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Geology and Geophysics
Subsurface Exploration Non-Destructive Evaluation

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February 21, 2014

US Army Corps of Engineers
Geotechnical Branch
PO Box 532711
Los Angeles, California 90053-2325

Attention: Mr. James Farley

Re: **FINAL REPORT**
Seismic Refraction Profiling for Subsurface Investigation of Winslow Levee, Winslow, Arizona
US Army Corps of Engineers Contract: W912PL-13-P-0030

INTRODUCTION

This report summarizes the recent seismic refraction profiling completed for the subsurface investigation of the Winslow Levee. In accordance with our proposal dated July 15, 2013, seismic refraction surveys were conducted along ten survey lines positioned by the US Army Corps of Engineers across the levee embankment. These survey lines were positioned to investigate the depth profile of the bedrock surface and lithologic conditions within the alluvium and Moenkopi Formation bedrock unit.

The seismic refraction surveys were performed by Advanced Geoscience on September 16 through September 24, 2013. Refraction tomography data were recorded along the ten survey lines designated as Lines 1 through 10, shown on the topographic maps in Figures 1 through 4. These data were used to prepare subsurface profiles showing seismic compressional-wave velocity variations in the upper 120 feet.

The following sections provide a summary of our field survey procedures and methods of data processing and evaluation. A concluding section discusses the results of this seismic refraction profiling and our interpretation of subsurface conditions beneath Lines 1 through 10.

FIELD SURVEY

Advanced Geoscience arrived at the project site on September 16 and started the seismic surveys on Line 1 the northern-most survey line. The initial data recorded on Line 1 showed that the 90-pound, accelerated weight drop provided sufficient seismic energy to record longer geophone lines consisting of more than 100 geophone channels spaced 10-feet apart. Due to the more difficult terrain conditions, these longer geophone lines helped facilitate the data collection along Lines 1 through 10, which was completed on September 24.

The seismic refraction tomography data were recorded along each survey line using a multi-channel Seistronix EX-6 seismic data acquisition system. This recording system was connected to various "geophone lines" set up along the survey lines. Lines 1, 3, 5, 8, 9, and 10 were recorded using one geophone line consisting of 82 to 102 geophones spaced 10-feet apart. The longer-length, Lines 2, 4, 6, and 7 were recorded using two overlapping geophone lines consisting of 102 to 108 geophones spaced 10-feet apart. The geophones used were 14-Hertz (low-cut frequency), vertically-aligned velocity transducers. The total length of geophone coverage setup along each survey line is listed below.

Line 1	900 feet
Line 2	1,490 feet
Line 3	1,010 feet
Line 4	1,550 feet
Line 5	810 feet
Line 6	1,250 feet
Line 7	1,670 feet
Line 8	1,010 feet
Line 9	810 feet
Line 10	950 feet

The refraction data were recorded into each 82 or 108-channel geophone line from seismic energy "source points" positioned along the survey lines. The source points started at the west end of the geophone lines and continued to the east at 50 to 70-foot intervals between the geophone positions. Overlapping source points were recorded for the longer-length Lines 2, 4, 6, and 7 which were set up with two overlapping geophone lines. The last source point was positioned at the east end of the survey line.

The seismic energy source was generated using a 90-pound, accelerated weight drop mounted on a 4WD Polaris Ranger. This weight drop was used to impact a metal plate placed on the ground surface. To increase the signal-to-noise ratio several impacts were recorded at each energy source point and summed together to generate a single recording. At locations where the Polaris Ranger could not drive into a 20-pound sledge hammer was used to make multiple impacts on the metal plate. A two-man crew was used to deploy this equipment along the survey lines.

Line 4 was also used to record a small amount of data for multi-channel analysis of surface waves (MASW) near the center of this survey line. This data was used to prepare a one-dimensional shear-wave velocity profile to help interpret the alluvium-bedrock contact in this area. Active-source MASW data were recorded between stations 700 to 1,000 feet using a separate 28-channel geophone line set up with lower cut off frequency 4-Hertz geophones spaced 10-feet apart. These data were recorded with the accelerated weight drop in an “end-on” recording configuration. The first source point was positioned 20-feet west the first geophone position and recorded into 28 geophone positions from stations 720 to 990 feet. The second source point was positioned at station 710 feet and recorded in 28 geophone positions from stations 730 to 1,000 feet.

After the data recording was completed a DGPS survey was performed along each survey line to measure the coordinates and elevations of the starting and ending geophone positions. Additional geophone positions were also measured near the sharp breaks in topography along the survey lines.

DATA PROCESSING AND EVALUATION

The field record data quality for Lines 1, 2, 3, 4, 5, 7, 9, and 10 was mostly good to excellent. Lines 6 and 8, however, showed some noise interference in the longer-offset part of the field records which was caused by strong wind gusts on Line 6 and vehicle traffic from Interstate 40 on Line 8.

The field records from each survey line were input into the RAYFRACT seismic refraction tomography software developed by Intelligent Resources, Inc. (www.rayfract.com). RAYFRACT was used to generate seismic compressional-wave velocity depth profiles. This refraction tomography modeling procedure is generally more capable of imaging sharper lateral velocity variations due to bedrock channels than other refraction tomography methods and conventional two to four-layer refraction interpretation methods such as the Generalized Reciprocal Method (Sheehan et al., 2005).

RAYFRACT was first used to graphically pick first arrival times (“first breaks”) for refracted waves traveling through the surface layer and into deeper higher-velocity layers. These time-distance data were used together with geophone station coordinates and elevations to conduct refraction tomography imaging of the shallow seismic velocity layering. RAYFRACT generated an initial velocity-depth model based on the Delta TV method. This initial model was then refined to produce a closer fit to the arrival time data using the Wavepath Eikonal Traveltime (WET) tomographic inversion method with 60 to 80 iterations with a maximum velocity 3,500 m/sec. The best-fit velocity-depth models were then gridded and color contoured with SURFER (written by Golden Software, Inc.) to show estimated vertical and lateral velocity variations.

Figures 5 through 12 show the resulting refraction velocity-depth profiles for Lines 1 through 10. These profiles are displayed at three different horizontal scales (1 inch= 60, 80, and 100 feet) with a 2:1 vertical exaggeration to show as much detail as possible. Each profile is also displayed with a similar color velocity spectrum.

The MASW data recorded on Line 4 was processed using the SurfSeis software Developed by the Kansas Geological Survey (www.kgs.ku.edu/software/surfseis/). The 28-channel field records from the two source points were used to generate surface-wave amplitude displays of phase velocity versus frequency. These displays were used to pick dispersion curves for the fundamental-mode, Rayleigh wave. The resulting curves were used to conduct a least-squares inversion to calculate one-dimensional models of shear-wave velocity layering near stations 840 to 850 feet on Line 4. Figure 15 displays these shear-wave velocity depth profiles.

DISCUSION OF RESULTS

The bedrock depth profile beneath Lines 1 through 10 is interpreted to follow the yellow-highlighted 6,000 to 6,500 ft/sec velocity contours shown in Figures 5 through 14. This interpretation is consistent the MASW shear-wave velocity profiles from Line 4 which show a higher-velocity, 1,550 to 1,600 ft/sec shear-wave velocity layer near the depth of this yellow-highlighted surface (Figures 8 and 15). No borehole information on depth to bedrock was available; however, boreholes DWR DH-39 and DWR DH-32 located near Lines 1 and 2 ended their total depth in alluvium and help to support the interpretation of a deeper bedrock surface in this area.

The yellow-highlighted depth profiles (in Figures 5 through 14) show that the bedrock surface generally deepens to the north between Lines 1 and 10. The depth profiles also reveal the locations of possible ancient river channels (“paleo-channels”). The locations of these channels are noted on the profiles.

The most prominent paleo-channel is located beneath Lines 3 and 4 west of the levee. This channel appears to be over 100 feet deep with a north-south orientation that may extend to the north beneath the levee. Beneath Line 3 this channel is filled with lower-velocity, saturated alluvium, with compressional-wave velocity of 5,000 ft/sec or less. This lower velocity alluvium extends beneath the levee and occurs in the area where the 1993 levee breach and 2004 piping failure occurred.

Another prominent paleo-channel is located beneath Line 7, about 150 feet east of the levee. This channel also appears to be over 100-feet deep. However, this channel is filled with higher-velocity, saturated alluvium, with a velocity of 6,500 ft/sec. Based on our experience, compressional-wave velocities of 6,500 ft/sec in saturated alluvium indicate deposits of cobbles or boulders.

The upper-most groundwater surface (free “water table”) beneath Lines 1 through 10 occurs mostly in the finer-grained floodplain deposits with variable lateral permeability. For this reason this surface is mostly undetectable as a continuous layer on the refraction profiles. However, a separate analysis of the data on Line 1 made using a three-layer refraction model generated from the modified Generalized Reciprocal Method (GRM) in RAYFRACT shows a stronger refracting layer near the 3,000 ft/sec velocity contour in Figure 5. This indicates this mostly flat 3,000 ft/sec velocity horizon is probably near the upper part of the permeable groundwater layer beneath Lines 1 through 10.

RECOMMENDATIONS

Advanced Geoscience recommends that additional seismic surveys be performed to map the orientation of paleo-channels which could extend beneath the levee. In the area surrounding Lines 3 and 4 one paleo-channel is identified that could extend beneath the levee. To investigate this possibility a series of more closely-spaced surveys lines could be positioned from Line 4 to the north beyond borehole DWR DH-25. These survey lines could be set up to record both seismic refraction tomography and high-resolution seismic reflection profiles using the same setup of geophone lines. These profiles would provide a delineation of the depth and orientation of this channel and the seismic velocity conditions of the channel fill. Data on lithologic conditions from deeper test boreholes could also be integrated with these profiles to provide a more accurate evaluation of subsurface conditions.

Advanced Geoscience appreciates this opportunity to be of service to US Army Corps of Engineers. If you have any questions or additional requests concerning this seismic refraction profiling investigation please contact the undersigned.

Sincerely,

Advanced Geoscience, Inc.

Mark G. Olson
Principal Geophysicist
California Registered Professional Geophysicist No. GP970
California Registered Professional Geologist No. 6239

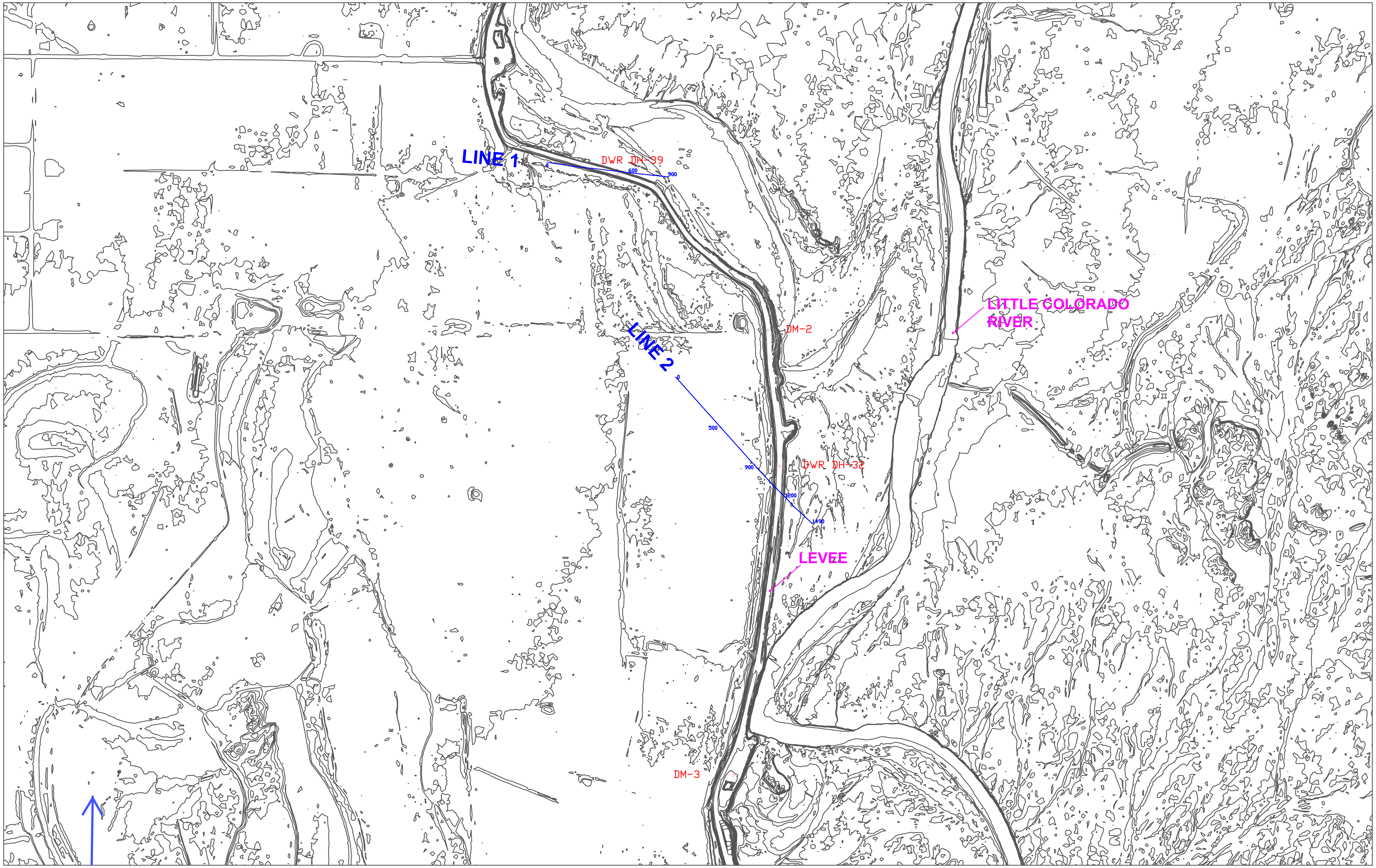
Attachments:

Figures 1-4	Maps Showing the Locations of Survey Lines 1 through 10
Figures 5-14	Seismic Refraction Profiles for Lines 1 through 10
Figure 15	Line 4 MASW Shear-Wave Velocity Profiling

References:

Sheehan et al., 2005, An evaluation of methods and available software for seismic refraction tomography, Journal of Environmental and Engineering Geophysics, volume 10, Environmental and Engineering Geophysical Society, March 2005.

Palmer, 1980, The Generalized Reciprocal Method of Seismic Refraction Interpretation, Society of Exploration Geophysicists, Tulsa, Oklahoma



North
Scale 1 inch= 600 ft
*Printed Scale Reduced to 1 inch= 800 ft

Map Showing Location of Survey Lines 1 and 2
Winslow Levee Seismic Refraction Surveys
Winslow, Arizona

Figure 1
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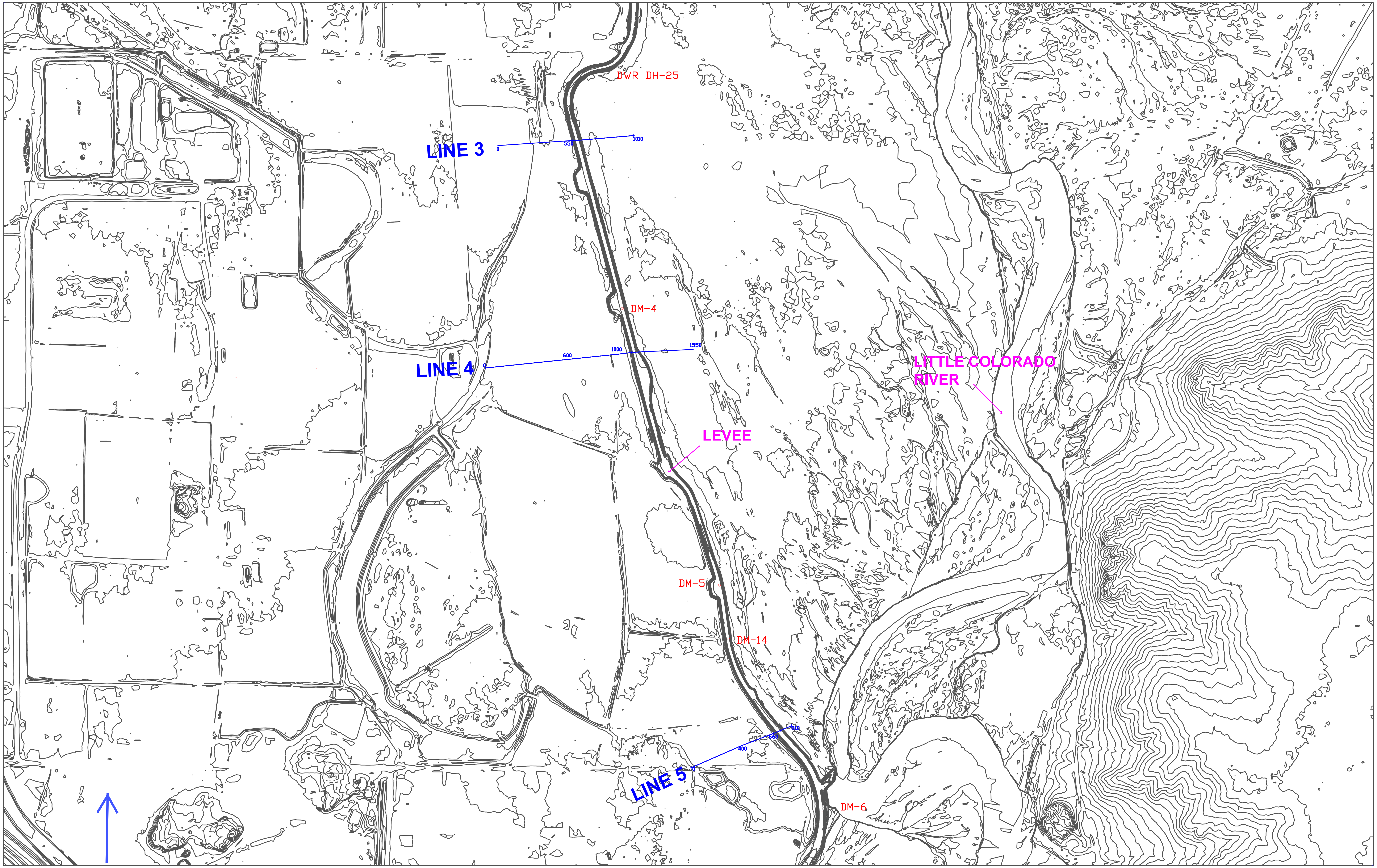
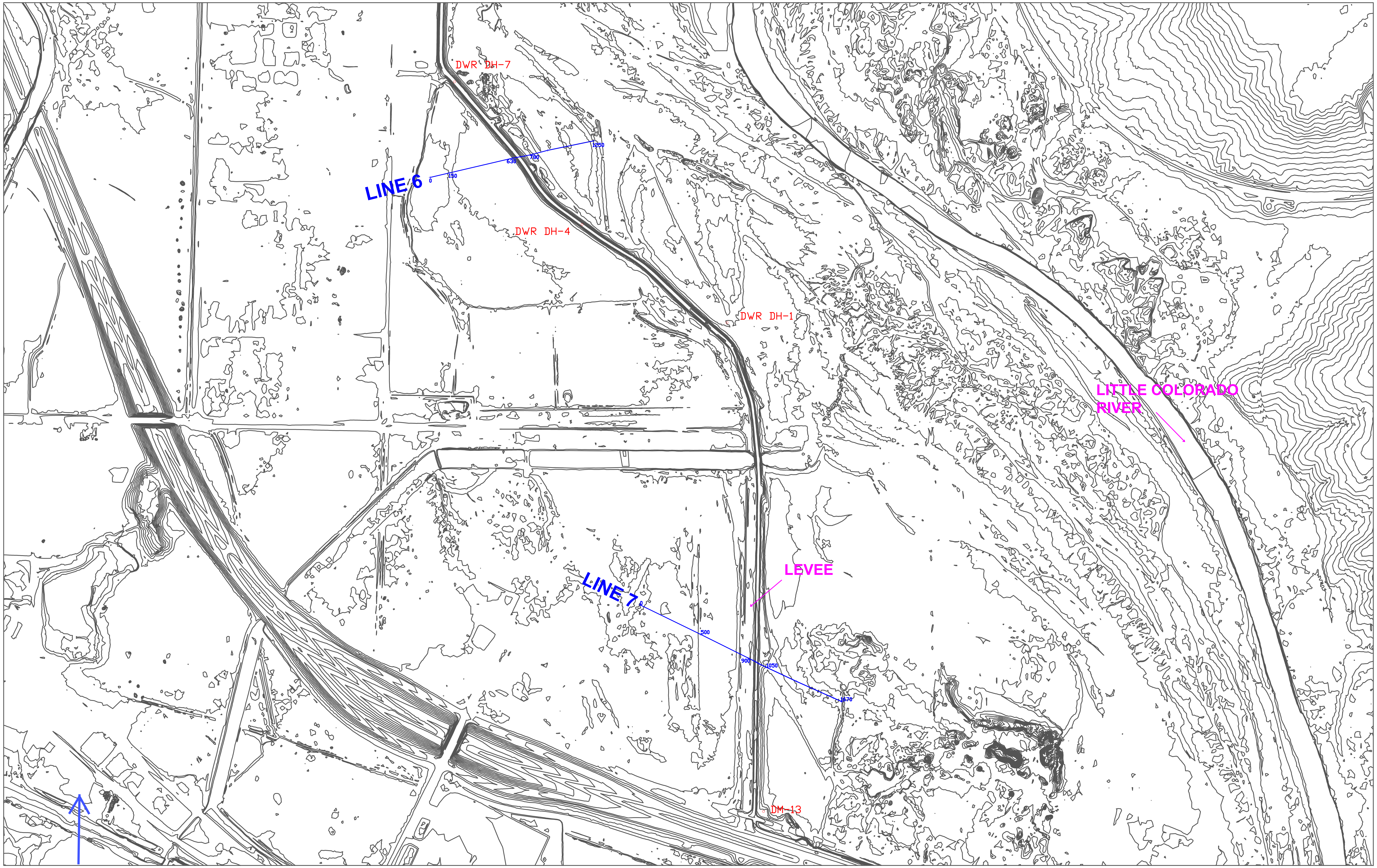


North
Scale 1 inch= 600 ft
*Printed Scale Reduced to 1 inch= 800 ft

Map Showing Location of Survey Lines 3, 4 and 5
Winslow Levee Seismic Refraction Surveys
Winslow, Arizona

Figure 2
Advanced Geoscience, Inc.



North

Scale 1 inch= 600 ft

*Printed Scale Reduced to 1 inch= 800 ft

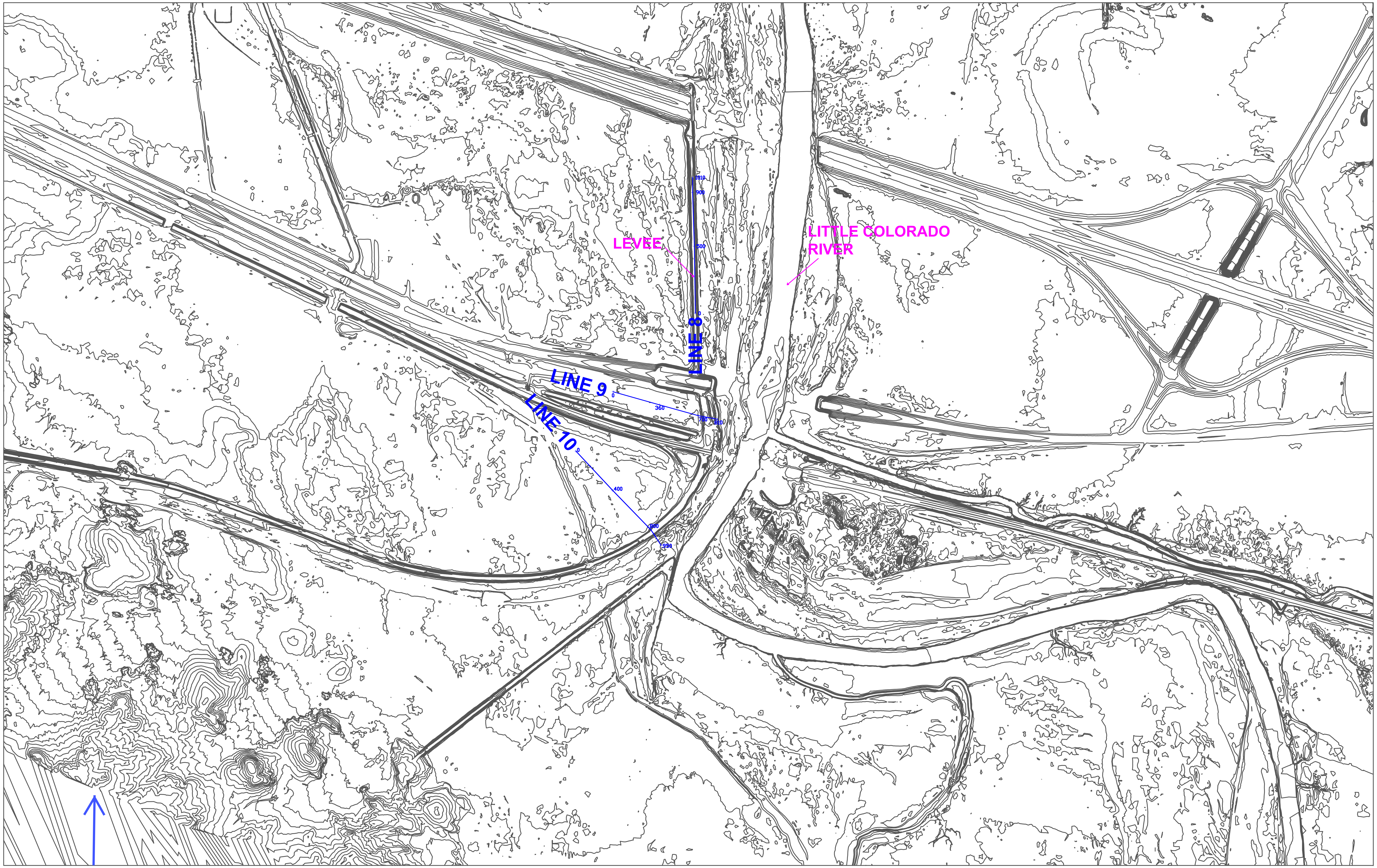
Map Showing Location of Survey Lines 6 and 7

Winslow Levee Seismic Refraction Surveys

Winslow, Arizona

Figure 3

Advanced Geoscience, Inc.



North
Scale 1 inch= 600 ft
*Printed Scale Reduced to 1 inch= 800 ft

Map Showing Location of Survey Lines 8, 9 and 10
Winslow Levee Seismic Refraction Surveys
Winslow, Arizona

Figure 4
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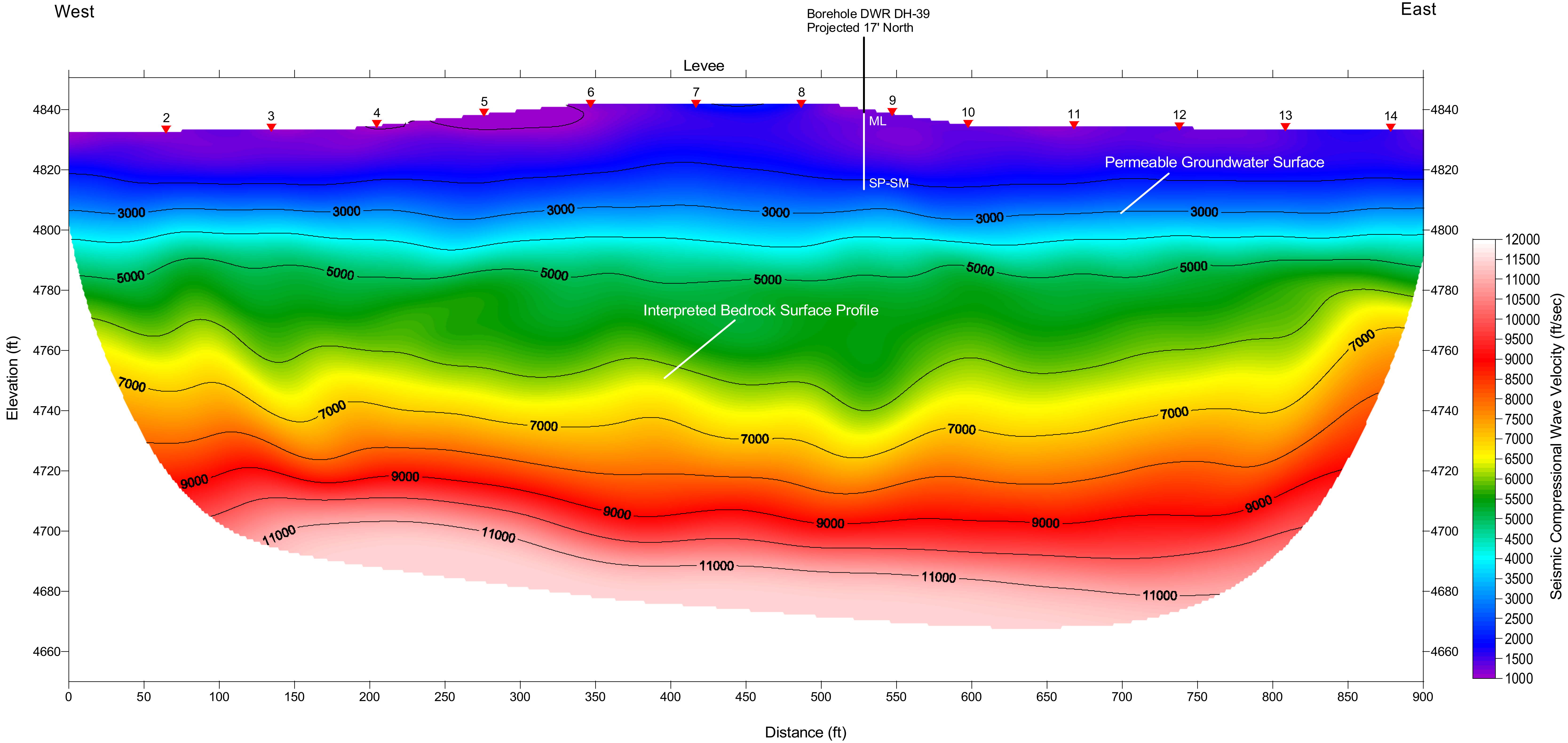
Line 1- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

0 50 100

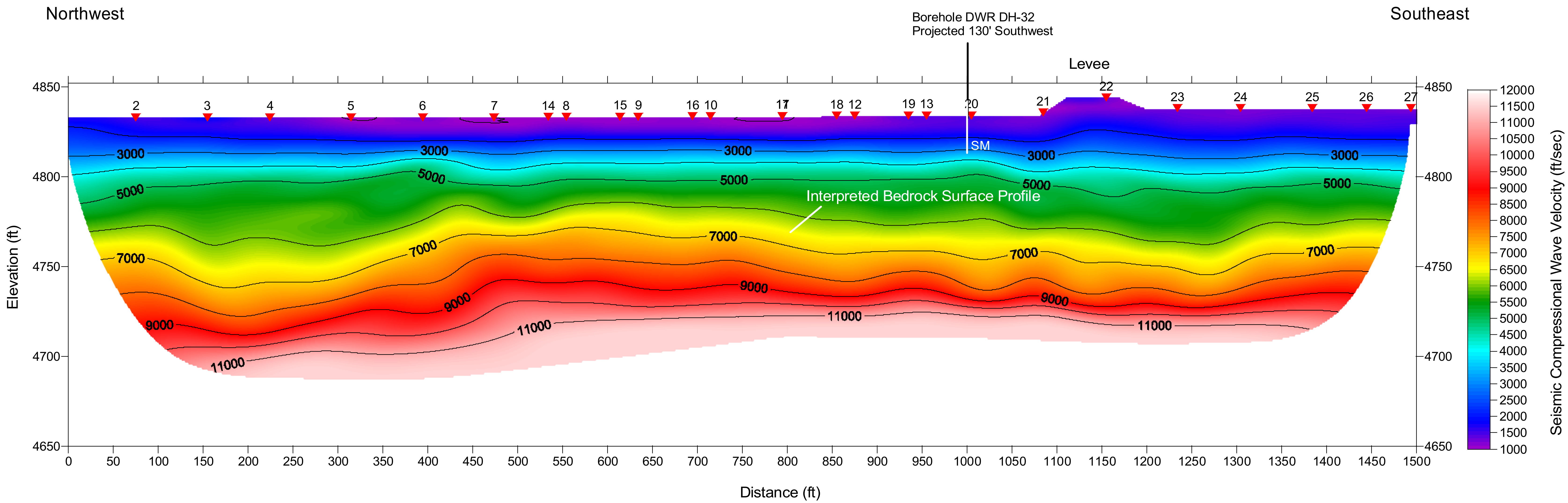
Horizontal Scale 1 inch= 60 Feet
Vertical Scale x2 1 inch= 30 Feet

*Printed Scale Reduced 75%

Line 1 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 5
Advanced Geoscience, Inc.

Line 2- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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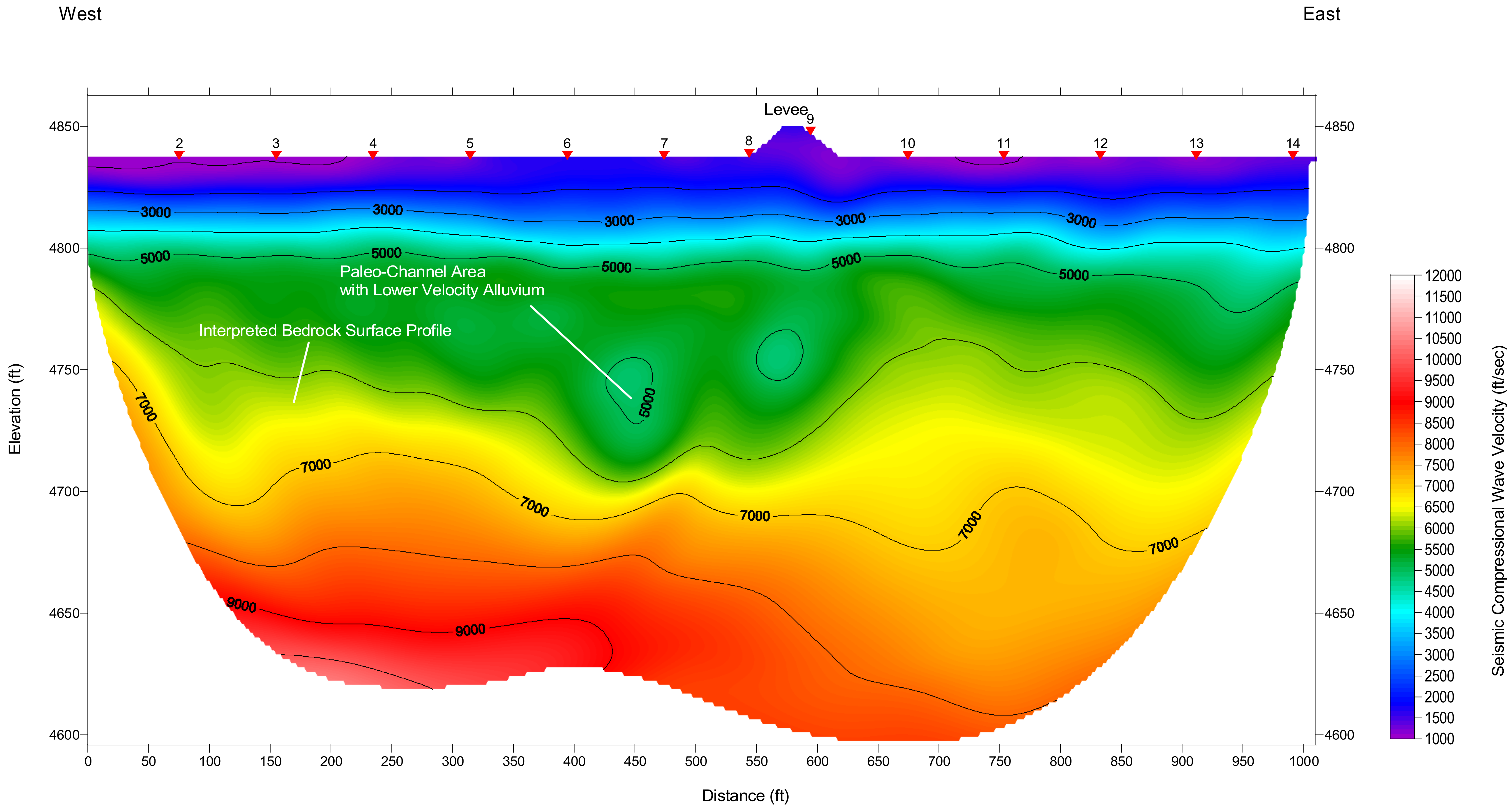
Horizontal Scale 1 inch= 100 Feet
Vertical Scale x2 1 inch= 50 Feet

*Printed Scale Reduced 75%

Line 2 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 6
Advanced Geoscience, Inc.

Line 3- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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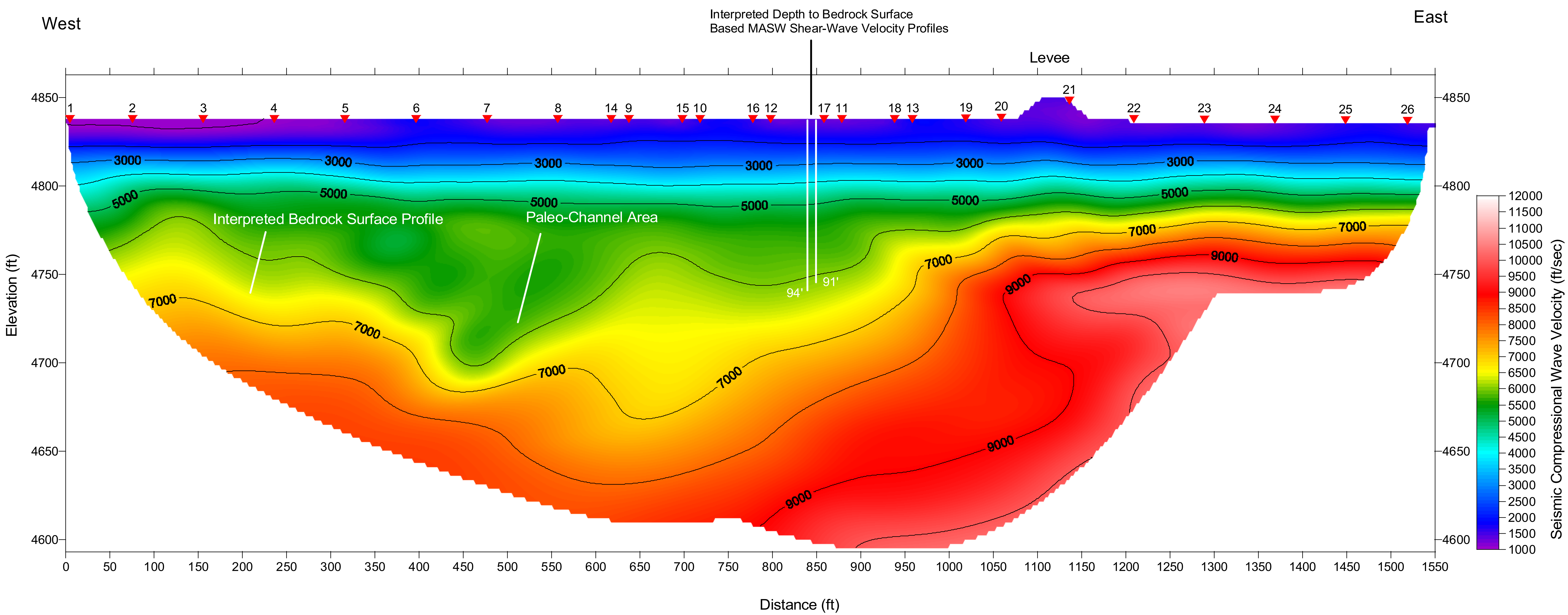
Horizontal Scale 1 inch= 80 Feet
Vertical Scale x2 1 inch= 40 Feet

*Printed Scale Reduced 75%

Line 3 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 7
Advanced Geoscience, Inc.

Line 4- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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Horizontal Scale 1 inch= 100 Feet
Vertical Scale x2 1 inch= 50 Feet

*Printed Scale Reduced 75%

Line 4 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 8
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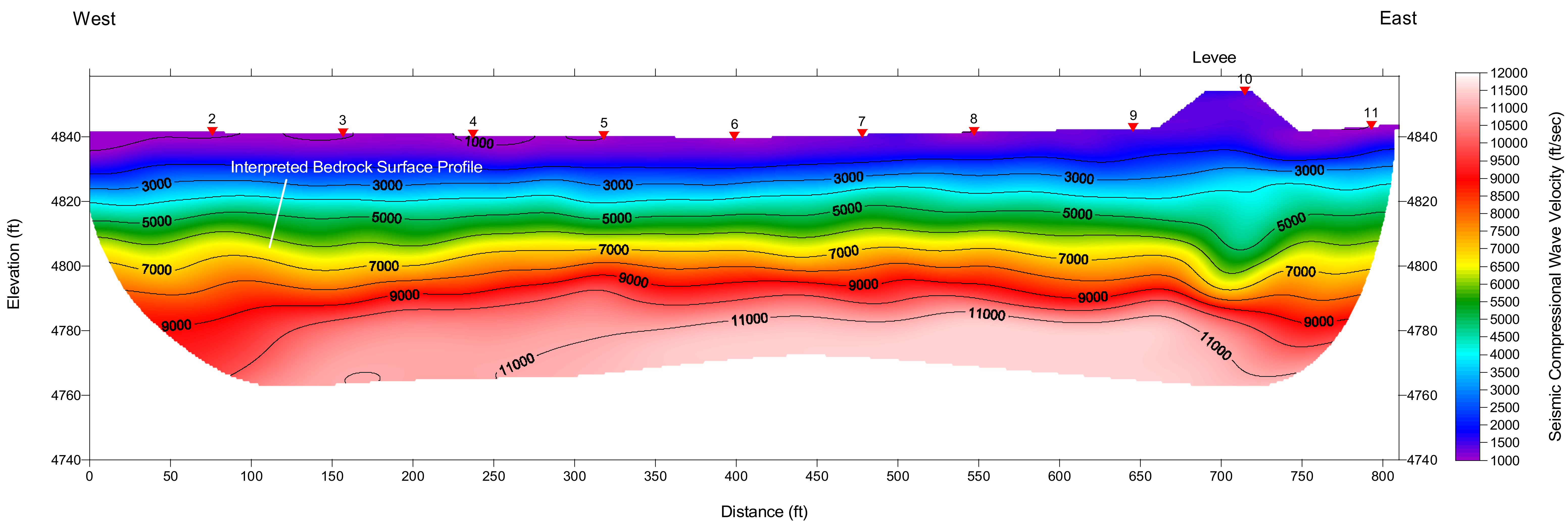
Line 5- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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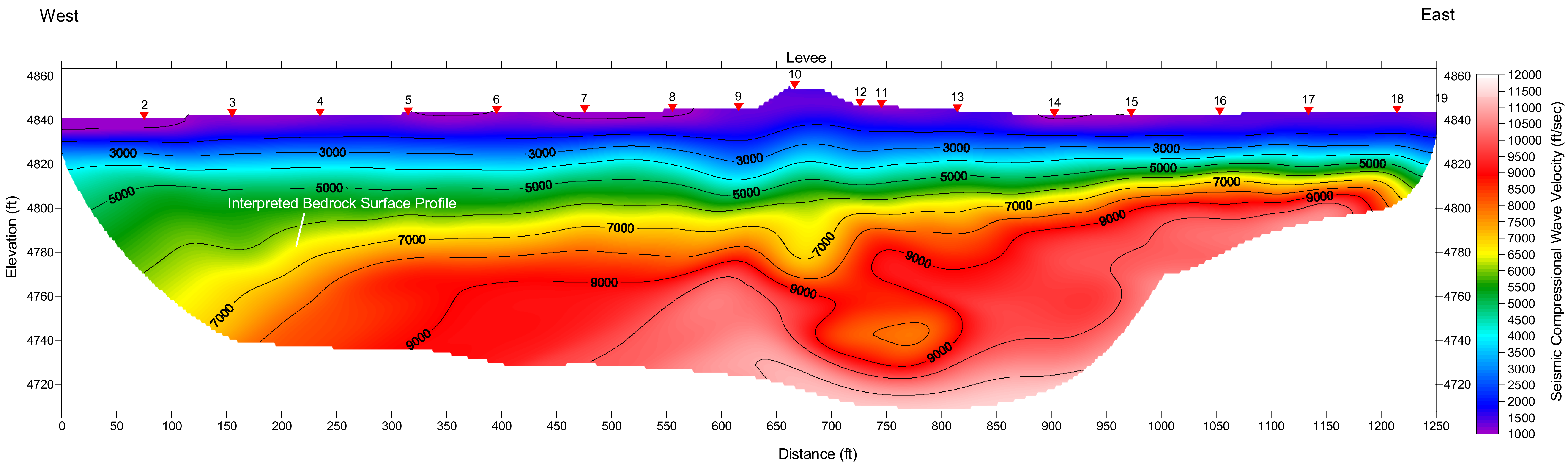
Horizontal Scale 1 inch= 60 Feet
Vertical Scale x2 1 inch= 30 Feet

*Printed Scale Reduced 75%

Line 5 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 9
Advanced Geoscience, Inc.

Line 6- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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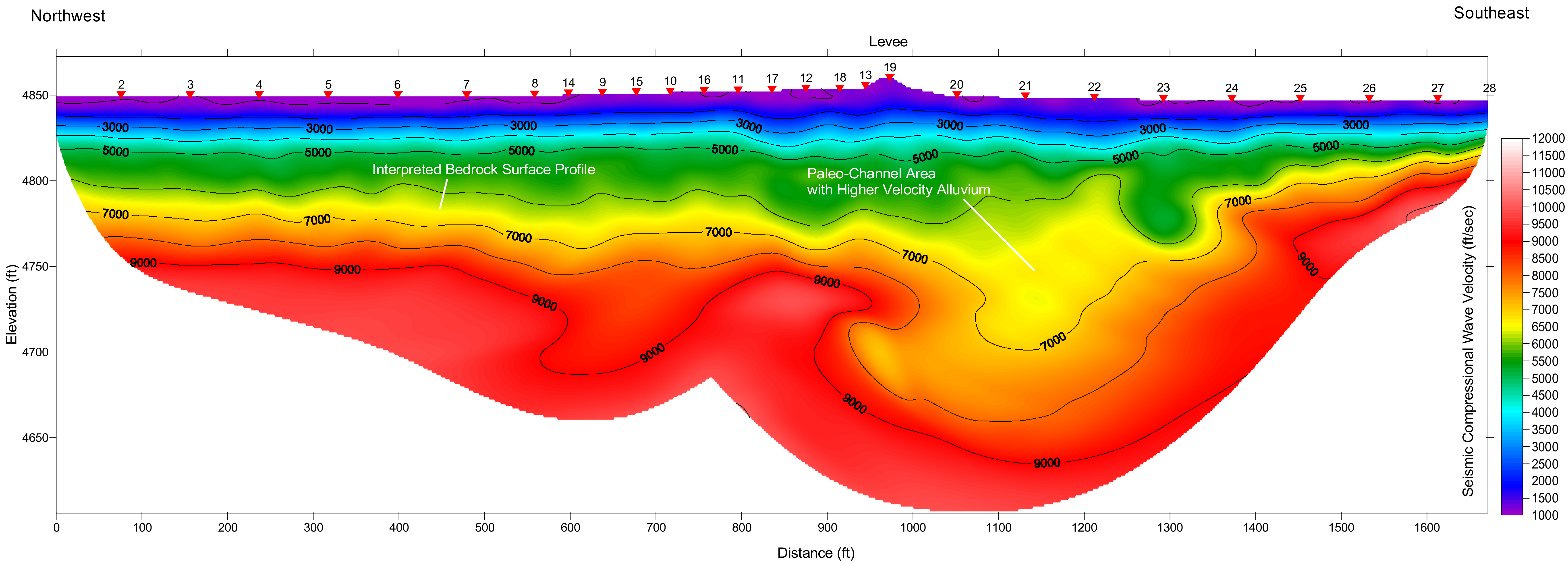
Horizontal Scale 1 inch= 80 Feet
Vertical Scale x2 1 inch= 40 Feet

*Printed Scale Reduced 75%

Line 6 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 10
Advanced Geoscience, Inc.

Line 7- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

0 100 200

Horizontal Scale 1 inch= 100 Feet
Vertical Scale x2 1 inch= 50 Feet

*Printed Scale Reduced 75%

Line 7 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 11
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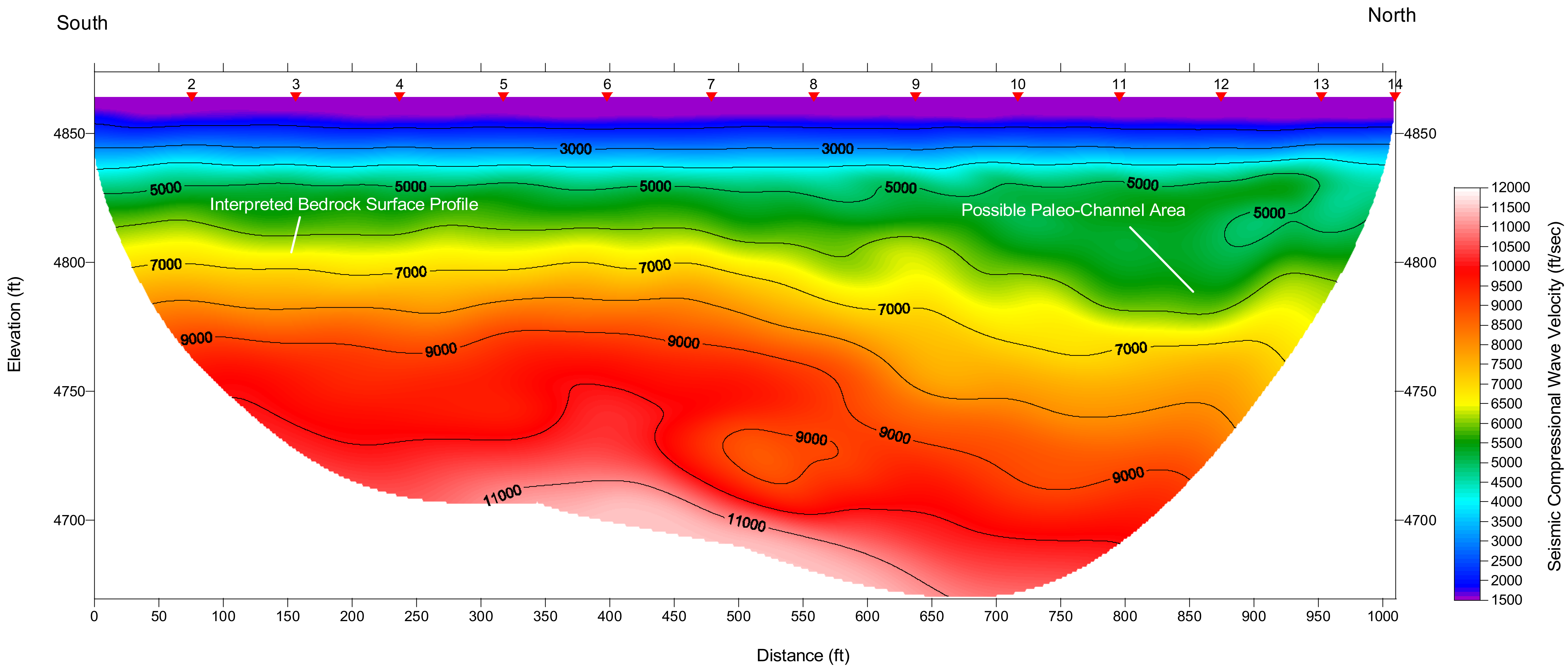
Line 8- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

Line 8 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

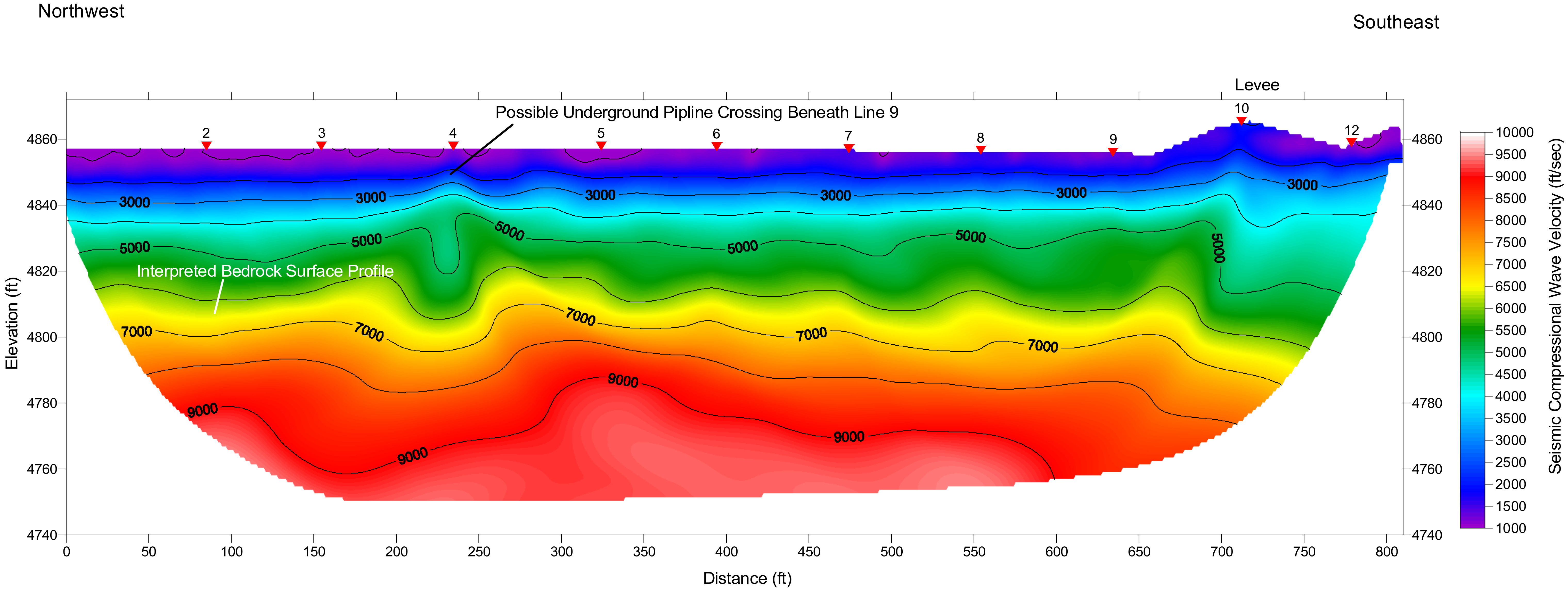
0 100 200

Horizontal Scale 1 inch= 100 Feet
Vertical Scale x2 1 inch= 50 Feet

*Printed Scale Reduced 75%

Figure 12
Advanced Geoscience, Inc.

Line 9- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

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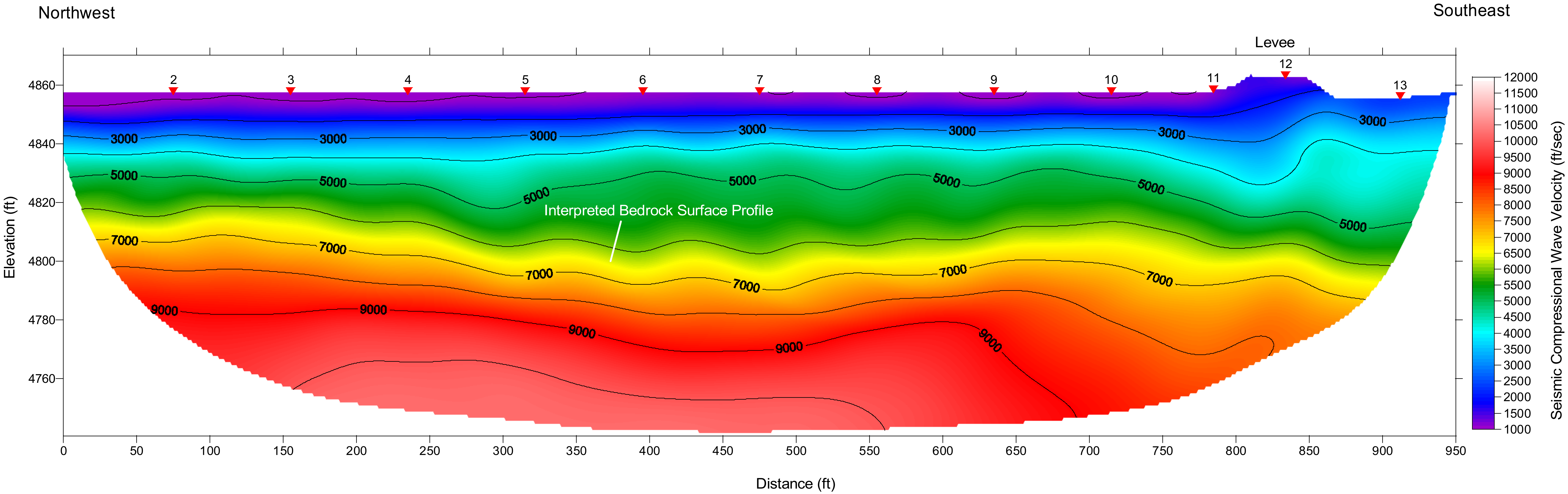
Horizontal Scale 1 inch= 60 Feet
Vertical Scale x2 1 inch= 30 Feet

*Printed Scale Reduced 75%

Line 9- Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 13
Advanced Geoscience, Inc.

Line 10- Seismic Refraction Velocity Depth Profile



RAYFRACT Initial Delta TV Velocity + WET Iterations w/Vmax=3500 m/sec

0 50 100

Horizontal Scale 1 inch= 60 Feet
Vertical Scale x2 1 inch= 30 Feet

*Printed Scale Reduced 75%

Line 10 Seismic Refraction Profile for
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 14
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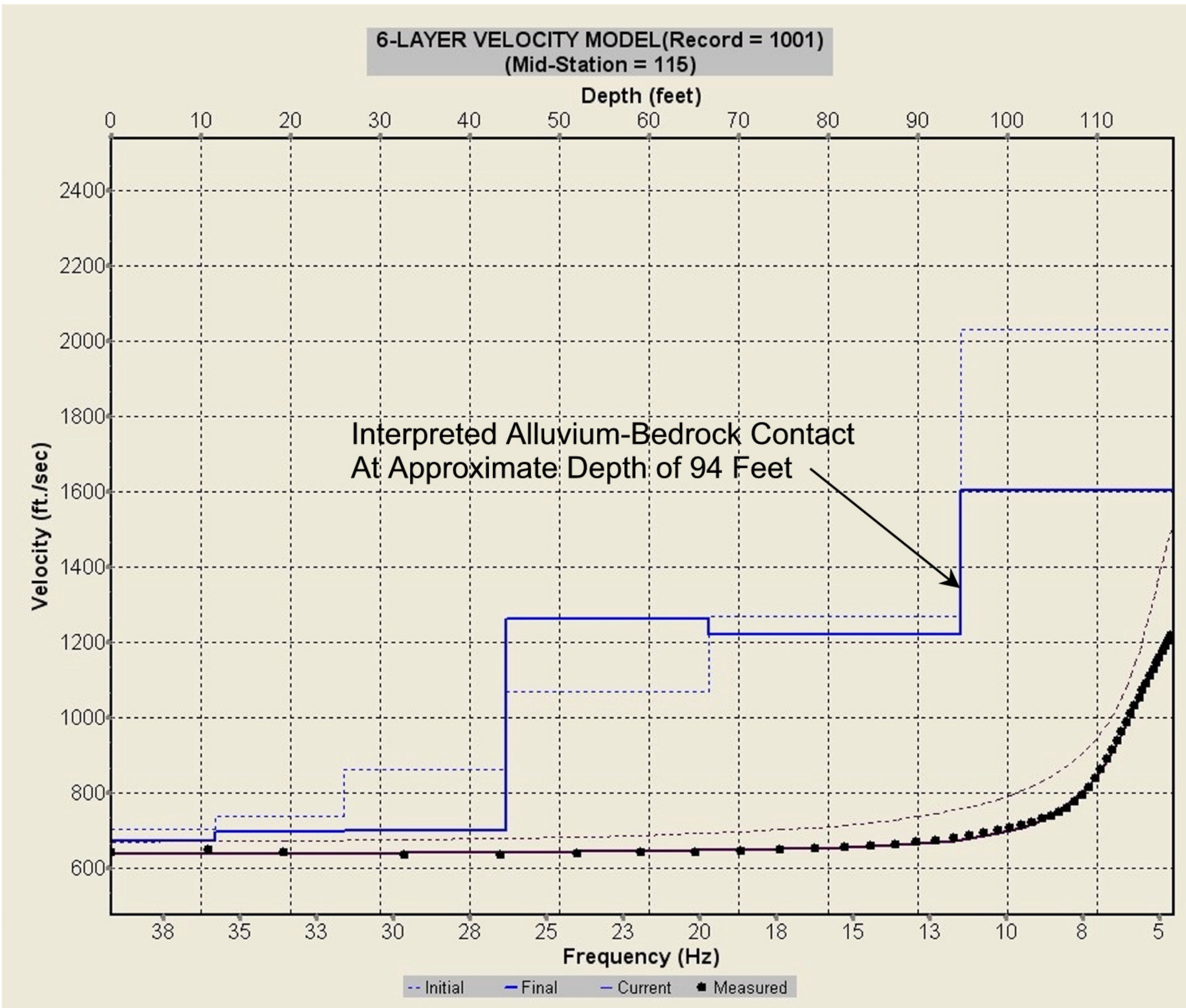
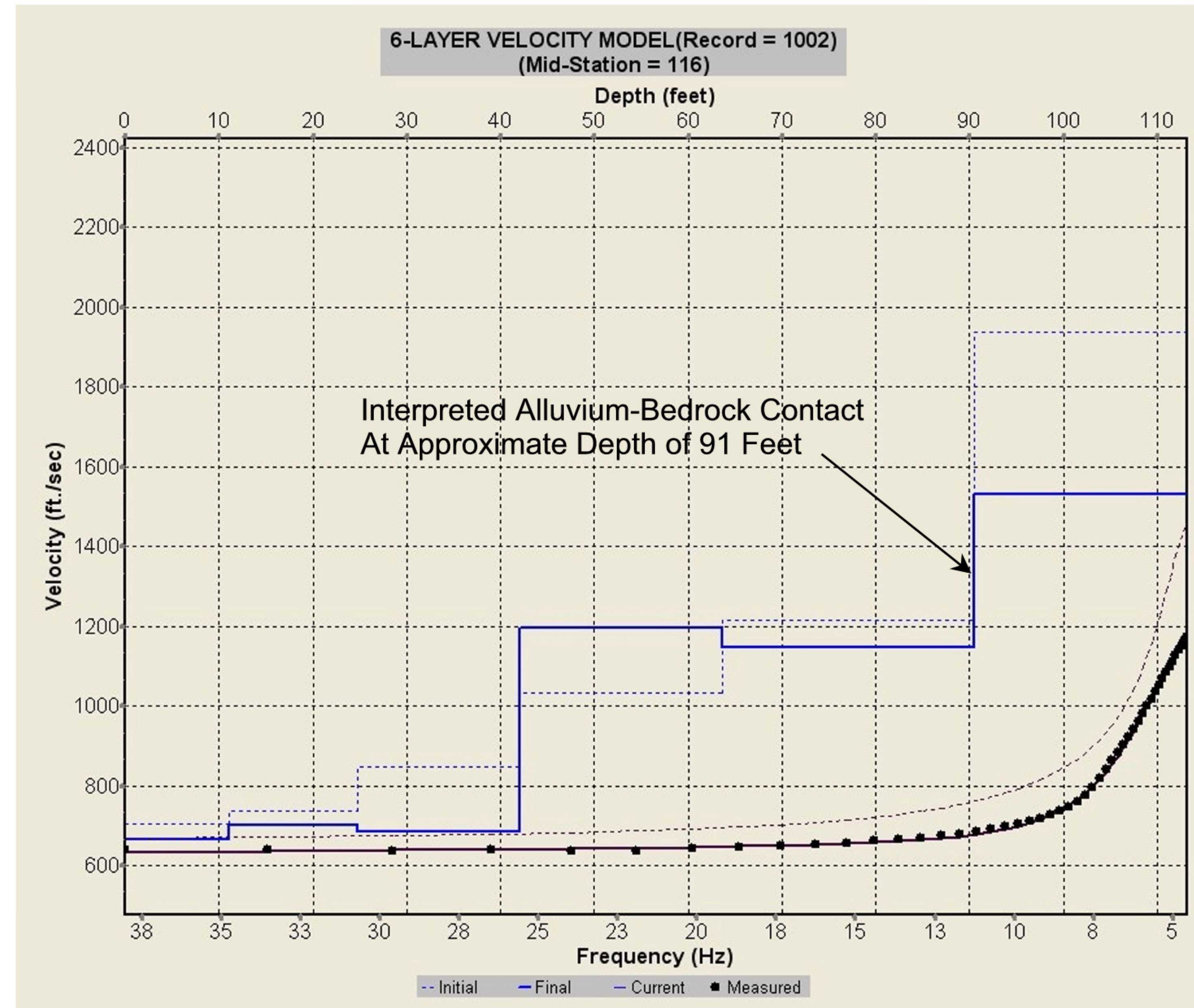
Estimated Shear-Wave Velocity Depth Profiles

Line 4 Station 840 Feet



Line 4 Station 850 Feet



Line 4 MASW Shear-Wave Velocity Profiling
Subsurface Investigation of Winslow Levee
Winslow, Arizona

Figure 15
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