Mountain Valley Pipeline Project

Docket No. CP16-10-000

Attachment DR4 Geology 8

February 2017

Response:

Mountain Valley evaluated the Indian Creek Report and notes that it neither documents nor demonstrates experience in the analysis of geologic hazards for natural gas pipeline construction in karst terrain, on steep slopes, or in the analysis of seismic hazards, materials, and engineering controls. It is vital that infrastructure projects such as the Mountain Valley Pipeline Project be evaluated for efficacy by scientific and engineering analyses. Mountain Valley developed numerous detailed analyses and documents on the topics of karst terrain, hydrogeology, foundation and slope analyses, water resources, seismic hazards analysis, and materials design. The resulting documents include the Karst Hazards Assessment, Karst Mitigation Plan, Seismic Hazards Assessment, Materials Engineering and Design, and the Water Supply Identification and Testing Plan.

Comment	Response
Acreage Requirements for Work Activities:	The Indian Creek Report states there will be over 100 acres of access roads associated with Project construction; however, many of the access roads included in this acreage are currently in use and would be improved for Project use.
Geology of Summers and Monroe County:	The Indian Creek Report discusses caves in the Avis Limestone. However, none of these caves in Summers County are within 10 miles of the proposed route. In fact, there are only two known caves in the Avis limestone that are over 1,000 feet in length and both are located in Mercer County, which is not part of the Project area. There is no risk to these caves from Project construction.
Geology of Summers and Monroe County:	Referring to the Abbs Valley Anticline in the Ellison Ridge area, the Indian Creek Report states that the underlying Greenbrier Formation is observed in caves accessed through openings in the overlying sandstone and shale. This statement is not accurate because there are no known caves on Ellison Ridge.
Table 2 and Table 3 – Karst.	These tables reference “open throats” for sinkholes even if the maps do not indicate open throats. The vast majority of sinkholes visited did not have open throats and exhibited bottoms that were consistent with the surrounding ground cover.

Karst:	An un-named cave area is referenced in the Indian Creek Report. However, investigation of this area by the Karst Specialist Team determined that this is not a karst feature, but was developed entirely in sandstone and is not karstic in nature. This section of the Indian Creek Report also discussed Haala Cave, which is a small cave located in the creek bank approximately 2 miles downstream from the pipeline crossing of Indian Creek. It is not situated in a location relative to local hydrology that presents risk for impact from pipeline construction.
Seismic Hazards:	Mountain Valley addressed seismic hazards in Resource Report #6, and concluded that there is minor to negligible risk presented to the pipeline (i.e., design criteria are well within acceptable factor of safety). Mountain Valley is also addressing slopes and potential landslide activation from a seismic triggering event. Mountain Valley has determined that slopes are generally stable in this area and does not consider there to be a significant risk presented to pipeline, slopes, or karst features in the area referenced by the Indian Creek Report.
Soils of Summers and Monroe Counties:	The Indian Creek Report asserts concerns over topsoil formation after reclamation, the presence of acid-forming soils, negative impacts from soil erosion, and effects on soil permeability. Mountain Valley will stockpile topsoil during land clearing and use this for reclamation of the pipeline limit of disturbance. Mountain Valley is aware of the potential for encountering acid forming materials (AFM) during construction. An assessment of AFM was presented in Resource Report #6. Natural gas pipelines have been installed in many regions of the United States, included the Appalachian region, and there is no record of notable and extensive degradation of soil or related surface conditions due to pipeline construction and operation.

Soils of Summers and Monroe Counties:	The Indian Creek Report asserts that blasting will probably be required for all areas where bedrock is less than 10 feet below ground surface. However, this assertion is false. Standard mechanical ripping will be sufficient to remove "red shale" along the proposed alignment in this area. Harder bedrock, if encountered, will be excavated to the extent possible, using rippers, breakers, and hoe rams. Blasting would be employed as a last resort, and is not anticipated to be extensive.
Water Resources of Summers and Monroe Counties:	This section did not present any new information that Mountain Valley has not already considered or accounted for through 1) proposed alignment adjustments, 2) avoidance-monitoring-mitigation techniques described in the Karst Hazards Assessment, Karst Mitigation Plan, Erosion and Sediment Control Plan, and 3) the Water Resources Identification and Testing Plan.
Streams:	The Indian Creek Report asserts that when aquatic habitats are impacted by the physical activity of trenching and utilization of stream crossing work spaces, the stream habitats cannot be restored. Based on the nature of the proposed construction (narrow excavation typically less than 10 feet below ground) Mountain Valley does not concur with the Indian Creek Report on habitat restoration. For pipeline construction projects, habitat restoration at stream crossings occurs rapidly.
Mitigation for Wetlands:	The potential for impacts to wetlands is not significant because Mountain Valley completed route adjustments to avoid these features to the maximum extent practicable. Wetlands that are impacted will be restored following the FERC's Procedures.
Hydrostatic Testing:	The Indian Creek Report asserts that disposing of thousands of gallons of hydrostatic test water would destroy aquatic habitat. On the contrary, all hydrostatic test water discharges will be conducted in upland areas with no discharge occurring directly to any waterbody, wetland, or other sensitive resources. As such, impacts from hydrostatic test discharges are not anticipated.

Conclusions:	The remaining discussion presented in the Indian Creek Report regarding groundwater, groundwater and surface water interactions, and ecological systems. Mountain Valley has already addressed these issues with alignment adjustments to avoid potential risk for impact or through mitigation measures included in the Project plans referenced previously in this response. In addition, Mountain Valley has provided responses to the same or similar issues raised by the same author in the Roanoke County Hydrogeological Assessment. See the response to General, Question 3g.

Mountain Valley Pipeline Project

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ELECTRICAL RESISTIVITY IMAGING STUDY

October 2016 Proposed Alignment

Milepost 221.8 to 227.2

Prepared for:

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February 2017

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DAA Project Number: B14188B-02

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Executive Summary

Mountain Valley conducted two-dimensional electrical resistivity (ER) surveys on the physically-accessible portions on all parcels of the October 2016 Proposed Route between mileposts 221.8 and 227.2 south of the Pulaski Fault. In these areas, Mountain Valley utilized a spacing of 3-5 meters between electrodes. Using a long line of electrodes connected to a cable on the surface, hundreds of resistivity measurements were collected to create a data set for a two-dimensional cross-section of sub-surface ERs.

Mountain Valley's geophysical experts collected the ER data and used computer software and expertise to analyze the data to determine whether a notable karst feature was present below the ground surface. The ER analysis demonstrated an irregular bedrock surface, which is common in karst terrain. The ER analysis also indicated a stable sub-surface within the design depth of the pipeline excavation and through a depth where the pipeline could affect, or be affected by, any karst features. For example, the ER analysis indicated that open, air-filled voids are not present within these areas. The ER analysis also identified 15 locations that demonstrated low resistivity results interpreted to be soil cutters or sinkhole throats, which are features typically associated with karst terrain. Based on the ER study and field observations, these features are typically narrow and relatively shallow, rarely open to the surface, and unlikely to present construction related issues given BMPs and construction inspection to be implemented by Mountain Valley.

Based on this ER analysis, coupled with desktop analysis and other field reconnaissance, Mountain Valley does not expect any significant risks associated with karst terrain between mileposts 221.8 and 227.2 of the October 2016 Proposed Route. Any karst encountered during construction can be addressed through the processes detailed in the Karst Mitigation Plan, including minor route adjustments.

1.0 Introduction

Draper Aden Associates conducted a 2-dimensional subsurface electrical resistivity (ER) imaging study in karst terrain between mileposts 221.8 and 227.2 (Study Area) of the October 2016 Proposed Route (proposed alignment) for the Mountain Valley Pipeline (MVP) in the Mount Tabor area of Montgomery County, Virginia. Figure 1 illustrates the Study Area, and shows the ER centerline by the green line.

The purpose of the ER study was to support the Karst Hazards Assessment (October 2016 update) conducted by the Mountain Valley Karst Specialist Team in the vicinity of the proposed alignment (see Background discussion, below). The objective of the ER study was to identify whether notable karst features were present at the study depth beneath the proposed alignment. Typically, for a study designed such as this one, ER response is considered reasonable for evaluation to a depth of approximately 80 feet below ground surface. Results from the Karst Hazards Assessment and the ER study are combined to provide Mountain Valley with recommendations for avoidance and enhanced mitigation to protect karst features and limit hazards to pipeline construction and operation.

A total of 25,238 linear feet of resistivity data were collected between August 8, 2016 and October 27, 2016 along or near the centerline of the proposed alignment. ER data analysis resulted in a recommendation for additional follow-up ER data collection at 15 specific locations to further evaluate the nature and lateral extent of resistivity variations. An additional 8,818 linear feet of resistivity data were collected in short lines at the 15 selected locations that were offset to the proposed centerline in the vicinity of the observed features.

This report summarizes site geology, ER theory, field collection techniques, and data analysis. A detailed discussion evaluating the subsurface ER data along the Study Area and the 15 locations selected for follow-up is also presented below, including graphical cross-sections illustrating the ER data response to support the evaluations made herein. The evaluations of the ER response were made by Mountain Valley's geophysical experts, who possess over 40 years of experience in subsurface geophysical data collection and evaluation in karst terrain. The raw ER data were processed as described below, and presented in an industry-standard format showing 2-dimensional cross sections along the electrode array, with ER response shown in ohm-meters and contoured using colors (blue is low resistivity, red is high resistivity). This presentation method is similar to a “heat map”, where high response to whatever data are being illustrated is typically shown in red (hot), and low response in blue (cool).

1.1 Background

Karst terrain underlies much of the Mount Tabor area (Figure 2). The Mount Tabor sinkhole plain is a generalized area where karstification is more intense than other areas of the Mount Tabor area, bounded to the north and west by the Pulaski fault, to the east by Mill Creek, and to the south by the Mount Tabor fault. The Mountain Valley Karst Specialist Team prepared the Karst Hazards Assessment to assess karst terrain traversed by proposed alignment, including the Mount Tabor sinkhole plain.The re-route to avoid the Mount Tabor sinkhole plain would reduce the risk for potential impacts to karst features, lands under conservation easements, as well as avoid more densely inhabited portions of the sinkhole plain. Refer to Figure 2 showing the proposed alignment (approximated by the green line showing the ER centerline) located north and east of the Mount Tabor sinkhole plain and residential parcels.

Mountain Valley updated the Karst Hazards Assessment to incorporate the recommended alignment adjustment in the Mount Tabor area, and the Karst Hazards Assessment incorporated the ER study results in its evaluation of karst features. The Karst Hazards Assessment (October 2016 revision) documented surficial karst features and karst water resources, using the ER study for additional characterization, with the goal to avoid sensitive karst features through major or minor alignment adjustments, or to identify where necessary measures for mitigation and protection of sensitive features.

1.2 Study Objectives and Tasks

The objective of the ER study was to evaluate the subsurface under the proposed alignment in the Mount Tabor area for the presence of notable karst features and to characterize the likely nature of the identified features. The ER study tasks included:

1) Research of available geologic data and coordinating with the Mountain Valley Karst Hazards Assessment;

2) Collection, processing, and evaluation of electrical resistivity data; and

3) Preparation of this document to detail the principles of resistivity, field methods and findings, and recommendations.

2.0 SITE GEOLOGY

The Mount Tabor sinkhole plain (Study Area) is located within the folded and faulted Valley and Ridge geologic and physiographic province consisting of elongate parallel mountain ridges and valleys that are underlain by folded and faulted Paleozoic sedimentary bedrock. These parallel ridges and valleys are the result of differential weathering of layered siliciclastic and carbonate bedrock, where more weather-resistant sandstones tend to form ridges, and shales and carbonate bedrock forms the lowland valleys. The Study Area is mapped as being underlain by upper Cambrian and lower Ordovician carbonate rocks of the Elbrook, Conococheague, Beekmantown, New Market and Lincolnshire, and Edinburg Formations (Figure 3).

Progressing upward in stratigraphic sequence (from oldest to youngest rock strata), the Elbrook Formation is comprised of alternating beds of dolomite and limestone. The Conococheague Formation is comprised of fine-grained limestone alternating with laminated dolomite. Chert, sandy dolomite and sandstone beds are present in the lower portions of the formation. The Beekmantown Formation is comprised of significantly chert-bearing, medium- to thick-bedded dolomite, with lesser thin-bedded limestone. The New Market and Lincolnshire Formations (undivided) are comprised of limestone with the highest calcium carbonate content compared to all the other units present in the Study Area, which means these formations are more soluble and more susceptible to karst-forming processes. However, these units underlie only a small portion of the Study Area (approximately 500 feet between mileposts 226.8 to 226.9). The Edinburg Formation, which underlies the easternmost portion of the Study Area, is comprised of calcareous shale and thin-bedded, argillaceous limestone.

Two ancient, inactive thrust faults are mapped in the Study Area, one of which is located at the western margin of the Study Area, near mileposts 221.7 to 222.7 (the Pulaski Fault), and the other which is located near the middle of the Study Area, near milepost 225.55 (the Mount Tabor Fault). At the western Pulaski Fault, the Cambrian carbonate rocks of the Elbrook Formation are likely thrust over siltstone and mudstone layers of the Mississippian Price Formation. This fault boundary marks the western boundary of the area of interest of this study. At the Mount Tabor Fault, in the middle portion of the Study Area, the Cambrian Elbrook Formation is thrust over the

Beekmantown Formation. This fault creates a repetition of bedrock formations across the Study Area, such that, moving from the western edge of the Study Area to the east, the exposed rock units are: Elbrook, Conococheague, Beekmantown, Elbrook, Conococheague, Beekmantown, New Market and Lincolnshire, and Edinburg Formations (see geologic cross-section in Figure 3). The geologic map suggests that the bedrock strata beneath the entirety of the Study Area strike east-northeast/south-southwest, and dip between approximately 10 to 35 degrees to the southeast.

All of these units are prone to karst formation to varying degrees depending upon their lithologic makeup (which can vary within the formation due to depositional environment), structural controls and degree of fracturing, and relative position near boundaries with siliciclastic formations. Karst formation occurs in limestone and dolomite rocks due to enhanced weathering and dissolution, relative to non-carbonate rock (siliciclastic sandstone, siltstone and shale). Carbonate rocks are more susceptible to dissolution than other rock types because of the relatively soluble nature of carbonate mineralogy in contact with water, particularly water with $pH < 6$ that typically includes precipitation and surface water or groundwater that chemically equilibrated with siliciclastic bedrock. The carbonate mineral dissolution reactions typically occur primarily along bedding planes and joints as water percolates through those features. As the carbonates dissolve, the percolating water carries away the soluble components and leaves behind the insoluble clay minerals and silicates. The remaining soils are often plastic clayey soils and may be soft and compressible.

The continued dissolution of carbonate rocks can sometimes result in open cavities in the rock. As these cavities grow in the subsurface, the overlying soils (more generally, overburden) are susceptible to raveling (being carried by water infiltration) into the underlying cavities. As the surface overburden continues to ravel, the ground surface can subside and result in the gradual formation of closed depressions or sinkholes. This type of sinkhole is known as a cover subsidence sinkhole and forms very slowly (i.e., decades to centuries).

Where the overburden is stiff with high tensile strength, raveling at depth can result in formation of an overburden bridge. As the cavity enlarges over time it can eventually reach a point where the surface overburden cannot maintain the bridge, resulting in a collapse of the surface soils. This type of sinkhole is known as a cover collapse sinkhole, and is less common than the cover subsidence type in the area of the proposed alignment.

The majority of the sinkholes observed by the Karst Specialist Team during field reconnaissance for the Karst Hazards Assessment, within ¼-mile of the proposed alignment, were consistent with cover subsidence sinkholes. More discussion on karst features in the Mount Tabor area is provided in the Karst Hazards Assessment.

3.0 Electrical resistivity (ER) imaging

To provide continuous imaging of the subsurface beneath the proposed alignment for karst feature evaluation, two-dimensional surface resistivity imaging methods were employed. Resistivity imaging provides cross-sectional depictions of the resistance of subsurface materials to electric current, from which certain geologic conditions can be inferred. Electrical resistivity is a fundamental parameter describing how easily a material can transmit electrical current. High values of resistivity imply that the material is very resistant to the flow of electricity; low values of resistivity imply that the material transmits electrical current very easily.

3.1 Principles of Resistivity

Experiments by George Ohm in the early 19th century revealed the empirical relationship between the current flowing through a material and the potential required to drive that current. This relationship is described by

$$V = IR$$

where V is voltage in volts, I is the current in amperes, and R is the proportionality constant. Rearranging the equation to

$$\frac{V}{I} = R$$

gives resistance with the units of volts divided by amperes, or ohms.

The resistance of a material is dependent not only on the property of the material but also the geometry of the material. Specifically, a longer travel path for the current or smaller cross-sectional area would cause the resistance to increase. The geometry-independent property used to quantify the flow of electric current through a material is resistivity, given by

$$\rho = \frac{RA}{L}$$

where ρ (rho) is the resistivity, R is the resistance, A is the cross-sectional area through which the current flows, and L is the length of the current flow path. With all length units expressed as meters, the units associated with resistivity are ohm-meters.

Resistivity surveys are conducted by inducing an electric current into the ground between two electrodes, and measuring the potential at other electrodes. Numerous configurations of electrode placement are commonly employed, each with unique data characteristics. The configuration utilized for this study was the dipole-dipole array. For the dipole-dipole array, a current is applied to two adjacent electrodes positioned a predetermined distance apart (distance a). The voltage across two other electrodes is measured simultaneously with the applied current. The two sets of electrodes are always spaced distance "a" apart and the distance between the current and voltage electrodes is always a multiple of a (n• a). To obtain apparent resistivity values, the voltage and current measurements are input into the following formula for dipole-dipole surveys

$$\rho = 2\pi(n+1)\cdot(n+2)\cdot a\cdot\frac{V}{I}$$

3.2 Field Methods

Field data were collected using a SuperSting R8 IP® multi-electrode resistivity system manufactured by Advanced Geosciences Inc. Data were collected using the dipole-dipole array with a current of up to 2,000 milliamps. For each electrode configuration in the array, measurements were repeated a minimum of two times, and percent error between the repeated measurements were stored for subsequent evaluation of data quality. Large errors between repeated measurements can be an indication of poor data quality.

The electrodes were assigned a unique identifier consisting of the line number followed by a dash and the electrode number. For example, the first electrode on Line 1 is 1-1, the first electrode on Line 2 is 2-1, etc. The locations of the resistivity electrodes were recorded with a Trimble Pro 6H GPS unit and plotted onto topographic layers for the site. The elevation of each electrode location was extracted from high-resolution topographic data for the Study Area and incorporated into the resistivity data so that the resulting sections would reflect the local topographic relief.

Throughout the Study Area, a spacing of three to five meters between electrodes was utilized. Utilizing closer electrode spacing allows for greater resolution of subsurface features than a wider spacing, but results in shallower depth imaging acquired, and *vice versa*. Five-meter spacing provides a good balance between resolution and depth of imaging. All straight intervals along the centerline measuring greater than approximately 50 to 80 meters typically utilized five-meter spacing. For very short intervals, i.e. for closely spaced inflection points along the centerline, three-meter or four-meter electrode spacing was utilized along those shorter segments. Typically, additional offset resistivity data collected to further evaluate possible karst features observed in the centerline data utilized a three-meter spacing.

A total of 25,238 linear feet of resistivity data were collected between August 8, 2016 and October 27, 2016 along or near the centerline of the MVP October 2016 Proposed Route. These data were collected in a series of 32 individual resistivity data sets. It is necessary to collect 2D resistivity data in as straight a line as possible. Where the proposed alignment was relatively straight for long distances, the data were collected continuously in “roll-along” fashion along the centerline in the following manner: Initially, data for a linear distance of 275 meters (902 feet) were collected, and then 50% of the line length would be leap-frogged forward to append new resistivity data to the same data set, until a significant inflection point in the centerline is reached. At each significant inflection point, a new data set was initiated in the new direction of the centerline.

After review of the data collected along or near the centerline for ER responses that may represent possible karst features, follow-up ER imaging was completed at 15 specific areas selected by the Mountain Valley geophysical experts, who possess decades of experience in collection and evaluation of ER data. An additional 8,818 linear feet of resistivity data were collected in short lines that were offset to the proposed centerline in the vicinity of the observed features. The offset lines were collected in order to evaluate the lateral extent and nature of the ER variations observed in the centerline data. The data collected along the centerline are referred to hereafter as centerline data, and the additional data collected as offsets to observed possible karst features in the centerline data are referred to hereafter as offset data.

A map sheet index for the 32 centerline resistivity lines is provided in Figure 4, and the corresponding map sheets illustrating the individual electrode locations are illustrated in Figures 5 through 11. At several locations throughout the Study Area, it was not feasible to collect resistivity data immediately along the centerline due to dense vegetation. No vegetation clearing is permitted during the survey process. In many of these locations, it was also not feasible for the civil surveyors to stake the actual centerline. However, where feasible, resistivity data were collected as close as possible to the centerline.

Along the total length of the Study Area, a total of approximately 4,171 linear feet of the alignment was not evaluated with resistivity imaging. The intervals that were not evaluated are as follows, including the reason resistivity data were not collected:

1. Approximately mileposts 222.33 to 222.71. Most of this interval lies within parcel VA-MO-5514, which is the only property throughout the Study Area where landowner access was never granted. However, this parcel lies to the north of the mapped Pulaski Fault boundary, and as such, it does not lie on carbonate rock or karst terrane. The remaining portion of this interval lies within parcels VA-MO-5516 and VA-MO-5517. The southeastern-most portion of parcel VA-MO-5516 lies south of the mapped fault boundary, suggesting it is underlain by carbonate rocks. Resistivity data were collected on this portion of the property, but not on the portions that lie north of the mapped fault, i.e. beyond the mapped extent of the carbonate bedrock.
2. Approximately mileposts 224.08 to 224.25. This area lies within parcel VA-MO-5528 and was comprised of dense blackberry thickets that were impassable without clear-cutting.
3. Approximately mileposts 224.4 to 224.43. This area straddles the boundary between parcels VA-MO-5528 and VA-MO-5528, and had been clear cut in recent years, and was comprised of impassable dense, briery vegetation.
4. Approximately mileposts 225.38 to 225.42: This area lies within parcel VA-MO-5530 and was comprised of impassable dense blackberry thickets.
5. Approximately mileposts 225.68 to 225.72 and 225.8 to 225.9. These areas lie within parcel VA-MO-5530 and had been clear-cut in recent years. All observed portions of this parcel that did not lie along open roads were comprised of impassable dense briers and saplings.
6. Approximately mileposts 226.01 to 226.04. This area lies within parcel VA-MO-5532 and had also been clear-cut in recent years. This property was also predominately covered by impassable dense briers and saplings.

Along the total length of the Study Area, a total of approximately 2,534 linear feet of resistivity data were initially collected as "centerline" data, but which were located more than approximately 20 feet from the centerline. These data were collected as representing "centerline" data, but were offset from the proposed centerline due to the presence of intermittent impassable dense, briery vegetation along the actual staked centerline. The distances of these offset "centerline" data sets from the staked centerline in these intervals was typically between 20 and 50 feet, but was as much as 100 feet in two locations: approximately mileposts 225.85 and 226.17. Those intervals where the collected "centerline" data were located more than approximately 20 feet from the staked centerline are as follows:

1. Approximately mileposts 223.47 to 223.52. This area lies within parcel VA-MO-5526.
2. Approximately mileposts 224.65 to 224.69. This area lies within parcel VA-MO-5529.
3. Approximately mileposts 224.93 to 225.05. This area also lies within parcel VA-MO-5529.
4. Approximately mileposts 225.37 to 225.41. This area lies within parcel VA-MO-5530.
5. Approximately mileposts 225.72 to 225.8. This area also lies within parcel VA-MO-5530.
6. Approximately mileposts 225.83 to 225.89. This area also lies within parcel VA-MO-5530.
7. Approximately mileposts 226.12 to 226.21. This area also lies within parcel VA-MO-5532.

3.3 Inversion Modeling

The resistivity measurements on a section are called apparent resistivities. They may differ from the actual resistivities because of passage through inhomogeneous materials and the distance of travel through the media. Therefore, linear inversion techniques were applied to the data. Linear inversion modeling fits the measured data in the resistivity section to an earth model that may represent the actual resistivities in the section. The inversion modeling is completed by calculating apparent resistivity from the earth model for comparison to the measured data. If the comparison is within reasonable limits, the earth model can be accepted as an approximation of subsurface conditions. Details of the inversion process may be found in Lines and Treitel (1984), Loke and Barker (1995), and Loke and Barker (1996).

3.4 Primary Factors Affecting Resistivity of Earth Materials

The primary factors affecting the resistivity of earth materials are porosity, water saturation, clay content, and ionic strength of the pore water. In general, the minerals making up soils and rock do not readily conduct electric current and thus most of the current flow takes place through the material's pore water. The Mountain Valley geophysical experts consider a notable contrast in resistivity over a short distance to be of interest in the context of an ER study. The ER contrasts may or may not suggest a notable karst feature is present, or that additional study is warranted. Evaluation of ER response data requires significant expertise possessed by the Mountain Valley geophysical experts.

The relatively high levels of pore water in soils and other unconsolidated materials tend to give low resistivity values for the shallow subsurface. Soil typically encountered in karst terrain is usually clay-rich with a high moisture retention capacity, and in this study the term "moist soil" does not connote a phreatic surface or saturated conditions, but highlights that fine-grained, clay rich soils that retain moisture demonstrate low ER. Karst terrain is characterized by enhanced and preferential weathering. Zones of very low resistivity soil can be present as residuum from rock dissolution or transported by percolating surface water, and these soils tend to accumulate in subsurface karst features including preferential flow paths through overburden, or in highly weathered bedrock.

Soils in many portions of the Study Area may contain unconsolidated deposits of chemically resistant chert cobbles that weathered out of the carbonate rock and remain as overburden. The presence of abundant high-resistivity chert cobbles in soils overlying bedrock often makes evaluation of the soil-bedrock interface more difficult.

Rock contains significantly less pore water than soils resulting in generally higher resistivity values.

Karst voids in the subsurface can be filled with air, water, soil, or any combination of these. Because water and moist soil conduct electrical current more readily than the surrounding bedrock, karst voids filled with these materials tend to be expressed as low-resistivity features. Conversely, air is an insulator, so air-filled voids are expressed in theory as high-resistivity features in contrast to the surrounding bedrock.

Potential soil cutters or sinkhole throats are typically expressed by a large contrast in resistivity data (i.e., low resistivity data are shown as a narrow or abrupt variation to a relatively higher resistivity zone over a relatively short length of the survey). This result appears in graphical presentations of the ER data as prominent “gaps” in the high resistivity data (usually evaluated as bedrock). These low resistivity “gaps” are evaluated to be clay-rich soil with high moisture retention capacity (i.e., residuum or raveled soils, or some combination of both) extending vertically downward and deeper into the formation. These may lead to more developed open voids deeper in the bedrock, or just diffuse into the formation matrix. The relatively higher resistivity zones may be bedrock (variably weathered), or overburden. Soils within the throat of a sinkhole are typically significantly lower in resistivity than the surrounding overburden due to an abundance of fines (e.g., clay) and a resulting higher moisture retention capacity. The soil in-fill may be residuum derived from the relatively insoluble byproducts of carbonate weathering, or raveled fines transported into the throat by percolating surface water (i.e., a result of surface water infiltration raveling soil downward into the throat).

If low-resistivity gaps are observed, but no isolated features indicative of voids are evaluated to be present at depth beneath a low-resistivity gap, then the gap is evaluated to be an isolated, soil-filled slot in the bedrock surface, commonly referred to as a soil cutter. Conversely, if resistivity data at depth in the bedrock zone is evaluated as a potential void but did not directly underlie vertical breaks or gaps in the bedrock surface where soils may migrate vertically, soil subsidence or collapse into those deeper possible voids is considered unlikely due to the apparent presence of intact bedrock above the potential void.

4.0 Electrical Resistivity Imaging Results

The results and evaluations of the resistivity data collected along or near to the mapped or staked pipeline centerline are presented in Figures 12 through 14. Throughout each of the centerline resistivity sections, a dark grey line representing the installed pipeline at a depth of 10 feet below the existing ground surface is projected onto the resistivity sections for illustrative purposes.

4.1 General Evaluations

ER imaging methods comprise remote sensing geophysical data collection and processing and results derived from the study are evaluated through visual inspection of graphical data presentation. The ER data are presented in this study in the form of graphical 2-dimensional cross sections where pre-selected ranges of ER response are contoured in the cross section, and the area between the contour lines are colored. Figures 12 through 14 are overview cross sections, showing the entire Study Area broken into cross section segments that progress through the three figures. The figures are designed to illustrate the overall ER responses in the Study Area. More detailed figures are provided later at appropriate scale to allow the reader to observe more details in the ER distributions.

The evaluations of the ER responses were made by Mountain Valley's geophysical experts, possessing over 40 years of experience in subsurface geophysical data collection and evaluation in karst terrain.

Note that the cross sections (Figure 12 through 14, and the more detailed cross sections to follow) display the processed ER data in an industry-standard format showing 2-dimensional cross sections along the electrode array, with ER response shown in ohm-meters and contoured using colors (blue is low resistivity, red is high resistivity). As noted above, this is similar to a "heat map", where high response to whatever data are being illustrated is typically shown in red (hot), and low response in blue (cool).

A legend is presented for each ER response cross section (i.e., Figures 12 through 14, and Figures 16 through 30) that correlates the ER response value in ohm-meters to a prescribed color range.

As the colors in the cross sections change at any given location from blue to green to yellow, this represents increasing resistivity that is evaluated to be soil, overburden or highly weathered rock. Importantly, the blue or light green contours in the cross sections do not necessarily represent free-phase water or saturated conditions, but are evaluated through experience with karst terrain, and the desktop and field work completed for the Karst Hazards Assessment to represent clay-rich fine grain soil with high moisture retention capacity, which more readily transmits electrical current. Alternatively, ER color contours that transition from yellow to red represents high-resistivity results that are evaluated to be rocky overburden or intact less-weathered bedrock. (there are many factors that control Earth material resistivity, as discussed above).

The graphical representations were reviewed for high contrasts in resistivity were observed. As described above, a vertical zone of low-resistivity responses representing a “gap” in high resistivity responses are evaluated to be indicative of soil-filled cutter or possibly throat, depending upon ER response below these features. Where vertically uninterrupted low-resistivity responses were observed, these features were evaluated to represents possible soil-filled sinkhole throats. The ER data were also evaluated for the possible presence of open voids within the carbonate bedrock.

The ER study was not specifically designed to identify and quantify the depth to bedrock. If that were the objective, other remote sensing techniques would be employed. The ER study, as discussed above, was designed to evaluate the subsurface (primarily to depths of 30 to 50 feet below ground) for indications of sensitive or notable karst features. Nonetheless, the bedrock interface can be estimated from ER data when an abrupt vertical transition in resistivity values are observed. A transition from low resistivities (evaluated to be soil overburden) to high values (evaluated to be bedrock) can be evaluated as the soil-bedrock interface, which typically occurs at resistivity values beginning in the range of 100 to 150 ohm-meters and sharply increases with minor increases in depth. This range of resistivity (i.e., evaluated overburden-bedrock interface) is represented in each of the resistivity cross sections by a dotted black line. This is also observed by color transitions in the cross sections. Resistivity values at approximately 150 ohm-meters and less (evaluated to be clayey or moist soil) are blue to light green in the cross sections. Where resistivity values increase greater than 150 ohm-meters (evaluated to be overburden or bedrock) the color contours transition into dark green through yellow and orange. .

In many locations, high resistivity layers are present at or very near the ground surface underlain by layers of lower resistivities. Typically, these near-surface high resistivities are evaluated as rocky soil or overburden, or relatively thick deposits of unconsolidated chert cobbles. Chert is weather-resistant silica that can occur in carbonate bedrock and often remains as residuum after the carbonate mineralogy dissolves away. Examples of this are observed in Figure 12 beneath mileposts 222.1 to 222.2 and beneath milepost 223.1. The Beekmantown Formation typically contains relatively abundant amounts of chert relative to the other formations present in the Study Area, but chert can be present in varying degrees in most of the rock formations present in the Study Area.

In locations where high-resistivity responses are observed extending continuously from the near-surface to depth, the shallow high resistivities may be evaluated as shallow bedrock. Rocky soils immediately overlying bedrock may mask the actual bedrock interface (i.e., the contrast in resistivities may not be great enough to observe distinct features).

Overall, inspection of Figures 12 through 14 indicate that the resistivity data display a highly irregular bedrock surface that is typical of karst terrain. The bedrock interface is characterized by alternating deep soil cutters (blue to light green) and shallow bedrock pinnacles (yellow to red) near the ground surface in Figures 12 through 14.

Additionally, several isolated high-resistivity features (generally greater than approximately 50,000 ohm-meters shown as deeper red to brown surrounded by red; Figures 12 through 14) were observed that may be evaluated as possible air-filled voids within the bedrock. These features demonstrate a 5-fold or more increase in resistivity, within a fairly well defined location. For these features, review of Figures 12 through14 show that high resistivity values are observed at depths of approximately 50 feet below the ground surface, overlain by a substantial thickness of continuous and relatively high-resistivity zones that are likely bedrock. These high-resistivity features in what is evaluated to be bedrock are well below the depth of the proposed construction excavation. Many areas also exist where similarly high resistivity values are observed across broad portions of the resistivity section, both laterally and vertically. These broad high-resistivity areas are generally evaluated as thick intervals of high-resistivity bedrock such as dolomite, chert-bearing strata, or sandstone units.

From approximately milepost 221.75 to 222.85, the resistivity data are characterized by a predominance of low-resistivity discontinuities within evaluated bedrock. This portion of the alignment is proximal to the Pulaski thrust fault, such that low-resistivity discontinuities identified in the bedrock zone are evaluated to represent closely spaced bedrock fractures. Such closely spaced fractures create abundant pathways for groundwater infiltration into the bedrock structure, increasing susceptibility for solution weathering of the carbonate bedrock along those fractures. No additional ER imaging was completed between mileposts 221.75 to 222.85.

4.2 Detailed Discussion of Specific ER Features

The Mountain Valley geophysical experts, having a cumulative 40 years of combined experience in geophysical evaluationsof karst terrain, provided expert options in consultation with the Mountain Valley Karst Specialist Team, to identify 15 locations along the initial centerline data where additional study was warranted (Figure 15).

No high resistivity zones were observed within the excavation design depth indicating that no open voids (e.g., caves) are present at a depth that could be intercepted by trenching. In fact, high resistivity zones that may represent open air-filled voids in bedrock are as deep as 80 feet and all have substantial (tens of feet) of bedrock (evaluated from resistivity) between the proposed excavation bottom and the possible void.

The 15 locations selected for additional study demonstrated high contrasts (i.e., abrupt changes) in resistivities over a relatively short distance. The ER contrasts were low-resistivity responses within broader high resistivity material. Such ER results are generally evaluated to be soil (i.e., transported overburden or residual from carbonate weathering, or both) that is filling space in surrounding weathered (karst) bedrock. These features are evaluated to be either soil cutters or buried soil filled sinkhole throats (discussed below).

The following discussion describes each of the 15 locations where possible karst features of interest were observed in the centerline resistivity data and where offset resistivity data were subsequently collected (Figure 15). Figures 16 through 30 present the centerline data and offset data at each of the 15 locations, with the cross sections and inset maps designed to illustrate more details about the ER response, ER study lines for each specific area, and mapped surface features.

Note that each figure includes a legend that explains the color distributions for each of the resistivity cross sections. Blue is clay-rich residual soil with high moisture retention capacity. Progressing through green is the transition from overburden to bedrock. Bedrock is assumed (based on analyst experience) to be represented by resistivity values greater than 150 ohm-meters. Progressing from yellow to red typically represents the transition to less weathered intact bedrock (i.e., resistivity likely ranges in the bedrock interface due to weathering). The deep red to brown resistivity (>10,000 ohm meters) is evaluated to represent air-filled voids in the intact bedrock. The proposed pipeline excavation is shown as a gray line approximately 10 feet below ground surface. The approximate evaluated overburden to bedrock interface is shown by the dotted line in each cross section.

The term “soil-filled void” is used in the ER study evaluation and is designed to connote that residual or transported (raveling) soil occupies a void in the carbonate bedrock. The void likely formed contemporaneously with the soil in-filling (e.g., comprised of residual insoluble components of the weathered rock and raveling of soil along the infiltration pathway that formed the void).

Between approximately milepost 223.27 and the southeastern margin of the Study Area (milepost 227.2), fifteen locations were identified which displayed ER characteristics consistent with possible karst features (Table 1, below; Figure 15). These areas were evaluated further by collecting additional resistivity data offset from the initial ER centerline data. Where feasible, an additional series of two resistivity lines were collected offset to the observed possible karst feature in the centerline data. The offset data facilitated the evaluation of the lateral extent and the nature of the possible karst features identified in the centerline data. In some of the locations of follow-up ER investigation, more than one discrete possible karst feature existed within the same vicinity in the centerline data, such that the follow-up resistivity data collection straddled and evaluated more than one discrete feature of interest. The locations of these 15 possible karst features are illustrated in plan view in Figure 15 by the red circles and by their approximate milepost locations in Table 1 below. The results of the offset data collected at these locations are illustrated in Figures 16 through 30, and are described in detail in the following section.

Table 1. List of 15 Possible Karst Features (See Figure 15 for Map Locations)

Feature Number	Approximate Milepost
1	223.27
2	223.4
3	223.5
4	223.68
5	223.8
6	223.93
7	224.52
8	224.6
9	224.69
10	224.87
11	224.98
12	225.46
13	225.98
14	226.27
15	226.63

4.2.1 Feature #1 - Milepost 223.27 (Figure 16)

In Figure 16, near Milepost 223.27 south of Mount Tabor Road, Feature #1 lies beneath electrodes 23-15 to 23-18, approximately 70 feet southwest of a sinkhole. This feature is evaluated as a soil-filled void in bedrock, with a potential sinkhole throat extending into it beneath electrode 23-18. The offset data collected at this location suggest that the conditions observed in the centerline ER response extend southwestward from the sinkhole observed at the ground surface.

4.2.2 Feature #2 - Milepost 223.4 (Figure 17)

In Figure 17, Feature #2 is characterized by a grouping of several low-resistivity features in the centerline data near the intersection of Lines 18 and 22, which are evaluated to be soil and overburden residuum from weathered carbonate bedrock. A sinkhole was observed approximately 40 feet east of milepost 223.4, in the vicinity of electrode 18-12 of the centerline data. The offset data reveal similar low-resistivity features at depth similar to what was observed in the centerline data, evaluated to be soil-filled, solution-enlarged voids. The portion of the centerline data immediately beneath the sinkhole (i.e., beneath electrode 18-12) reveals the possible throat of that sinkhole visible at the surface. Another possible sinkhole throat is evaluated in the centerline data beneath electrode 22-9. A similar but less pronounced possible sinkhole throat (e.g., low-resistivity ER response) is observed in the offset data beneath electrode 18/22n-15.

4.2.3 Feature #3 - Milepost 223.5 (Figure 18)

In Figure 18, Feature #3 is characterized by a low-resistivity materials (likely clayey soils) extending to approximately 50 feet below the ground surface. This is evaluated to represent a weathered zone with soil in-filling. This feature is immediately overlain by a narrow gap in the bedrock surface (beneath electrode 18-33, just northwest of milepost 223.5), which may represent a possible narrow sinkhole throat. Only one offset was feasible at this location due to the presence of dense briers. The offset data at this location are evaluated to represent a likely soil-filled slot (cutter) beneath electrode 1833s-20. This feature does not display any obvious throat-like characteristics extending into deeper voids. The “centerline” resistivity data were located north of the staked centerline, due to the presence of impassable dense briers along the staked centerline (impassable vegetation restricting the location of “centerline” data was discussed previously). The centerline and offset data bracket the proposed mapped and staked pipeline alignment.

4.2.4 Feature #4 - Milepost 223.7 (Figure 19)

In Figure 19, Feature #4 is characterized by a vertically extensive, soil-filled slot (cutter) extending to a depth of approximately 70 feet below ground, while adjacent high-resistivity data suggest a bedrock surface approximately 5 to 15 feet below ground. At depth, this feature apparently undercuts the adjacent bedrock. The offset data do not display apparent soil-filled voids at depth and this feature may represent a deep soil cutter

4.2.5 Feature #5 - Milepost 223.8 (Figure 20)

In Figure 20, Feature #5 is characterized by a pair of evaluated deep soil slots (cutters) extending downward into the bedrock surface north and south of milepost 223.8. Beneath electrode 20-20 (north of milepost 223.8), the evaluated cutter extends to approximately 35 feet below ground, without any indication of deeper voids beneath. Beneath electrode 20-25.5 (south of milepost 223.8), the evaluated cutter extends to approximately 40 feet below the ground surface, also with no void-like features beneath. The western offset profile (“2023w”) suggests the possibility of a soil-filled sinkhole throat beneath electrode 2023w-18.5.

4.2.6 Feature #6 - Milepost 223.9 (Figure 21)

In Figure 21, Feature #6 is characterized by a zone of evaluated deep soil (beneath electrodes 20-60 to 20-67) measuring approximately 40 feet in depth, and by the presence of multiple low-resistivity features within the evaluated bedrock zone which likely represent solutionally enlarged, soil-filled zones (these features are evaluated based on the results of the Karst Hazards Assessment to be above the base level groundwater elevation). The offset data bears similar characteristics, with evaluated soil-filled zones observed beneath the evaluated bedrock surface. Additionally, in the offset line “2065w”, a possible narrow sinkhole throat is observed beneath electrode 2065w-18. Another possible sinkhole throat is evaluated at the end of the line (beneath electrode 2065w-27). A sinkhole approximately five feet in diameter was observed near the electrode 2065w-27 location with characteristics of being a cover collapse sinkhole.

4.2.7 Feature #7 - Milepost 224.5 (Figure 22)

In Figure 22, the proposed alignment changes direction from south-southeast to east-southeast near milepost 224.52, which is also reflected by the intersections of ER Lines 15 and 16. Beneath electrodes 16-1 to 16-5 in the centerline data, the ER data indicate relatively well defined low resistivity zone extending greater than 50 feet below ground, with relatively high resistivity zones bounding to the northwest and southeast (Feature #7). The higher resistivity zones (yellow to red;

Figure 22) are evaluated to be intact bedrock, and the low resistivity (blue to green; Figure 22) is evaluated to be an area of highly weathered bedrock. The offset ER data for Line “15/16ns” reveal a possible deeper soil-filled void beneath electrode 15_16ns-20, with a possible sinkhole throat extending diagonally downward into it from electrode 15_16ns-12. It should be noted that electrode 15_16ns-12 does not lie on the proposed alignment, but instead lies approximately 36 feet south of the alignment. The offset ER data for Line “15/16ew” reveal an evaluated zone of deep soil between electrodes 15_16ew-10 and 15_16ew-15 extending to an approximate depth of 60 feet. This deep soil zone bears similar characteristics to the partial feature imaged beneath electrodes 16-1 to 16-5 in the centerline data.

4.2.8 Feature #8 - Milepost 224.6 (Figure 23)

In Figure 23, the “centerline” data were collected approximately 35 feet north of the staked centerline (as discussed earlier in this report). Feature #8, located beneath electrode 15-89, is characterized by a vertical low-resistivity zone extending downward into the bedrock zone and undercutting an evaluated bedrock ledge, resulting in what is evaluated as a soil-filled void. Offset data were collected along the centerline (line 1588a) and approximately 25 feet south of the centerline (1588s). Along the centerline (offset resistivity line “1588a”) the deeper evaluated soil-filled void persists, but the vertical connectivity to surface soils (possible sinkhole throat) appears diminished from that which is seen in the original data collected north of the staked centerline.

4.2.9 Feature #9 - Milepost 225.7 (Figure 24)

In Figure 24, the “centerline” data were collected approximately 25 feet north of the staked centerline (as discussed previously in this report). Feature #9, located beneath electrode 15-57, is characterized by a vertical low-resistivity feature evaluated as a deep (approximately 60 feet) soil slot with no discernible voids below where soils may migrate. Two offset lines were collected south of the “centerline” data: Line “1557a” located near the staked centerline and line 1557s, located approximately 25 feet south of the staked centerline. The offset data reveal likely solutional weathering in the same vicinity as Feature 9 in Line 15, with a possible soil-filled void evaluated beneath electrode 15-57a-13 and soil-filled slot beneath electrode 15-57s-10.

4.2.10 Feature #10 - Milepost 224.9 (Figure 25)

In Figure 25, the "centerline" data were collected approximately 20 feet north of the staked centerline (as discussed earlier in this report). Feature #10, located beneath electrode 14-160, is characterized by a possible sinkhole throat extending downward into an evaluated soil-filled void. Both offset resistivity lines exhibit similar characteristics, with offset Line 14-160s (south of the staked centerline) exhibiting the most prominent feature characteristic of a soil-filled void and sinkhole throat extending into it.

4.2.11 Feature #11 - Milepost 225.0 (Figure 26)

In Figure 26, the "centerline" data were collected approximately 30 feet north of the staked centerline (as discussed previously in this report). Feature #11, located near electrode 14-125, is characterized by a pair of low-resistivity features indicative of possible soil-filled throats extending downward toward likely soil-filled zones within the bedrock. The westernmost of these two features, beneath electrode 14-127, is connected to a deeper evaluated soil-filled void by a dipping zone of slightly lower resistivity values (approximately 400 ohm-meters; yellow color contours) than those immediately above and below. The easternmost of these two features, beneath electrode 14-122, is characterized by vertically extensive lower resistivities indicative of moist or clayey soils to a depth of approximately 50 feet. Both offset resistivity lines 14-122a and 14-122s reveal similar possible throats (beneath electrodes 14-122a-12 and 14-122s-6) as that which is seen beneath electrode 14-122.

4.2.12 Feature #12 - Milepost 225.45 (Figure 27)

In Figure 27, Feature #12 is comprised of a pair of low-resistivity responses that are evaluated to be a potential sinkhole throat and a soil slot (or cutter) beneath electrodes 11-31 and 12-7, respectively. Both offset resistivity lines (Lines 11E and 11W) reveal vertically extensive low-resistivity zones in the vicinity of Feature 12 that are indicative of solutional weathering. Possible throats are evaluated both in the east and west offset resistivity lines.

4.2.13 Feature #13 - Milepost 226.0 (Figure 28)

In Figure 28, the portion of Line 8 containing Feature #13 lies approximately 30 feet southwest of the staked centerline (as discussed previously). Feature #13 is characterized by two discrete features in the ER response: 1) a low-resistivity response evaluated to be a soil-filled void underlying what is evaluated to be enhanced secondary bedrock porosity and a potential sinkhole throat (beneath electrode 8-8); 2) a vertical low-resistivity zone evaluated to be a possible sinkhole throat along the margin of the resistivity data set (beneath electrode 8-3). To evaluate the possibility of these evaluated features extending beneath the staked centerline, offset Line 8A was collected along the staked centerline near milepost 226.0. Offset Line 8A reveals the presence of two vertically extensive low-resistivity zones suggestive of possible sinkhole throats (beneath electrodes 8A-12 and 8A-22).

4.2.14 Feature #14 - Milepost 226.3 (Figure 29)

In Figure 29, Feature #14 is characterized by a possible soil-filled void beneath electrode 1-13 with a narrow potential throat extending downward into it. In the east offset line (Line "113e"), the ER data demonstrate relatively high resistivity material near the ground surface (possibly overburden with abundant chert cobbles) between electrodes 113e-10 and 113e-22 that is underlain by lower-resistivity material evaluated to be soil infilling of solutionally weathered bedrock. This feature measures approximately 120 feet in width, and is evaluated to be infilled with soil/overburden measuring approximately 50 to 65 feet in thickness, with the upper 10 to 25 feet likely comprised of high-resistivity chert cobbles. In contrast, the evaluated soil/overburden thickness along the north and south margins of Line 113e is approximately 10 to 12 feet. The west offset line (Line "113w") does not reveal a lateral continuation of the Feature #14 in a westerly direction.

4.2.15 Feature #15 - Milepost 226.63 (Figure 30)

In Figure 30, Feature #15 is characterized by an evaluated soil-filled void beneath electrode 2-46.5 (low-resistivity zone; blue color contours), with a "bridge" of mid-range resistivities suggestive of weathered rock overlying it. While the bedrock surface at this location is not characterized by a prominent gap suggestive of a possible sinkhole throat, the presence of a sinkhole just east of the staked centerline (see inset map in Figure 30) warranted further evaluation of this feature. In both of the offset lines (Lines “247e” and “247w”), somewhat similar features are observed in the vicinity of Feature #15. In the eastern offset (247e), mid-range resistivities are observed beneath electrode 247e-9 extending vertically downward into the evaluated bedrock, suggesting fractured or weathered rock, but no discernible throat or deeper voids are observed. In the western offset (247w), mid-range resistivity values are observed which bear the characteristics of a possible throat overlying a possible soil-filled void. An isolated high-resistivity feature (dark red contour colors >10,000 ohm-meters) suggests a possible air-filled void is present approximately 70 feet beneath electrode 2-57 in the centerline data. ER data suggest that continuous bedrock is present above the possible air-filled void, such that subsidence or collapse into the possible void is unlikely.

5.0 Conclusions AND recommendations

An overall description of the ER results was presented in Section 4.1 (Figures 12 through 14). The ER indicated an irregular bedrock surface, which is common in karst terrain of the Valley and Ridge geologic province, with the evaluated depth to bedrock ranging from the ground surface (outcrop) to greater than 50 feet.

Detailed discussions of the 15 areas selected for the follow-up ER data collection (see Table 1 and Figure 15), including graphical data presentation and descriptive evaluation was presented in Section 4.2.

Isolated high-resistivity zones that may represent air-filled voids were observed at substantial depth in the evaluated bedrock zone. These features are well below the limit of excavation for the Project, and construction will not encounter these potential voids. The ER data further suggest that these possible air-filled voids are overlain by a relatively thick section of bedrock overburden, and thus appear to have low susceptibility for promoting ground subsidence or cover collapse sinkhole formation. Based on the ER study, excavation for pipeline construction is not anticipated to encounter open voids.

Data analysis conducted by the Mountain Valley geophysical experts identified 15 areas that demonstrated narrow or abrupt low resistivity contrast to surrounding higher-resistivity materials. These low resistivity "gaps" are evaluated to be clay-rich soil with high moisture retention capacity extending vertically downward as a soil cutter or sinkhole throat.

Of the 15 locations identified as possible karst features (Section 4.2), five features (#3, #4, #8, #9, #14) were evaluated to be soil-filled cutters, or relatively limited soil-filled sinkhole throats. The remaining ten features were evaluated to be vertically extensive soil-filled throats. The ER results demonstrated features that are generally consistent with karst terrain.

Based on the ER study and field observations, these sinkhole throats are typically narrow and relatively shallow, rarely open to surface, and unlikely to present construction related issues given BMPs and construction inspection to be implemented by Mountain Valley.

5.1 Recommendations

The ER study results indicate soil filled cutters and possible soil-filled sinkhole throats are karst features of concern along the proposed alignment that traverses the Study Area. The general locations of these features are presented in Table 1, and shown in Figure 15.

Mountain Valley has prepared a Karst Mitigation Plan to guide avoidance and mitigation measures where the proposed alignment traverses karst terrain, including but not limited to the Mount Tabor area. The Karst Mitigation Plan specifies karst features inspection and monitoring procedures, as well as avoidance and mitigation measures. Mountain Valley has also prepared a Project-specific Erosion and Sediment Control Plan, with a karst sub-section designed to support construction in karst terrain. Mountain Valley will deploy the Karst Specialist Team as inspectors during all phases of construction in karst terrain. The Karst Specialist Team will ensure that the recommendations and procedures in the Karst Mitigation Plan and the Erosion and Sediment Control Plan, are followed to protect karst resources, and reduce karst hazards to pipeline construction and operation to the maximum extent practicable.

It is recommended that in addition to the karst avoidance and mitigation procedures identified in the Karst Mitigation Plan and Erosion and Sediment Control Plan for karst terrain, that the Karst Specialist Team inspectors refer to this ER study during all phases of construction in the Mount Tabor area. The 15 areas of concern identified in this report (Table 1; Figure 15) will require additional vigilance by the Karst Specialist Team during all phases of construction in the vicinity of these 15 locations. It is recommended that Mountain Valley be prepared to make minor adjustments within the approved right-of-way where possible to avoid any or all of these areas (as a matter of precaution). In addition, the limit of disturbance and local karst features (e.g., sinkholes) should be monitored at these 15 locations to provide early warning of potential soil raveling.

With these precautions in place, and based on the Karst Hazards Assessment results with support from this ER study, Mountain Valley does not expect a significant increase in risks associated with pipeline construction in karst terrain between mileposts 221.8 and 227.2 of the proposed route.

6.0 Limitations

This study was conducted by qualified geologists, including registered professional geologists, with over 40 years of combined experience in the collection, processing, and evaluation of geophysical data. ER imaging methods comprise remote sensing geophysical data collection and processing. The scope of this study provided thorough geophysical data coverage across the Study Area, where accessible. No guarantees or warranties are expressed or implied in connection with this study or report. Conclusions presented are based upon a review of available information, the results of our field studies, and/or professional judgment. This report makes no predictions regarding the likelihood, rate, or magnitude of potential ground subsidence associated with any evaluated karst features. Evaluated karst features described in this report are considered those areas that are relatively susceptible to subsidence or cover collapse by natural processes or ground disturbance related to general construction.

7.0 References

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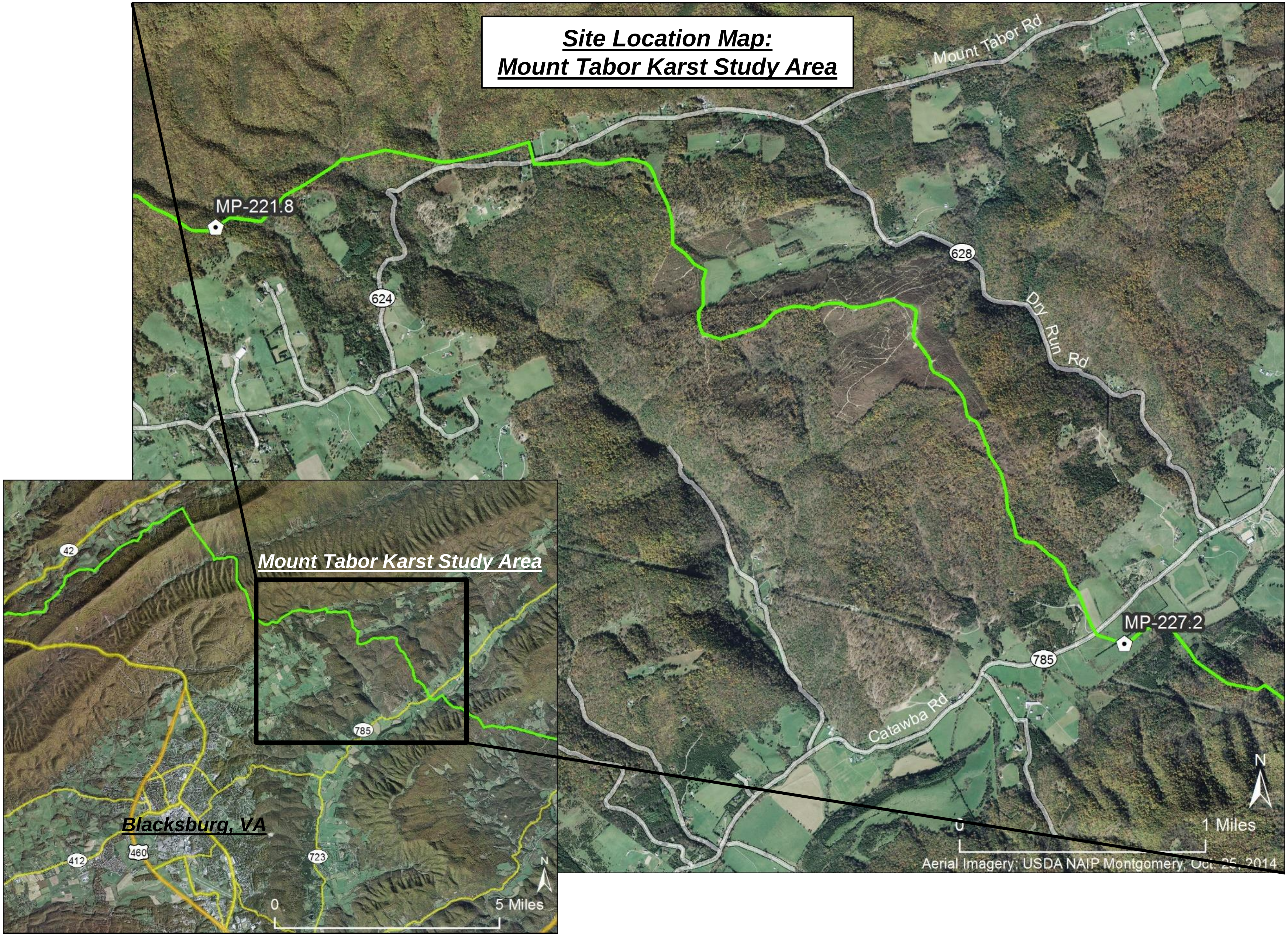
8.0 FIGURES



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Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
Mount Tabor Karst Area
Blacksburg, VA
DAA Project Number: B14188B-02

FIGURE 1

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FIGURE
2

Mountain Valley Pipeline Project

Mountain Valley PIPELINE

Figure 3
Geologic Map of the Study Area

11-18-16

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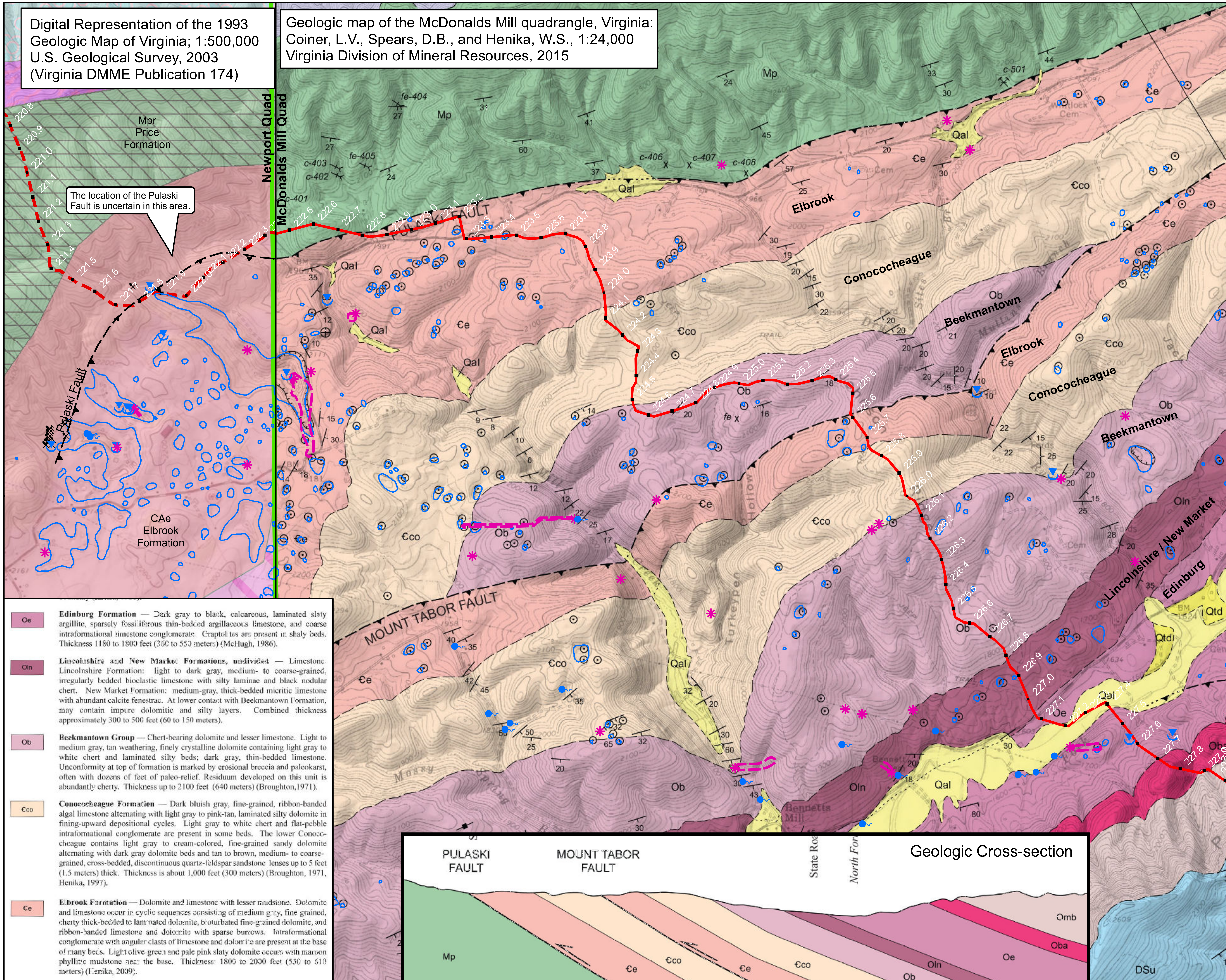
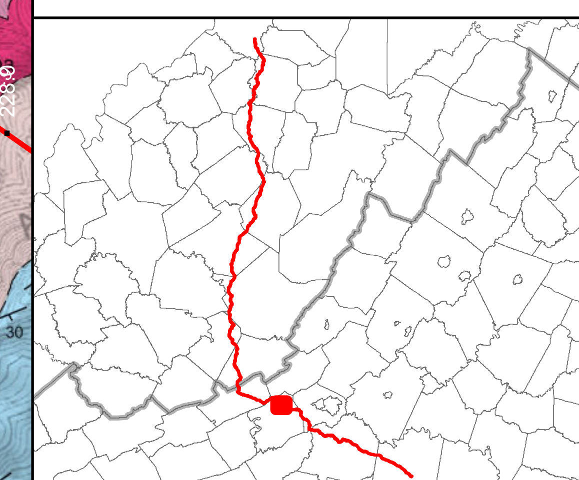


Legend

- MVP October 2016 Proposed Route with Mile Posts
- Cave
- Spring
- Swallet
- Known Cave Extent
- Sinkholes VaDMME
- Sinkholes, McDonalds Mill Geologic Quad



Sinkholes: Publication 083: Selected Karst Features of the Central Valley and Ridge Province, Virginia. 1:250,000-scale map and text. D. A. Hubbard. Virginia Department of Mines Minerals and Energy, 1988. Digital version 2012 Va DMME.

Oe	**Edinburg Formation** — Dark gray to black, calcareous, laminated slaty argillite, sparsely fossiliferous thin-bedded argillaceous limestone, and coarse intraformational limestone conglomerate. Graptolites are present in shaly beds. Thickness 1180 to 1800 feet (360 to 550 meters) (McHugh, 1986).
Oln	**Lincolnshire and New Market Formations, undivided** — Limestone. Lincolnshire Formation: light to dark gray, medium- to coarse-grained, irregularly bedded bioclastic limestone with silty laminae and black nodular chert. New Market Formation: medium-gray, thick-bedded micritic limestone with abundant calcite fenestrae. At lower contact with Beekmantown Formation, may contain impure dolomitic and silty layers. Combined thickness approximately 300 to 500 feet (60 to 150 meters).
Ob	**Beekmantown Group** — Chert-bearing dolomite and lesser limestone. Light to medium gray, tan weathering, finely crystalline dolomite containing light gray to white chert and laminated silty beds; dark gray, thin-bedded limestone. Unconformity at top of formation is marked by erosional breccia and paleokarst, often with dozens of feet of paleo-relief. Residuum developed on this unit is abundantly cherty. Thickness up to 2100 feet (640 meters) (Broughton, 1971).
Ꞓco	**Conococheague Formation** — Dark bluish gray, fine-grained, ribbon-banded algal limestone alternating with light gray to pink-tan, laminated silty dolomite in fining-upward depositional cycles. Light gray to white chert and flat-pebble intraformational conglomerate are present in some beds. The lower Conococheague contains light gray to cream-colored, fine-grained sandy dolomite alternating with dark gray dolomite beds and tan to brown, medium- to coarse-grained, cross-bedded, discontinuous quartz-feldspar sandstone lenses up to 5 feet (1.5 meters) thick. Thickness is about 1,000 feet (300 meters) (Broughton, 1971, Henika, 1997).
Ꞓe	**Elbrook Formation** — Dolomite and limestone with lesser mudstone. Dolomite and limestone occur in cyclic sequences consisting of medium gray, fine grained, cherty thick-bedded to laminated dolomite, bioturbated fine-grained dolomite, and ribbon-banded limestone and dolomite with sparse burrows. Intraformational conglomerate with angular clasts of limestone and dolomite are present at the base of many beds. Light olive-green and pale pink slaty dolomite occurs with maroon phyllitic mudstone near the base. Thickness: 1800 to 2000 feet (550 to 610 meters) (Henika, 2009).

N 1:24,000 NAD 1983 UTM 17N 0 2,000 4,000 Feet

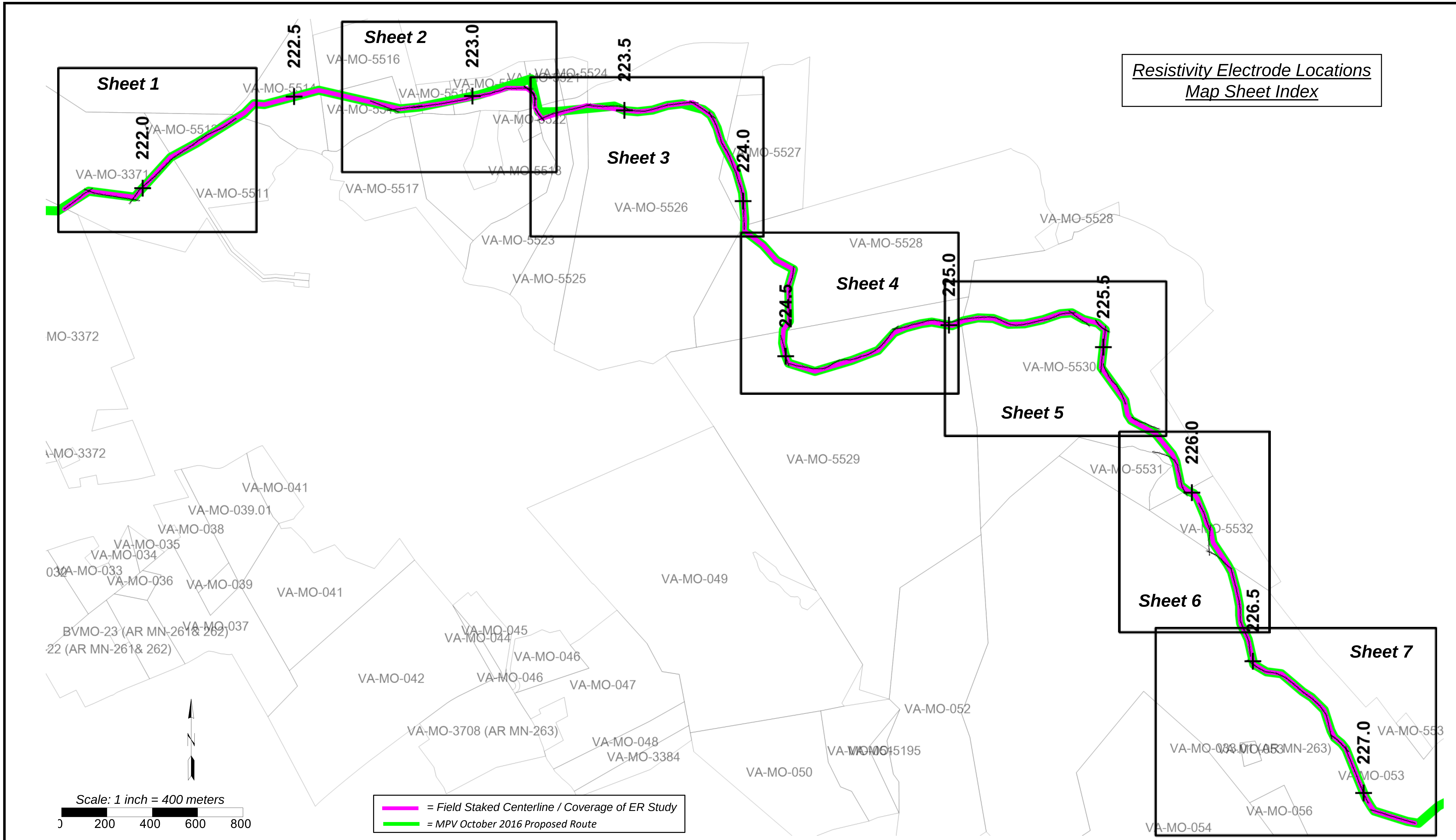


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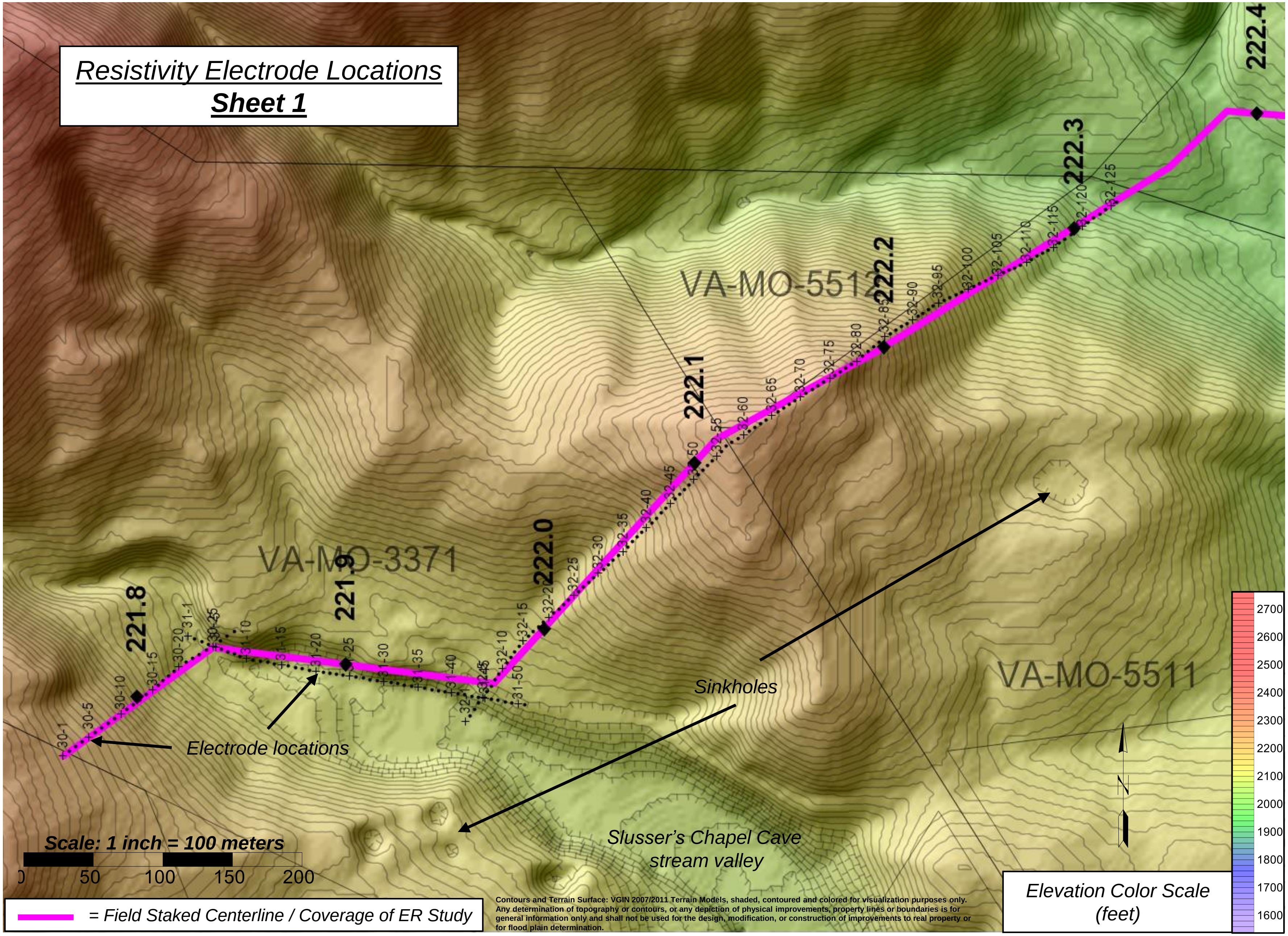
FIGURE
4



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Blacksburg, VA
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FIGURE 5

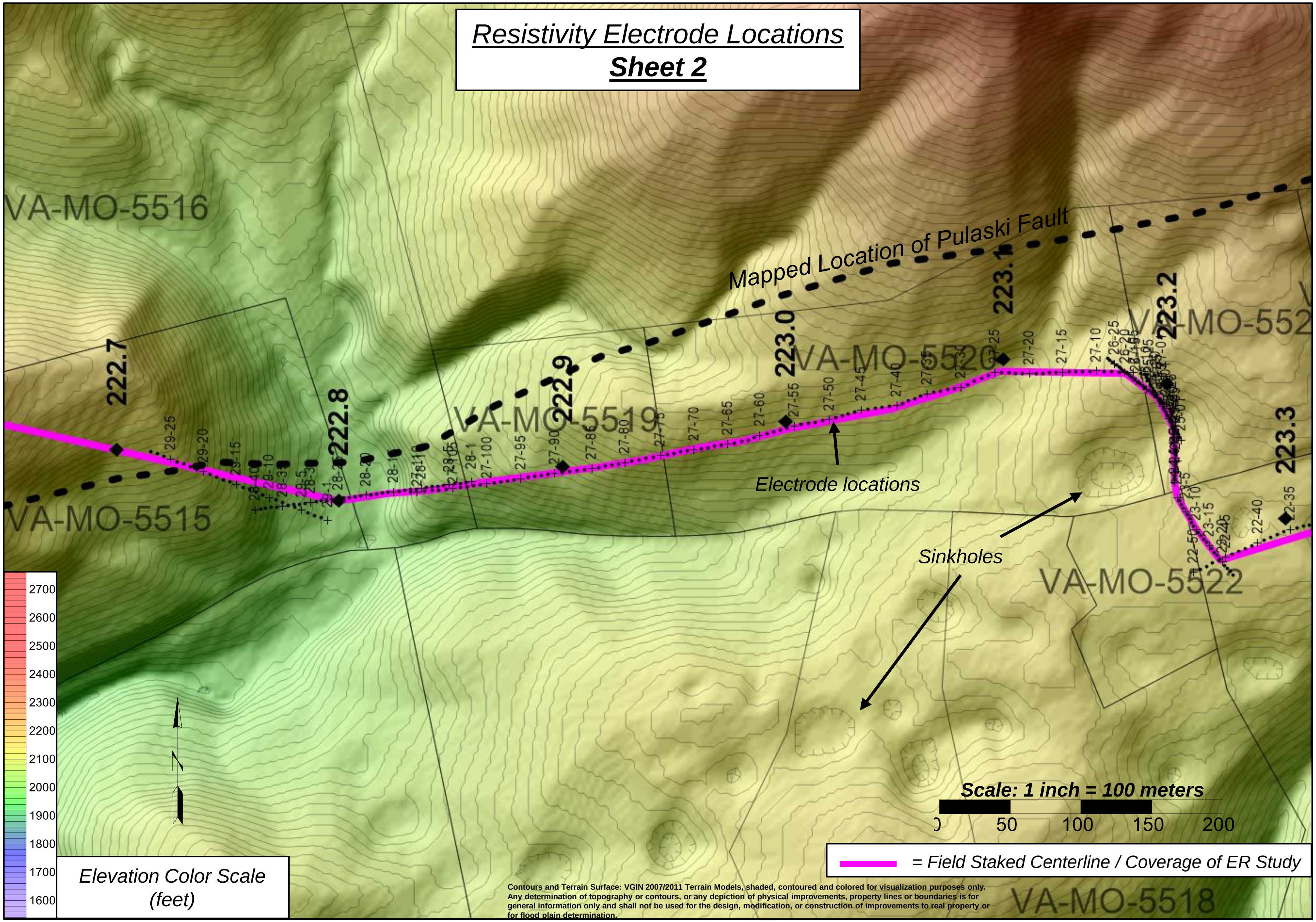

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FIGURE
6

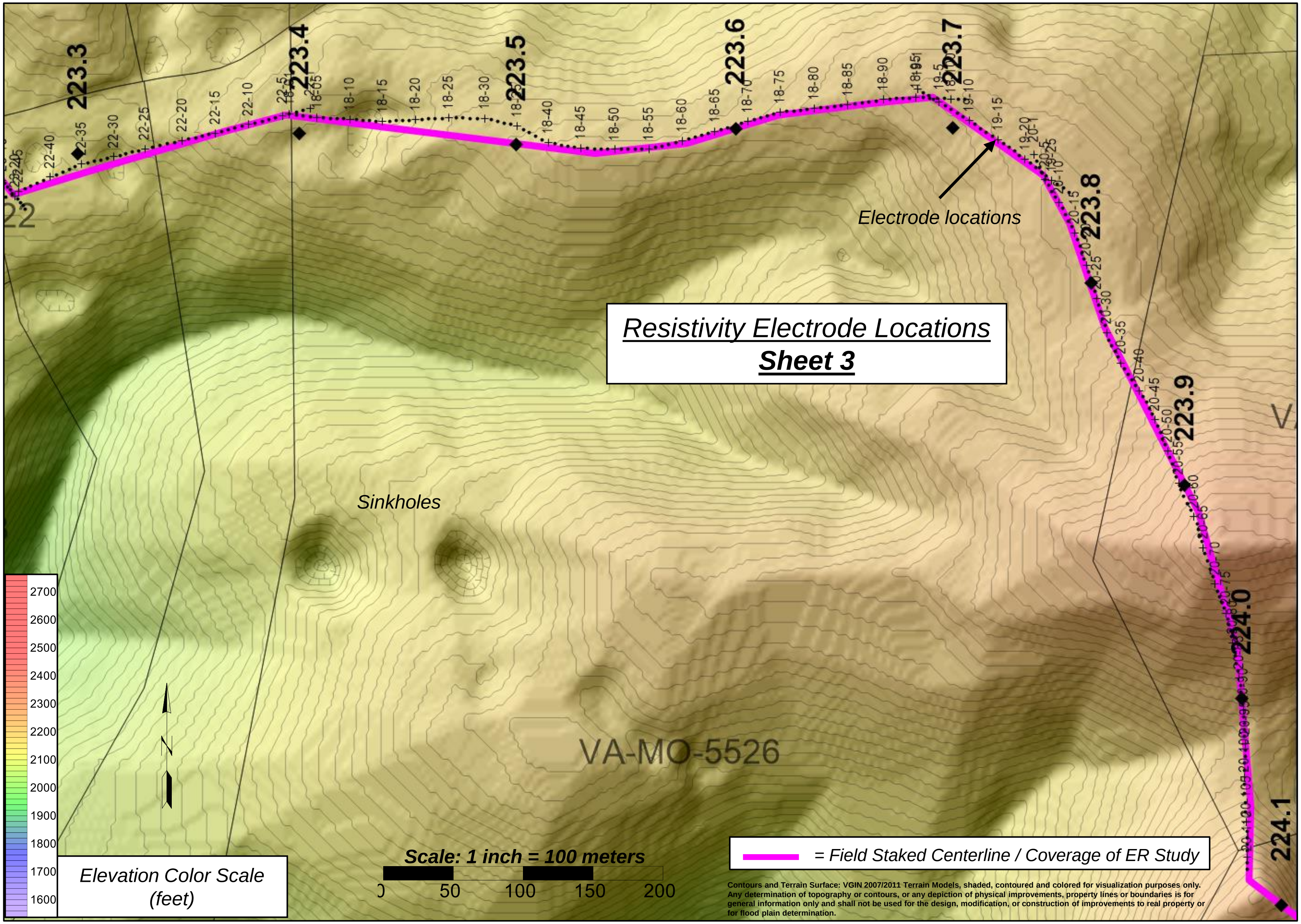

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FIGURE 7

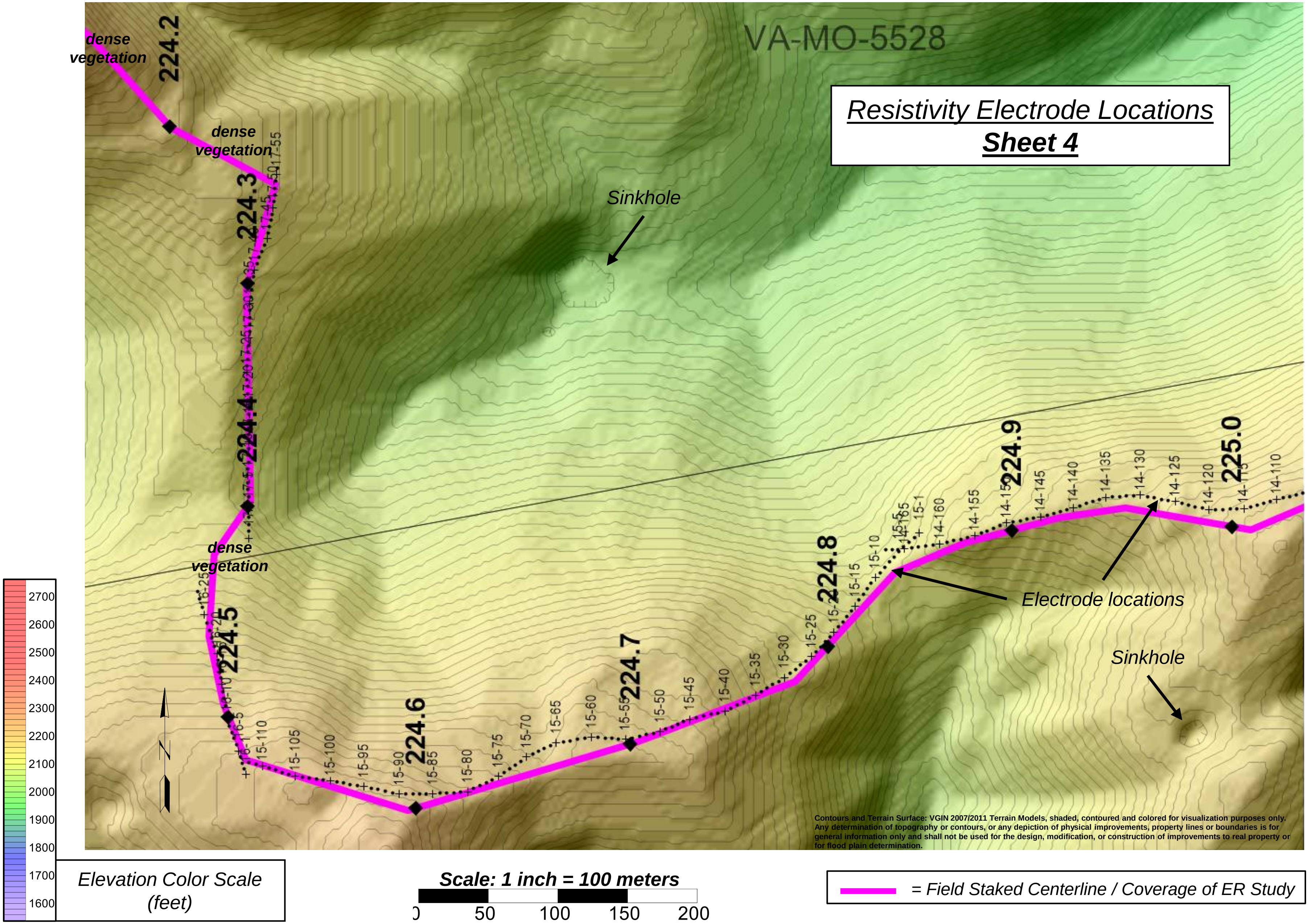

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FIGURE 8

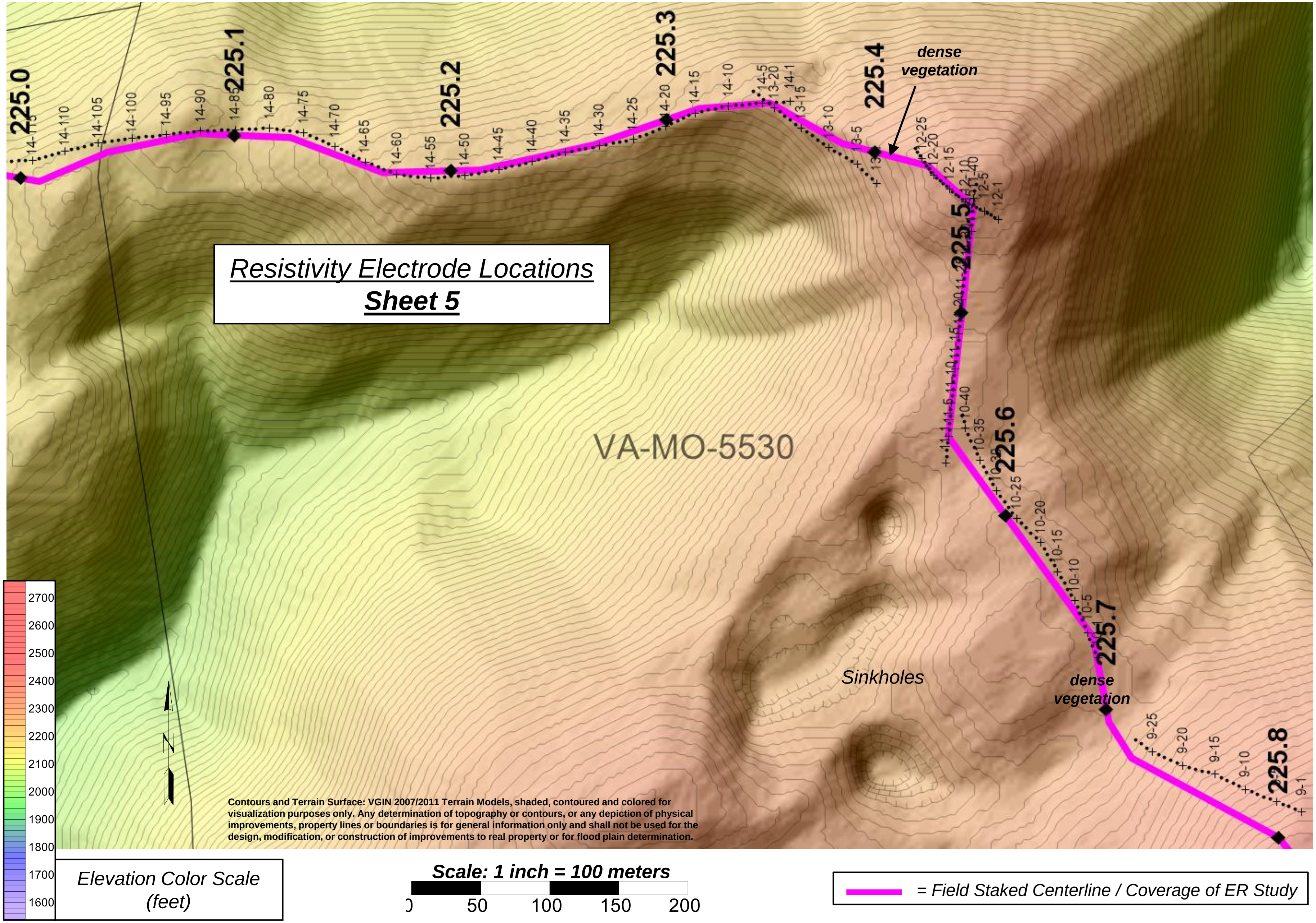

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FIGURE 9

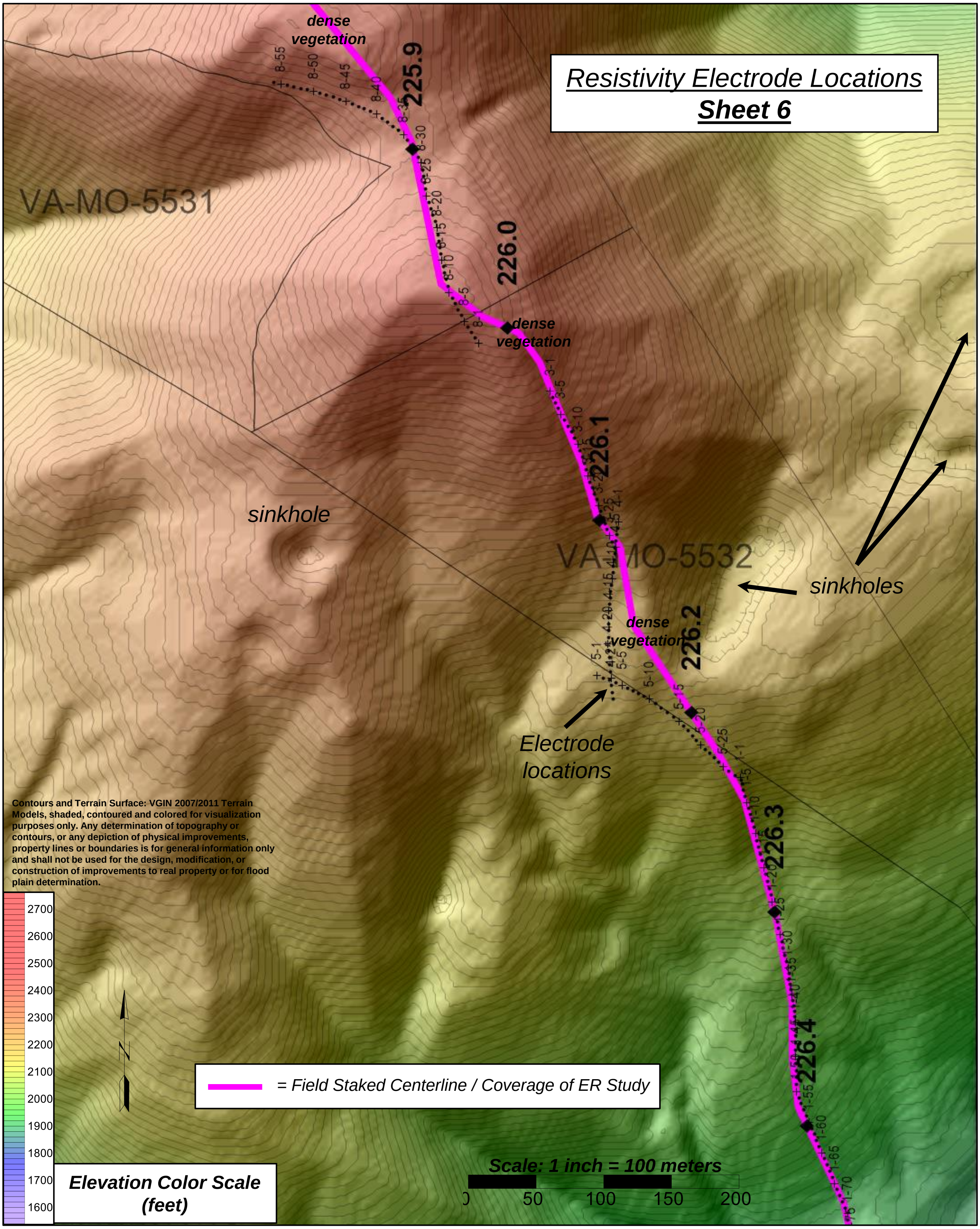

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FIGURE 10

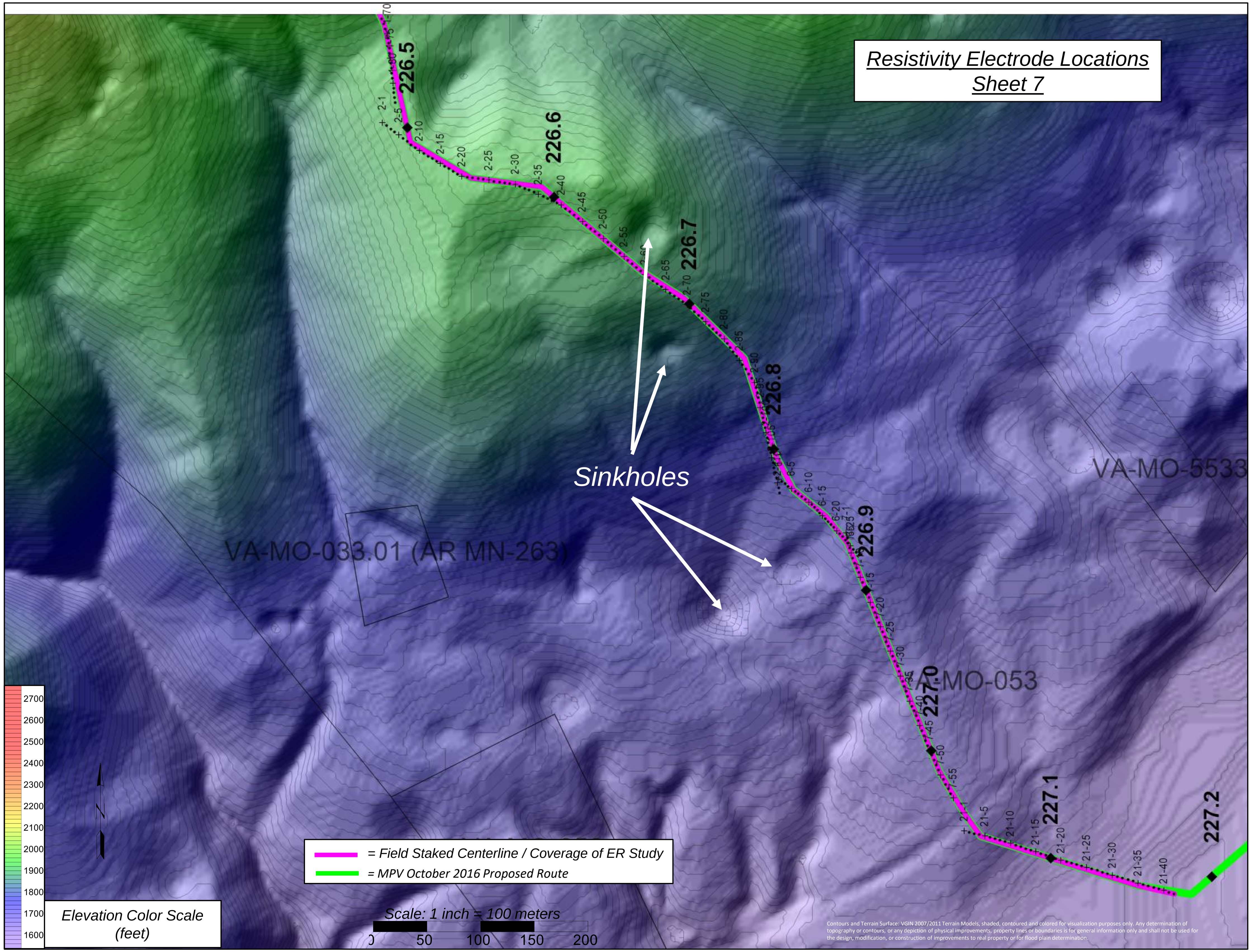

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FIGURE
11

Resistivity Results and Interpretations: Mileposts 221.8 to 224.2

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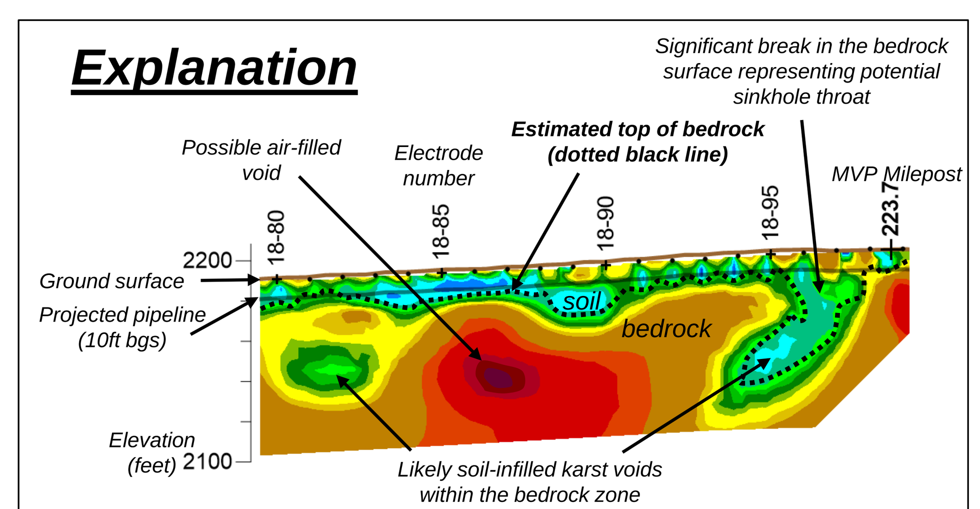
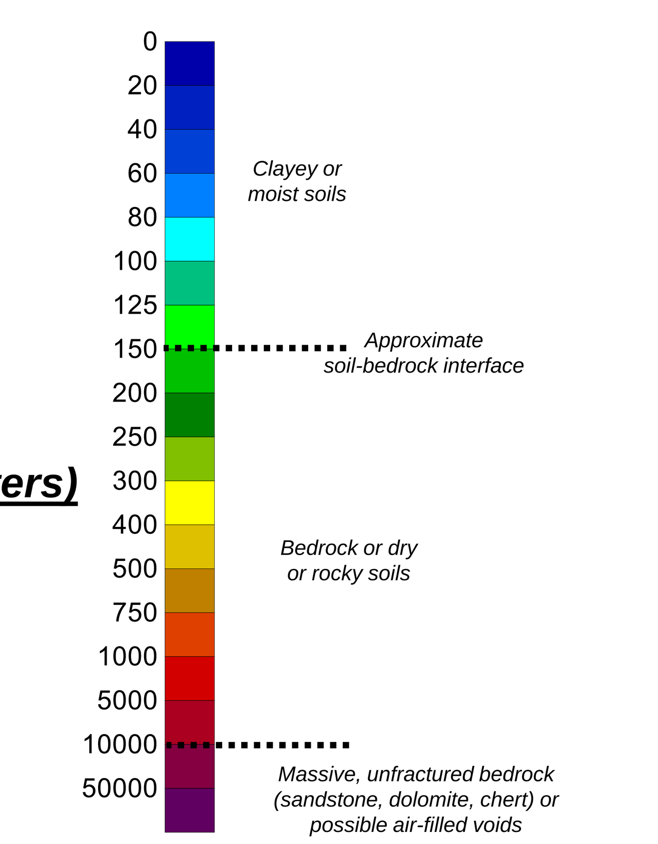
FIGURE
12

Resistivity Results and Interpretations: Mileposts 223.7 to 225.4





Resistivity Color Scale (ohm-meters) and Geologic Interpretations

Scale: 1 inch = 100 feet
0 50 100 150 200

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FIGURE
13

Resistivity Results and Interpretations: Mileposts 225.5 to 227.1

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FIGURE 14

Locations of 15 Possible Karst Features Evaluated With Supplemental Resistivity Data

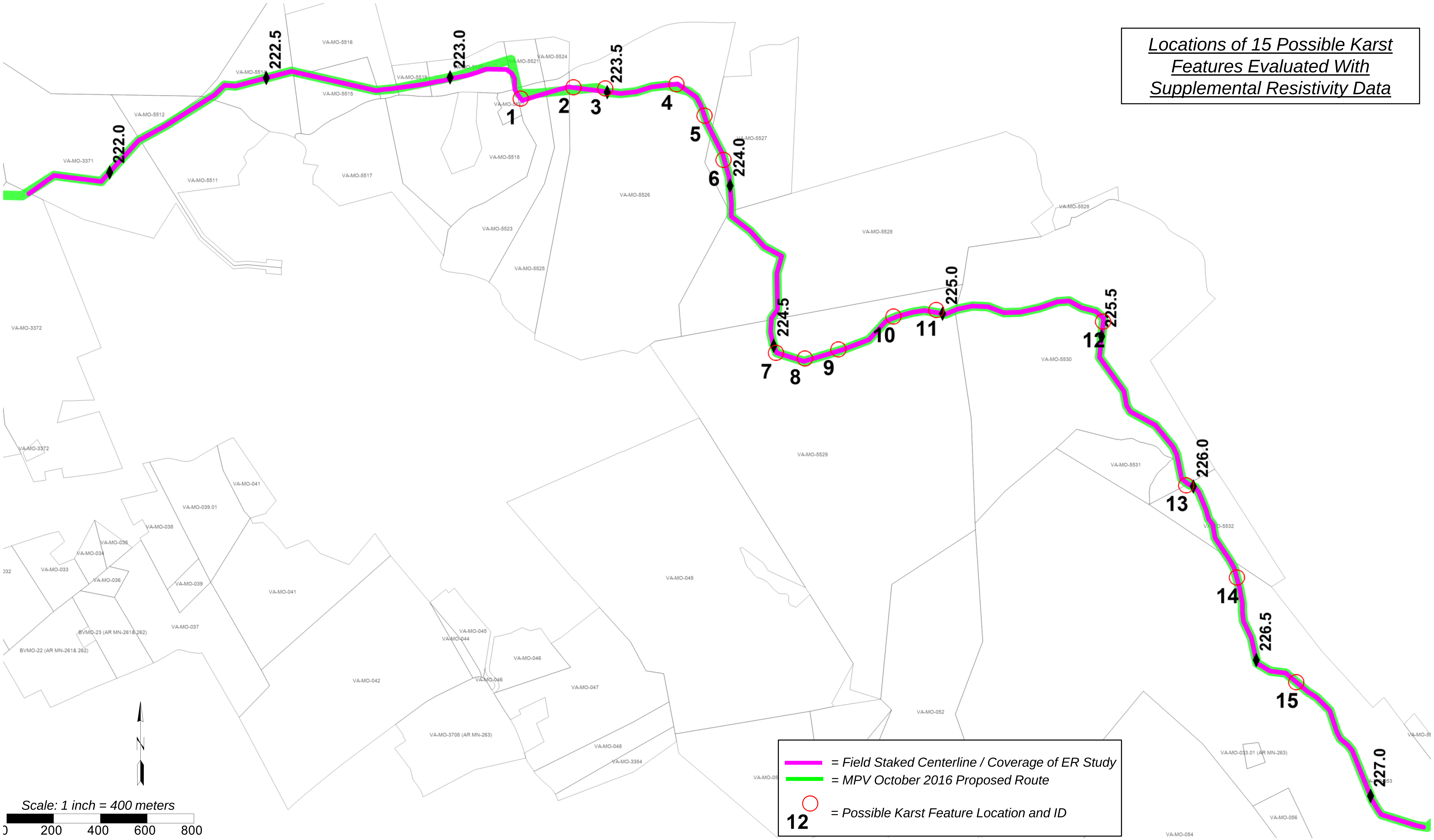

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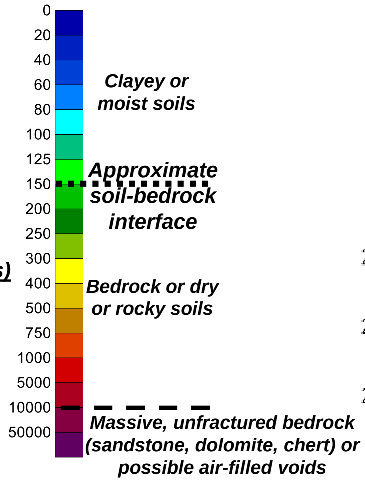
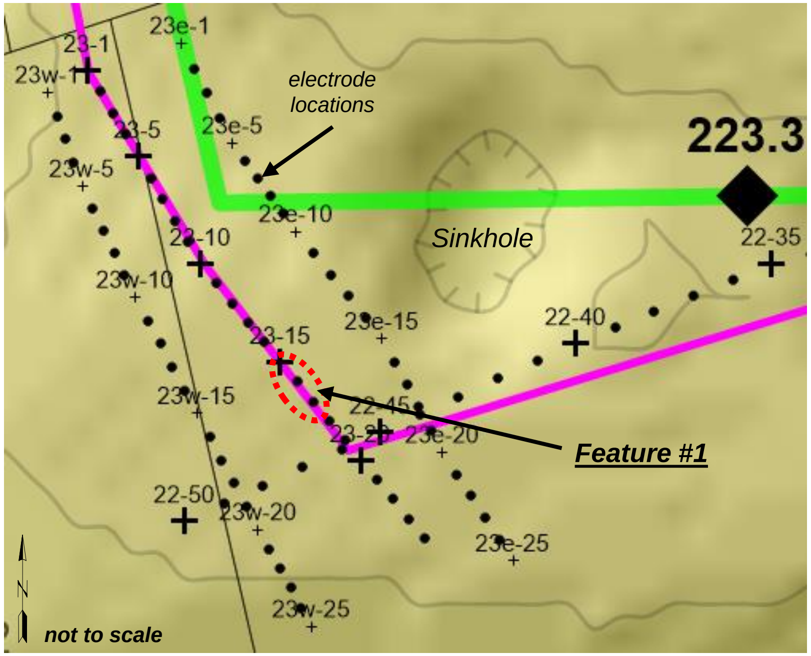
FIGURE
15

Possible Karst Feature #1 Follow-up
Near Milepost 223.27

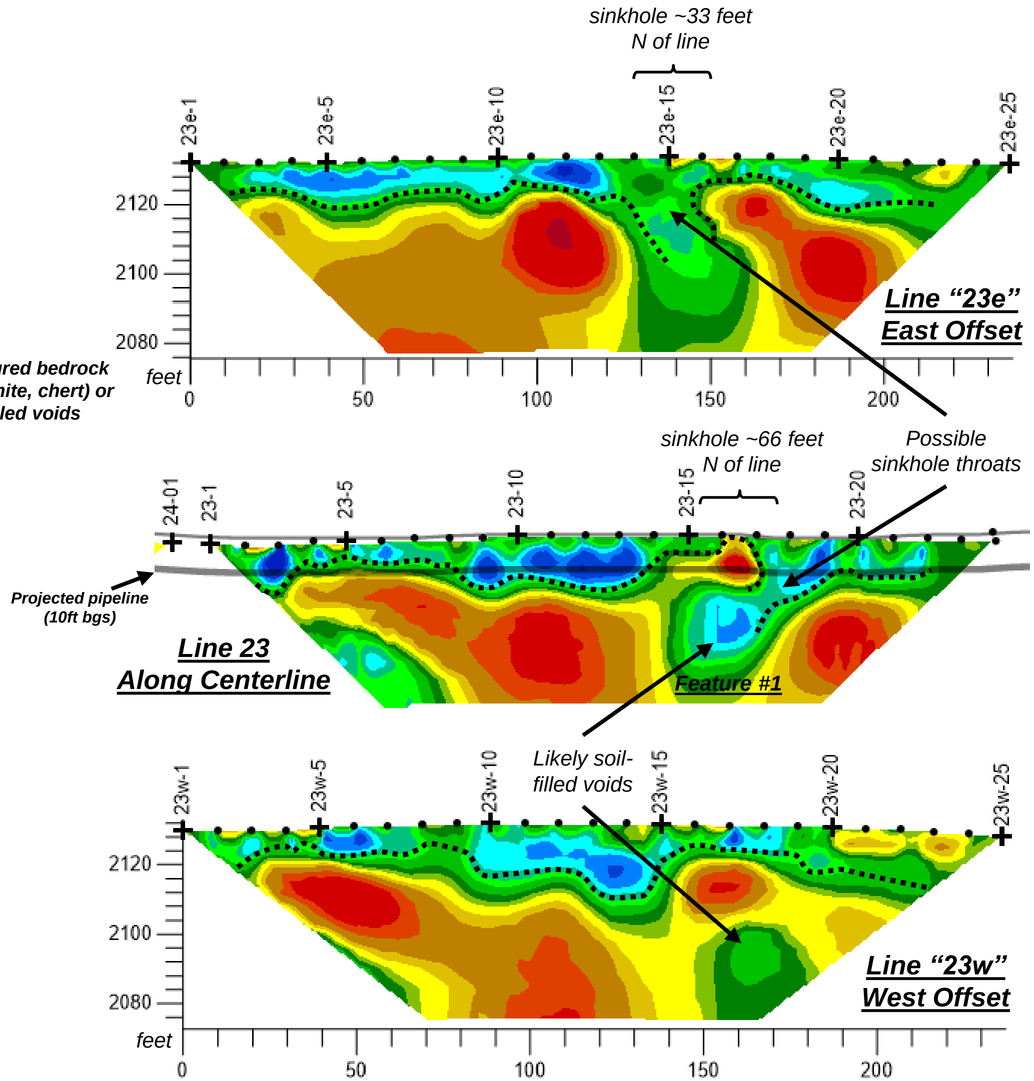


Resistivity Color Scale (ohm-meters) and Geologic Interpretations

Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.



(magenta line)	= Field Staked Centerline / Coverage of ER Study
(green line)	= MPV October 2016 Proposed Route
	23w / 23e = Offset Resistivity Lines



= Interpreted top of bedrock

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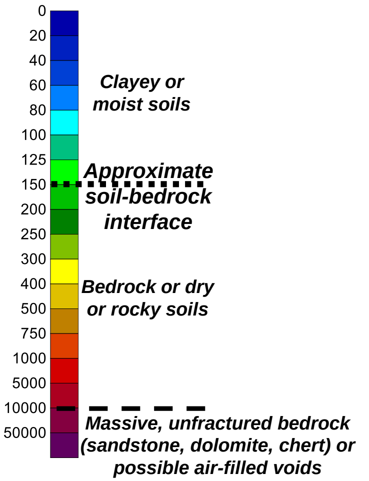
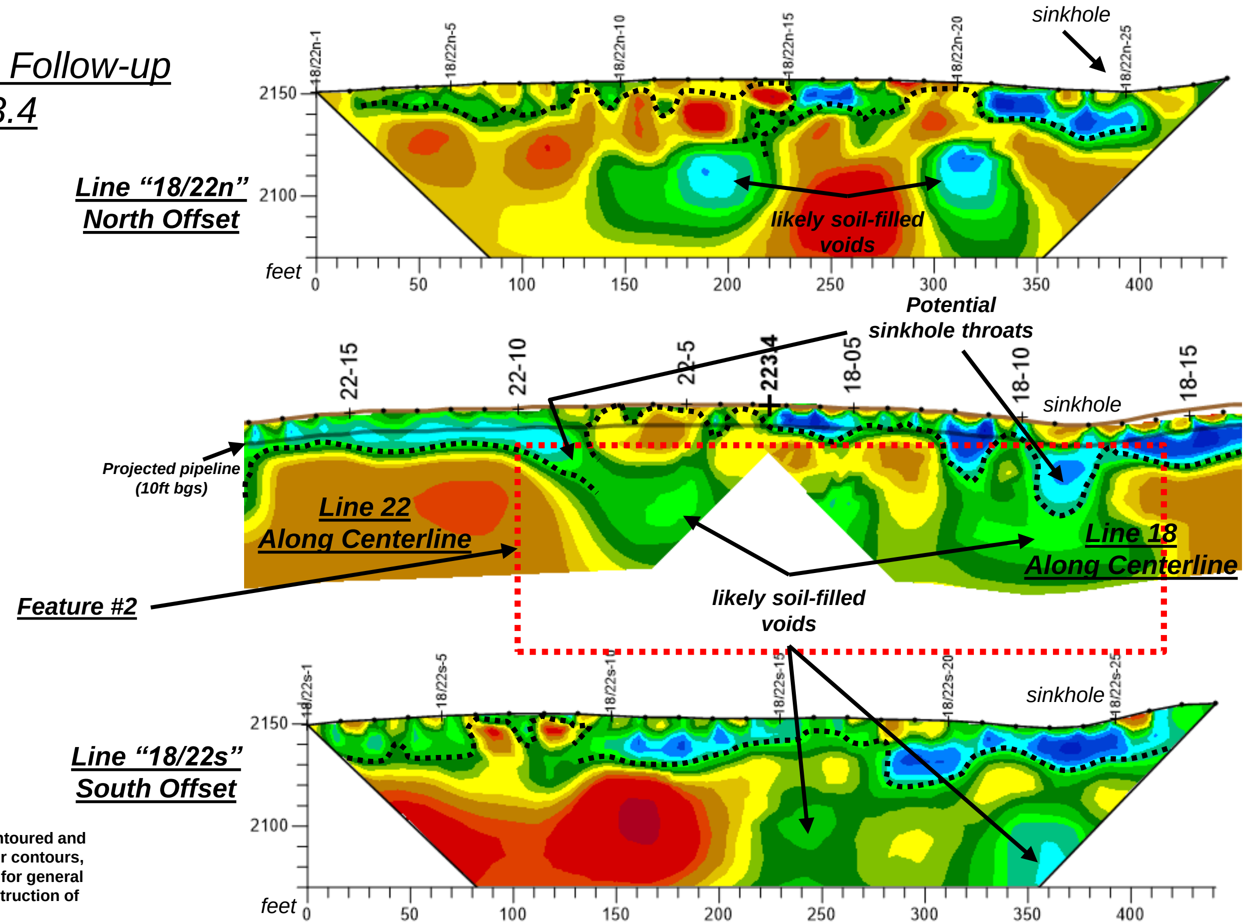
FIGURE 16

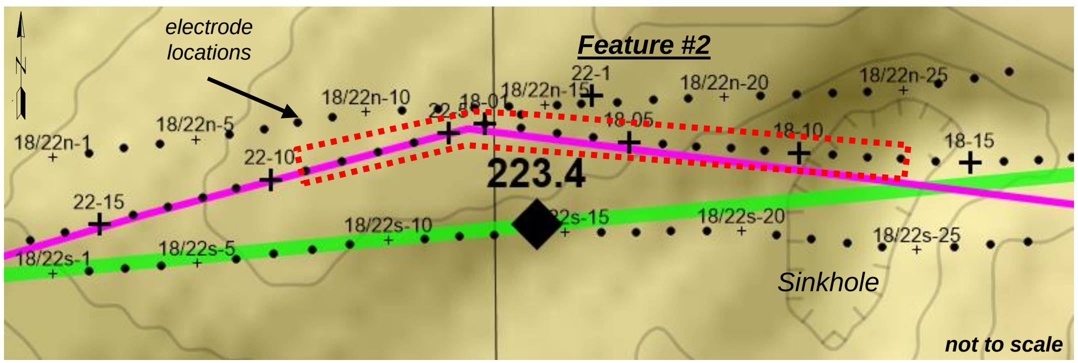
Possible Karst Feature #2 Follow-up
Near Milepost 223.4



Resistivity Color Scale (ohm-meters) and Geologic Interpretations



Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.



= Interpreted top of bedrock

= Field Staked Centerline / Coverage of ER Study
= MPV October 2016 Proposed Route
18/22n / 18/22s = Offset Resistivity Lines

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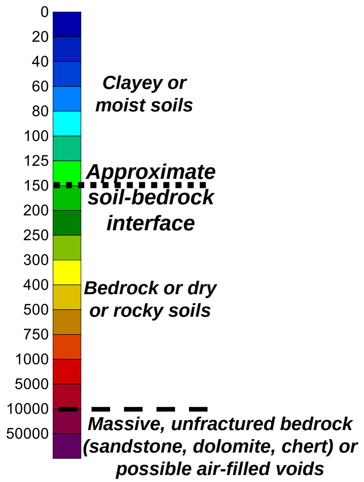
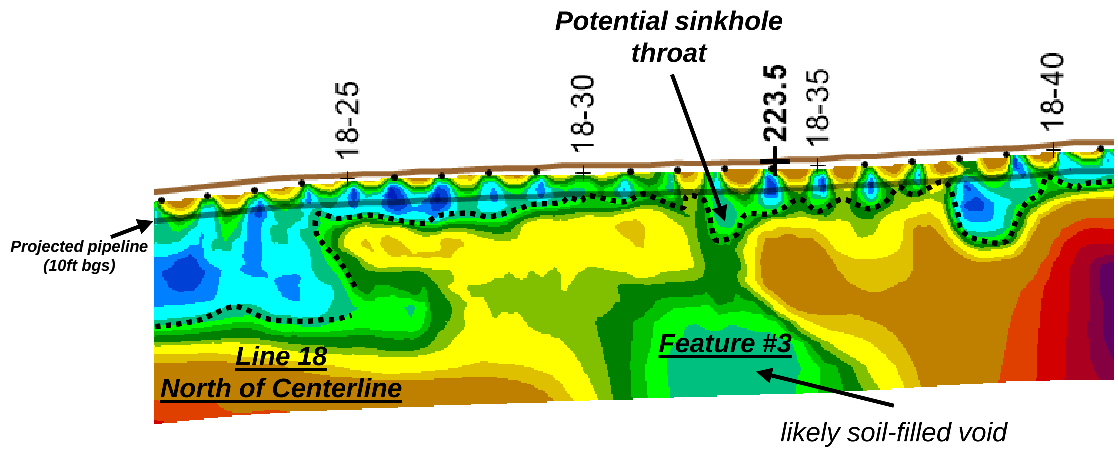
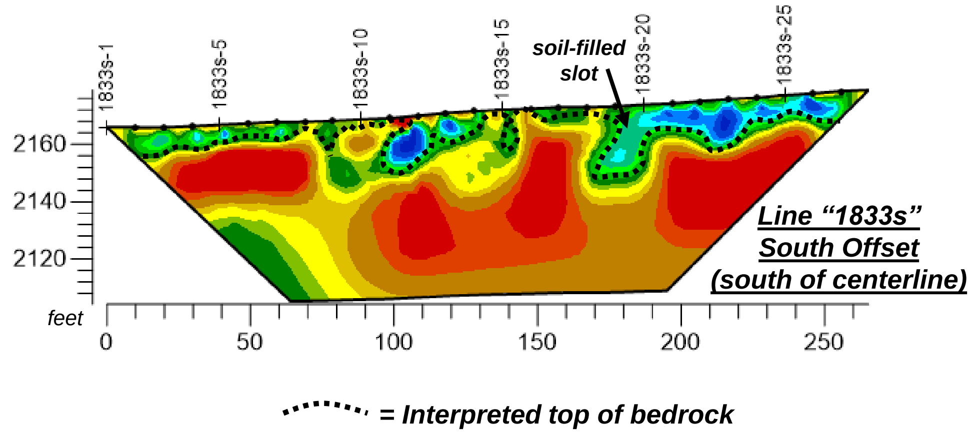
FIGURE 17

Possible Karst Feature #3 Follow-up
Near Milepost 223.5

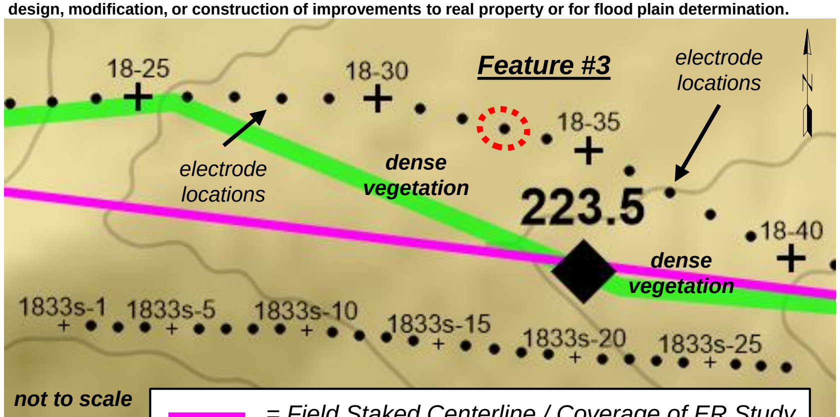


Resistivity Color Scale (ohm-meters) and Geologic Interpretations





Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.



= Field Staked Centerline / Coverage of ER Study
= MPV October 2016 Proposed Route
1833s = Offset Resistivity Line

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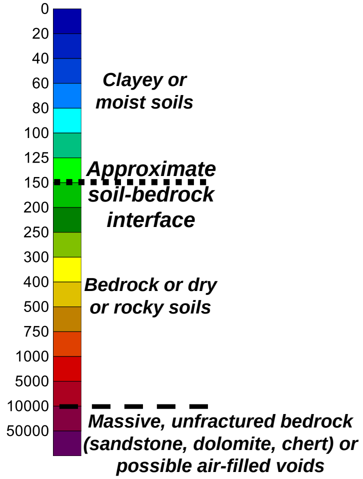
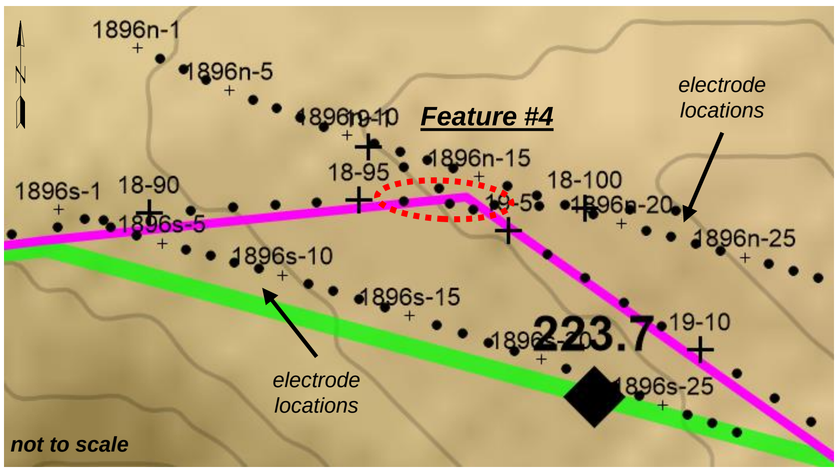
FIGURE 18

Possible Karst Feature #4 Follow-up
Near Milepost 223.7

Resistivity Color Scale (ohm-meters) and Geologic Interpretations



Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.



= Field Staked Centerline / Coverage of ER Study
= MPV October 2016 Proposed Route
1896n / 1896s = Offset Resistivity Lines

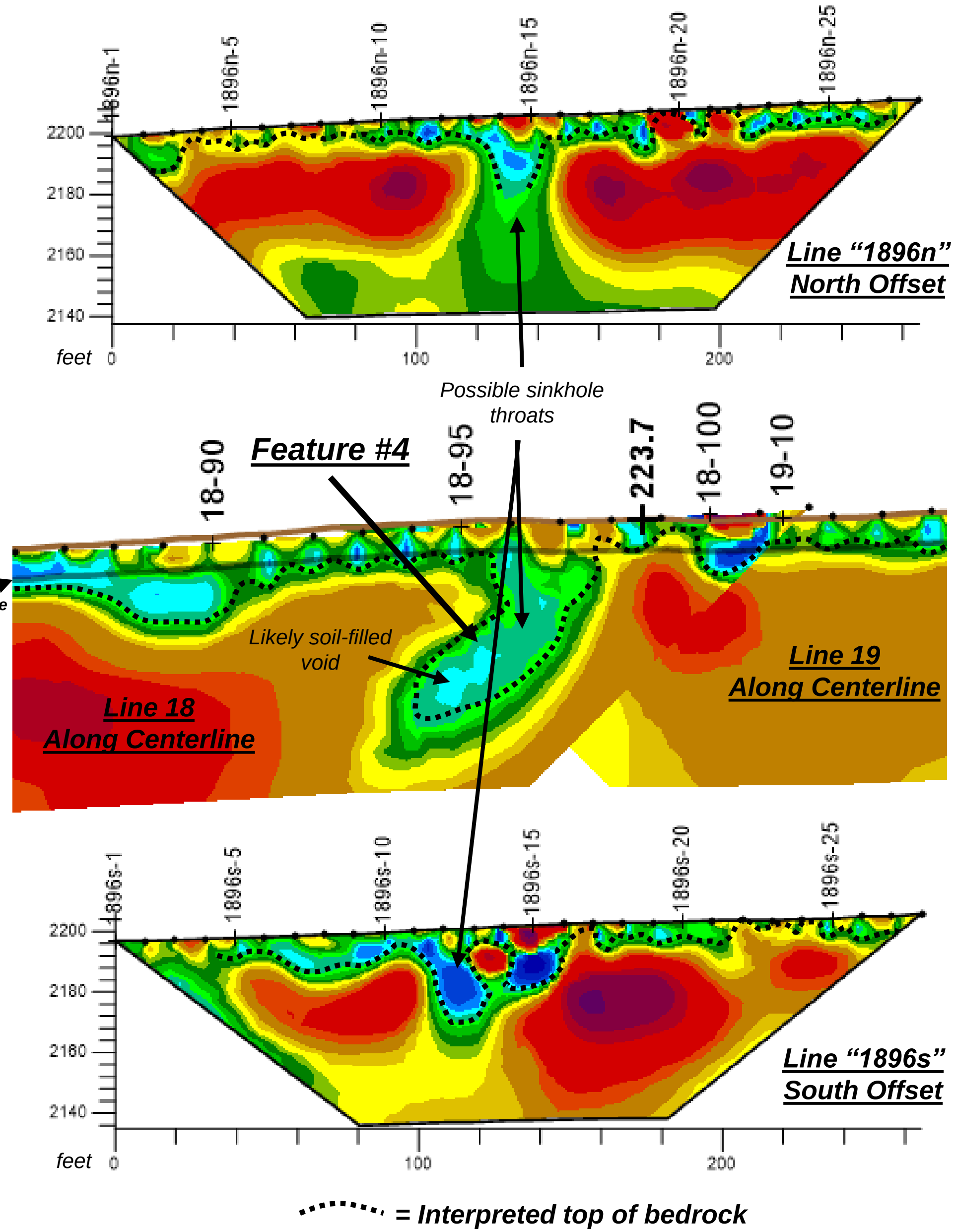


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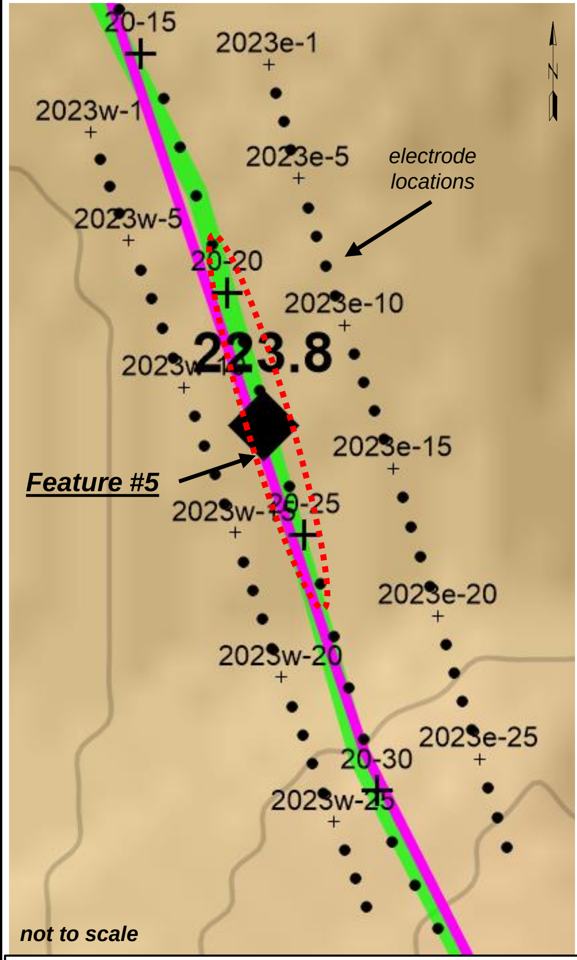
FIGURE 19

Possible Karst Feature #5 Follow-up
Near Milepost 223.8

Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.



= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

2023w / 2023e = Offset Resistivity Lines

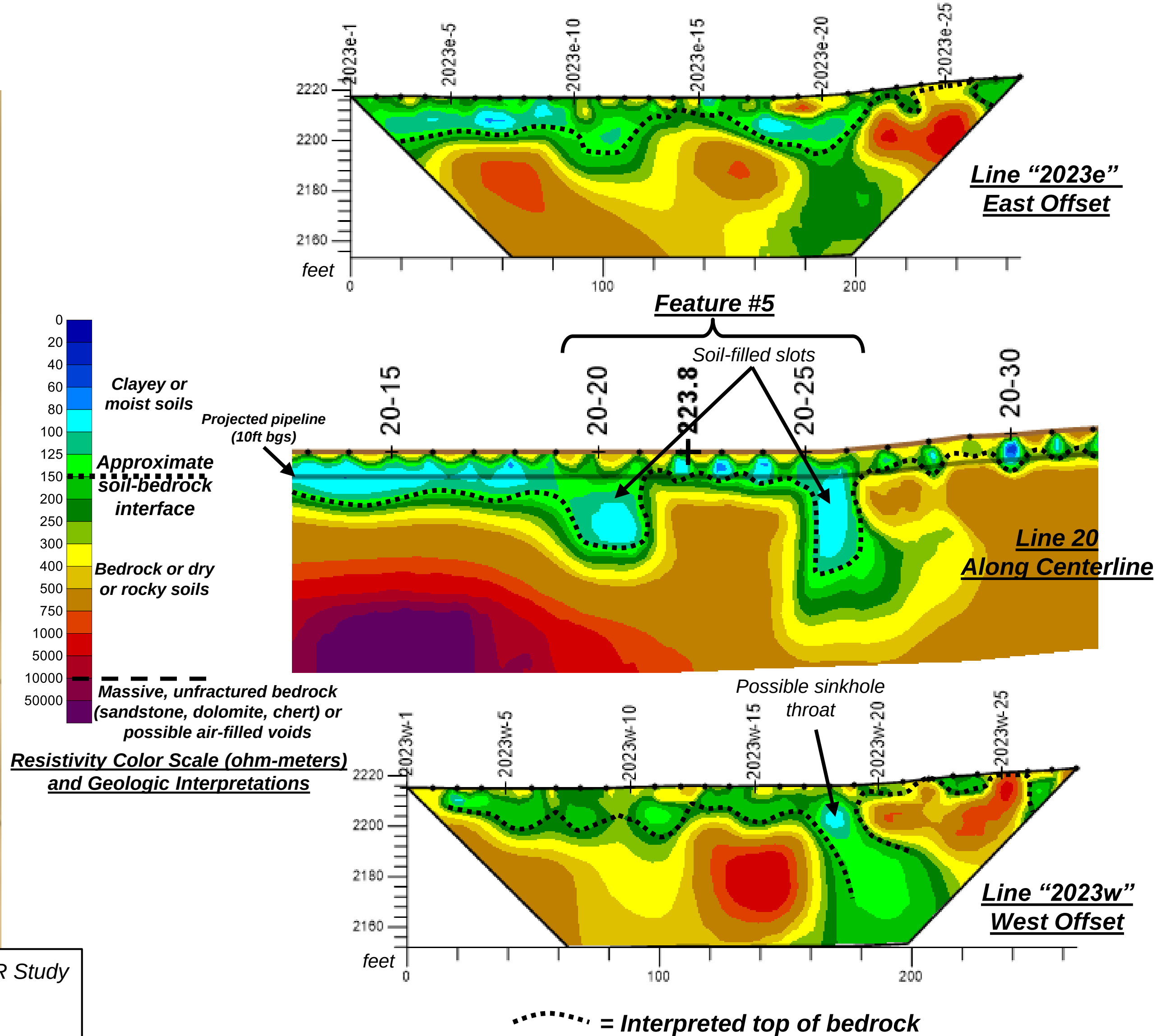


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FIGURE 20

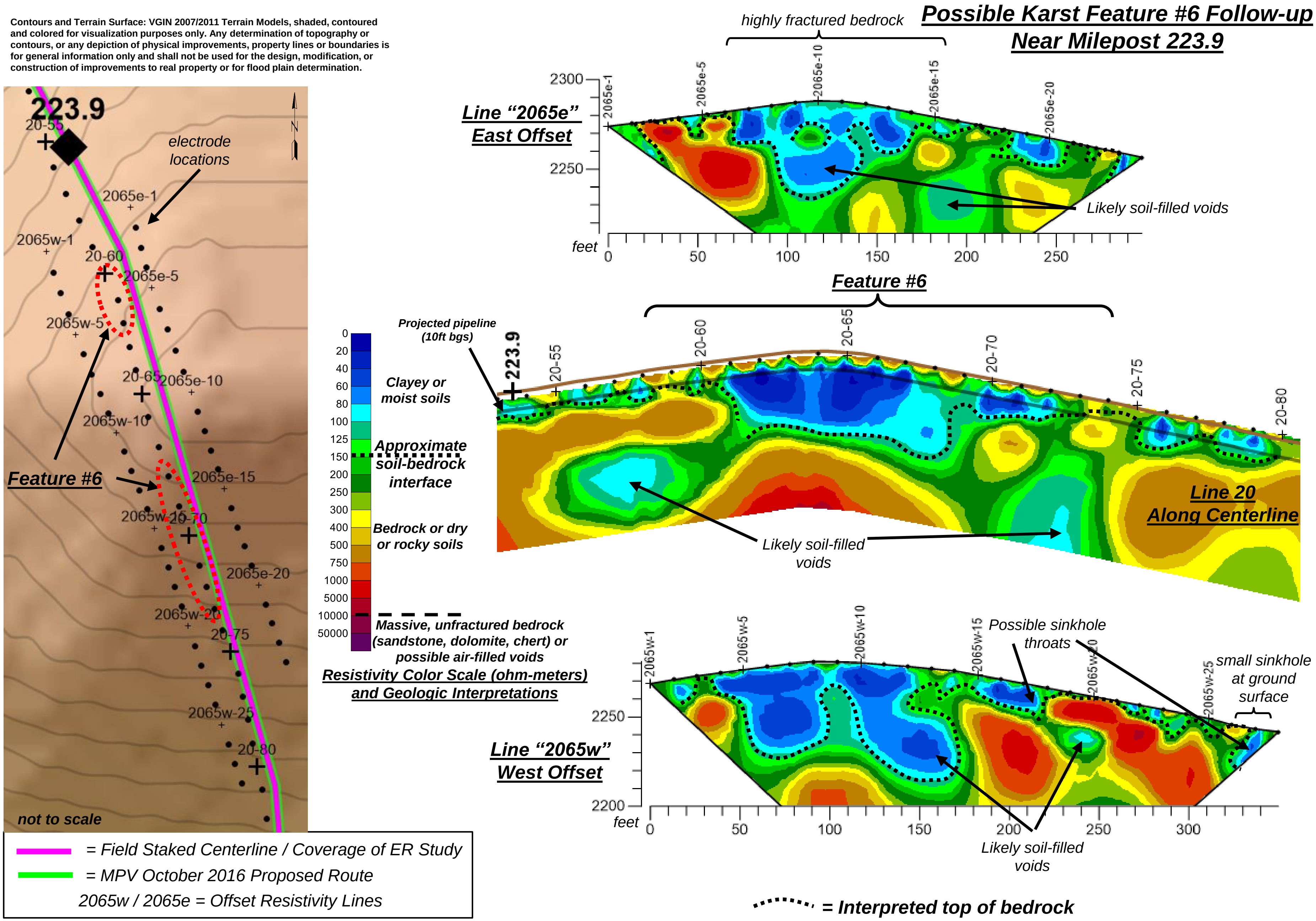

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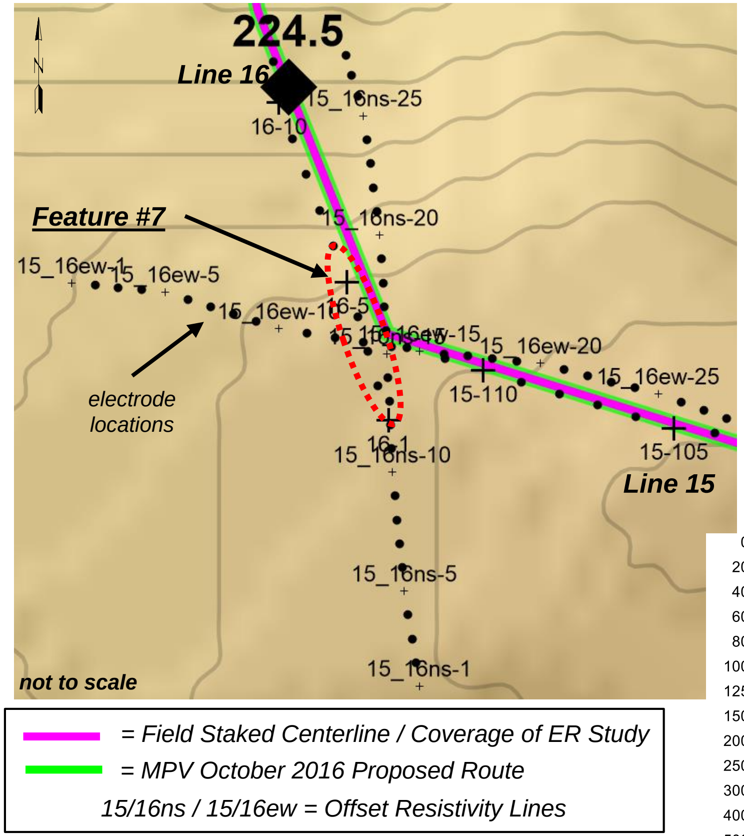
FIGURE 21

Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.

Possible Karst Feature #7 Follow-up
Near Milepost 224.5



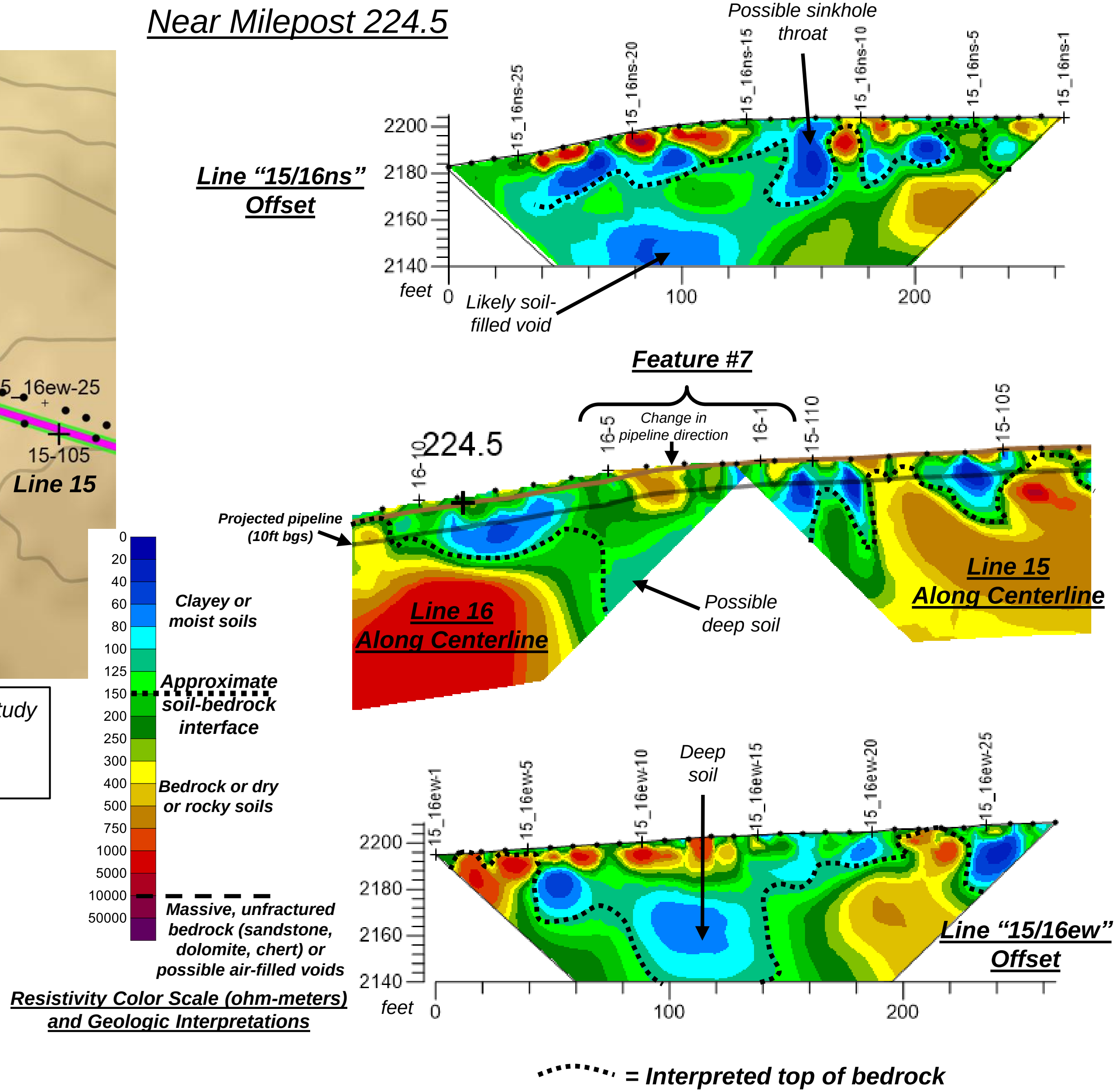


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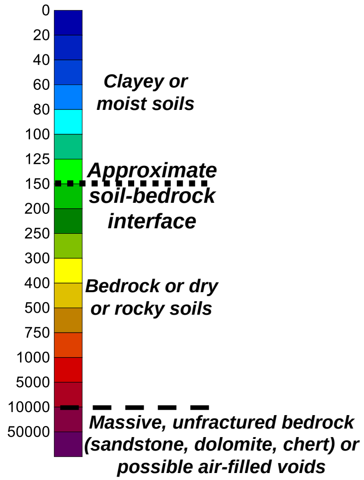
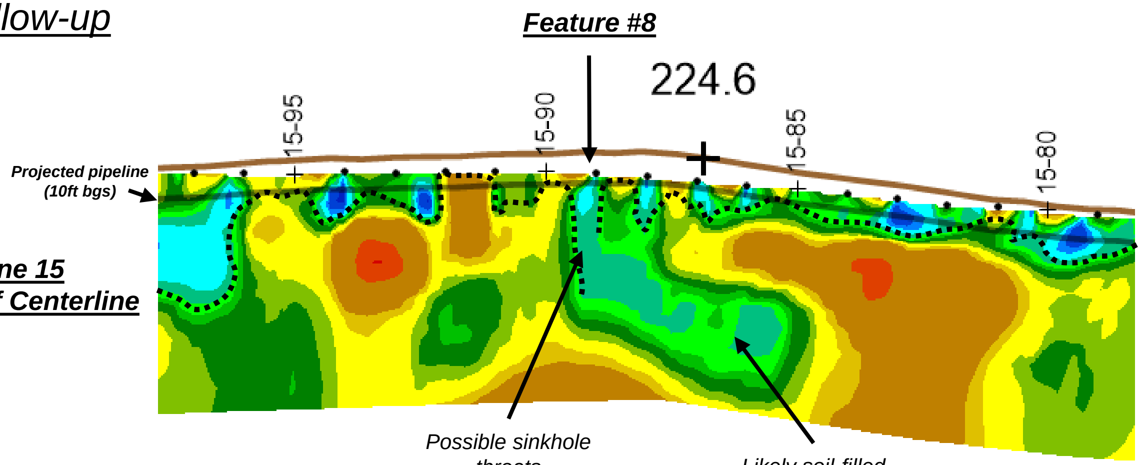
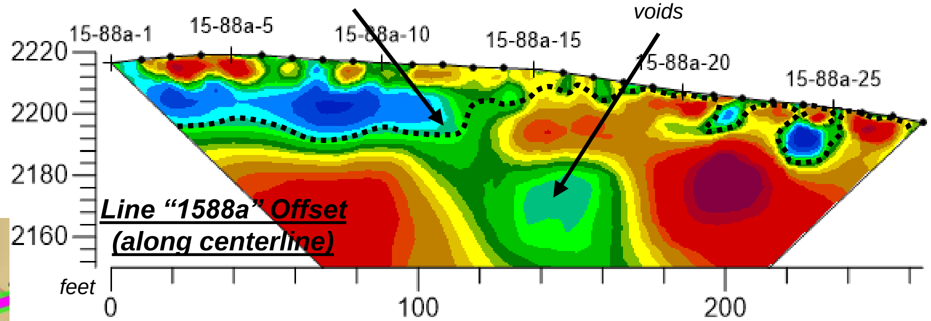
FIGURE 22

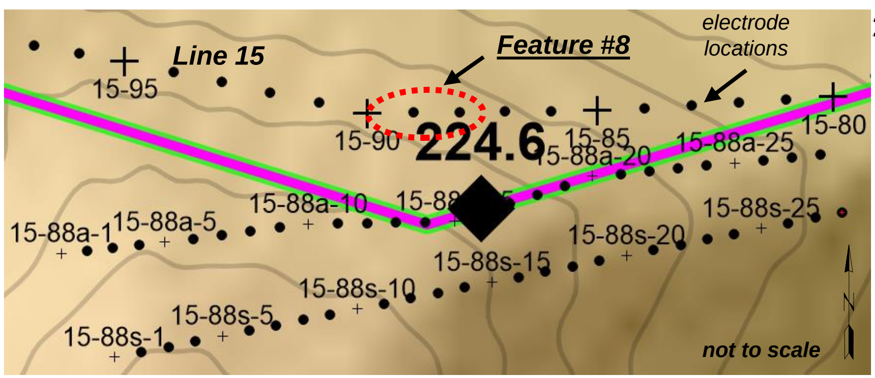
Possible Karst Feature #8 Follow-up
Near Milepost 224.6

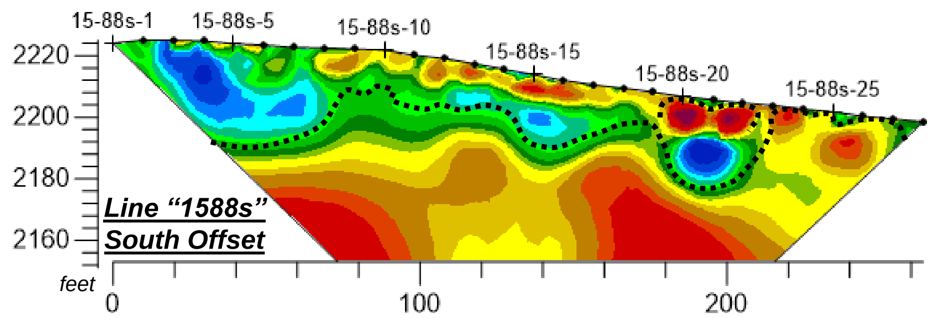


Resistivity Color Scale (ohm-meters) and Geologic Interpretations









= Field Staked Centerline / Coverage of ER Study
= MPV October 2016 Proposed Route
1588a / 1588s= Offset Resistivity Lines

= Interpreted top of bedrock

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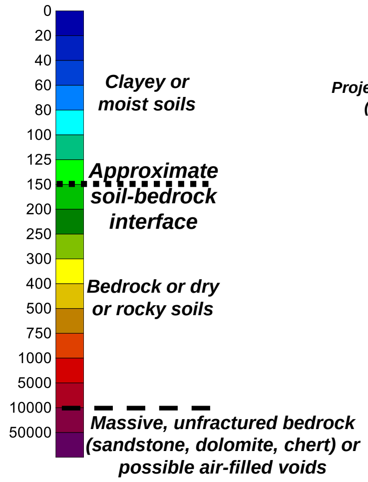
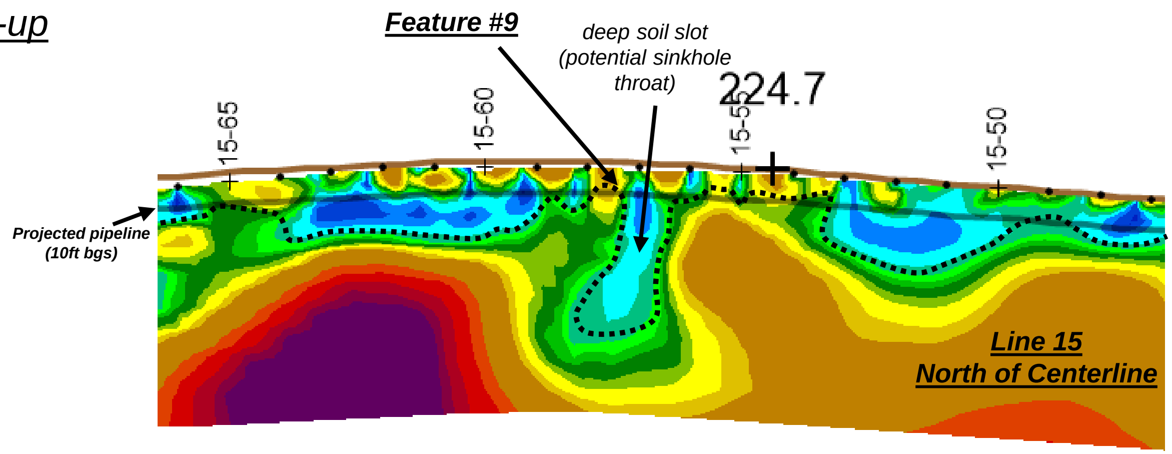
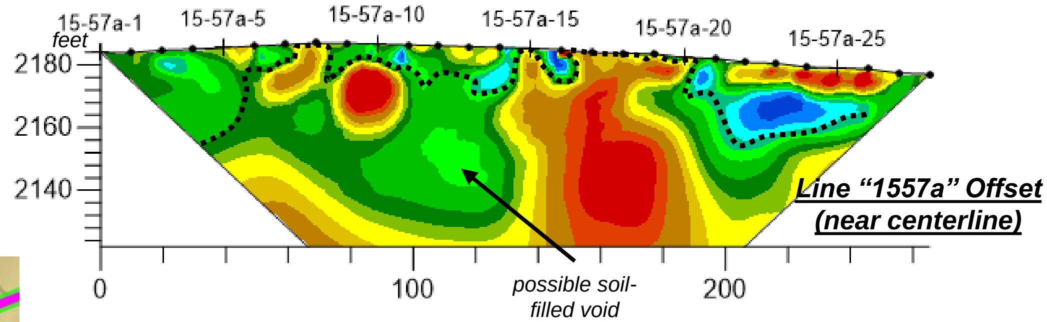
FIGURE 23

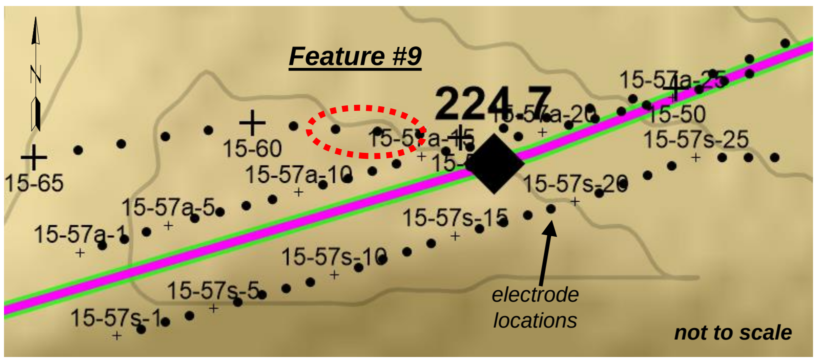
Possible Karst Feature #9 Follow-up
Near Milepost 224.7

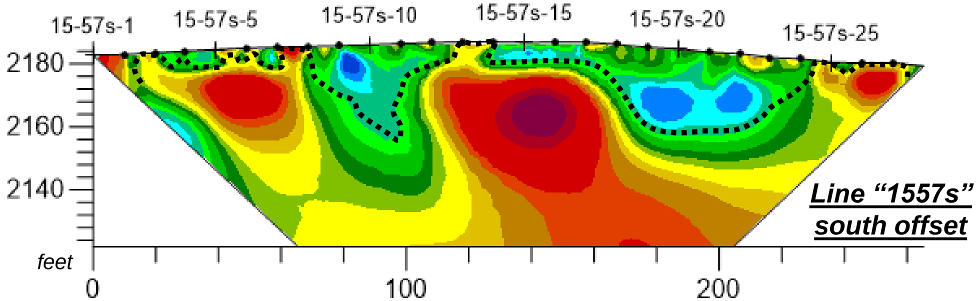


Resistivity Color Scale (ohm-meters) and Geologic Interpretations









= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

1557a / 1557s= Offset Resistivity Lines

= Interpreted top of bedrock

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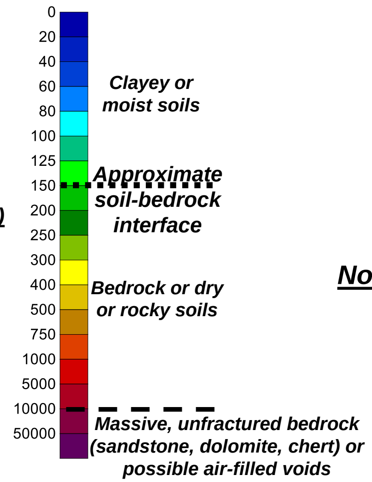
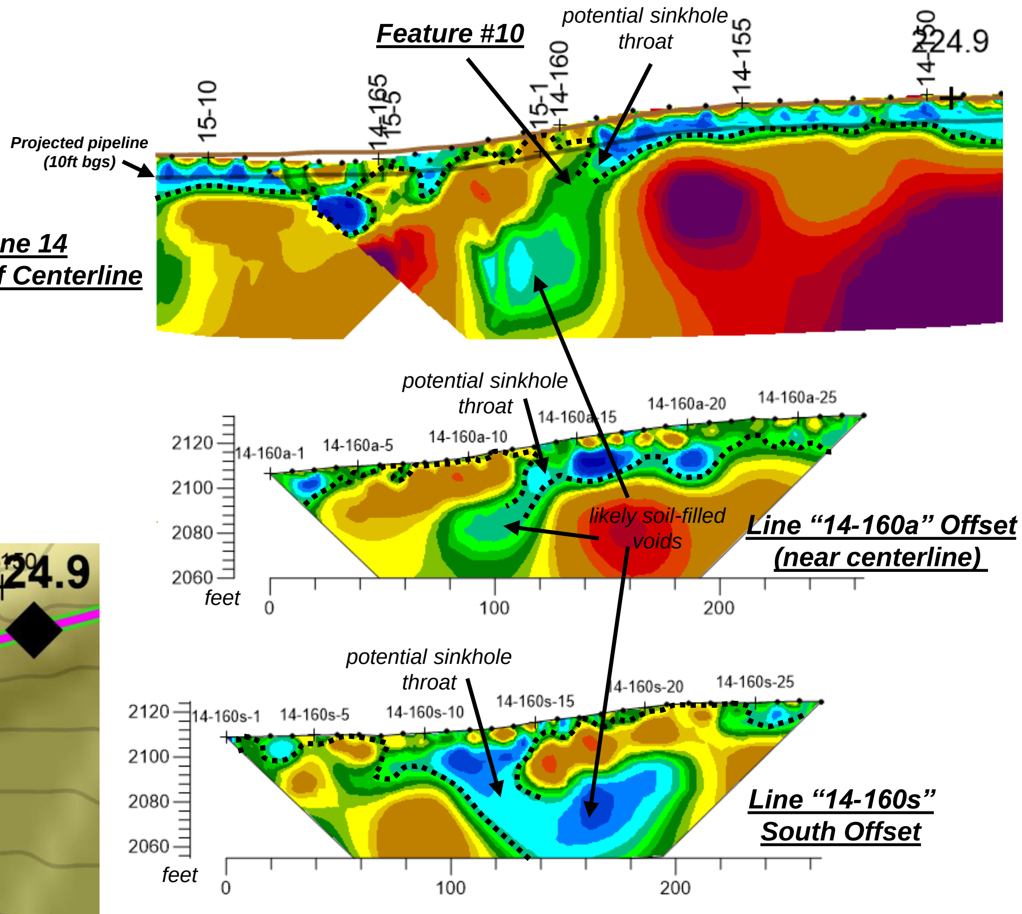
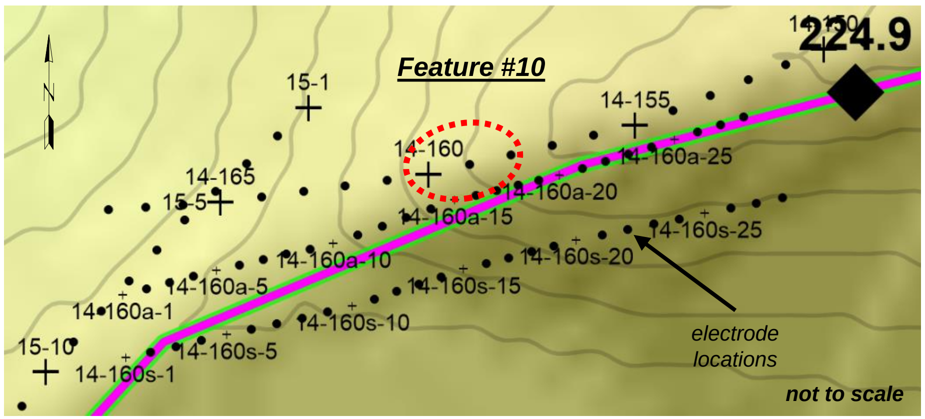
FIGURE 24

Possible Karst Feature #10 Follow-up
Near Milepost 224.9

Resistivity Color Scale (ohm-meters) and Geologic Interpretations







= Interpreted top of bedrock

= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

14-160a / 14-160s= Offset Resistivity Lines

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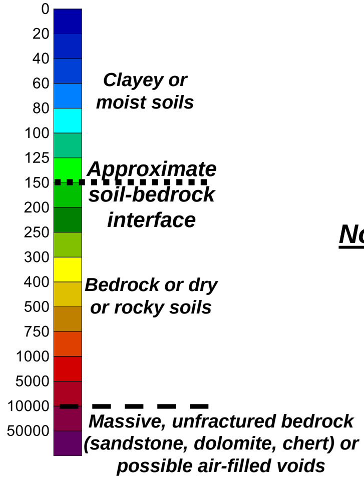
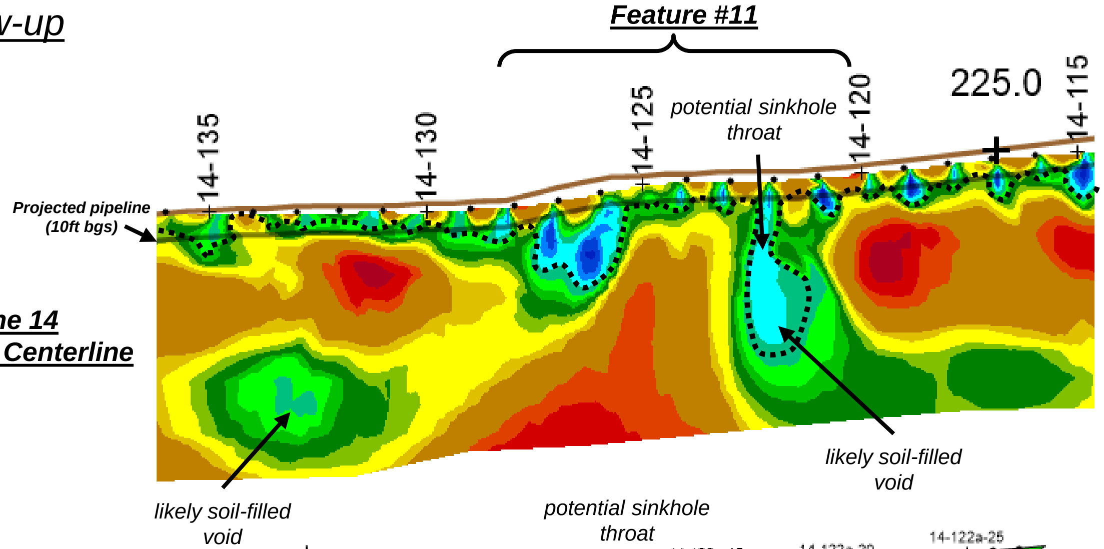
Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
Mount Tabor Karst Area
Blacksburg, VA
DAA Project Number: B14188B-02

FIGURE 25

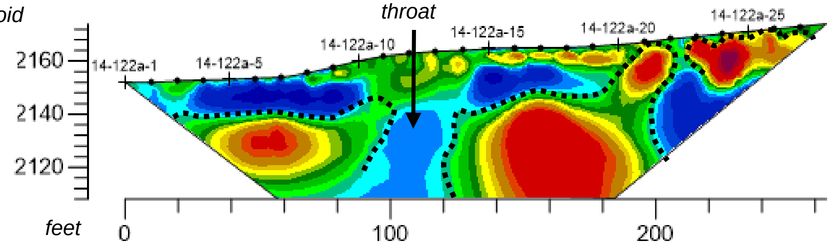
Possible Karst Feature #11 Follow-up
Near Milepost 225.0



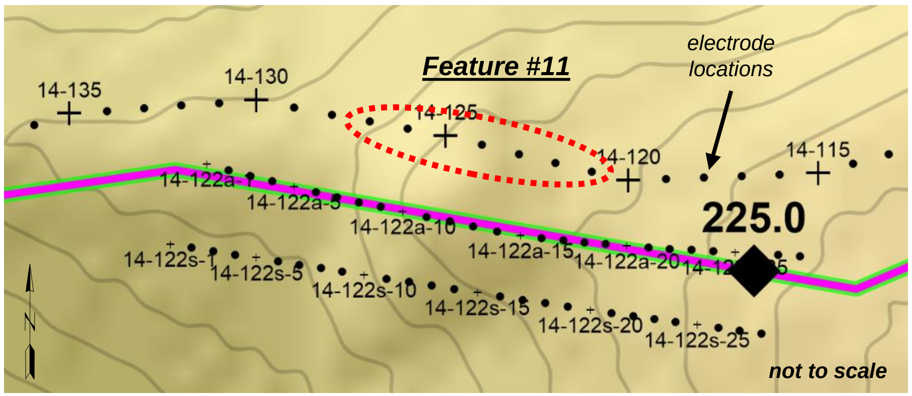
Resistivity Color Scale (ohm-meters) and Geologic Interpretations

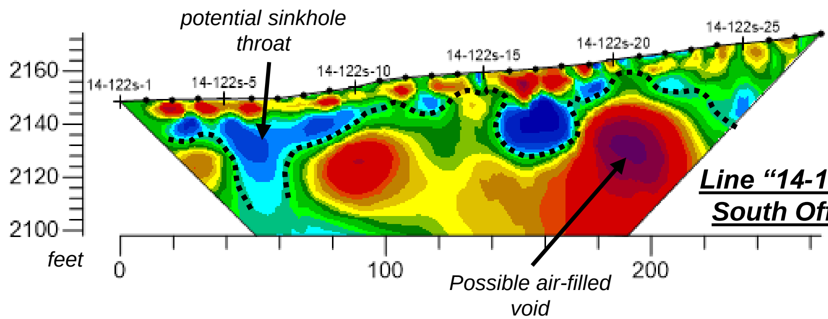


Line 14 North of Centerline



Line "14-122a" Offset (along centerline)





Line "14-122s" South Offset

= Field Staked Centerline / Coverage of ER Study
= MPV October 2016 Proposed Route
14-122s / 12-122a = Offset Resistivity Lines

= Interpreted top of bedrock

Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.

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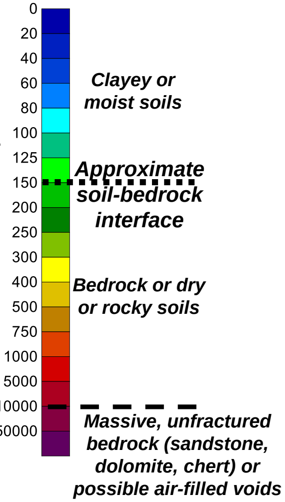
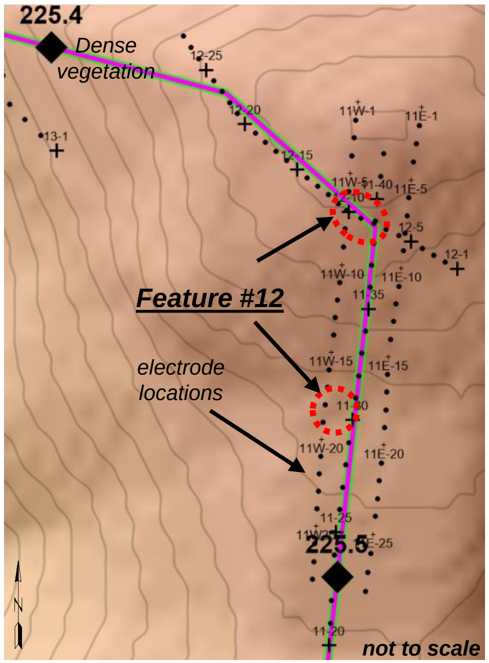
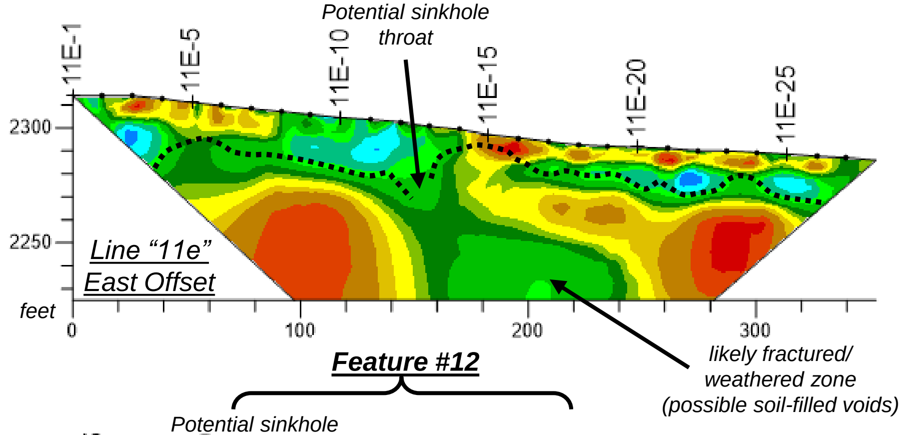
Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
Mount Tabor Karst Area
Blacksburg, VA
DAA Project Number: B14188B-02

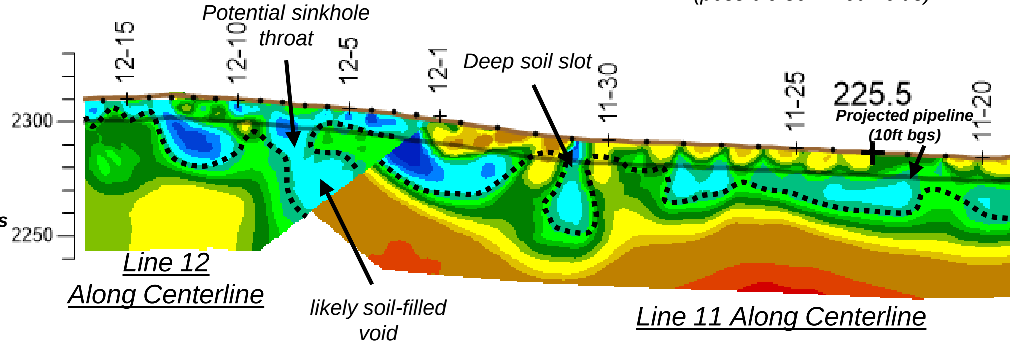
FIGURE 26

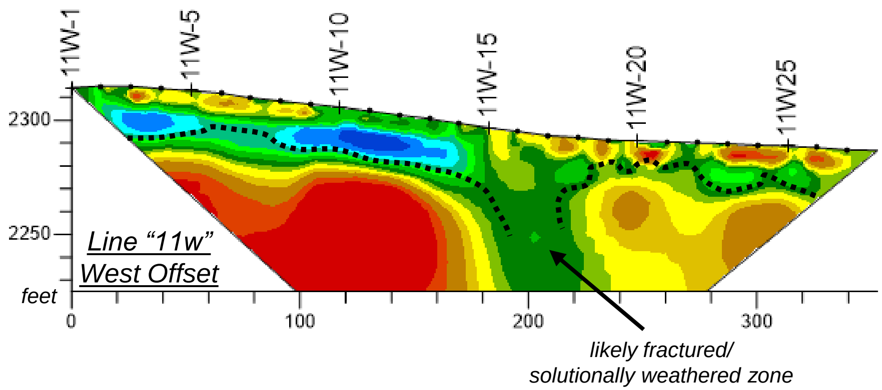
Possible Karst Feature #12 Follow-up
Near Milepost 225.45











= Interpreted top of bedrock

= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

11w / 11e = Offset Resistivity Lines

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Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
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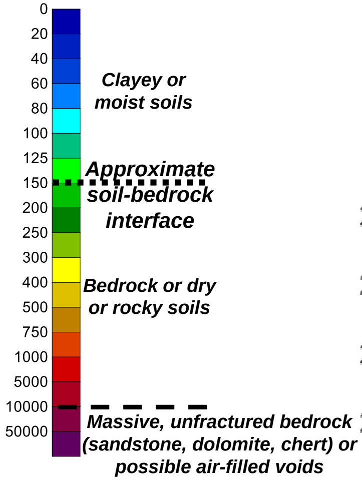
Blacksburg, VA
DAA Project Number: B14188B-02

FIGURE 27

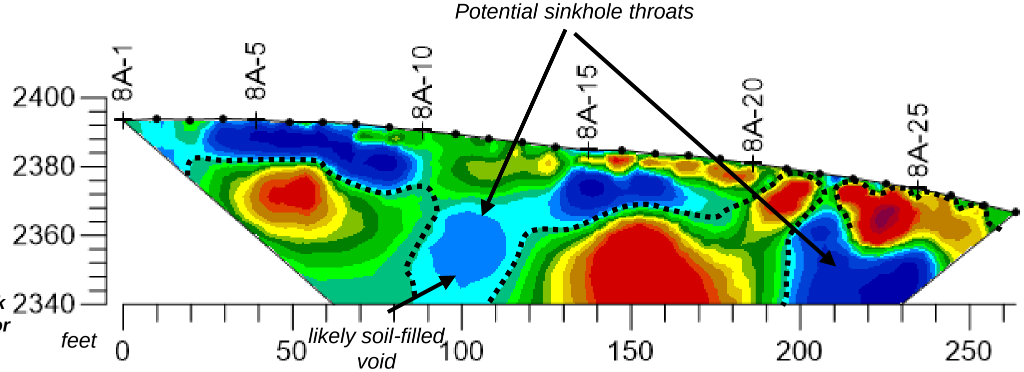
Possible Karst Feature #13 Follow-up
Near Milepost 226.0

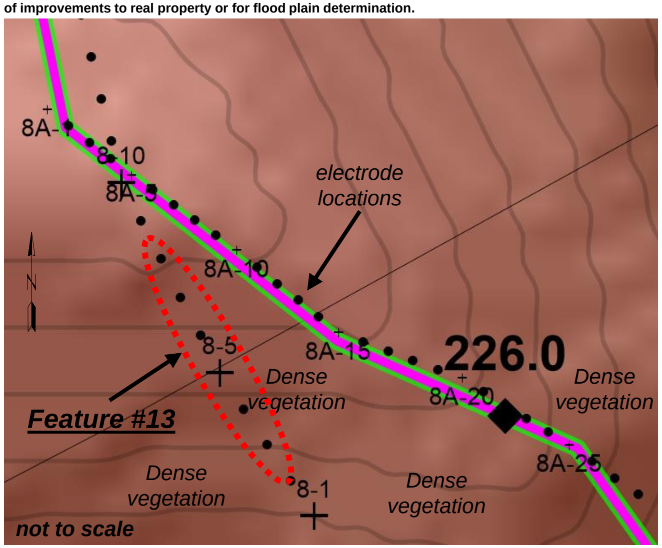
Resistivity Color Scale (ohm-meters) and Geologic Interpretations



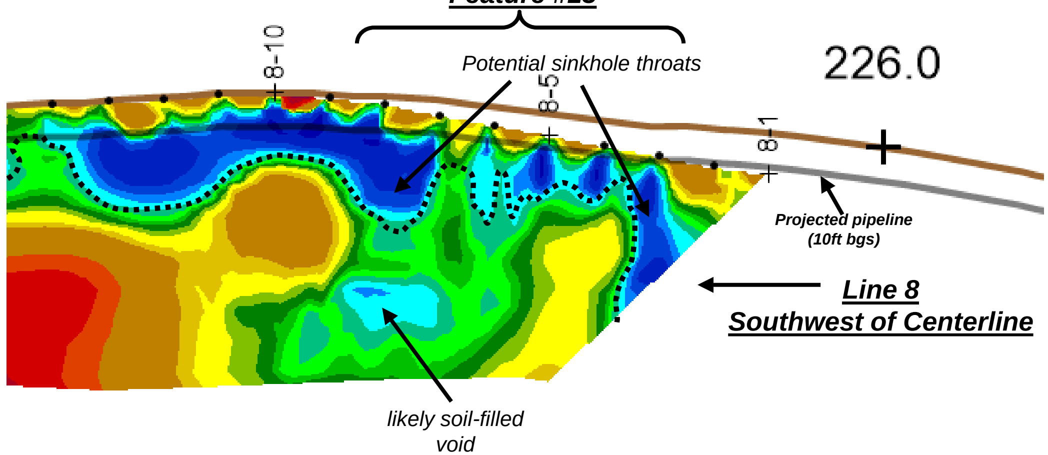
Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.

Line "8a" Northeast Offset Along Centerline





Feature #13



Line 8 Southwest of Centerline

= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

8A= Offset Resistivity Lines

= Interpreted top of bedrock

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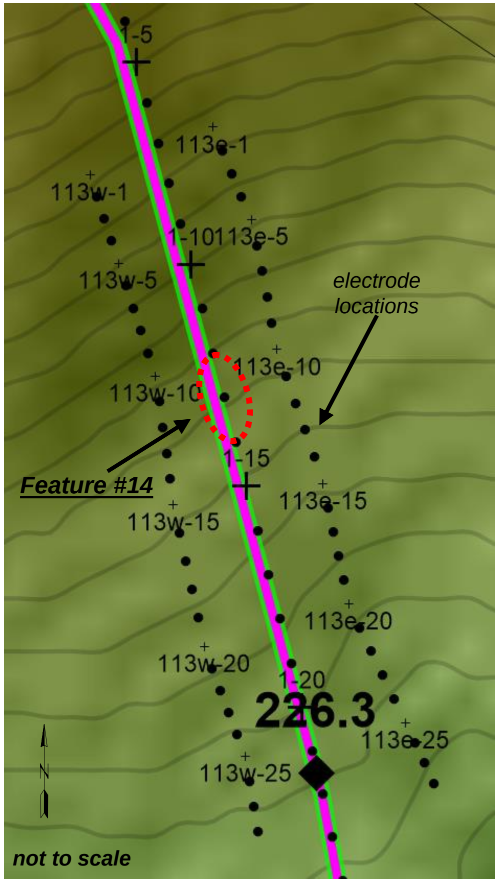
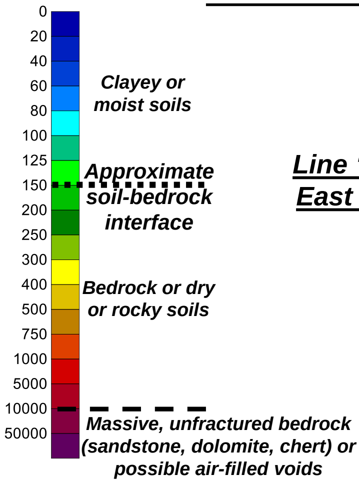
Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
Mount Tabor Karst Area
Blacksburg, VA
DAA Project Number: B14188B-02

FIGURE 28

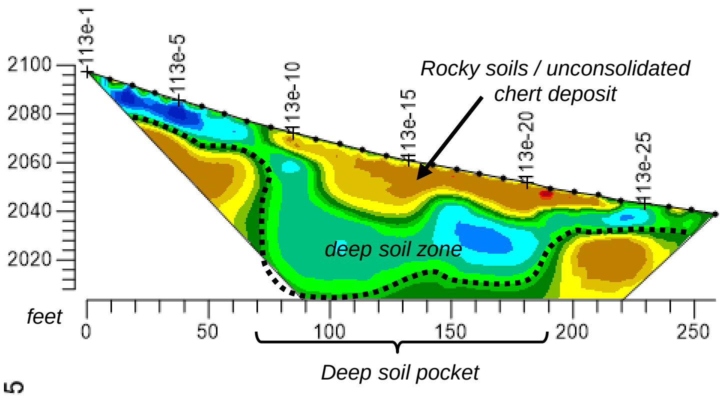
Possible Karst Feature #14 Follow-up
Near Milepost 226.3



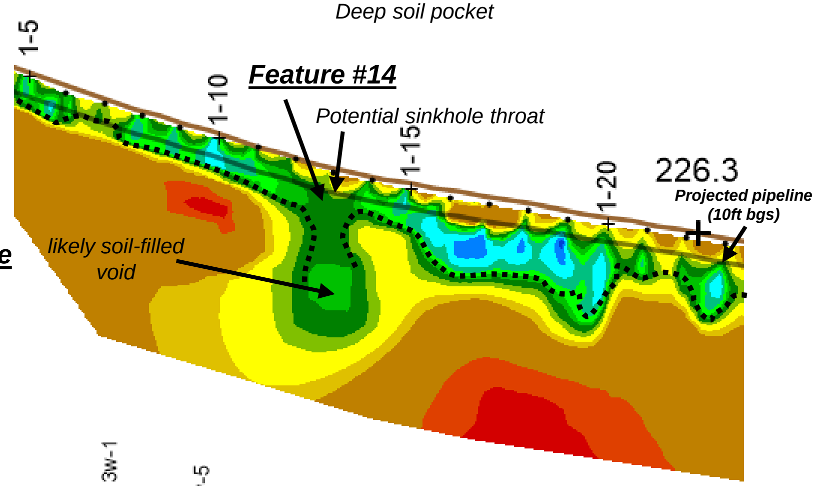


Resistivity Color Scale (ohm-meters) and Geologic Interpretations

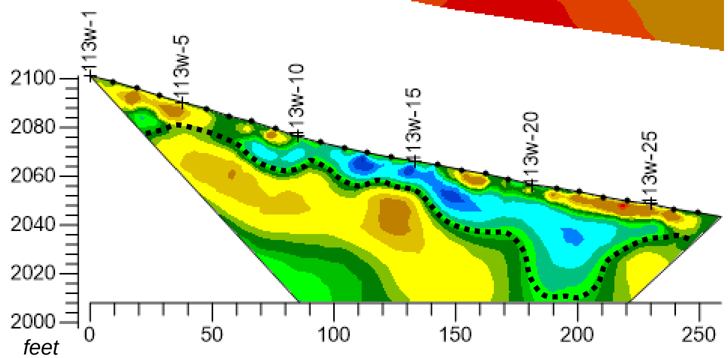
Line “113e” East Offset



Line 1 Along Centerline



Line “113w” West Offset



= Interpreted top of bedrock

(magenta line)	*= Field Staked Centerline / Coverage of ER Study*
(green line)	*= MPV October 2016 Proposed Route*
	113w / 113e = Offset Resistivity Lines

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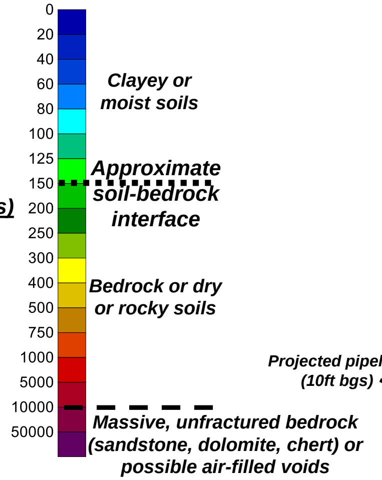
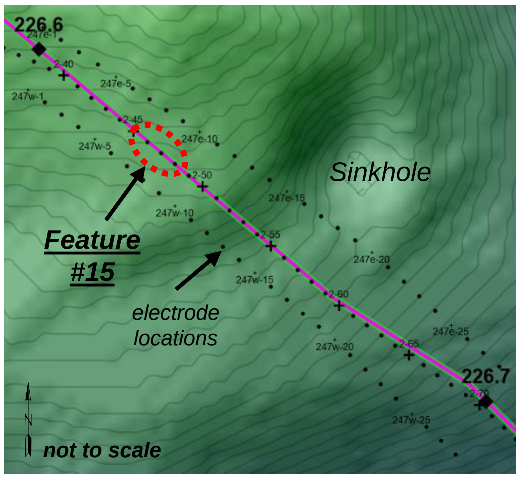
DAA Project Number: B14188B-02

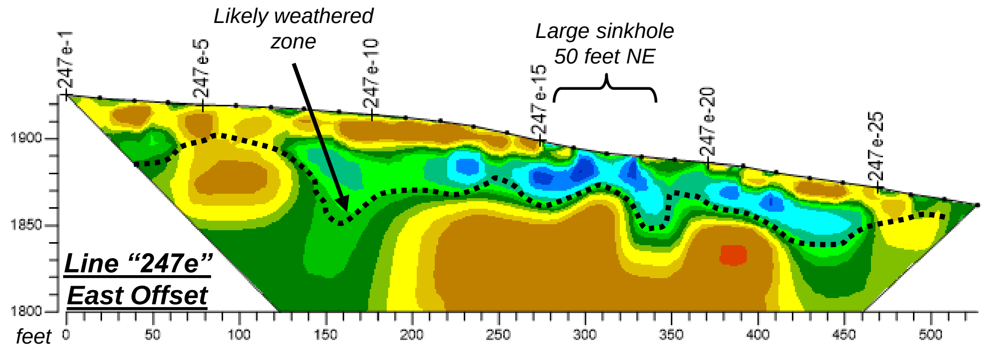
FIGURE 29

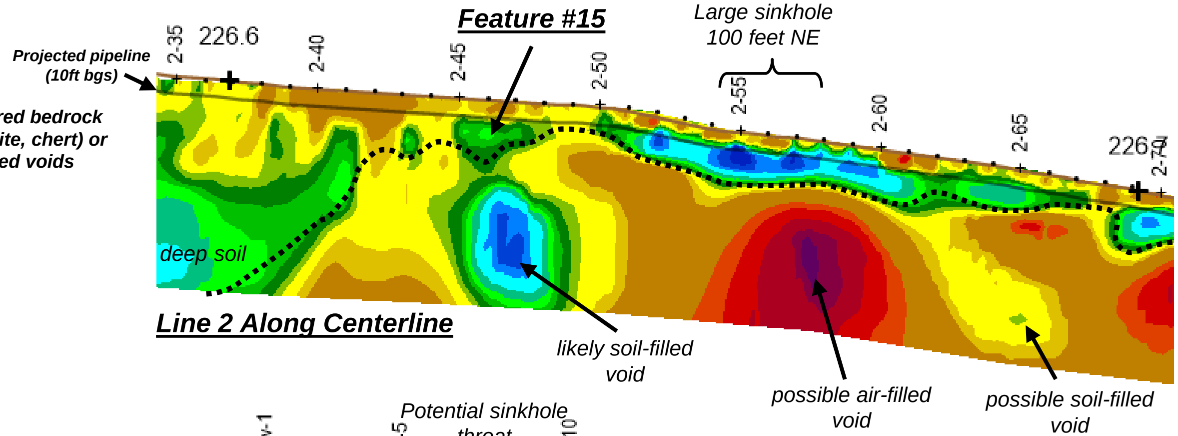
Possible Karst Feature #15 Follow-up
Near Milepost 226.63

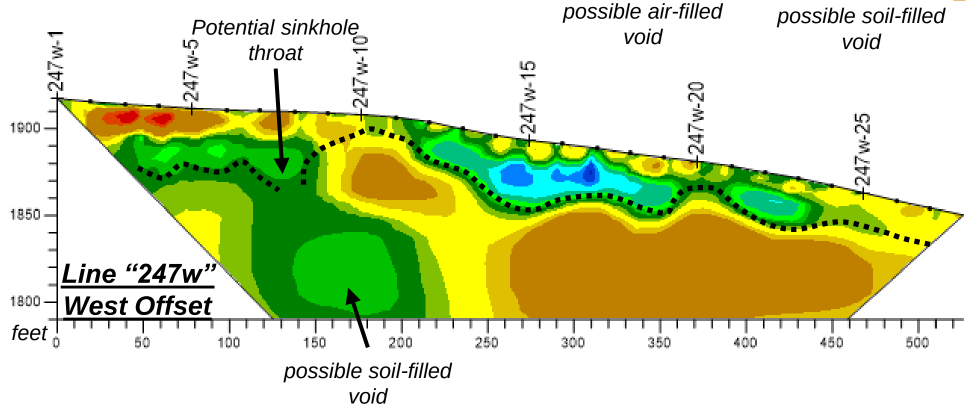
Resistivity Color Scale (ohm-meters) and Geologic Interpretations











= Field Staked Centerline / Coverage of ER Study

= MPV October 2016 Proposed Route

247w / 247e = Offset Resistivity Lines

Contours and Terrain Surface: VGIN 2007/2011 Terrain Models, shaded, contoured and colored for visualization purposes only. Any determination of topography or contours, or any depiction of physical improvements, property lines or boundaries is for general information only and shall not be used for the design, modification, or construction of improvements to real property or for flood plain determination.

= Interpreted top of bedrock

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Electrical Resistivity Imaging Study for the Mountain Valley Pipeline
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Blacksburg, VA
DAA Project Number: B14188B-02

FIGURE 30

Mountain Valley Pipeline Project

Docket No. CP16-10-000

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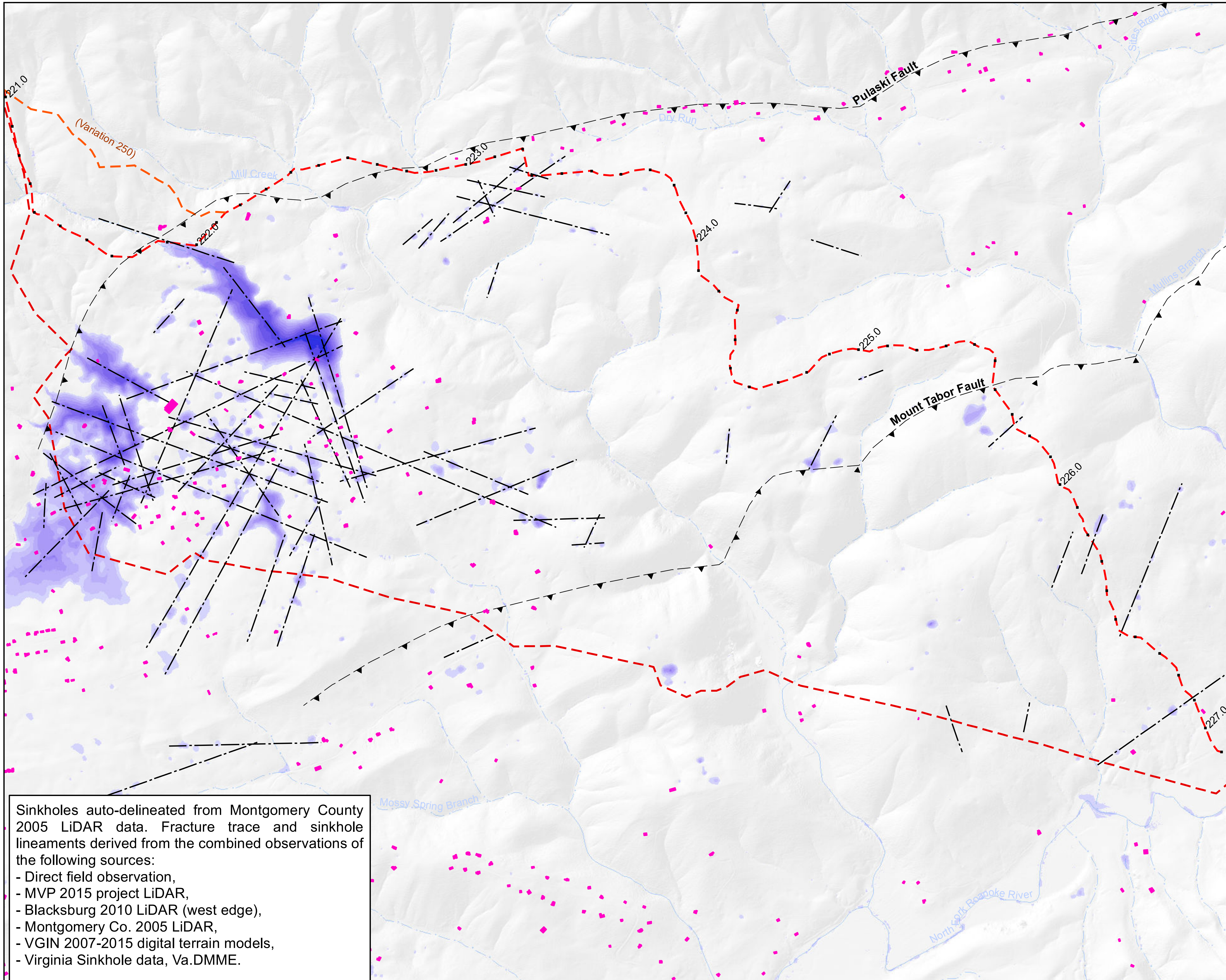
February 2017



Sinkholes auto-delineated from Montgomery County 2005 LiDAR data. Fracture trace and sinkhole lineaments derived from the combined observations of the following sources:
- Direct field observation,
- MVP 2015 project LiDAR,
- Blacksburg 2010 LiDAR (west edge),
- Montgomery Co. 2005 LiDAR,
- VGIN 2007-2015 digital terrain models,
- Virginia Sinkhole data, Va.DMME.

N

1:20,000

NAD 1983 UTM 17N

0 500 1,000 1,500 2,000 2,500 3,000 Feet

Service Layer Credits: Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Mountain Valley Pipeline Project

Mountain Valley PIPELINE

Fracture Trace and Sinkhole Lineaments
Mount Tabor Area
MVP October 2016 Proposed Route

Figure 1

02-10-17

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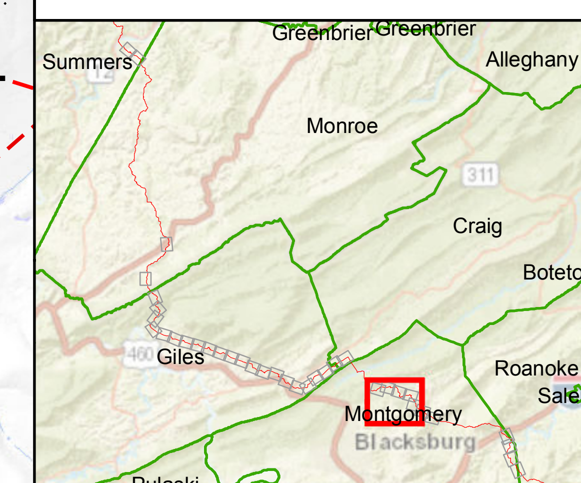
Legend

- Fault
- Fracture Traces and Sinkhole Alignments
- Sinkholes (Montgomery Co. 2005 LiDAR)
- Buildings (Montgomery Co GIS)
- Variation 250
- MVP October 2016 Proposed Route
- MVP FERC 4.0.0 Filing Alignment



Fault locations from field observation and the
Geologic map of the McDonalds Mill quadrangle, Virginia:
Coiner, L.V., Spears, D.B., and Henika, W.S., 2015,
Virginia Division of Mineral Resources 2015.

Background (light gray) Montgomery County 2005 LiDAR hillshade.

Document Path: P:\B14100\B14188B\B14188B-00\GIS\FERC Comments\Montgomery_Fractures\MtTabor Fracture Trace.mxd

Mountain Valley Pipeline Project

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Mountain Valley Pipeline Project

Docket No. CP16-10-000

Unanticipated Mine Pool Mitigation Plan

1.0 Introduction

Mountain Valley Pipeline, LLC (MVP, LLC), a joint venture between MVP Midstream Partners, LP and affiliates of NextEra Energy, Inc., WGL Holdings, Inc., RGC Midstream, LLC, and Con Edison Midstream, LLC is approximately a 303-mile, 42-inch-diameter natural gas pipeline traversing 17 counties in West Virginia and Virginia. The Project will extend from the existing Equitrans, L.P. transmission system and other natural gas facilities in Wetzel County, West Virginia to Transcontinental Gas Pipe Line Company, LLC's (Transco) Zone 5 compressor station 165 in Pittsylvania County, Virginia. In addition to the pipeline, the Project will include approximately 171,600 horsepower (hp) of compression at three compressor stations currently planned along the route, as well as measurement, regulation, and other ancillary facilities required for the safe and reliable operation of the pipeline. The pipeline is designed to transport up to 2.0 million dekatherms per day of natural gas.

2.0 Purpose

The purpose of this plan is to establish procedures for encountering unanticipated mine drainage situations that currently exist during the pipeline construction process. The procedures are designed to allow the pipeline construction to continue while protecting the pipeline and construction activities and having a neutral effect on the environment. The majority of the actions will follow routine water body and wetland crossing procedures.

The majority of encountered drainage should be associated with visible, and in some cases documented, surface flows. Construction may also expose some "unknown" sources of subsurface flow, but again, these will be pre-existing rather than new sources of mine drainage. It is important to understand that pipeline construction efforts should not create any new sources of acid mine drainage.

3.0 Procedure

Surface or ground water that comes into contact with areas disturbed by mining can be significantly altered by that contact. In the bituminous coal fields of Appalachia, low pH values and acidic conditions are common effects of degraded water quality as water is exposed to mined areas.

Mountain Valley will follow FERC's Wetland and Waterbody Construction and Mitigation Procedures which provide a standard for wetland and waterbody crossings. Incorporation of these standard procedures will accommodate handling of mine drainage encounters. Additional protocols identified below will also be incorporated into Mountain Valley's Construction Procedures for proper identification and applicability of proper drainage control methods.

Mine drainage encountered during trenching activities as a surface flow will typically be contained within one defined channel, or spread out across the surface of the ground in a series of smaller flows. Construction methods with channelized flow, or flow that can be readily channelized, can be managed utilizing the FERC Wetland and Waterbody Construction and Mitigation Procedures. Should an unanticipated mine pool be encountered, it is anticipated that the site specific construction method will be similar to "minor stream crossings" that can be completed within one to two days per crossing. Construction methods with non-channelized flow can follow the FERC Wetland and Waterbody Construction and Mitigation Procedures for the crossing of wetlands. This procedure is to be followed because of the saturated soil conditions often encountered in these diffuse flow situations.

Should an unanticipated mine pool disturbance occur during construction of the right-of-way preparation or during pipeline construction, Mountain Valley will follow the following procedure:

1. Construction activity in the immediate area will halt.
2. The equipment operator will inform the Construction Superintendent and Environmental Inspectors of the identified flow.
3. An inspector or qualified representative will evaluate the water and determine if it is related to mine drainage based on pH or mineral testing. Mine water typically has a blue or orange cast or smells of Sulphur. Water with a pH at or above 6 is essentially freshwater related to springs or surface runoff rather than mine drainage discharges and will be treated as such.
4. If the water has a pH below 6, the governing state environmental department (WV DEP or VA DEQ) will be contacted to discuss the situation and obtain concurrence on the handling of the encountered mine water.
5. Depending on the site specific situation, proper water handling can occur with various methods. A couple examples are described below:
    a. Surface flows will be channeled across the pipeline in the most direct manner possible under DEP or DEQ direction during construction and reclamation.
    b. Sub-surface flows will be contained in an earthen pit adjacent to the ditch excavation as construction continues so as not to obstruct its original flow prior to construction.
6. The water will be returned to its original path through drainage piping or other designed control devices under DEP or DEQ advisement during backfill and restoration.

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Mountain Valley personnel have utilized the proposed mitigation measures described in the Landslide Mitigation Plan and the JNF Site-Specific Stabilization document on previous pipeline alignments in the Appalachian region. One such example is the recently-completed Ohio Valley Connector pipeline. Also, the mitigation measures have been used as remediation techniques on older pipeline-related landslides. As many of these landslides are remediated via removing the slide material, installing drains or structural measures similar to those outlined in Mountain Valley's plan – and also replacing the slide material in compacted lifts – installing such mitigations during construction will have a high degree of success in preventing similar slope movements from occurring. Mountain Valley's landslide inspection team will be prescribing mitigations in addition to those included in the Landslide Mitigation Plan and JNF Site-Specific Stabilization document based on subsurface conditions encountered during construction.

The mitigations to be employed by Mountain Valley are consistent with those prescribed in INGAA's *Mitigation of Land Movement in Steep and Rugged Terrain for Pipeline Projects*. This document presents industry best management practices for mitigating landslide hazards in the Appalachian region. These best management practices have been employed on numerous pipeline projects in the Appalachian region and anecdotal evidence from recent projects indicates that employing these mitigations has decreased the incidence of earth movement observed on pipeline projects as compared to pipelines constructed without the benefit of these mitigation techniques.

Several examples of landslide mitigation and remediation measures installed on EQM pipelines are described below.

Example #1

The slope shown in Figure 1-1 was identified prior to construction as having an increased risk for sliding because colluvial soils were mapped in the area (per the USGS Landslide Hazard Maps) and the slope is steep (averaging approximately 27 degrees or 51 percent slope).

Water migrating along the trench between trench breakers, if not properly relieved, can pond behind them and eventually saturate the trench backfill and other soils adjacent to the trench. Water saturation increases the weight of the soil while reducing the strength of the soil, which can lead to a landslide. In order to mitigate against potential landslides, trench breaker drains were installed to discharge water from the trench at intervals throughout the hillside. These controls were installed during construction in July 2016, and have undergone several freeze/thaw cycles and large precipitation events. Figure 1-2 shows a close-up of the discharge point of one trench breaker drain on the slope with a rock apron to disperse flow before going off the ROW. No landslides have occurred on this slope to date.

Figure 1-1: Steep Slope at Road Crossing (photo taken 1/26/2017)

Figure 1-2: Close-up of Trench Breaker Drain Discharge Point (photo taken 1/26/2017)

Example #2

Figure 2-1: Steep Slope Stream Crossing (photo taken 1/26/2017)

The slope shown in Figure 2-1 was identified prior to construction as having an increased risk for sliding as it is located in an area with mapped colluvial soils (based on USGS Landslide Hazard Maps), the slope is steep (averaging approximately 34 degrees or 67.5 percent slope), and there is a stream crossing at the toe of the slope.

On-site rock was used to protect the toe of the stream embankment from erosion. Above the stream embankment, the pipeline trench was constructed through a rock ledge. Instead of backfilling the excavated trench with loose soil, a sakrete revetment was constructed in this area to provide stability to the trench. The revetment was constructed as follows:

1) Install sakrete trench breakers with trench breaker drains at 15 ft intervals
2) Backfill in between the sakrete trench breakers around the pipeline with sandbags
3) Place continuous layer of sakrete bags the width full width of the trench on top of the sandbags, allowing the trench breaker drains to daylight
4) Tie bags together by driving rebar through sakrete bags as specified in engineering details

These controls were installed in August 2016, and have undergone several freeze/thaw cycles and large precipitation events, including high stream elevations at the toe of the slope. No landslides have occurred in this area to date. Temporary E&S controls are still in place on Figure 2-1 as the project permit is not yet closed out.

Example #3

Figure 3-1: Remediated Slope (photo taken 1/26/2017)

During a routine pipeline inspection in March 2014, a landslide was discovered on the ROW shown in Figure 3-1. Pipeline construction was completed in November 2012. The following factors were identified as primary causes of the slide:

- Grading pattern and natural contours channeled surface runoff to this area
- Steep sidehill topography (approximately 15 degrees or 26.8 percent slope)
- Burial of organic material within the ROW (which will not be permitted on MVP)

Company geotechnical engineers developed a remediation plan and construction drawings to repair the slide, which also affected a large area downslope of the ROW. The remediation plan utilized the following controls, all of which are also used as slide mitigation controls:

- Rock lined swales to collect and divert surface runoff
- Cutoff drains to collect and divert groundwater
- Geogrid and compaction to increase shear strength of the backfilled soil

This remediation plan was executed in the summer of 2015 and has remained stable since the remediation was completed.

Example #4

Figure 4-1: Remediated Slope (photo taken 1/26/2017)

During a routine pipeline inspection in March 2014, a landslide was discovered on the ROW shown in Figure 4-1. Pipeline construction was completed in November 2012. The following factors were identified as primary causes of the slide:

- Natural swale channeled surface runoff to this area
- Presence of a slip-prone clay layer
- Steep sidehill topography (approximately 15 degrees or 26.8 percent slope)
- Burial of organic material within the ROW (which will not be permitted on MVP)

Company geotechnical engineers developed a remediation plan and construction drawings to repair the slide, which also affected a large area downslope of the ROW. The remediation plan utilized the following controls, all of which are also used as slide mitigation controls:

- Rock lined swales to collect and divert surface runoff
- Cutoff drains to collect and divert groundwater
- Geogrid and compaction to increase shear strength of the backfilled soil

This remediation plan was executed in the summer of 2015 and has remained stable since the remediation was completed.

Example #5

Figure 5-1: Remediated Slope (from Google Earth 10/5/2016)

During a routine pipeline inspection in August 2014, a landslide was discovered on the ROW shown in Figure 5-1. Pipeline construction was completed in December 2013. The following factors were identified as primary causes of the slide:

- Natural swale channeled surface runoff to this area
- Steep sidehill topography (approximately 32 degrees or 62.5 percent slope)

Company geotechnical engineers developed a remediation plan and construction drawings to repair the slide, which also affected a large area downslope of the ROW. The remediation plan utilized the following controls, all of which are also used as slide mitigation controls:

- Rock lined swales to collect and divert surface runoff
- Cutoff drains to collect and divert groundwater
- Compaction to increase shear strength of the backfilled soil

This remediation plan was executed in the fall of 2015 and has remained stable since the remediation was completed.

Example #6

Figure 6-1: Remediated Slope (from Google Earth 10/5/2016)

During a routine pipeline inspection in March 2014, a landslide was discovered on the ROW shown in Figure 6-1. Pipeline construction was completed in December 2013. The following factors were identified as primary causes of the slide:

- Roadway drainage concentrated to this area
- Steep sidehill topography (approximately 23 degrees or 42.4 percent slope)

Company geotechnical engineers developed a remediation plan and construction drawings to repair the slide, which also affected a large area downslope of the ROW. The remediation plan utilized the following controls, all of which are also used as slide mitigation controls:

- Rock lined swales to collect and divert surface runoff
- French drains to collect and divert groundwater

This remediation plan was executed in the fall of 2015 and has remained stable since the remediation was completed.

The landslide mitigation measures described in the Landslide Mitigation Plan were developed by analyzing landslides along pipelines constructed without the benefit of geotechnical best management practices (such as those described in examples 3, 4, 5, and 6). The proximate cause of most landslides along these older pipelines is saturation of trench backfill and associated fill soils by surface water or groundwater following the pipeline trench.

Many of the mitigation measures developed by Mountain Valley are subsurface and surface drains intended to prevent such saturation and associated loss of soil shear strength. Recent pipeline projects such as the

Ohio Valley Connector have employed these mitigation measures with success (as demonstrated in Examples 1 and 2). Since INGAA's publication of *Mitigation of Land Movement in Steep and Rugged Terrain for Pipeline Projects*, similar techniques to those already employed by Mountain Valley personnel have become industry best management practices for constructing pipelines in the Appalachian region.

Mountain Valley will employ these mitigation measures throughout the project, including but not limited to the areas described in the Landslide Mitigation Plan. Geotechnical inspectors will observe surface conditions and subsurface conditions revealed during construction and recommend additional mitigation measures as necessary to minimize the risk of landslides associated with the pipeline. Based on the success of recent projects such as the Ohio Valley Connector and the publication of INGAA's document as a best management practice, Mountain Valley believes that the mitigations described and illustrated in the landslide mitigation plan are effective means of mitigating the risk of landslides along the project route.