A Ground Penetrating Radar Survey to Find and Delineate the Pinery Feeder Dam in the Cuyahoga River, Near Ohio State Route 82

Final Report

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Executive Summary

This report describes and interprets the results of a ground penetrating radar (GPR) survey of the Brecksville Dam pool on the Cuyahoga River in northern Summit County, Ohio. The purpose of this GPR survey was to locate and delineate the former Pinery Feeder wooden-timber crib dam first built in 1827. In 1951 the concrete Brecksville Dam was built downstream, thus submerging the Pinery Feeder Dam in the slack water of the existing Brecksville Dam pool. A GSSI radar system, with a 120 MHz antenna, was deployed in a rubber boat setup to digitally record GPR profiles of the river bottom. A gridwork of longitudinal and transverse tracklines were collected on August 19, 2010 to provide complete coverage of the dam pool.

The GPR search for the Pinery Feeder Dam located in the Brecksville Dam pool was successful. Using GPR we found and mapped the location of the Pinery Feeder Dam. A person then entered the water to confirm that the GPR reflections were, in fact, the wooden crib dam. On the day of the survey the water was only about 0.8 m deep above the Pinery Feeder Dam and uniformly about 1.4 m deep on either side of the submerged dam. Stair-step features are present on the sides of the Pinery Dam and likely represent actual parts of the crib structure. The Pinery Feeder Dam shows a V-shaped pattern, pointed upstream. In addition, the GPR profiles also allow for an estimate of the sediment accumulation within the Brecksville Dam pool. From the center of the river channel to the west bank, the channel floor is comprised of bedrock with little

to no sediment accumulation. From the center of the river channel to the east bank, greater than 80 cm of muddy fluvial sediment has accumulated above bedrock.

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1. Introduction

Within the Cuyahoga River, approximately 3 miles east of Brecksville, Ohio, there is a 14-foot tall concrete dam, near where State Route 82 crosses the river (Figure 1). This dam, known as the Brecksville Dam, was built in 1951 to replace an aging crib dam located approximately 120 feet upstream (Tamburro, 2003). This crib dam, named the Pinery Feeder Dam, or the Ohio and Erie Canal diversion dam, was first built in 1827 to divert river water into the Ohio and Erie Canal for canal boat transportation (Tamburro, 2003). The Pinery Feeder Dam consisted of wooden timbers bolted to the bedrock and stacked on one another to form a V-shape dam pointed upstream. Large rocks and clay were piled in the cribs and on the upstream side of the dam to deflect the energy of the river water from the timbers, thereby giving the dam a longer lifespan. The original crib dam underwent several major reconstructions due to flooding events. It is reported that on at least two occasions half of the dam structure was rebuilt (Tamburro, 2003). When the new concrete dam was installed in 1951, the old crib dam was breeched across a 20-foot section and left *in-situ*. The crib dam became submerged under the slack water of the new concrete dam pool because the new dam height exceeded the crib dam height. The exact location and condition of the former dam was unknown. Therefore, we were asked to conduct a Ground Penetrating Radar (GPR) survey of the Brecksville Dam pool with the goal of determining if the Pinery Feeder Dam was still present and to delineate its extent if in fact it is present. This report presents the results of that GPR survey

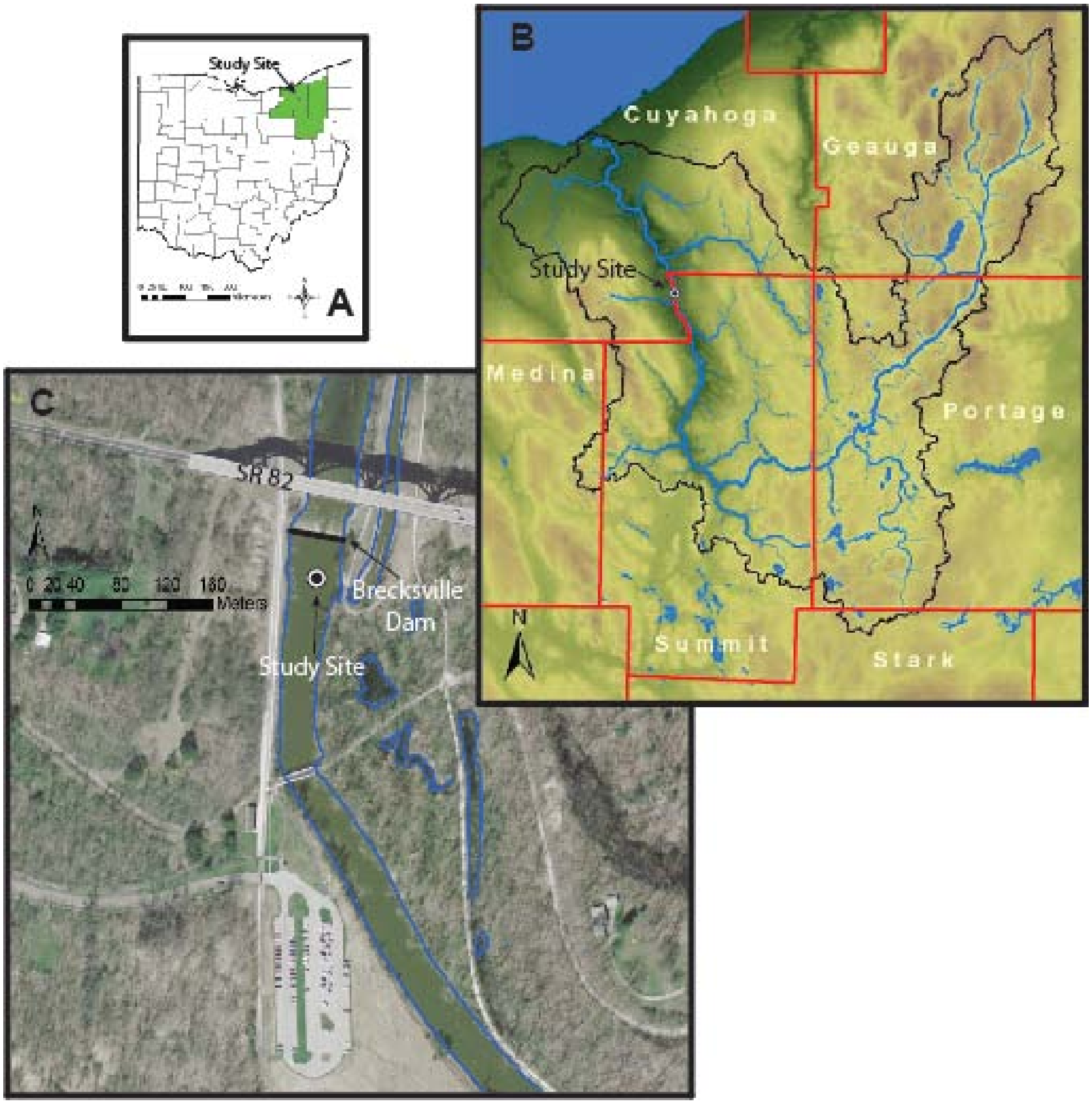

Figure 1. Location maps of the study site and Brecksville Dam. (A) State of Ohio with the 6 counties containing the Cuyahoga River watershed shaded in green. (B) The Cuyahoga River and watershed (black line), and county boundaries (red lines). (C) Detailed aerial photograph showing the Brecksville Dam and the location of the GPR study area. Watershed map in B taken from Cuyahoga River Remedial Action Plan (RAP) Brochure #2. Aerial photo in A from Summit County 2006 GIS OSIP data CD.

2. Methods

2.1 General Ground Penetrating Radar Methods

Ground penetrating radar (GPR) is a geophysical remote sensing tool usually employed on land, but can be used in water settings under the right conditions (Neal, 2004; Haeni, 1996). A general GPR system consists of 3 components: a control unit, an antenna to transmit and receive signals, and a battery supply. A signal is sent from the control unit to the antenna, where the signal is amplified and transmitted, as a radar pulse into the ground or other medium at a specific frequency. As the electromagnetic waves enter the medium they are reflected, refracted and diffracted in the subsurface by changes in electrical conductivity and dielectric properties of the medium. Some of the radar energy is reflected back to the antenna where it is received, sent to the control unit, displayed and stored digitally. Some of the radar energy continues through the subsurface and may be reflected back by another change in the electrical conductivity or dielectric properties of the medium. This process continues until the radar signal is completely attenuated. Figure 2 shows a simplified view of the process of transmitting and receiving radar signals.

Ground penetrating radar is a site specific tool. The depth of investigation ultimately determines the type of antenna needed. Radar antennas are rated on the frequency they can transmit and receive, typically they range in value from 16 MHz to 1600 MHz. The general rule in determining which antenna to use is, the higher the

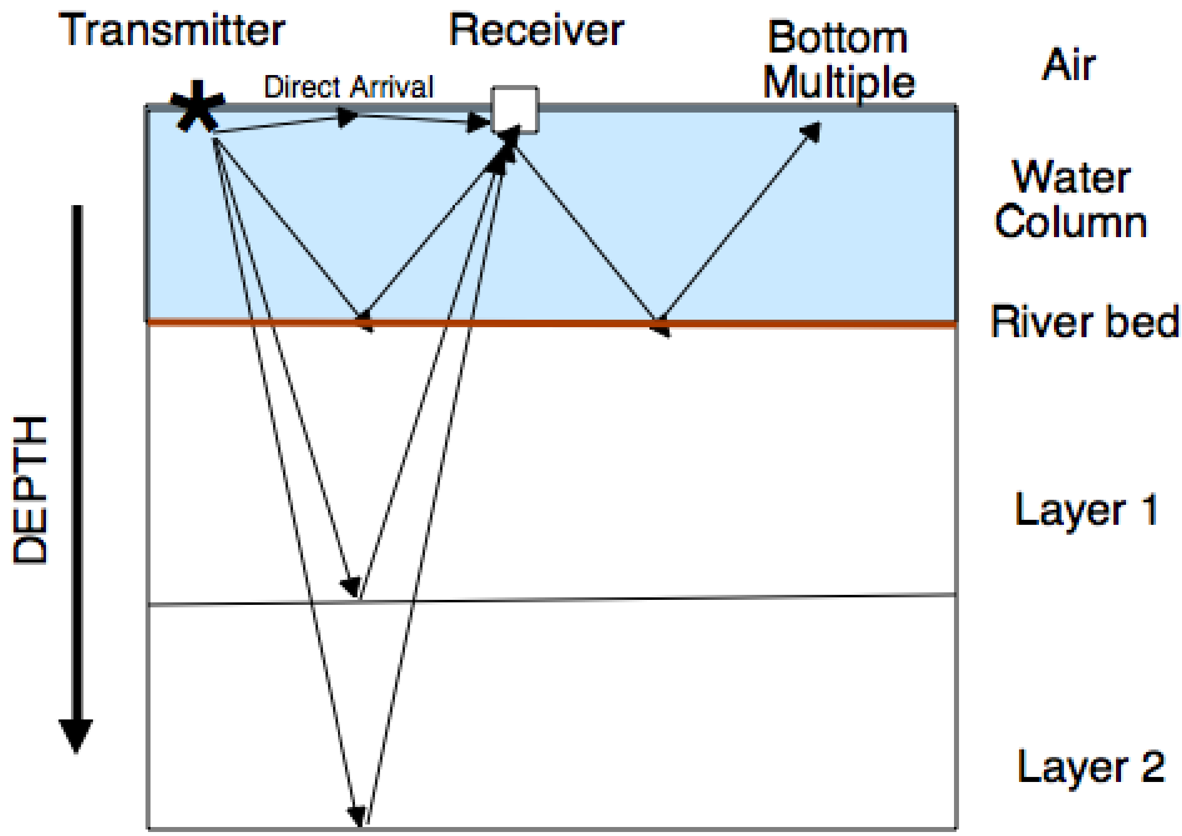

Figure 2. Simplified diagram of the process of transmitting and receiving radar signals. Each arrow represents a single ray path of a radar pulse. Some of the energy of the pulse travels directly to the receiver giving a direct arrival signal. Some of the energy extends into the subsurface where it may encounter a change in conductivity or a change in dielectric properties and become reflected energy back to the receiver. The radar signal will continue into the subsurface until the signal is attenuated.

frequency, the less penetration but greater the resolution of buried reflectors. Resolution refers to the ability to distinguish one radar reflection from another. Higher frequencies attenuate faster; therefore less penetration is achieved into the subsurface. For this study, we chose to use a 120 MHz frequency antenna, which can provide up to 3.12 meters of penetration through water, or 20 meters of penetration through land.

This choice of antenna provided a balance between depth of penetration versus resolution needed for the survey.

GPR data is recorded in two-way travel time having units of nanoseconds (ns). Two-way travel time measures the time it takes for a signal to propagate from the antenna into the subsurface, reflect off of a change in medium, and then return to the antenna. In order for GPR data to be useful for surveys, the two-way travel time needs to be converted to depth so that spatial scales can be better assessed. Various materials (e.g., rock, sand, mud, water) propagate radar waves at different velocities. Therefore, when the radar wave velocity in a specific material is known, the measured travel time can be converted to depth. Most often the radar wave propagation velocity for different materials is found from published reference tables (Neal, 2004).

2.2 Ground Penetrating Radar Methods Specific to the Pinery Feeder Dam Study

On August 19, 2010 a GPR survey was conducted within the Brecksville Dam pool on the Cuyahoga River (Figure 1). The purpose of this survey was to determine if the Pinery Feeder Dam still existed and, if it did, to determine its location. A Geophysical Survey System Inc. (GSSI) SIR-2000 radar system with a 120 MHz antenna was used for this study (Figure 3). The system was powered by a 12-volt marine battery. The entire array was placed in rubber boats that were lashed

Figure 3. (Top) Photograph of the GPR survey. Two rubber boats were lashed together to allow for separation of the antenna from potential interference by the motor, battery, GPR control unit, and cables. The 120 MHz antenna was placed by itself in the front boat. (Bottom) Photograph showing the measurements of a GPR survey trackline, location of the Brecksville Dam and approximate location of the Pinery Feeder Dam. Photos by Greg Tkachyk.

together. The radar control unit, battery and operators were in the back boat, and the antenna was in the front boat (Figure 3). Rubber boats were used because the conductivity of a metal boat would have interfered with the radar signal. Figure 3 shows the setup of the two boats and radar equipment. This setup was lightweight and allowed for quick maneuvering throughout the survey area. The low flow condition of the Cuyahoga River on August 19, 2010, allowed for a safe survey close to the Brecksville Dam. Figure 4 shows a 30-day interval of mean daily discharge from the Old Portage stream gauging station. The survey occurred when the mean daily discharge was approximately 200 cfs. On August 19, 2010 the water elevation was measured at 5.7 ft. on the gauging staff located at the Pinery Feeder canal gate. Because saline water limits the effectiveness of the GPR method a water sample was collected the day of the survey. On August 19, 2010 the conductivity of the water was measured to be 862 microsiemens.

Radar data were collected with the GSSI system set to continuous scanning and a shallow setting of 200 ns. The shallow setting was chosen because the depth of investigation was less than 3 meters. In order to convert the radar wave travel time (ns) to depth (m) we chose to determine a site specific dielectric constant rather than use the listed value of 59 ns per meter listed in the GSSI manual. A dielectric constant of 64 ns per meter was determined by the following method. First, the water depth was directly measured with an incremented staff while GPR data was being recorded at the same location (Figure 5). Second, the dielectric constant value was adjusted until the GPR control unit displayed the profile plotted to match the measured depth (Figure 6). The rest of the GPR settings were set on the default options on the control unit. All of the

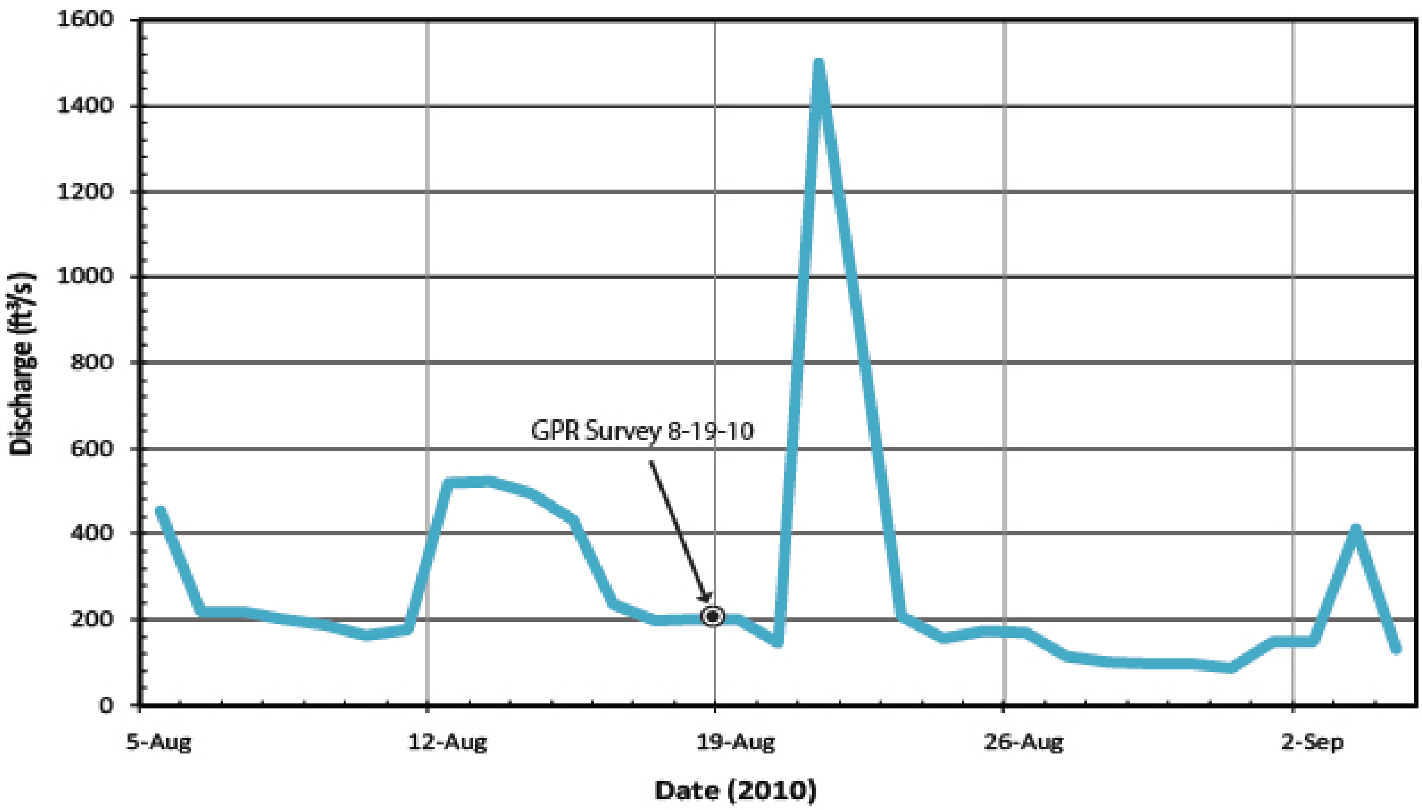

Figure 4. Mean daily discharge of the Cuyahoga River at the USGS gauging station at Old Portage Path in Summit County Ohio. The graph shows the hydrograph over a 30-day period. Note that the GPR survey took place during low flow conditions and 2 days before a rain event. Data from the USGS, 2010. Ohio Water Science Center, http://oh.water.usgs.gov/data.htm

Figure 5. Photograph showing the method of determining a site specific dielectric constant by physically measuring the water depth while simultaneously collecting GPR data. Photo by Greg Tkachyk.

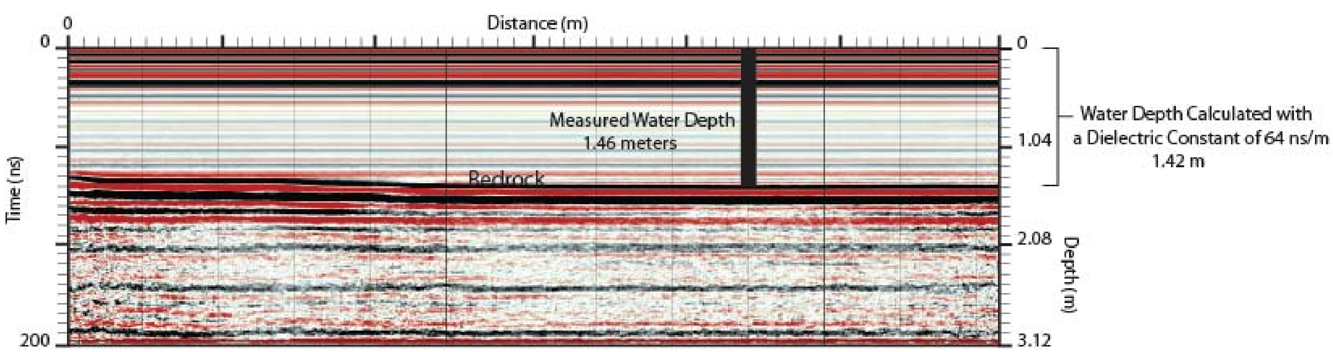

Figure 6. Line 96, used for determining a site specific dielectric constant needed for the time to depth conversion. No GPS coordinates were taken at this location, rather the boat remained stationary as the water depth was measured with the rod and the GPR data were collected. The estimated water depth (1.42 m) determined by using a dielectric constant of 64 ns/m agrees very well with the actual measured water depth (1.46 m).

radar data were collected in RADAN format, a proprietary format used by GSSI systems. The RADAN files were converted to Bitmap files using the open source program, *rad2bmp*. The *rad2bmp* program does not allow for color-scale changes, rather it uses grayscale. The grayscale bitmap data closely resembles the output display data for the GPR unit in the field. For better visualization of the data, the bitmap files were converted to seg-y files using the open source program *kogeo*. The kogeo program offers a variety of options to define color scales. An example of the radar data is shown in Figure 7, where the original grayscale bitmap and color seg-y conversion profiles are shown for comparison. Because of the greater clarity of the colored profiles, all survey lines were processed into seg-y format.

A handheld Trimble, Juno series global positioning system (GPS) was used to gather latitude and longitude coordinates during the survey. According to the manufacturer, the Trimble, Juno series has a horizontal accuracy of 2-5 meters. Moreover, there were slight delays (in seconds) in activating the GPS to record a location fix, especially while the boat was underway close to the active Brecksville Dam. The coordinates were collected into a point shapefile loaded into ArcPad 8.0. A GPS coordinate was taken each time we began recording data (start of line) and another coordinate was taken when we stopped recording data (end of line). These coordinates allow each survey line to be located on a map. Additional features, such as the crest of the submerged dam were also surveyed with the GPS. All GPS data were imported into ArcGIS ver. 9.3 to produce various maps of the survey.

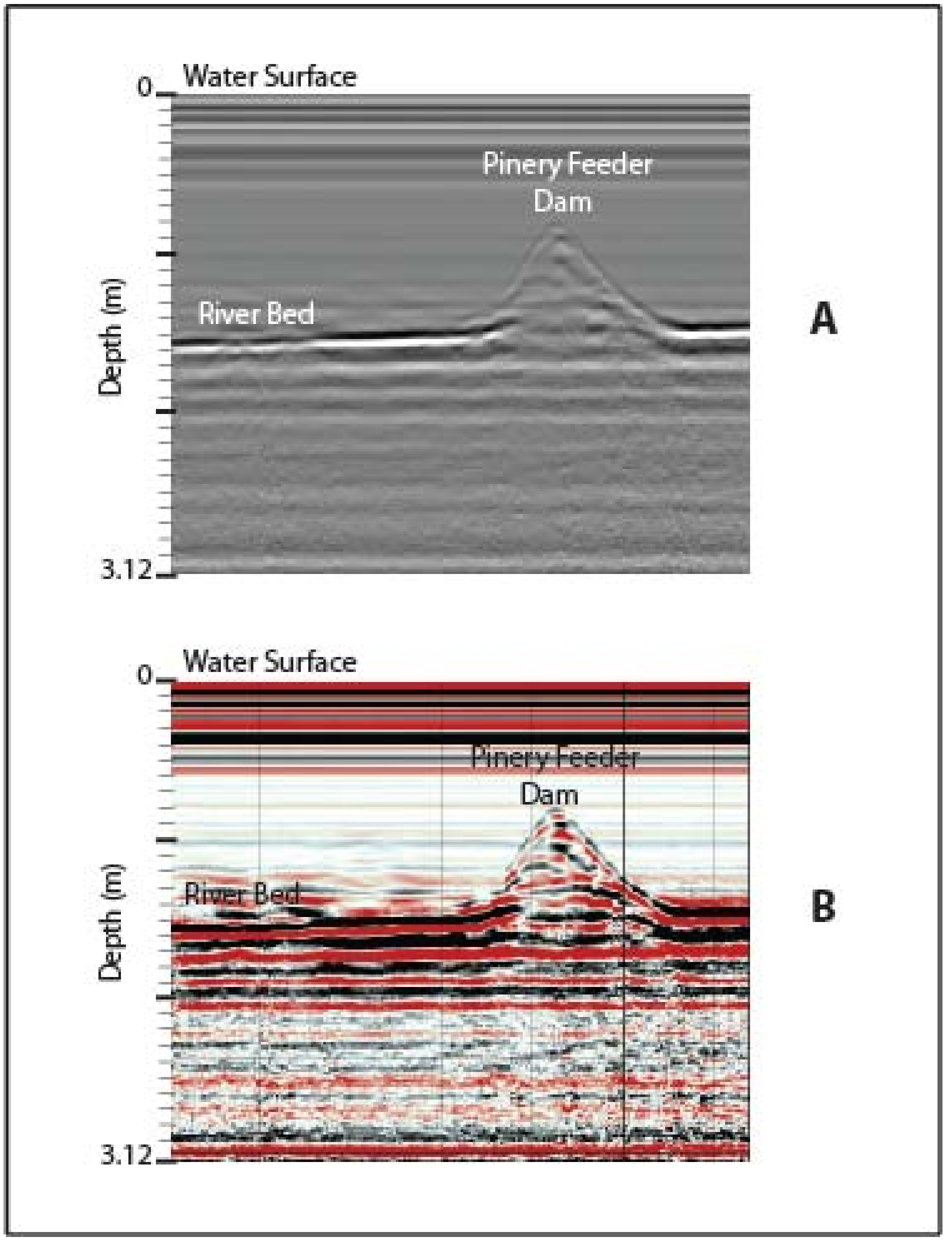

Figure 7. Comparison of the GPR profile data. (A) RADAN, proprietary GSSI, data converted to bitmap format shown in grayscale. This format closely resembles the display screen on the GPR control unit in the field. (B) Bitmap file converted to seg-y format and plotted on a color scale. On B the black color represents positive amplitudes and the red represents negative amplitudes.

2.3 Test of the Suitability of GPR as a Survey Tool on the Cuyahoga River

As stated earlier, GPR is a geophysical tool that is normally used on land surfaces; however it is also a proven technique on water and ice (Versteeg, 2001). Tests of the University of Akron's GSSI GPR were performed within the Cuyahoga River, Lafever Dam pool on July 29, 2010. The purpose of these tests were to determine if the boat setup could be managed on the river, if the river bed could be imaged by GPR methods, and if buried logs could be identified by GPR. These tests were needed to help ensure a successful survey of the Brecksville Dam pool. A location map showing 2 examples from the Lafever test survey is shown in figure 8. For this test survey, the setup of the equipment and the GSSI radar parameters were identical to those used in the latter survey of the Pinery Feeder Dam. This test survey showed that the GPR could locate log structures in both the water column and buried in the river sediment (Figures 9 and 10). Therefore, we felt confident that a GPR survey of the Pinery Feeder dam site could be beneficial in locating the submerged crib dam.

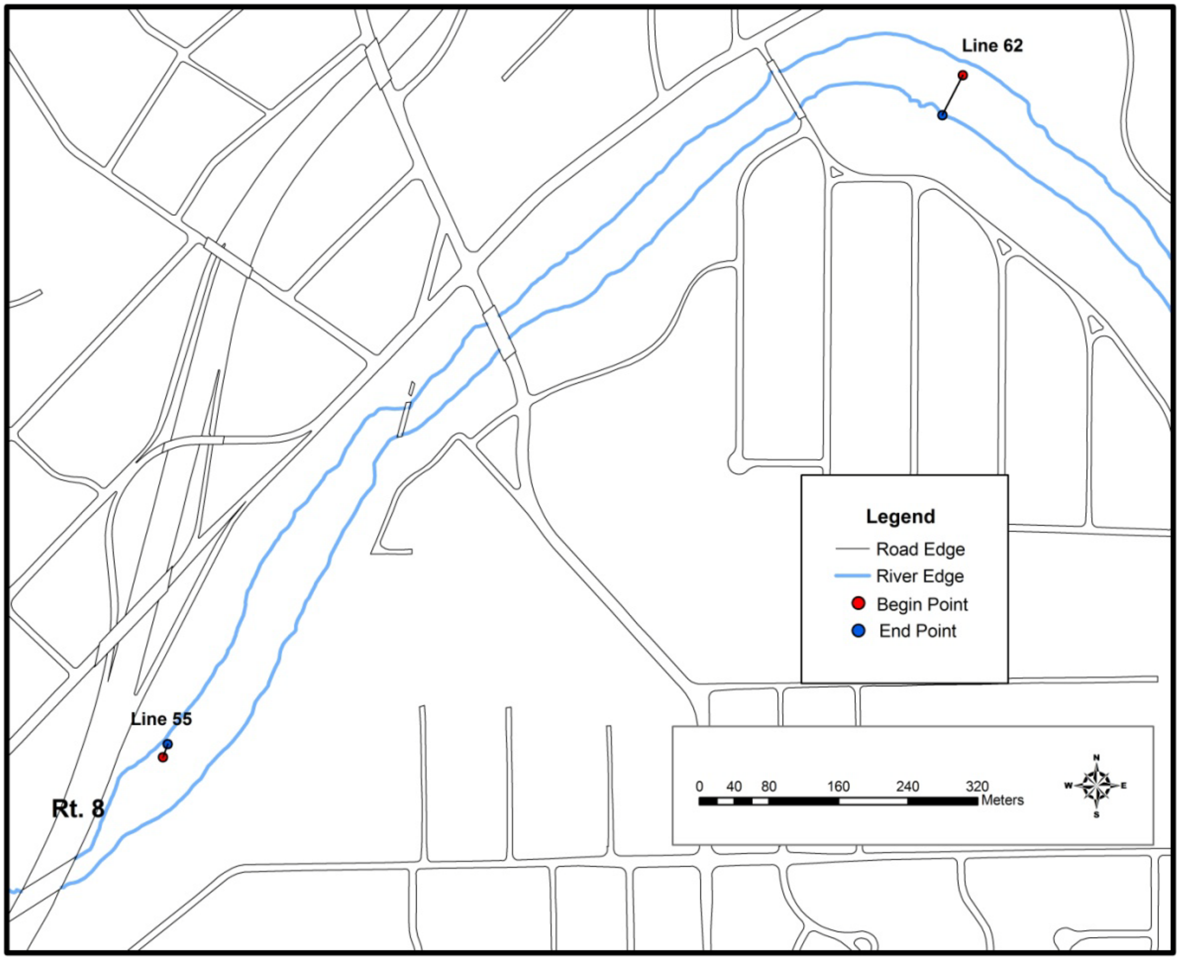

Figure 8. Location map of the GPR test surveys in the Lafever Dam pool, Cuyahoga Falls, Ohio. Shown are 2 profile locations where logs were visually observed within the river and also on the radar profiles. Road and river datasets from Summit County 2000 GIS.

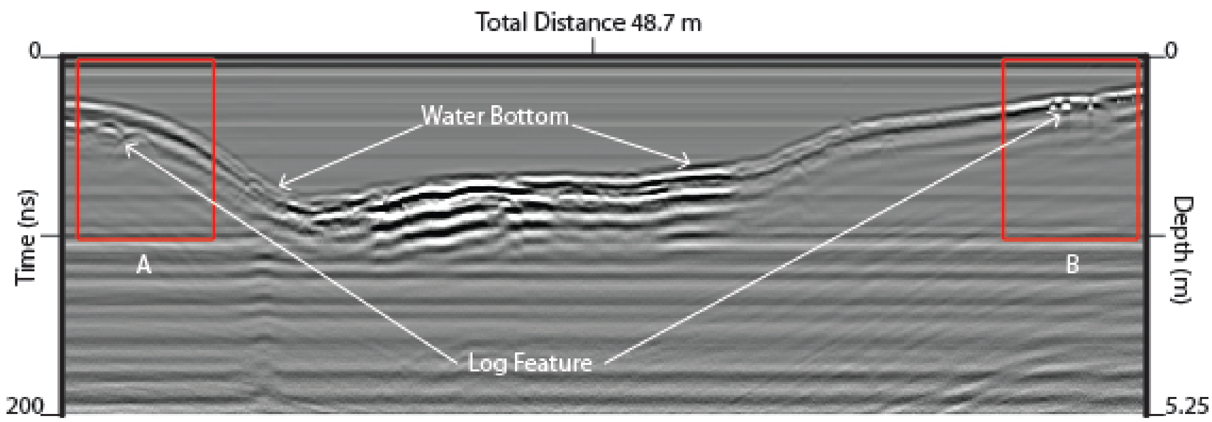

Figure 9. Radar profile of line 62 taken on 7-29-10. View is looking upstream. Log features were present in the shallow water margins of the river channel and are noted as A and B. Enlargements of each feature are shown below as 9a and 9b.

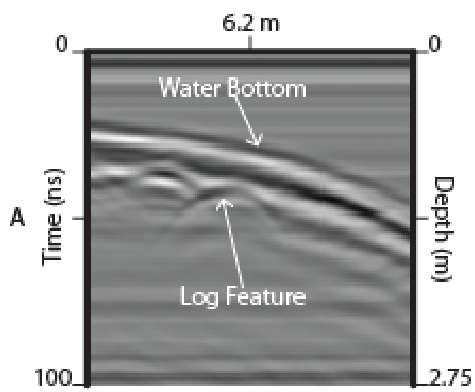

Figure 9a: Close-up of feature A. Parabolic reflectors indicate a buried log beneath muddy fluvial sediment. This feature was not confirmed with probing.

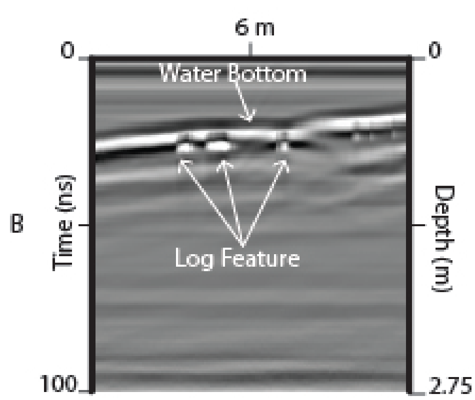

Figure 9b: Close-up of feature B. 3 seperate bright spots indicate buried logs. Each one was confirmed by probing beneath the sediment.

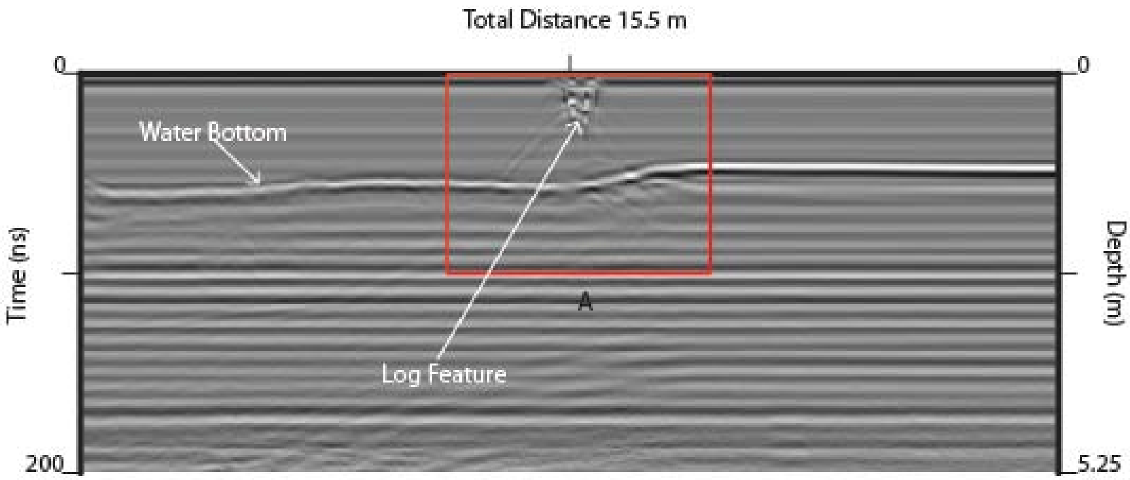

Figure 10. Radar profile of line 55 taken 7-29-10. This line passed over a visually identified log in the water 150 meters upstream of the Route 8 bridge along the right bank.   The log feature is noted as parabolic reflector. An enlargement is shown below in 10a.

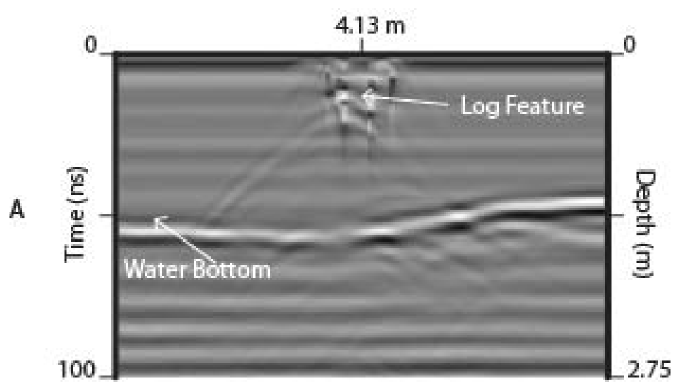

Figure 10a. Close-up of feature A. The log was observed above the sediment. The log is indicated by a bright reflector (high amplitude) having parabolic reflectors below.

3. Results and Discussion

The GPR search for the Pinery Feeder Dam located in the Brecksville Dam pool was successful. Using GPR we found and mapped the location of the Pinery Feeder Dam. A person then entered the water to confirm that the GPR reflections were in fact the wooden crib dam structure.

The dam pool was surveyed in a gridwork pattern with both longitudinal and transverse tracklines allowing for complete coverage of the area (Figure 11). The radar system was able to penetrate through the water column and reflect back the profile of the river channel bed. A total of twenty eight GPR profiles were collected. Several representative profiles are shown and discussed in this section. All of the GPR profiles are present in the appendix.

The location of the Pinery Feeder Dam was obtained from the longitudinal GPR profiles. Figure 12 is a location map showing 4 representative longitudinal profiles used to delineate the dam. It was readily apparent that there was a large bathymetric high present in many of the profiles (Figure 13). The water was only about 0.8 m deep above this feature whereas, most of the survey area was uniformly about 1.4 m deep. This bathymetric high was crossed in the same location as subsequent profiles were measured. The bathymetric high feature varied in shape across the river (Figure 13). Close to the left bank (when viewed looking downstream) the bathymetric high rose abruptly from the deep water of the river channel, peaked, and then descended abruptly back to the deep water of the river channel (Figure 13A). Just left of center in the river the bathymetric high still displayed an abrupt change in water depth and was well defined (Figure 13B). Along the right side of the river channel (as viewed looking downstream) the bathymetric high is less pronounced (Figure 13C). Although the feature is still submerged in similar water depths (about 0.90 m), the accumulation of muddy sediment elevates the nearby river bed from 1.4 m deep, to only 0.9 m deep. Closest to the right bank (Figure 13D, GPR line 76), the feature has become buried in sediment and is much less apparent on the profile. This bathymetric high feature was interpreted as the Pinery Feeder dam. Probing the feature with a steel measuring rod revealed it to have both hard, ringing impacts characteristic of rock, and scratchy impacts of sand and gravel. Through closely spaced (centimeters) probing, some of the inferred rock blocks are estimated to be about 0.5 m in size. Additionally, probing also indicated a soft squishing impact possibly due to the wooden timbers. Mud was ruled out as the bottom type for the soft impacts based upon countless probing made by the authors over the years. When it was determined that this structure was shallow enough to stand on and walk along, Ohio EPA environmental scientist Bill Zawiski entered the water and physically confirmed the presence of wooden timbers. In addition, he also felt what appeared to be an occasional metal spike present in the wooden timbers.

To delineate the extent of the dam structure, the longitudinal profiles were analyzed. The GPS coordinates of the start of line (SOL) and end of line (EOL) were plotted into ArcMap 9.3. Constant boat speed was assumed along the length of the line and the total distance traveled between SOL and EOL was scaled into equally spaced units. The dam was identified on each profile, marked and measured. The measured values were then plotted on ArcMap using the ruler measuring tool and measuring from

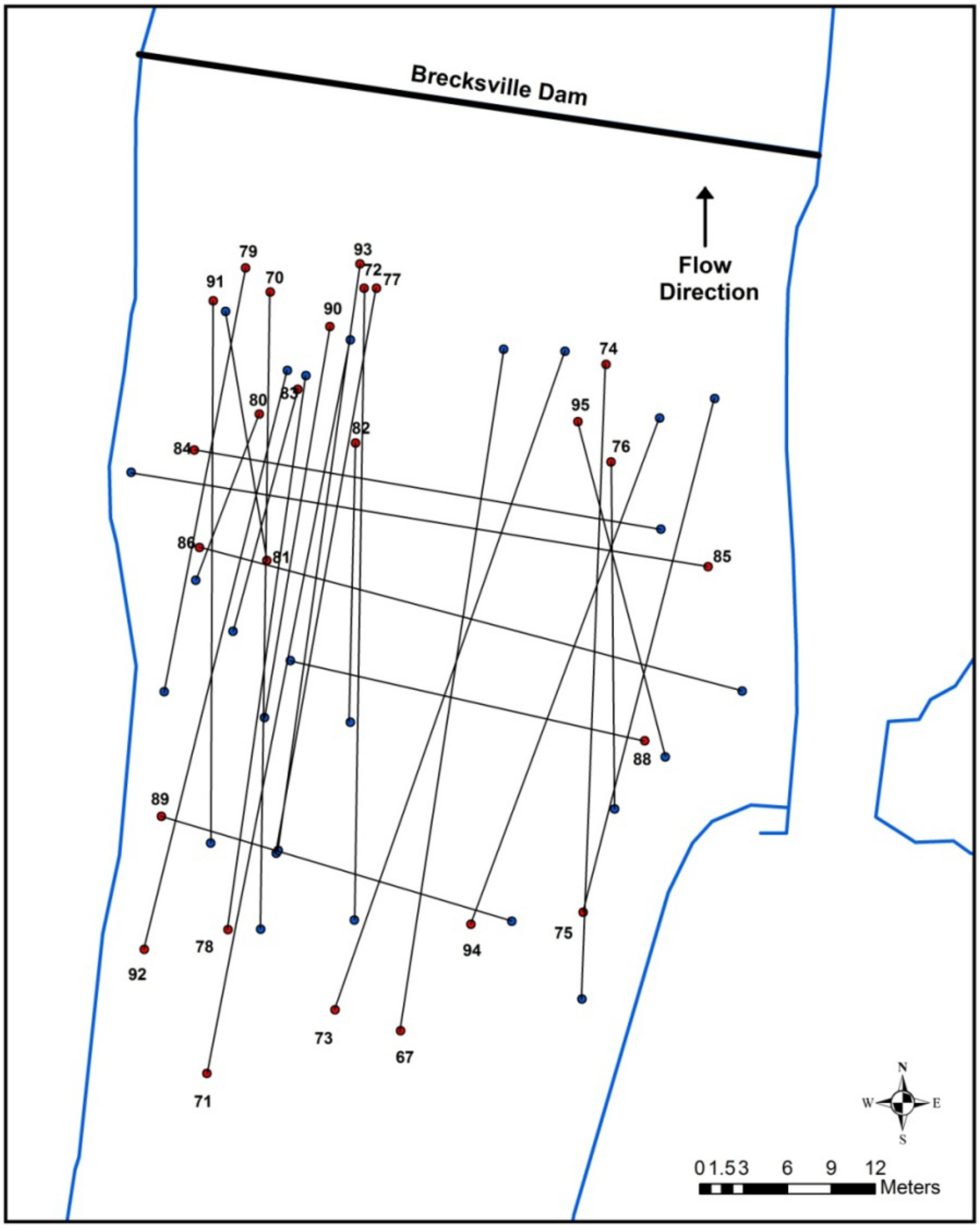

Figure 11. GPR profile trackline map of the Brecksville Dam pool study site. The Brecksville Dam is shown for reference and the Cuyahoga River flows north toward the top of the page. Red points mark the start of radar lines and blue points mark the end of radar lines. Numbers identify each GPR profile line. The blue line is the rivers edge obtained from Summit County 2000 GIS data.

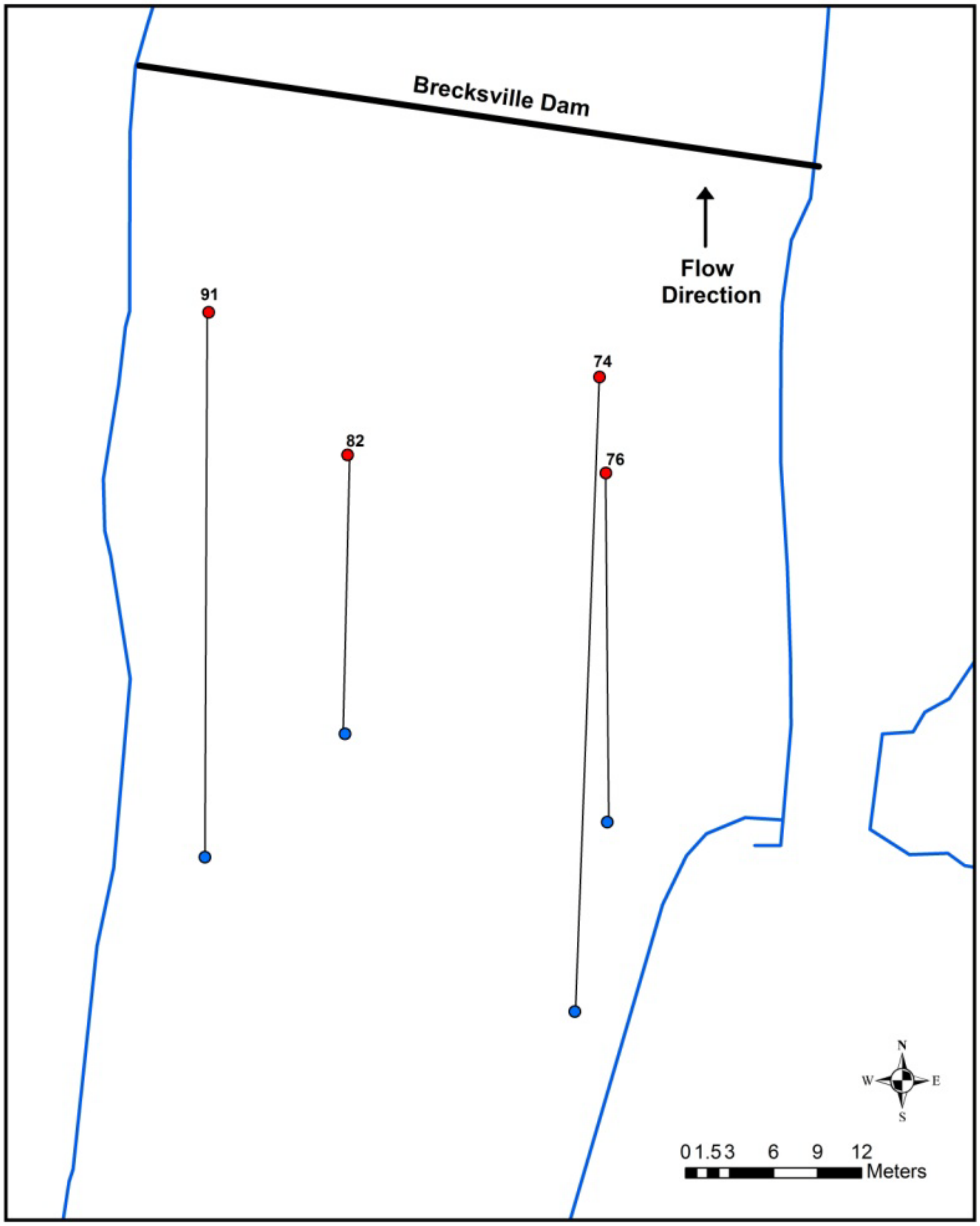

Figure 12. Location map of 4 longitudinal profiles showing the bathymetric high feature and its variability across the river channel. River data from Summit County 2000 GIS.

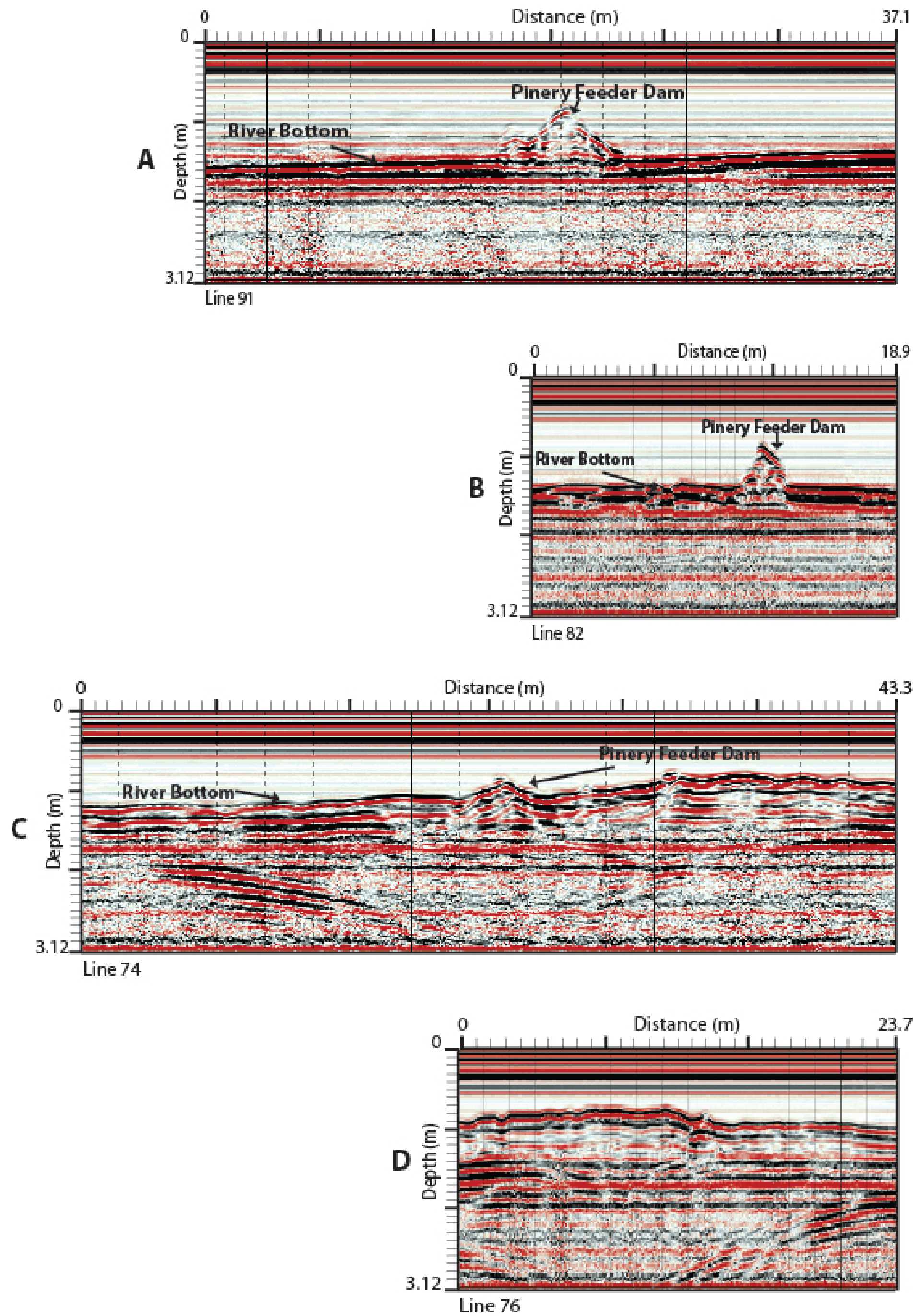

Figure 13. Four representative longitudinal GPR profiles whose location is shown in figure 12. (A) Line 91 is representative of the left bank profiles. (B) Line 73 is representative of the left-of-center profiles. (C) Line 74 is representative of the right bank profiles. (D) Line 76 shows the dam buried in sediment. The vertical exaggeration for each line is 4.04. The bathymetric high feature is labeled as the Pinery Feeder Dam on each profile.

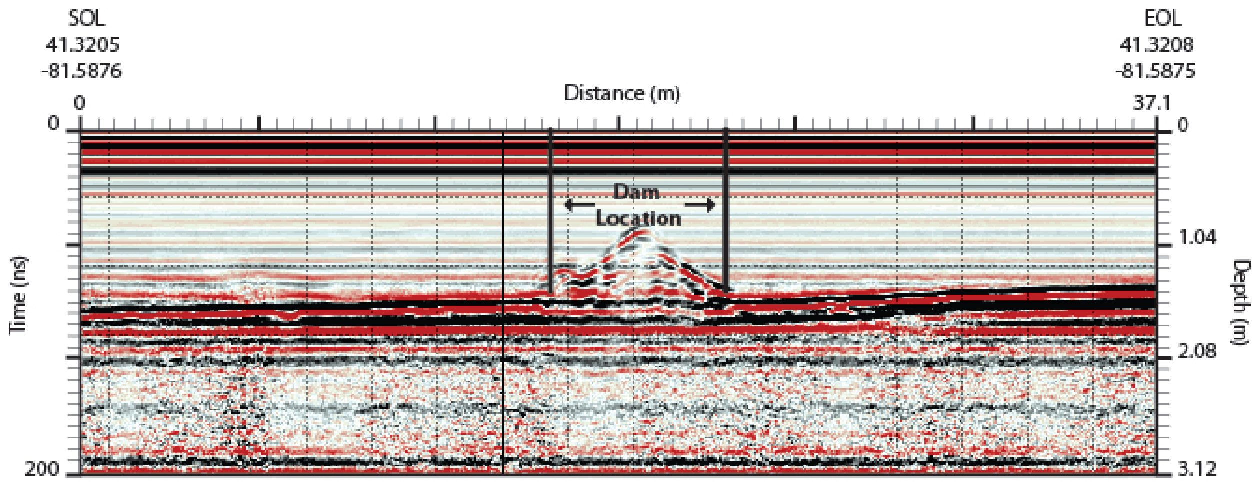

Figure 14. Line 91, vertical exaggeration is 3.81. Start of line (SOL) and end of line (EOL) GPS coordinates were plotted into ArcMap 9.3. Assuming constant boat speed, the distance between was divided into equally spaced units. Black vertical lines define the upstream and downstream sides of the dam. The distance from the SOL and the vertical lines were measured with the ruler tool in ArcMap thus allowing the Pinery Feeder Dam location to be plotted in map view.

the SOL. This process was performed on 19 separate profiles and an example profile can be seen in Figure 14.

Line 91 shows the typical dam structure also seen on many of the other GPR profiles. Stair-step features are seen on either side of the dam structure. These stair-step features likely represent actual parts of the crib structure. The high-amplitude reflection of the river bottom leading up to and extending away from the dam, is the result of bedrock. Using the metal probe rod, the bedrock nature of the channel floor was confirmed. The channel floor reflection loses intensity under the dam due to attenuation of the GPR signal through the dam structure.

The upstream and downstream extent of the dam structure was identified on 19 GPR profiles and plotted in map view (Figure 15). This mapping exercise allowed the approximate extent of the Pinery Feeder Dam to be delineated and the area to be shaded green (Figure 15). The Pinery Feeder Dam area shows a V-shaped pattern, pointed upstream. The upstream to downstream extent of the Pinery Feeder Dam is approximately 5 meters. In addition, the GPR survey to delineate the Pinery Feeder Dam location is in agreement with historical accounts of the Pinery Feeder Dam location (Tamburro, 2003).

During the GPR survey, the Pinery Feeder Dam location was identified by several additional methods. Spot GPS readings were obtained when the boat traversed across the crib dam structure as seen on the display screen of the GPR control unit. These spot GPS measurements were compiled in ArcMap (Figure 16). A V-shaped pattern, pointed upstream is observed (Figure 16). Bill Zawiski who entered the river and walked on the wooden timbers also physically identified the dam. GPS coordinates were collected as he traversed the structure, to produce a map (Figure 17). The points show the same trend of pointing upstream as one moves away from the left bank (Figure 17). There is dispersion to the GPS mapping of locations visited by Bill Zawiski because of both GPS error and the possibility of dislodged portions of the dam structure.

All Pinery Feeder Dam location datasets were placed onto one map to infer the location of the Pinery Feeder Dam (Figure 18). Although the GPS has error (2-5m, according to the manufacturer), all datasets generally agree with one another. Based upon these different methods, a shaded area was outlined to represent the best inferred location of the Pinery Feeder Dam within the Brecksville Dam pool (Figure 18). We chose not to shade the center of the river channel because of limited data coverage in that region and historical accounts indicate the dam was breeched in the center when the Brecksville Dam was constructed (Tamburro, 2003). In order to delineate the Pinery Feeder Dam at meter resolution, a more detailed survey by people wading in the river, would be needed.

In addition to determining the location of the Pinery Feeder Dam, the GPR profiles also allow for an estimate of the sediment accumulation within the Brecksville Dam pool. Shown in Figure 19 are three transverse profiles. Each transverse profile reveals the shape of the river channel from left to right bank. A dashed line was added to identify the top of the bedrock. The bedrock is characterized by the high-amplitude, continuous GPR reflector and was confirmed by probing with the metal rod. From the center of the river channel to the left bank the channel floor is comprised of bedrock with little to no sediment accumulation (Figures 19 and 20). From the center of the river channel to the right bank, muddy fluvial sediment has accumulated above bedrock (Figures 19 and 20). This muddy sediment accumulation was confirmed by probing with the metal rod. The sediment has a low-amplitude, less-continuous GPR reflector signal (Figure 19). Wherever sediment was identified on the GPR profiles, its thickness was measured. The thickness of the fluvial sediment within the Brecksville Dam pool was then contoured (Figure 20).

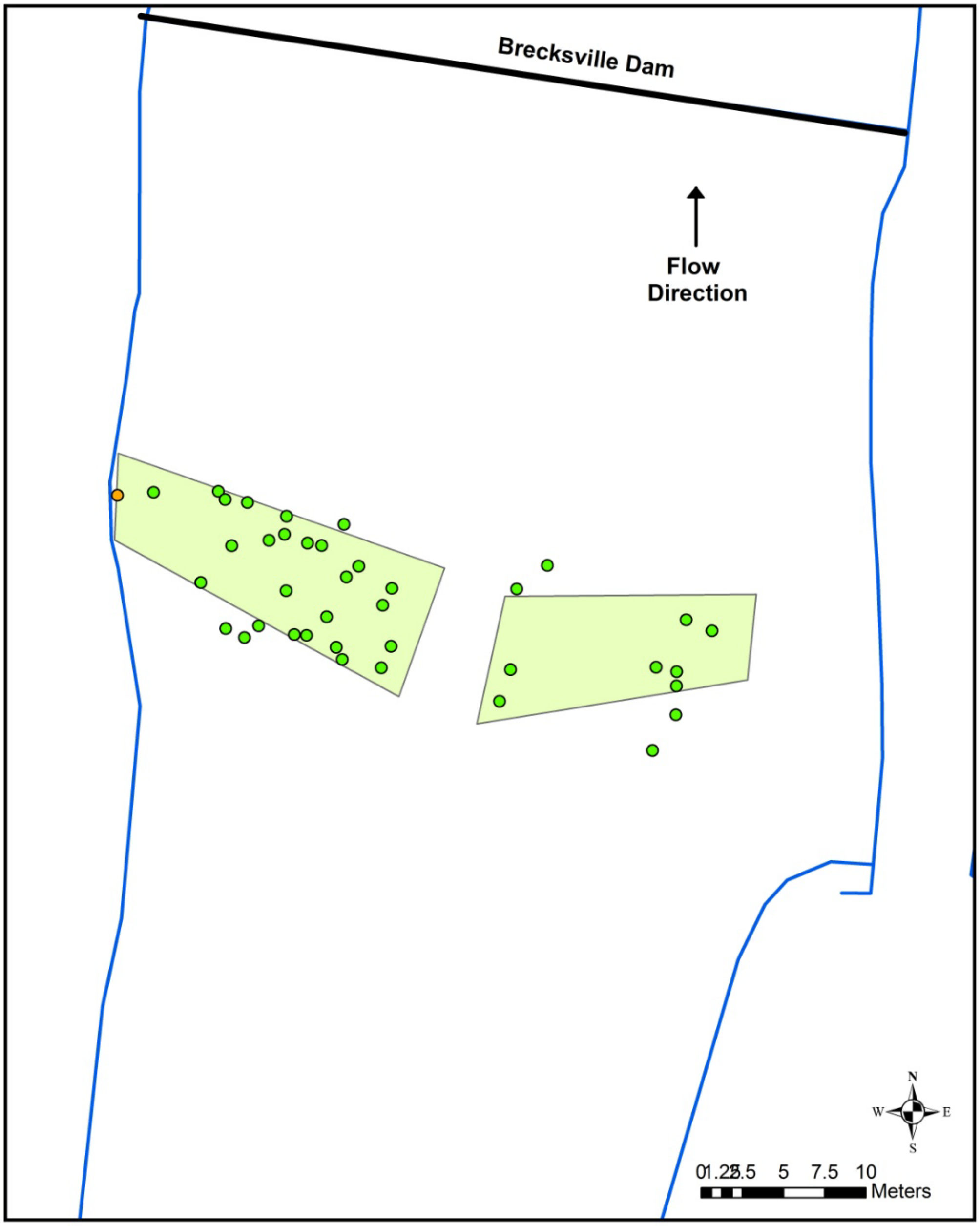

Figure 15. Map showing the approximate extent of the Pinery Feeder Dam (area shaded green) based upon GPR profiles. Green points represent the upstream and downstream extent of the dam as measured on 19 GPR profiles. Orange dot represents location of dam exposed on the left bank A V-shaped pattern, pointing upstream, is revealed. From upstream to downstream, the dam is approximately 5 meters wide. River data from Summit County 2000 GIS.

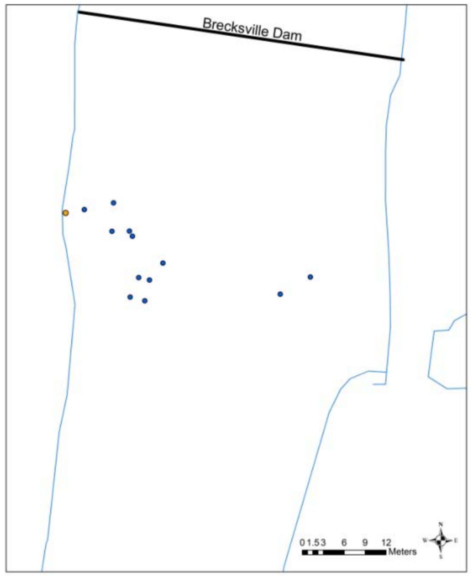

Figure 16. Map of GPS readings (blue points) obtained as the boat traversed over dam structure. At the left bank the dam structure was visually identified (orange point). A V-shaped pattern, pointing upstream, is identified by the distribution of points. River data from 2000 Summit County GIS.

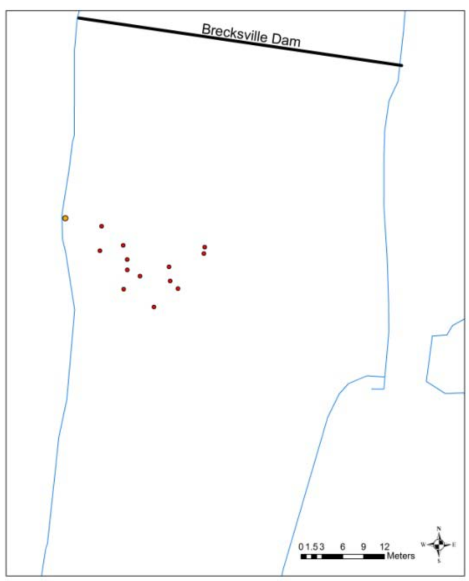

Figure 17. Map of physically identified points (red points) on the crib structure as a person walked along the structure. At the left bank edge, the dam structure was visually identified (orange point). The distribution of points trend upstream from the left bank. River data from 2000 Summit County GIS.

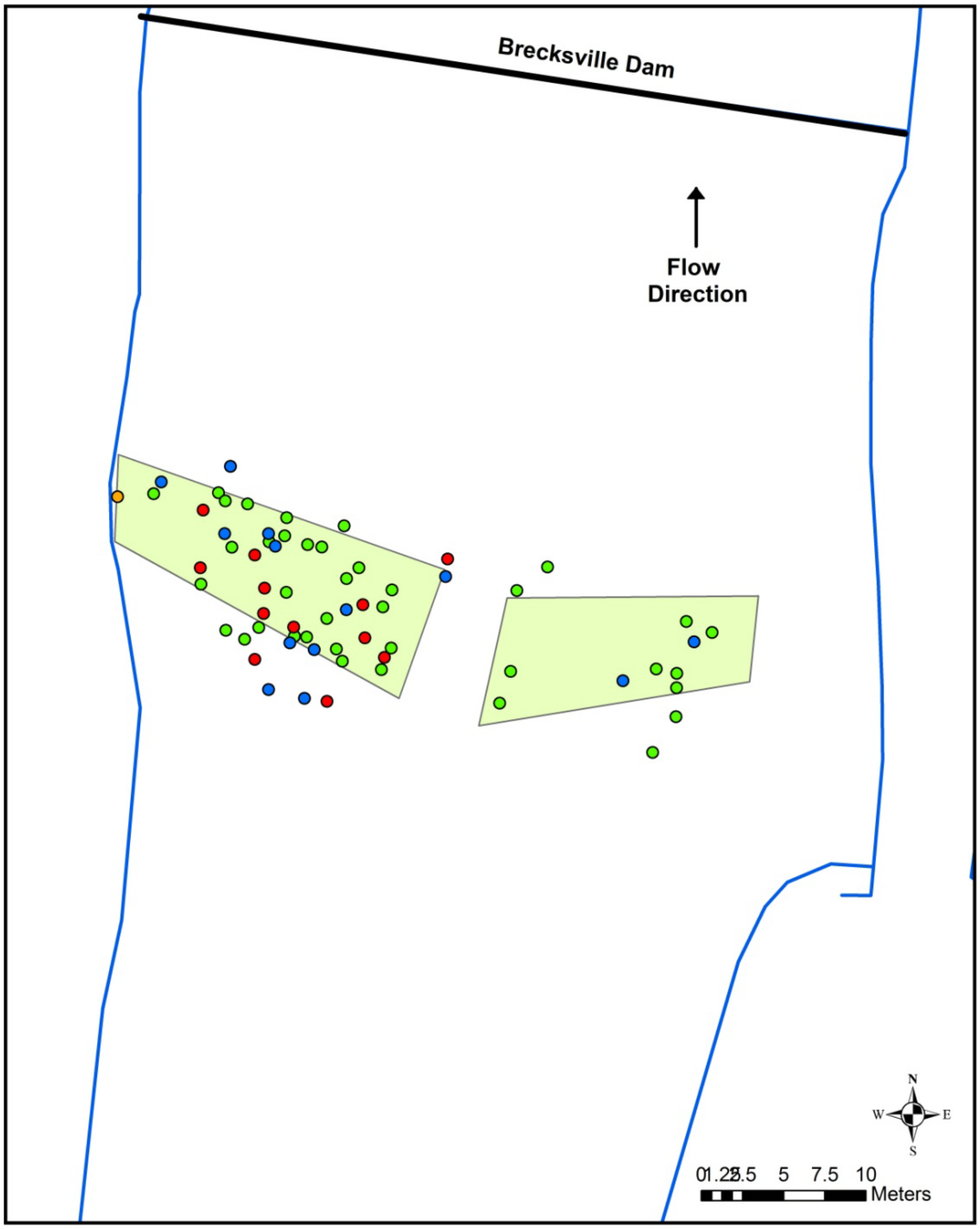

Figure 18. Combined datasets showing the inferred location of the Pinery Feeder Dam. Approximate area of dam structure shaded in green. Upstream and downstream extent of the dam based upon GPR profiles (green dots); GPS spot readings of the dam structure (blue dots); physically identified crib dam (red dots); and dam exposed at the bank (orange dot). The combined dataset indicates a V-shaped structure pointing upstream. River data from 2000 Summit County GIS.

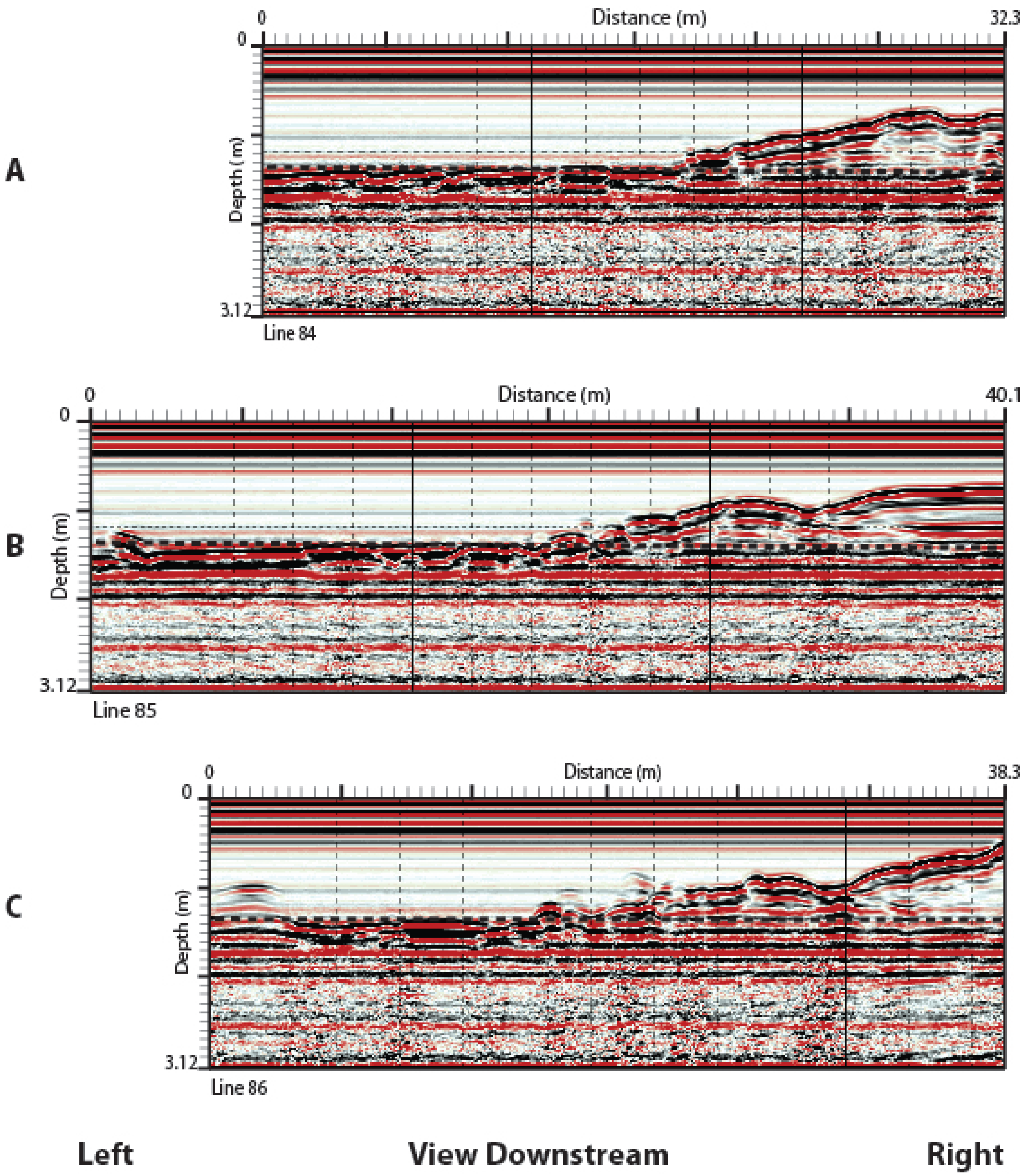

Figure 19. Three transverse GPR profiles viewed looking downstream. Vertical exaggeration of each is 4.12. The dashed line marks the top of the bedrock. Sediment accumulation in the Brecksville Dam pool is largely confined to the right portion of the channel.

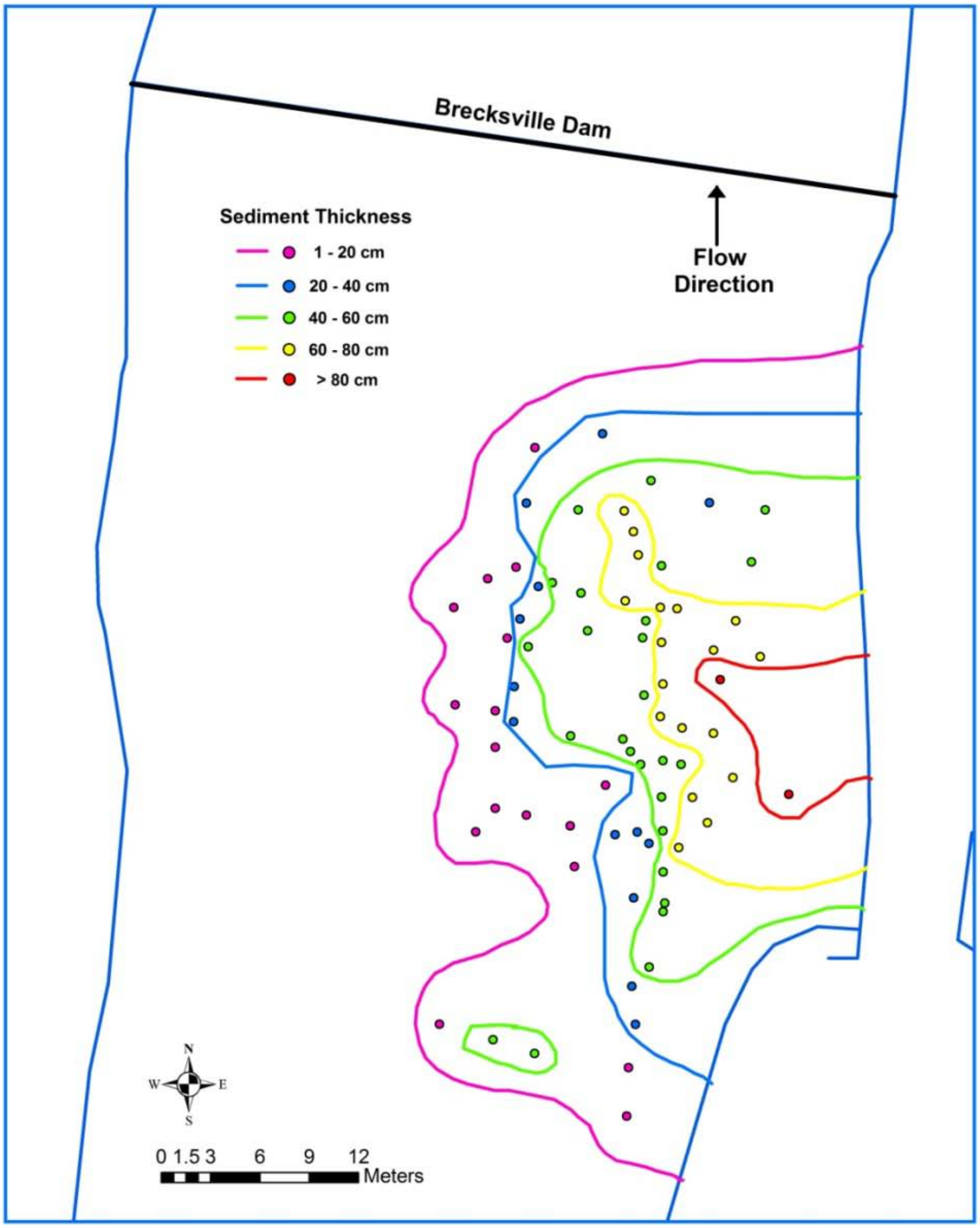

Figure 20. Isopach map showing the thickness fluvial sediments within the Brecksville Dam pool. Sediment thickness was determined from the GPR profiles. Sediment thickness contour interval is 20 cm. Red dots represents locations with the greatest sediment thickness (>80 cm); yellow dots show 60-80 cm thick sediment; green dots show 40-60 cm thick sediment, blue dots show 20-40 cm thick sediment; and purple dots show <20 cm thick sediment. River data from 2000 Summit County GIS.

Acknowledgements:

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APPENDIX

This appendix contains all 28 GPR profiles obtained from the Brecksville Dam pool survey. Each profile is labeled with an identifying number. Figure 11 in the report text provides the location for all GPR profiles.   All longitudinal lines are plotted from upstream to downstream, going from left to right on the page. All transverse lines are shown from left bank to right bank when viewed looking downstream, going from left to right on the page. Vertical exaggeration is present in all the profiles and is given for each profile in the figure caption. The vertical scale is given in both travel time (ns) and after conversion to depth (m). See the methods section for a description of the time to depth conversion.

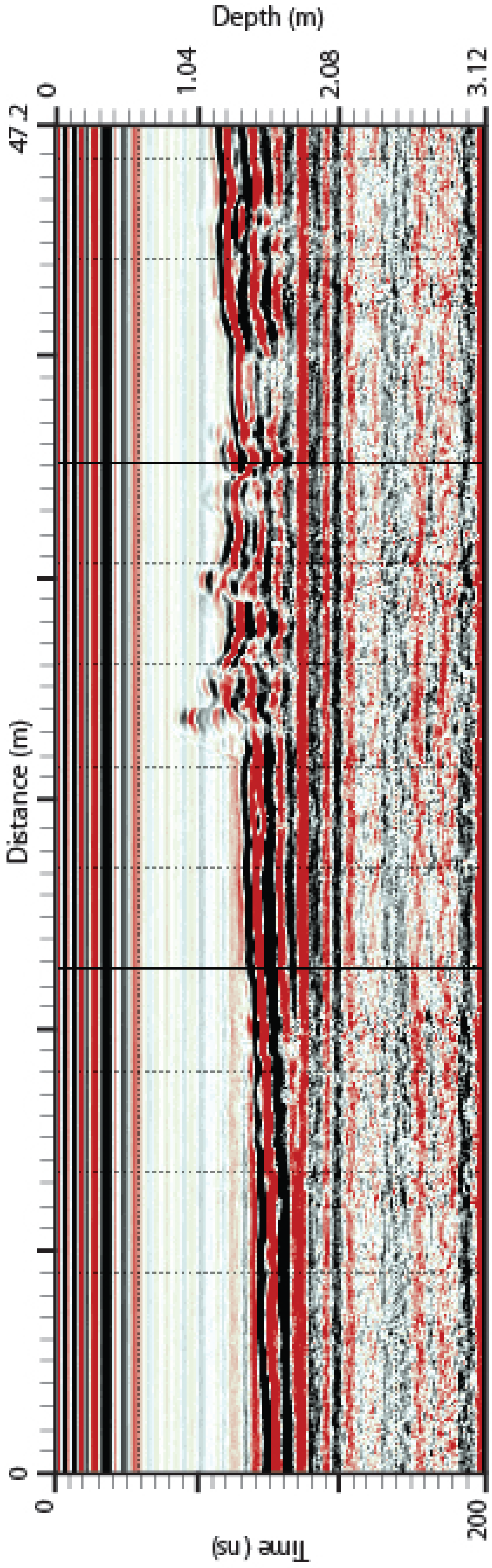

Figure A1: Line 67, an upstream to downstream longitudinal radar profile, located in the central portion of the river study site. Vertical exaggeration 4.84.

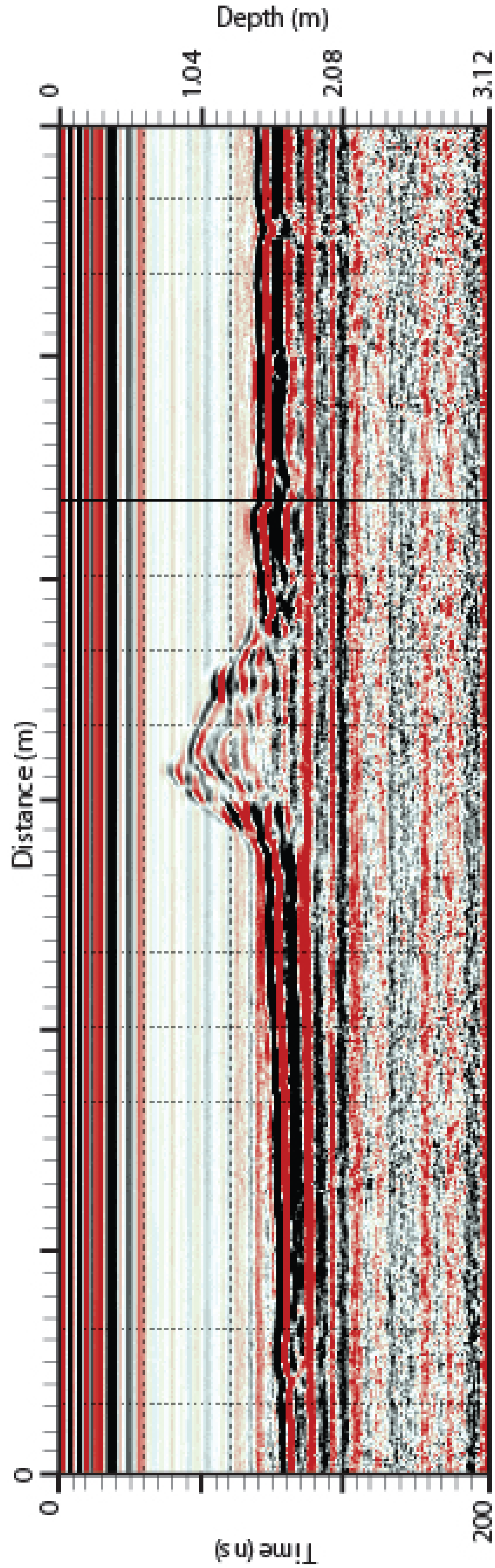

Figure A2: Line 68, an upstream to downstream longitudinal radar profile. No GPS coordinates were collected for this profile.

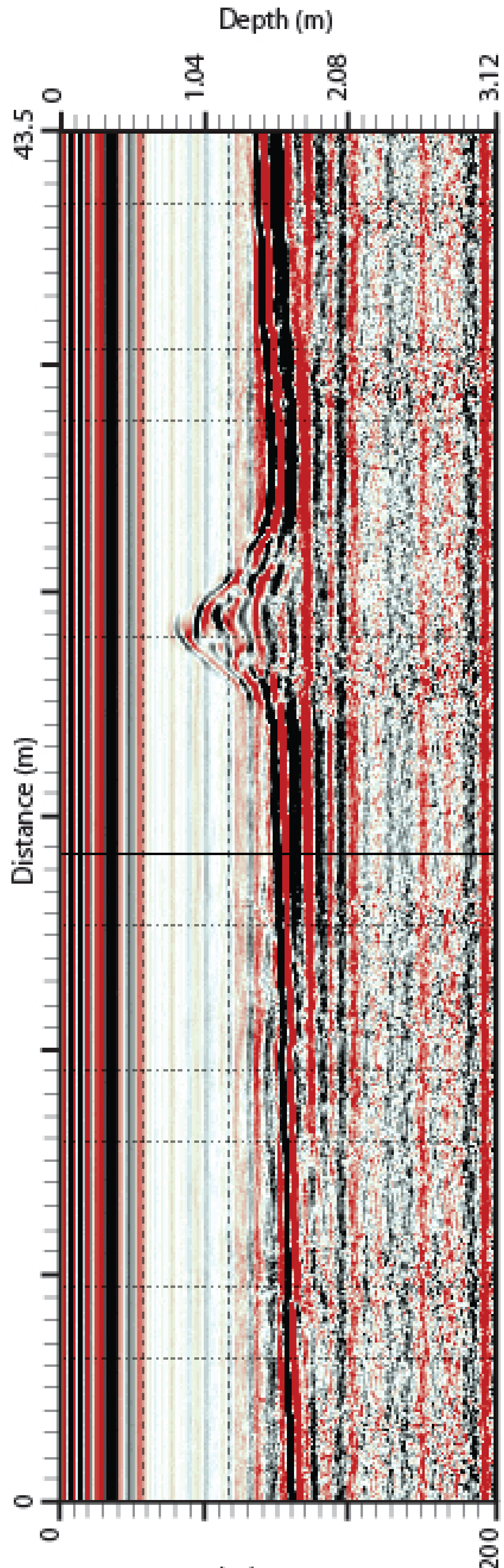

Figure A3: Line 70, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 4.46.

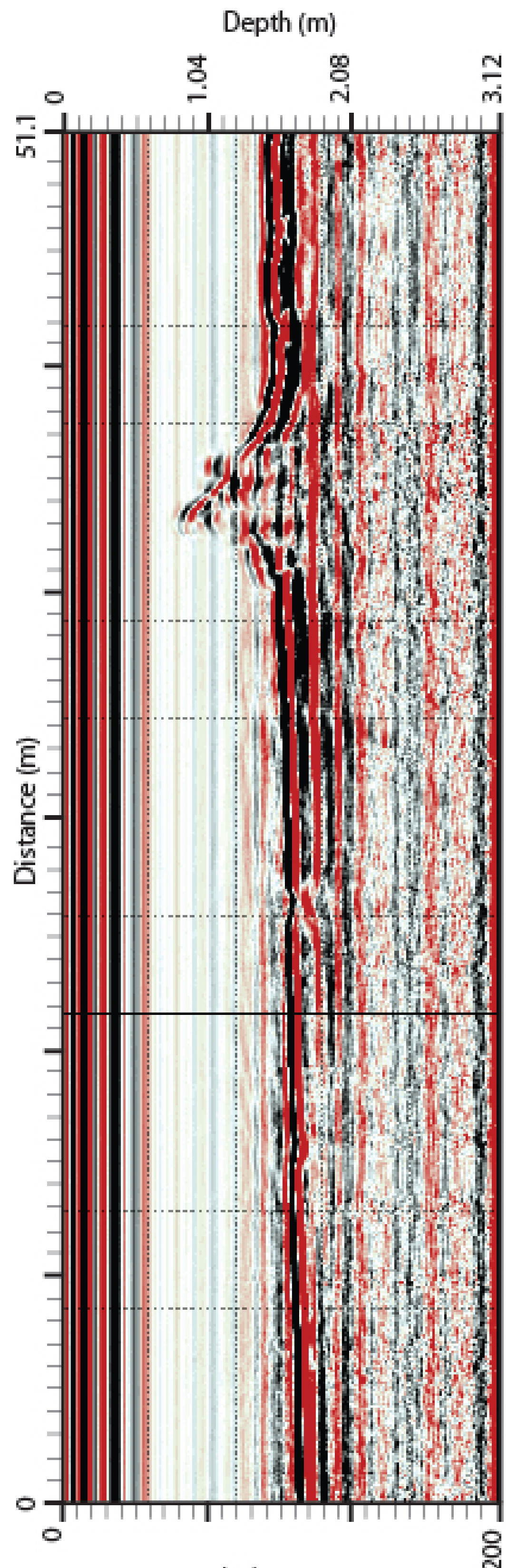

Figure A4: Line 71, an upstream to downstream longitudinal profile, located in the left side of the river. Vertical exaggeration 5.24.

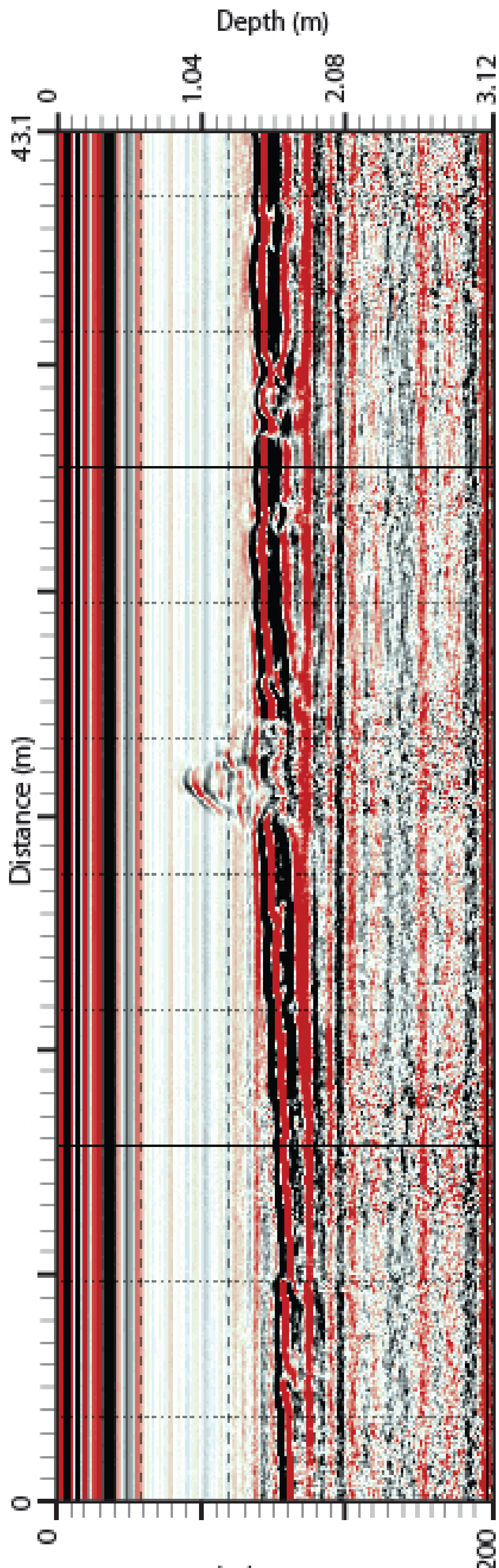

Figure A5: Line 72, an upstream to downstream longitudinal radar profile, located in the central portion of the river. Vertical exaggeration 4.42.

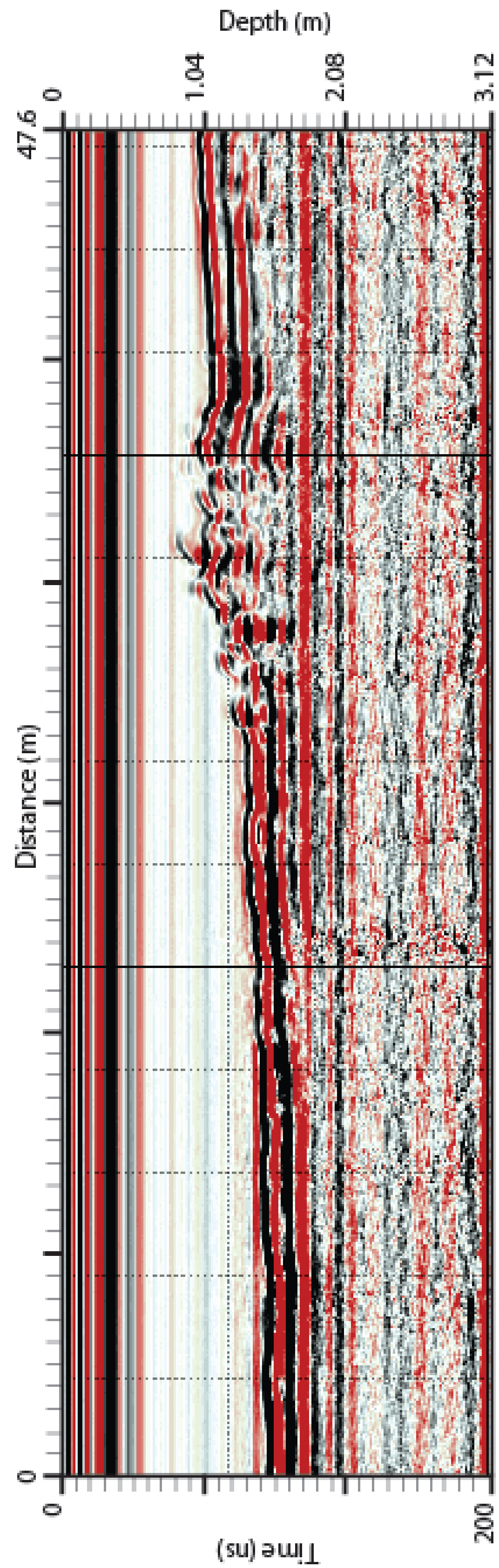

Figure A6: Line 73, an upstream to downstream longitudinal radar profile, located in the central portion of the river. Vertical exaggeration 4.88.

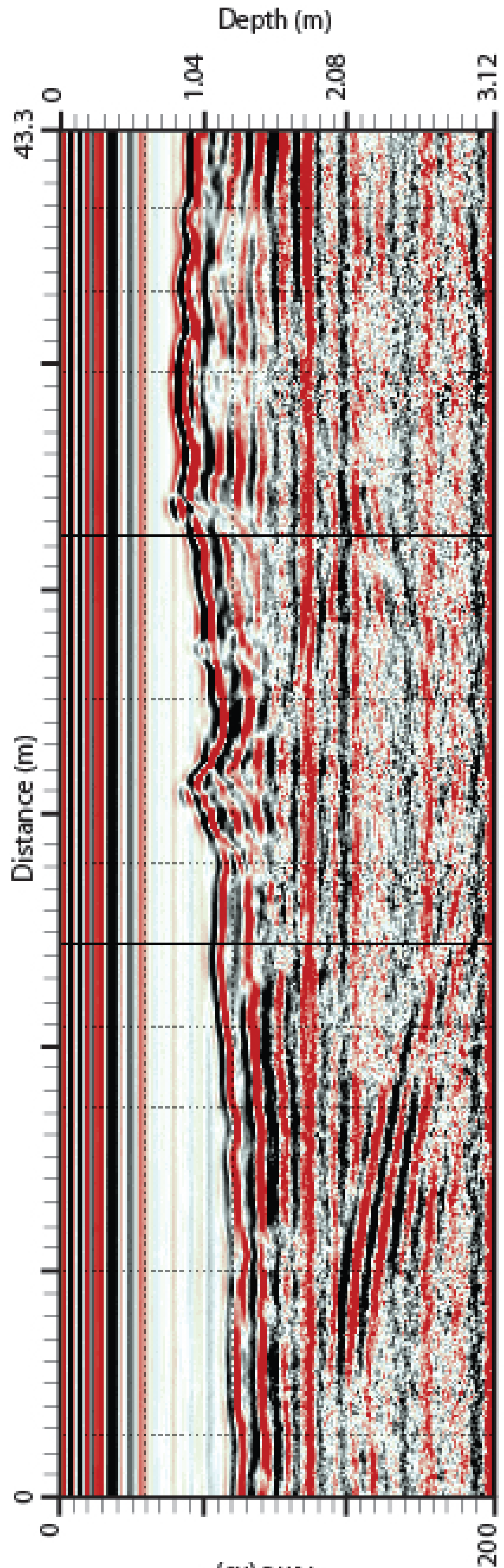

Figure A7: Line 74, an upstream to downstream longitudinal radar profile, located in the right side of the river. Vertical exaggeration 4.44.

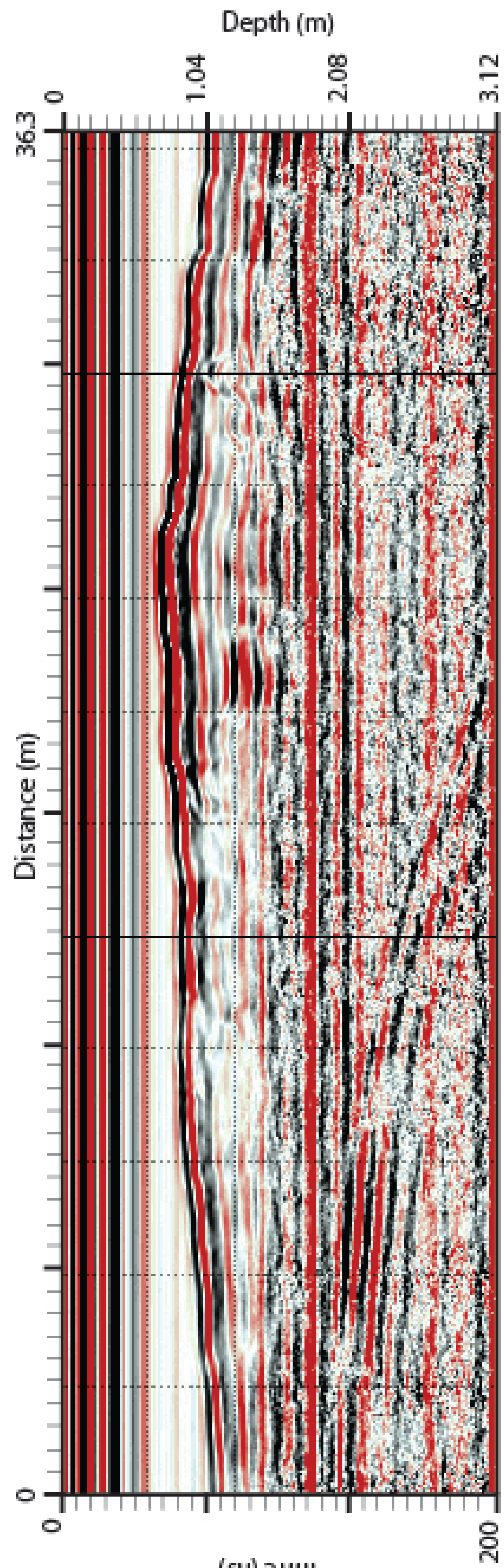

Figure A8: Line 75, an upstream to downstream longitudinal radar profile, located in the right side of the river. Vertical exaggeration 3.73.

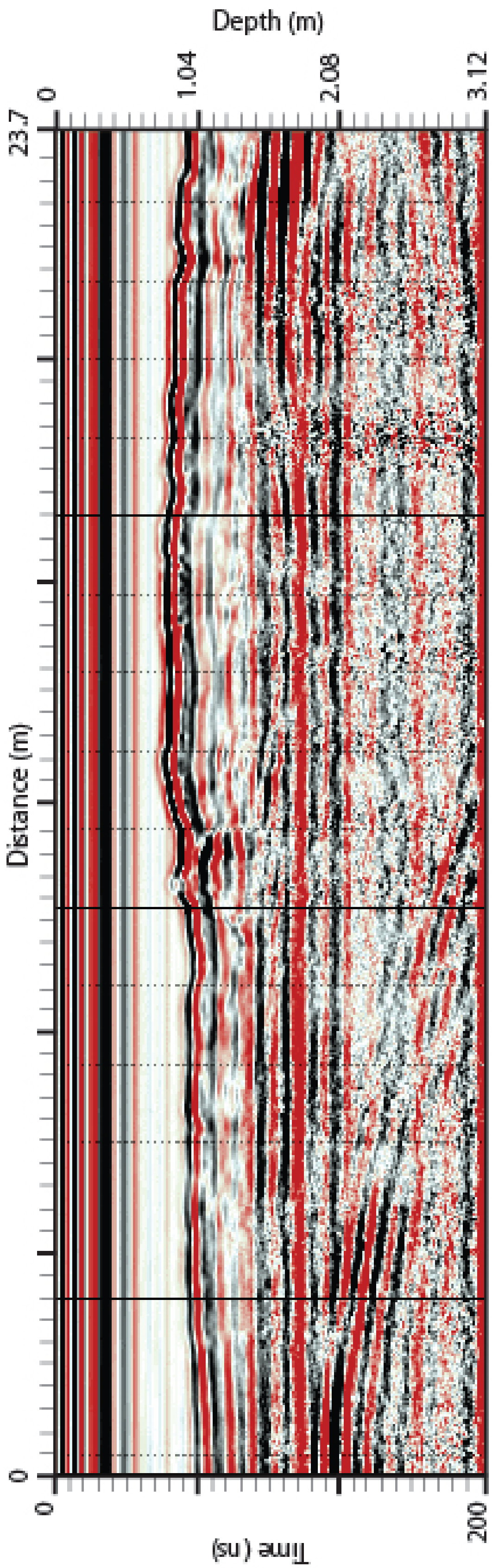

Figure A9: Line 76, an upstream to downstream longitudinal radar profile, located in the right side of the river. Vertical exaggeration 2.43.

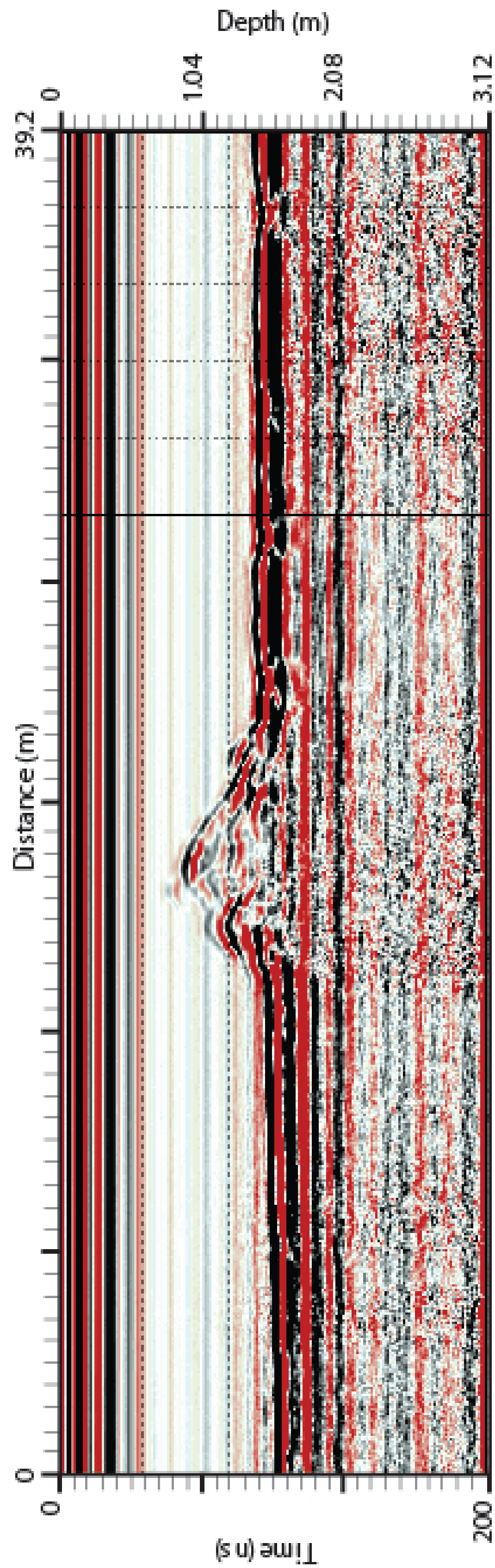

Figure A10: Line 77, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 4.02.

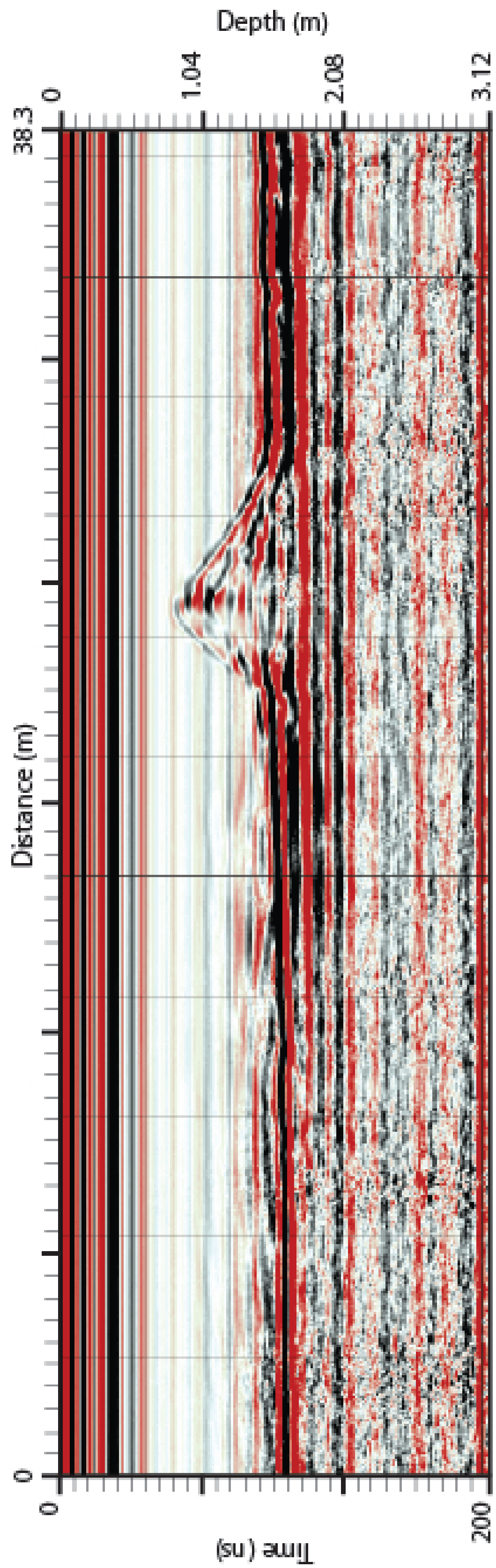

Figure A1 1: Line 78, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 3.93.

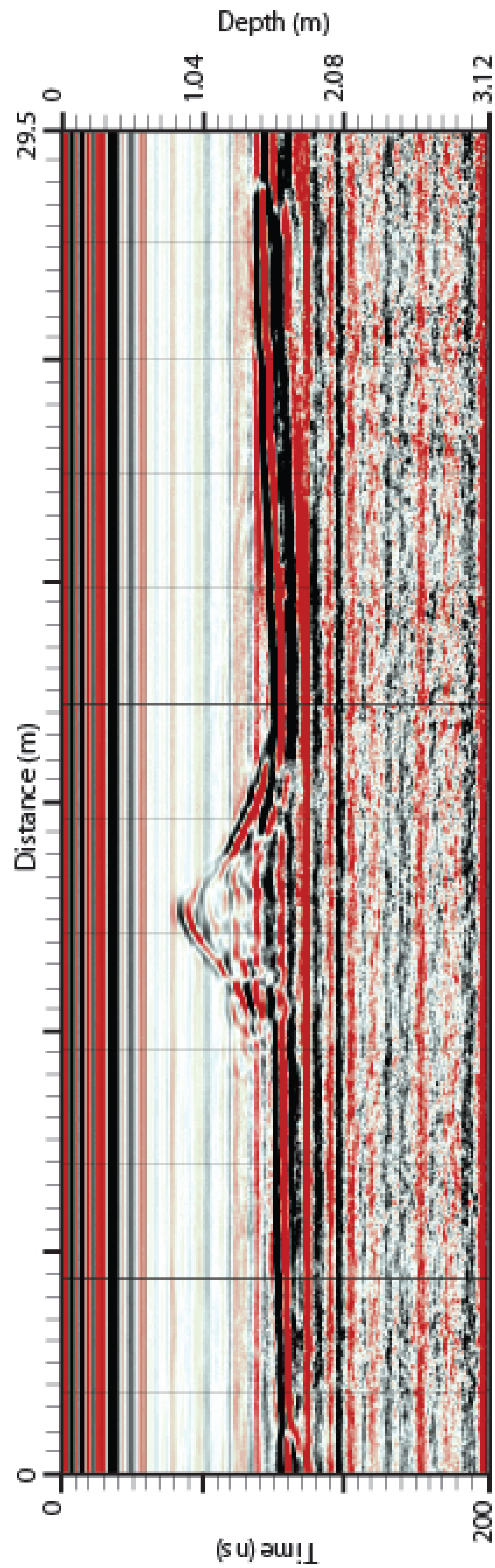

Figure A1 2: Line 79, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 3.03.

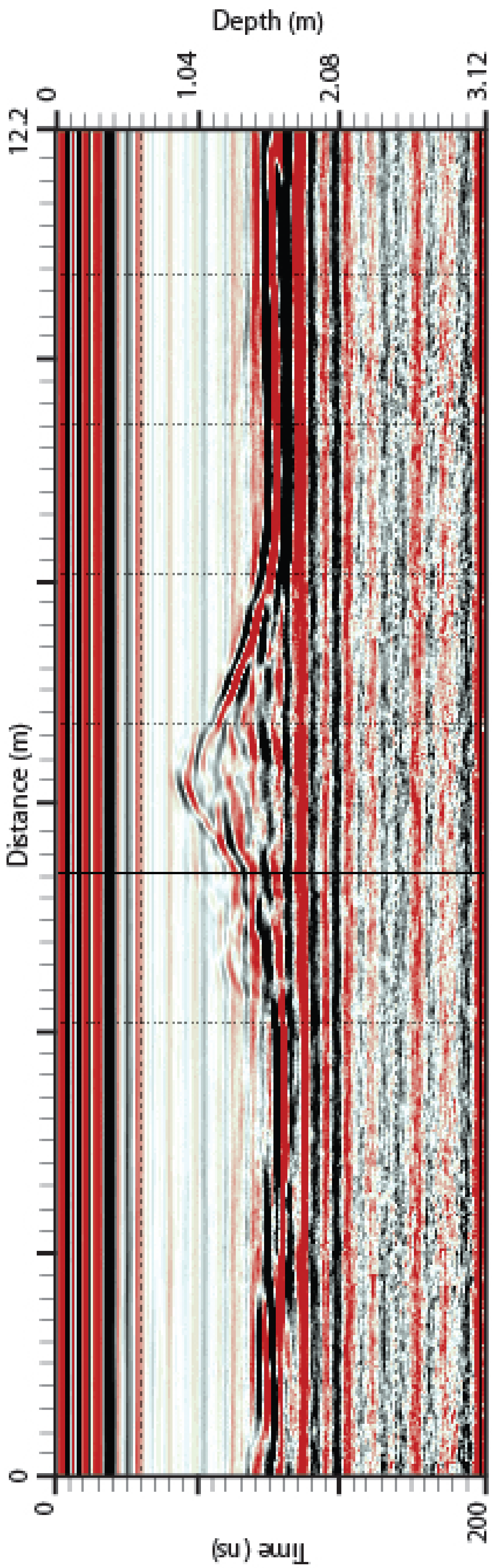

Figure A13: Line 80, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 1.25.

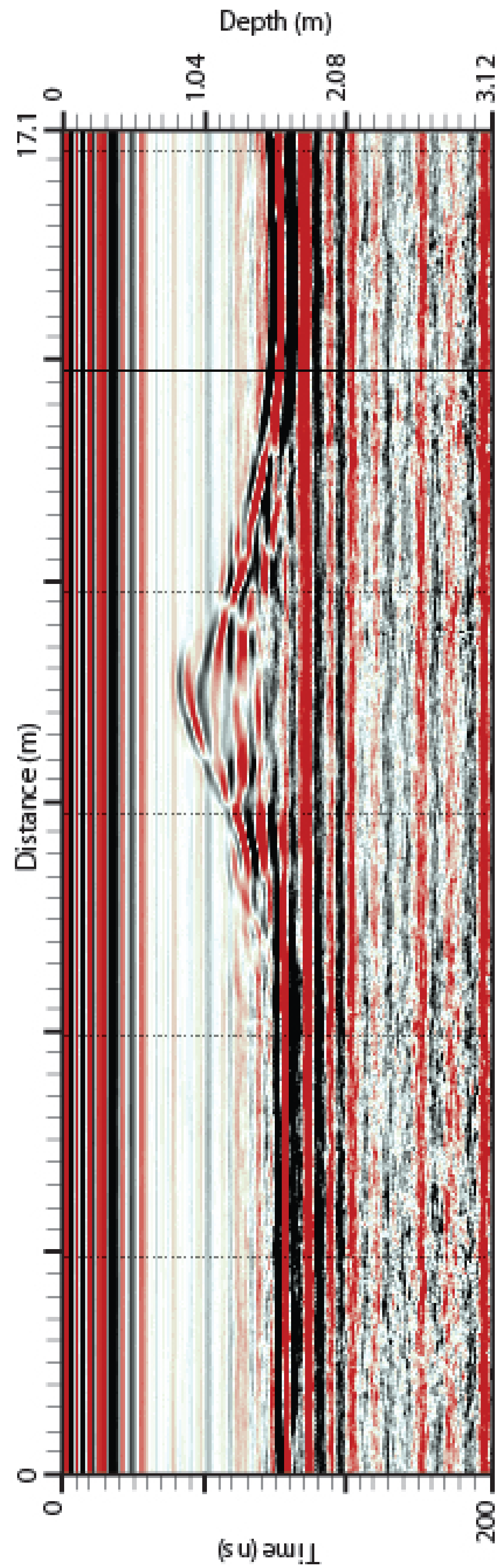

Figure A14: Line 81, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 1.75.

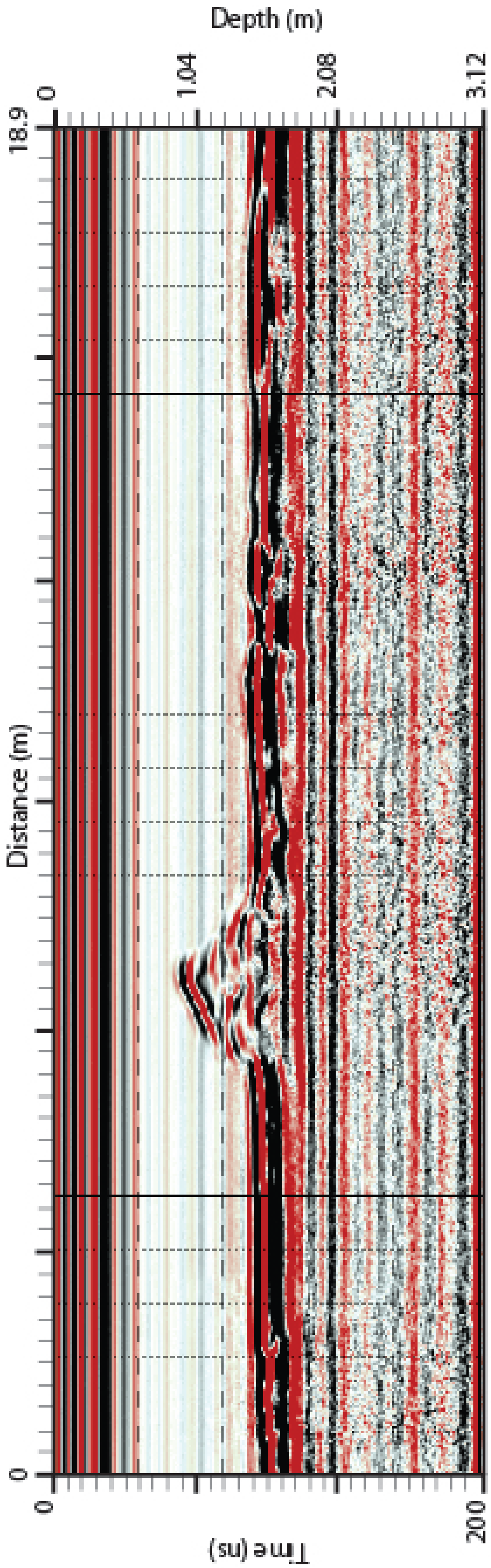

Figure A15: Line 82, an upstream to downstream longitudinal radar profile, located in the central portion of the river. Vertical exaggeration 1.94.

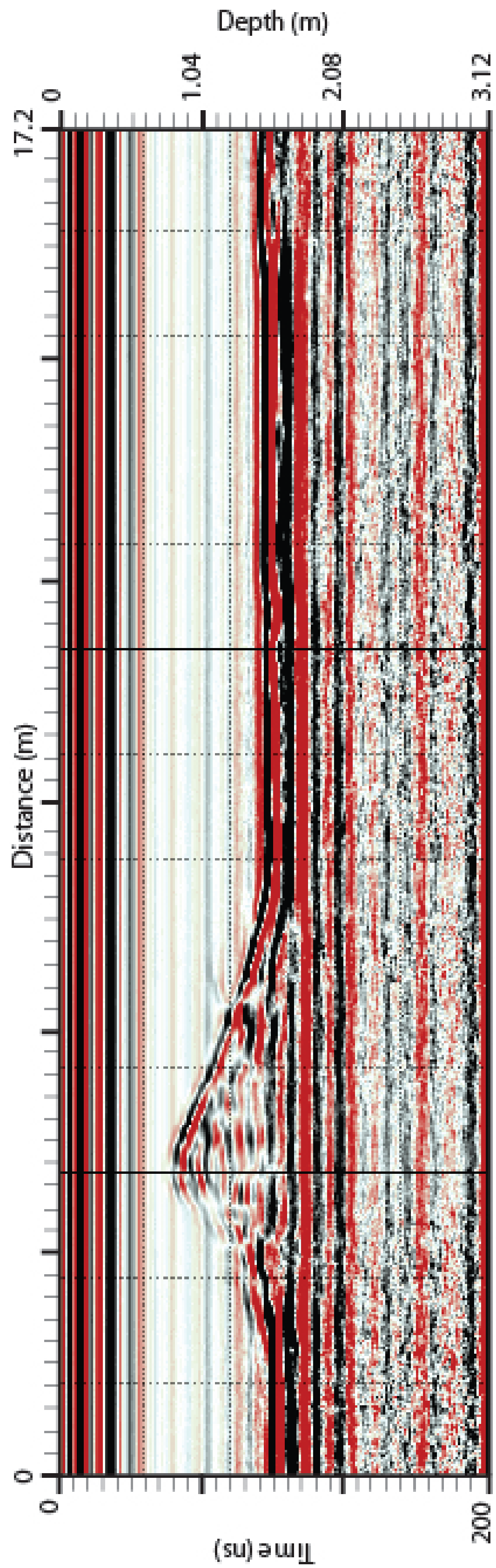

Figure A16: Line 83, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 1.77.

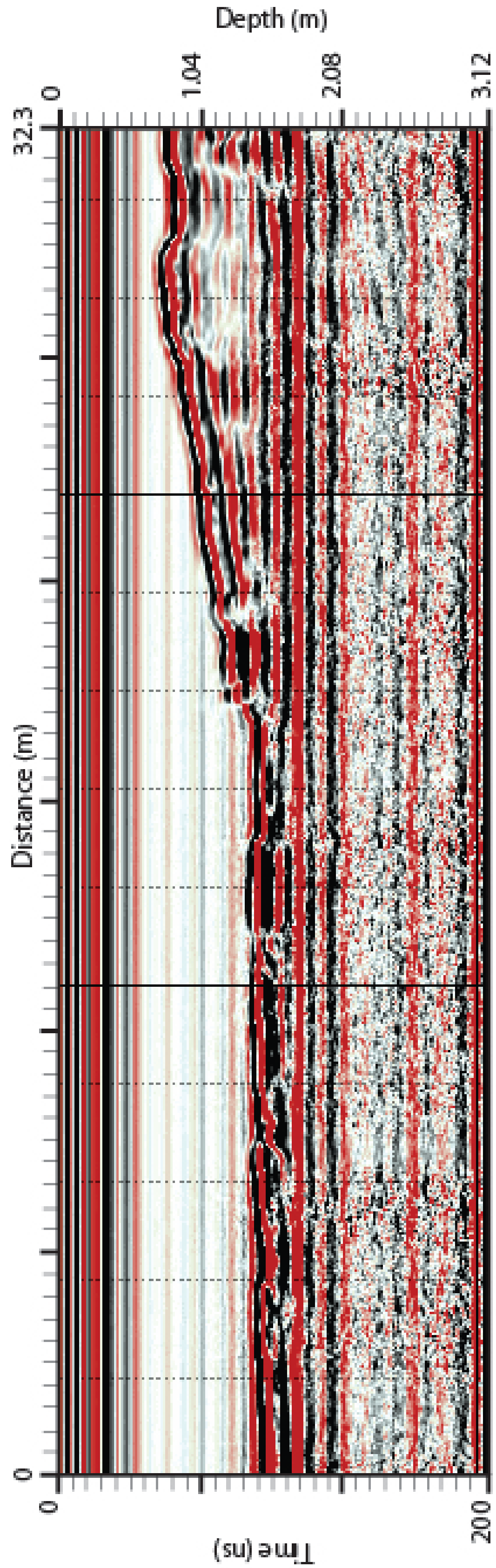

Figure A17: Line 84, a left to right bank transverse radar profile, located in northern portion of river study site. Vertical exaggeration 3.31.

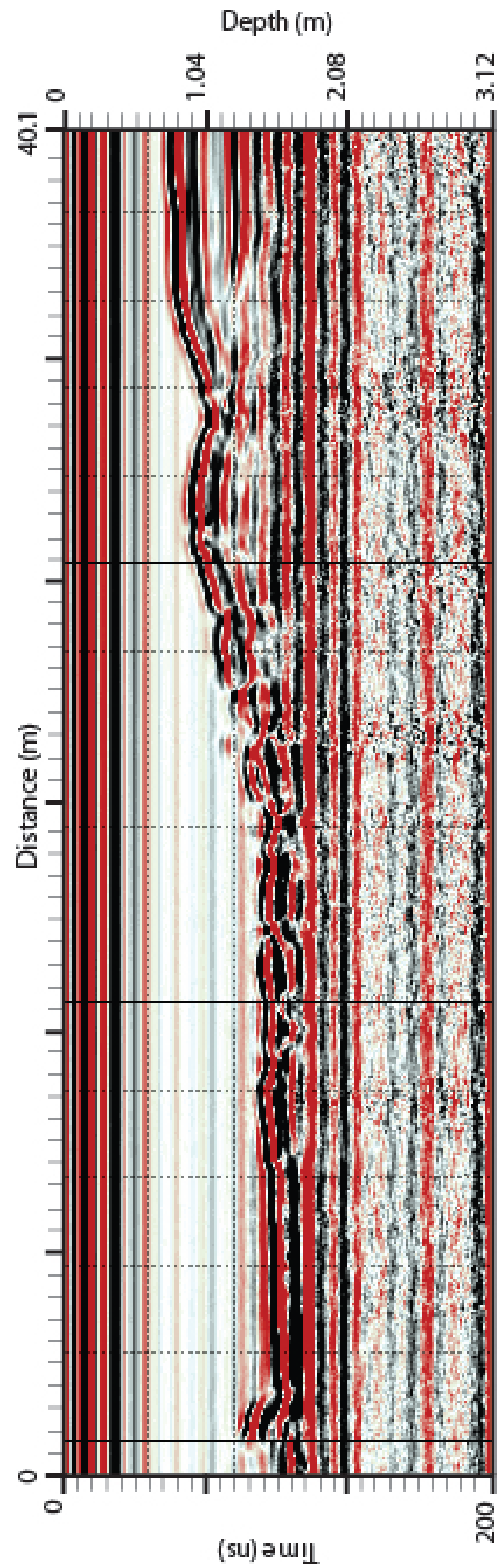

Figure A18: Line 85, a left to right bank transverse radar profile, located in northern portion of river study site. Vertical exaggeration 4.12.

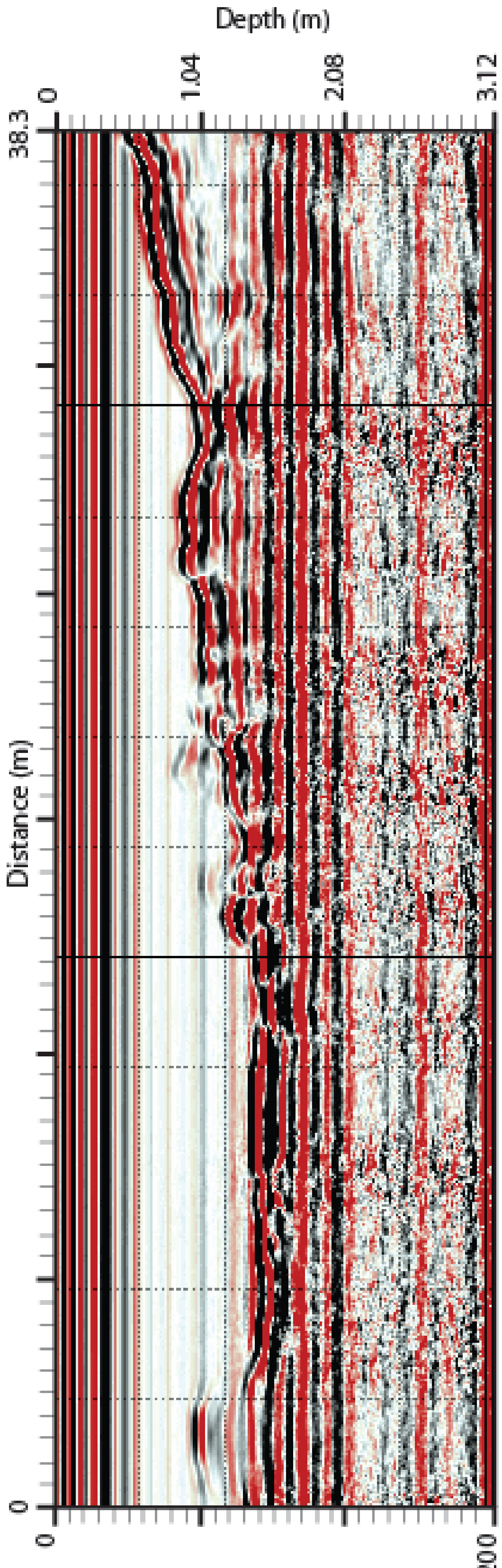

Figure A19: Line 86, a left to right bank transverse radar profile, located in the central portion of the river study site. Vertical exaggeration 3.93.

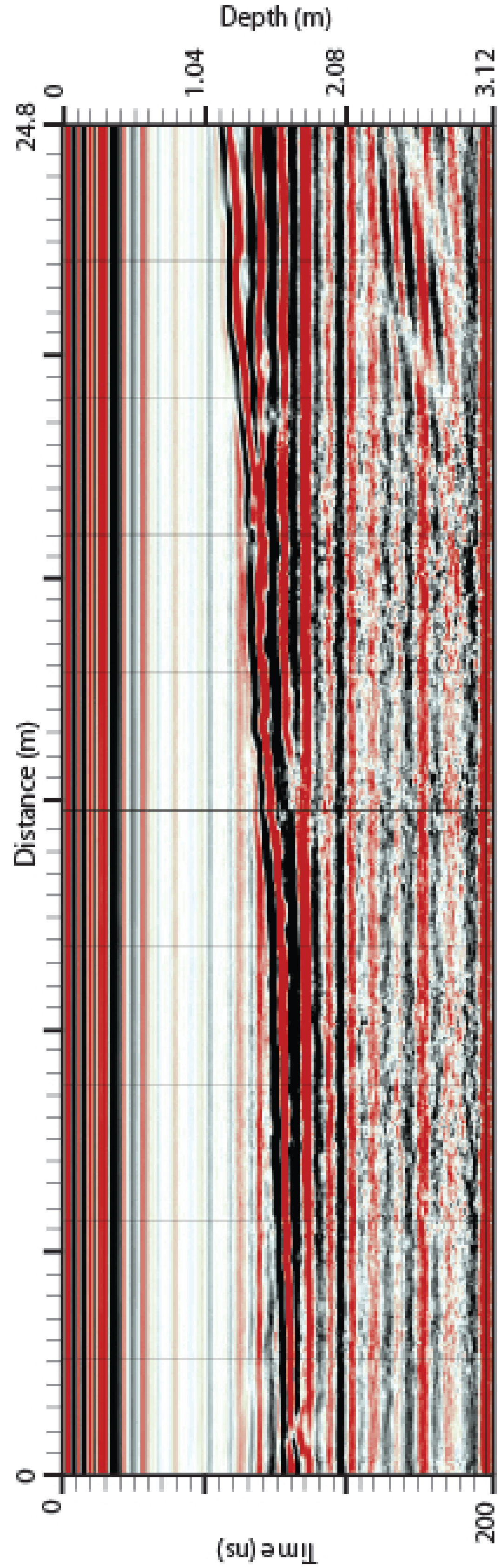

Figure A20: Line 88, a left to right bank transverse radar profile, located in the central portion of the river study site. Vertical exaggeration 2.55.

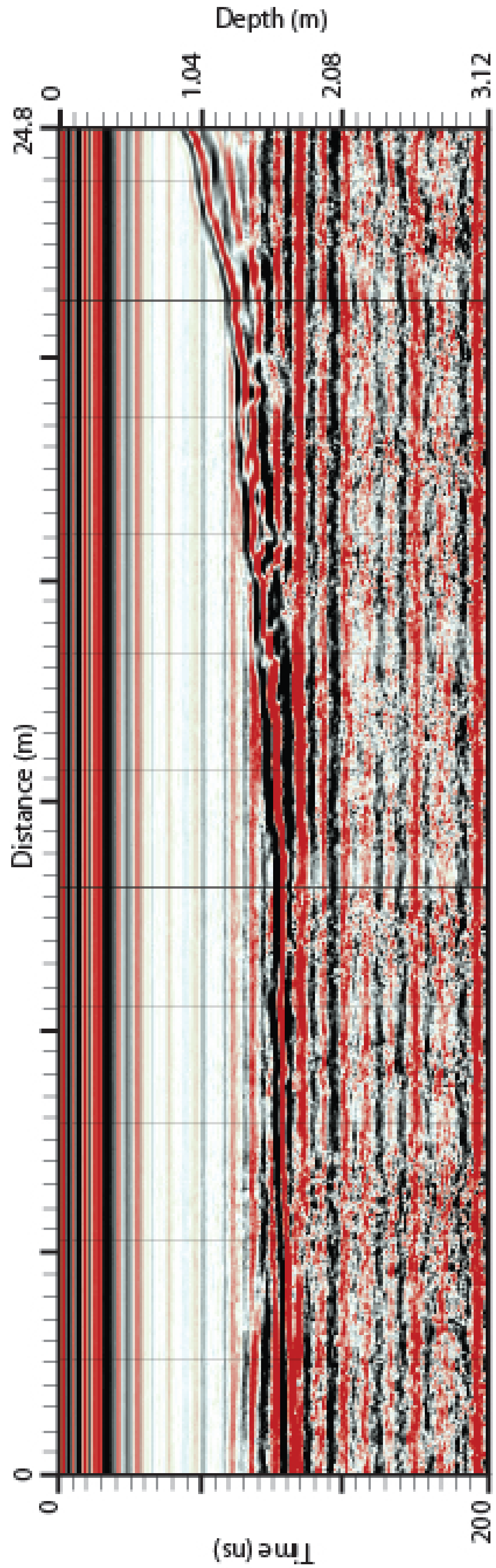

Figure A21: Line 89, a left to right transverse radar profile, located in the southern portion of the river study site. Vertical exaggeration 2.55.

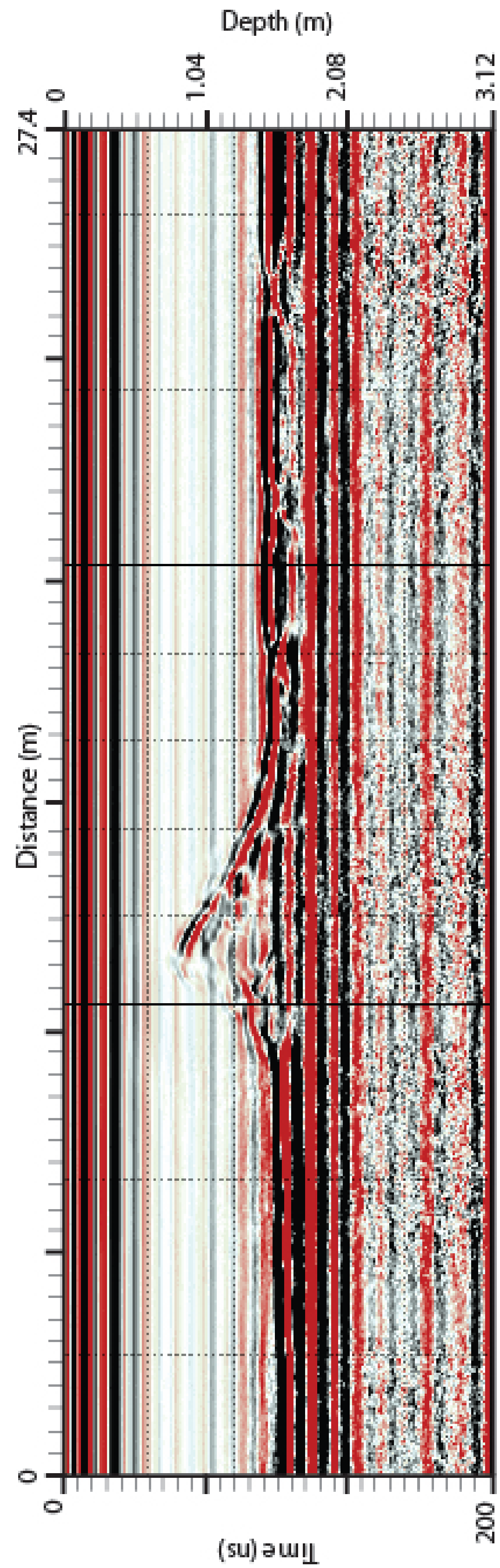

Figure A22: Line 90, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 2.81.

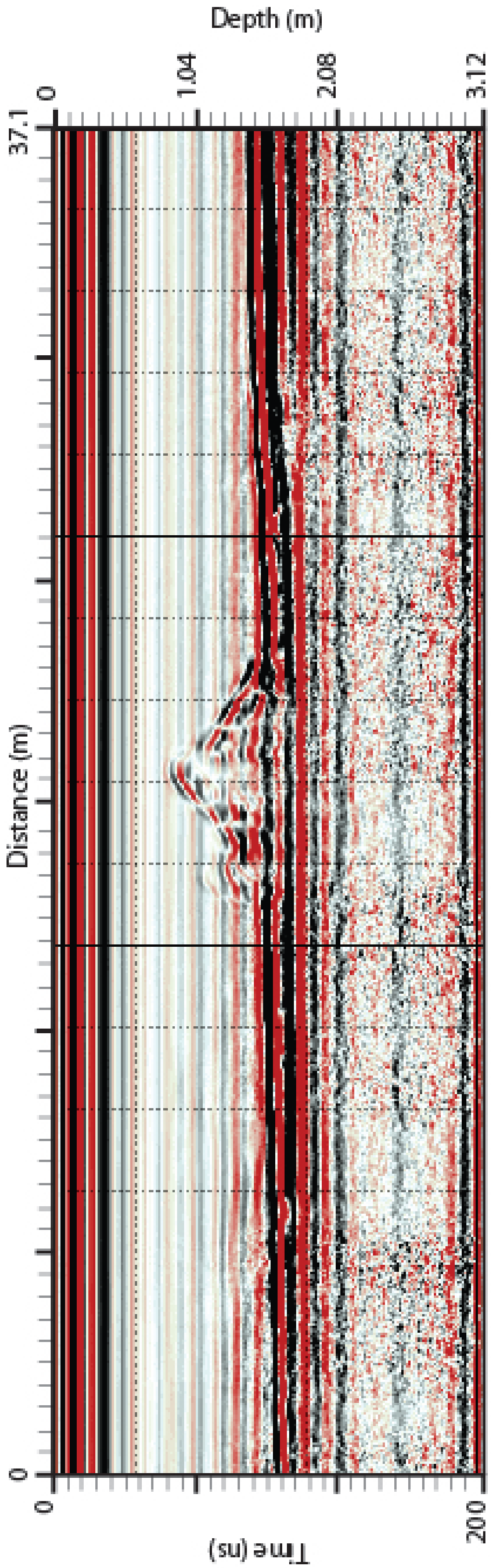

Figure A23: Line 91, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 3.81.

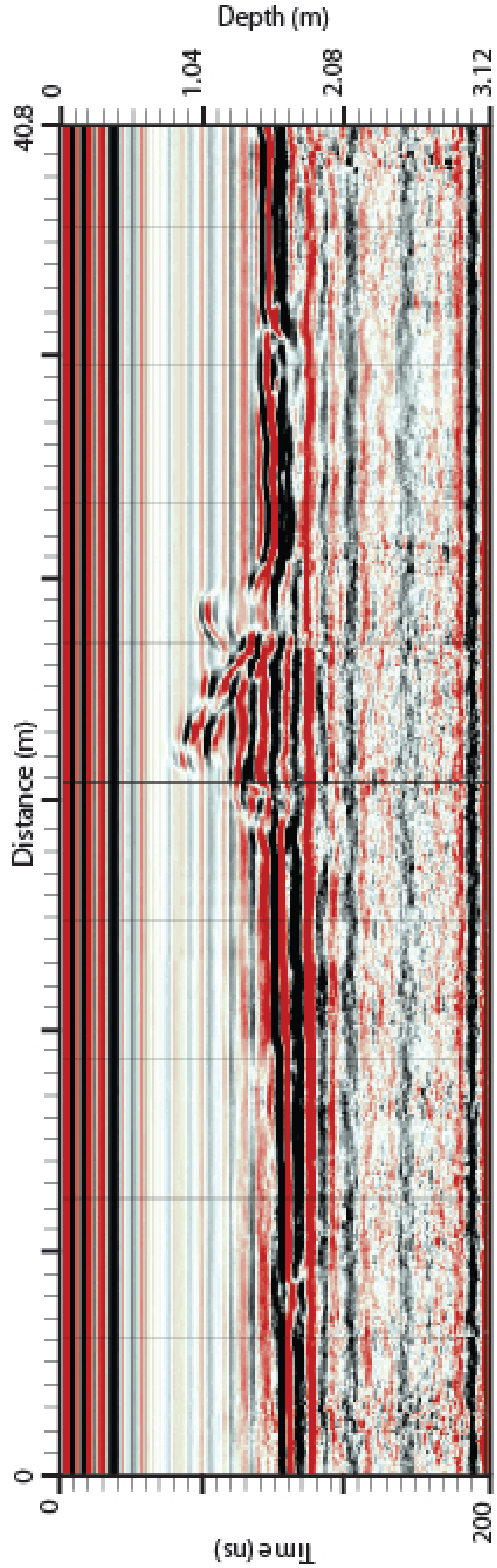

Figure A24: Line92, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 4.19.

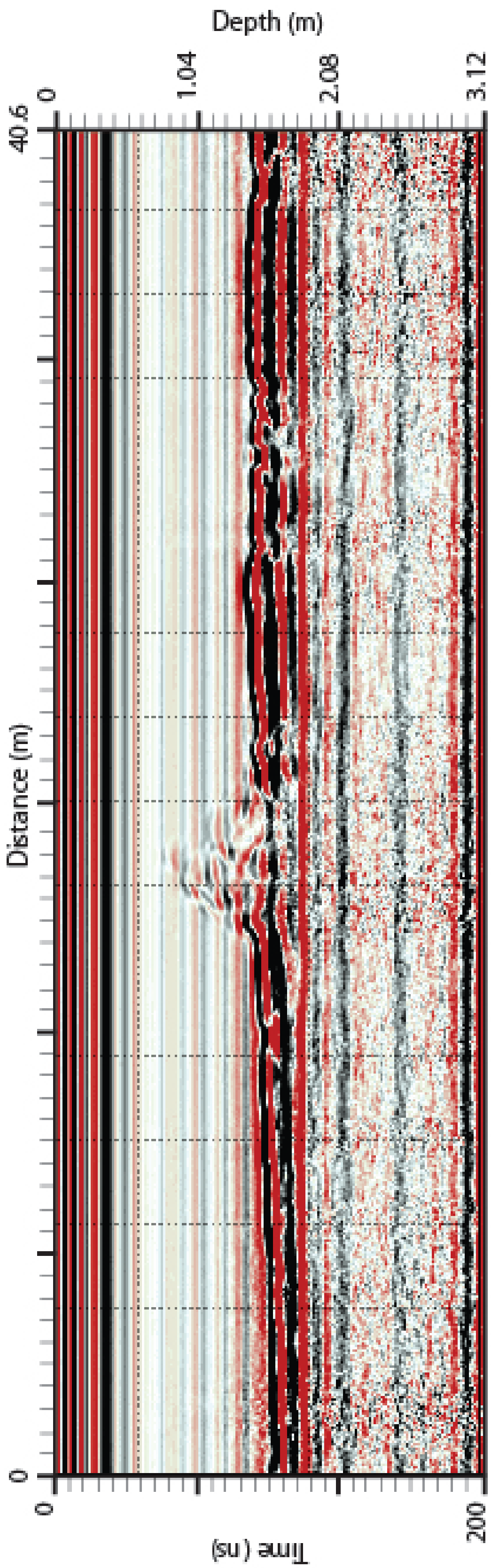

Figure A25: Line 93, an upstream to downstream longitudinal radar profile, located in the left side of the river. Vertical exaggeration 4.17.

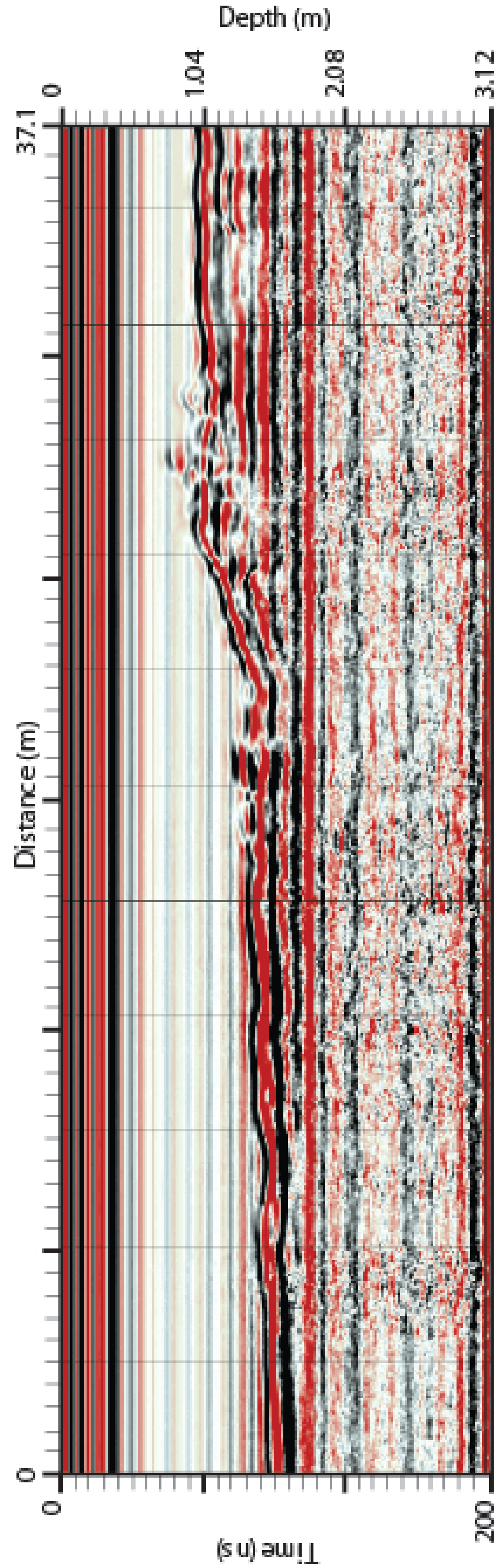

Figure A26: Line 94, an upstream to downstream longitudinal radar profile, located in the right side of the river. Vertical exaggeration 3.81.

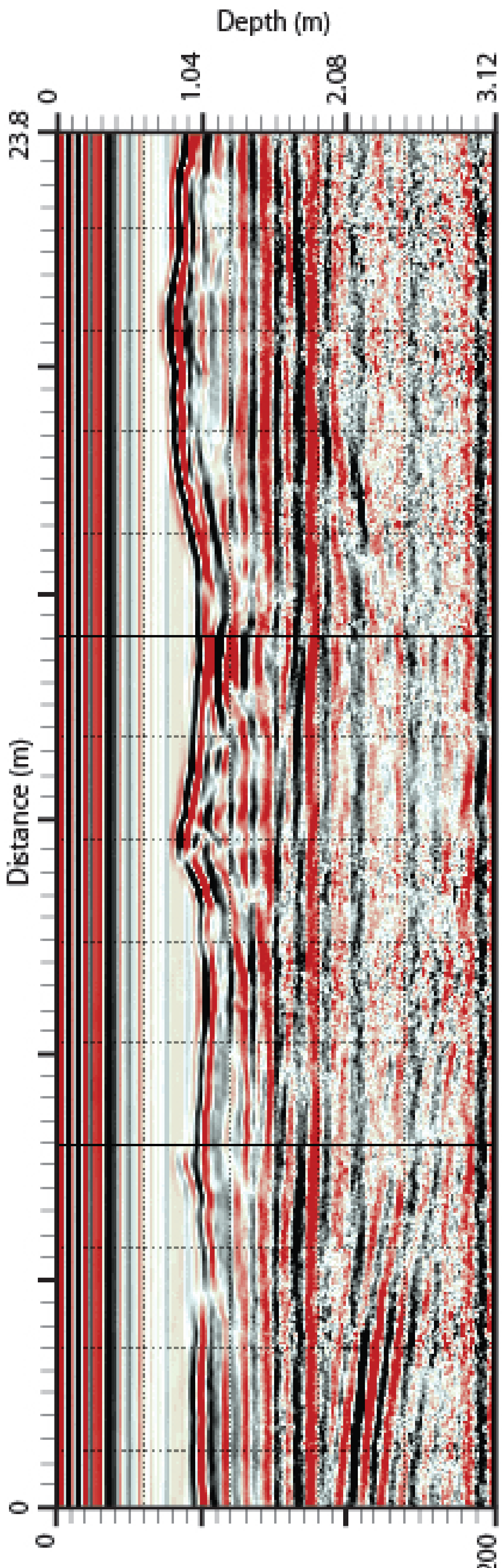

Figure A27: Line 95, an upstream to downstream longitudinal radar profile, located in the right side of the river. Vertical exaggeration 2.44.

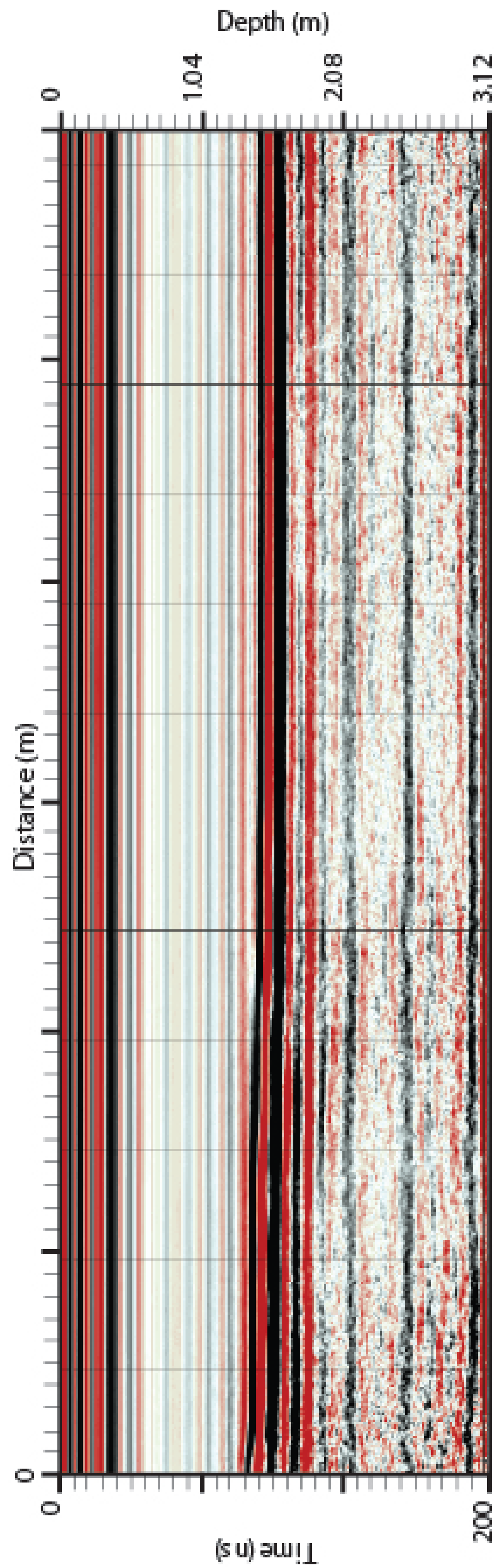

Figure A28: Line 96, a ground truth line for measuring water depths manually to determine the correct dielectric constant for the depth conversion to meters. No GPS coordinates were taken at this location.