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Delaware River Deepening Project
Resistivity Survey

Reach B – Stations 96+000 to 157+000

FINAL
Delaware River Deepening Project
Resistivity Survey
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Report: Delaware River Deepening Project Resistivity Survey
Reach B - Stations 96+000 to 157+000
July 2012

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Contents

Attached Figures

1. Introduction

As requested by Gahagan & Bryant Associates, Inc. (GBA), a geophysical survey was conducted by Dexco (Dexco is the US subsidiary of the parent company Demco NV) on the Delaware River from Stations 139+000 to 157+000 and Stations 120+000 to 127+000 for an upcoming dredging project organized by the US Army Corps of Engineers for the Port of Philadelphia. Additionally, Dexco was contracted to re-plot and review resistivity data collected in 2009 (Stations 96+000 to 140+000) based on boring data collected since the 2009 resistivity survey was performed.

The purpose of the survey was to acquire additional information about the geological structures of the riverbed to assist in the evaluation of materials expected to be encountered in future dredging operations.

The resistivity survey was performed between January 10 and 12, 2012. A total of 86 resistivity line miles were surveyed in order to develop a three dimensional (3D) model of the material's resistivity underlying the river channel bottom.

2. Method(s)

For the requested survey, the Aquares resistivity method was applied. The Aquares resistivity method utilizes a bottom towed multichannel cable, which is designed for penetrating to depths of approximately 10 meters.

2.1. Land based applications

An electrical current is injected into the subsurface by means of two current electrodes. The voltage gradient associated with the electrical field of this current is measured between two voltage electrodes placed in between the current electrodes (see Figure A). Based on the measured values of current and voltage the average resistivity of the subsurface is calculated for a subsurface volume down to a certain penetration depth. The penetration depth depends on the distance between the current electrodes. Larger electrode distances are correlated to deeper penetration depths.

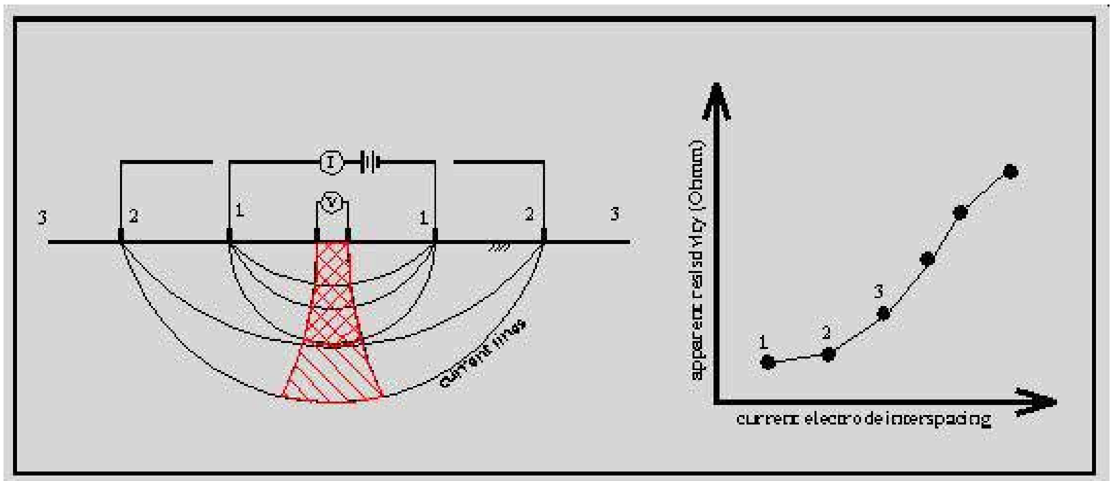

Figure A: Principles of Vertical Electrical Sounding

If the measurements are repeated with progressively increasing current electrode distances, information is obtained from progressively deeper geological structures (Figure A). As such, a field curve is obtained showing the resistivity as a function of the (horizontal) distance between the current electrodes. After computer modeling, this field curve is transformed into a real geophysical subsurface section showing the resistivity as a function of depth.

The resistivity of a geological structure depends on its porosity, water saturation, and water resistivity as well as other physical and chemical parameters of the soil and rock materials and interstitial fluids. In most geological materials, the conduction of electric current primarily occurs through water occupying the pore spaces or fractures, and thus the materials themselves are generally nonconductive. This results in the porosity becoming a major factor in controlling the conductivity or resistivity of a soil or rock material. Gravel generally has a lower porosity than sand and thus its resistivity is higher. Clay with generally a very high porosity shows a very low resistivity. Rock generally has a low porosity and shows a very high resistivity. Weathered rock tends to show a low resistivity. Varying geological structures can be distinguished from each other based on their specific resistivity.

2.2. *Fluvial and marine applications*

For water based applications the electrodes are placed on a multichannel cable trailing behind the survey vessel (Figure B). The electrode geometry is chosen such that good quality data may be obtained even for shallower targets.

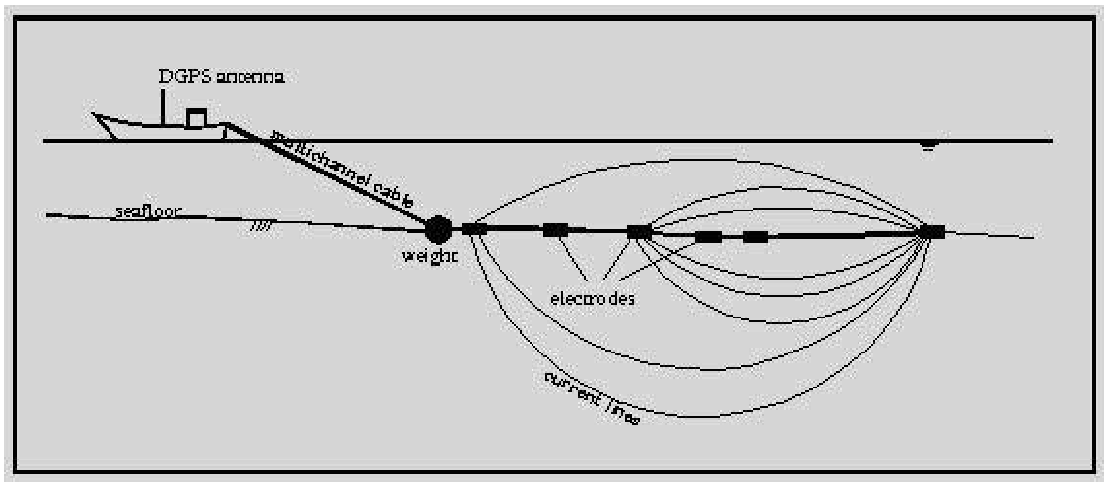

Figure B: Marine/Fluvial Applications

While the survey vessel is sailing, the measurements are carried out and stored automatically without any intervention from the operator. An entire electrical sounding may be obtained every second. At a boat speed of 2 m/s this corresponds to a horizontal resolution of 1 sounding every 2 meters.

The time of measurement is stored with each resistivity measurement. This gives the opportunity to synchronize the resistivity data with the Differential Global Positioning System (DGPS) positioning data, bathymetric information (echo-sounder), and tidal information.

During the field survey, qualitative results are immediately shown on the computer screen. The quality of the field data may be monitored in real time so the operator can adjust and optimize the survey parameters at any time.

2.3. Data processing and interpretation

A complicated sequence of mathematical operations has to be followed before interpretable results are obtained.

First the resistivity field data is edited and filtered to increase the signal/noise ratio. The processed bathymetric and positioning data is then combined with the resistivity data to develop a three dimensional model of the results.

Geometrical corrections are applied to correct for the fact that the sailed line (and the cable as well) may show more or less significant curvatures. Measurements made with a strongly curved cable are rejected. In the case of a bottom towed cable, other corrections are made to account for the water depth. A water correction requires homogeneous vertical water column resistivity or a detailed knowledge of vertical resistivity layering associated with chemical and physical properties of the water, which are monitored at various depths.

An important phase in the processing sequence is the resistivity data inversion. In this step, the apparent resistivity data is transformed into a vertical section of the subsurface showing depths and thickness of the varying resistivity measurement.

The resistivity information is interpolated into a regular grid either on a cross section or in two dimensions. Each interpolated grid point represents a complete geological profile of the subsurface showing the resistivity as a function of depth. The results are visualized in color on cross sections showing the different geological structures in function of depth and geographical position. The results can be calibrated with information obtained by physical geotechnical investigations (including test pits, vibracoring, Standard Penetration Test (STP) borings, and or coring, etc) in order to correlate physical data with resistivity data for geological structures.

The processing procedure described above is an iterative process. In order to extract the most information out of the raw survey data the processing sequence has to be repeated several times to find the optimum processing parameters.

3. Data acquisition

A bottom towed cable was used with an approximate penetration depth of about 10 meters. GBA provided their survey vessel, "Sea Fix", including a full hydrographic system to tow the cable and provide positioning data. Only minor delays were encountered during the survey, which included normal ship traffic and ongoing maintenance dredging activities.

4. Results

4.1. Bathymetry

Figure 1 shows the bathymetry of the entire survey area as acquired by GBA by multibeam hydrographic survey immediately after the resistivity survey and digitized into a 10x10 ft^2 grid. The survey lines were run parallel to the channel axis at approximately 50 ft intervals to ensure 100 percent survey overlap. Bathymetric elevations are provided relative to the Mean Lower Low Water (MLLW) datum and are color coded based on depth.

The sailed lines (during the resistivity data collection) and all vertical resistivity section cut lines are shown in Figure 3 as well as the boring locations provided by GBA.

4.2. Resistivity sections

After the application of geometrical and water corrections, the water corrected apparent resistivities are inverted and interpolated into a regular grid in order to obtain a 3D model of the subsurface. This allows a number of vertical and horizontal cross sections to be presented.

Figures 2a through 2g show the vertical resistivity sections running at 100 ft offsets parallel to the channel limits.

Figure 3 provides the plan view drawing of where the vertical resistivity sections were cut from the 3D resistivity model. The vertical resistivity sections are color coded following the legend shown. A vertical exaggeration of 100x was applied. Very high resistivity values are shown in purple (>400 Ohmm), high resistivity values are shown in red and brown (200-300 Ohmm), intermediate resistivity values are shown in yellow and green (40-80 Ohmm), and low resistivity values in shades of blue and grey (< 40 Ohmm).

The boring results are projected onto each of the vertical resistivity sections. Additionally, the -45, -47, and -49 ft MLLW elevation is marked and labeled on each vertical section. These elevations also indicate the elevations at which horizontal sections were cut from the 3D model (see Figure 3).

Low resistivity values (< 40 Ohmm) tend to correlate with soft sediments including silt, gravelly silt, gravelly sand, silty clay and silty sand. Intermediate resistivity values (green-yellow-orange: 40-200 Ohmm) usually correlate with soft, weathered and fractured gneiss often described as gravel and saprolite in the borings. High and very high resistivity values (red-brown-purple: >200 Ohmm) usually correlate with hard gneiss showing no or modest fracturing in the borings. Very high resistivity values (purple: >400 Ohmm) also correlate with river bed gravels resting on top of gneiss. From the borings it is not always clear if the gravel is riverbed gravel or weathered gneiss. Riverbed gravels are expected to have very high resistivity values because they generally have very low clay content while softer gravel fractions with higher clay content tend to disintegrate during transport along the river bed.

4.3. Vertical resistivity sections – Stations 139+000 to 157+000

Figure 2a shows the vertical sections from Stations 139+000 to 157+000 at 400, 300, 200 and 100 ft west of the centerline. Figure 2b shows the vertical sections from Stations 139+000 to 157+000 at the centerline itself and 100, 200, 300 and 400 ft east of the centerline.

In general a high resistivity top structure is found resting on top of a low resistivity base structure. As suggested by the borings the high resistivity top structure correlates with gravel and sand resting on top of low resistivity silt and silty clay. The lower part of the sand and gravel deposits appears to show slightly lower resistivity values (yellow-red: 60-300 Ohmm) as compared to the very high resistivity top gravels (magenta: >400 Ohmm) most likely due to their higher silt content.

At 143+000 ft a high resistivity anomaly extending over the entire depth range is most likely related to noise resulting from to a trench structure at the surface as visible in the west sections (Figure 2a).

In the upstream reaches (NE) the gravel deposits appear to be thickening and around 140+500 to 139+000 (Figure 2b) a high resistivity structure (magenta: >400

Ohmm) appears to be rising up to the surface. These high resistivity structures appear to be related to hard gneiss.

In the sections situated east of the centerline, the high resistivity sand and gravel deposits on the riverbed appear to be thinning. At section 200 ft east between 155+200 and 151+600 ft structures are seen at the surface resembling current ripples in sand (sand waves).

4.4. Vertical resistivity sections – Stations 120+000 to 127+000

Figure 2c shows a number of vertical resistivity sections spaced every 100 ft in Stations 120+000 to 127+000. Figure 2c shows all of the vertical sections (400 ft West to 400 ft East).

The high resistivity top sand and gravel appears in general to be considerably thinner and often absent as compared to Stations 139+000 to 157+000 ft. In the upstream reaches of the survey area between 121+600 and 120+000 ft very high resistivity structures (magenta: > 400 Ohmm) are rising up to dredge level in the western sections and are interpreted as hard gneiss. At 122+800 another high resistivity pinnacle rises up to the -49 ft MLLW mark. The rocky base structures appear to be deepening towards the eastern sections.

4.5. Vertical resistivity sections – Stations 96+000 to 120+000 and Stations 120+000 to 140+000

Figures 2d through 2g show vertical resistivity sections from the data collected during the 2009 resistivity survey. Demco NV was contracted to re-plot the vertical resistivity sections based on new boring data collected since the 2009 resistivity survey was performed. Further information can found in the resistivity report R090310a4 entitled Delaware River Deepening Project Resistivity Survey prepared in March 2009.

Dexco utilized the 2009 resistivity survey data and repotted the data with the new geotechnical information. No significant changes were observed. All plots are provided in Figures 2d through 2g.

4.6. Horizontal resistivity sections

Figure 3 shows a number of horizontal resistivity sections for Stations 120+000 to 127+000 and Stations 139+000 to 157+000 at elevations of 45, 47 and 49 ft below the MLLW. The same color scale is used as for the vertical resistivity sections.

On the horizontal section at 45 ft below MLLW, Stations 139+000 to 157+000 show very high resistivity values correlating with river gravels along the central part of the channel with slightly lower but still high resistivity values correlating most probably with a higher silt content within the sand and gravel deposits underneath the very high resistivity top gravels along the western rim of the channel.

At -47 ft MLLW the highest resistivity values have mostly been replaced by the slightly lower resistivity (silty) sand and gravel deposits underlying the very high resistivity top gravels except for the deeper parts of the channel where the very high resistivity top gravels still are visible. In the upstream portion of the Bellevue Range between Stations 140+000 and 139+000 ft there is a very high resistivity spot in the vicinity of boring CB-254, which marks the location of the hard gneiss. Along the eastern edge of the channel between 145+00 and 139+00 a low resistivity rim appears marking the presence of silty sediments. In the upstream portion of the Marcus Hook Range around Station 120+500, the hard gneiss outcrop is described by boring CB-289.

At -49 ft MLLW the southern half of Bellevue Range between Stations 150+000 and 157+000 shows intermediate resistivity values (green-yellow: 40-100 Ohmm) in the channel correlating with silty sand and gravel deposits and low resistivity values outside the channel correlating with silty sediments. In the northern half of Bellevue Range between Stations 139+000 and 157+000 intermediate to high resistivity values (silty sand and gravel deposits) are found most everywhere except for the eastern edge of the channel where low resistivity values mark the presence of silty sediments. Very high resistivity values (magenta: >400 Ohmm) mark the location of hard gneisses. In the northern section of the Marcus Hook Range between 120+100 and 120+800 the very high resistivity values of the hard gneiss pinnacles are covering a more significant area and a new very high resistivity spot is marked along the western edge of the survey area between Stations 121+000 and 121+500.

5. Conclusions

The Bellevue Range, between Stations 139+000 and 157+000, yielded varying results in the northern and southern extents of the range. In the northern portion of the range, very high resistivity river bed gravels overlay slightly lower resistivity sediments correlating with sand and gravel with a higher silt and at deeper elevations silt and silty clay is found. Also a number of hard gneiss outcrops are found marked by very high resistivity values, which generally extend vertically through the full cross-section. In the southern portion of the Bellevue Range, intermediate to low resistivity levels were recorded, indicating sand and gravel which correlates to Borings CB-309 through CB-312.

In the Marcus Hook Range between Stations 120+000 and 127+000 river bed gravels are less common, less thick and often absent. A high resistivity gneiss base structure is seen in the northern portion of the range above -55 FT MLLW with some rock outcrops rising above -49 FT MLLW. The majority of the reach resistivity is very low and correlates to silts and clays and is similar to material encountered during annual maintenance dredging preformed in this area.

In general a very good correlation is found between the provided geotechnical data and resistivity values to such extent that even hard (moderately fractured) and soft/fractured gneisses can be distinguished based on resistivity results. Since river gravels and hard gneisses are both marked by very high resistivity values, the distinction between both geological structures is to be carried out by looking at the lateral extent of both very high resistivity structures. The gneisses always extend to deeper levels while gravels usually form thinner deposits with a larger lateral extent.

6. Recommendations

In evaluating the efficiency and effectiveness of the Aquares resistivity survey results from the current investigation, it is recommended that for future exploration strategies, the Aquares resistivity survey be conducted prior to the performance of the drilling operations. This may enable a smaller number of boreholes to be carried out on a limited number of very specific drilling locations selected based upon the resistivity results. The drilling results can be used to specify the nature of the material to be dredged whereas the resistivity results would provide a better estimate of the extent and volumes of the dredge material. The result would provide a well-defined geological profile involving lower dredging risks and, as a consequence, more cost effective dredging rates offered by the dredging contractors responding to a detailed understanding of the subsurface conditions.

7. Limitations

The Contractor may rely upon the general accuracy of the technical data contained in this report and drawings, but such reports and drawings are not to be misinterpreted as completely accurate based on current technology. The information presented in this report is provided as a guide to interpreting the subsurface conditions beneath the channel. The actual subsurface conditions may deviate from those indicated by DEMCO's interpretation of the acquired data. The Contractor may not rely upon or make any claim against the Owner, or any of their related entities with respect to the completeness of this report and drawings for the Contractor's purposes, including, but not limited to, any aspects of the means, methods, techniques, sequences, and procedures of construction to be employed by the Contractor; or other data, interpretations, opinions, and information contained in this report or shown or indicated in the drawings; or any Contractor interpretation of or conclusion drawn from any technical data or any such other data, interpretations, opinions, or information.

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DEMCO Dredging Exploration Mining Consultants Demco NV Wintershovenstraat 8 B3722 Wintershoven Belgium tel. +32-11-371197	Client: GBA ENGINEERS ★ SURVEYORS Gahagan & Bryant Associates, Inc. 9008 Yellow Brick Rd, Unit O-P Baltimore, MD 21237 USA tel. +1 (410) 682-5595 **Gahagan & Bryant Associates, Inc.**	Project: **Delaware Deepening Project 2012 Resistivity Survey**	**Bathymetry** **(In Feet Relative to MLLW)**	**Figure 1**	File: Figure 1.dwg Date: June 2012 Scale: 1" : 800 ft Report: R120216a

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DEMCO Dredging Exploration Mining Consultants Demco NV Wintershovenstraat 8 B3722 Wintershoven Belgium tel. +32-11-371197	Client: GBA ENGINEERS ★ SURVEYORS Gahagan & Bryant Associates, Inc. 9008 Yellow Brick Rd, Unit O-P Baltimore, MD 21237 USA tel. +1 (410) 682-5595 **Gahagan & Bryant Associates, Inc.**	Project: **Delaware Deepening Project Resistivity 2012 Survey**	**Vertical Resistivity Sections at 400, 300, 200, & 100 ft West of the Centerline Stations 139+000 to 157+000**	**Figure 2a**	File: Figure 2A_139+000-157+000.dwg Date: June 2012 Scale: horizontal: 1" : 500 ft vertical: 1" : 5 ft Report: R120216a

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Project:

Delaware Deepening Project Resistivity 2012 Survey

Vertical Resistivity Sections
at the Centerline, 100, 200, 300 & 400 ft East of the Centerline
Stations 139+000 to 157+000

Figure 2b

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Date: June 2012

Scale: horizontal: 1" : 500 ft
vertical: 1" : 5 ft

Report: R120216a

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Vertical Resistivity Sections
at 400, 300, 200, 100 ft West of the Centerline, Centerline & 100, 200, 300, 400 ft East of the Centerline
Stations 120+000 to 127+000

Figure 2c

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Date: June 2012
Scale: horizontal: 1" : 500 ft; vertical: 1" : 5 ft
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Vertical Resistivity Sections
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Stations 96+000 to 120+000

Figure 2d

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Scale: horizontal: 1" : 500 ft
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Vertical Resistivity Sections
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Stations 96+000 to 120+000

Figure 2e

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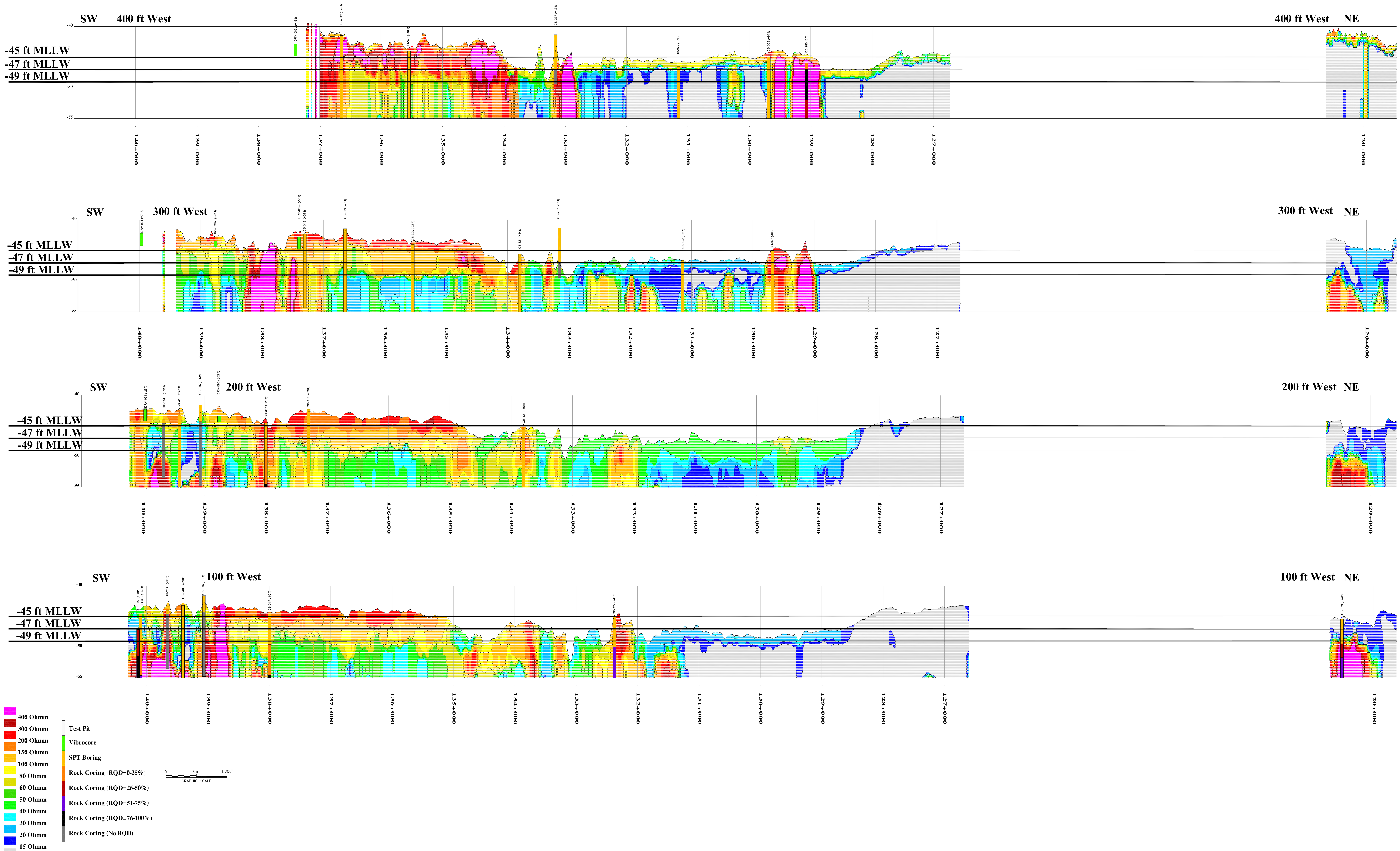

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Delaware Deepening Project Resistivity 2009 Survey

Vertical Resistivity Sections
at 400, 300, 200 & 100 ft West of the Centerline
Stations 120+000 to 140+000

Figure 2f

File: Figure 2F-120+000-140+000_west.dwg
Date: June 2012
Scale: horizontal: 1" : 500 ft
vertical: 1" : 5 ft
Report: R120216a

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Vertical Resistivity Sections
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Stations 120+000 to 140+000

Figure 2g

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Date: June 2012

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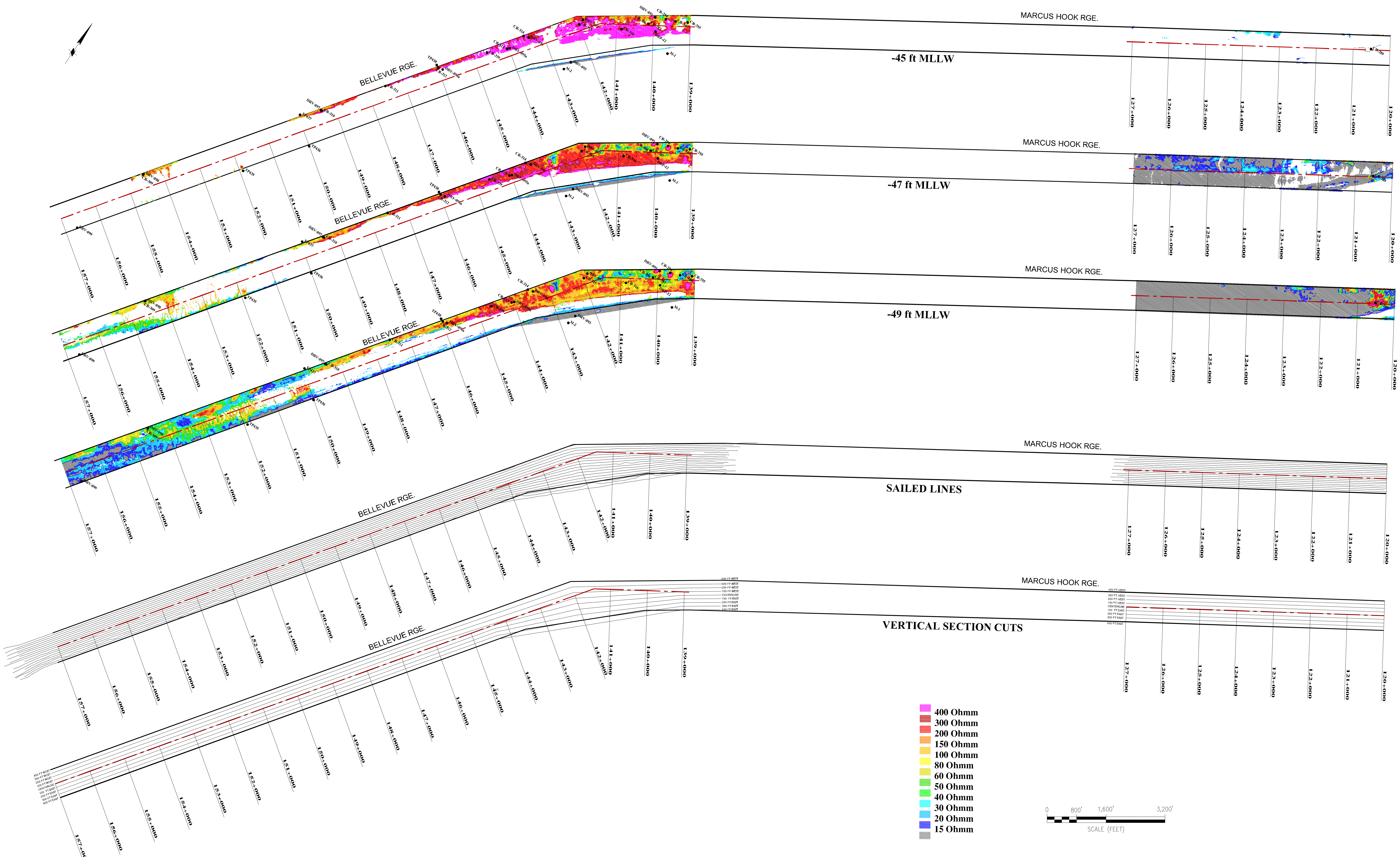
Report: R120216a



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DEMCO Dredging Exploration Mining Consultants Demco NV Wintershovenstraat 8 B3722 Wintershoven Belgium tel. +32-11-371197	Client: Gahagan & Bryant Associates, Inc. 9008 Yellow Brick Rd, Unit O-P Baltimore, MD 21237 USA tel. +1 (410) 682-5595 **Gahagan & Bryant Associates, Inc.**	Project: **Delaware Deepening Project 2012 Resistivity Survey**	**Horizontal Resistivity Sections** **at 45, 47, & 49 ft Below MLLW, Sailed Lines, and Vertical Section Cuts**	**Figure 3**	File: Figure 3.dwg Date: June 2012 Scale: 1" : 800 ft Report: R120216a