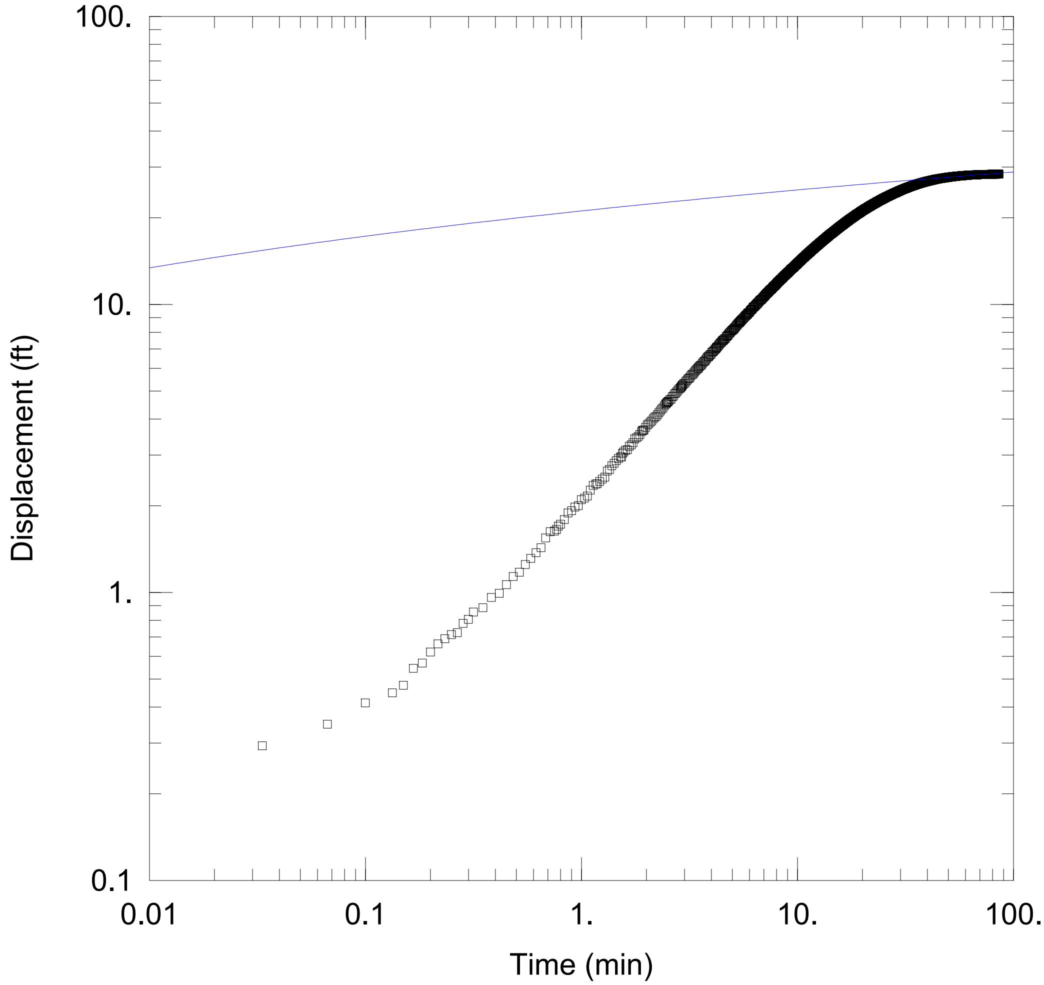
T = 42.9 ft^2/day

S = 5.235E-8

Kz/Kr = 1.

b = 69. ft

Figure RC-02:10D. AQTESOLV Analysis Using Theis Solution: Interval 192ft to WL; Jacobs; Union Pacific; Spokane, WA; Wellbore: RC-02



WELL TEST ANALYSIS

Data Set: RC-02 WSP 192ft to TD.aqt

Date: 06/07/19 Time: 15:30:11

PROJECT INFORMATION

Company: Colog, Inc.
Client: Jacobs
Project: Union Pacific
Location: Freeman, WA
Test Well: RC-02
Test Date: 21 May 2018

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RC-02	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ RC-02	0	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

T = 18.09 ft^2/day

S = 1.809E-6

Kz/Kr = 1.

b = 33. ft

APPENDIX B

RC-03 GEOPHYSICAL & HYDROPHYSICAL DATA RESULTS

FIGURE RC-03:1. Ambient Temperature and Fluid Electrical Conductivity; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

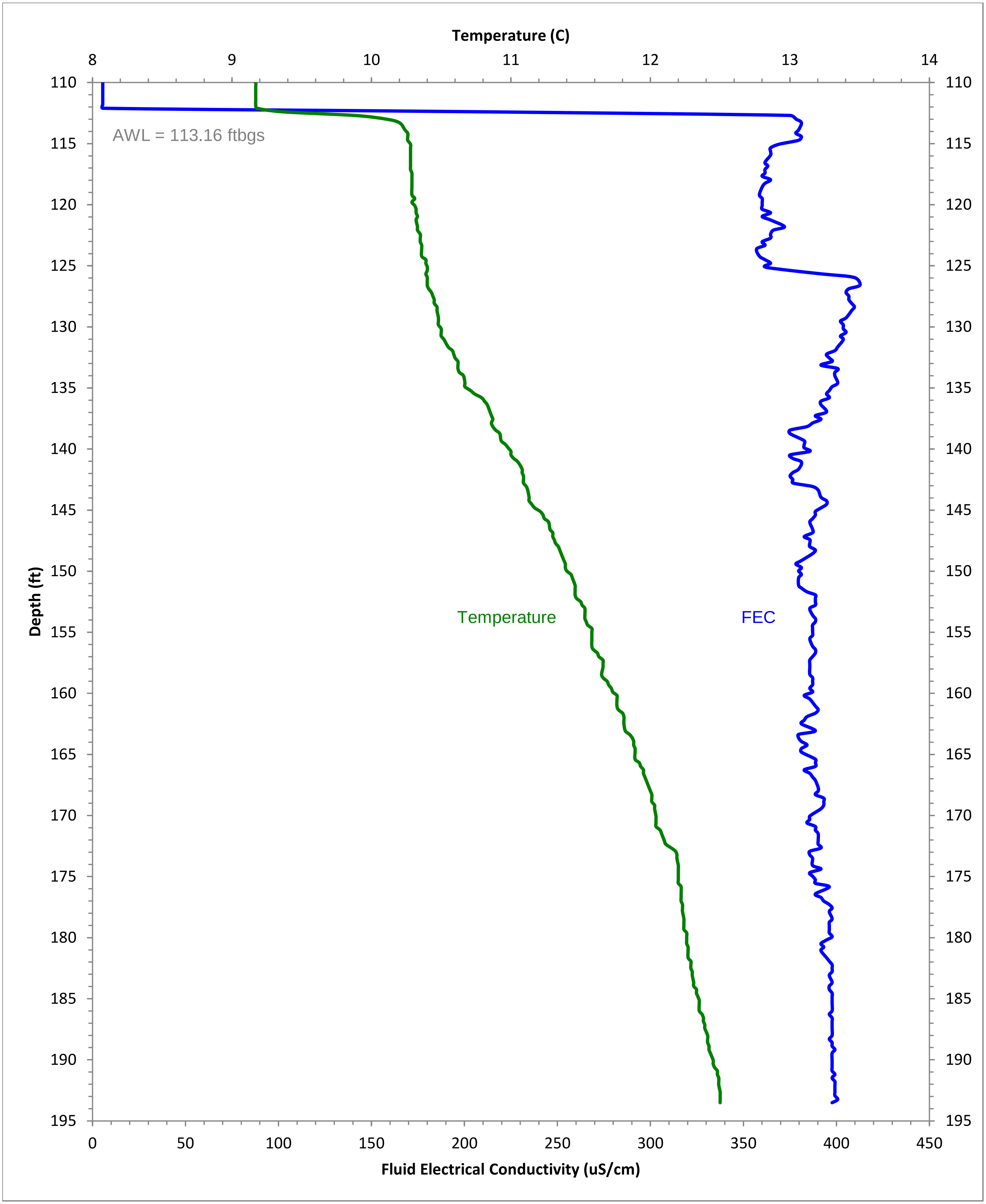


FIGURE RC-03:2. Summary of Hydrophysical Logs During Ambient Flow Characterization; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

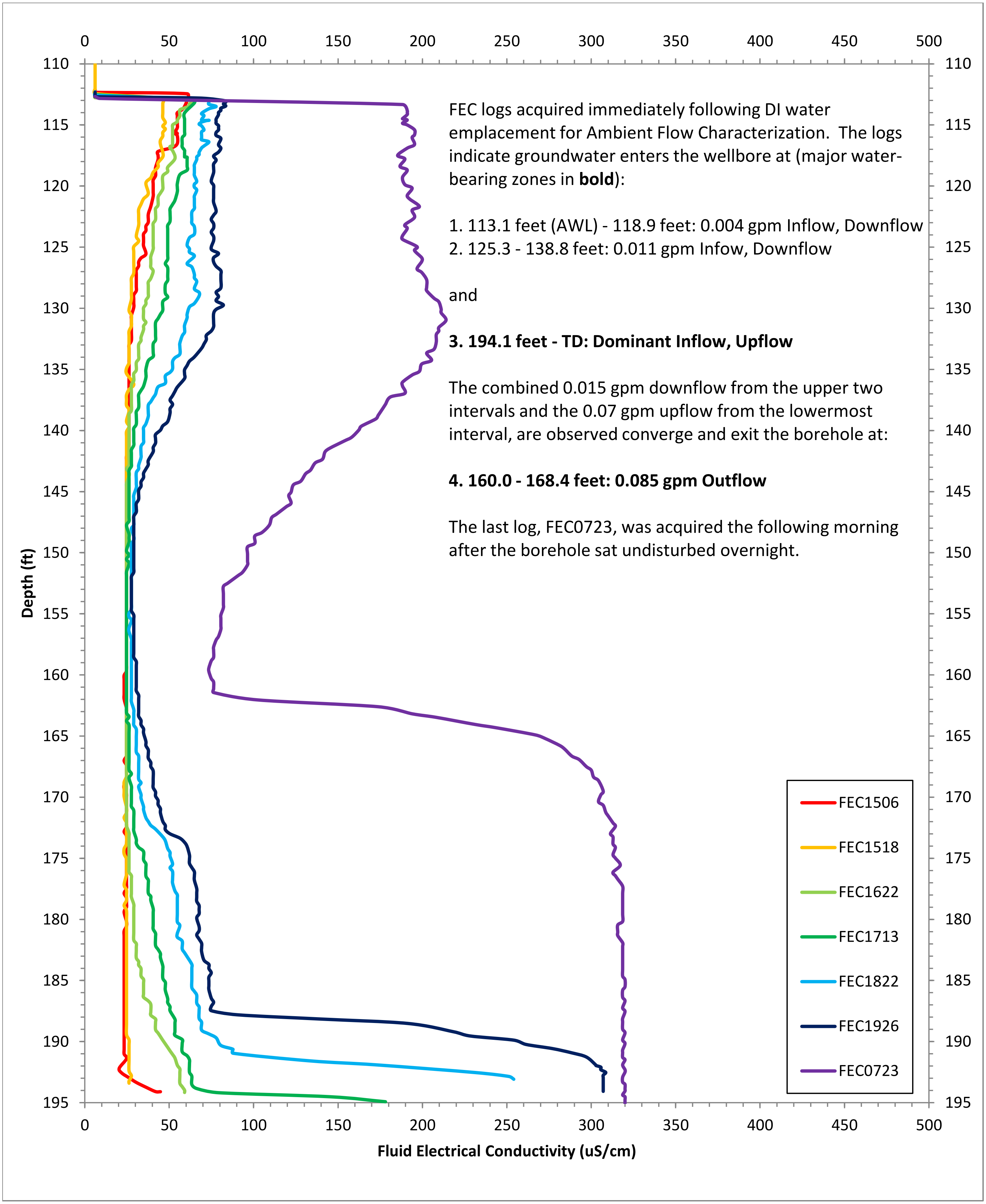


FIGURE RC-03:3. Pumping And Drawdown Data During 13 GPM Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

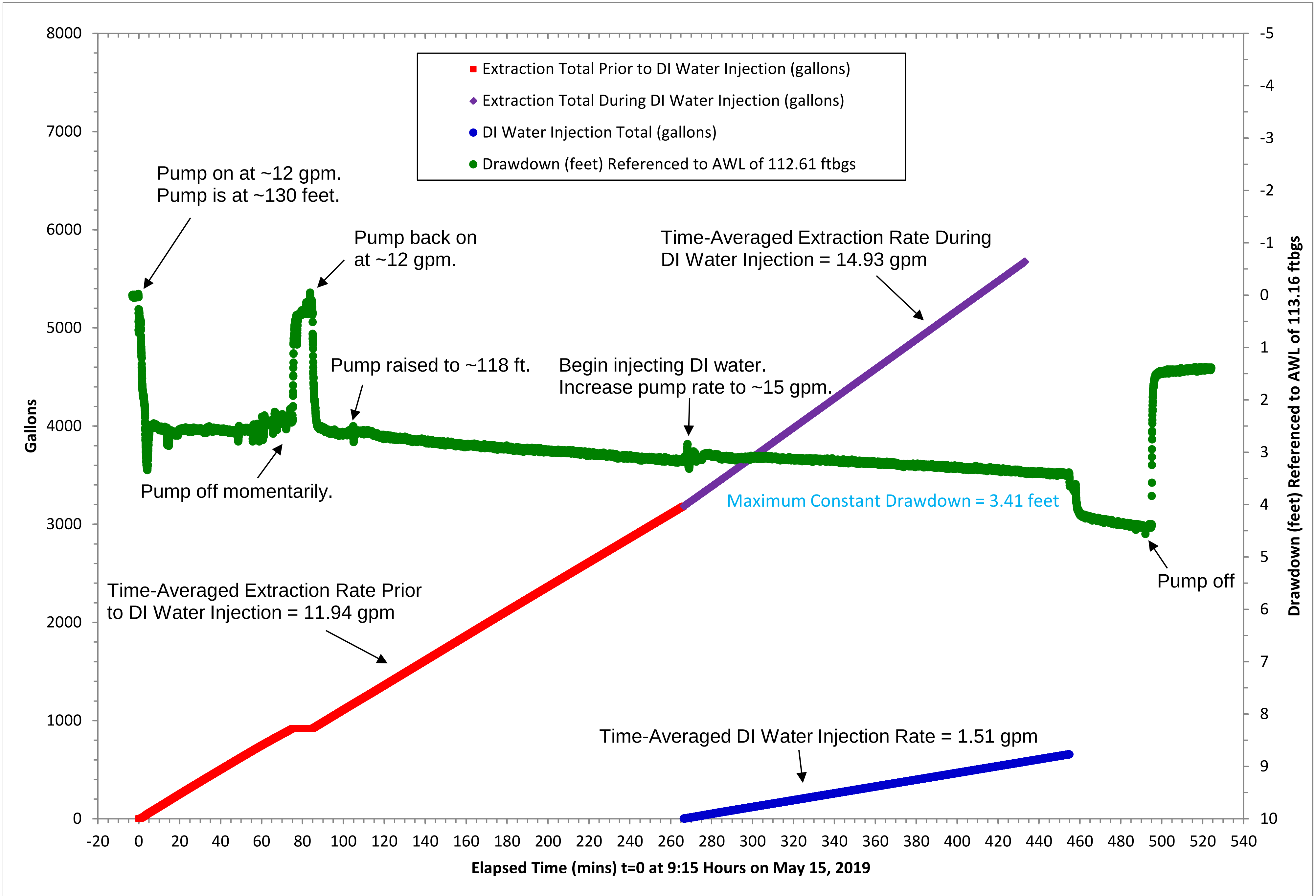


FIGURE RC-03:4A. Summary of Hydrophysical Logs During 13 GPM Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

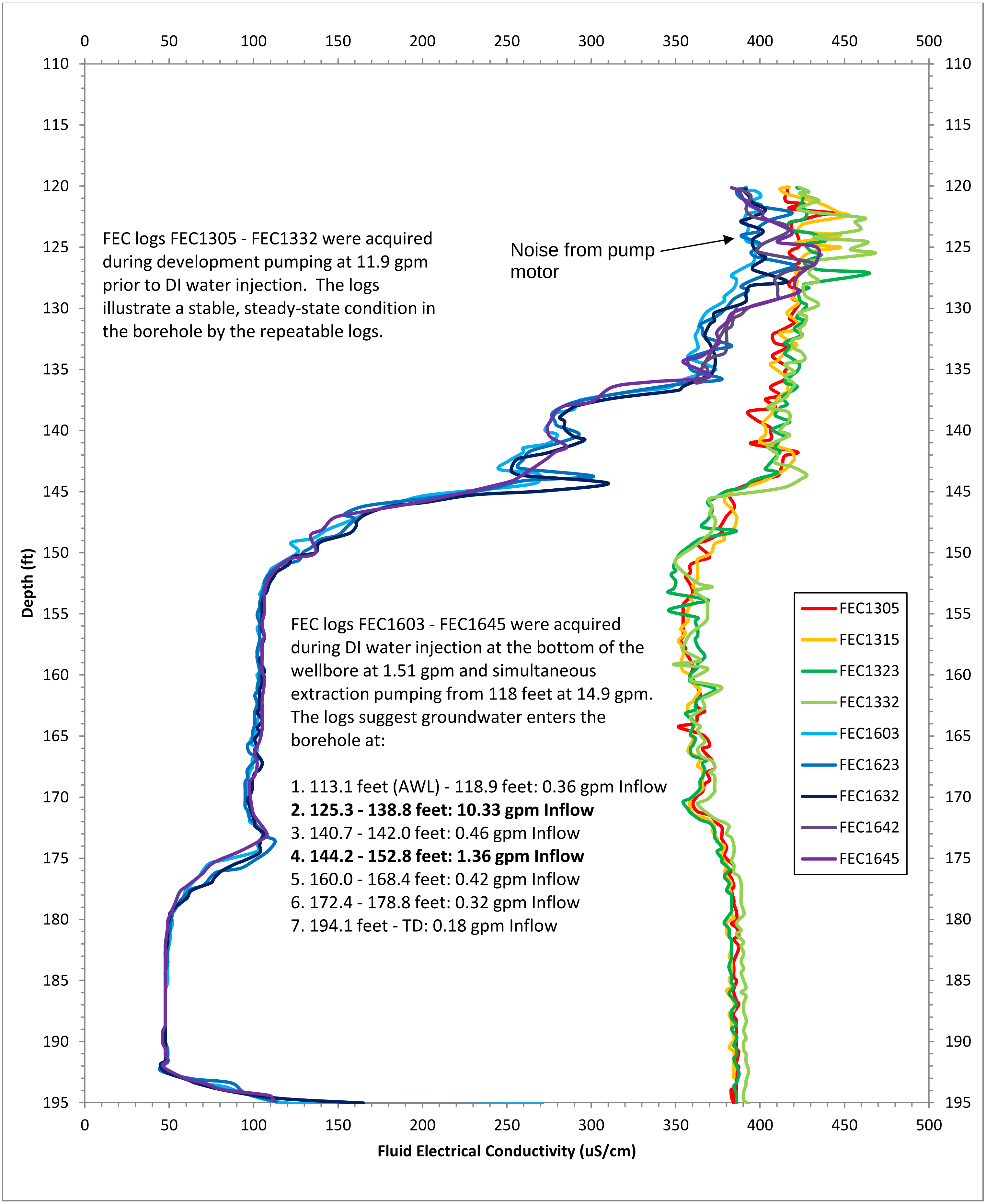


FIGURE RC-03:4B. Summary of Hydrophysical Logs During Re-Development Pumping at 14.93 gpm After the Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

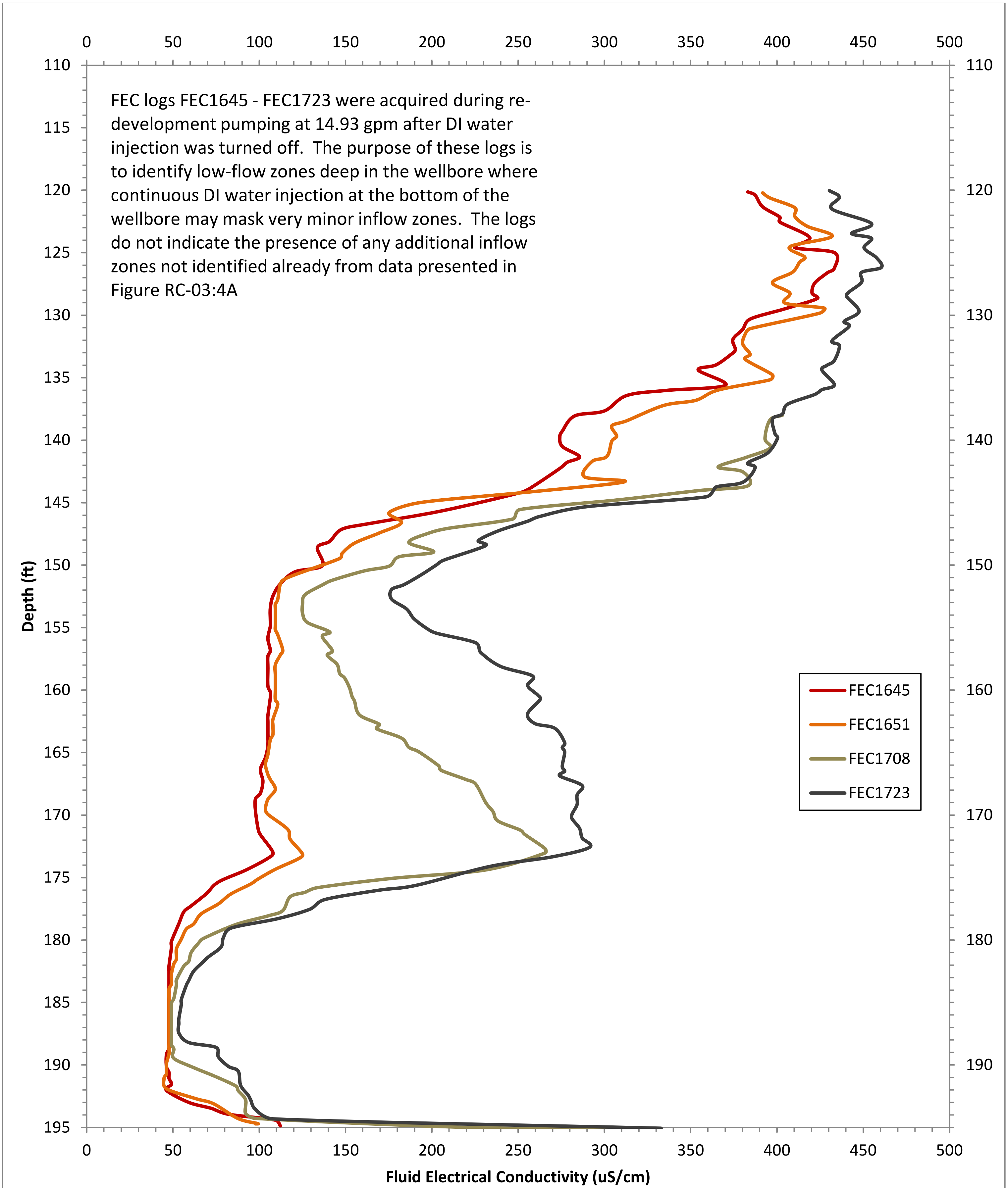


Table RC-03:1. Summary Of Hydrophysical Logging Results With Hydraulic Conductivity And Transmissivity Estimations; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-03

Well Name	RC-03
Ambient Depth to Water (ftbtoc)	115.62
Ambient Depth to Water (ftbgs)	113.16
Cased Interval (ftbgs)	0 - 83.0

Diameter of Well (ft)	0.46
Maximum Drawdown (ft)	3.41
Effective Radius (ft)	100
Well Specific Capacity (gpm/ft-dd)	3.94

Hydrophysical Logging Results - RC-03

Interval No.	Top of Interval (ft)	Bottom of Interval (ft)	Length of Interval (ft)	Ambient Flow[1] (gpm)	Darcy Velocity in Aquifer[2] (ft/day)	Interval-Specific Flow Rate During Pumping (gpm)	Interval-Specific Hydraulic Conductivity[3] (ft/day)	Transmissivity (ft^2/day)	Interval-Specific Fluid Electrical Conductivity (uS/cm)
1*	113.1	118.9	5.8	0.004	NA	0.36	3.35E+00	1.94E+01	360
2	125.3	138.8	13.5	0.011	NA	10.33	4.17E+01	5.64E+02	429
3	140.7	142.0	1.3	0.000	NA	0.46	1.93E+01	2.51E+01	411
4	144.2	152.8	8.6	0.000	NA	1.36	8.64E+00	7.43E+01	427
5	160.0	168.4	8.4	-0.085	NA	0.42	3.28E+00	2.76E+01	359
6	172.4	178.8	6.4	0.000	NA	0.32	2.73E+00	1.75E+01	366
7	194.1	196.5	2.4	0.070	NA	0.18	2.50E+00	6.01E+00	386
Borehole Transmissivity Using Thiem Equation (ft^2/day)								**7.33E+02**	
ole Hydraulic Conductivity (K=T/b; b=length of saturated interval of 113.1'-196.5' = 83.4') (ft/day)							**8.79E+00**		

Note: Negative flow, if any, is outflow from the borehole to the aquifer, positive flow is inflow to the borehole.

* The top of this interval is assumed to be the bottom of the casing.

[1] Downward and upward vertical flow are identified in this borehole under ambient conditions.

[2] Darcy Velocity, or Specific Discharge in aquifer, is calculated using the observed volumetric flow rate, the cross-sectional area of the flow interval in the wellbore and a wellbore convergence factor of 3.0 (Drost, 1968). The Darcy Velocity is only applicable to ambient horizontal flow.

All depths reported herein are referenced to ground surface.

NA = Not Applicable

borehole geophysics / hydrophysics

810 Quail Street
Suite E
Lakewood, Colorado
80215
Office: 303.279.0171
Fax: 303.278.0135
www.colog.com

Optical & Acoustic Televiewer 3-Arm Caliper

Company Jacobs
Well RC-03
Project Union Pacific
County Spokane
State WA

COMPANY Jacobs
WELL RC-03
PROJECT Union Pacific
COUNTY Spokane **STATE**

LOCATION
Freeman High School

QTR **SEC** **TWP** **RGE**

OTHER SERVICES
Hydrophysical Logging
WSP Testing

PERMANENT DATUM **ELEVATION**

LOG MEAS. FROM Ground Surface **ABOVE PERMANENT DATUM**

DRILLING MEAS. FROM

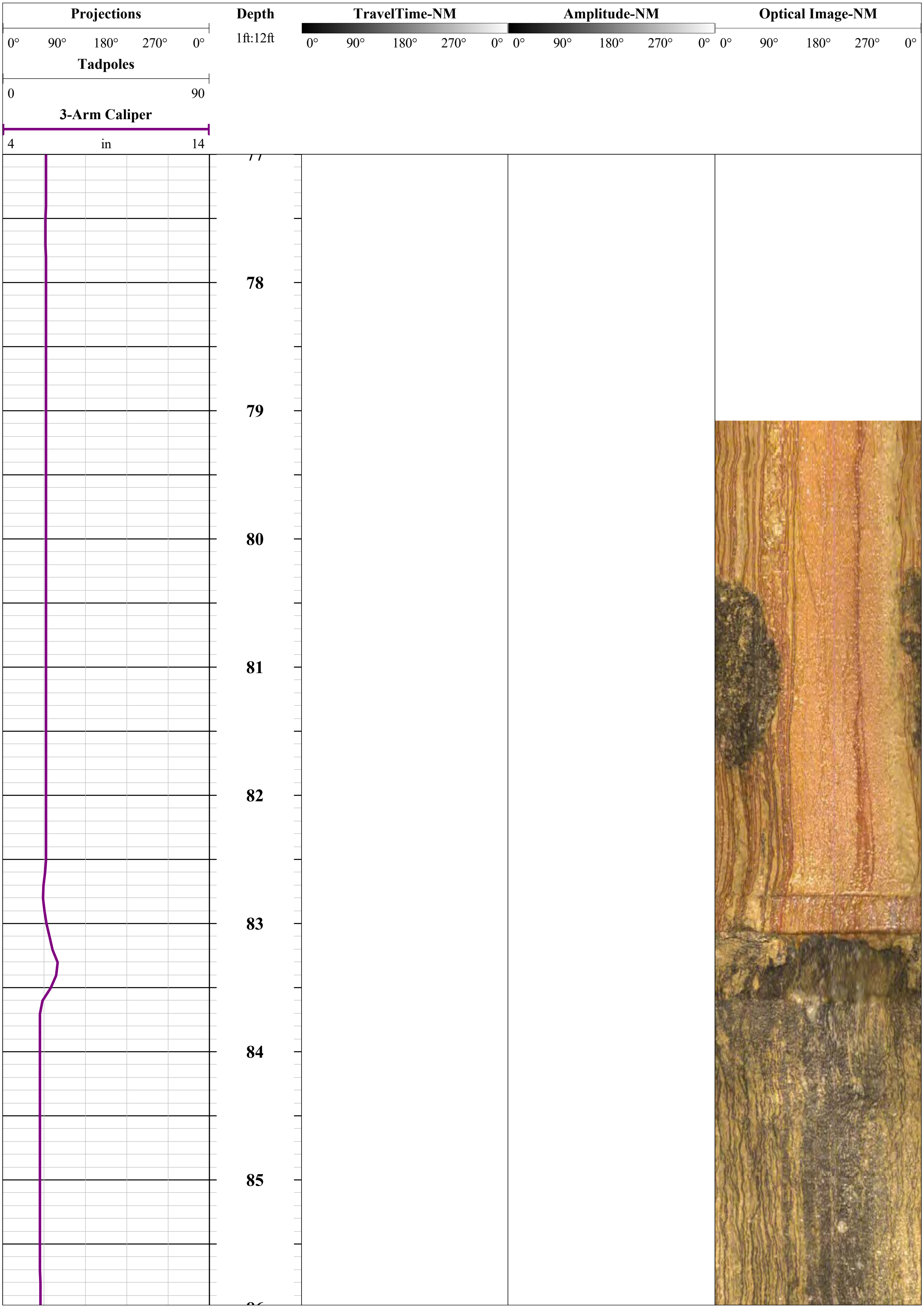
DATE ACQUIRED	4/25/2019	4/25/2019	4/25/2019	4/25/2019
RUN NUMBER	1,2	3	4,5,6	9
LOG TYPE	OBI	Fluid Temp. & Cond.	ABI	Caliper
DEPTH-DRILLER				
DEPTH-LOGGER	206.67			
BTM LOG INTERVAL	206.67	200.38	195.14	196.87
TOP LOG INTERVAL	79.05	106.05	111.03	66.55
RECORDED BY	BEH, KMG	BEH, KMG	BEH, KMG	BEH, KMG
WITNESSED BY				
PROBE TYPE, S/N	OBI40, 063702	HpL Probe	ABI40, 121206	2CAA, 5837
LOGGING SPEED	4 ft/min (down)	NA (down)	4 ft/min (up)	15 ft/min (up)
A.S.D.E. / Sample Interval	0.81 ft / 0.0075 ft	NA / NA	0.78 ft / 0.0075 ft	0.91 ft / 0.1 ft
Fluid Level / Fluid Type				

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**

COMMENTS

NA - Not Available, N/A - Not Applicable

AWL = 112.62 ftbgs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Tadpoles
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3-Arm Caliper
4 in 14
Depth
1ft:12ft
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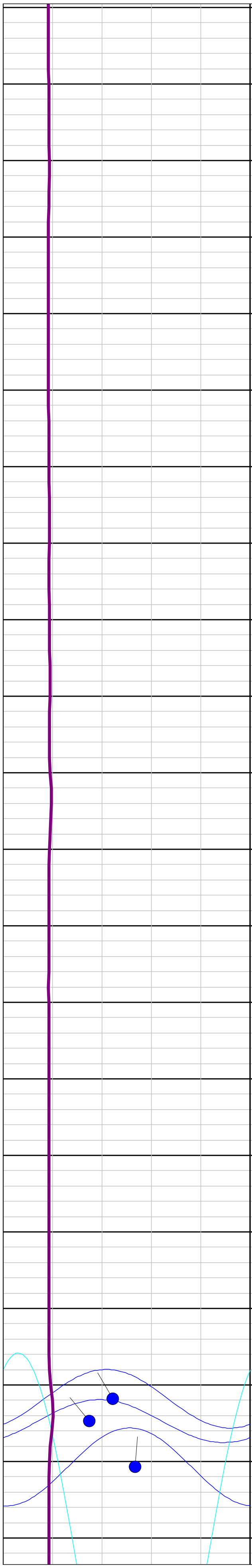

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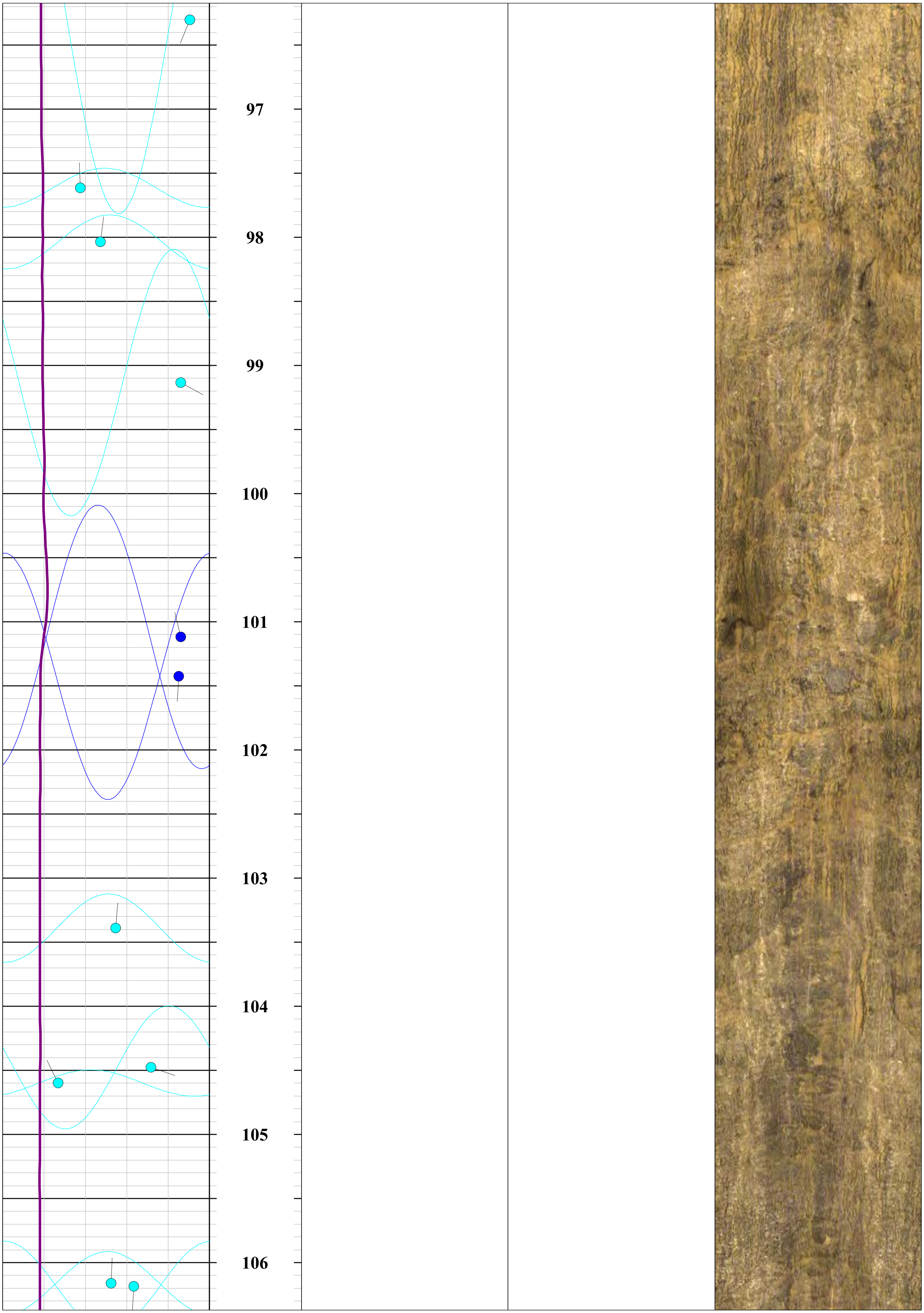
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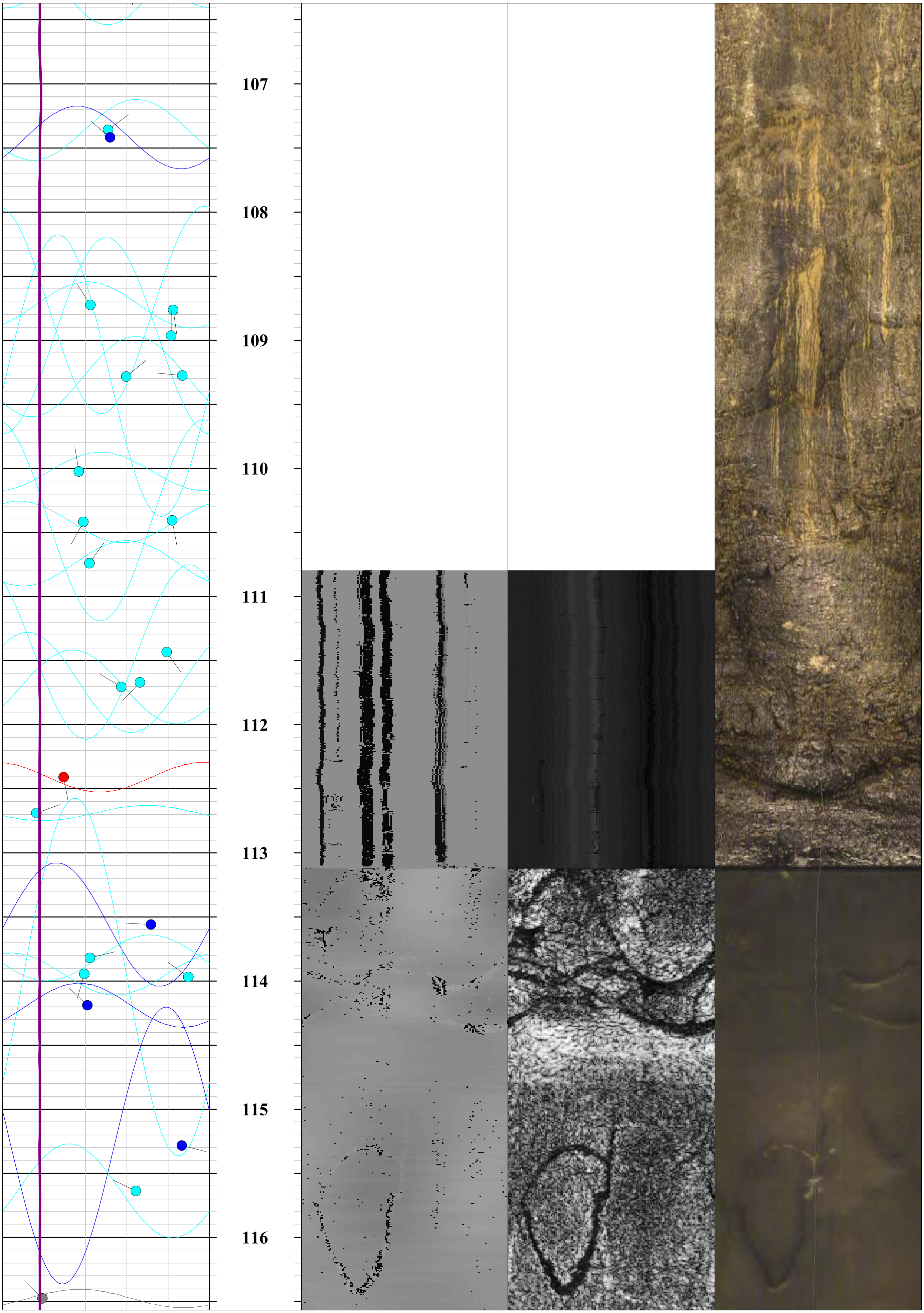
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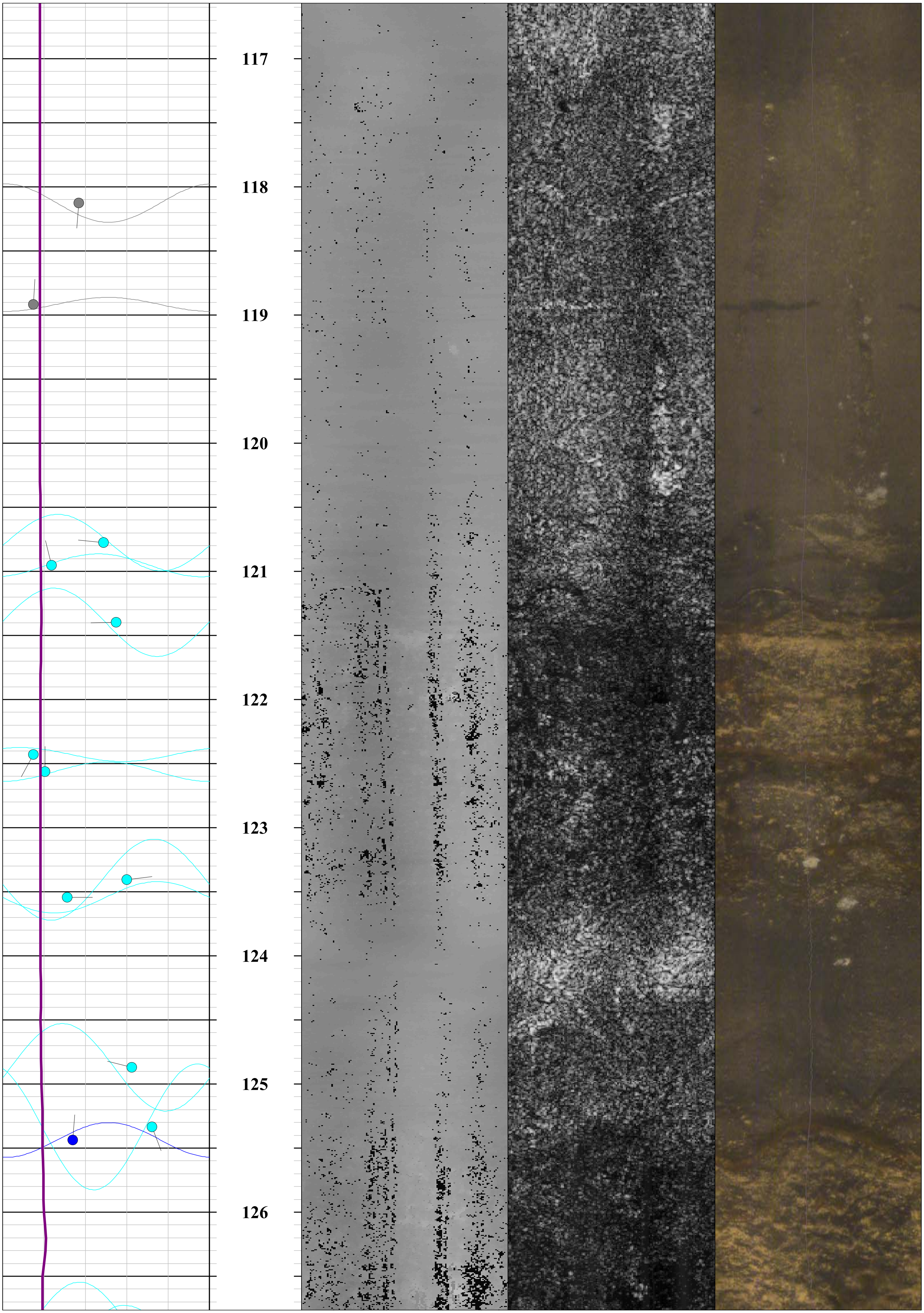
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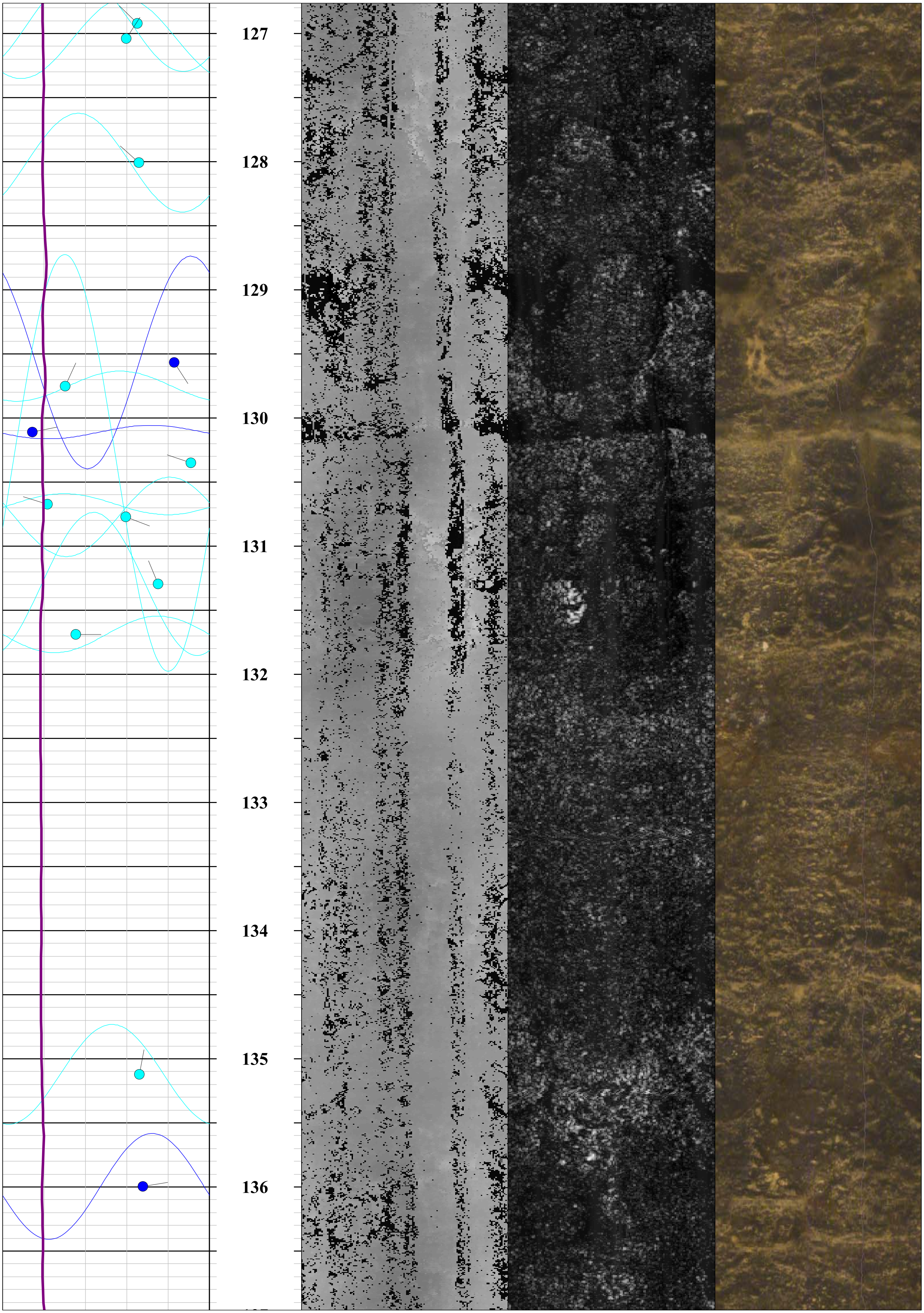
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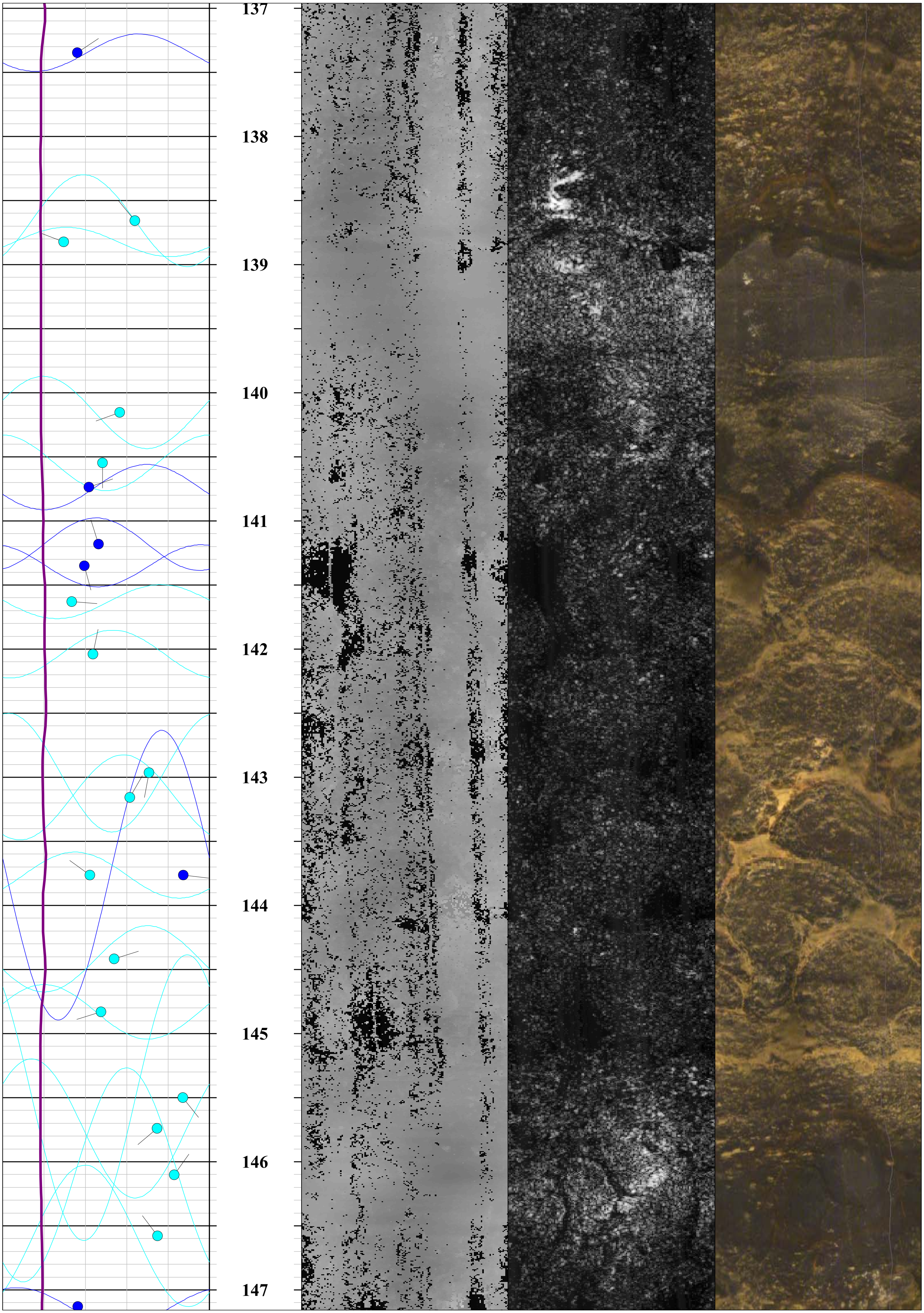

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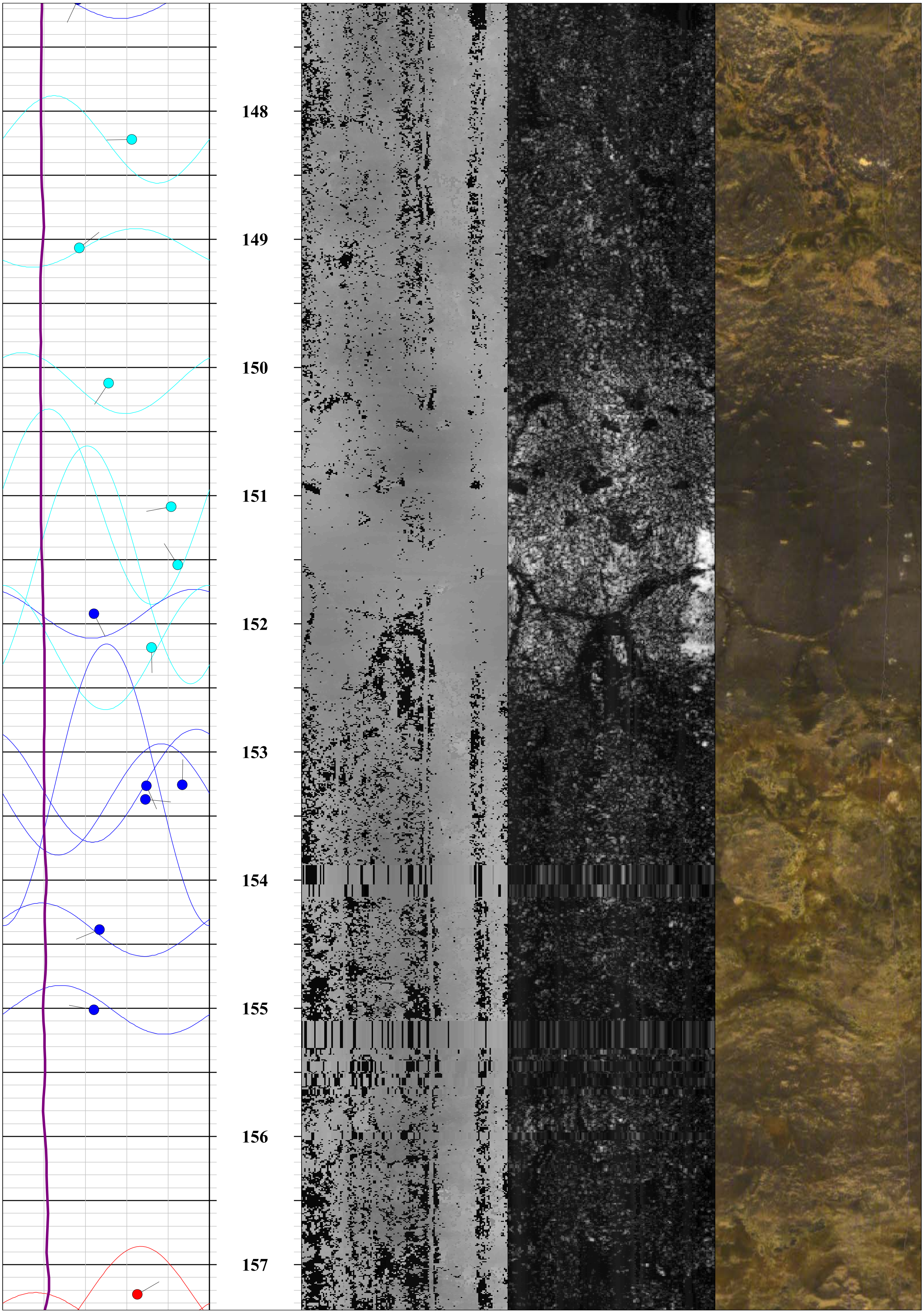
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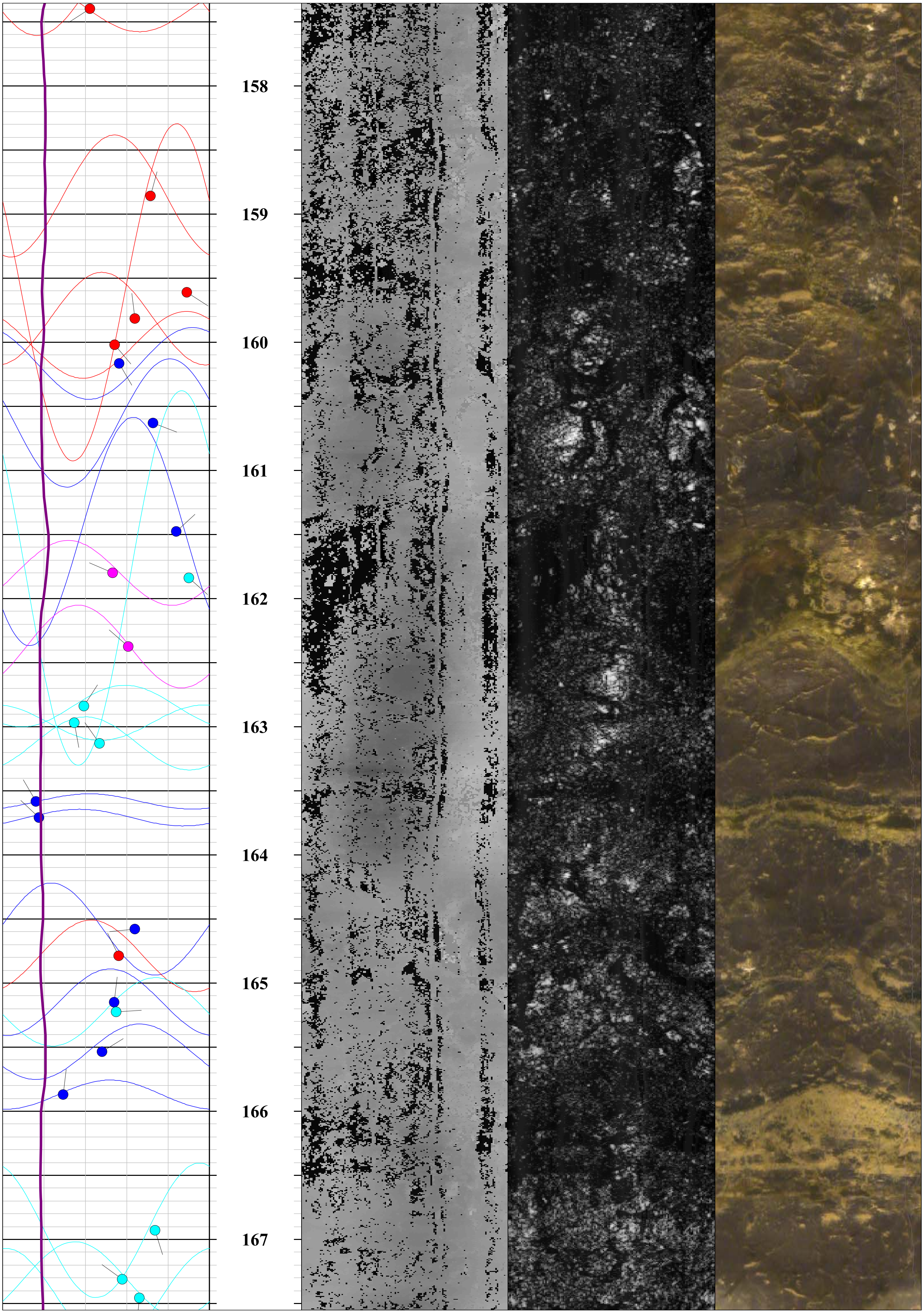
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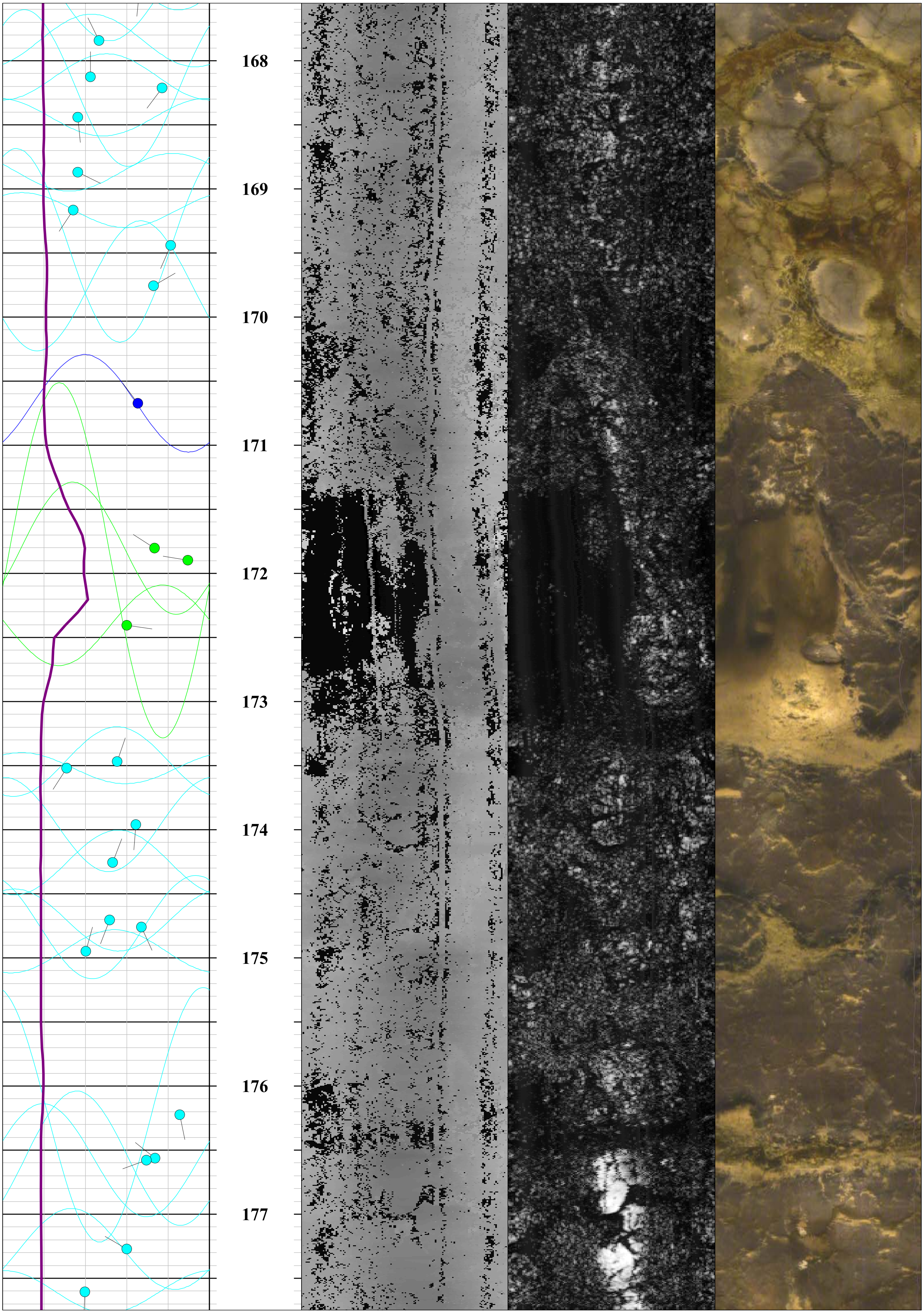
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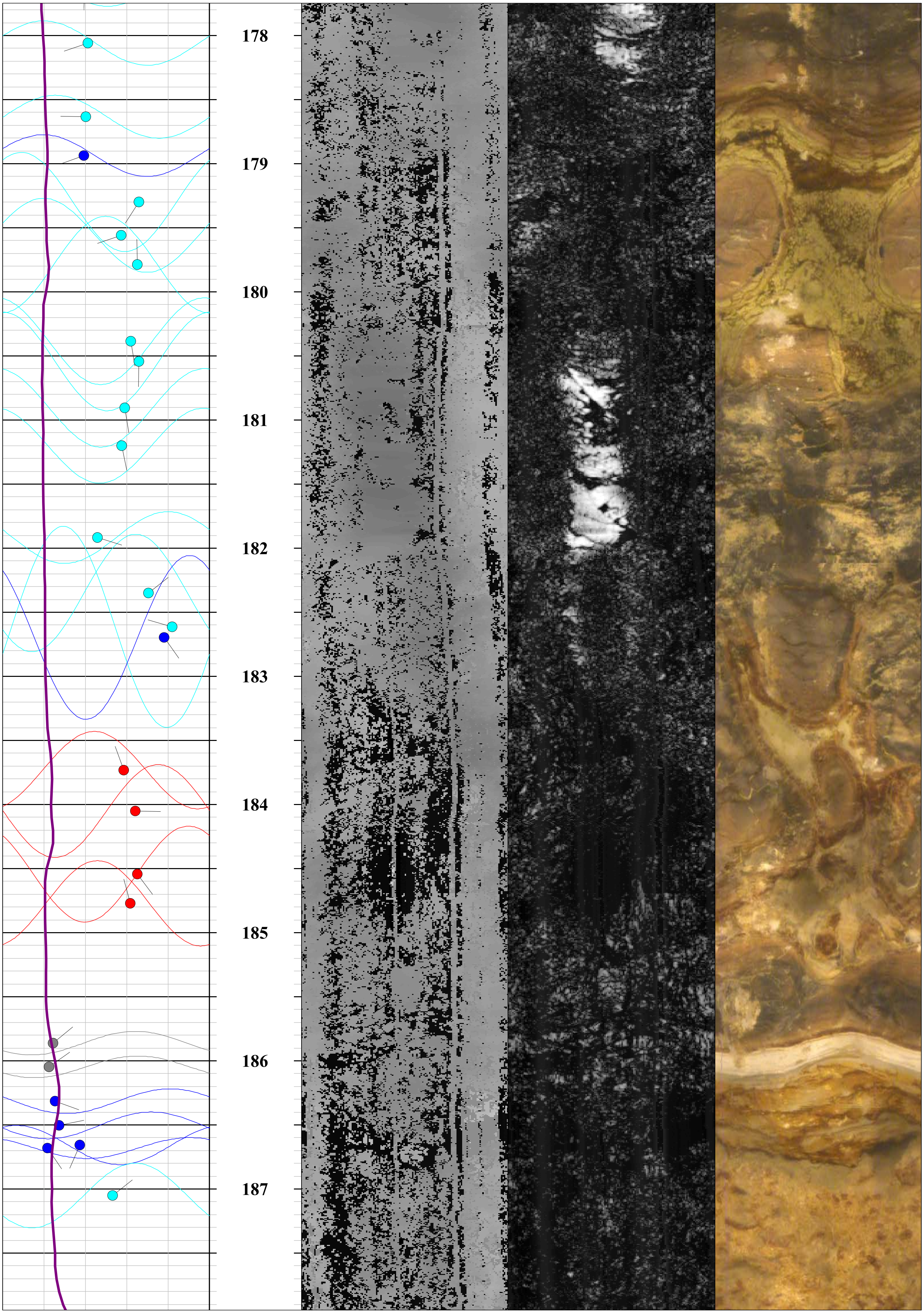
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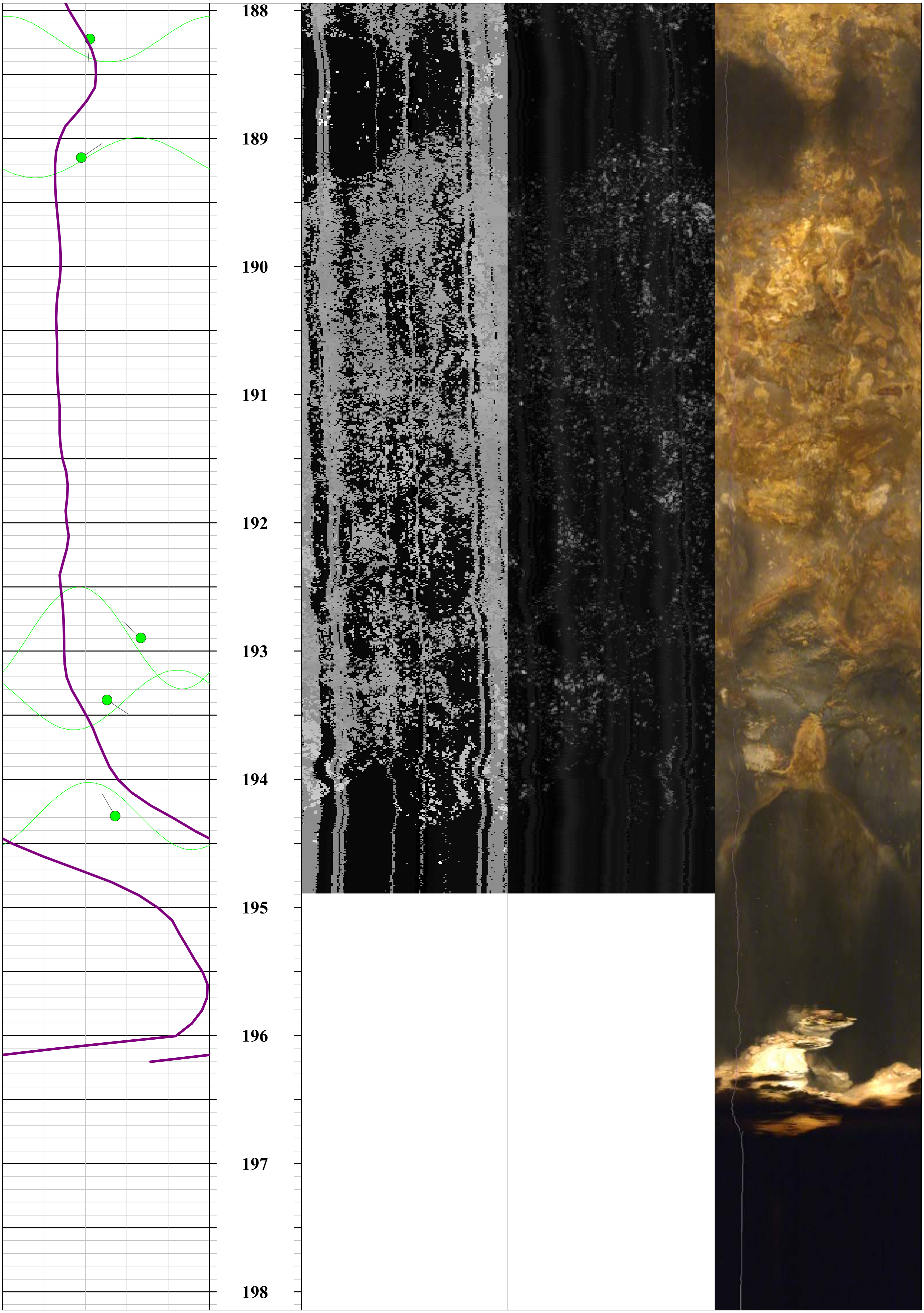
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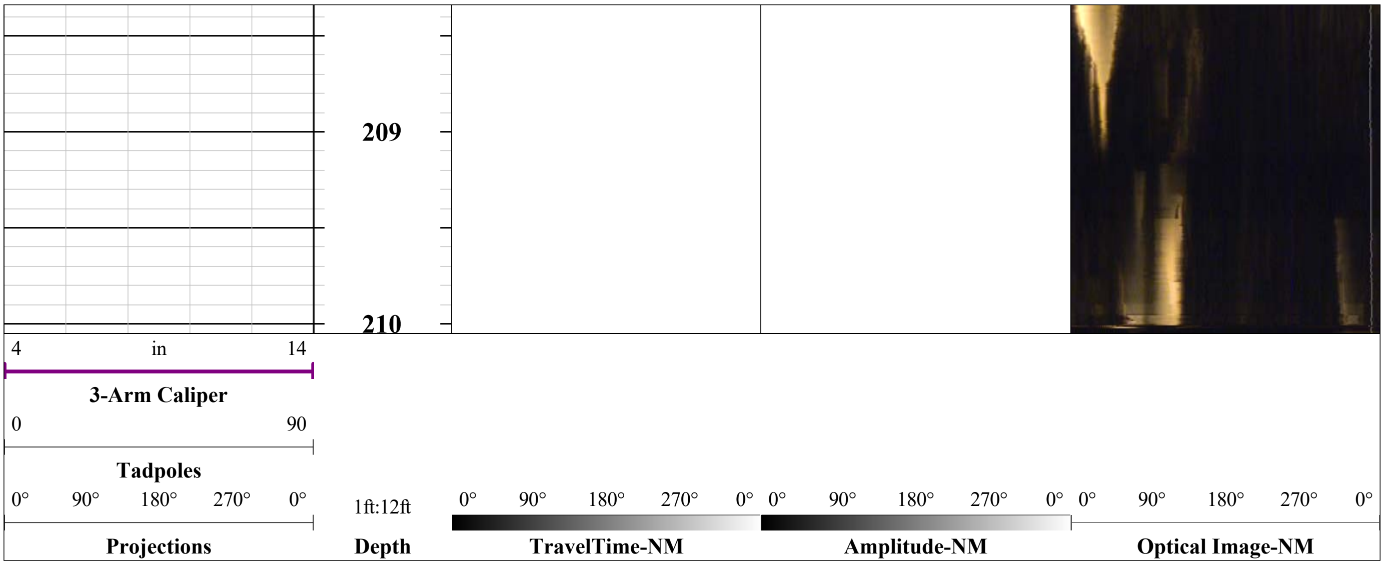
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210
4
in
14
3-Arm Caliper
0
90
Tadpoles
0° 90° 180° 270° 0°
Projections
1ft:12ft
Depth
0° 90° 180° 270° 0°
TravelTime-NM
0° 90° 180° 270° 0°
Amplitude-NM
0° 90° 180° 270° 0°
Optical Image-NM

Table RC-03:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
1	28.98	95.1	330	40	2
2	29.03	95.2	321	31	2
3	29.12	95.5	4	48	2
4	29.35	96.3	202	81	1
5	29.75	97.6	357	34	1
6	29.88	98.0	7	43	1
7	30.21	99.1	119	78	1
8	30.82	101.1	346	77	2
9	30.92	101.4	183	77	2
10	31.51	103.4	4	49	1
11	31.85	104.5	109	64	1
12	31.88	104.6	333	24	1
13	32.36	106.2	3	47	1
14	32.36	106.2	183	57	1
15	32.72	107.4	53	46	1
16	32.74	107.4	310	47	2
17	33.14	108.7	328	38	1
18	33.15	108.8	172	74	1
19	33.21	109.0	1	73	1
20	33.31	109.3	276	78	1
21	33.31	109.3	51	54	1
22	33.54	110.0	351	33	1
23	33.65	110.4	170	74	1
24	33.66	110.4	209	35	1
25	33.75	110.7	36	38	1
26	33.96	111.4	145	71	1
27	34.04	111.7	223	60	1
28	34.05	111.7	301	52	1
29	34.26	112.4	169	27	3
30	34.35	112.7	70	15	1
31	34.61	113.6	273	65	2
32	34.69	113.8	76	38	1
33	34.73	113.9	196	36	1
34	34.74	114.0	306	81	1
35	34.81	114.2	313	37	2
36	35.14	115.3	104	78	2
37	35.25	115.6	296	58	1
38	35.50	116.5	315	17	0
39	36.01	118.1	185	33	0
40	36.25	118.9	3	13	0
41	36.81	120.8	276	44	1
42	36.87	121.0	346	21	1
43	37.00	121.4	269	49	1
44	37.32	122.4	209	13	1
45	37.36	122.6	360	18	1

All directions are with respect to Magnetic North.

Table RC-03:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019

Feature	Depth	Depth	Dip	Dip	Feature
No.			Direction	Angle	Rank
	(meters)	(feet)	(degrees)	(degrees)	(0 to 5)
46	37.62	123.4	83	54	1
47	37.65	123.5	90	28	1
48	38.06	124.9	284	56	1
49	38.20	125.3	158.7	65.0	1
50	38.23	125.4	4.8	30.6	2
51	38.69	126.9	314.0	58.6	1
52	38.72	127.0	32.3	53.8	1
53	39.02	128.0	311.7	59.3	1
54	39.49	129.6	147.5	74.6	2
55	39.55	129.8	24.2	27.1	1
56	39.66	130.1	78.5	12.9	2
57	39.73	130.4	288.2	82.0	1
58	39.83	130.7	287.1	19.6	1
59	39.86	130.8	110.9	53.5	1
60	40.02	131.3	338.2	67.7	1
61	40.14	131.7	90.3	31.9	1
62	41.18	135.1	10.2	59.6	1
63	41.45	136.0	80.4	61.0	2
64	41.86	137.3	56.4	32.4	2
65	42.26	138.7	320.4	57.4	1
66	42.31	138.8	291.0	26.5	1
67	42.72	140.2	250.4	50.9	1
68	42.84	140.6	179.9	43.5	1
69	42.90	140.7	71.4	37.6	2
70	43.03	141.2	342.0	41.7	2
71	43.08	141.4	165.2	35.6	2
72	43.17	141.6	94.6	30.0	1
73	43.29	142.0	11.8	39.2	1
74	43.58	143.0	190.2	63.7	1
75	43.64	143.2	30.0	55.4	1
76	43.82	143.8	96.8	78.5	2
77	43.82	143.8	306.1	38.1	1
78	44.02	144.4	72.3	48.5	1
79	44.14	144.8	252.4	42.9	1
80	44.35	145.5	141.1	78.4	1
81	44.42	145.7	230.2	67.1	1
82	44.53	146.1	35.4	74.7	1
83	44.68	146.6	323.1	67.5	1
84	44.85	147.1	205.1	32.7	2
85	45.18	148.2	269.3	56.1	1
86	45.44	149.1	51.4	33.4	1
87	45.76	150.1	213.5	46.0	1
88	46.05	151.1	259.8	73.3	1
89	46.19	151.5	327.3	76.1	1
90	46.31	151.9	154.5	39.8	2

All directions are with respect to Magnetic North.

Table RC-03:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
91	46.39	152.2	179.0	64.7	1
92	46.71	153.3	1.1	78.2	2
93	46.71	153.3	156.2	62.5	2
94	46.75	153.4	96.3	62.2	2
95	47.06	154.4	247.1	42.2	2
96	47.25	155.0	280.9	39.8	2
97	47.92	157.2	59.8	58.5	3
98	47.98	157.4	237.8	38.0	3
99	48.42	158.9	14.8	64.3	3
100	48.65	159.6	122.7	80.1	3
101	48.71	159.8	352.6	57.6	3
102	48.77	160.0	139.5	48.7	3
103	48.82	160.2	149.9	50.7	2
104	48.96	160.6	111.0	65.4	2
105	49.22	161.5	47.0	75.6	2
106	49.32	161.8	293.8	47.9	4
107	49.33	161.8	131.5	81.1	1
108	49.49	162.4	311.4	54.6	4
109	49.63	162.8	32.6	35.3	1
110	49.67	163.0	170.0	31.1	1
111	49.72	163.1	324.7	42.1	1
112	49.86	163.6	330.0	14.5	2
113	49.90	163.7	313.6	15.8	2
114	50.16	164.6	264.6	57.5	2
115	50.23	164.8	334.3	50.6	3
116	50.34	165.2	7.2	48.6	2
117	50.36	165.2	86.2	49.4	1
118	50.46	165.5	58.1	43.3	2
119	50.56	165.9	6.6	26.3	2
120	50.88	166.9	162.6	66.4	1
121	51.00	167.3	306.1	51.9	1
122	51.04	167.5	185.7	59.4	1
123	51.16	167.8	334.4	41.8	1
124	51.25	168.1	0.4	38.1	1
125	51.27	168.2	217.6	69.5	1
126	51.34	168.4	174.0	32.6	1
127	51.47	168.9	115.6	32.7	1
128	51.56	169.2	214	31	1
129	51.65	169.4	204	73	1
130	51.74	169.8	60	66	1
131	52.02	170.7	323	59	2
132	52.36	171.8	302	66	5
133	52.40	171.9	279	81	5
134	52.55	172.4	98	54	5
135	52.87	173.5	19	50	1

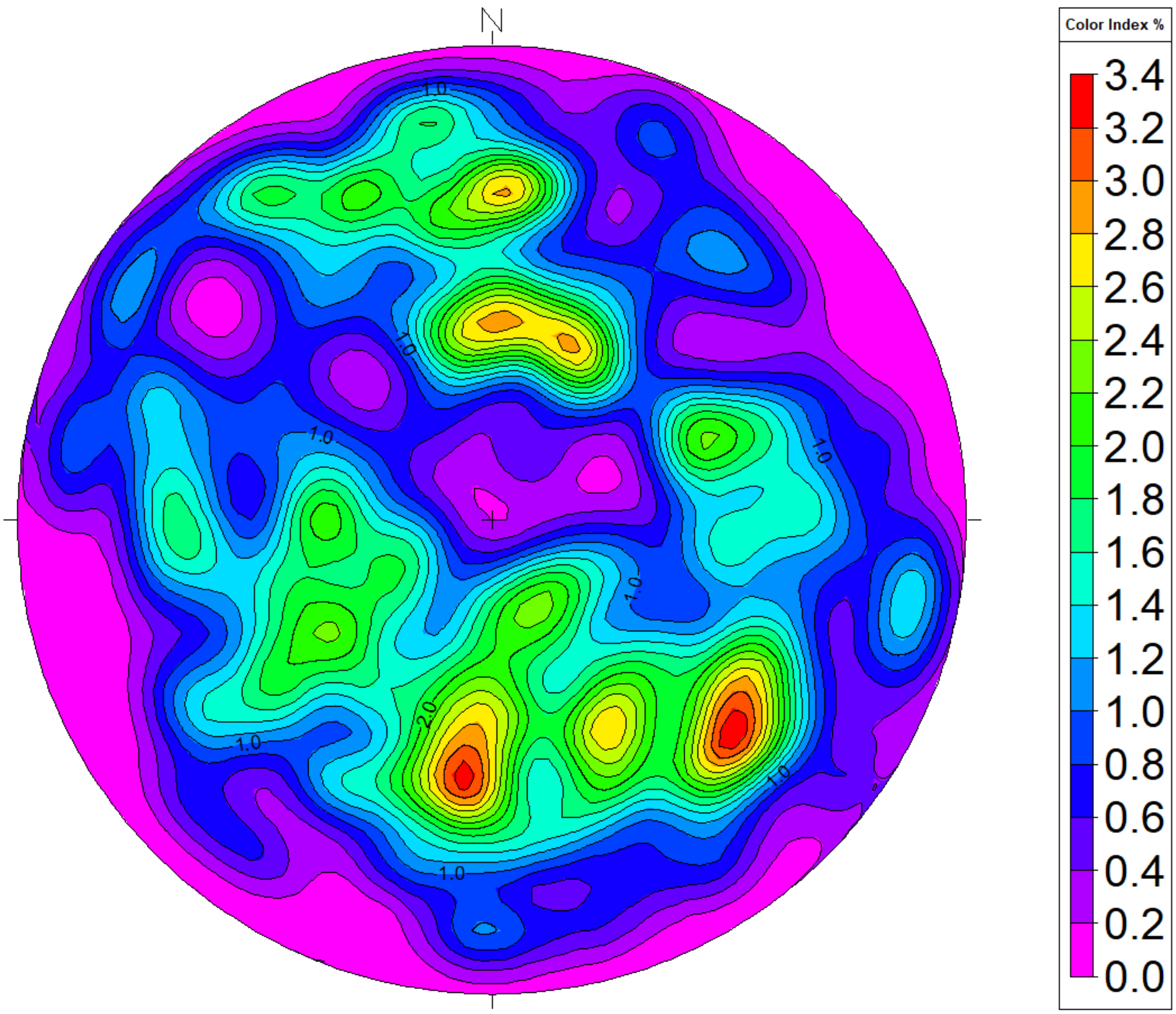
All directions are with respect to Magnetic North.

Table RC-03:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
136	52.89	173.5	213	28	1
137	53.02	174.0	184	58	1
138	53.11	174.3	21	48	1
139	53.25	174.7	201	47	1
140	53.27	174.8	156	60	1
141	53.32	175.0	15	36	1
142	53.71	176.2	169	77	1
143	53.82	176.6	309	66	1
144	53.82	176.6	250	63	1
145	54.03	177.3	300	54	1
146	54.13	177.6	183	36	1
147	54.27	178.1	251	37	1
148	54.45	178.6	272	36	1
149	54.54	178.9	251	35	2
150	54.65	179.3	213	59	1
151	54.73	179.6	251	52	1
152	54.80	179.8	359	59	1
153	54.98	180.4	170	56	1
154	55.03	180.5	181	59	1
155	55.14	180.9	171	53	1
156	55.23	181.2	169	52	1
157	55.45	181.9	108	41	1
158	55.58	182.4	52	63	1
159	55.66	182.6	286	74	1
160	55.69	182.7	145	70	2
161	56.00	183.7	340	53	3
162	56.10	184.1	91	58	3
163	56.25	184.5	143	59	3
164	56.32	184.8	345	55	3
165	56.65	185.9	51	22	0
166	56.71	186.1	55	20	0
167	56.79	186.3	110	23	2
168	56.85	186.5	78	25	2
169	56.89	186.7	204	34	2
170	56.90	186.7	146	20	2
171	57.01	187.1	51	48	1
172	57.37	188.2	185	38	5
173	57.65	189.2	56	34	5
174	58.80	192.9	312	60	5
175	58.94	193.4	124	45	5
176	59.22	194.3	330	49	5

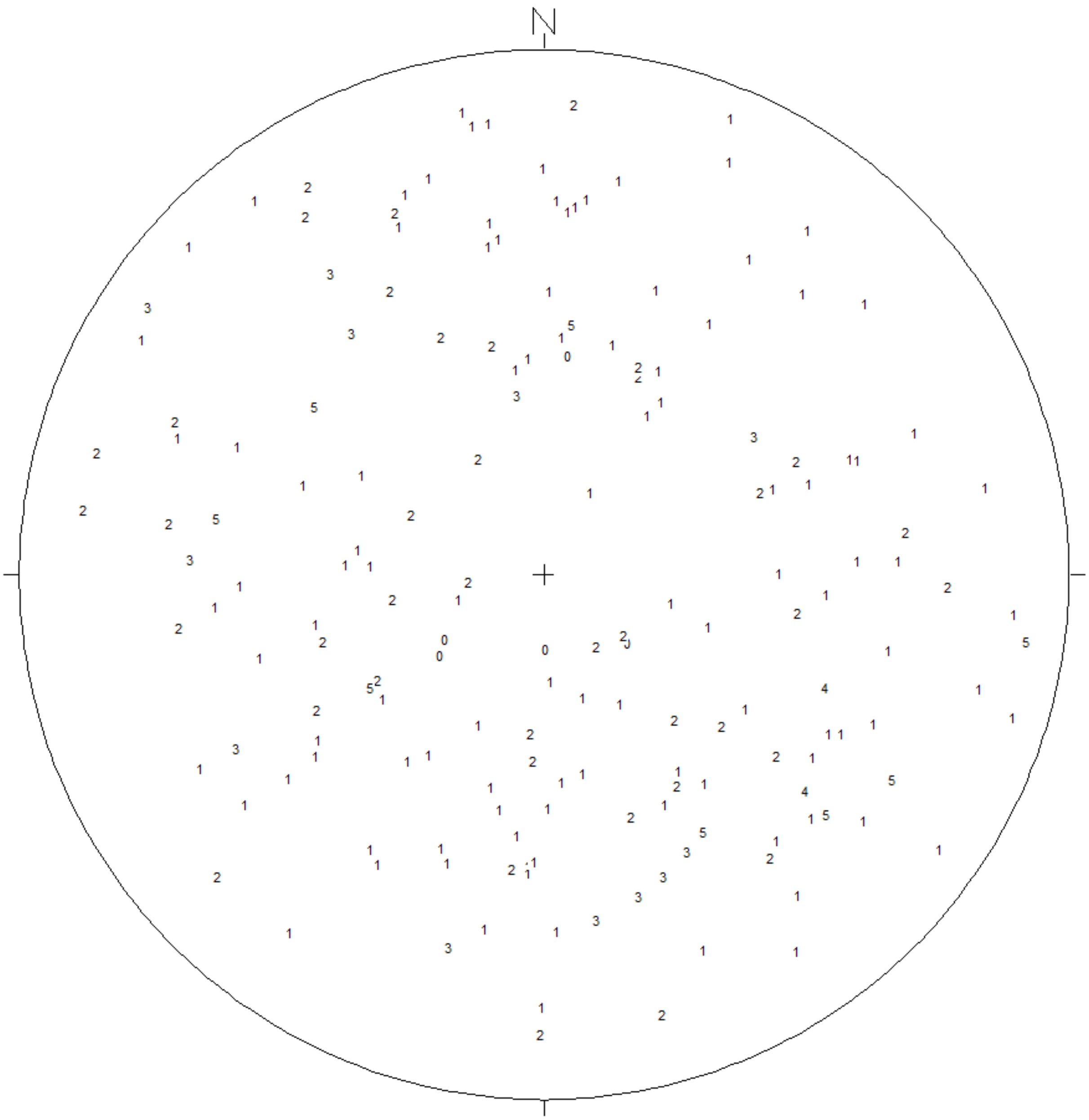
All directions are with respect to Magnetic North.

Figure RC-03:5. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019



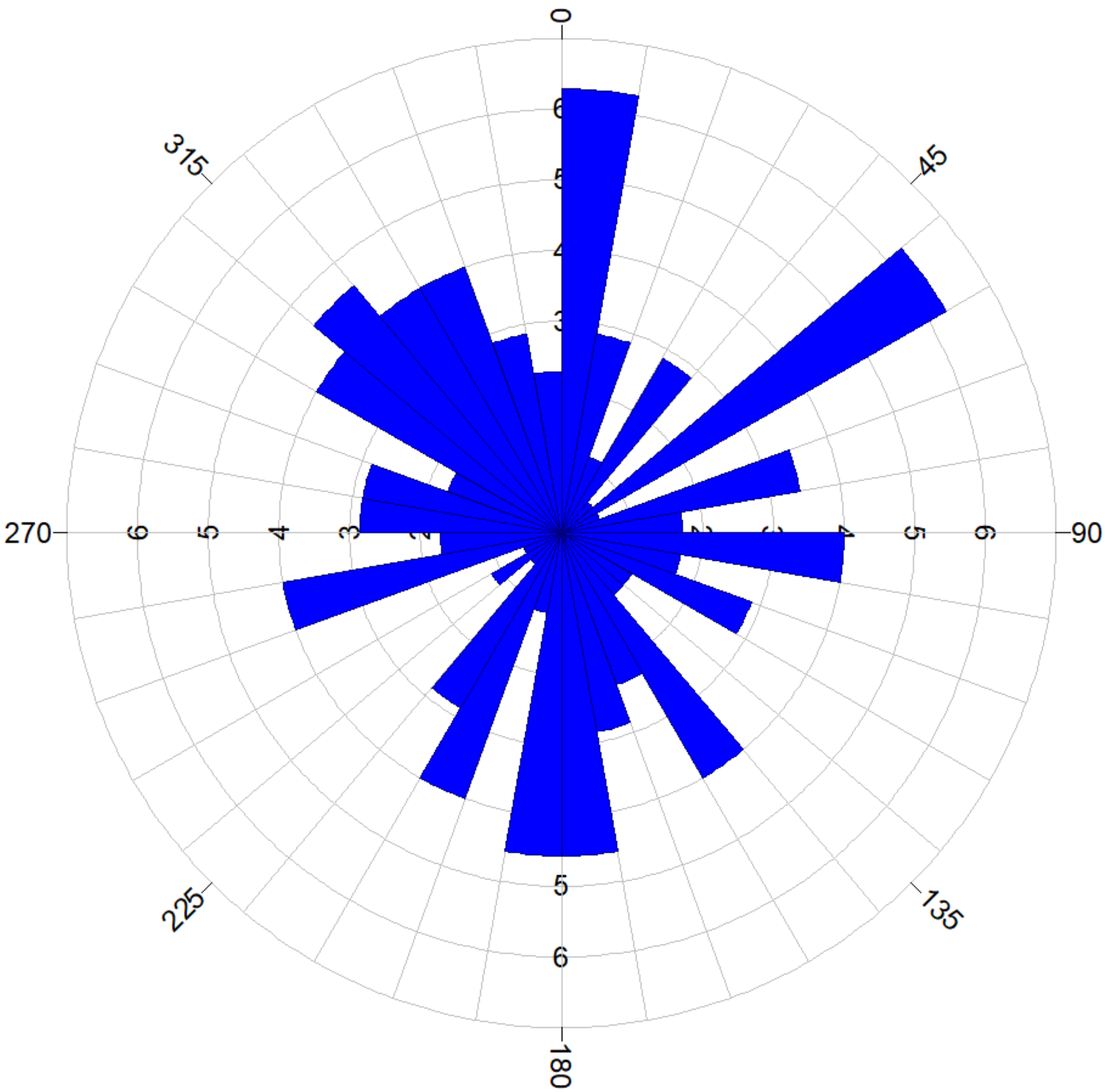
All directions are with respect to Magnetic North.

Figure RC-03:6. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019



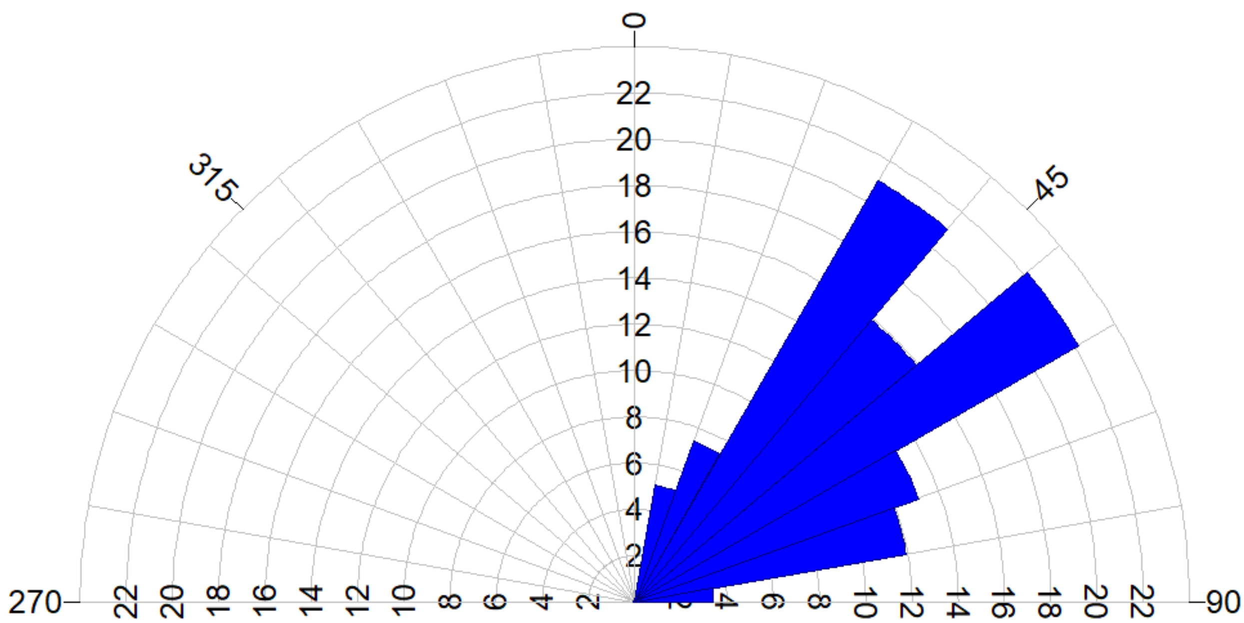
All directions are with respect to Magnetic North.

Figure RC-03:7. Rose Diagram – Dip Directions
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019



All directions are with respect to Magnetic North.

Figure RC-03:8. Rose Diagram – Dip Angles
Televiewer Image Features
Jacobs
Union Pacific
RC-03
25 April 2019



All directions are with respect to Magnetic North.

APPENDIX C

RC-04 GEOPHYSICAL & HYDROPHYSICAL DATA RESULTS

FIGURE RC-04:1. Ambient Temperature and Fluid Electrical Conductivity; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

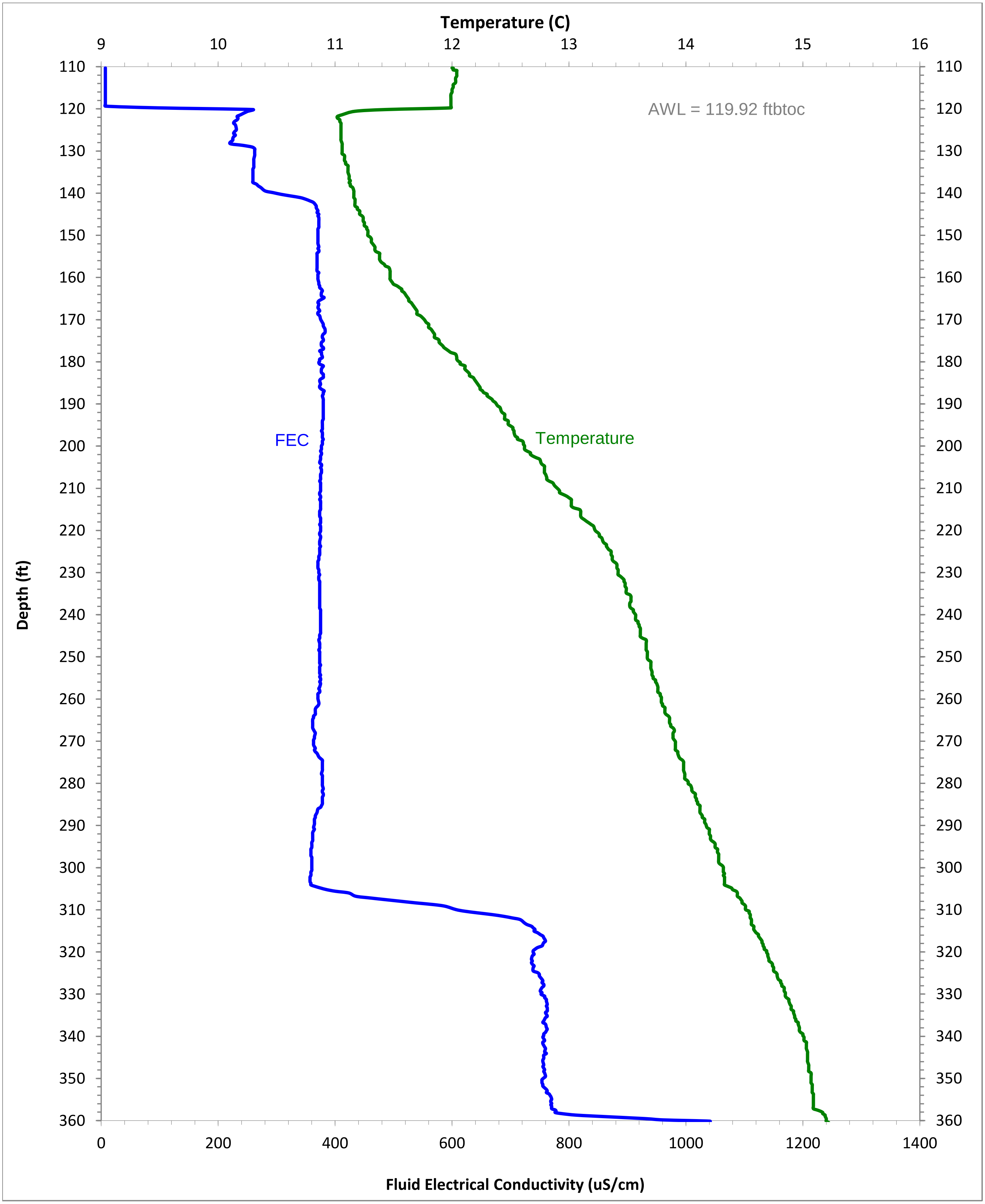


FIGURE RC-04:2. Summary of Hydrophysical Logs During Ambient Flow Characterization; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

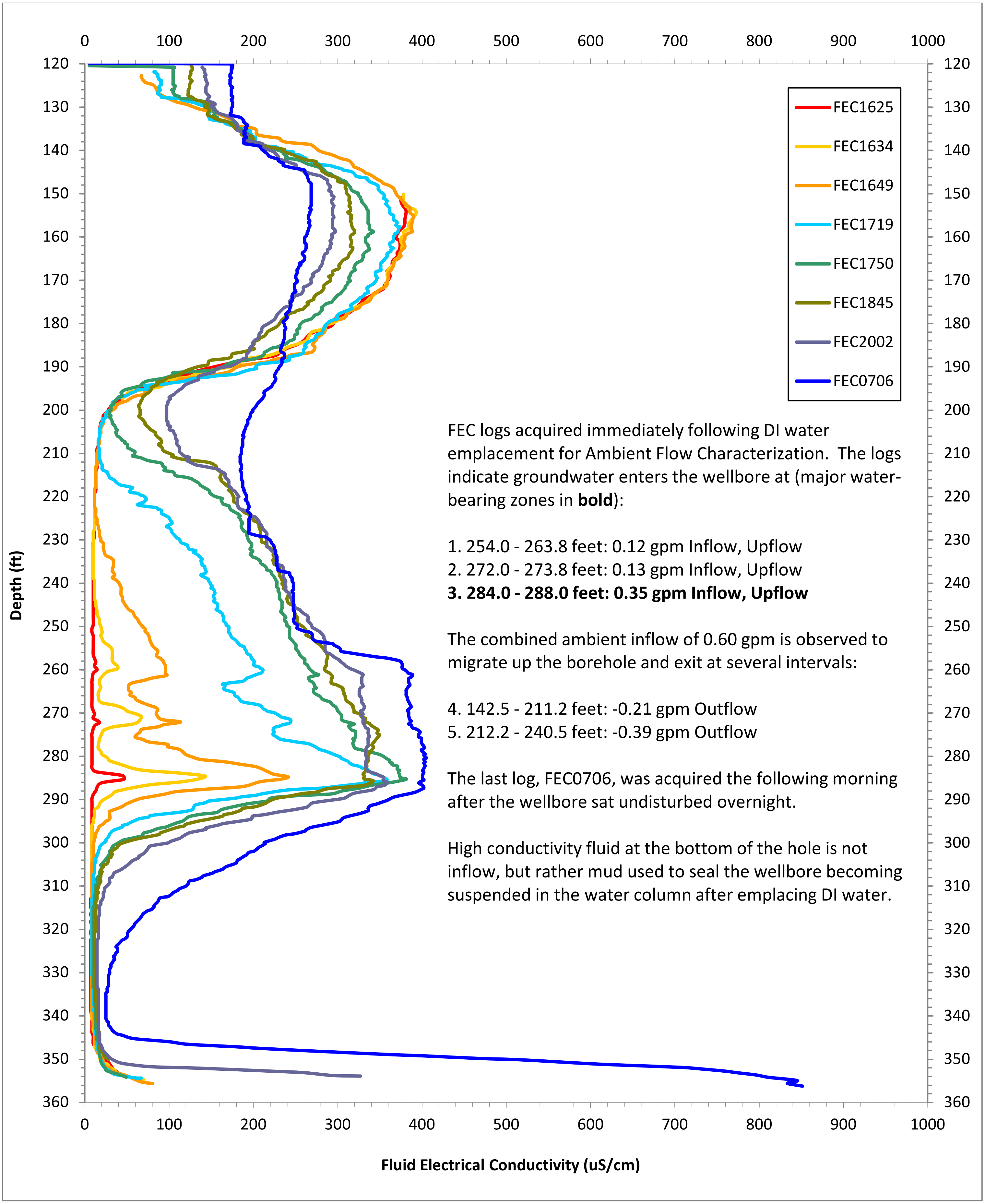


FIGURE MW-83:3. Pumping and Drawdown Data During 15 GPM Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Borehole: RC-04

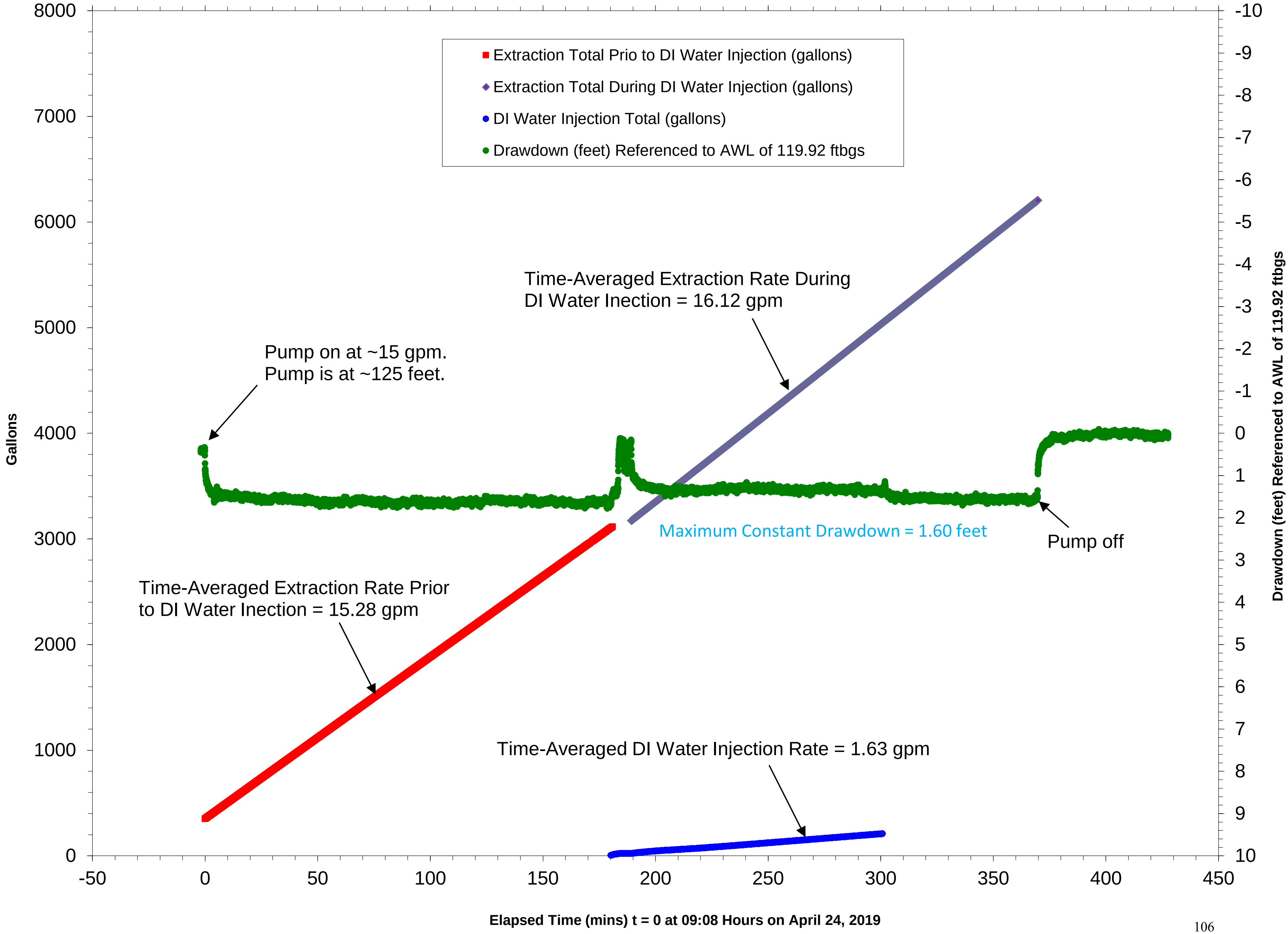


FIGURE RC-04:4A. Summary of Hydrophysical Logs During 15.0 gpm Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

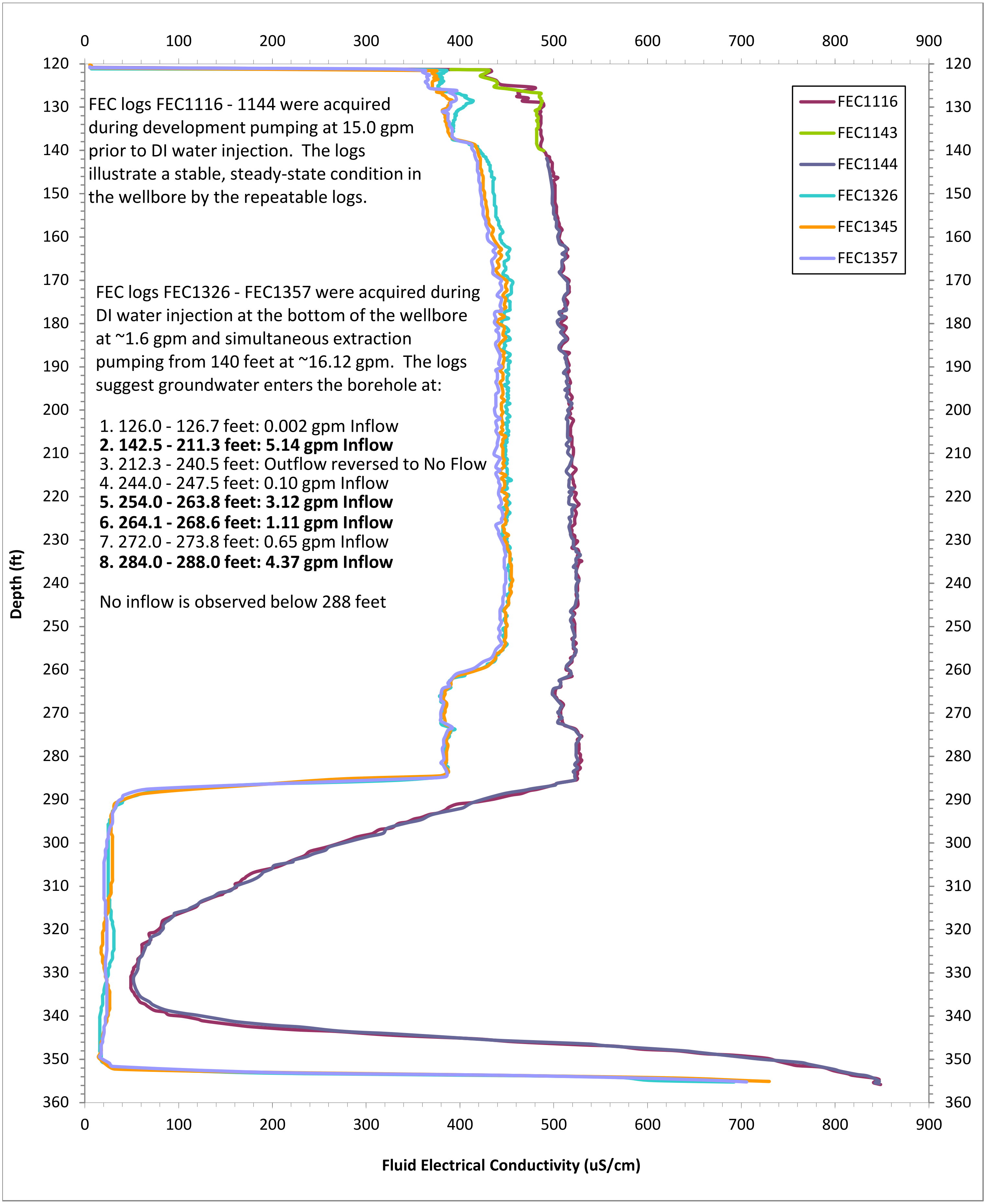


FIGURE RC-04:4B. Summary of Hydrophysical Logs During Re-Development Pumping at 16.1 GPM After The Hydrophysical Production Test; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

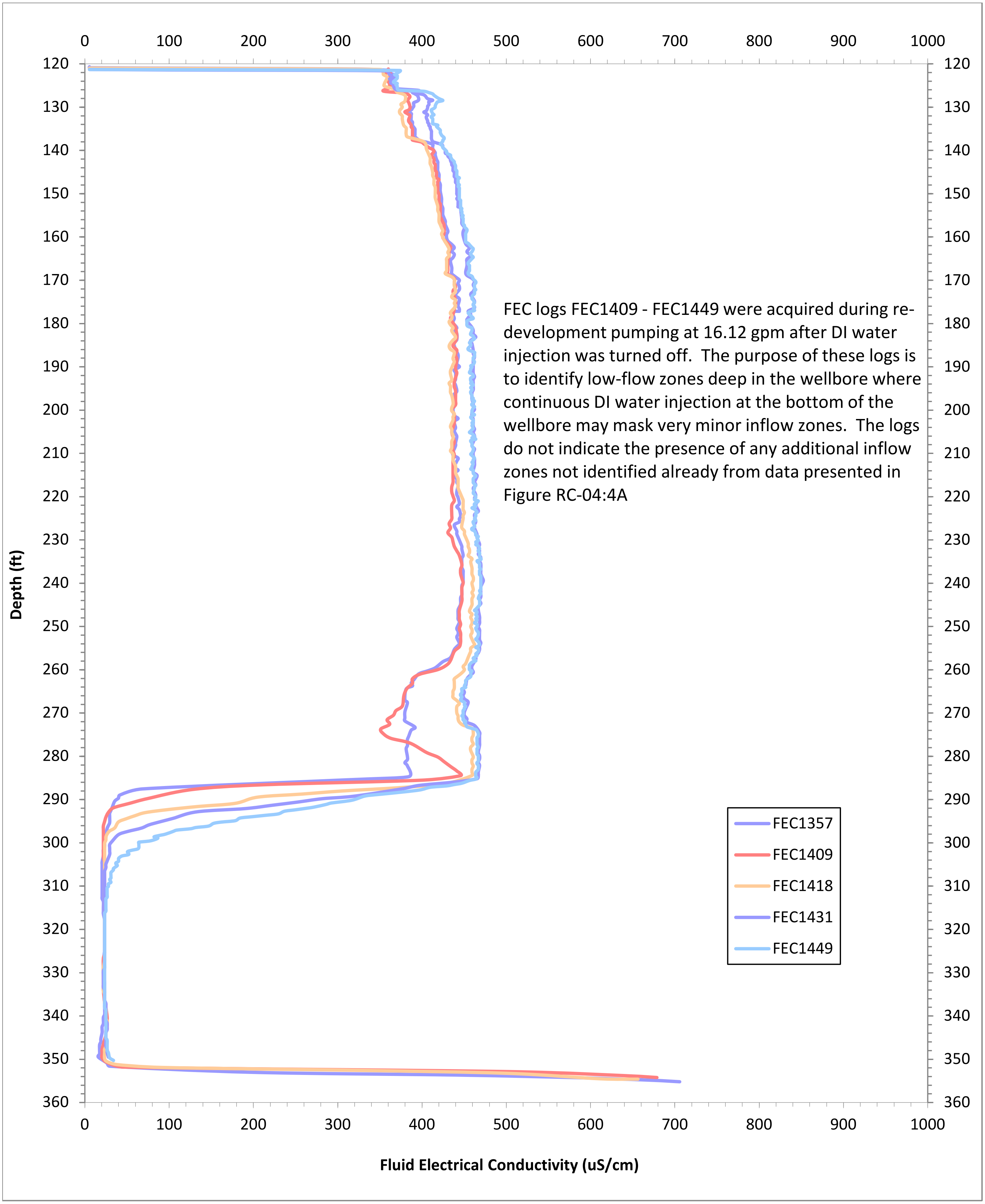


Table RC-04:1. Summary Of Hydrophysical Logging Results With Hydraulic Conductivity And Transmissivity Estimations; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

Well Name	RC-04
Ambient Depth to Water (ftbtoc)	121.92
Ambient Depth to Water (ftbgs)	119.92
Cased Interval (ftbgs)	0 - 81.0

Diameter of Well (ft)	0.46
Maximum Drawdown (ft)	1.60
Effective Radius (ft)	100
Well Specific Capacity (gpm/ft-dd)	9.06

Hydrophysical Logging Results - RC-04									
Interval No.	**Top of Interval (ft)**	**Bottom of Interval (ft)**	**Length of Interval (ft)**	**Ambient Flow[1] (gpm)**	**Darcy Velocity in Aquifer[2] (ft/day)**	**Interval-Specific Flow Rate During Pumping (gpm)**	**Interval-Specific Hydraulic Conductivity[3] (ft/day)**	**Transmissivity (ft^2/day)**	**Interval-Specific Fluid Electrical Conductivity (uS/cm)**
1	126.0	126.7	0.7	0.00	NA	0.002	3.33E-01	2.33E-01	238
2	142.5	211.2	68.7	-0.21	NA	5.14	9.06E+00	6.23E+02	426
3	212.2	240.5	28.3	-0.39	NA	0.00	1.60E+00	4.54E+01	NA
4	244.0	247.5	3.5	0.00	NA	0.10	3.33E+00	1.16E+01	595
5	254.0	263.8	9.8	0.12	NA	3.12	3.56E+01	3.49E+02	581
6	264.1	268.6	4.5	0.00	NA	1.11	2.87E+01	1.29E+02	420
7	272.0	273.8	1.8	0.13	NA	0.65	3.36E+01	6.05E+01	373
8	284.0	288.0	4.0	0.35	NA	4.37	1.17E+02	4.68E+02	523
Borehole Transmissivity Using Thiem Equation (ft^2/day)								**1.69E+03**	
ole Hydraulic Conductivity (K=T/b; b=length of saturated interval of 119.9'-360.0'= 240.1') (ft/day)							**7.03E+00**		

Note: Negative flow, if any, is outflow from the borehole to the aquifer, positive flow is inflow to the borehole.

* The top of this interval is assumed to be the bottom of the casing.

[1] Upward vertical flow is identified in this borehole under ambient conditions.

[2] Darcy Velocity, or Specific Discharge in aquifer, is calculated using the observed volumetric flow rate, the cross-sectional area of the flow interval in the wellbore and a wellbore convergence factor of 3.0 (Drost, 1968). The Darcy velocity is only applicable to ambient horizontal flow.

All depths reported herein are referenced to ground surface.

NA = Not Applicable

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Optical & Acoustic Televiewer 3-Arm Caliper

Company Jacobs
Well RC-04
Project Union Pacific
County Spokane
State WA

COMPANY Jacobs
WELL RC-04
PROJECT Union Pacific
COUNTY Spokane **STATE** WA

LOCATION
Freeman High School

QTR **SEC** **TWP** **RGE**

OTHER SERVICES
Hydrophysical Logging
WSP Testing

PERMANENT DATUM **ELEVATION**

LOG MEAS. FROM Ground Surface **ABOVE PERMANENT DATUM**

DRILLING MEAS. FROM

DATE ACQUIRED	4/22/2019	4/25/2019	4/25/2019	4/22/2019
RUN NUMBER	3,4	8,9,10,12	11	2
LOG TYPE	ABI	OBI	Caliper	Fluid Temp. & Cond.
DEPTH-DRILLER				
DEPTH-LOGGER	360.56 ftbgs			
BTM LOG INTERVAL	360.56	341.55	360.05	110.05
TOP LOG INTERVAL	116.40	3.33	74.81	360.56
RECORDED BY	KMG, BEH	KMG, BEH	KMG, BEH	BEH, KMG
WITNESSED BY				
PROBE TYPE, S/N	ABI40, 121206	OBI40, 063702	2CAA, 5837	HpL Probe
LOGGING SPEED	6 ft/min (down)	2.6 ft/min (down)	NA	23 ft/min (down)
A.S.D.E. / Sample Interval	0.9 ft / 0.0075 ft	1.14 ft / 0.0075 ft	0.75 ft / NA	1.4 ft / N/A
Fluid Level / Fluid Type				

BOREHOLE RECORD				CASING RECORD			
RUN No.	**BIT**	**FROM**	**TO**	**SIZE**	**WGT.**	**FROM**	**TO**

COMMENTS

NA - Not Available, N/A - Not Applicable

AWL = 119.92 feet TOC

Unable to get image on OBI below 341 feet. Too muddy.

Projections	Depth	TravelTime-NM	Amplitude-NM	Optical Image - NM
0° 90° 180° 270° 0°	1ft:12ft	0° 90° 180° 270° 0°	0° 90° 180° 270° 0°	0° 90° 180° 270° 0°
Tadpoles				
0 90				
3-Arm Caliper				
4 in 8				

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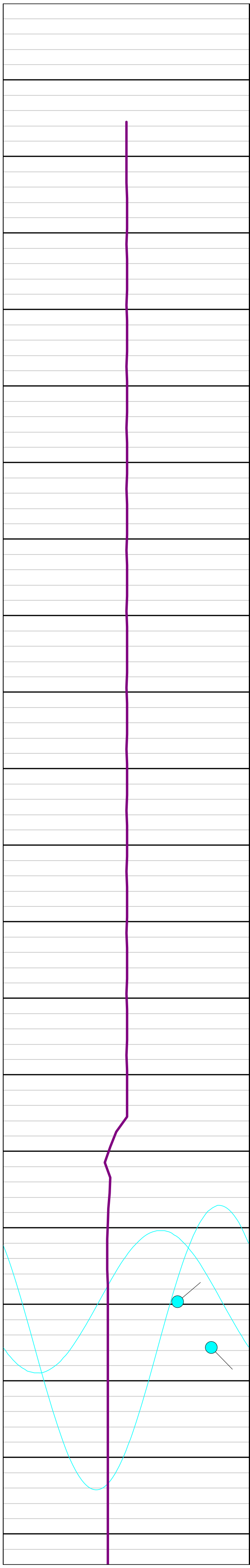

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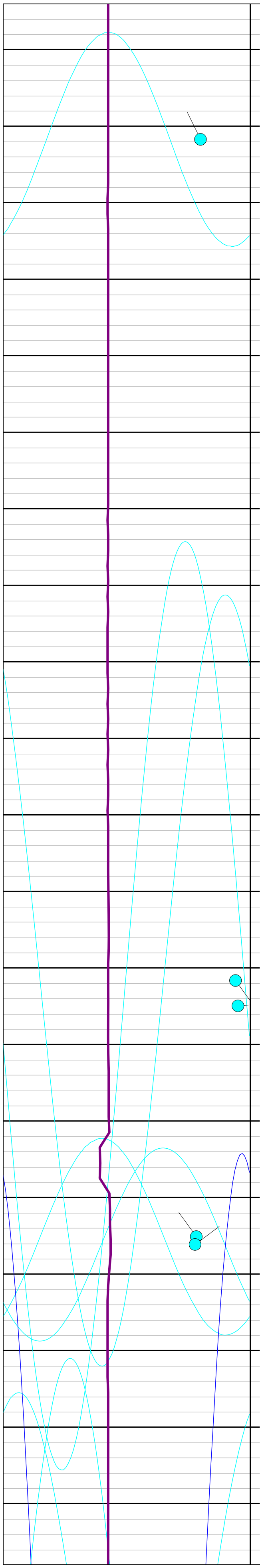

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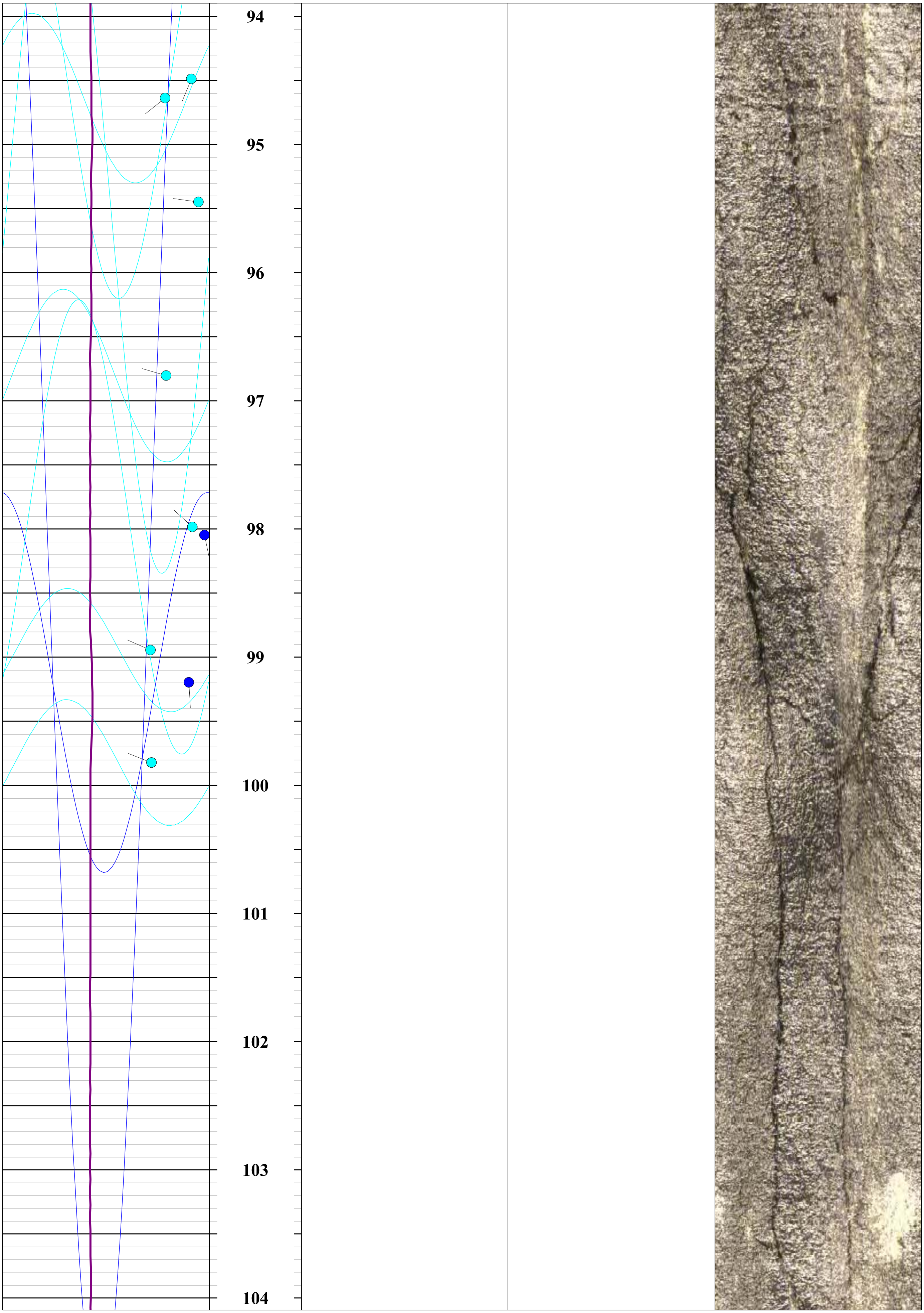
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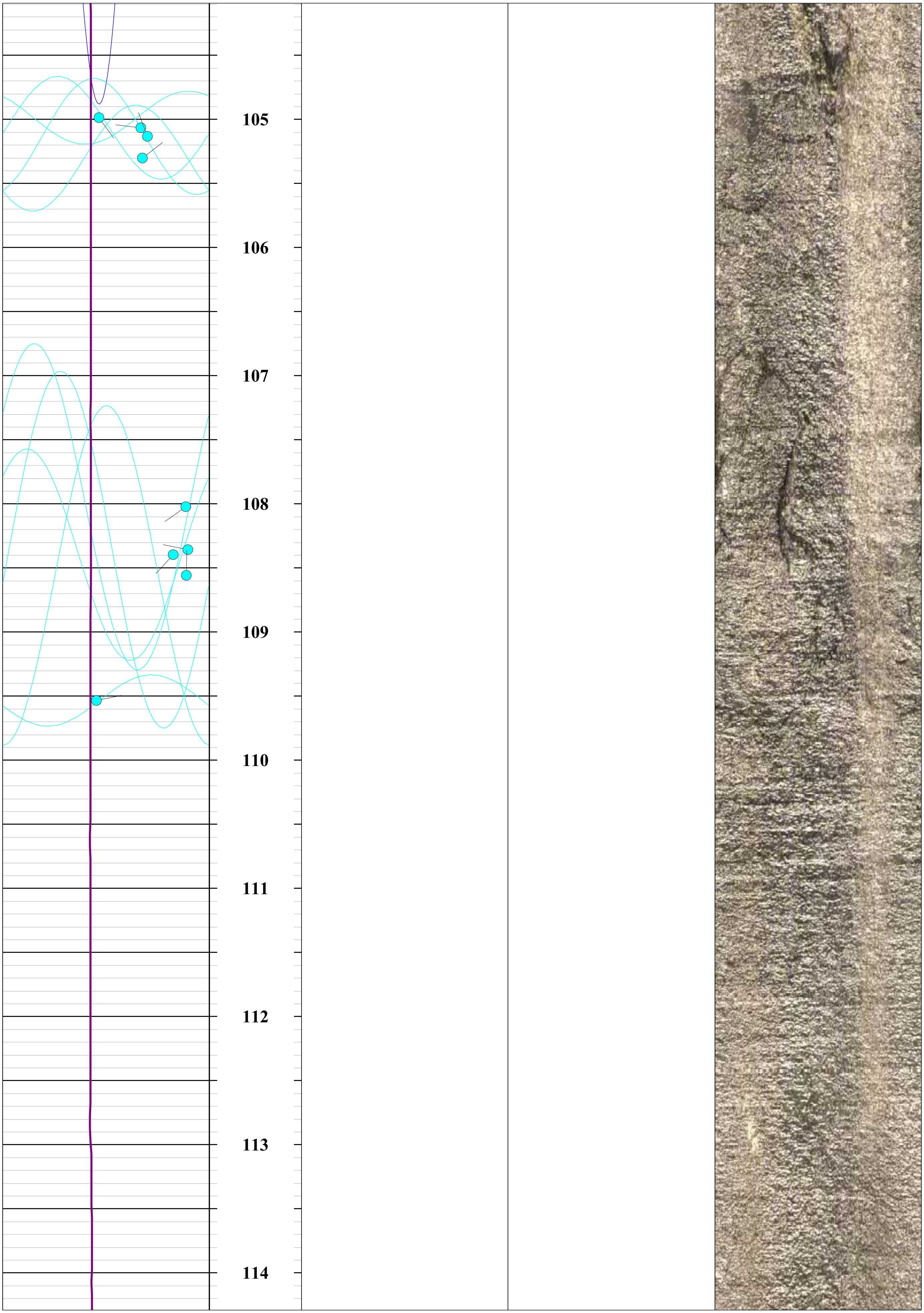
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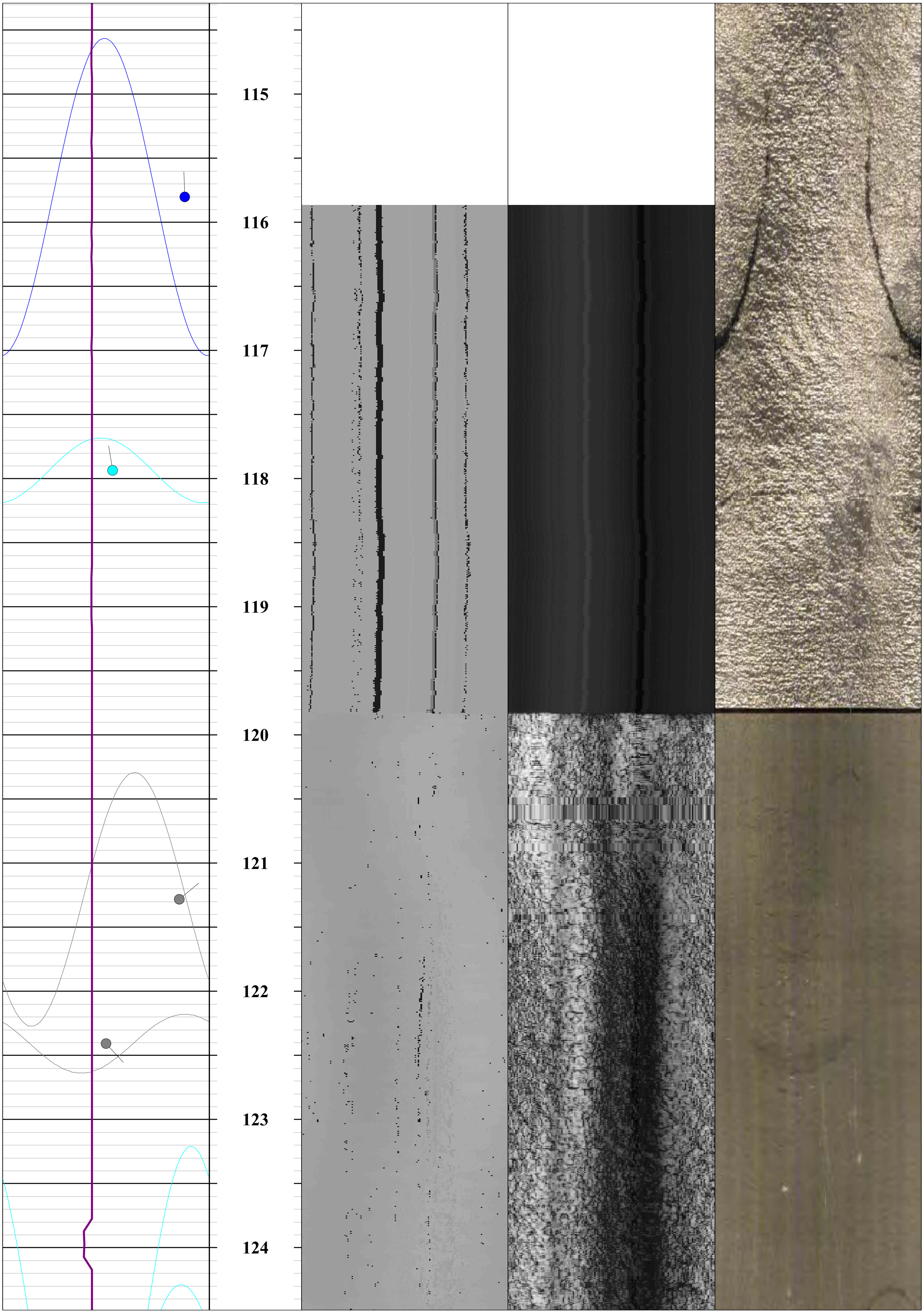
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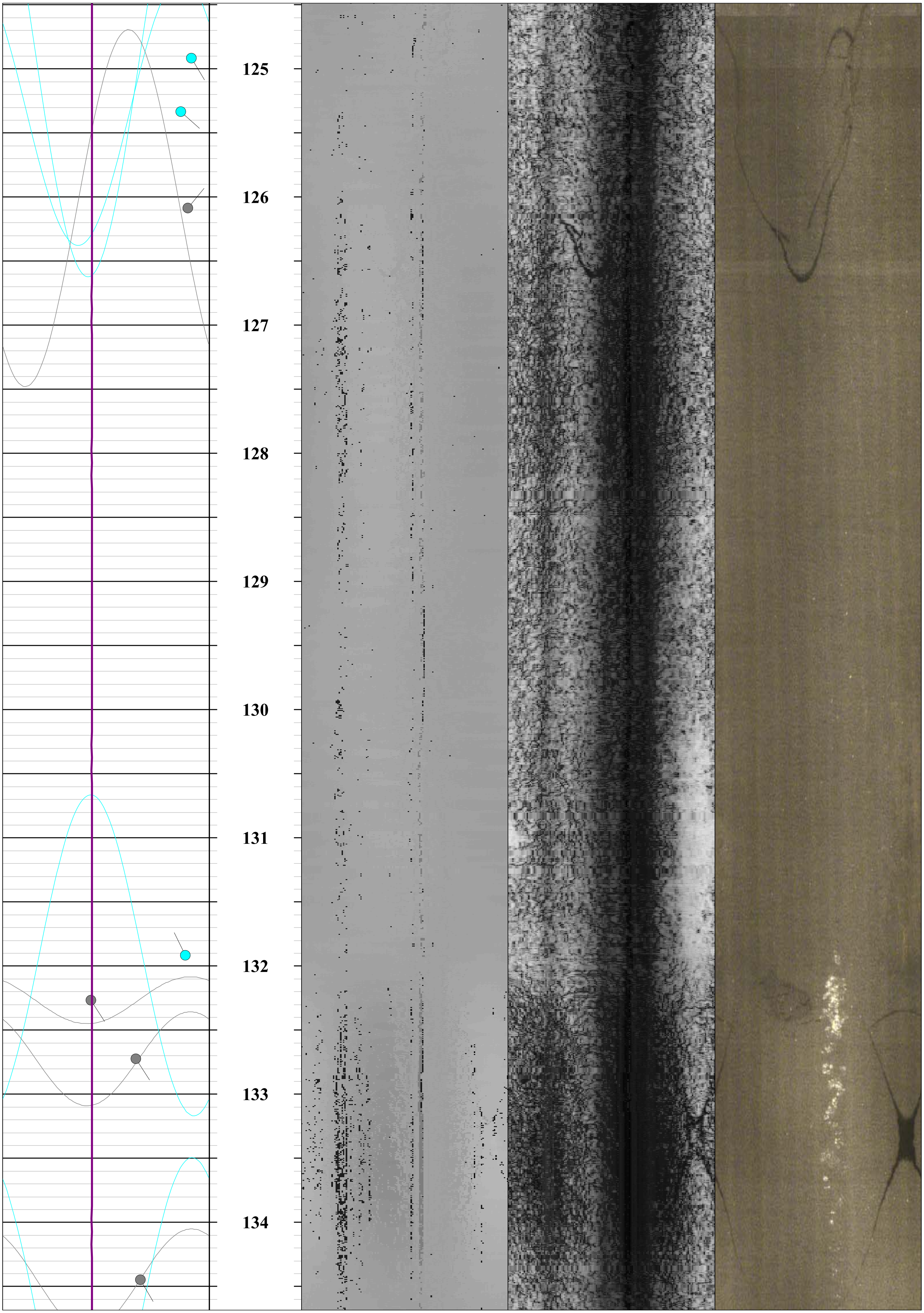
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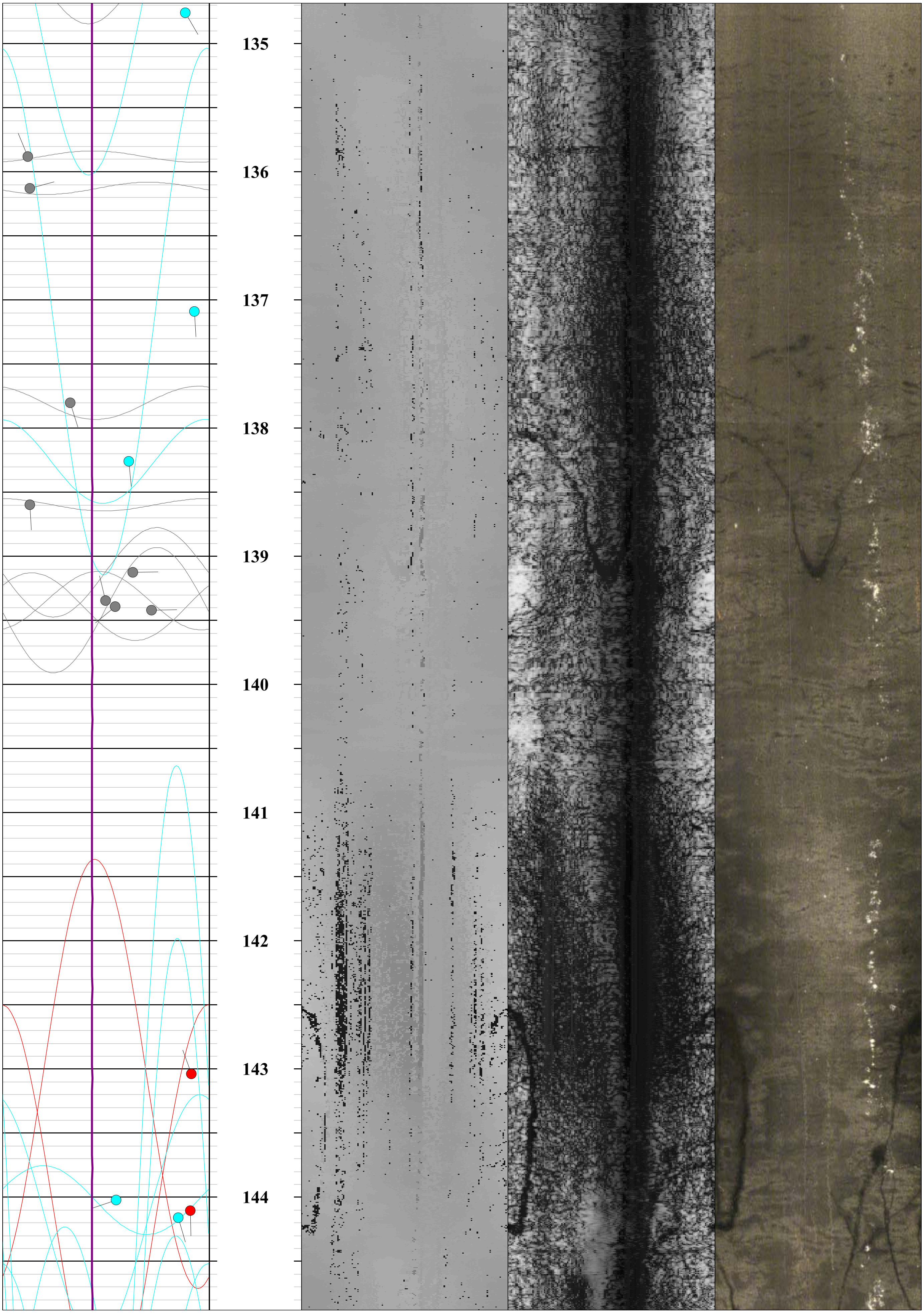

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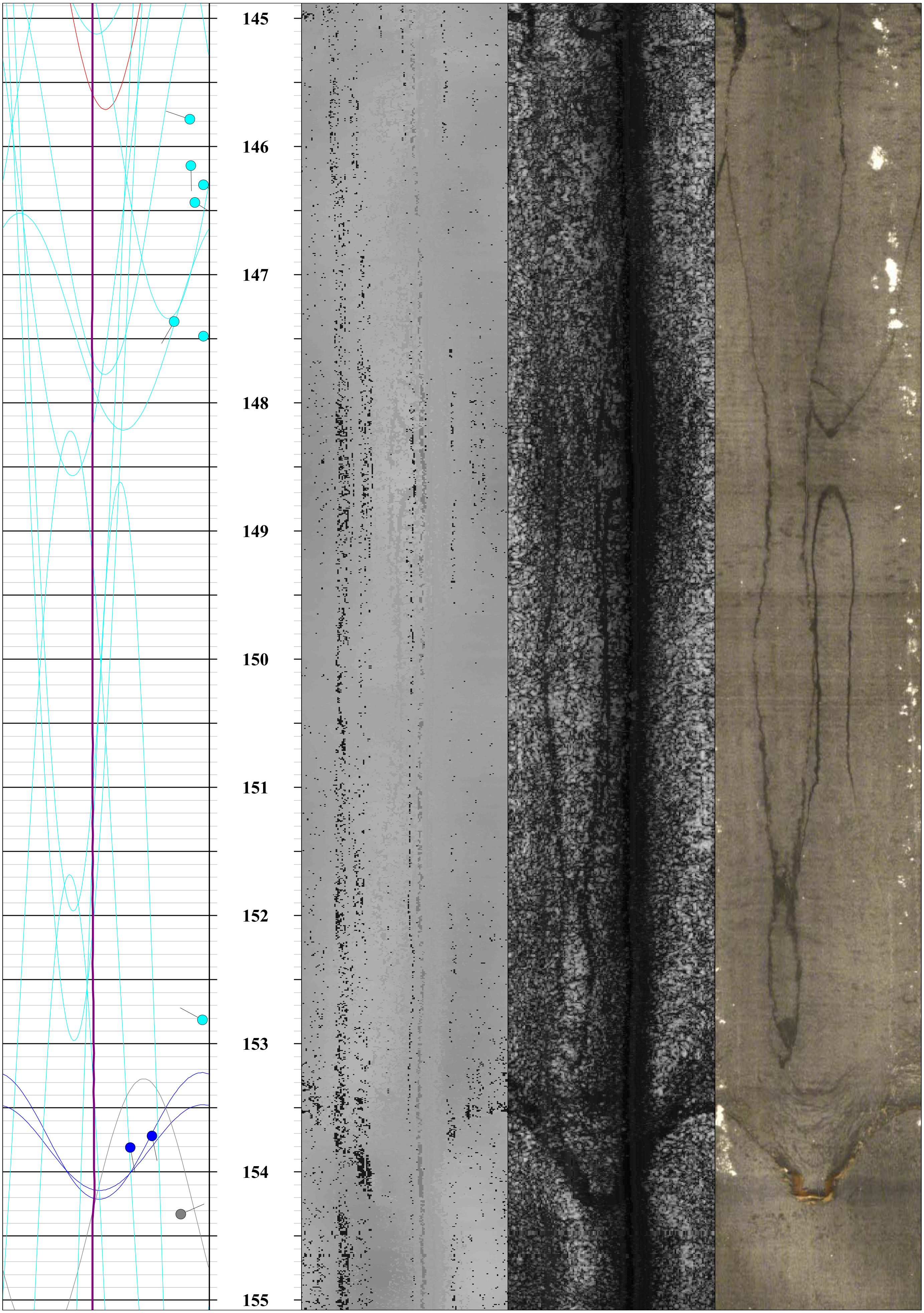
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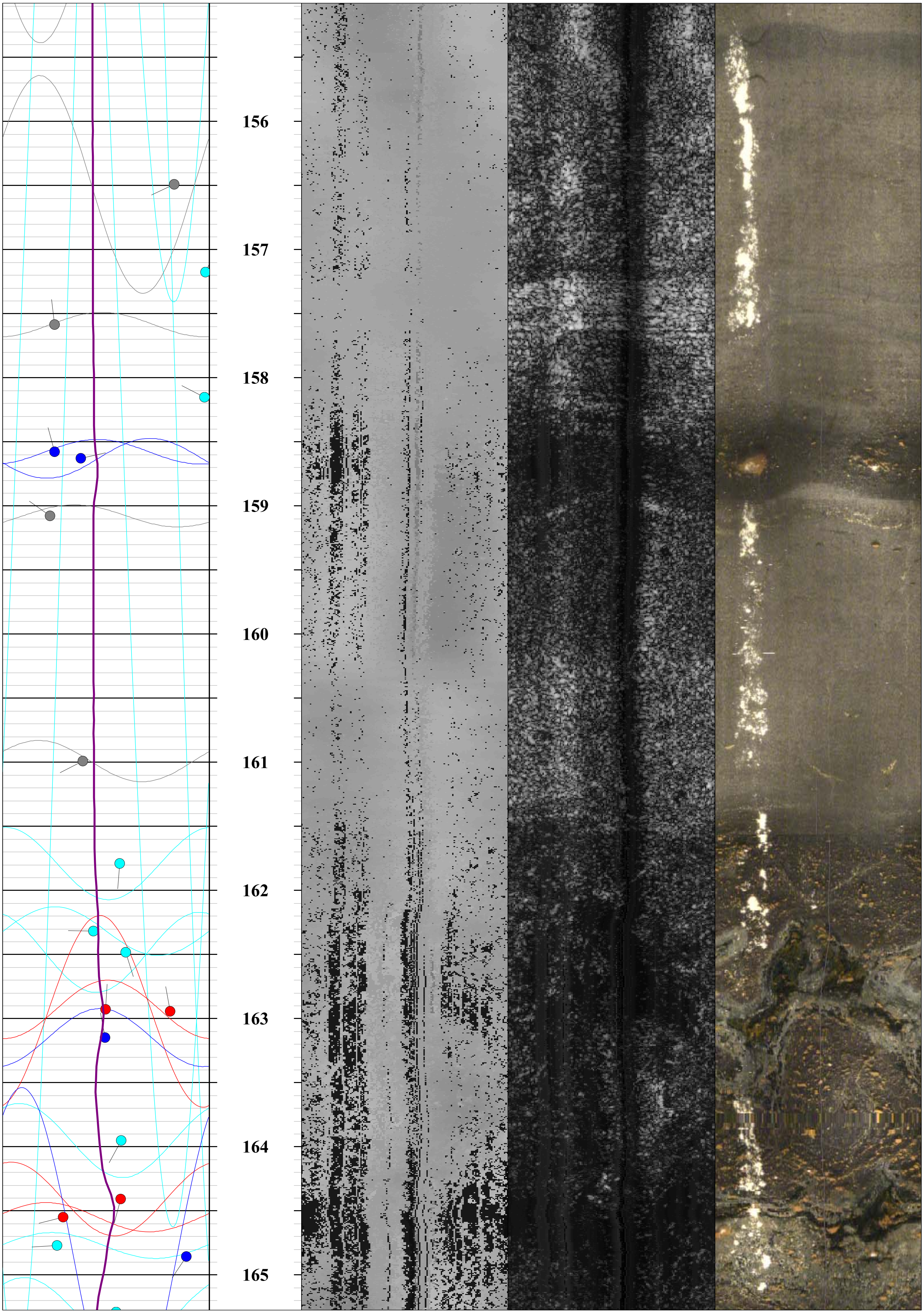
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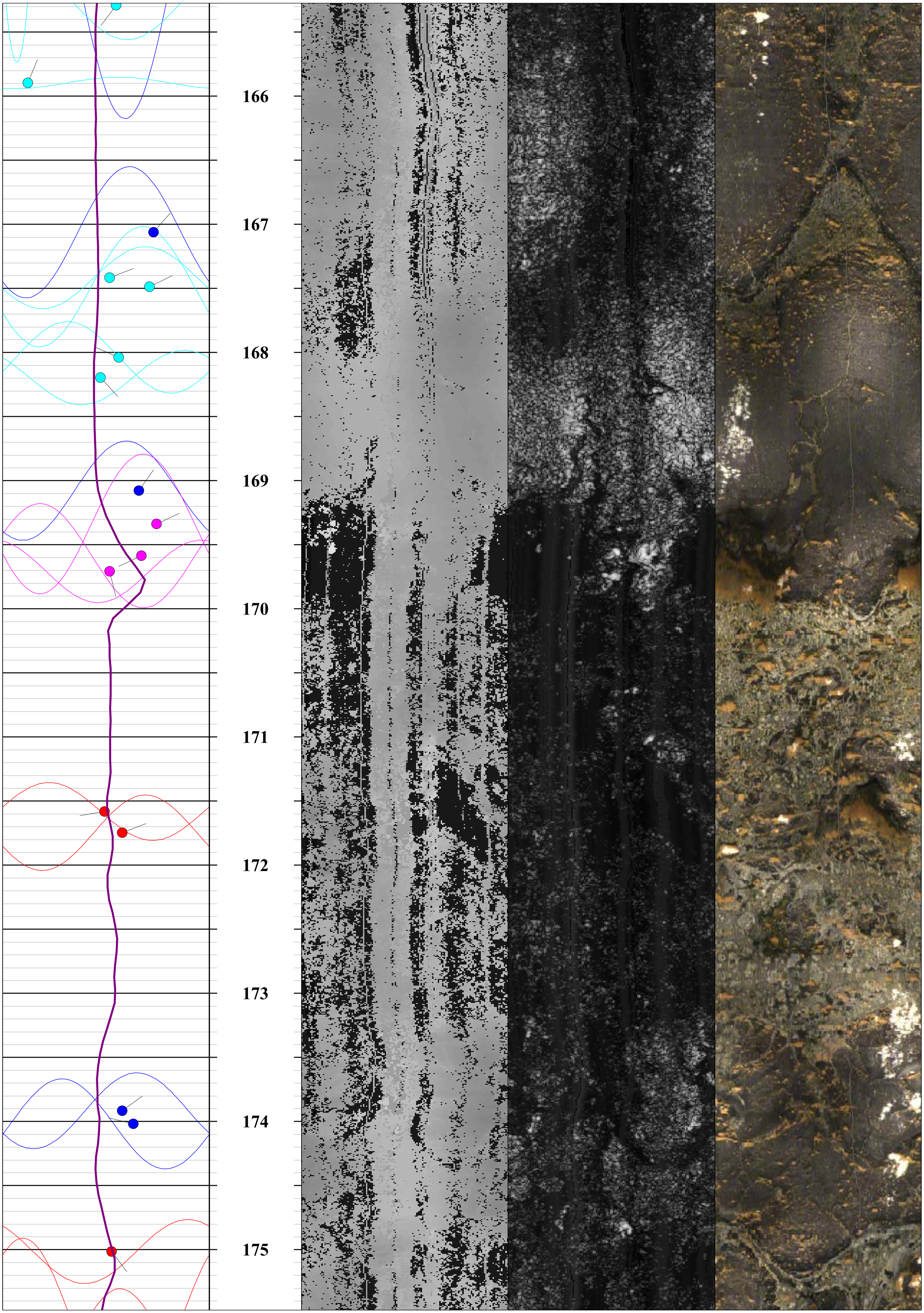
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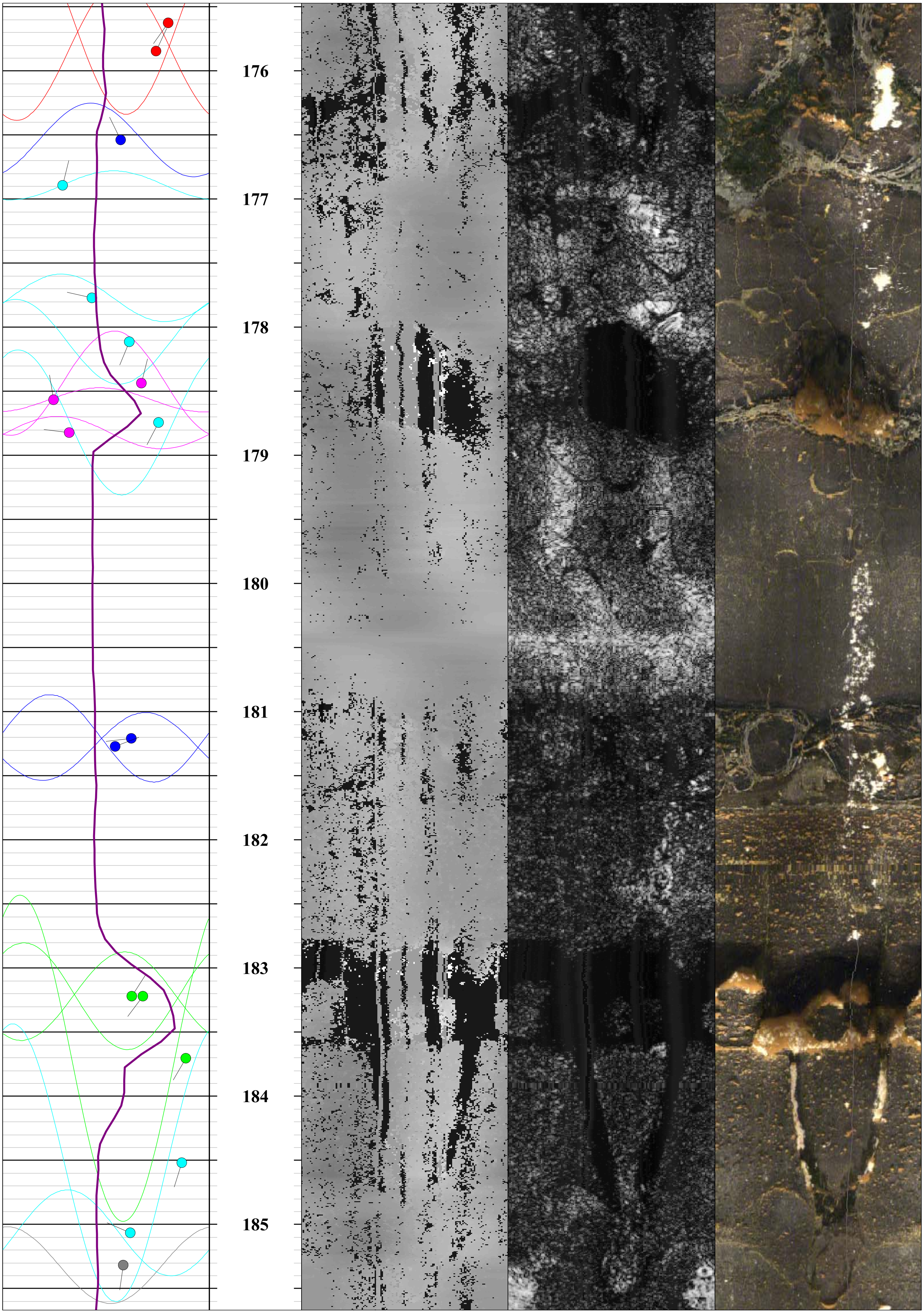
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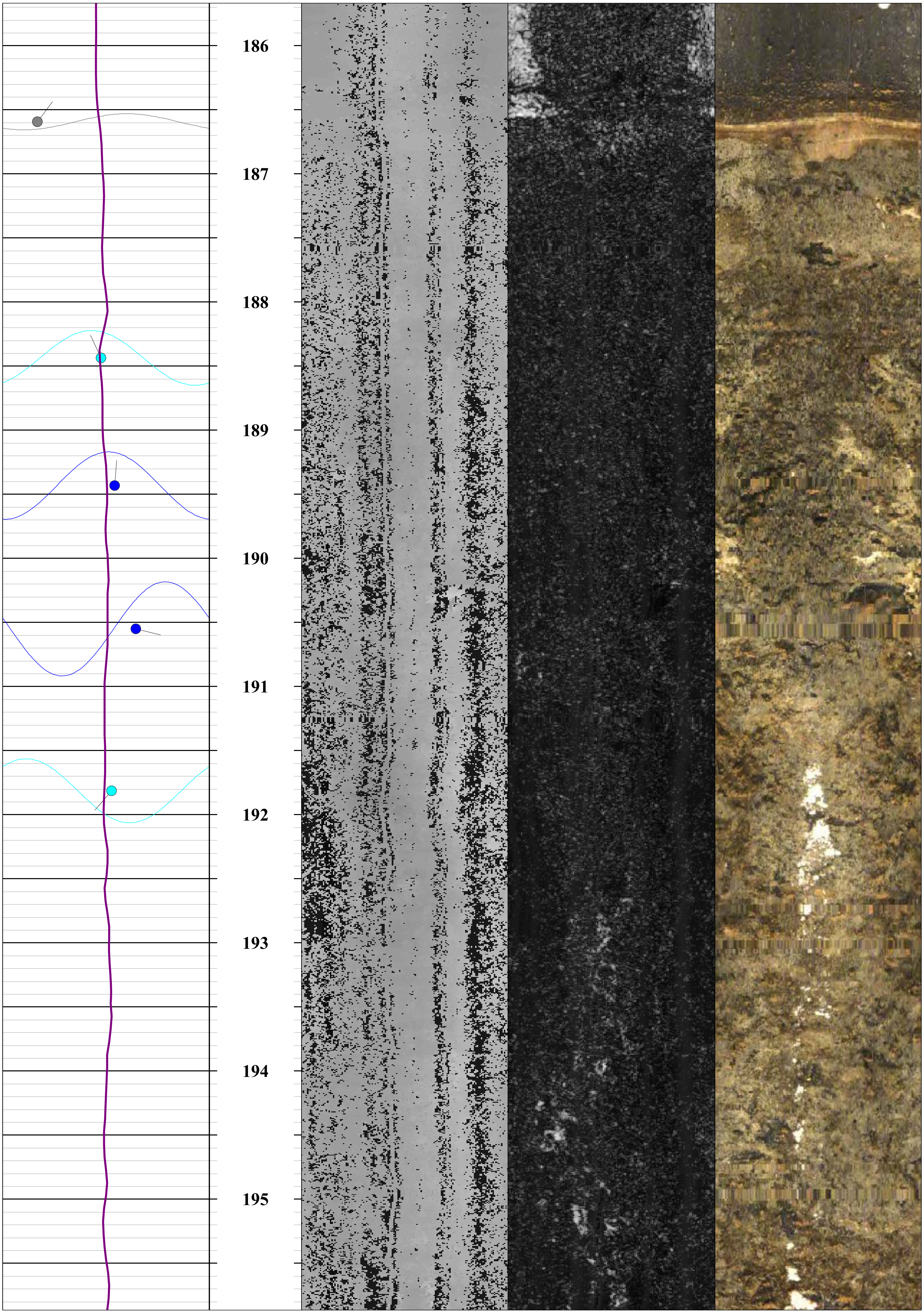

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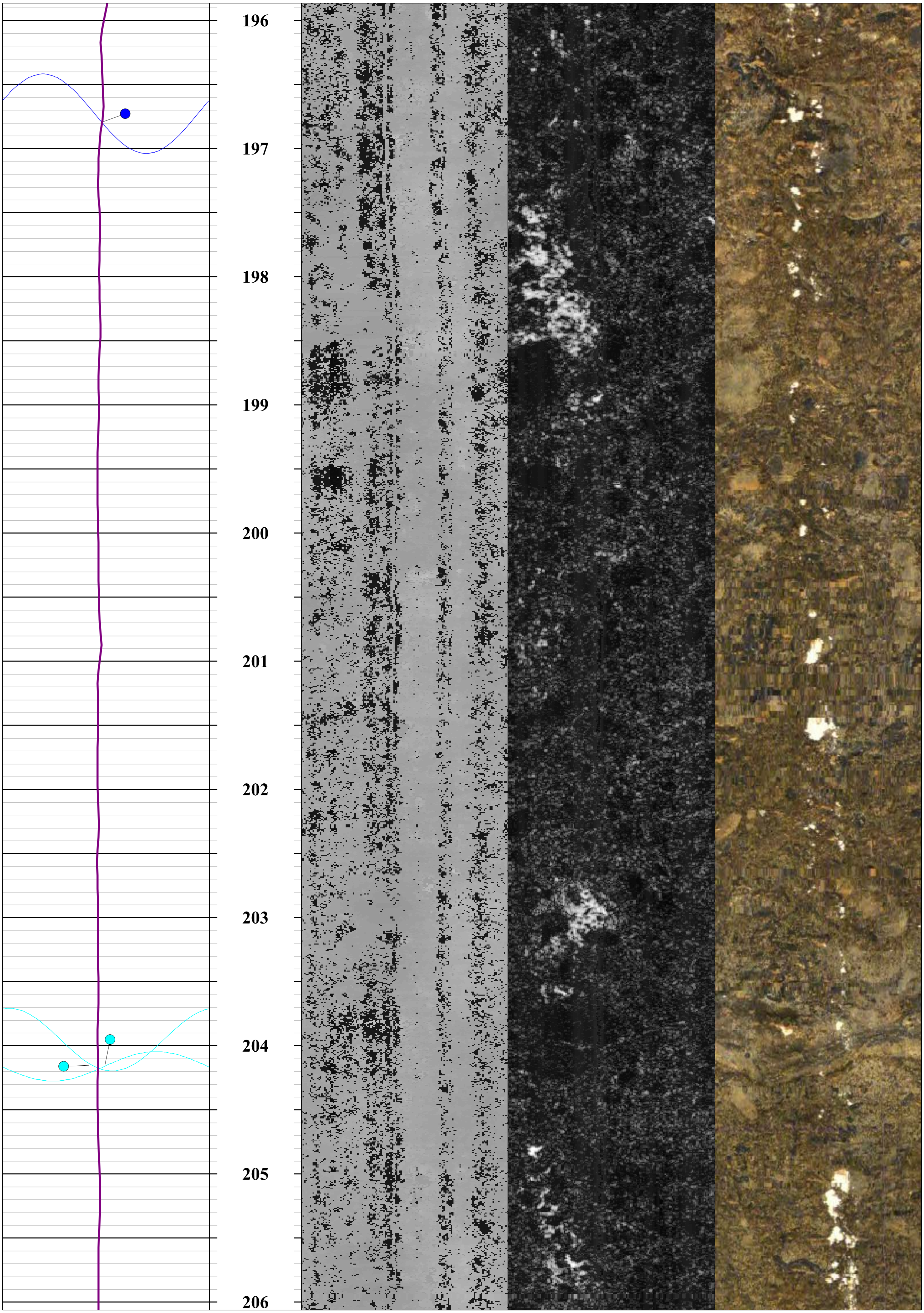
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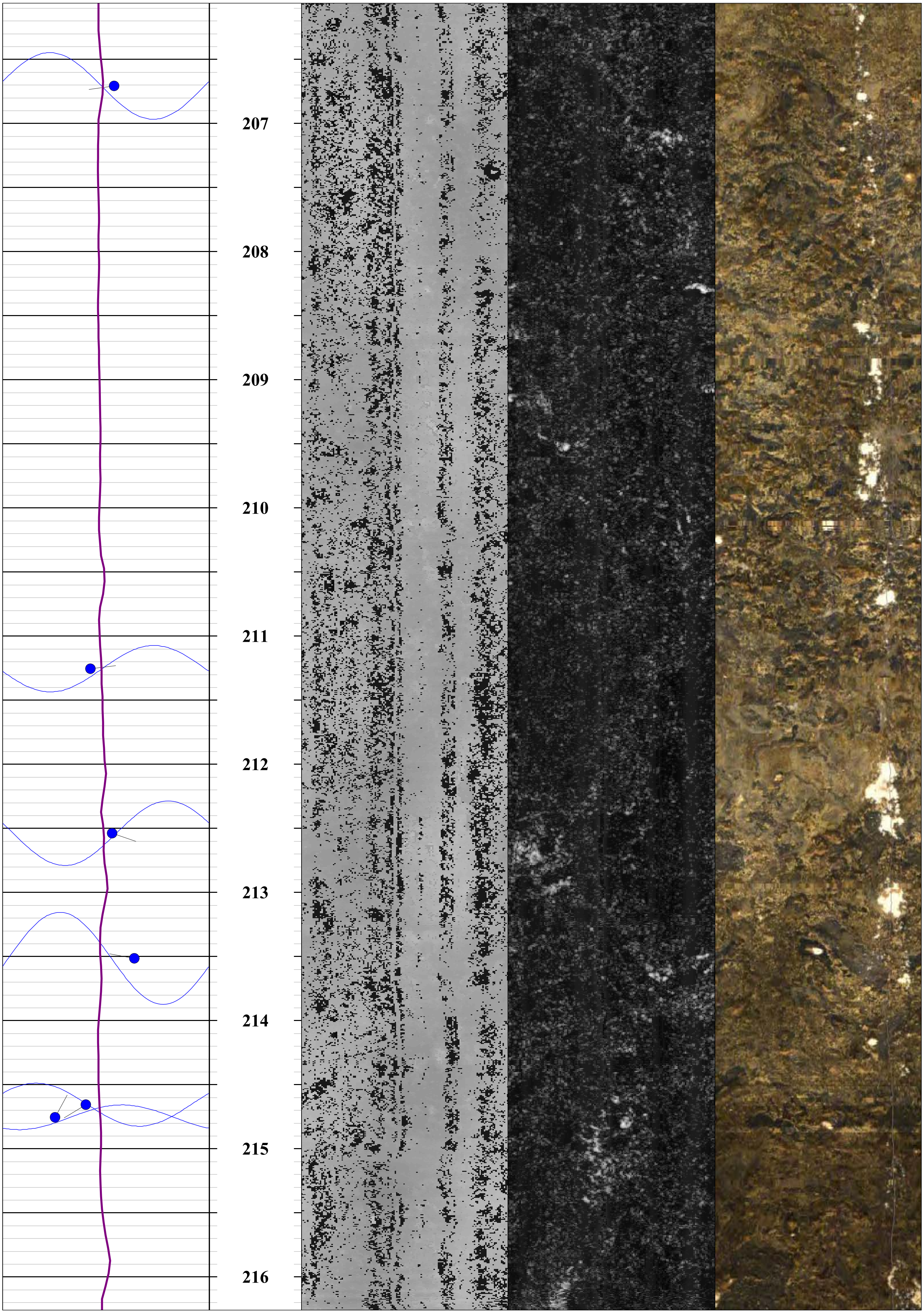
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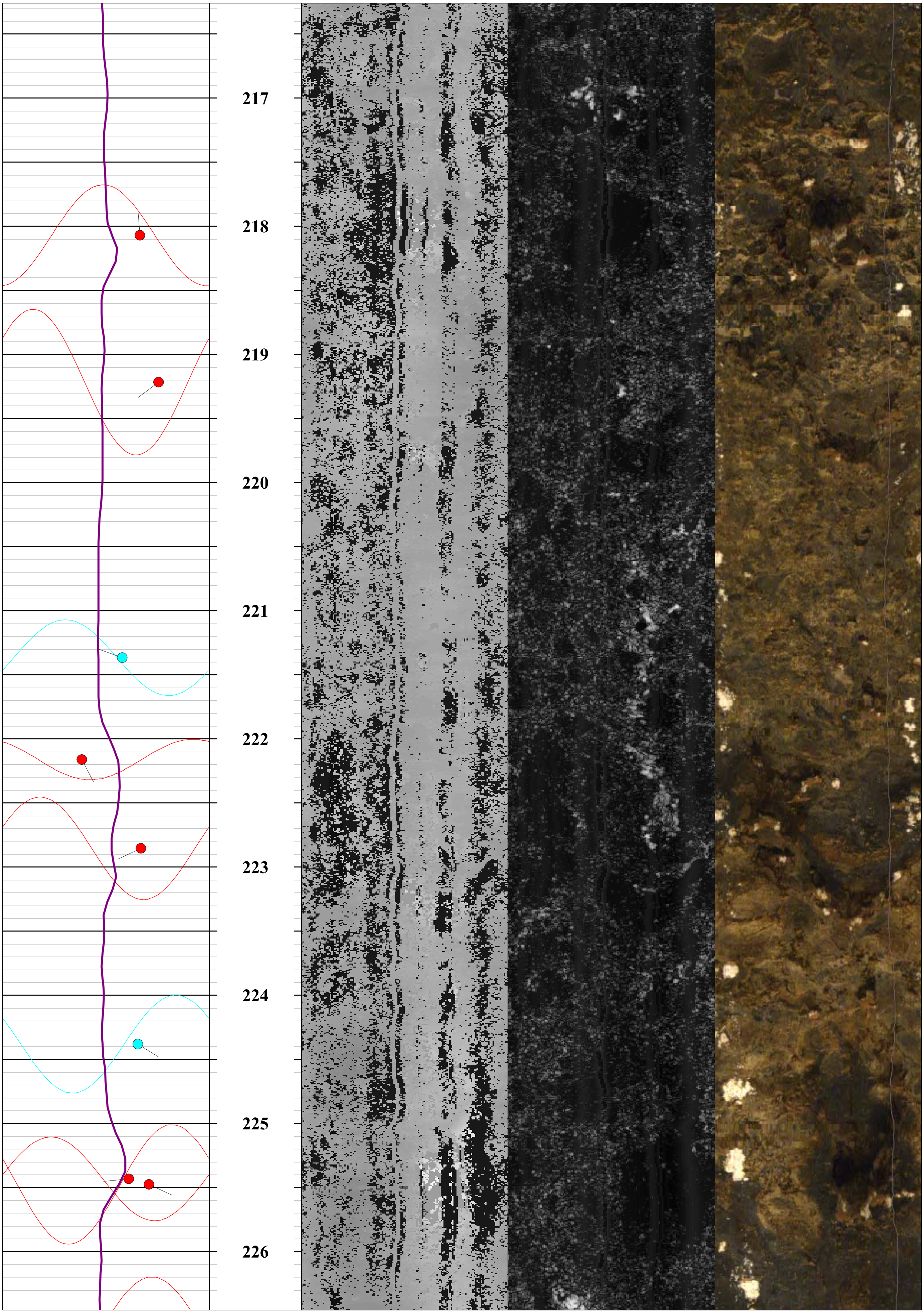
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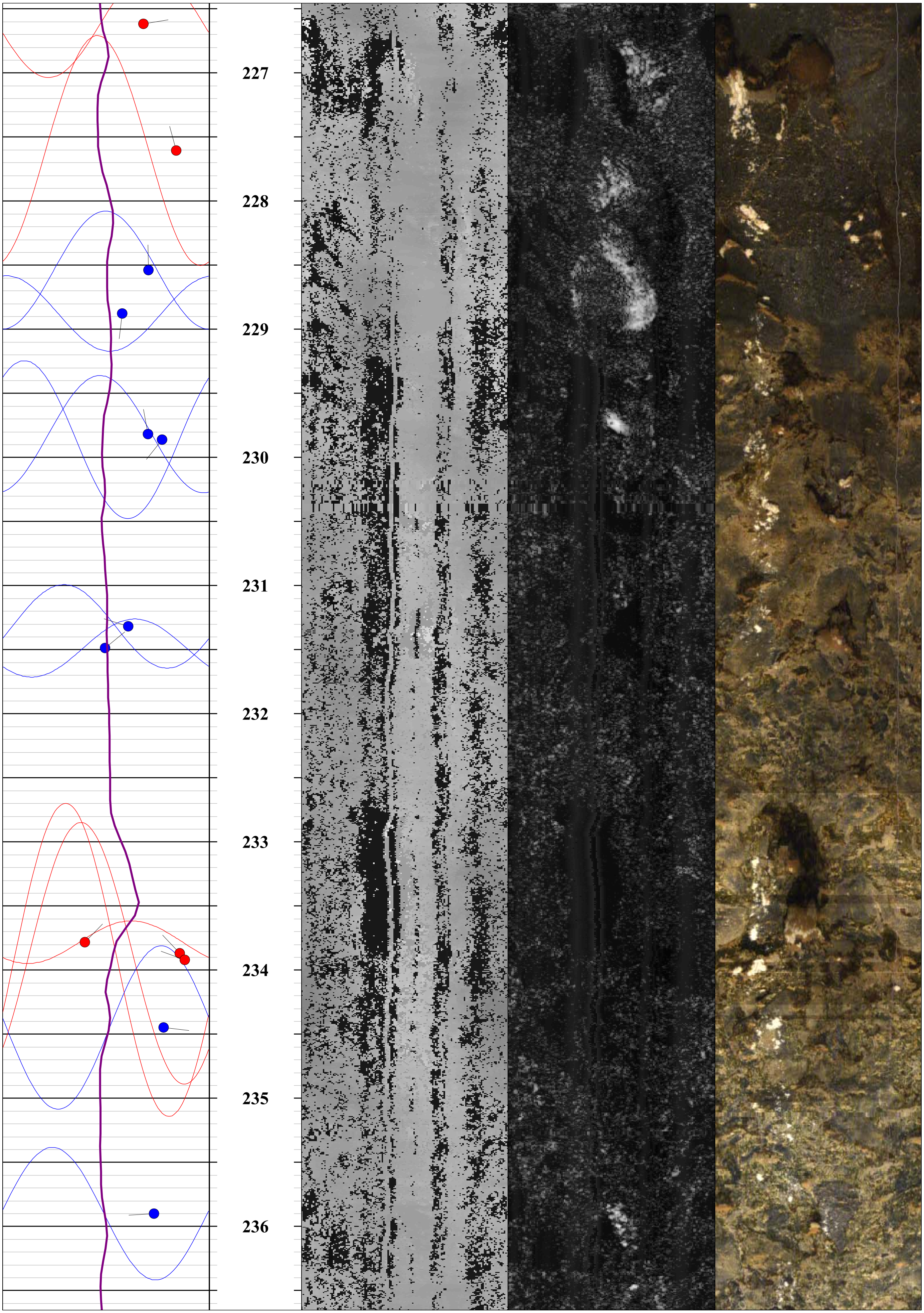
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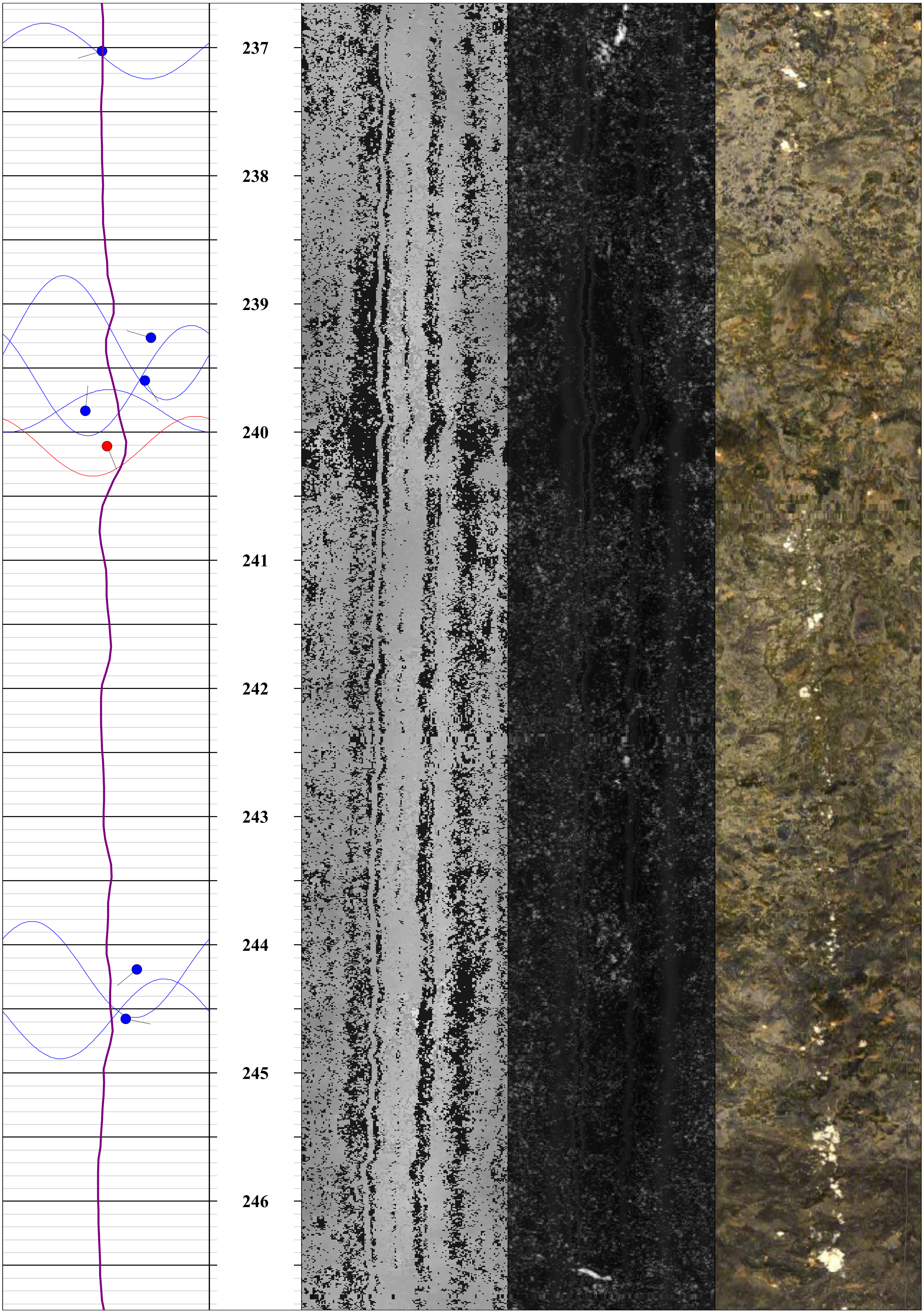

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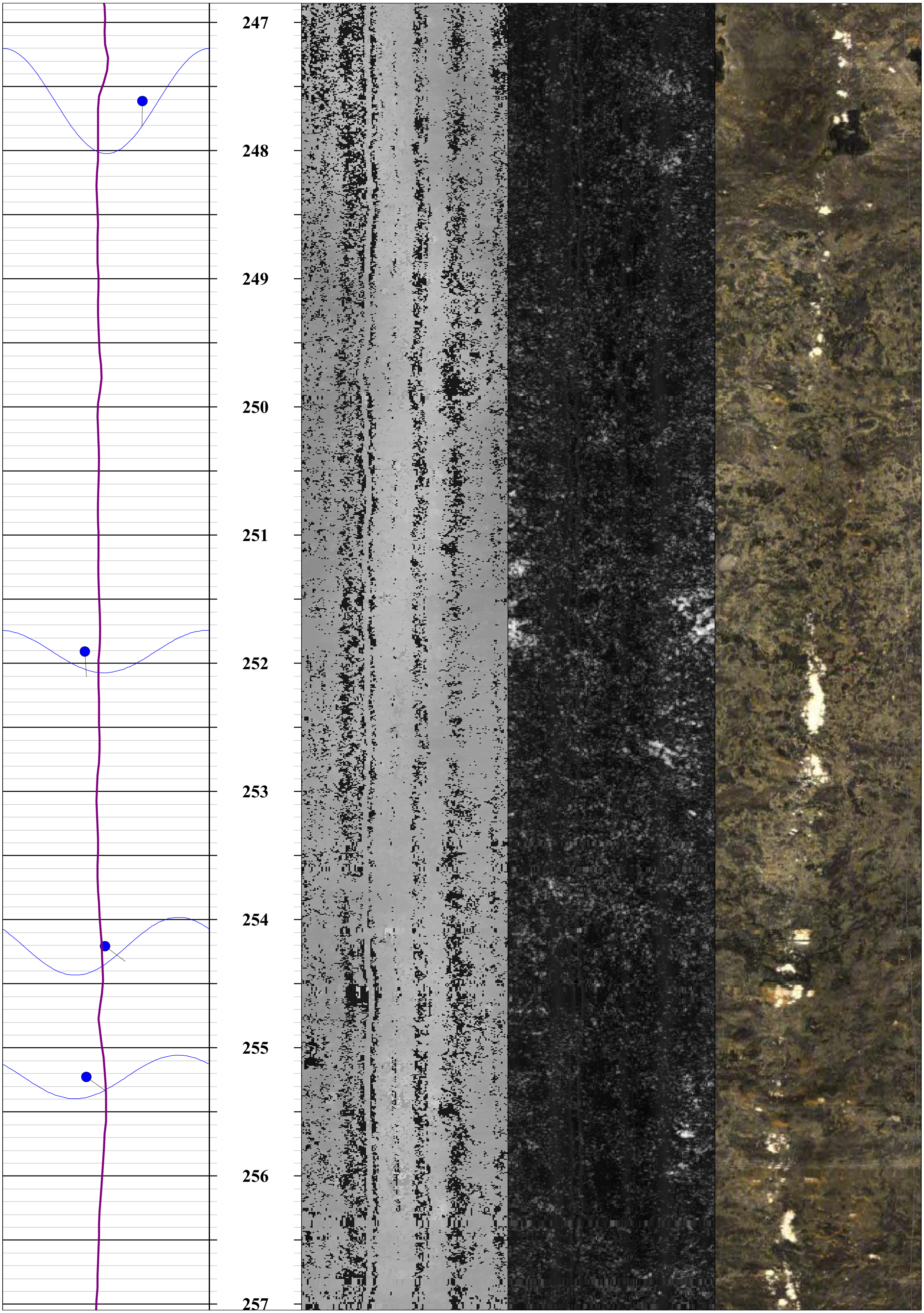
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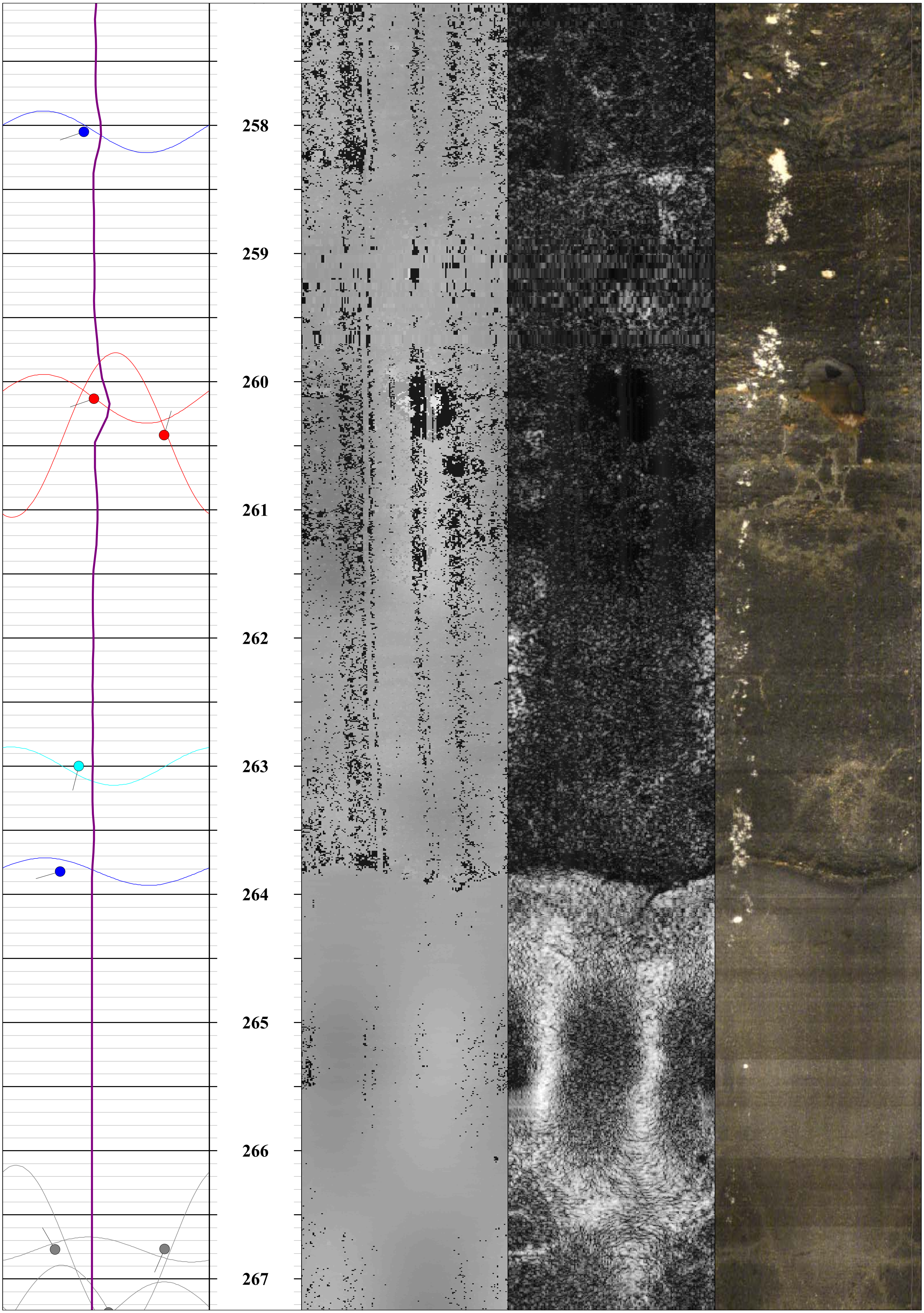
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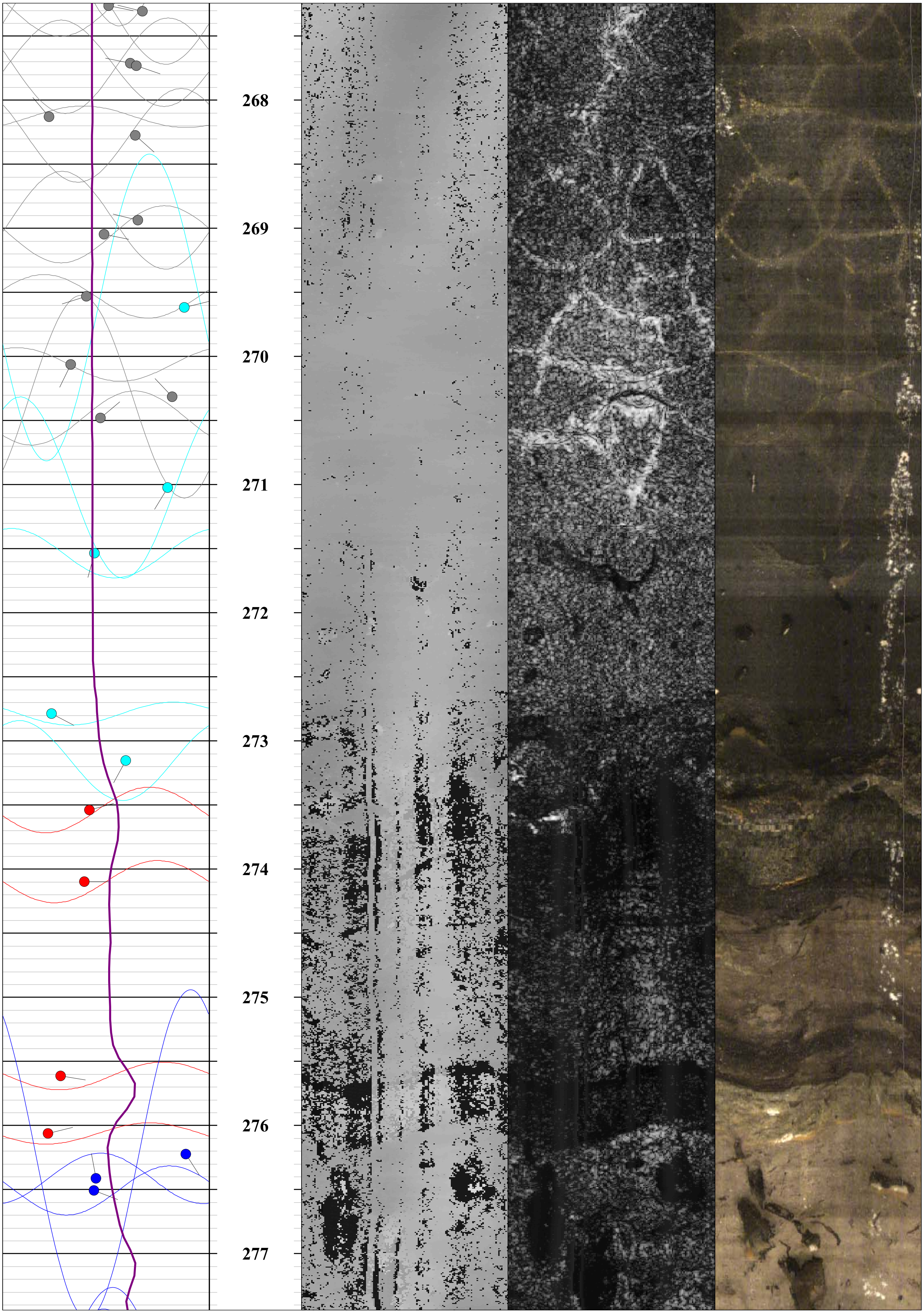
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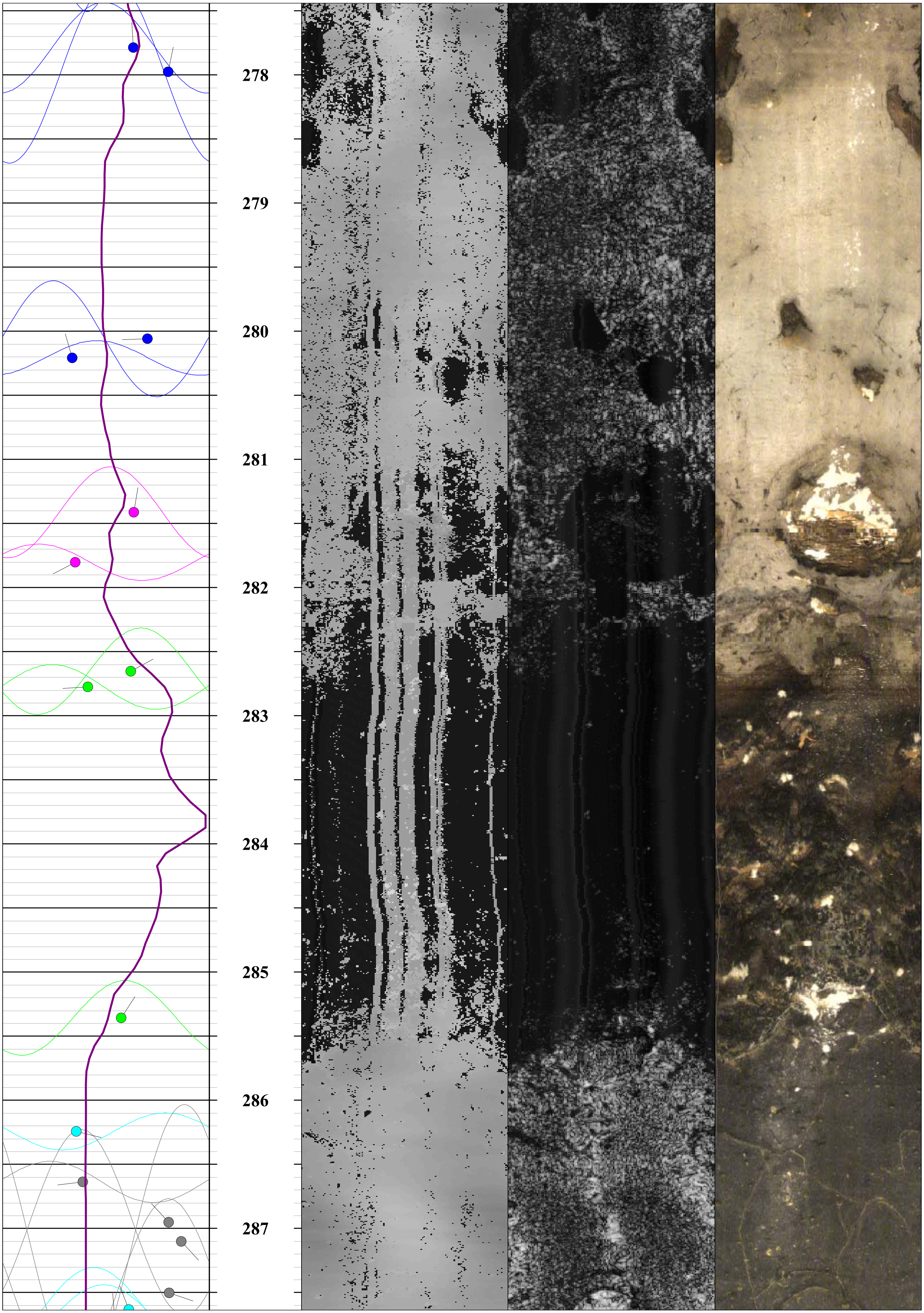

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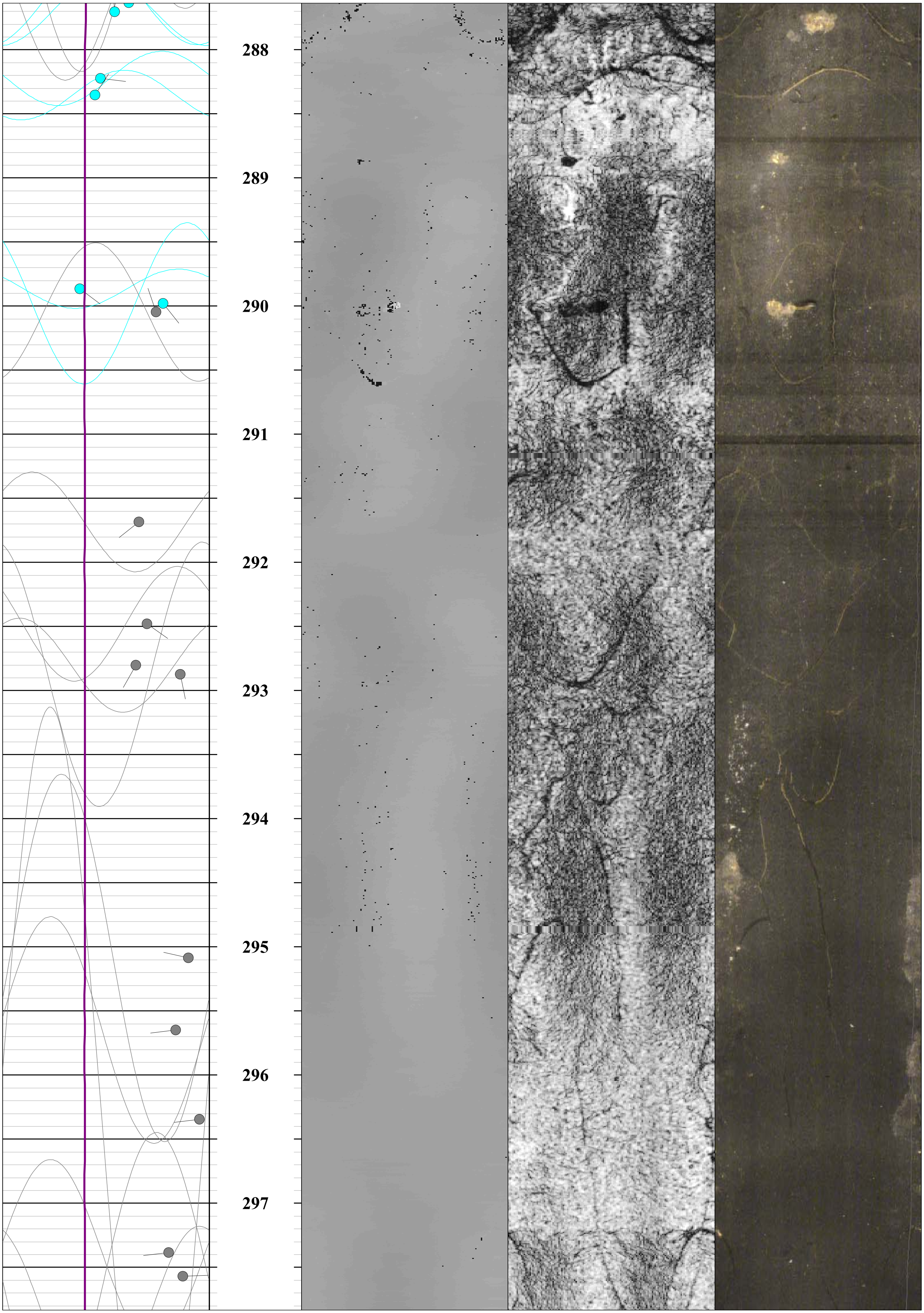
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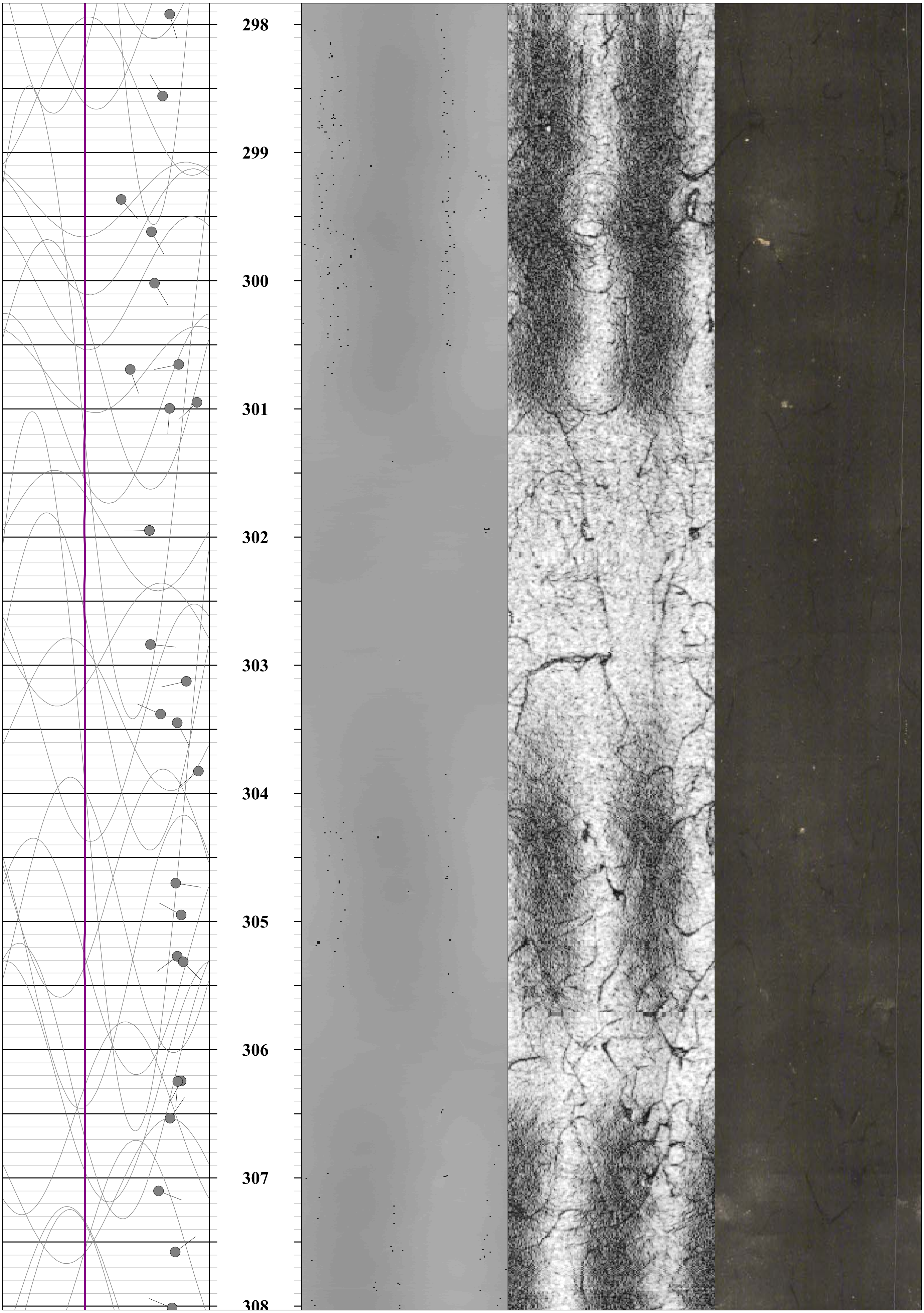
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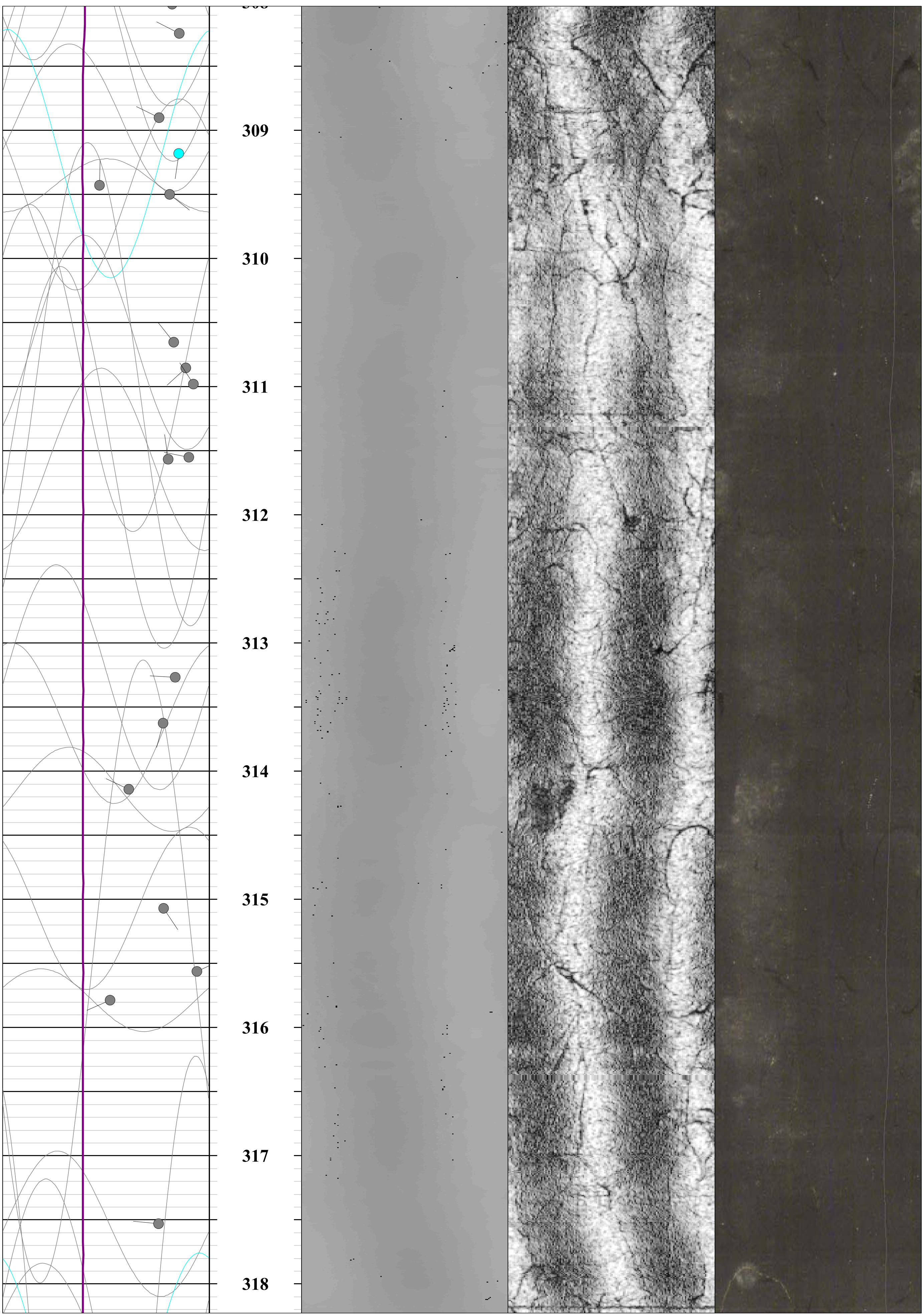

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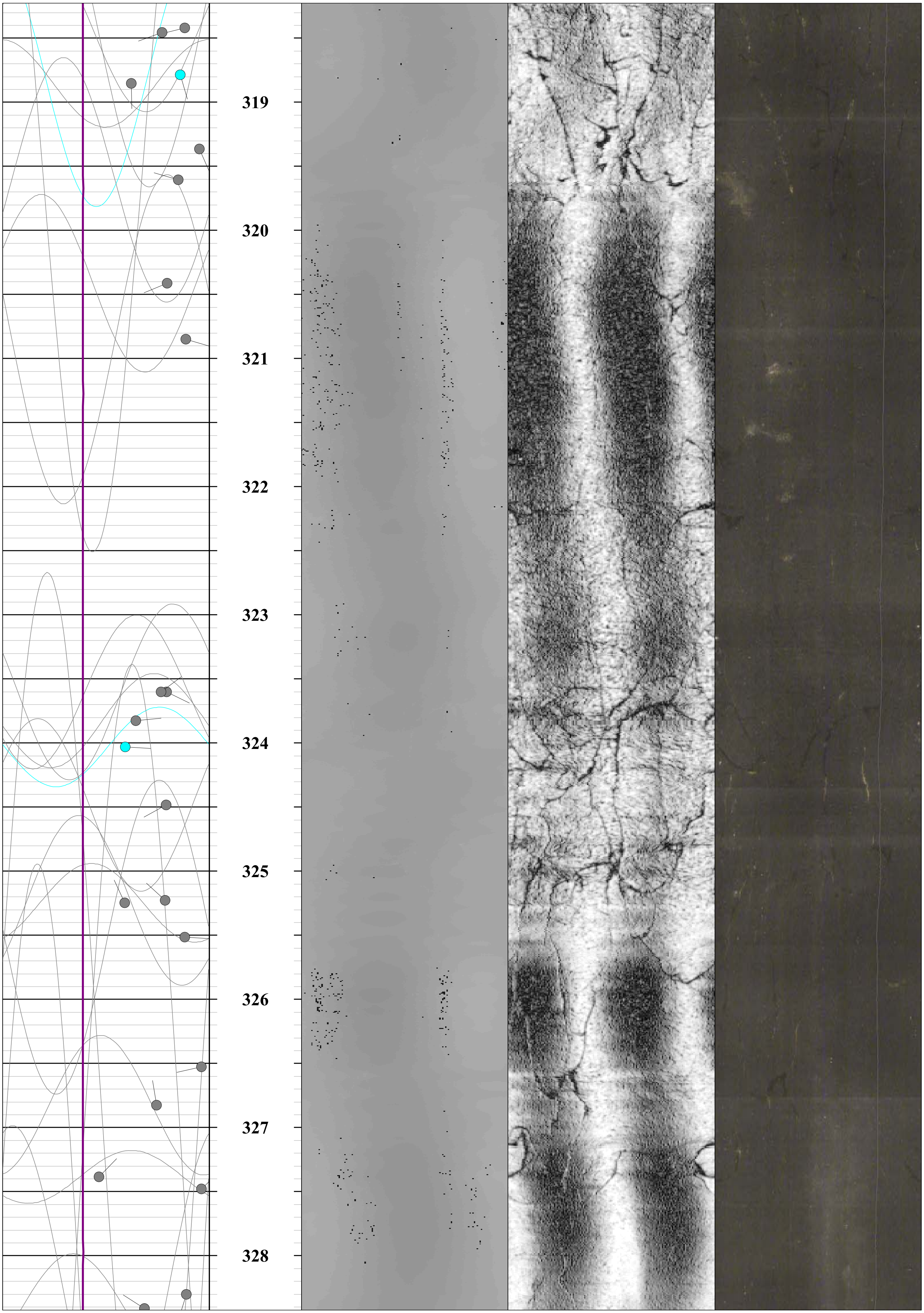

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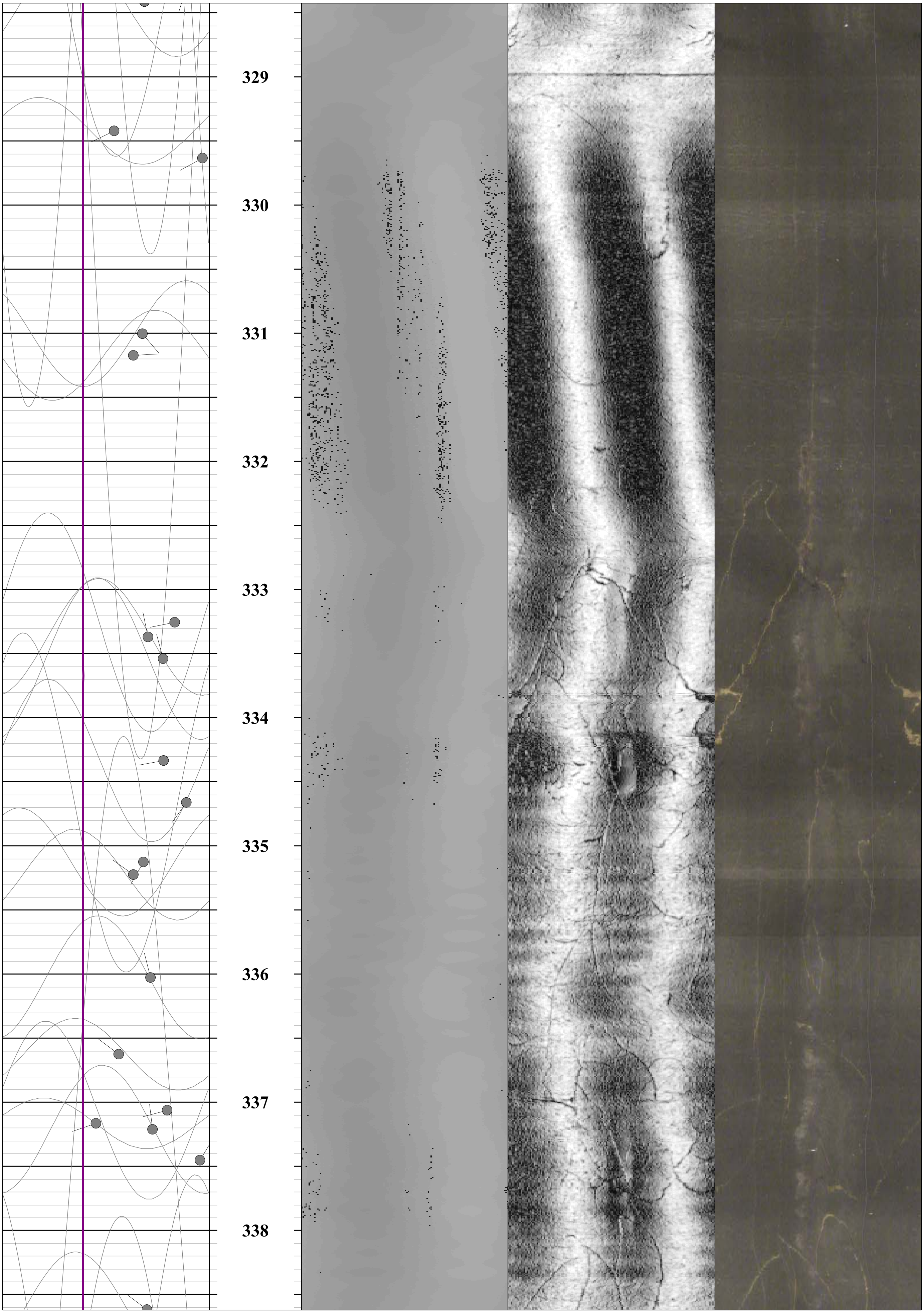
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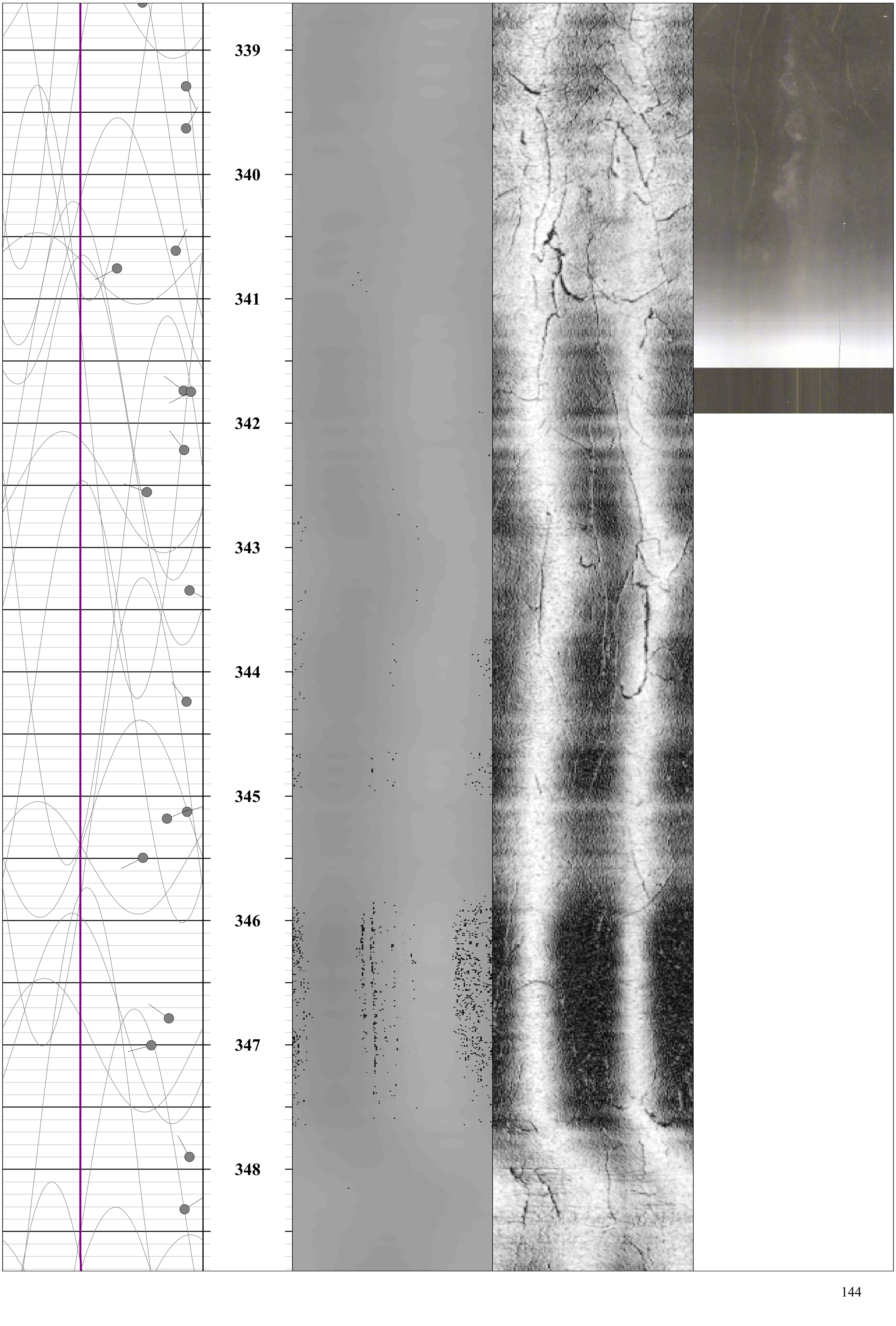
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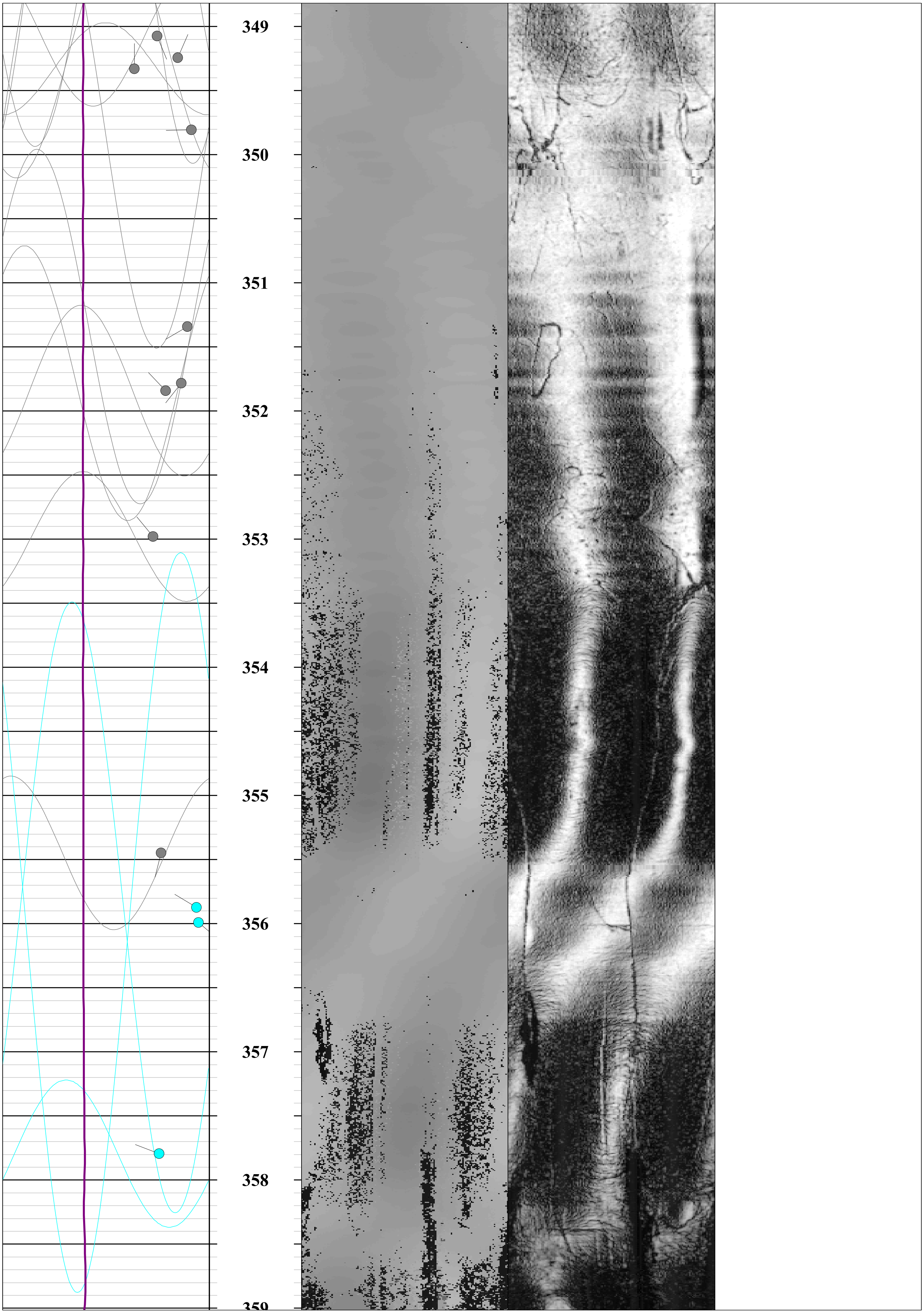
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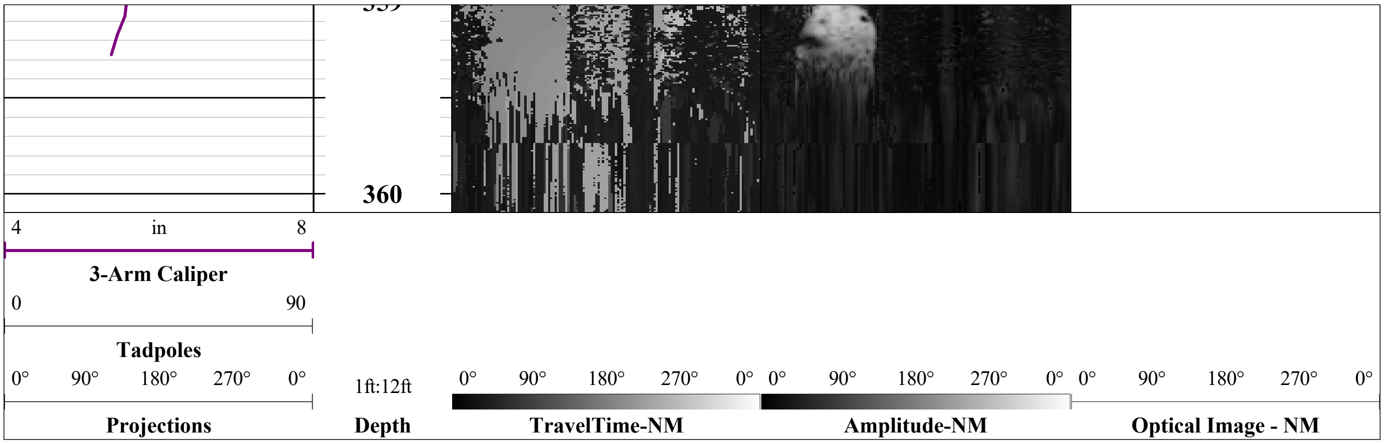
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0° 90° 180° 270° 0°
Projections
1ft:12ft
Depth
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TravelTime-NM
0° 90° 180° 270° 0°
Amplitude-NM
0° 90° 180° 270° 0°
Optical Image - NM

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
1	24.99	82.0	50	64	1
2	25.08	82.3	136	76	1
3	25.78	84.6	333	72	1
4	27.46	90.1	144	85	1
5	27.51	90.3	85	86	1
6	27.97	91.8	324	70	1
7	27.98	91.8	53	70	1
8	28.80	94.5	203	82	1
9	28.85	94.6	232	71	1
10	29.09	95.5	278	85	1
11	29.50	96.8	286	71	1
12	29.86	98.0	312	83	1
13	29.89	98.1	168	88	2
14	30.16	98.9	293	65	1
15	30.24	99.2	177	81	2
16	30.43	99.8	292	65	1
17	32.00	105.0	144	42	1
18	32.03	105.1	276	60	1
19	32.04	105.1	339	63	1
20	32.10	105.3	52	61	1
21	32.92	108.0	235	80	1
22	33.03	108.4	281	81	1
23	33.04	108.4	223	74	1
24	33.09	108.6	1	80	1
25	33.38	109.5	79	41	1
26	35.30	115.8	357	80	2
27	35.95	117.9	351	48	1
28	36.97	121.3	50	77	0
29	37.31	122.4	137	45	0
30	38.08	124.9	149	82	1
31	38.20	125.3	132	78	1
32	38.43	126.1	40	81	0
33	40.21	131.9	334	80	1
34	40.32	132.3	147	39	0
35	40.45	132.7	148	58	0
36	40.98	134.5	149	60	0
37	41.07	134.8	150	80	1
38	41.42	135.9	337	11	0
39	41.49	136.1	75	12	0
40	41.79	137.1	176	84	1
41	42.00	137.8	162	29	0
42	42.14	138.3	175	55	1
43	42.25	138.6	176	12	0
44	42.40	139.1	89	57	0
45	42.47	139.4	347	45	0

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Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
46	42.49	139.4	231	49	0
47	42.50	139.4	88	65	0
48	43.60	143.0	341	82	3
49	43.90	144.0	251.2	49.6	1
50	43.92	144.1	179.1	81.9	3
51	43.94	144.2	163.9	76.6	1
52	44.44	145.8	288.4	81.6	1
53	44.55	146.2	178.3	82.0	1
54	44.59	146.3	123.2	87.7	1
55	44.63	146.4	121.8	83.9	1
56	44.92	147.4	210.6	74.8	1
57	44.95	147.5	124.7	87.6	1
58	46.58	152.8	298.3	87.2	1
59	46.85	153.7	168.0	65.1	2
60	46.88	153.8	169.1	55.6	2
61	47.04	154.3	66.0	77.8	0
62	47.70	156.5	244.8	74.9	0
63	47.91	157.2	24.8	88.5	1
64	48.03	157.6	353.3	22.7	0
65	48.20	158.2	296.8	88.0	1
66	48.34	158.6	345.0	22.7	2
67	48.35	158.6	77.1	34.1	2
68	48.49	159.1	305.3	20.6	0
69	49.07	161.0	243.0	35.1	0
70	49.31	161.8	184.8	51.0	1
71	49.48	162.3	270.9	39.7	1
72	49.52	162.5	163.1	53.8	1
73	49.66	162.9	3.3	44.8	3
74	49.67	163.0	349.5	73.0	3
75	49.73	163.2	349.6	44.7	2
76	49.97	164.0	209.0	51.6	1
77	50.11	164.4	195.2	51.5	3
78	50.15	164.6	255.8	26.5	3
79	50.22	164.8	266.3	23.7	1
80	50.25	164.9	213.6	80.1	2
81	50.38	165.3	217.2	49.6	1
82	50.57	165.9	21.9	11.0	1
83	50.92	167.1	41.1	65.9	2
84	51.03	167.4	69.4	46.6	1
85	51.05	167.5	64.4	64.0	1
86	51.22	168.0	293.4	50.5	1
87	51.27	168.2	137.0	42.8	1
88	51.54	169.1	35.3	59.4	2
89	51.61	169.3	64.9	67.2	4
90	51.69	169.6	245.5	60.6	4

All directions are with respect to Magnetic North.

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
91	51.73	169.7	165.9	46.7	4
92	52.30	171.6	261.1	44.6	3
93	52.35	171.7	68.9	52.1	3
94	53.01	173.9	54.0	52.3	2
95	53.04	174.0	283.7	56.9	2
96	53.35	175.0	143.2	47.4	3
97	53.53	175.6	215.4	72.2	3
98	53.60	175.9	24.6	67.0	3
99	53.81	176.5	333.5	51.4	2
100	53.92	176.9	13.4	26.3	1
101	54.18	177.8	282.9	39.0	1
102	54.29	178.1	202.9	55.3	1
103	54.39	178.4	14.3	60.6	4
104	54.43	178.6	350.3	22.2	4
105	54.48	178.7	207.4	68.0	1
106	54.50	178.8	276.4	29.0	4
107	55.23	181.2	262.6	56.1	2
108	55.25	181.3	69.2	49.2	2
109	55.85	183.2	32.8	56.4	5
110	55.85	183.2	217.2	61.2	5
111	55.99	183.7	210.4	79.8	5
112	56.24	184.5	197.6	78.1	1
113	56.41	185.1	293.3	55.6	1
114	56.49	185.3	188.3	52.5	0
115	56.87	186.6	36.8	15.3	0
116	57.43	188.4	335.3	43.0	1
117	57.74	189.4	4.7	48.9	2
118	58.08	190.6	103.6	58.0	2
119	58.46	191.8	221.2	47.5	1
120	59.96	196.7	250.5	53.5	2
121	62.16	204.0	191.1	46.8	1
122	62.23	204.2	87.6	26.5	1
123	63.01	206.7	262.4	48.6	2
124	64.39	211.3	83.5	38.3	2
125	64.78	212.5	108.3	47.7	2
126	65.08	213.5	279.8	57.5	2
127	65.43	214.7	238.3	36.2	2
128	65.46	214.8	28	23	2
129	66.47	218.1	355	60	3
130	66.82	219.2	233	68	3
131	67.47	221.4	289	52	1
132	67.71	222.2	152	35	3
133	67.92	222.9	245	60	3
134	68.39	224.4	122	59	1
135	68.71	225.4	264	55	3

All directions are with respect to Magnetic North.

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
136	68.72	225.5	115	64	3
137	69.07	226.6	80	61	3
138	69.38	227.6	345	76	3
139	69.66	228.5	359	64	2
140	69.76	228.9	187	52	2
141	70.05	229.8	350	63	2
142	70.06	229.9	218	70	2
143	70.51	231.3	287	55	2
144	70.56	231.5	50	45	2
145	71.26	233.8	44	36	3
146	71.28	233.9	317	77	3
147	71.30	233.9	290	79	3
148	71.46	234.5	97	70	2
149	71.90	235.9	267	66	2
150	72.25	237.0	253	43	2
151	72.93	239.3	286	65	2
152	73.03	239.6	148	62	2
153	73.10	239.8	6	36	2
154	73.19	240.1	157	46	3
155	74.43	244.2	231	59	2
156	74.55	244.6	101	54	2
157	75.47	247.6	181	61	2
158	76.78	251.9	177	36	2
159	77.48	254.2	127	45	2
160	77.79	255.2	126	37	2
161	78.65	258.1	251	35	2
162	79.29	260.1	251	40	3
163	79.38	260.4	17	70	3
164	80.16	263.0	194	33	1
165	80.41	263.8	254	25	2
166	81.31	266.8	204	71	0
167	81.31	266.8	330	23	0
168	81.46	267.3	101	46	0
169	81.48	267.3	284	61	0
170	81.60	267.7	281	56	0
171	81.60	267.7	109	58	0
172	81.73	268.1	320	20	0
173	81.77	268.3	131	58	0
174	81.97	268.9	284	59	0
175	82.01	269.1	102	44	0
176	82.15	269.5	253	36	0
177	82.18	269.6	76	79	1
178	82.31	270.1	206	30	0
179	82.39	270.3	317	74	0
180	82.44	270.5	50	43	0

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Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
181	82.61	271.0	211	72	1
182	82.76	271.5	195	40	1
183	83.14	272.8	118	21	1
184	83.26	273.2	209	54	1
185	83.37	273.5	75	38	3
186	83.55	274.1	90	36	3
187	84.01	275.6	99	25	3
188	84.14	276.1	76	20	3
189	84.19	276.2	148	80	2
190	84.25	276.4	350	41	2
191	84.28	276.5	111	40	2
192	84.67	277.8	356	57	2
193	84.73	278.0	12	72	2
194	85.36	280.1	268	63	2
195	85.41	280.2	344	30	2
196	85.77	281.4	9	57	4
197	85.89	281.8	243	32	4
198	86.15	282.7	61	56	5
199	86.19	282.8	266	37	5
200	86.98	285.4	33	52	5
201	87.25	286.2	104	32	1
202	87.37	286.6	263	35	0
203	87.46	287.0	317	72	0
204	87.51	287.1	137	78	0
205	87.63	287.5	109	73	0
206	87.67	287.6	339	55	1
207	87.69	287.7	356	49	1
208	87.85	288.2	97	43	1
209	87.89	288.4	32	40	1
210	88.35	289.9	127	34	1
211	88.39	290.0	141	70	1
212	88.41	290.1	342	67	0
213	88.91	291.7	232	59	0
214	89.15	292.5	125	63	0
215	89.25	292.8	209	58	0
216	89.27	292.9	168	77	0
217	89.94	295.1	283	81	0
218	90.11	295.7	264	75	0
219	90.33	296.4	263	86	0
220	90.64	297.4	263	72	0
221	90.70	297.6	88	78	0
222	90.81	297.9	164	73	0
223	91.00	298.6	330	70	0
224	91.24	299.4	140	52	0
225	91.32	299.6	152	65	0

All directions are with respect to Magnetic North.

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
226	91.45	300.0	149	66	0
227	91.64	300.7	258	77	0
228	91.65	300.7	161	56	0
229	91.73	301.0	227	85	0
230	91.74	301.0	185	73	0
231	92.03	302.0	271	64	0
232	92.31	302.8	96	64	0
233	92.39	303.1	257	80	0
234	92.47	303.4	294	69	0
235	92.49	303.5	153	76	0
236	92.61	303.8	231	85	0
237	92.87	304.7	100	76	0
238	92.95	305.0	298	78	0
239	93.05	305.3	233	76	0
240	93.06	305.3	136	79	0
241	93.34	306.2	209	78	0
242	93.35	306.3	185	76	0
243	93.43	306.5	34	73	0
244	93.60	307.1	112	68	0
245	93.75	307.6	53	75	0
246	93.88	308.0	292	74	0
247	93.95	308.2	297	77	0
248	94.15	308.9	296	68	0
249	94.24	309.2	188	77	1
250	94.31	309.4	1	42	0
251	94.34	309.5	128	73	0
252	94.69	310.7	322	75	0
253	94.75	310.9	227	80	0
254	94.79	311.0	328	83	0
255	94.96	311.6	282	81	0
256	94.97	311.6	352	72	0
257	95.48	313.3	274	75	0
258	95.59	313.6	195	70	0
259	95.75	314.1	295	55	0
260	96.03	315.1	146	70	0
261	96.18	315.6	65	85	0
262	96.25	315.8	247	47	0
263	96.78	317.5	276	68	0
264	97.05	318.4	256	80	0
265	97.06	318.5	250	70	0
266	97.16	318.8	163	77	1
267	97.19	318.9	178	56	0
268	97.34	319.4	157	86	0
269	97.42	319.6	286	76	0
270	97.66	320.4	247	72	0

All directions are with respect to Magnetic North.

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
271	97.80	320.9	106	80	0
272	98.63	323.6	117	72	0
273	98.63	323.6	53	69	0
274	98.70	323.8	84	58	0
275	98.76	324.0	93	54	1
276	98.90	324.5	241	71	0
277	99.13	325.2	313	71	0
278	99.14	325.3	335	53	0
279	99.22	325.5	93	79	0
280	99.53	326.5	258	87	0
281	99.62	326.8	351	67	0
282	99.79	327.4	45	42	0
283	99.82	327.5	46	87	0
284	100.07	328.3	197	80	0
285	100.10	328.4	303	62	0
286	100.41	329.4	243	49	0
287	100.47	329.6	241	87	0
288	100.89	331.0	140	61	0
289	100.94	331.2	87	57	0
290	101.57	333.3	258	75	0
291	101.61	333.4	348	63	0
292	101.66	333.5	345	70	0
293	101.90	334.3	260	70	0
294	102.00	334.7	215	80	0
295	102.14	335.1	210	61	0
296	102.18	335.2	305	57	0
297	102.42	336.0	346	65	0
298	102.60	336.6	306	51	0
299	102.74	337.1	255	72	0
300	102.77	337.2	252	41	0
301	102.78	337.2	354	65	0
302	102.85	337.5	31	86	0
303	103.21	338.6	307	63	0
304	103.42	339.3	156	82	0
305	103.52	339.6	28	82	0
306	103.82	340.6	27	78	0
307	103.86	340.8	243	51	0
308	104.16	341.7	307	81	0
309	104.17	341.8	243	85	0
310	104.31	342.2	323	82	0
311	104.41	342.6	290	65	0
312	104.65	343.3	116	84	0
313	104.92	344.2	323	83	0
314	105.20	345.1	71	83	0
315	105.21	345.2	67	74	0

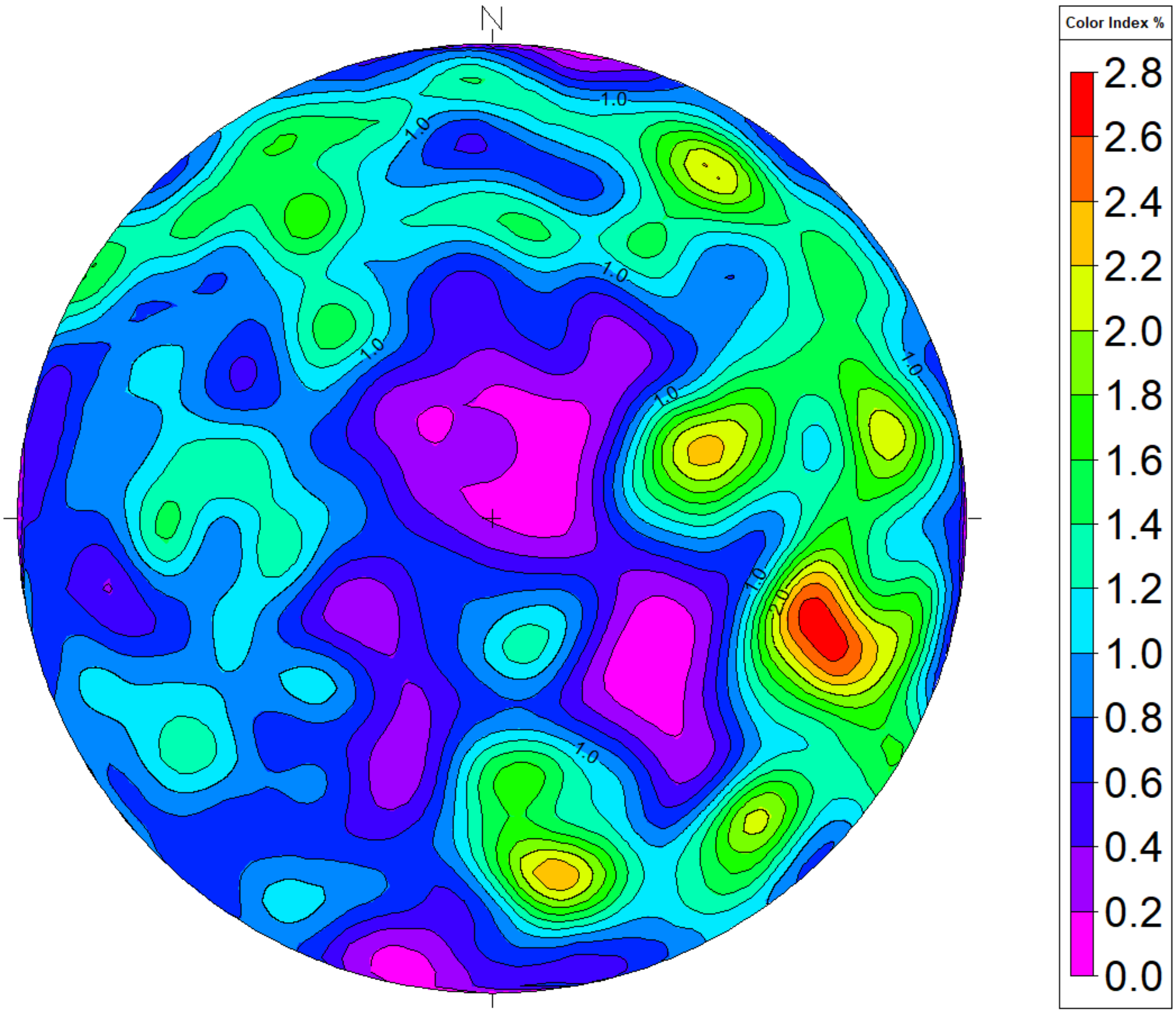
All directions are with respect to Magnetic North.

Table RC-04:2. Orientation Summary Table
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 and 25 April 2019

Feature No.	Depth (meters)	Depth (feet)	Dip Direction (degrees)	Dip Angle (degrees)	Feature Rank (0 to 5)
316	105.31	345.5	244	63	0
317	105.70	346.8	305	75	0
318	105.77	347.0	255	67	0
319	106.04	347.9	331	84	0
320	106.17	348.3	57	82	0
321	106.40	349.1	158	67	0
322	106.45	349.2	23	76	0
323	106.48	349.3	359	57	0
324	106.62	349.8	269	82	0
325	107.09	351.3	240	81	0
326	107.22	351.8	218	78	0
327	107.24	351.8	317	71	0
328	107.59	353.0	320	66	0
329	108.34	355.5	194	69	0
330	108.47	355.9	301	85	1
331	108.51	356.0	130	85	1
332	109.05	357.8	291	68	1

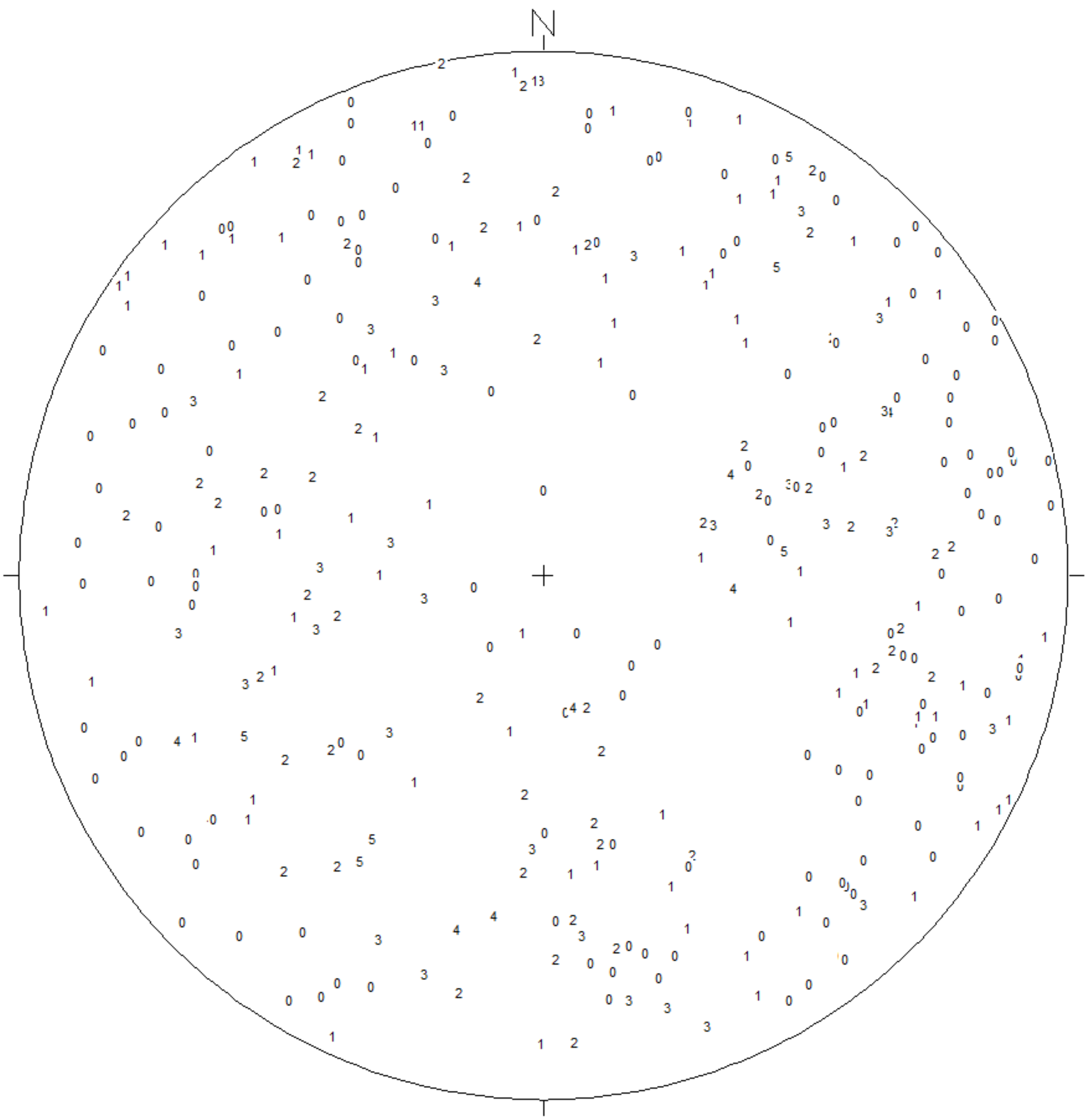
All directions are with respect to Magnetic North.

Figure RC-04:5. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 & 25 April 2019



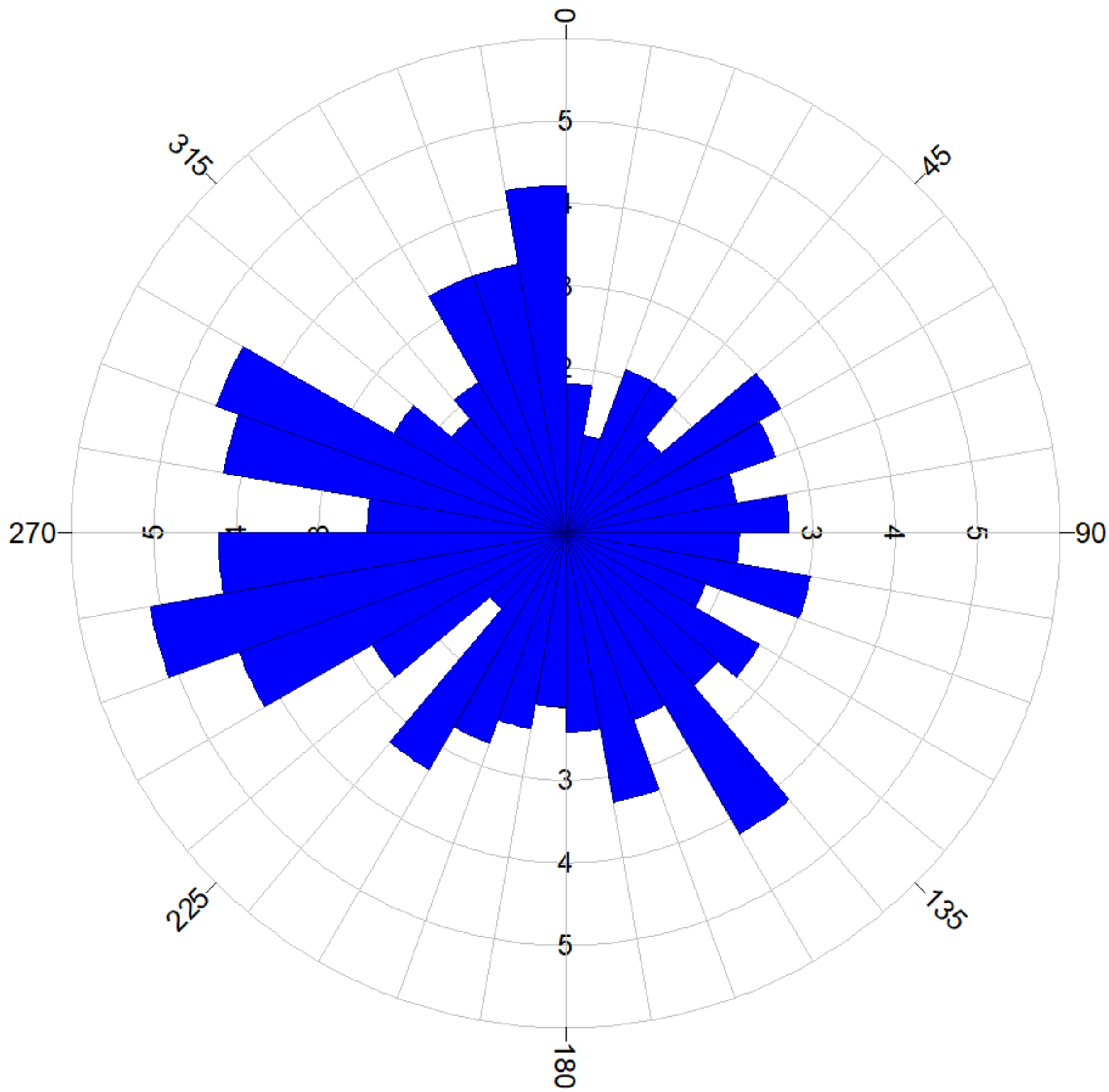
All directions are with respect to Magnetic North.

Figure RC-04:6. Stereonet Diagram – Schmidt Projection
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 & 25 April 2019



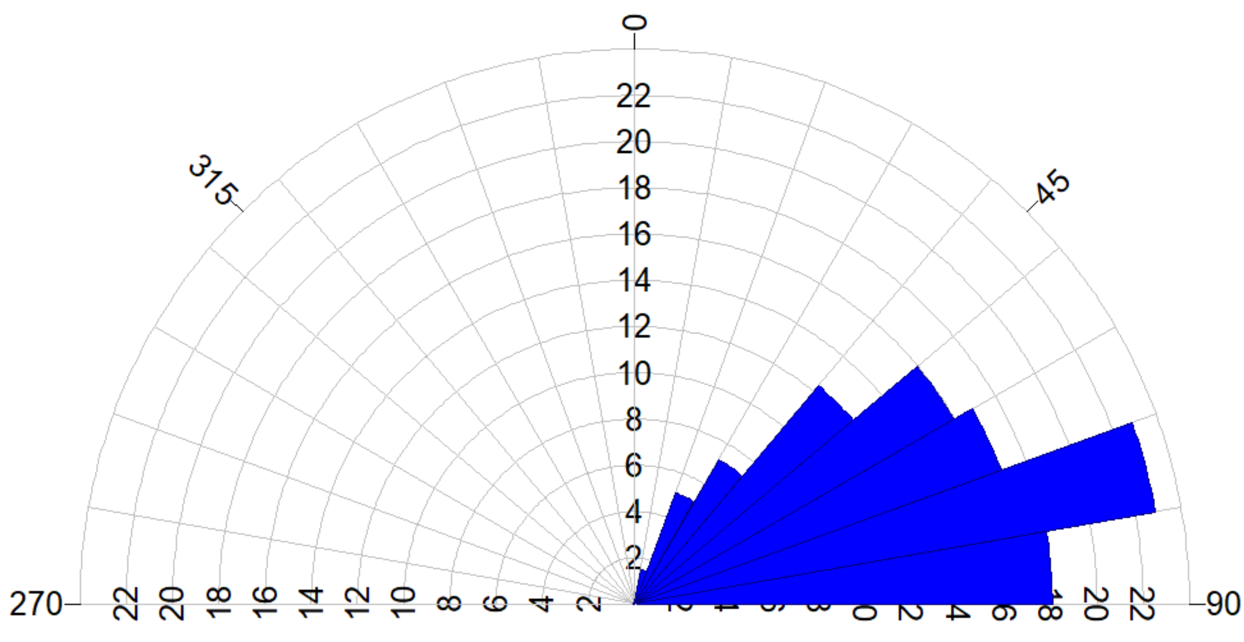
All directions are with respect to Magnetic North.

Figure RC-04:7. Rose Diagram – Dip Directions
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 & 25 April 2019



All directions are with respect to Magnetic North.

Figure RC-04:8. Rose Diagram – Dip Angles
Televiewer Image Features
Jacobs
Union Pacific
RC-04
22 & 25 April 2019



All directions are with respect to Magnetic North.

FIGURE RC-04:9A. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 148.0 Feet to WL; Jacobs; Union Pacific; Wellbore: RC-04

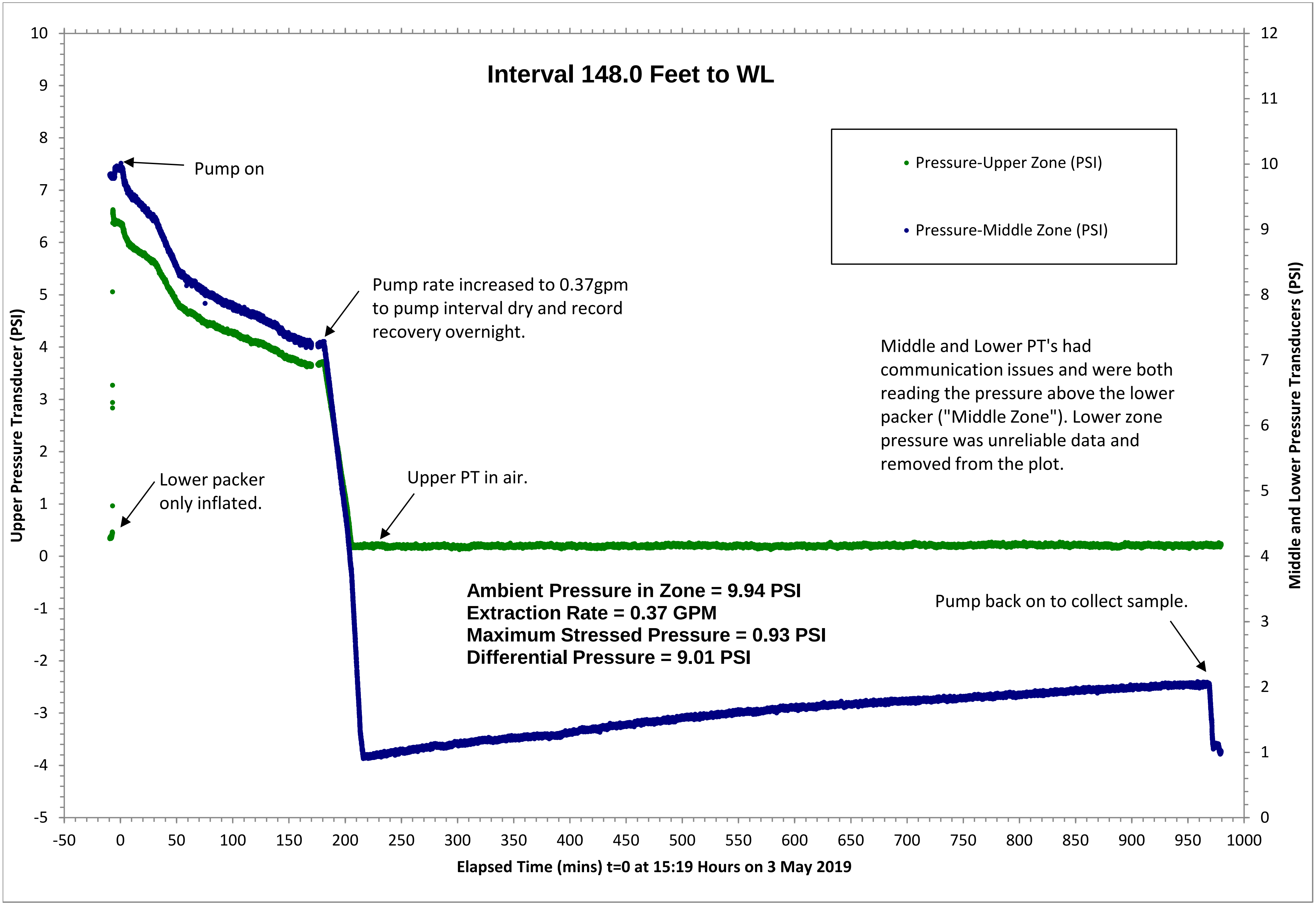


FIGURE RC-04:9B. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 254.0 to 264.5 Feet; Jacobs; Union Pacific; Wellbore: RC-04

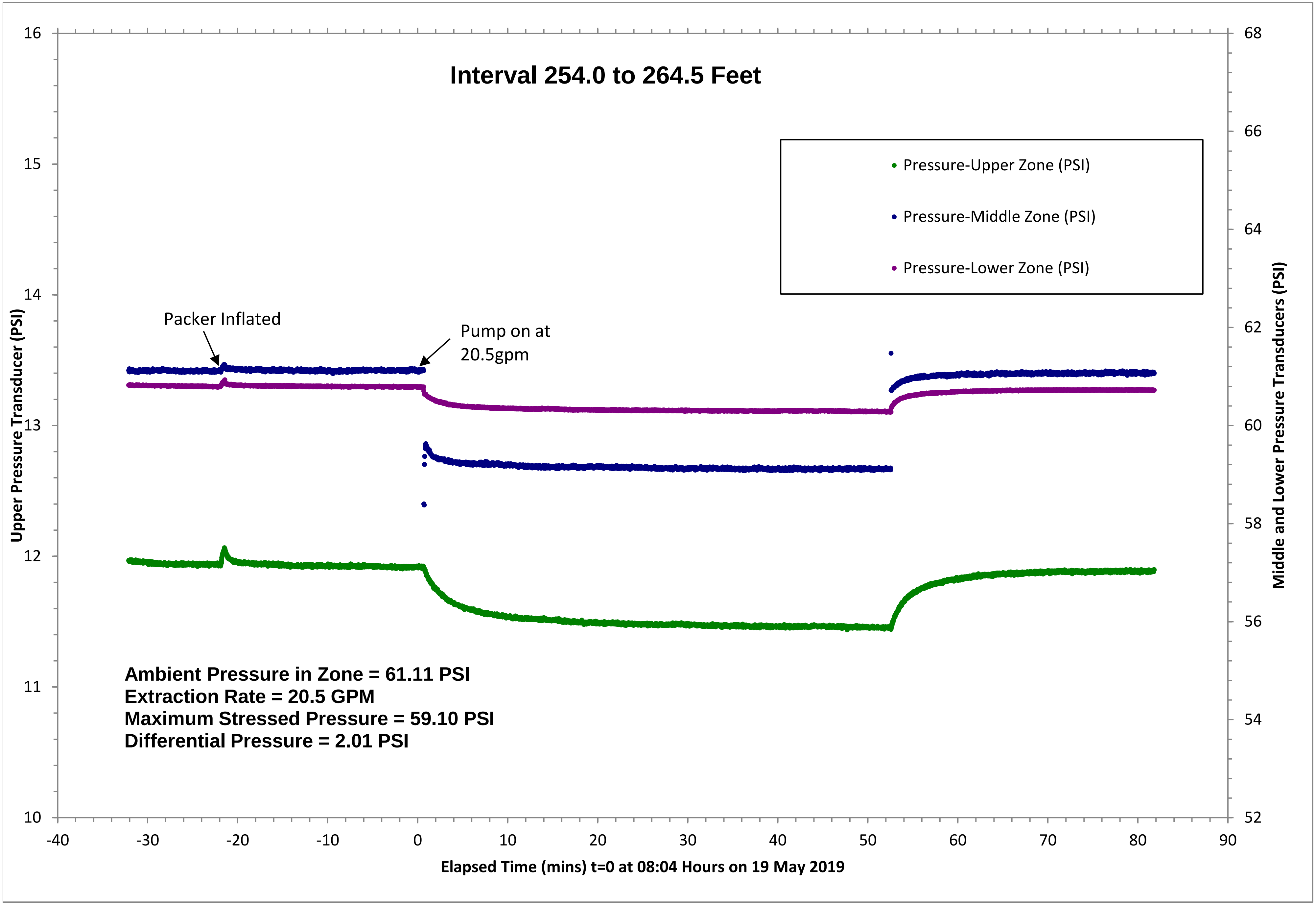


FIGURE RC-04:9C. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 265.5 to 276.0 Feet; Jacobs; Union Pacific; Wellbore: RC-04

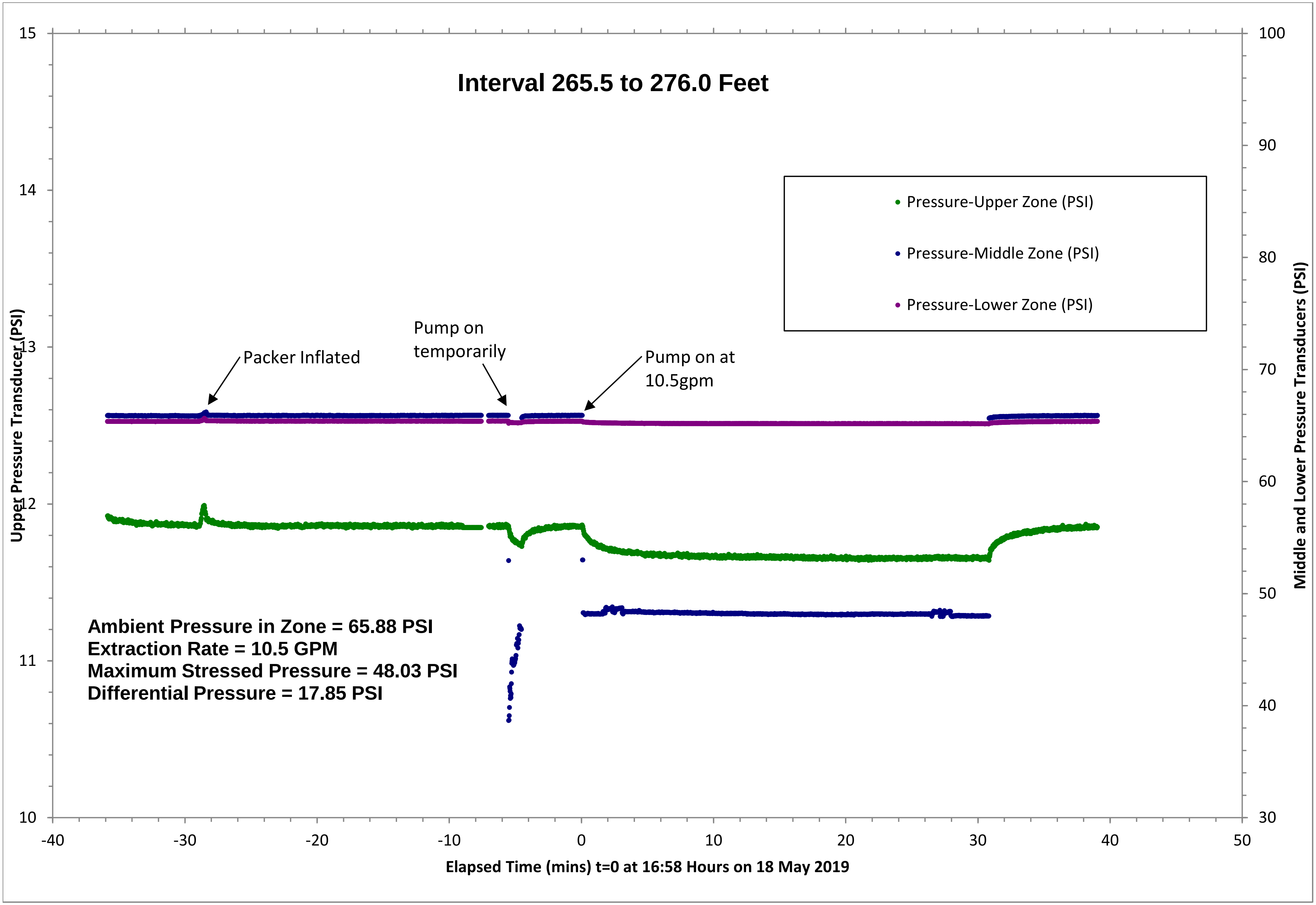


FIGURE RC-04:9D. Pressure and Extraction Rate Data During Wireline Straddle Packer Sampling at 282.0 to 292.5 Feet; Jacobs; Union Pacific; Wellbore: RC-04

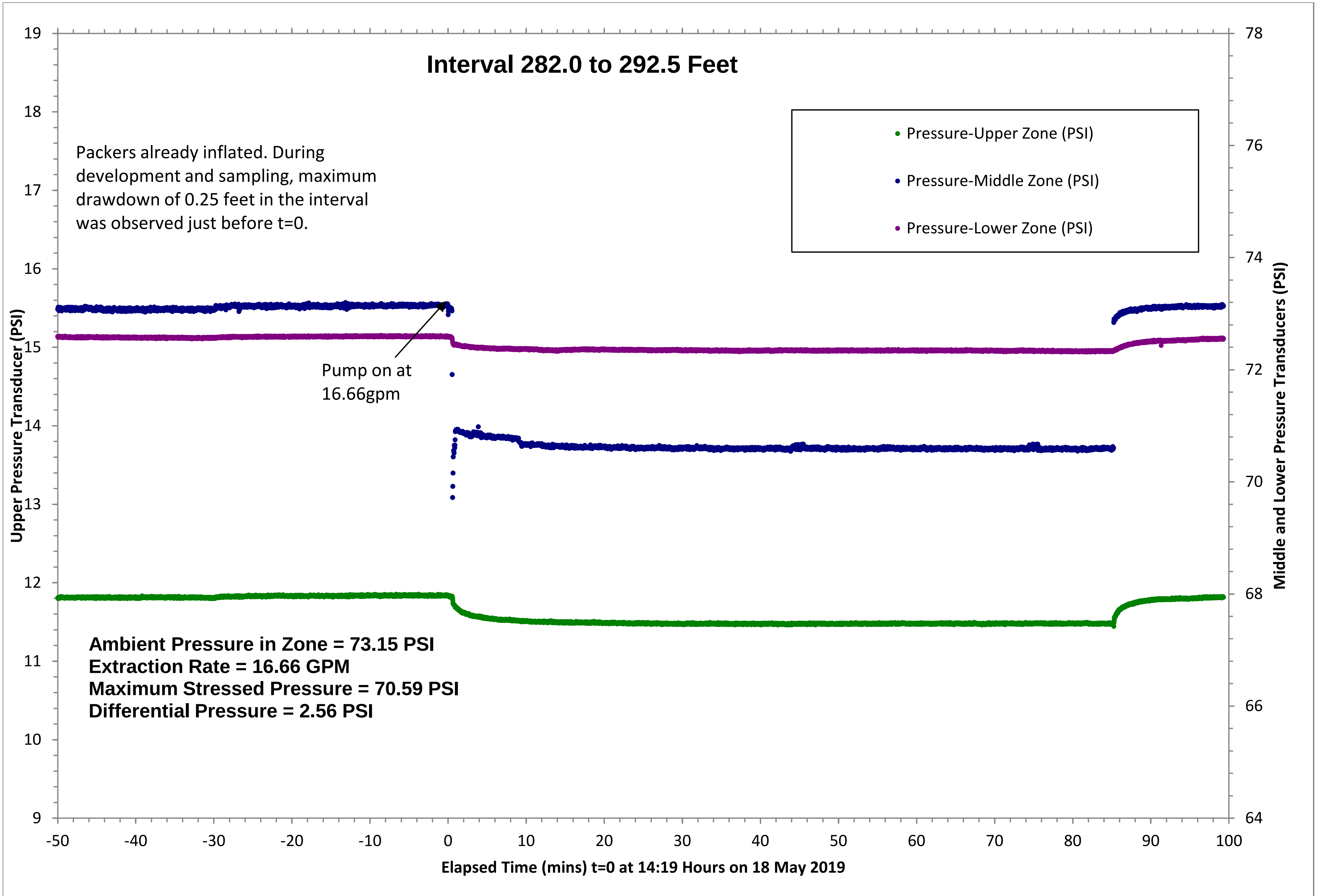


Table RC-04:4. Summary Of Wireline Straddle Packer Testing With Hydraulic Conductivity And Transmissivity Estimations; Jacobs; Union Pacific; Freeman, WA; Wellbore: RC-04

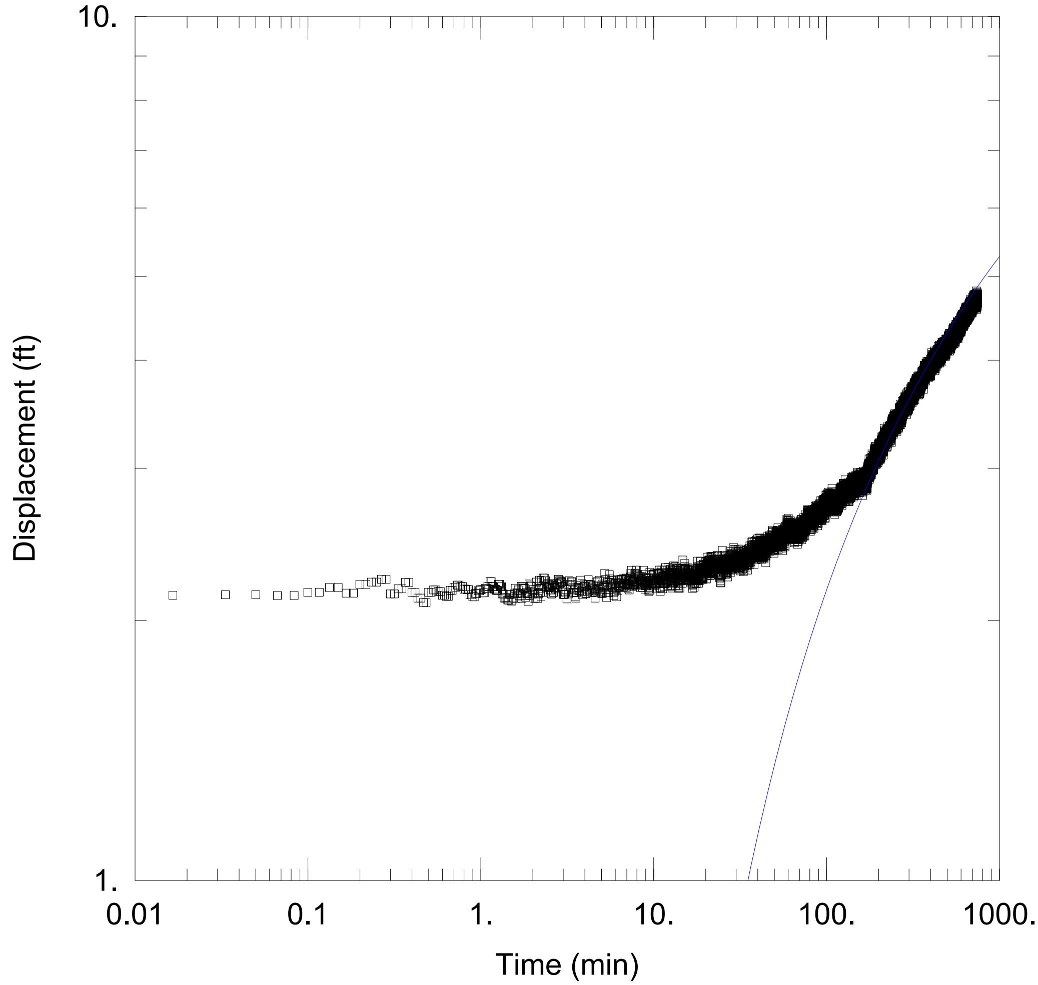
Well Name	RC-04
Ambient Depth to Water (ftbgs)	120.27
Diameter of Borehole (ft)	0.46
Effective Radius (ft)	100

Wireline Straddle Packer Testing Results - RC-04										
Interval No.	**Top of Interval (ft)**	**Bottom of Interval (ft)**	**Length of Interval (ft)**	**Differential Pressure (psi)**	**Drawdown (feet)[1]**	**Interval Specific Extraction Rate: WSP Stress Test (gpm)**	**Interval Specific Extraction Rate: WSP Stress Test (ft^3/min)**	**Interval Specific Hydraulic Conductivity (ft/day)**	**Thiem Method Transmissivity (ft2/day)**	**AQTESOLV (Theis) Method Transmissivity (ft2/day)**
1	120.3	148.0	27.7	9.01	20.81	0.37	0.049	1.19E-01	3.31E+00	3.98E+00
2	254.0	264.5	10.5	2.01	4.64	20.50	2.741	7.83E+01	8.22E+02	NA
3	265.5	276.0	10.5	17.85	41.22	10.50	1.404	4.52E+00	4.74E+01	NA
4	282.0	292.5	10.5	2.56	5.91	16.66	2.227	5.00E+01	5.25E+02	NA

[1] Drawdown is the difference between ambient pressure and stressed pressure, converted to feet.

NA = Not Applicable

Figure RC-04:10A. AQTESOLV Analysis Using Theis Solution: Interval 148ft to WL; Jacobs; Union Pacific; Spokane, WA; Wellbore: RC-04



WELL TEST ANALYSIS

Data Set: RC-04 WSP 148ft to WL.aqt

Date: 06/11/19 Time: 11:04:18

PROJECT INFORMATION

Company: Colog, Inc.
Client: Jacobs
Project: Union Pacific
Location: Freeman, WA
Test Well: RC-04
Test Date: 3 May 2018

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
RC-04	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ RC-04	0	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis

T = 3.979 ft^2/day
Kz/Kr = 1.

S = 2.934
b = 27.73 ft

APPENDIX D

STANDARD OPERATING PROCEDURES FOR HYDROPHYSICAL™ LOGGING

Standard Operating Procedures
HydroPhysical™ Logging for Aquifer Characterization

1. Purpose

Application of the HydroPhysical™ (HpL™) logging method to analyze and determine:

- The location of hydraulically conductive intervals within a wellbore
- The interval specific rate of inflow during well production, in conjunction with the drawdown data, can be used to estimate interval specific hydraulic conductivity or transmissivity
- Ambient (non-pumping) flow conditions (inflow and outflow rates, and locations)
- The hydrochemistry (fluid electrical conductivity (FEC) and temperature) of the associated formation waters

In addition, when downhole, discrete point fluid sampling is coupled with the HydroPhysical™ Logging technique, analysis of the actual contaminant concentrations associated with each identified conductive interval is accomplished for any aqueous phase contaminant.

2. Equipment and Materials

This SOP specifically applies to application of the technique using COLOG's HydroPhysical™ Logging Truck 16, which has been specially configured to handle those field conditions associated with small diameter, low-moderate yield wells The maximum capability of the van is to a total depth of 700 ft and 350 ft total drawdown (maximum depth to water) . In the event of high yield wells, the wireline capability of any COLOG truck can be used to accompany fluid management equipment.

- HydroPhysical™ logging truck field equipment includes:

- Fluid management system
    - Back Pressure Regulator or orifices
    - Rubber hose (0.75-inch i.d.) for injection
    - Submersible Pump
    - Evacuation Line
    - Storage tanks (as required) with inlet/outlet valves
    - Surface Pump
    - Fluid management manifold/Monitoring Panel
    - Data Acquisition System (for recording volumes, flow rates, time)
    - Wireline System
    - Wireline winch unit
    - Depth encoder
    - Water level indicator
    - Computer System
        - HydroPhysical™ Logging tool
        - Downhole Fluid Sampler
- Deionizing Units
- Deionized water (prepared with wellbore fluids or transported on-site)
- Standard Reference Solutions - Electrical conductivity reference solutions (set of 3 solutions).

3. Procedures

1.) Review well construction details and complete general well information sheet. The HydroPhysical™ logging technique involves dilution of the wellbore fluids with DI water and profiling of the wellbore dynamics using a HydroPhysical™ logging tool. Significant aberrations or reductions in the borehole diameter should be identified as the downhole equipment can become lodged in the borehole. Additionally, application of the technique requires certain wellbore conditions:

- In open bedrock boreholes, casing must be installed through the overburden and grouted at the rock/alluvium interface to inhibit water leakage into the borehole from the saturated alluvium. For cased boreholes, the well should be fully cased and gravel packed with single or multiple screened intervals;
- The diameter of the borehole must be approximately 4 inches or greater for application with the slim-tool (1.5-inch o.d.). Two inch i.d. boreholes may be tested using the slug test approach described in Section 5.
- For newly drilled wells, cuttings and drill fluids must be removed from the affected fractures by standard well development procedures.

2.) Review and record additional wellbore construction/site details and fill out the general well information form which includes the following information:

- Ambient depth-to-water
- Depth of casing
- Total depth of well
- Lithology (if available)
- Estimated well yield and any available drawdown data
- Type and concentration of contamination

3.) Prepare the deionized (DI) water. Consult with DI water tank firm for assistance if necessary. If DI water has not been transported to the site, surface or groundwater may be used if it is of suitable quality Generally source water containing less than 1000 micro Siemens per centimeter (µS/cm) and less then 200 ppb VOCs will not significantly affect the deionizing units, but this should be confirmed with DI water firm. If the groundwater from the well under construction cannot be used for DI water generation, then DI water must be transported to the site and containerized at the wellhead.

Depending on the amount of HydroPhysical™ testing to be performed (ambient and/or during production) the typical volume of DI water required for each borehole is approximately three times the volume of the standing column of formation water in the wellbore per type of HydroPhysical™ characterization.

If preparation takes place on site, pump the source water through a pre-filter, to the deionizing units, and into the storage tanks.

Monitor the FEC of the DI water in-line to verify homogeneity; the target value is 5 to 25 µS/cm.

4.) Calibrate the HydroPhysical™ logging tool using standard solutions prepared and certified by a qualified chemical supply manufacturer. Fill out tool calibration form following the steps defined in the software program, "tools" under the directory, calibration. Also use a separate field temperature / FEC / pH meter to support calibration data. Record the results of the tool calibrations, specifically noting any problems on the tool calibration form. Also record the certification number of the standard solutions.

5.) Set datum on the depth encoder with the FEC sensor on the tool as 0 depth at the top of casing. If inadequate space is available at the wellhead, measure 10 feet from the FEC sensor up the cable (using measuring tape) and reference with a wrap of electrical tape. Lower the tool down the hole to the point where the tape equals the elevation at the top of the casing and reference that as 10 feet depth on the depth encoder.

6.) Place the top of the tool approximately 3 feet below the free-water surface to allow it to achieve thermal equilibrium. Monitor the temperature output until thermal stabilization is observed at approximately $\pm$ .02 °C.

7.) After thermal stabilization of the logging tool is observed, log the ambient conditions of the wellbore (temperature and FEC). Fill out the water quality log form. During the logging run, the data are plotted in real time in log format on the computer screen and, the data string is simultaneously recorded on the hard drive.

Log the ambient fluid conditions in both directions (i.e. record down and up). The ideal logging speed is 5 feet per minute (fpm). For deeper wells the logging speed can be adjusted higher, but the fpm should not exceed 20.

At completion of the ambient log, place the tool approximately 10 feet below the free water surface. The tool will remain there during equipment set up as long as borehole conditions permit. Establish and record ambient depth to water using top of protective casing as datum.

8.) Attach back pressure regulator or orifice, if used, and weighted boot, to end of emplacement line and secure. Insure that the injection line is of adequate length to reach the bottom of the wellbore.

9.) Lower the flexible emplacement line to the bottom of the well allowing one foot of clearance from the well bottom to the outlet of the injection line.

10.) Lower tool about 10 feet below the water surface. The tool will be stationed beneath the submersible pump during non-logging times.

11.) Lower submersible pump in the well to a depth just above the logging tool. Record approximate depth of the pump location.

12.) Record all initial readings of gauges at elapsed time 0.0 minutes. Fill out well testing data form.

13.) Mark hoses with a round of electrical tape for reference. In addition, establish datum for tool depth to the nearest foot and mark on wire with wrap of tape. Reset datum on optical encoder for this depth.

14.) When ambient flow characterization is to be conducted, it should be done now, before disturbing the aquifer (i.e. by pumping). Fill out ambient flow characterization (AFC) form. Skip to Section 17 for procedures.

15.) After AFC, if performed, conduct a controlled, short term well production test (pump test) to characterize the overall hydraulics of the wellbore (drawdown at given pumping rate provides total well transmissivity or yield) and to make an initial assessment of formation water hydrochemistry. Begin pumping at a total extraction flow rate appropriate for wellbore under investigation (see Section 4 Special Notes). During this period, record elapsed time of pumping, depth to water, total gallons extracted, and extraction flow rate at approximately one minute intervals.

During extraction, log the fluid column continuously until at least three wellbore volumes have been extracted from the wellbore, or a stabilized water level elevation is obtained.

Review fluid logging results to verify that true formation water is present within the affected borehole interval and that the vertical distribution of water quality parameters within this interval is stable.

16.) Review data obtained during the pumping test to determine DI water emplacement and pumping/logging procedures. Extraction procedures for detection and characterization of hydraulically conductive intervals and the formation water hydrochemistry are determined based on the pumping test information. The emplacement, testing and pumping procedures will differ depending upon well yield and determined lengths of intervals of interest. In wellbore situations where intervals of interest are small (less than 30 feet) and hydraulic characteristics observed during borehole advancement and preliminary hydraulic testing indicate hydraulically conductive intervals with extremely low flow rates (i.e. <0.10 gpm/foot of drawdown), a slug testing procedure can be employed. In wellbore cases where the preliminary hydraulic testing indicates low to moderate total yield (i.e. $0.10 < Q < 4$ gpm/foot of drawdown), constant low flow rate pumping after DI water emplacement procedures can be employed. In wellbore situations where intervals of interest are large, and high total yield (i.e. > 4 gpm/foot of drawdown) is observed, constant pumping during DI water injection procedures will be employed.

17.) When the fluid column is to be replaced with DI water, (vertical flow characterization, slug testing, logging during pumping after DI water emplacement) the following emplacement procedures apply:

Pump the DI water to the bottom of the wellbore using the surface pump and the injection riser. Simultaneously use the submersible pump to maintain a stable, elevated total head by extracting groundwater from near the free-water surface. When groundwater from the subject well is used for DI water generation, generate DI water from the extracted formation water and re-circulated to the well bottom via the solid riser.

Use the water level meter to observe the elevated total head during emplacement. If borehole conditions permit (i.e. the absence of constricted borehole intervals), the logging tool is used to monitor the advancement of the fluid up the borehole as it displaces the standing formation water. Draw the logging tool up the wellbore in successive increments as the DI water is emplaced. Monitor the electrical conductivity of the fluid expelled from the evacuation pump during emplacement procedures. When FEC values are representative of the DI water, or sufficiently diluted formation water, terminate emplacement procedures.

Emplacement is complete when DI water, or sufficiently diluted formation water, is observed from the evacuation pump or when logging tool stationed near the pump indicates DI water or sufficiently diluted formation water.

Upon completion, turn off the evacuation pump. Then turn off the injection line.

18.) Record volumes of extracted and injected fluids on the well testing data form. Calculate the volume of DI water lost to the formation.

19.) Take initial background HydroPhysical™ log, or begin continuous logging depending upon extraction method (i.e. slug vs. continuous).

20.) Pumping and testing procedures vary depending upon wellbore hydraulics and construction detail.

21.) Continuous logging is conducted until stabilized and consistent diluted FEC logs are observed. If inflow characterization at a second pumping rate is desired, increase extraction rate and assure the proper DI water injection rate. Perform continuous logging until stabilized and consistent FEC logs are observed and all diluted formation water is re-saturated with formation water.

22.) After stabilized and consistent FEC traces are observed, terminate DI water injection. Reduce the total extraction flow rate to the net formation rate and conduct continuous logging. Conduct logging until stable and consistent FEC values are observed.

23.) Conduct depth specific sampling at this time.

24.) At the conclusion of the above procedures, assess the wellbore fluid conditions and compare them with those observed during the original pumping (Step 14).

25.) Turn all pumps off. First remove the extraction pump from the borehole. During removal, thoroughly clean the evacuation line (2-inch o.d.) with a brush and alconox and rinse DI water. Also clean the outside of the pump. Place the pump in a drum of DI water and flush DI water through the system.

Remove the tool. Clean the wireline for the tool in a similar manner during its withdrawal from the borehole.

Remove the injection line from the well. Follow the same procedures when cleaning the injection line as for the evacuation line.

Store the pumps and logging tools properly for transport.

Place cover on well and lock (if available).

4. Special Notes

On-site pre-treatment of groundwater using activated carbon, can be conducted prior to DI water generation, if there is a contaminated groundwater source. In addition, on-site treatment can also be considered to handle extracted fluids that would require containerization and treatment prior to disposal.

The rate(s) of pumping are determined by drawdown information previously obtained or at rate(s) appropriate for the wellbore diameter and saturated interval thickness. The appropriate extraction rate is a function of length of saturated interval, borehole diameter, and previous well yield knowledge. The appropriate pumping procedures to be employed are also dictated by the length of the exposed rock interval. In general, the extraction flow rate should be sufficient to induce adequate inflow from the producing intervals. The concern is that the extraction flow rate does not cause extreme drawdown within the well i.e. lowering the free water surface to within the interval of investigation.

5. Discussion

LOW YIELD: Extraction Slug Test After DI water Emplacement

In wells with very low total flow capability (i.e. < 0.10 gpm/foot of drawdown), perform a slug test in accordance with procedures developed by Hvorslev (1951). Rapidly extract a small volume of water from near the free water surface using the extraction riser and pump. A drop in piezometric head of about 2 feet should be adequate for the initial test. Record the rise in the free water surface with time and develop a conventional time-lag plot.

When the free water surface has recovered to a satisfactory elevation, log the wellbore fluid conditions. Repeat the procedures described above with successive increases in the drop of piezometric head (or volume extracted). Let the wellbore recover and record the rise in the free water surface. Repeat logging of the wellbore fluid after the free water surface has recovered to a satisfactory elevation. The number of slug tests performed is determined in the field after review of previous logging results.

MODERATE YIELD: Time Series HydroPhysical™ Logging During Continuous Pumping After DI water Emplacement

In the case of moderate yield wells (i.e. 0.10 < Y < 4 gpm/foot of drawdown), maintain a constant flow rate from the evacuation pump and record the total volume of groundwater evacuated from the wellbore. Employ a continuous reading pressure transducer (or equivalent device) to monitor the depressed total head during pumping, along with the associated pumping rate.

Hold the flow rate from the evacuation pump constant at a rate determined for the specific borehole. Drawdown of the free water surface produced during pumping should not overlap any identified water producing interval. Conduct hydrophysical logging continuously. The time interval is a function of flow rate and is specific to each well. The number of logging runs and the length of time required to conduct all loggings is a function of the particular hydraulic conditions. Logging and pumping is continued until the fluid column is re-saturated with formation water (i.e. all DI water is removed from the borehole).

HIGH YIELD: Time Series Wellbore Fluid Logging During Continuous Pumping and Simultaneous DI Water Injection

When wells exhibit high yield (> 4 gpm/foot of drawdown), as determined by a review of the interval of interest, the borehole diameter and the results obtained from previous information and preliminary hydraulic testing, the appropriateness of time series fluid logging during continuous pumping and simultaneous DI water injection is determined.

In this case, maintain a constant flow rate from the evacuation pump and record this rate and the associated drawdown. During this period, conduct hydrophysical logging until reasonably similar HydroPhysical™ logs are observed and stabilized drawdown is achieved. After reasonably similar downhole fluid conditions are observed and simultaneous with extraction pumping, inject DI water at the bottom of the well at a constant rate of 10 to 20% of that employed for extraction. Increase the total rate of extraction to maintain total formation production reasonably similar to that prior to DI water injection (i.e. increase the total extraction by amount equal to the DI water injection rate).

Periodically record the total volume and flow rate of well fluids evacuated and the total volume and flow rate of DI water injected. Use a continuous reading pressure transducer or similar device to monitor the depressed total head during pumping. Record the depressed total head (piezometric surface) periodically, with the associated pumping and injection data.

The evacuation and DI water injection flow rates are held constant at a rate determined for the specific wellbore. Drawdown of the free water surface during pumping must not overlap any identified water producing intervals. HydroPhysical™ Logging is conducted continuously. The number of logging runs and the length of time required to conduct all loggings is a function of the particular hydraulic conditions exhibited by the well under investigation.

APPENDIX E

BORE II MODELING SOFTWARE

LBNL-46833

BORE II – A Code to Compute Dynamic Wellbore Electrical Conductivity Logs with Multiple Inflow/Outflow Points Including the Effects of Horizontal Flow across the Well

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September 2000

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(c) 1993-2000 The Regents of the University of California (through E.O. Lawrence Berkeley National Laboratory), subject to approval by the U.S. Department of Energy. Portions of BORE II were developed by COLOG, 17301 W. Colfax, Suite 265, Golden, Colorado 80401; (303) 279-0171.

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Abstract

Dynamic wellbore electrical conductivity logs provide a valuable means to determine the flow characteristics of fractures intersecting a wellbore, in order to study the hydrologic behavior of fractured rocks. To expedite the analysis of log data, a computer program called BORE II has been developed that considers multiple inflow or outflow points along the wellbore, including the case of horizontal flow across the wellbore. BORE II calculates the evolution of fluid electrical conductivity (FEC) profiles in a wellbore or wellbore section, which may be pumped at a low rate, and compares model results to log data in a variety of ways. FEC variations may arise from inflow under natural-state conditions or due to tracer injected in a neighboring well (interference tests). BORE II has an interactive, graphical user interface and runs on a personal computer under the Windows operating system. BORE II is a modification and extension of an older code called BORE, which considered inflow points only and did not provide an interactive comparison to field data. In this report, we describe BORE II capabilities, provide a detailed user's guide, and show a series of example applications.

1. Introduction

The variation of formation permeability surrounding a wellbore is useful information not only for identifying hydraulically conducting fractures or other high-conductivity features intercepted by the well, but also for quantifying the heterogeneity of the medium. These are essential data in the evaluation of in-situ flow and transport characteristics at a given site.

Methods to evaluate permeability values along the depth of a well include the packer method, in which constant pressure, constant flow, or pulse tests are conducted in packed-off intervals in a wellbore, and various downhole flow meters. The packer method has the disadvantage that it is very time consuming and costly, and the vertical resolution is limited by the interval between the two packers that can be set in the well. Flow meter methods such as spinners and heat pulse flow meters generally allow better vertical resolution than the packer method, but they are not as accurate in determining permeability, because they mostly measure the wellbore fluid velocity, which is very sensitive to variations in the wellbore radius.

In 1990, Tsang et al. (1990) proposed a method using logs of fluid electric conductivity (FEC) at successive times under constant-pumping conditions to obtain inflow from the formation into the well as a function of depth in the well. In this method, the wellbore is first filled by de-ionized water or water of a constant salinity (i.e., ion concentration) distinct from that of the formation water. This is usually done by passing the de-ionized water down a tube to the bottom of the wellbore at a given rate while simultaneously pumping at the top of the well at the same rate. After this is done, the well is pumped at a constant flow rate, which can be adjusted to optimize wellbore flow conditions. An electric resistivity probe is lowered into the wellbore to scan FEC as a function of depth along the wellbore. This is what is called fluid conductivity logging. A series of five or six such logs are obtained at time intervals over a one- or two-day period. At the depth levels where water enters the wellbore, the conductivity log displays peaks, which grow with time and become skewed in the direction of water flow. By analyzing these logs, it is possible to obtain the permeability and salinity of each hydrologic layer transmitting water. The method has been very successful, being much more accurate than flow meters and much more efficient (much cheaper) than packer tests (Tsang et al. 1990), particularly in low permeability formations. A typical 1000-m section in a deep hole can be tested in two or three days at a spatial resolution of ~0.10 m all along the length of the wellbore section. The method is now being widely used in Europe and the U.S. (Marschall and Vomvoris, 1995; Pedler et al., 1992; Bauer and LoCoco, 1996), both under natural-state flow conditions and while tracer is injected in a neighboring well (i.e., interference tests).

Along with the method, a code was developed called BORE (Hale and Tsang, 1988), which performed the forward calculation to produce wellbore FEC profiles given different inflow positions, rates, and concentrations. The code has been well used over the last decade. However, it appears now that there is a need to revise the code to make it more suitable for current computer environments and to add new capabilities. Thus, the code has been updated to run under current operating systems, provide interactive modification of model parameters, and produce graphical comparisons between model and field data. More importantly, the revised code allows the possible inclusion of both flows into and out of the well at various depths, a feature that has been observed in real field conditions when different layers penetrated by the well have different hydraulic heads. Furthermore, the new code allows the calculation of the case with equal inflow and outflow at the same depth level, which is effectively the special case of horizontal flow across the wellbore. Drost (1968) proposed a measurement of solute dilution in the wellbore to evaluate ambient horizontal flow velocity in the formation and it has become a well-accepted method. The new code provides the opportunity to analyze such cases and to identify the depth interval of horizontal flow to within ~0.1 m as well as to estimate the flow rate. Moreover, one can analyze the combination of horizontal flow across the wellbore and vertical diffusion or dispersion along the length of the wellbore, which is not possible with Drost's solution.

The report is organized as follows. In Section 2, the basic capabilities of the revised code, called BORE II, are described, and the key parameters associated with BORE II are defined. Details of the mathematical background and numerical approach are described in Appendix 1, which is adapted from Hale and Tsang (1988). A user's guide is presented in Section 3, which includes a description of BORE II's interactive user interface, required input items, and options available when running BORE II. Four example applications are given in Section 4 to conclude the report.

We are still open to further improvements of BORE II; any suggestions and comments are invited and should be addressed to the authors.

2. BORE II Capabilities

BORE II calculates FEC as a function of space and time in a wellbore containing multiple feed points given the pumping rate of the well, the inflow or outflow rate of each feed point, its location and starting time, and, for inflow points, its ion concentration. A simple polynomial correlation between ion concentration, C, and FEC is assumed. Ion transport occurs by advection and diffusion along the wellbore, with instantaneous mixing of feed-point fluid throughout the wellbore cross-section. These assumptions allow use of a one-dimensional model. BORE II divides the wellbore section under study into equal height cells and solves the advection/diffusion equation using the finite difference method. Further details of the mathematical and numerical approach are given in Appendix 1.

Inflow and Outflow Feed Points

The original BORE code (Hale and Tsang, 1988) considered inflow points only, so flow through the wellbore was upward at all depths. BORE II allows both inflow and outflow points, so flow in the wellbore can be upward, downward, or horizontal at different depths and flow at either end of the wellbore section being studied can be into or out of the wellbore section or be zero. By convention, upward flow in the wellbore is positive and flow into the wellbore is positive.

Steady and Varying Fluid Flow

The original BORE code considered steady fluid flow, so feed points had constant flow rates. They also had constant concentrations, but delayed starting times for feed-point concentration to enter the wellbore were allowed. BORE II permits both steady and varying fluid flow. For the steady-flow case, the user specifies flow rate, concentration, and concentration start time for each feed point, but for outflow points (those with negative flow rates) the concentration and concentration start time are not used. Variable flow rate or concentration can be specified for feed points by interpolating from a table of time, flow rate, and concentration. If a table includes both positive and negative flow rates (i.e., a feed point alternates between inflow and outflow), the concentration for the positive flow rate is used when interpolating between positive and negative flow rates.

Concentration Boundary Conditions

If the flow at the top of the wellbore section under study is into the wellbore, the initial concentration for the uppermost cell in the wellbore is used as the inflow concentration. Analogously, if flow at the bottom of the wellbore section is a flow up from greater depths, the initial concentration for the lowermost cell in the wellbore is used as the inflow concentration. Furthermore, for inflow points with a concentration start time greater than zero, the initial concentration of the wellbore is used as the inflow concentration for times less than concentration start time.

Horizontal Flow

The special case of horizontal flow through the wellbore, as described by Drost (1968), can also be considered, by locating an inflow point and an outflow point with equal magnitude flow rates at the same depth. The flow rates may be specified as either (1) the Darcy velocity through the aquifer or (2) the volumetric flow rate into/out of the wellbore. BORE II multiplies Darcy velocity by the cross-sectional area of the feed point (wellbore diameter times cell height) and Drost's α_h convergence factor to convert it to a volumetric flow rate. The value of α_h can range from 1 (no convergence) to 4 (maximum possible convergence, which occurs for the case of a thick, highly-permeable well screen). Drost suggested that for a uniform aquifer with no well screen, $\alpha_h = 2$, and that for typical applications, a good choice for α_h is 2.5. Horizontal flow feed points may have time-varying flow rates, but for Darcy-velocity calculations to make sense, the inflow and outflow rates must be equal and opposite at any time. Thus, if a feed point location changes from a horizontal flow point to a non-horizontal flow point with time, volumetric flow rates must be specified rather than Darcy velocities.

BORE II Parameters

The key parameters associated with BORE II are defined below.

Parameter	I/O units*	Description
C	g/L	Ion concentration in the wellbore; converted to FEC using FEC $= \gamma + \beta C + \alpha C^2$, where α, β, and γ are user-specified constants (default values are provided in the code, see Section 3)
C_i	g/L	Ion concentration of *i*th feed point
C_0	g/L	Initial ion concentration in wellbore
D_0	m^2/s	Diffusion coefficient (may include dispersive effects as well molecular diffusion)
d_w	cm	Wellbore diameter (assumed constant)
FEC	μS/cm	Fluid electrical conductivity
q	L/min	Fluid flow rate in wellbore (upward flow is positive)
q_i	L/min	Fluid flow rate of *i*th feed point; positive for inflow and negative for outflow
q_w	L/min	Fluid flow rate in wellbore at $x_{\max}$, specified by the user
q_0	L/min	Fluid flow rate in wellbore at $x_{\min}$ (or any depth of interest), calculated internally
T or TEMP	°C	Temperature (assumed constant)
t	hr	Time
$t_{\max}$	hr	Maximum simulation time
t_{0i}	hr	Concentration start time of *i*th feed point
v_d	m/day	Darcy velocity through aquifer for horizontal flow ($q_i = v_d\ \alpha_h\ \Delta x\ d_w$)
x	m	Depth (positive, increases down the wellbore)
$x_{\min}$, $x_{\max}$	m	Top and bottom, respectively, of wellbore interval being studied
Δx	m	Cell height for wellbore discretization
α_h	–	Drost (1968) convergence factor for horizontal flow

*I/O units are chosen for convenience; all quantities are converted to SI units before BORE II calculations.

3. BORE II User's Guide

Operating System

BORE II may be run under Windows 95, 98, or 2000 by double-clicking the executable icon (BOREII.EXE) in Windows Explorer, by double-clicking on a desktop shortcut key to BOREII.EXE, or by typing BOREII in the Run command in the Start Menu or in a DOS-prompt window. BORE II will not run in stand-alone DOS or in the DOS-mode of Windows. BORE II was compiled using Microsoft Fortran PowerStation™ Version 4.0, but this software is not necessary to run the program.

BORE II Graphical Output

The primary user interface with BORE II is interactive, with the user responding to on-screen prompts to modify model parameters and choose options (described below) for the real-time graphical display of model results and data. The basic BORE II output screen consists of three windows.

- The borehole profile window shows FEC profiles as a function of depth and time. Simulation time t is shown in the upper left corner. Fluid flow rate at a user-specified depth in the wellbore, q_0, is shown in the middle of the top line (the depth at which q_0 is calculated is set by option P). The depth of a C-t plot is also shown.
- The inflow parameters window shows the feed-point characteristics for the model that can be modified with option M (location, flow rate, and concentration). Often there are more feed points than can be displayed at once on the screen. BORE II starts out showing the first few (deepest) feed points, then shows the feed points in the neighborhood of any point that is being modified.
- The dialog window allows the user to select options (described below) when running BORE II.

On computers with small screens, it may be desirable to run BORE II in full-screen mode, so that the entire BORE II screen can be seen at once without scrolling. Full-screen mode is entered by pressing Alt-VF (or on some computers by pressing Alt-Enter). Pressing Esc (or Alt-Enter) terminates full-screen mode. There are three potential problems associated with the use of full-screen mode.

(1) The status line describing what BORE II is doing (e.g., running, waiting for input) is not visible.

(2) Drawing an x-t plot (options X, S, D, F, and I), which creates a new window, may be very slow and the graphics quality poor.

(3) On some computers, text is difficult to read after closing the x-t plot window.

To address the latter two problems, one may terminate full-screen mode before using options X, S, D, F, and I. The new window will be small, but after drawing is complete it may be expanded by pressing Alt-VF to enter full-screen mode. Full-screen mode should be terminated before the new window is closed to avoid the final problem.

To print an image of the screen, press Alt-PrintScreen to copy the screen image into the clipboard. Then open a program such as Microsoft Paint and paste in the image. It can be manipulated, saved in a variety of graphics formats, or printed from Paint. The image can also be pasted directly into another Windows application such as MS Word.

Input/Output File Overview

Running BORE II requires one or two external files: a file with an initial set of model input parameters (mandatory, known as the input file) and a file with observed data (optional, known as the data file). These files are plain ASCII text, and must reside in the same folder as the BORE II executable. The input file contains model parameters such as the depth interval being studied, feed point characteristics, problem simulation time, and *C*-to-FEC conversion factors. The data file contains observed values of FEC and temperature, and optionally contains other fluid properties such as pH. Detailed instructions for preparing an input file and a data file are given below.

BORE II always creates a temporary file, called BOREII.TMP (see options C and R), and optionally creates a new input file (see option V), which is useful if model parameters have been changed during the BORE II run.

Line-by-line Instructions for Input File

After starting BORE II, the user is prompted to choose the input file from the list of files residing in the folder where the BORE II executable is. Input file names with more than 8 characters before a period or blanks will appear in the list of files in an abbreviated form. File names can be at most 20 characters long.

A sample input file is provided that can be modified as needed using a text editor such as Notepad or a word processor such as MS Word. If a word processor is used to create or modify an input file, be sure that the file is saved as plain ASCII text.

The input file is designed to be self-documenting, with header lines preceding data lines. These header lines must be present, but BORE II does not use the text on them. Data entries are read in free format, with individual entries on a given line separated by blanks, tabs, or commas. This means that entries cannot be left blank, even if they are not being used (e.g., concentration for an outflow point). Unused entries may be set to zero or any convenient value. Comments may be added on data lines, after the requisite number of entries. In the sample input file, comments begin with an exclamation point.

Item	**Computer Variables**	**Unit**	**Description**
1.	TITLE	–	A description of the problem, 80 characters maximum
2 header for wellbore geometry			
2.	RXMIN	m	Top of study area, x_{min}
	RXMAX	m	Bottom of study area, x_{max}
	RDIAM	cm	Wellbore diameter, d_w
3 header for flow parameters			

3.	RQW	L/min	Flow into (positive) or out of (negative) the bottom of the study area, q_w
	HALPHA	–	Factor to account for convergence of horizontal flow lines toward the wellbore, α_h (Drost, 1968) Range: 1.0 – 4.0; default value: 2.5 Only used for horizontal flow

4 header for feed points			
4.	IINFN	–	Number of feed points (maximum 180)
	IQFLAG	–	Variable flow-rate flag – a 3 digit integer used to identify feed points with variable flow (suggested value 999)
5 header for constant- flow-rate feed points			
5. Repeat IINFN times	RINFX	m	Location of feed point, x_i * For horizontal flow put two feed points at the same location, with equal magnitude, opposite sign flow rates
	RINFQ	L/min (m/day if IINFV=1)	Constant inflow rate (positive) or outflow rate (negative) of feed point, q_i For a variable flow rate, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a For horizontal flow, v_d replaces q_i if IINFV = 1
	RINFC	g/L	Constant feed point concentration, C_i - only used for inflow points For a variable concentration, set RINFQ = IIIJJ, where III = IQFLAG, and JJ is a two digit integer giving the number of times in the variable-flow-rate table, which follows in 5a
	RINFT	hr	Start time for constant feed point concentration, t_{0i} - only used for inflow points Feed point concentration is C_0 of cell containing feed point for t < t_{0i}
	IINFV	–	Horizontal flow Darcy-velocity flag (must be zero for non-horizontal flow case): = 0: RINFQ is flow rate q_i into/out of the wellbore in L/min = 1: RINFQ is +/–Darcy velocity v_d through the aquifer in m/day

5a header for variable-flow-rate table (only when RINFQ = IQFLAGJJ)			
5a. Repeat JJ times when RINFQ = IQFLAGJJ	RINFQT	hr	Time t_j (set $t_1 = 0$, set $t_{JJ} > t_{max}$)
	RINFQQ	L/min (m/day if IINFV=1)	Volumetric flow rate q_j at time t_j For horizontal flow, v_d replaces q_j if IINFV = 1
	RINFCC	g/L	Concentration C_j at t_j
6 header for misc. parameters			
6.	TMAX	hr	Maximum simulation time, t_{max}
	DPYMAX	μS/cm	Maximum FEC for plots
	RK	m^2/s	Diffusion coefficient, D_0
7 header for C-to-FEC conversion			
7.	RGAMMA	μS/cm	Conversion from C in g/L to FEC in μS/cm: $FEC = \gamma + \beta C + \alpha C^2$
	RBETA	[μS/cm]/ [g/L]	Default values (for 20°C): $\gamma = 0$, $\beta = 1870$, $\alpha = -40$
	RALPHA	[μS/cm]/ $[g/L]^2$	Set $\gamma = 0$, $\beta = 1$, $\alpha \approx$ 1.e-8 for FEC $\approx C$
8 header for initial conditions			
8.	IC0FLAG	–	Initial concentration flag: = 0: $C_0 = 0$, no further input for item 8 < 0: read uniform non-zero C_0 in 8a > 0: read IC0FLAG (x,$C_0(x)$) pairs in 8b to describe variable initial concentration
8a header for uniform initial conditions (only when IC0FLAG < 0)			
8a. when IC0FLAG<0	RC0	g/L	Uniform non-zero C_0
8b header for non-uniform initial conditions (only when IC0FLAG > 0)			
8b. repeat IC0FLAG times when IC0FLAG>0	RX	m	x value*
	RC0	g/L	$C_0(x)$
9 header for data file name			
9.	CFDATA	–	Name of data file, 20 characters maximum; 'NONE' if there is no data file

*see Appendix 1, Section A1.5, for additional information on locating feed points and specifying non-uniform initial conditions

Sample Input File

An input file illustrating many of these options is shown below. Text or numbers following an exclamation point (!) are comments, and are not used by BORE II.

```
TITLE: Sample Input File with flow from below, horizontal flow, variable flow
XMIN(m)     XMAX(m)     DIAM(cm)
```

```
.0000        60.00        7.600
QW(L/min)    HALPHA       !QW=flow from below; HALPHA=hor. flow constriction
 0.50        0.           !default value of HALPHA will be used
#FEED_PTS    VARIABLE_FLOWRATE_IDENTIFIER
   4               999
DEPTH(m)     Q (L/min)    C(g/L)       T0(hr)       Q/V_FLAG
 25.         +1.           6.0         .0000        1 !1st 2 feed pts-hor. flow
 25.         -1.           6.0         .0000        1 !C & T0 not used (outflow)
 30.         99905.        6.0         .0000        0 !C & T0 not used (table)
     T(hr)        Q(L/min)    C(g/L)       !#entries is two digits after  999
      .0000        .0000        6.         !first time in table is zero
      .3000        .2800E-01    5.
      .5000        .3200        4.
      1.000        .4600        3.
      1.500        .4600        2.         !last time in table is > tmax
 35.         .5            4.0         .2000        0 !final feed pt
TMAX(hr)     FECMAX       DIFFUSION_COEF.(m2/s)
 1.000       5000.        .7500E-09
RGAMMA       RBETA        RALPHA       !FEC = RGAMMA + C*RBETA + C*C*RALPHA
0.           0.           0.           !default values will be used
IC0FLAG      !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
    1
X(m)         C0(g/L)            !#entries is IC0FLAG
60.          2.                 !Concentration associated with Qw
DATA_FILE    !'NONE' if there is no data file
NONE
```

The first two feed points represent constant horizontal flow, and since the Q/V flag (IINFV) is one, flow rate is given as Darcy velocity through the aquifer in m/day. The third feed point has variable flow rate and concentration, with a five-entry table specifying the variation with time. The fourth feed point is an inflow point with constant flow rate and concentration and a non-zero concentration start time.

Note that the flow from below, q_w, is positive (into the wellbore section), so the corresponding concentration is specified as the initial condition of the lowermost cell in the wellbore (at $x = x_{\min}$) by using IC0FLAG = 1. If IC0FLAG = 0, the concentration associated with q_w would be zero, and if IC0FLAG = -1, the concentration associated with q_w would be the uniform non-zero initial concentration in the wellbore.

When BORE II writes an input file (option V), it changes several things to the file form shown above. Comments found in the original input file are not reproduced, but two comments are added. First, the cell height and the equation used to calculate it are shown on the line with $x_{\min}$, $x_{\max}$, and d_w. Second, if feed points represent horizontal flow, then the flag IINVF is set to 0, flow rate is given in L/min, and the corresponding Darcy velocity through the aquifer in m/day is added as a comment. Finally, if IC0FLAG > 0, BORE II sets IC0FLAG to the number of wellbore cells, and explicitly shows every (x, $C_0(x)$) pair. This option is useful for identifying the x values of various cells, which may expedite assignment of feed point locations or initial conditions. Part of the input file created by BORE II for the above sample is shown below.

```
TITLE: Sample Input File with flow from below, horizontal flow, variable flow
XMIN(m)      XMAX(m)      DIAM(cm)     !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
 .0000        60.00        7.600       ! .3333
```

```
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
 .5000       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
    4               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 35.00       .5000       4.000       .2000        0
 30.00      99905.       6.000       .0000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after  999
      .0000       .0000       6.000
      .3000       .2800E-01   5.000
      .5000       .3200       4.000
      1.000       .4600       3.000
      1.500       .4600       2.000
 25.00       .4398E-01   6.000       .0000        0         ! 1.000
 25.00      -.4398E-01   6.000       .0000        0         !-1.000
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 1.000       5000.       .7500E-09
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1870.      -40.00
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
  179
X(m)        C0(g/L)           !#entries is IC0FLAG
 59.83       2.000
 59.50       .0000
 59.17       .0000
 58.83       .0000
…(169 entries with C0=0 not shown)…
 2.167       .0000
 1.833       .0000
 1.500       .0000
 1.167       .0000
 .8333       .0000
 .5000       .0000
DATA_FILE   !'NONE' if there is no data file
NONE
```

Line by Line Instructions for Data File

The data file is read in the fixed format shown below. If data are available in a different format, an auxiliary program should be used to convert it to this form (a simple preprocessor called PREBORE, described in Appendix 2, converts the data file format used by BORE to the new format shown below). Note that because a fixed format is used, blank entries are allowed; they are interpreted as zero.

Lines 1-8 are header lines, not used by BORE II.

Each line of the remainder of the file contains:

Variable	*x*	FEC	TEMP	DAT3	DAT4	DAT5	HR	MIN	SEC
Units	m	μS/cm	°C				–	–	–
Format	F10.3	F10.3	F10.3	E10.3	E10.3	E10.3	I3	I2	I2
Columns	1-10	11-20	21-30	31-40	41-50	51-60	62-64	66-67	69-70

The entries DAT3, DAT4, and DAT5 represent optional data types that may be collected with certain logging tools, such as pH and dissolved oxygen (see options A and Y for ways to display this data). Note that there is one blank column before each of the HR, MIN, and SEC entries, to make the data file more readable. The first time entry corresponds to $t = 0$ for the model.

BORE II Options

The following options are available on the BORE II main menu. Either uppercase or lowercase letters may be used, and should be followed by pressing ENTER.

C – (C)-x plot – Displays FEC versus depth for data and/or model continuously in time (an animation); stores [*x* (m), *t* (sec), data FEC (μS/cm), model FEC (μS/cm)] in file BOREII.TMP for later use by option R or post-processing.

T – c-(T) plot – Displays FEC versus time for data and model for a chosen depth.

R – d/m cu(R)ve – Displays FEC versus depth plots for data and model at a series of times (snapshots of the option C display); uses results of most recent option C, read from BOREII.TMP. Does not work if there is no data file or if there are only data at one depth in data file.

N – i(N)flow-c – Displays inflow FEC for a chosen feed point as a function of time.

A – p(A)ram display – Displays all data profiles (FEC, TEMP, DAT3, DAT4, DAT5) simultaneously, using user-specified plot limits (selections 3-6). For selection 1, all points are connected on one continuous curve; for selection 2, points that are beyond depth or time limits start new curve segments.

X – (X)-t plot – Displays a color-coded plot of model FEC versus depth and time in a new window, then repeats the plot in the borehole profile window.

S – tool (S)tudy x-t plot – Same as X, but limits display to what would be obtained with a tool whose parameters (number of probes, gap between probes, and tool velocity) are specified by the user.

D – (D)ata x-t – Displays a color-coded plot of data traces versus depth and time in a new window, then repeats the plot in the borehole profile window (data type specified by option Y, default is FEC).

F – (F)ill data x-t – Same as D, except that data traces are interpolated to fill the *x*-*t* plane.

I – d/m d(I)ff x-t – Displays a color-coded plot of the difference between model and data FEC versus depth and time in a new window, then repeats the plot in the borehole profile window. User selects whether to show data traces (mode 1) or filled data (mode 2).

M – (M)odify inp– Opens interactive session for modifying location, flow rate, and concentration of feed points, or adding new feed points. User is prompted to enter feed point number and given the chance to modify or maintain current parameters. To add a new feed point, specify a feed point number greater than that for any existing feed point. If horizontal flow is implemented using option M, flow rate must be specified as volumetric flow rate through the wellbore in L/min.

P – (P)lot adjust – Sets new values of parameter minimum and maximum; t_{max}; difference range for option I; and depth for which wellbore flow rate q_0 is displayed in borehole profile window (default depth is x_{min}).

G – (G)rid – Sets grid spacing for new window showing *x*-*t* plots.

Y – data t(Y)pe – Chooses data type (FEC, TEMP, DAT3, DAT4, DAT5) to display in options C, T, D, and F. Model results always show FEC, so option C and T plots, which show both model and data, must be read carefully. Note that options R and I are not affected by the choice of data type, but always compare model and data FEC.

Z – print – Displays instructions for printing a screen image.

V – sa(V)e – Creates a new input file with current model parameters. User is prompted for new file name.

Q – (Q)uit – Terminates BORE II program.

4. Example Applications

Five example applications are presented to illustrate the capabilities of BORE II. Although BORE II simulates the forward problem (it produces wellbore FEC profiles given different inflow positions, rates, and concentrations), it is most commonly used in an inverse mode, in which inflow positions, rates and concentrations are varied by trial and error until the model matches observed values of wellbore FEC profiles. Initial guesses for the trial and error process may be obtained using direct integral methods (Tsang and Hale, 1989; Tsang et al., 1990) or other means (see example 2 below). Example applications 3, 4, and 5 demonstrate such comparisons to real data provided to us as typical field data sets by G. Bauer (private communication, 2000). The results of these example applications do not necessarily provide physically realistic flow rates and inflow concentrations, because they employ the artificial equality FEC = *C*. Furthermore, rough matches to real data, as are obtained here, can often be obtained equally well with a variety of different parameters (i.e., the solution of the inverse problem is non-unique). The input files for the example applications are shown in Appendix 3.

	Problem	Data File	Input File	Features
1	Up flow	up_num.dbt (numerically simulated)	up_num.inp	Advection and dilution, diffusion/dispersion minor
2	Horizontal flow	hor_an.dbt (analytical solution)	hor_an.inp	Dilution only, no advection or diffusion/dispersion One pair inflow/outflow points
3	Horizontal flow	hor_real.dbt (real data)	hor_real.inp	Dilution and diffusion/dispersion Multiple pairs inflow/outflow points Initial time added to data
4	Down flow	down_c.dbt (real data)	down_c.inp	Advection, dilution, and diffusion/dispersion Variable inflow concentration
5	Combination flow	comb_ic.dbt (real data)	comb_ic.inp	Advection, dilution, and diffusion/dispersion Non-uniform initial conditions

1. Up Flow – Numerically Simulated Data

Perhaps the most common application of BORE II is to the case of up flow - when one pumps from the top of the wellbore section, and fluid enters the wellbore at one or more feed points. Figure 1 shows *C* versus *x* for several times for a typical up flow case (obtained with BORE II option R). Each feed point has the same inflow rate and the same concentration, and there is also up flow from below. At early times, the feed points show up as individual FEC peaks, but as time passes, the deeper peaks merge with those above them, creating a step-like structure. The data set for this example is not real, but the results of a numerical simulation using the flow and transport simulator TOUGH2 (Pruess, 1987; 1991; 1995; 1998). TOUGH2 has been verified and validated against analytical solutions, other numerical models, and laboratory and field data. The TOUGH2 simulation uses a one-dimensional model with the same cell spacing as BORE II and constant mass sources located at the BORE II feed points. Thus, BORE II and TOUGH2 are solving the same problems, and comparing the results for wellbore FEC profiles verifies that the BORE II calculations are done correctly.

2. Horizontal Flow – Analytical Solution and Numerically Simulated Data

For horizontal flow in the absence of diffusion/dispersion along the wellbore, an analytical solution for the concentration observed in the wellbore as a function of time, *C*(*t*), is given by (Drost, 1968):

$$C(t) = C_i - [C_i - C(0)]\exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right), \qquad (1)$$

where C_i is the formation (inflow) concentration, t is time (s), v_d is the Darcy velocity through the aquifer (m/s), α_h is the aquifer-to-wellbore convergence factor, and r_w is the wellbore radius (m). Figure 2 shows the analytical solution and the BORE II results for this problem, obtained using option T. The agreement is excellent. Note that for small values of v_d, if C(0) = 0, the analytical solution becomes approximately

$$C(t) = C_i\left[1 - \exp\left(\frac{-2tv_d\alpha_h}{\pi r_w}\right)\right] \approx C_i\left[1 - \left(1 - \frac{2tv_d\alpha_h}{\pi r_w}\right)\right] = \frac{C_i 2tv_d\alpha_h}{\pi r_w}. \qquad (2)$$

Thus, any combination of C_i and v_d whose product is a constant gives the same value of *C*. This condition corresponds to the early-time straight-line portion of Figure 2. The analytical solution may be implemented in a spreadsheet to expedite the choice of BORE II parameters, by examining the solution for various values of v_d and C_i. Note that care must be taken to use a consistent set of units for t, v_d, and r_w in Equations (1) and (2). For example, when time is in seconds, BORE II input parameters v_d in m/day and r_w in cm must be converted to m/s and m, respectively.

Figure 2 also shows the evolution of concentration at and near a horizontal flow layer when diffusion/dispersion along the wellbore is significant ($D_0 = 10^{-5}$ m^2/s). For this case, the analytical solution is not applicable, but BORE II results compare very well to numerically simulated data obtained using TOUGH2. When dispersion is significant, use of the Drost solution generally results in an underestimation of C_i and an overestimation of v_d. These errors do not arise when using BORE II, since diffusion/dispersion can be explicitly included.

3. Horizontal Flow – Real Data

As indicated in Figure 2, the addition of diffusion or dispersion modifies the depth-FEC profile arising from a thin layer of horizontal flow, by widening the base of the FEC peak. A thick layer of horizontal flow produces a distinct signature, with an FEC response that has a wide peak as well as a wide base. To model a thick layer of horizontal flow, one may use several adjacent inflow/outflow point pairs in the model. Figure 3 compares model and data profiles (G. Bauer, private communication, 2000) of *C* versus *x* for several times, using option R. Seven pairs of inflow/outflow points are used, assigned to seven adjacent cells. By multiplying the number of inflow/outflow pairs by cell thickness, one may estimate the thickness of the layer of horizontal flow, in this case 2.3 m. See Appendix 1, Section A1.5, for additional information about assigning feed points to specific cells.

For this particular data set, the earliest observations show a variable FEC profile. One possible way to address this is to specify a non-uniform initial concentration distribution in the wellbore. An alternative approach (used here) is to add a dummy entry to the data file, specifying a time prior to the first real data time, at which the FCE distribution in the wellbore is assumed to be uniform. In general, it is not possible to determine when, if ever, the FEC distribution in the wellbore is uniform, but the approach can work quite well, as shown in Figure 4, which shows *C* versus *t* at the center of the horizontal flow zone (option T). The data zero time taken from the header of the data file, where the date and time of the logging run are specified.

4. Down Flow – Real Data

Figure 5 compares model and data profiles (G. Bauer, private communication, 2000) of *C* versus *x* for several times (option R) for a case with primarily down flow. A uniform non-zero initial concentration is used (IC0FLAG < 0) to approximate the low, slightly variable initial concentration. Two shallow inflow points have variable concentrations that increase in time, which suggests that de-ionized water penetrated into the fractures when it was introduced into the wellbore to establish low-concentration initial conditions for logging. A low-concentration feed point at x = 158.5 m creates up flow above it, but the remainder of the wellbore section shows down flow.

5. Combination Flow – Real Data

Figure 6 compares model and data profiles (G. Bauer, private communication, 2000) of *C* versus *x* for several times (option R) for a case with combination flow. A non-uniform initial condition has been used, which is extracted from the data file using the preprocessor PREBORE (see Appendix 2). Note that there are more entries in the initial condition specification (232) than there are cells in the model (179). Thus, some cells are assigned more than one initial condition. For cells where this occurs, only the final initial condition assigned is used. See Appendix 1, Section A1.5, for additional information on specifying non-uniform conditions. Figure 7 shows the same information as Figure 6, but plotted in a different way, with the difference between data and model FEC plotted as an *x-t* plot (option I). The blue and orange diagonal features indicate that the largest discrepancy between model and data gradually deepens with time.

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Appendix 1: Mathematical Background and Numerical Approach

The principal equation governing wellbore FEC variation is the equation for the transport of mass (or ion concentration) in the wellbore. However, additional consideration must be given to the determination of FEC as a function of ion concentration and the temperature dependence of FEC.

A1.1 FEC as a Function of Concentration

The relationship between ion concentration and FEC is reviewed, for example, by Shedlovsky and Shedlovsky (1971), who give graphs and tables relating these two quantities. Hale and Tsang (1988) made a sample fit for the case of NaCl solution at low concentrations and obtained

$$\mathrm{FEC} = 1{,}870\,C - 40\,C^2, \qquad \text{(A.1)}$$

where C is ion concentration in kg/m^3 ($\approx$ g/L) and FEC is in μS/cm at 20^{o}C. The expression is accurate for a range of C up to $\approx$ 6 kg/m^3 and FEC up to 11,000 μS/cm. The quadratic term can be dropped if one is interested only in values of C up to $\approx$ 4 kg/m^3 and FEC up to 7,000 μS/cm, in which case the error will be less than 10%.

Fracture fluids typically contain a variety of ions, the most common being Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^-. If a hydrochemical analysis has been completed, various methods are available for computing an equivalent NaCl concentration for other ions. Schlumberger (1984) presents charts of multiplicative factors that convert various solutes to equivalent NaCl concentrations with respect to their effect on electric conductivity.

A1.2 Temperature Dependence of FEC

BORE II calculations are made assuming a uniform temperature throughout the wellbore. Actual wellbore temperatures generally vary with depth, so temperature corrections must be applied to field FEC data to permit direct comparison with model output.

The effect of temperature T on FEC can be estimated using the following equation (Schlumberger, 1984)

$$\mathrm{FEC}(20^o\,\mathrm{C}) = \frac{\mathrm{FEC}(\mathrm{T})}{1 + \mathrm{S}(\mathrm{T} - 20^o\,\mathrm{C})}, \qquad \text{(A.2)}$$

where S = 0.024.

Generally, temperature increases with depth below the land surface. If full temperature logs are available, these data can be used to correct the corresponding FEC values. However, if no complete logs are available, a simplifying assumption may be made that the temperature variation in the wellbore is linear and can be modeled by:

$$T = Ax + B, \qquad \text{(A.3)}$$

where A and B are parameters determined by fitting any available temperature versus depth data. If the fit is unsatisfactory, other relationships with higher order terms must be used.

A1.3 Governing Equation

The differential equation for mass or solute transport in a wellbore is:

$$\frac{\partial}{\partial x}\left(D_o \frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial x}(Cv) + S = \frac{\partial C}{\partial t}, \qquad (A.4)$$

where x is depth, t is time, and C is ion concentration. The first term is the diffusion term, with D_0 the diffusion/dispersion coefficient in m^2/s, the second term is the advective term, with v the fluid velocity in m/s, and S is the source term in kg/m^3s. This one-dimensional partial differential equation is solved numerically using the finite difference method, with upstream weighting used in the advective term. The following initial and boundary conditions are specified:

$C(x,0) = C_0(x)$, (A.5)

$C(x_{min},t) = C_0(x_{min})$ for flow into the wellbore from above,

$C(x_{max},t) = C_0(x_{max})$ for flow into the wellbore from below,

$D_0 = 0$ for $x < x_{min}$ and $x > x_{max}$.

The first condition allows for the specification of initial ion concentrations in the wellbore. The second and third conditions allow for advective flow of ions into the wellbore interval from above and below. The final condition indicates that diffusion and dispersion do not take place across the boundaries of the wellbore interval. In general, advection will be the dominant process at the boundaries. If diffusion or dispersion is dominant for a particular problem, the boundaries should be extended in order to prevent improper trapping of electrolyte.

A1.4 Discretization in Time

Time stepping is explicit, with the time step Δt determined by stability constraints for advection

$$\Delta t \le \frac{\pi d_w^2 \Delta x}{8 q_{max}}, \qquad (A.6)$$

and diffusion

$$\Delta t \le \frac{\Delta x^2}{4 D_0}, \qquad (A.7)$$

where q_{max} (m^3/s) is the maximum fluid flow rate anywhere in the wellbore. BORE II starts its calculation at $t = 0$. The first time in the data file is also identified with $t = 0$. If it is apparent that model and data times are not synchronized, then one may insert an additional line into the data file after the header lines, with an earlier time than the first real data time, in order to reset the data zero time. On the inserted line, FEC, x, and other data entries may be left blank or copied from the first real data line.

A1.5 Discretization in Space

The wellbore interval between x_{min} and x_{max} is uniformly divided into N cells and it is assumed that the wellbore has uniform diameter, d_w. Cell height Δx is determined as the larger of $(x_{max} - x_{min})/180$ and d_w. Position values indicate depth in the wellbore and thus x is zero at the surface and increases downward. The cell index increases upward, with cells 1 and N located at the bottom and top, respectively, of the wellbore interval. In general, the ith node (the center of the ith cell) is located at

$$x_i = x_{max} - (i\text{-}1/2)\Delta x, \tag{A.8}$$

with the ith cell extending from $x_{max} - (i - 1)\Delta x$ to $x_{max} - i\Delta x$.

BORE II assigns feed points and initial concentrations to cell i if the location of the feed point or $C_0(x)$ value lies within the boundaries of the ith cell. If multiple feed points are assigned to the same cell, they will all be accounted for, but if multiple initial conditions are assigned to the same cell, only the final one assigned will be used. By definition, the lower boundary of cell 1 is at x_{max}, but due to round-off errors, the upper boundary of cell N may not be at x_{min}. Hence, it is often useful to know the x coordinates of each node. These are displayed in the input file written by BORE II (option V) when IC0FLAG > 0. Thus, if the user sets IC0FLAG = 1, inputs one (x, $C_0(x)$) pair, and uses option V, then a new input file will be created with IC0FLAG = N and a complete list of the x coordinates for all nodes, with $C_0 = 0$ for all cells except the one identified in the original input file. Alternatively, if the initial conditions are taken from the data file with PREBORE (or taken from any source that is independent of the nodal coordinates), then using option V will create an input file that shows the actual initial conditions assigned to each cell.

The list of nodal x coordinates may be useful when modeling a thick fracture zone or aquifer, in order to place one feed point in each cell over a given depth range. Similarly, when using IC0FLAG > 0 to specify non-uniform initial concentrations, one must assign a C_0 value to each cell in the interval of interest in order to obtain a continuous C profile, because no interpolation is done between scattered initial concentrations. Finally, knowing the coordinate of the top cell in the model is useful for assigning the initial concentration that serves as the boundary condition for inflow into the wellbore interval from above. For inflow from below, either $x = x_1$ or $x = x_{max}$ may be used.

A1.6 Calculation of Flow Rates

Feed point flow rates may be constant in time, in which case a steady-state flow field is assumed in the wellbore, or variable, with feed point flow rates determined by linear interpolation between tabulated values. Although feed point flow rate may vary, true transient wellbore flow including fluid compressibility effects is not considered. Rather, the wellbore fluid flow field is assumed to change instantly from one steady-state flow field to another. In other words, the flow rate out of cell i is always the sum of the flow rates from all feed point locations within the boundaries of cell i plus the flow rate out of cell i-1.

Appendix 2: The Preprocessor PREBORE

PREBORE is a simple Fortran program that does preprocessing for BORE II. It runs under either Windows or DOS. PREBORE converts the old BORE data file format into the new BORE II data file format. Depth is converted from feet to meters, and other data columns are realigned. PREBORE can also create a file with (x,C_0) pairs to be added to the BORE II input file as initial conditions (this option requires that x values steadily increase or steadily decrease in each profile).

If data file conversion is being done, the user is prompted to enter the old and new data file names.

If a file with initial conditions is being created, the user is prompted for the following information: the name of the BORE II data file; a name for the initial condition file; which profile in the data file to use; the direction of logging (downward assumes x values increase in the data file, upward assumes they decrease, and both assumes the profiles alternately increase and decrease in x); and the conversion factors (γ, β, α) between FEC and C (default values 0, 1870, -40). In addition to creating an ASCII text file with (x,C_0) pairs, which may be added to the BORE II input file using a text editor or word processor, PREBORE prints out the number of pairs on the screen, which should be used for IC0FLAG. Note that IC0FLAG may be greater than the number of cells in the model (usually about 180), but that in this case not all the C_0 values will be used (see Appendix 1, Section A1.5).

Data file conversion and initial condition creation can be done in the same PREBORE run. In this case the user must specify both old and new data file names in addition to the parameters describing the creation of initial conditions.

Appendix 3: Input Files for Example Applications

A2.1 Example Application 1 – Up Flow – up_num.inp

```
TITLE: up flow with flow from below, compare to synthetic data
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
 .0000       180.0       14.00      ! 1.000
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
 .7500       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
    3               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 160.5       .7500       100.0       .0000        0
 130.5       .7500       100.0       .0000        0
 50.50       .7500       100.0       .0000        0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 24.00       100.0       .7500E-09
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
    0
DATA_FILE   !'NONE' if there is no data file
up_num.dbt
```

A2.2 Example Application 2 – Horizontal Flow Analytical Solution – hor_an.inp

```
TITLE: Horizontal Flow - Compare to Analytical Solution
XMIN(m)     XMAX(m)     DIAM(cm)
0.000       50.000      7.600
QW(L/min)   HALPHA
0.          2.850000
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
       2    999
DEPTH(m)    Vd(m/d)     C(g/L)      T0(hr)      Q/V_FLAG
  25.0000     1.        1000.     .0000          1
  25.0000    -1.        1000.     .0000          1
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
3.0000      1000.       1.e-10
RGAMMA      RBETA       RALPHA
0.000000    1.000000    1.e-08
IC0FLAG
0
DATA_FILE
hor_an.dbt
```

The input file for the case with significant dispersion is identical, except that the diffusion coefficient is increased from 10^{-10} m^2/s to 10^{-5} m^2/s.

A2.3 Example Application 3 – Horizontal Flow - hor_real.inp

```
TITLE: Horizontal Flow Example
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
 .0000       60.00       7.600      ! .3333
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
 .0000       2.500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   14               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/d)
 26.73       .5295E-02   730.0       .0000        0         ! .1204
 26.73      -.5295E-02   .0000       .0000        0         !-.1204
 26.39       .5295E-02   730.0       .0000        0         ! .1204
 26.39      -.5295E-02   .0000       .0000        0         !-.1204
 26.06       .5295E-02   730.0       .0000        0         ! .1204
 26.06      -.5295E-02   .0000       .0000        0         !-.1204
 25.73       .5295E-02   730.0       .0000        0         ! .1204
 25.73      -.5295E-02   .0000       .0000        0         !-.1204
 25.39       .5295E-02   730.0       .0000        0         ! .1204
 25.39      -.5295E-02   .0000       .0000        0         !-.1204
 25.06       .5295E-02   730.0       .0000        0         ! .1204
 25.06      -.5295E-02   .0000       .0000        0         !-.1204
 24.73       .5295E-02   730.0       .0000        0         ! .1204
 24.73      -.5295E-02   .0000       .0000        0         !-.1204
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 4.000       400.0       .7500E-04
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
    0
DATA_FILE   !'NONE' if there is no data file
hor_real.dbt
```

A2.4 Example Application 4 – Down Flow – down_c.inp

```
TITLE: downflow, variable source conc., uniform non-zero initial conc.
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
 140.0       240.0       7.600      ! .5556
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
 .0000       2.850
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   12               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 239.0      -.7000       .0000       .4000        0
 212.0      -1.000       .0000       .4000        0
 187.0       .7500       1800.       .4000        0
 183.0       .1900       1900.       .4000        0
 181.0       .1200       1900.       .4000        0
 178.0       .5000E-01   1900.       .4000        0
 176.0       .4000E-01   1900.       .4000        0
 174.0       .3000E-01   1900.       .4000        0
 171.0       .1000E-01   1900.       .4000        0
 164.4      99905.       1900.       .4000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after  999
      .0000       .4400       80.00
      .4000       .4400       100.0
      1.200       .4400       1100.
      1.900       .4400       1650.
      4.500       .4400       1950.
 162.0      99904.       1800.       .0000        0
     T(hr)       Q(L/min)    C(g/L)      !#entries is two digits after  999
      .0000       .6000E-01   80.00
      .4000       .6000E-01   200.0
      1.900       .6000E-01   1650.
      4.500       .6000E-01   1950.
 158.5       .1000       80.00       .0000        0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 4.400       1700.       .1000E-02
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .0000       1.000       .1000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
   -1
C0 (g/L)    !Uniform, non-zero C0
 80.00
DATA_FILE   !'NONE' if there is no data file
down_c.dbt
```

A2.5 Example Application 5 – Combination Flow – comb_ic.inp

```
TITLE: Combination flow example, non-uniform initial concentration
XMIN(m)     XMAX(m)     DIAM(cm)    !DX(m) = MAX(|XMIN - XMAX|/180, DIAM/100)
 .00000      50.000      7.6000     ! .2778
QW(L/min)   HALPHA      !QW=flow from below; HALPHA=hor. flow constriction
 .00000      2.8500
#FEED_PTS   VARIABLE_FLOWRATE_IDENTIFIER
   12               999
DEPTH(m)    Q(L/min)    C(g/L)      T0(hr)      Q/V_FLAG    !Vd(m/day)
 45.000     -.13000      .00000      .00000       0
 33.300      .11000      800.00      .15000       0
 33.300     -.31000      .00000      .00000       0
 27.500     -1.0500      .00000      .00000       0
 25.700      .30000      810.00      .15000       0
 25.400      .30000      810.00      .15000       0
 25.140      .30000      810.00      .15000       0
 24.900      .30000      810.00      .15000       0
 23.500      .12000      800.00      .15000       0
 21.500      .40000E-01  800.00      .15000       0
 14.000      .15000E-01  750.00      .15000       0
 12.200      .10000E-01  750.00      .15000       0
TMAX(hr)    FECMAX      DIFFUSION_COEF.(m2/s)
 1.0000      1000.0      .50000E-03
RGAMMA      RBETA       RALPHA      !FEC = RGAMMA + C*RBETA + C*C*RALPHA
 .00000      1.0000      .10000E-07
IC0FLAG     !If 0, C0=0; If <0, read one C0; If >0,read IC0FLAG (X,C0) pairs
  232
X(m)        C0(g/L)          !#entries is IC0FLAG
1.524       2
1.615       2
1.707       3
1.829       3
1.951       3
2.073       3
2.225       3
2.377       3
2.53        3
2.713       3
2.865       3
3.018       3
3.353       589
3.536       597
3.719       588
3.871       583
4.054       584
…(208 entries not shown)…
43.282      2
43.8        2
43.983      2
44.166      1
44.318      1
44.501      1
44.684      1
DATA_FILE   !'NONE' if there is no data file
comb_ic.dbt
```

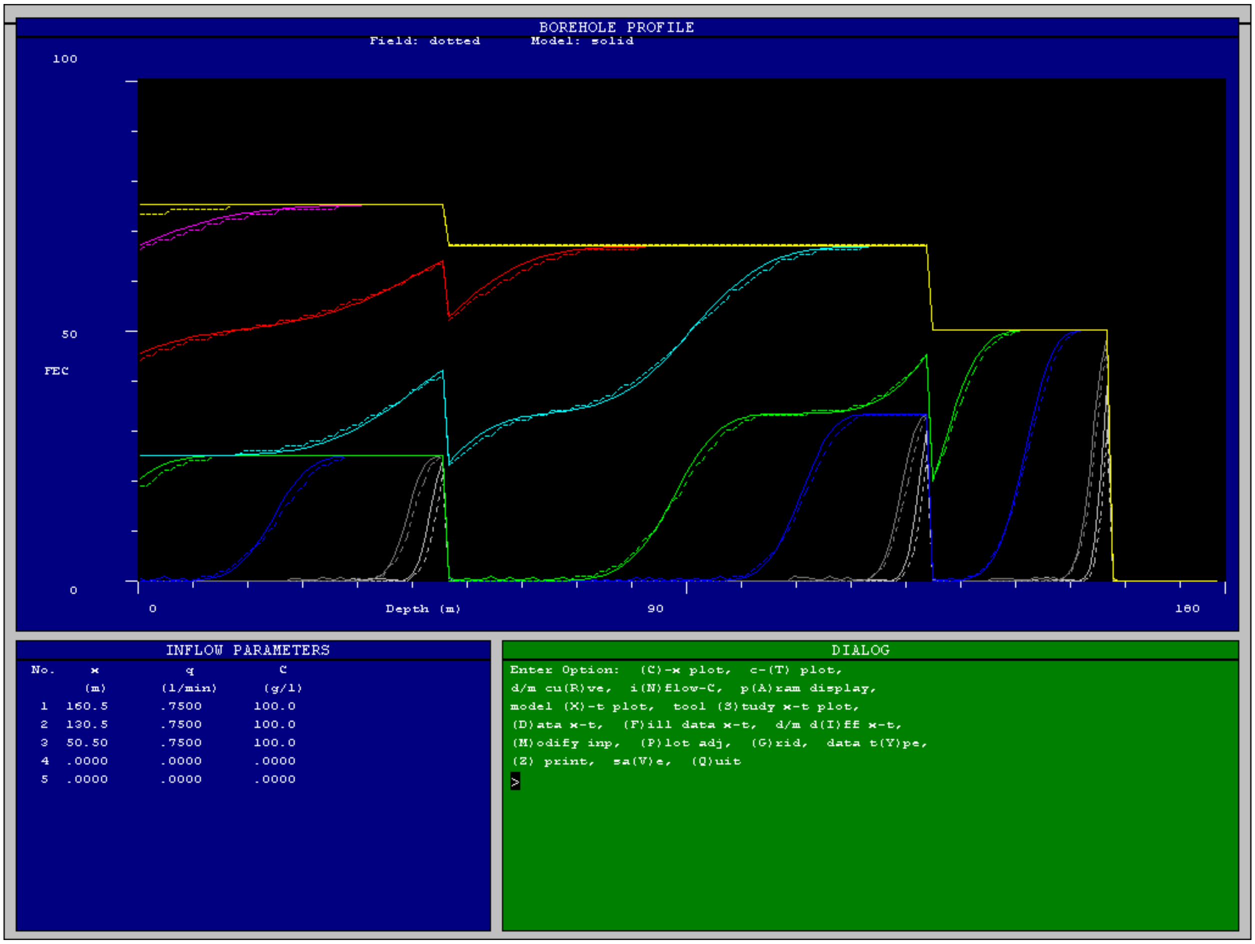

Figure 1. Concentration (=FEC) versus depth at a series of times for example application 1 - up flow. Data are numerically simulated using the TOUGH2 code. Figure is a BORE II screen-print after running option R.

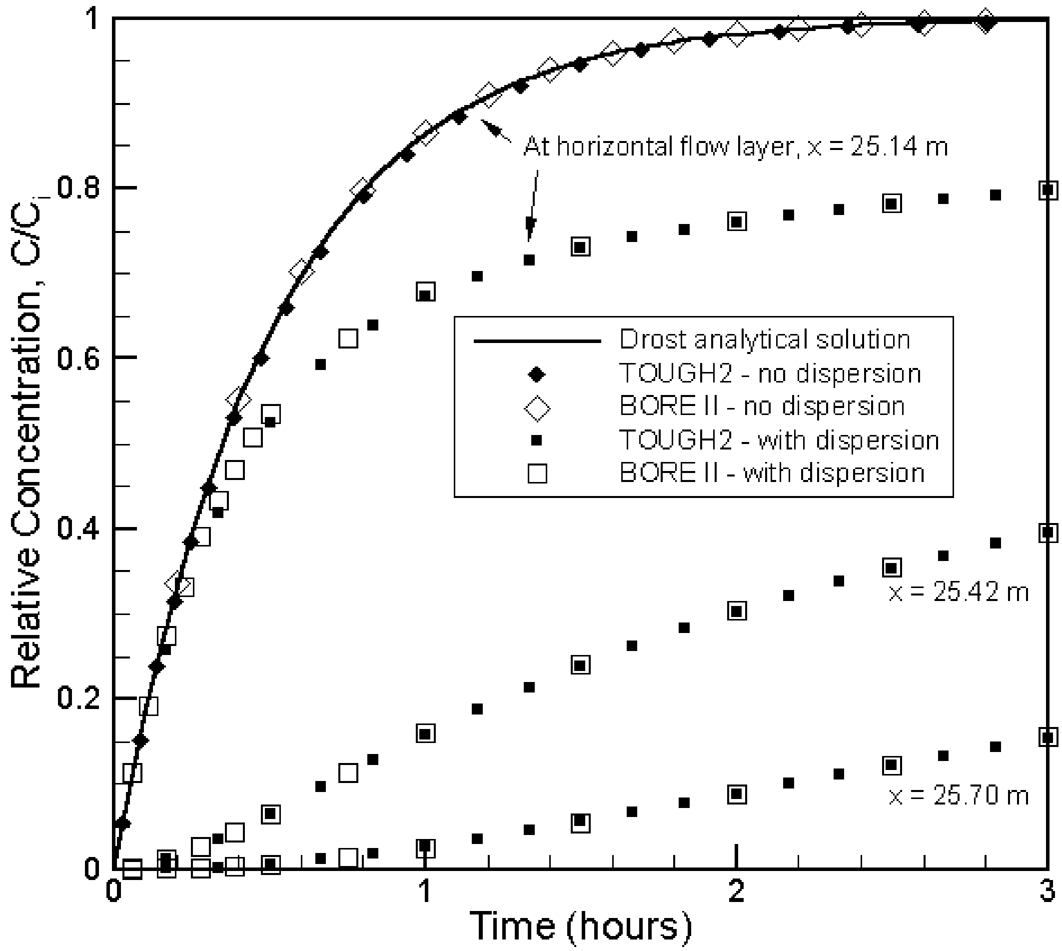

Figure 2. Relative concentration versus time for example application 2 – horizontal flow. When diffusion/dispersion is negligible, the concentration increase only occurs at the depth of the horizontal flow layer. The solid line shows the analytical solution as given by Drost (1968), Equation (1).

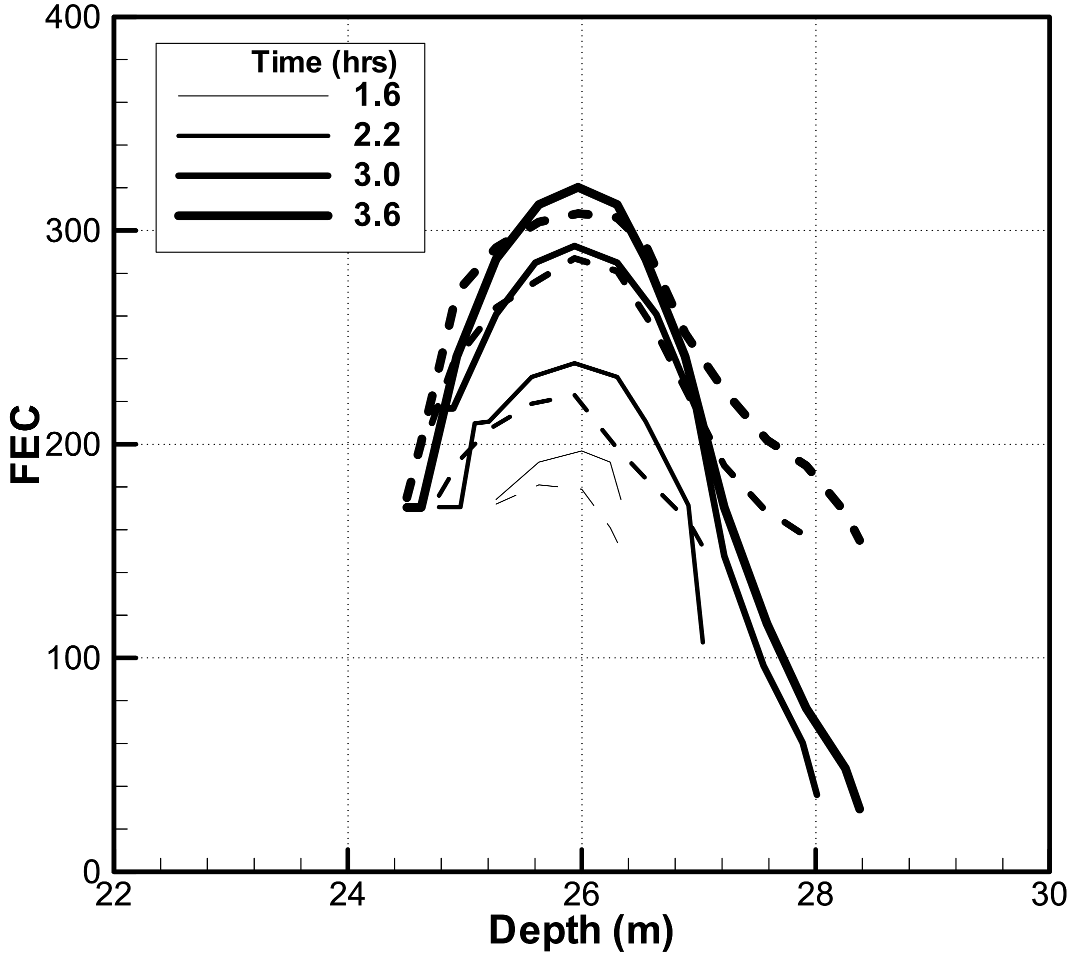

Figure 3. Concentration (= FEC) versus depth at a series of times for example application 3 – a thick layer of horizontal flow. Dashed lines represent field data, solid lines represent BORE II results. Diffusion/dispersion is significant.

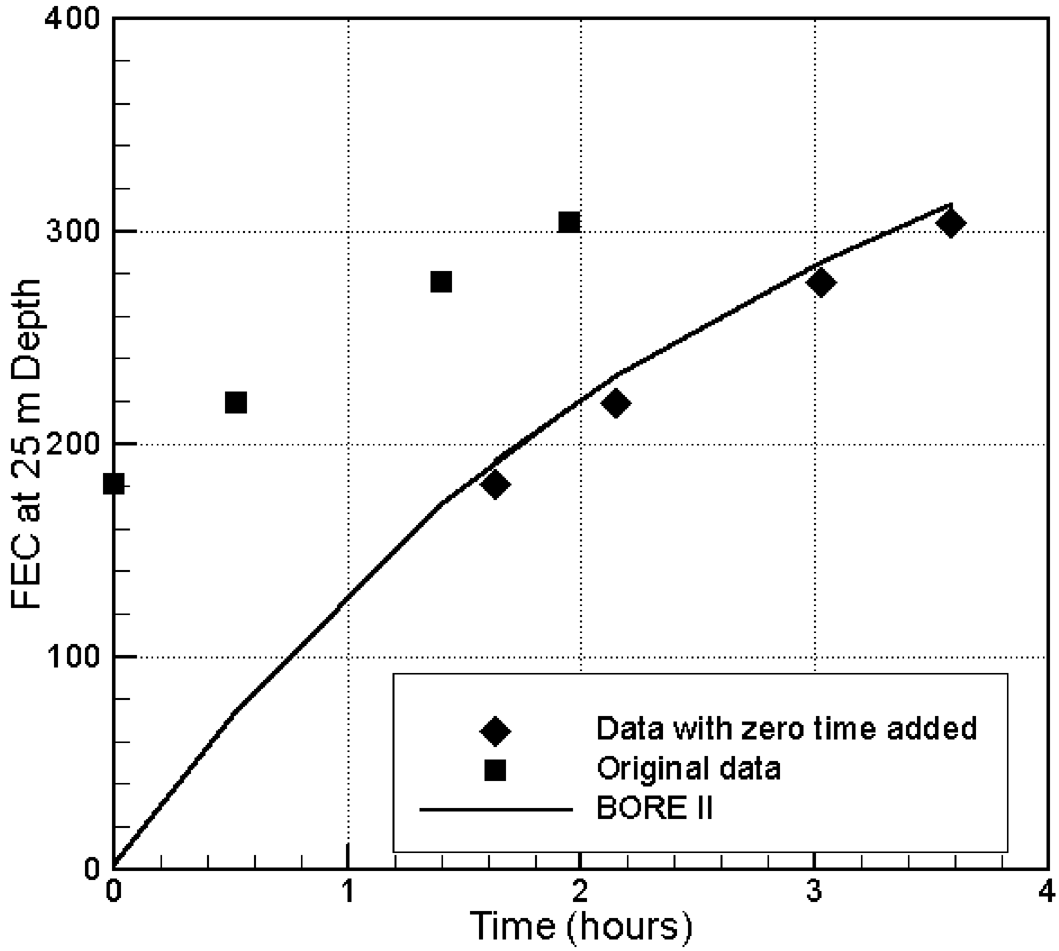

Figure 4. Concentration (= FEC) versus time at the center of the horizontal flow zone of example application 3, illustrating the addition of a data zero time.

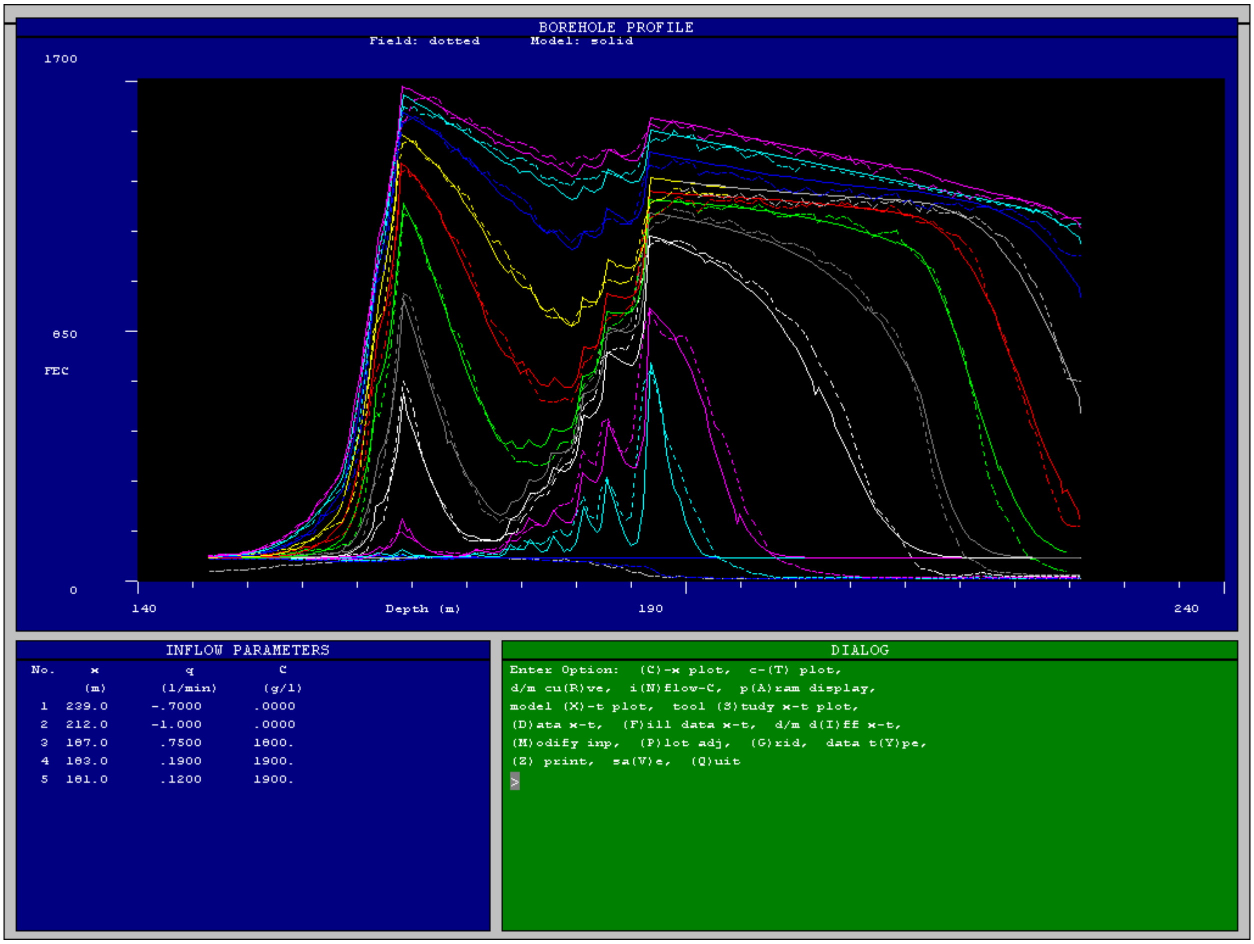

Figure 5. Concentration (= FEC) versus depth at a series of times for example application 4 – down flow. Figure is a BORE II screen-print after running option R.

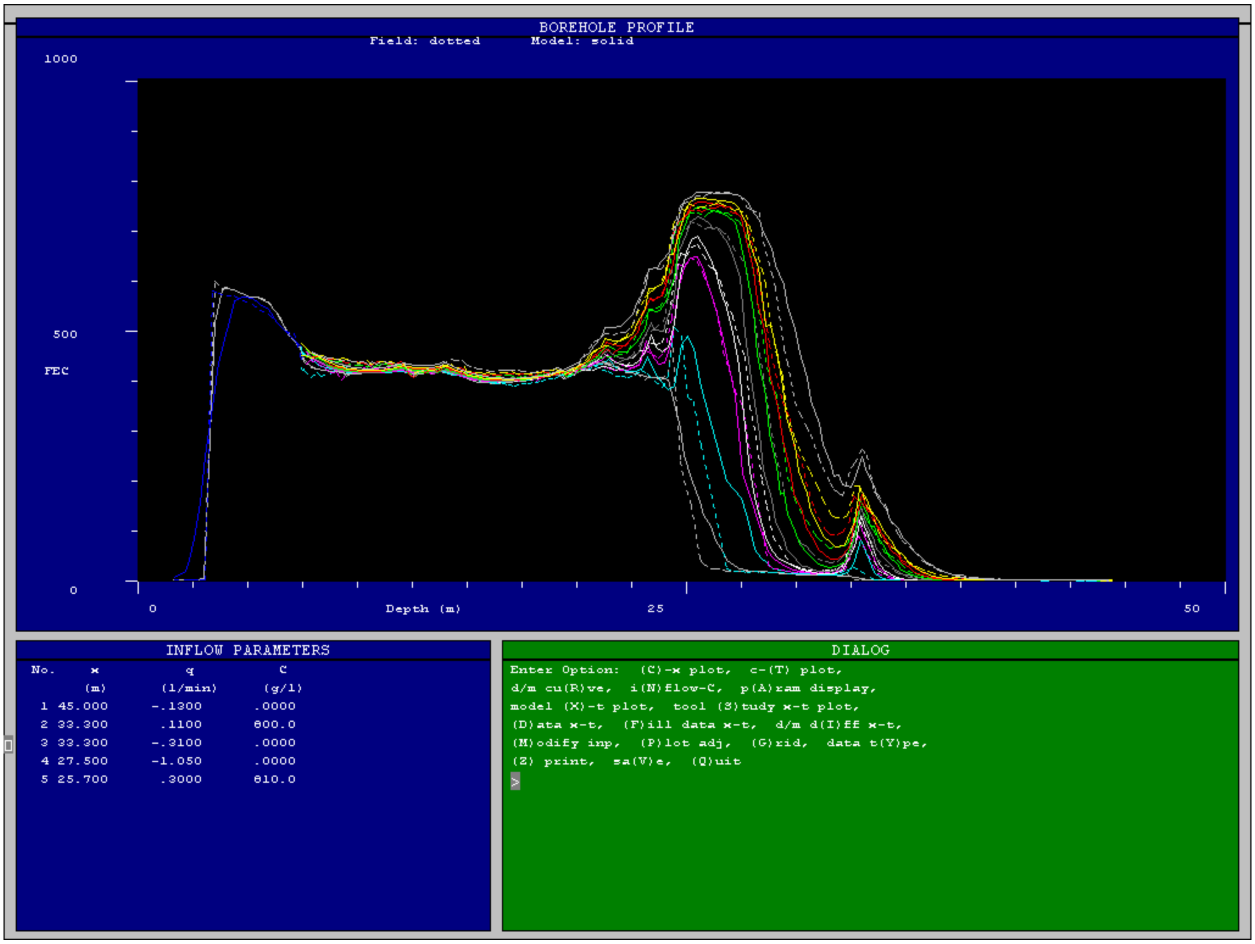

Figure 6. Concentration (= FEC) versus depth at a series of times for example application 5 – combination flow. Figure is a BORE II screen-print after option R.

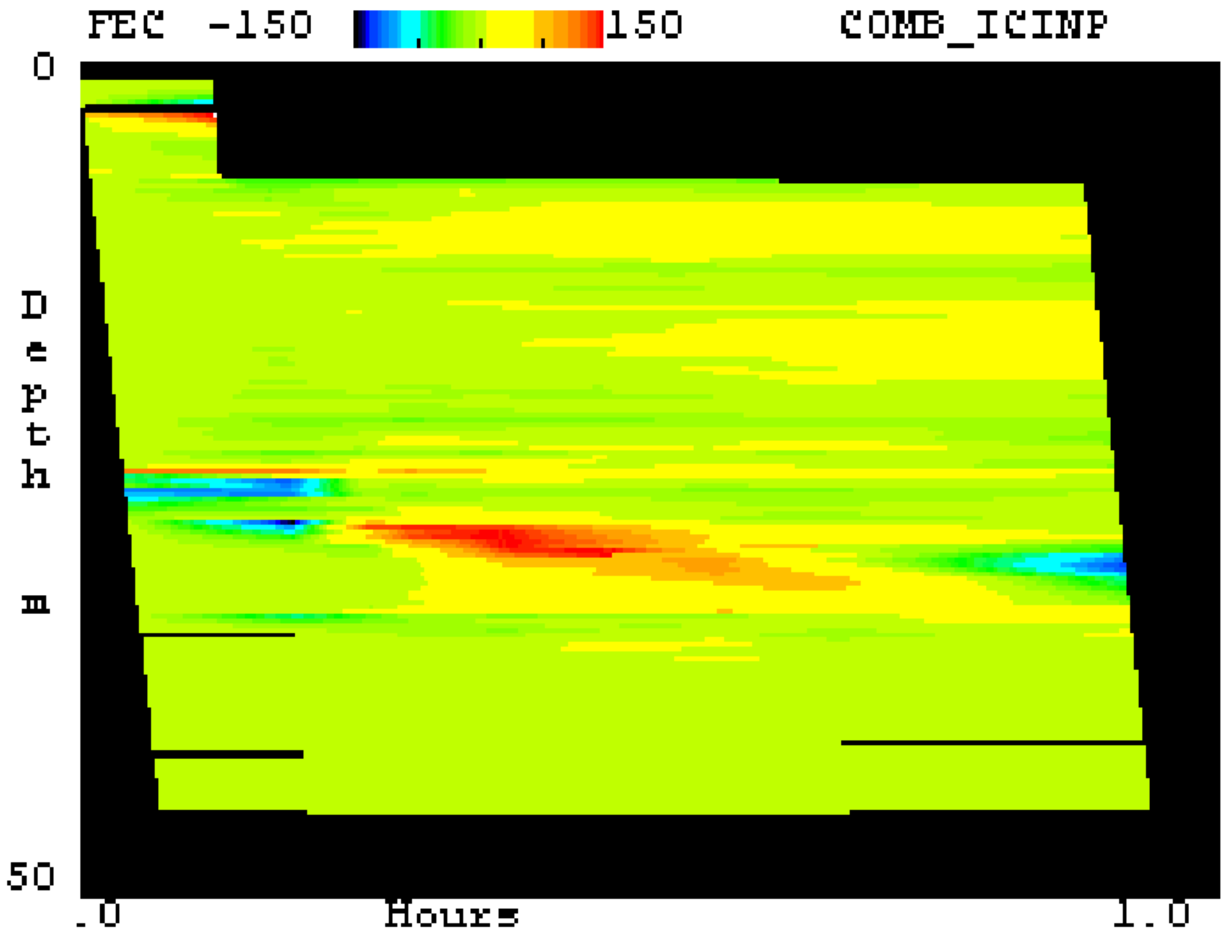

Figure 7. FEC difference between model and data as a function of depth and time (an *x*-*t* plot) for example application 5 – combination flow. Figure is a BORE II screen-print after option I, mode 2.

APPENDIX F

LIMITATIONS

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COLOG's logging was performed in accordance with generally accepted industry practices. COLOG has observed that degree of care and skill generally exercised by others under similar circumstances and conditions. Interpretations of logs or interpretations of test or other data, and any recommendation or hydrogeologic description based upon such interpretations, are opinions based upon inferences from measurements, empirical relationships and assumptions. These inferences and assumptions require engineering judgment, and therefore, are not scientific certainties. As such, other professional engineers or analysts may differ as to their interpretation. Accordingly, COLOG cannot and does not warrant the accuracy, correctness or completeness of any such interpretation, recommendation or hydrogeologic description.

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