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Application of Chirp Acoustic Sub-Bottom Data in Riverine Environments: Identification of Underlying Rocky Hazards at Cape Girardeau, Missouri, and Thebes, Illinois

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Mississippi River Geomorphology and
Potamology Program

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Application of Chirp Acoustic Sub-Bottom Data in Riverine Environments: Identification of Underlying Rocky Hazards at Cape Girardeau, Missouri, and Thebes, Illinois

Heidi M. Wadman and Jesse E. McNinch

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
Field Research Facility
1261 Duck Rd.
Kitty Hawk, NC 27948

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Abstract

Shallow acoustic reflection (chirp) data have been utilized to map the elevation of underlying stratigraphy in a wide range of aqueous environments. Of particular concern in riverine regions is the elevation of near-surface underlying rock that, if exposed during normal migration of sedimentary bedforms, can cause grounding and damage to vessels transiting the region during periods of low water. Given the ephemeral nature of the rock's exposure, traditional surveying methods are insufficient to map rock when it is covered by a thin veneer of sediment, increasing the potential hazard. Accordingly, the US Army Corps of Engineers, St. Louis District, (MVS) explored the use of chirp sub-bottom surveys to identify buried rock within the Mississippi River in the vicinity of Cape Girardeau, MO, and Thebes, IL. Hazard maps showing the distribution of buried rock were generated, and the base of the mobile sediment layer was identified where possible. These data will allow MVS to accurately identify potentially hazardous regions during periods of low water. Although the study did not result in the complete mapping of all near-surface geologic hazards, regions that warrant further study are identified, and modifications to the original survey plan are provided to improve the accuracy of future data collection efforts.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE) as part of the Mississippi River Geomorphology and Potamology (MRG&P) Program, under Project 127672; "Mississippi River Geomorphology and Potamology Program." The MRG&P is part of the Mississippi River and Tributaries Program and is managed by the USACE, Mississippi Valley Division (MVD), and districts. At the time of publication of this report, the MRG&P Program Director was Dr. James W. Lewis. The MVD Commander was MG R. Mark Toy. The MVD Director of Programs was Mr. James A. Bodron.

Mississippi River engineering direction and policy advice were provided by the Mississippi River Commission. The Commission members were MG Toy, USACE, President; the Honorable James Reeder; the Honorable Norma Jean Mattei, PhD; RDML Shepard Smith, National Oceanic and Atmospheric Administration; BG D. Peter Helmlinger, USACE; and MG Robert F. Whittle, USACE.

The work was performed by the Coastal Observations and Analysis Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Dr. Jeff Waters was Chief of the Coastal Observations and Analysis Branch; Dr. Cary Talbot was Chief of the Flood and Storm Protection Division. The Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and the Director was Dr. Ty V. Wamsley.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

Acknowledgements

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1 Introduction

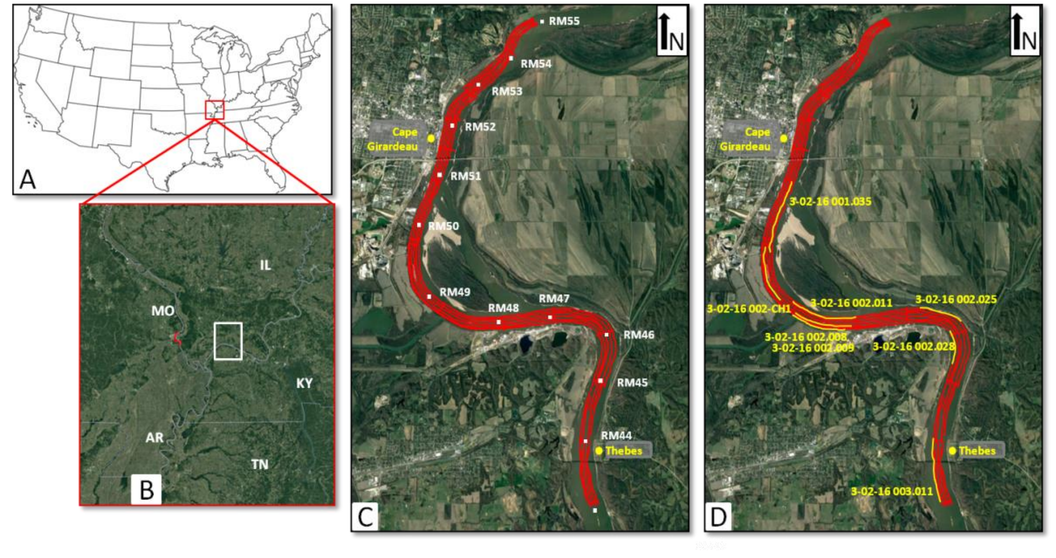
Background

Where outcrops of erosion-resistent geologic units, such as indurated or weakly lithified sedimentary layers or rock, are observed along riverbeds, the same geologic unit is also present in the shallow, sub-surface stratigraphy. However, the spatial extent of these geologic layers below the surface of a riverbed is often much more extensive than indicated by just the portion of the geology that is exposed at the riverbed surface. When the usually buried portion of these geologic layers is temporarily exposed above the riverbed via sediment transport of overlying mobile bedforms, especially during periods of low water, these erosion-resistant units can adversely impact the navigability of the river. In the region of Cape Girardeau, MO, and Thebes, IL, an extensive and irregular geologic formation of pinnacle-shaped rock underlies portions of the main navigation channel of the Mississippi River. During periods of high river flow and associated bedform migration, outcrops of this rock are often temporarily exposed in the navigation channel. Vessels transiting this region during subsequent periods of low water levels risk grounding along the pinnacle-shaped rock outcrops. However, due to the highly mobile nature of the bedforms in this region (e.g., sand waves), these navigation hazards are frequently buried as quickly as they are exposed, making them challenging at best to map via traditional geophysical surveys and subsequently incorporate into navigation charts.

Objective

Although the surficial expression of these units can be mapped via sidescan sonar (either via a dedicated sidescan survey or via the backscatter from a multibeam bathymetry survey), a veneer of sediment on the order of 1-2 inches (in.) in thickness will obscure indurated sedimentary layers or rock outcrops from these mapping methodologies. In addition, extensive debris on the surface of the riverbed can further complicate interpreting the presence and spatial extent of rock in the study area. Rather than rely on these traditional mapping technologies, The US Army Corps of Engineers (USACE), St. Louis District (MVS), Applied River Engineering Center, explored the use of chirp sub-bottom geophysical surveys to identify buried rock within the Mississippi River in the vicinity of Cape Girardeau, MO, and Thebes, IL (river mile [RM] 55-47 and RM 47-43, respectively; Figure 1). Hazard maps showing the distribution of rock buried within 15 ft of the surface of the riverbed were generated. In addition, the base of the mobile sediment layer was identified where possible. These maps will allow MVS to accurately identify potential hazards in navigable regions during periods of low water and to further identify the volume and depth of hazardous rock. Although the effort presented here is not a complete delineation of the potential buried stratigraphic hazards in this region, the study provides proof-of-concept of the methodology, and suggestions are provided for future efforts in this, and similar, environment.

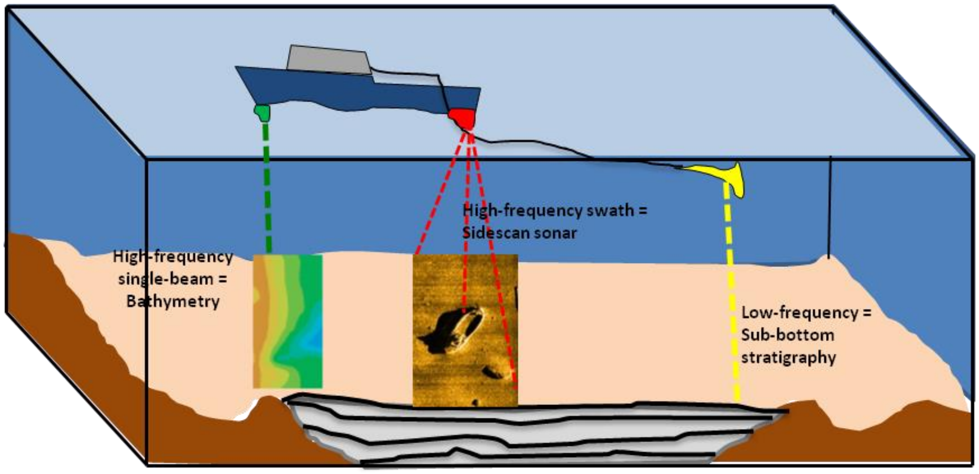
Figure 1. Location of the Cape Girardeau, MO, study area. Panel (A) shows the overall region expanded in panel (B). The actual survey lines (red) in the white inset box in panel (B) are presented in detail in panel (C), including the general location of each river mile. Sub-bottom cross-sections presented in subsequent figures are too small to be imaged on the regional map. Instead, the specific seismic profile line from which cross sections in subsequent figures were extracted (as annotated on each figure) is noted on panel (D).



Approach

All geophysical mapping methodologies share the same basic relationship: a towfish is towed from a survey vessel, and a sound source is generated from a transducer in the towfish towards the sediment-water interface (referred hereafter as the *riverbed*). The density change at the riverbed reflects the sound back to the surface where it is detected by receivers either embedded in the towfish or towed behind the towfish or vessel (Figure 2). Since the frequency of the acoustic pulse is known, the two-way travel time provides a measure of the distance (or water depth) between the towfish and the riverbed, and this relationship provides the basis for all bathymetric depth sounders. The acoustic frequency generated by these towfish is generally of a high-enough frequency (e.g. ~200 kilohertz [kHz]) such that all of the generated sound is reflected off of the riverbed, with little or no penetration below the surface.

Figure 2. Common geophysical acoustic survey techniques. The type of data collected depends primarily on the frequency of the transmitter.



The strength of the returned signal (referred to as the signal's amplitude) is a measure of the acoustic impedance of the geologic unit, which in turn is directly related to the density of the sediment, and thus the amplitude of the acoustic return can be used to delineate the geologic nature of the riverbed. Softer, less dense sediment (e.g., silty-clay) reflects less energy and thus has a lower amplitude return than more dense sediment (e.g., sand). The varying amplitudes require groundtruthing via sediment samples to determine what sediment type they are reflective of in a specific region, but significantly fewer samples are required to groundtruth amplitude data to generate a surface type map than without a survey. The frequency of the acoustic signal determines the size of features that can be resolved — the resolution — as well as the depth under the riverbed — the penetration — to which the signal can penetrate, if at all. Sidescan sonar systems measure a swath of high-frequency amplitude returns from the riverbed, allowing detailed maps of surficial sediment type and features (e.g., ripples) to be generated. However, sidescan sonars cannot penetrate more than the uppermost inch or two of the riverbed sediment, precluding their use for mapping subsurface stratigraphy (e.g., Mitchell 1993).

To map the stratigraphy below the riverbed, lower acoustic frequencies must be utilized. Although multiple strategies exist for generating these pulses, frequency-modulated (FM), acoustic chirp reflection systems are considered the industry standard for acquiring stratigraphic data in shallow, aqueous environments (e.g., Schock and LeBlanc 1990; LeBlanc et al. 1992; Roberts and Supan 2000; Schock 2004; Lee et al. 2009). Chirp systems produce an FM range of acoustic frequencies with each acoustic pulse (similar in audible sound to a bird chirp), providing a range of frequencies lower than those used for bathymetry or sidescan sonar applications. These lower frequencies are able to penetrate the sediment-water interface and thus be transmitted into the riverbed. Rather than getting a single reflection from the single frequency acoustic pulse, the different frequencies in a chirp pulse are reflected off of changes in density in the subsurface sediment, and different frequencies on the same chirp pulse are reflected at different amplitudes and time from different density changes and depths, allowing a detailed map of subsurface stratigraphy to be created. Similar to sidescan sonar data, the amplitude of each return is a function of the different acoustic impedance (or density) of each layer, and sediment samples via cores can be used to interpret the composition of the mapped layers. Acoustic chirp reflection systems have been utilized to map the shallow stratigraphy of a wide range of aqueous environments (e.g., Schock and LeBlanc 1990; Schock 2004; Roberts and Supan 2000), including rivers and estuaries (e.g. Carbotte et al. 2004; Nitsche et al. 2004; Nitsche et al. 2007; Plets et al. 2009), lacustrine (e.g. Schwamborn et al. 2002; Cukur et al. 2013; Cukur et al. 2015), and shallow coastal (e.g. LeBlanc et al. 1991; Schock 2004; Lee et al. 2009) environments. Note that the frequency of a chirp pulse cannot penetrate the crystalline structure of rock or discern differences in rock composition. Lithified and/or rocky layers are thus identified by the complete reflection of any acoustic energy off of the surface of the rock layer.

Study area

The framework geology in the region surrounding Cape Girardeau and Thebes is comprised primarily of relict deltaic, alluvial, and riverine deposits, many of which have been heavily faulted and folded (e.g., Pryor and Ross 1962; Johnson 1985; Saucier 1994). Although an extensive examination of the local geology is beyond the scope of this report, terrestrial mapping efforts have identified several limestone and shale formations that outcrop in the vicinity of the Mississippi River in this region.

2 Methods

Data collection

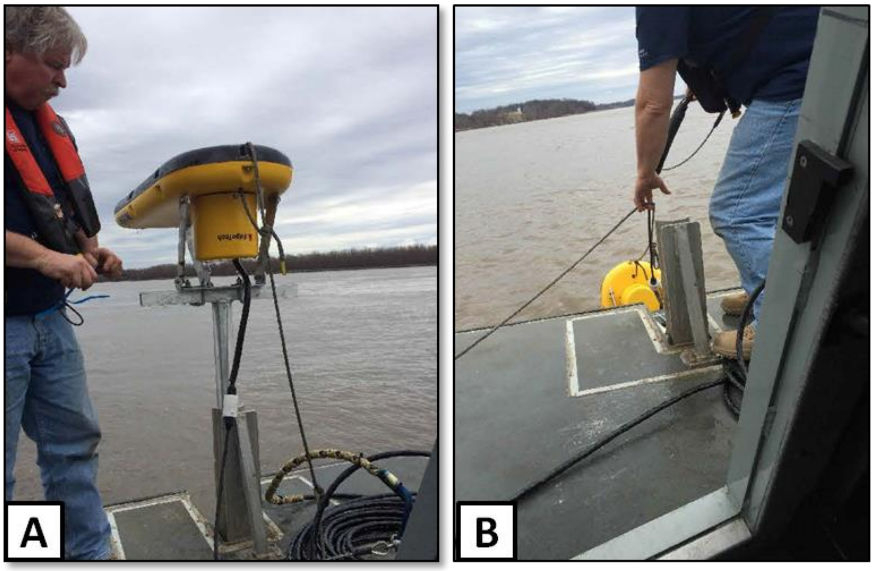
A chirp geophysical survey was conducted from 1-3 March 2016 by MVS and the USACE, Jacksonville District (SAJ). Approximately 77 linear miles of chirp data were collected between RM 55 and 43, and the track lines of all survey lines are shown in Figure 1. Data were collected using an EdgeTech 3100p (216s) sub-bottom unit, with an available FM acoustic range of 2-16 kHz. An Applanix POS MV 320/DGPS was used for vessel positioning, but the horizontal datum and geoid used were not noted during data collection. Single-beam bathymetric data were collected simultaneously during the chirp survey to allow for future rectification of sub-surface reflection surfaces to a vertical datum. The specific software used to acquire the chirp geophysical data was not noted. Although the data were clearly collected at a range of pulses, the specific pulses used for any given survey line were not provided to CHL and cannot be determined during post-processing. Vessel speed during collection was not noted. Project funding precluded the collection of either sediment cores or sediment surface grabs to groundtruth the survey data.

The EdgeTech towfish was pole-mounted to the survey vessel (Figure 3) and deployed at a consistent depth to minimize layback and positioning errors, precluding the need for an integrated pressure sensor to measure the depth of the towfish below the water surface. A fixed mount often reduces the impact of cavitation bubbles from the vessel engine on the acoustic signal and further provides an element of safety when towed in regions with subsurface hazards.

Data processing

Initial processing of the geophysical data was completed by SAJ in Fiscal Year 16 using Chesapeake Technology SonarWiz 6, version unknown. A swell filter was applied during this data processing effort to minimize the impact of vessel motion (swell) on the data. The reflection surfaces identified during this effort were not rectified to a vertical datum and instead were presented as depths below the towfish, a fairly inaccurate method that fails to account for vertical changes in the vessel and the towfish mount. Specifically, the freeboard of a vessel changes throughout a survey day, as personnel move around the vessel and as continued fuel usage in both the engine and the generator running the equipment result in a gradual lightening of vessel payload, and thus a measurable change in the relative position of the water line on the vessel (and/or towfish) to local water level. Accordingly, a vertical datum rectified to the towfish alone is not recommended in professional publications referencing chirp sub-bottom data. In addition to the riverbed, multiple reflection surfaces were noted and interpreted by SAJ based on a qualitative, visual appearance as representing buried bedrock, layers of gravel or sand, or anthropogenic features such as buried weirs or cables, but with no sediment cores to groundtruth the subsurface interpretations.

Figure 3. The EdgeTech 3100p (216s) utilized in the study. (A) Shows the towfish attached to the fixed pole mount along the side of the vessel; (B) shows the towfish being lowered into place below the water surface.



Due to uncertainties in the initial data interpretation, the raw chirp files were provided to the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL), for a secondary processing effort. The raw data were imported into Chesapeake Technology SonarWiz 7.01.006, and the horizontal datum during collection was determined to be Alabama State Plane, south, feet. Geographic x, y data are collected simultaneously as state plane data during acquisition, and these values were used to re-project the data to Missouri State Plane, East Zone, feet. Only the upper 70% of the data record was imported as the lower 30% of the record contained no data (see Appendix for line-specific settings). Gain was not applied during importation. Data were smoothed upon import using a moving box car filter with an ambient constant of 500 pings and an observed constant of 20 pings to remove spikes out of the acoustic record. A swell filter was initially applied, but the application of the filter resulted in numerous artifacts within the shallow record, so it was ultimately not used. A speed of sound of 1485 meters per second (m/s) (assumed freshwater and an average water temperature of 20 °C) was used to convert two-way travel time from milliseconds to depth below the towfish in feet.

The riverbed was identified using SonarWiz's seafloor bottom tracking tool, and the specific filters used to optimize this automated detection for each line are noted in the Appendix. Once identified, the riverbed on each seismic line was individually examined for erroneous data points and then converted into a reflection surface (identified in SonarWiz as a feature). Pertinent subsurface reflection surfaces, detailed in Chapter 3, below, were hand-digitized. Digitization was extended through any apparent heave or swell and was completed by a single operator to reduce errors introduced by having multiple individuals digitizing surfaces. A total of 855 features, including 83 riverbeds and 772 reflection surfaces, were identified and hand digitized in the project. Note that SonarWiz refers to the water/sediment interface as a *seafloor* by default; in this case, the term *seafloor* in the appendix or in any files associated with this report refers to the riverbed.

Once digitized, reflection surfaces were exported as .csv files containing location (latitude, longitude, x, y) and depth below the towfish (a depth of zero was used for the riverbed itself). To rectify the subsurface data to an acceptable vertical datum, the depth below the towfish was converted to depth below the riverbed by calculating the difference in the depth below the towfish between the riverbed and a pertinent reflection surface (e.g., the thickness between the two surfaces was calculated). This is a first-order accepted vertical datum for stratigraphy data as the relative distance between the riverbed and underlying geologic units is not subject to the same water level-driven fluctuations during the time of mapping as the riverbed is to the towfish. The thickness files were imported into Microsoft Excel and edited for importation into Matlab version 2017a. The data were subsequently gridded using nearest neighbor at a variety of grid spacings (see Chapter 3 for details) and exported as .asc files for importation into ArcGIS. Horizontal and vertical errors associated with the data collection and processing methods are detailed in Chapter 3 below.

3 Results

The overarching goals of the survey were (1) to provide proof-of-concept of the applicability of using acoustic chirp reflection data to map sub-surface stratigraphy in the Mississippi River and (2) to map the distribution and depth below the riverbed of potentially hazardous rock in and near the navigation channel in the vicinity of Cape Girardeau, MO, and Thebes, IL. An additional goal was to better constrain the volume of bedload transport by identifying where possible the base of the mobile sediment mapped at the surface of the riverbed.

Layer resolution

The resolution of stratigraphic layers, as well as the depth below the riverbed to which the acoustic signal could penetrate, is a function of the acoustic frequency used as well as the amplification power contained within the towfish. With respect to an EdgeTech 3100p (216s), the overall operating frequency ranges from 2-16 kHz, but the entire frequency range is not transmitted by the towfish at any one time. Instead, the operator selects a portion of the acoustic range to transmit from the towfish at a certain power. This allows the operator to focus efforts on obtaining (1) maximum layer resolution at the expense of vertical sound penetration, (2) maximum vertical penetration with a loss of data resolution, or (3) some balance between the two. The higher the frequency used, the smaller the layer that can be resolved but the lower the overall penetration of the sound into the bottom. Published minimal layer resolution for the EdgeTech 3100p (216s) is 2.5 in. to 4 in. (dependent on frequency), and published maximum sound penetration is reported to be 18 ft in sand, 260 ft in mud; however, these values represent maximum resolution and/or penetration under optimal conditions, and these standards are rarely achieved in the field. The typical minimum layer thickness resolved in field use is generally 6-7 in., and maximum penetration depths seen in sand vs. mud are on the order of 15 ft vs. 80 ft in sand vs. mud, respectively. Note that penetration greatly decreases when maximum data resolution is being achieved and vice versa, so the actual layer resolution and depth of penetration achieved is dependent on the user-directed settings (e.g., a setting that allows resolution of layers of less than 10 in. will yield much shallower penetration depths). In addition, the pulse rate of each chirp and the receive time between each pulse also directly impacts the minimal thickness of the resolved layers as well as the vertical penetration. Unfortunately, these settings were not available for the CHL data processing and interpretation effort described in this report, complicating the identification of the reflection surfaces described below.

Identification of sedimentary layers

The density of sediment below the riverbed changes with changes in sediment stratigraphy. At each density change, there is either an increase or decrease in speed of sound, depending on the different density of the two layers, and a portion of the acoustic energy that penetrates the sediment is reflected back to the surface to the towfish receivers. The amplitude of the returning signal is converted from an analog pulse to a digital signal and presented visually as a dark line drawn below the towfish (Figure 4). Darker-grey shading below a reflection surface indicates that the acoustic signal is being reflected back to the towfish (i.e., denser sediment, such as sand), while bright, more white color below a reflection surface usually indicates absorption of the acoustic energy into the sediment (i.e., less-dense sediment, such as silty clay), with less overall reflection. Harder, denser units may also refract the acoustic energy back to the towfish at a ~45° angle from the original contact, resulting in artifacts referred to as *bowties* (Figure 5).

Figure 4. Example sub-bottom profile from the Cape Girardeau region. The upper panel (A) is in this and all subsequent seismic profile figures is an un-interpreted image of the seismic profile, complete with the line file name for identification. The lower panel (B) shows interpretation of the riverbed, pertinent reflection surfaces, and the horizontal and vertical scales. Note that the image's scale will differ in subsequent seismic profile figures.

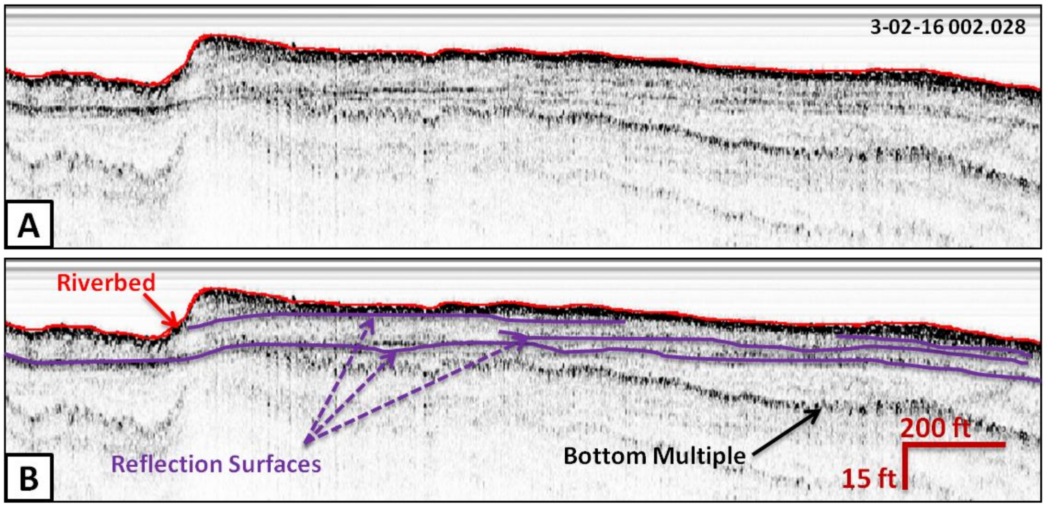
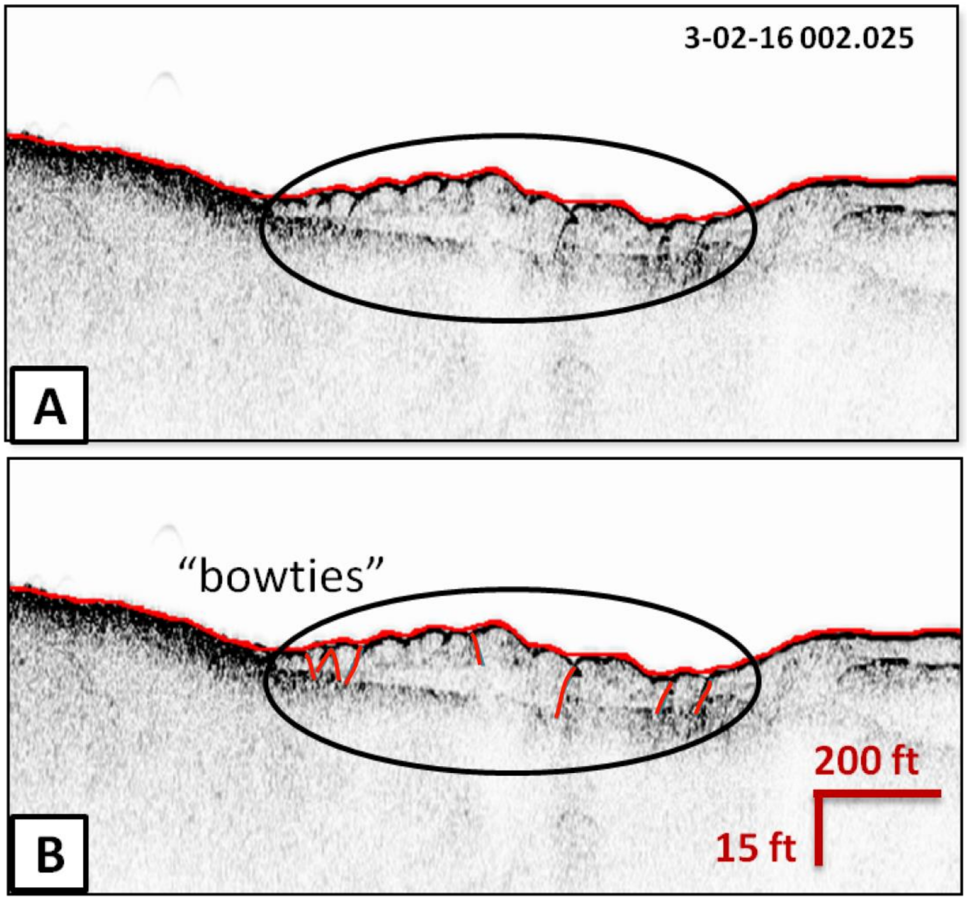


Figure 5. Example of bowtie artifacts in an (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile.

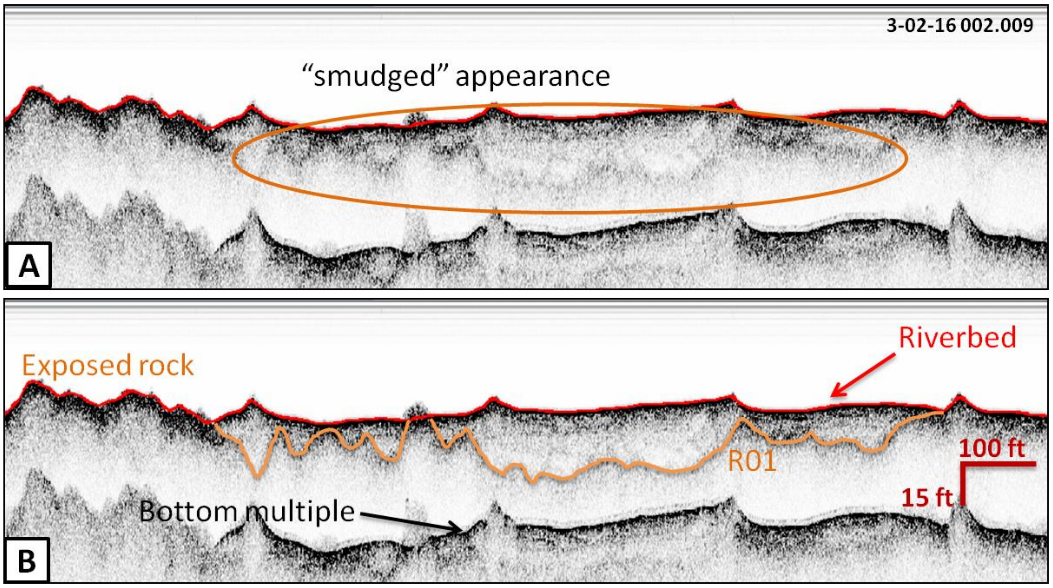


During data collection, an acoustic pulse is transmitted by the towfish. For a brief period of time (determined by the collector and usually noted as the *record length*), the towfish then operates in receiving mode, where it *listens* for the reflection of the acoustic data off of changes in underlying sediment density. The deeper the penetration desired, the longer the necessary listening time. During this time frame, it is possible for the sound source to travel through the water column and be reflected off of the riverbed to the towfish, where it then is reflected back down through the water column and is reflected once again from the riverbed to the towfish. The result is the towfish *seeing* the riverbed more than once. These artifacts are referred to as *bottom multiples* and are always found in exact multiples of the depth below the towfish and the riverbed (e.g., Figure 4b). The longer the listening time, the more likely that one or more bottom multiples will be recorded by the towfish. Because these multiples can obscure real reflection surfaces that are coincidently located at similar two-way travel time depths below the towfish, they cannot simply be filtered out from the data record. Accordingly, they are noted wherever they occur in the acoustic record.

Identification of bedrock

Chirp acoustic data, regardless of signal frequency, penetrates unconsolidated and weakly consolidated sediment with a range of efficiencies. The frequencies used are unable to penetrate rock due to a complete lack of pore space, resulting in the reflection of 100% of the acoustic energy that reaches the rock back to the towfish receivers at an angle from the surface of the rock. Qualitatively, at the surface and with depth, the rock appears in chirp data as a distinct reflection surface with no data (gray shaded image) below it, illustrating the reflection of the acoustic energy off of rock with no penetration through it (Figure 6). If the rock layer is sufficiently close to the riverbed and/or is overlain by soft sediment such as layers of silt and clay, the reflected acoustic energy is often visible as bowties extending into the acoustically transparent region below the rock (Figure 5). At greater depths and/or under harder sediment (e.g., well-sorted sand), the bowtie artifacts are less visible, and the scattered energy appears more as *smudges*” just below the reflection surface (Figure 6).

Figure 6. Example of buried rock in: (A) un-interpreted seismic profile; and (B) interpreted image of the seismic profile (orange R01).



Identification of specific reflection surfaces

Two reflection surfaces with distinctive reflection amplitudes were identified in the study region. A brief description of their qualitative appearance, amplitude, and spatial distribution is presented below.

R01

The single-most dominant reflection surface observed in the study site was digitized as R01. This surface is characterized by both high amplitudes as well as acoustic transparency below it – indicating complete reflection of the acoustic signal (Figure 6). The depth of this surface below the riverbed was highly variable – ranging from exposed at the riverbed to up to 20 ft below it. Where exposed at the riverbed, it has been previously identified as outcropping, irregular rock. Both near the surface and with depth, the unit was highly irregular in elevation, and was rarely noted at the same elevation on parallel survey lines, suggesting a great deal of spatial variability in the elevation of the unit. Near the surface, bowtie features were occasionally observed below the layer, and with depth the layer often had a smudged appearance below it. No reflection surfaces were noted below this unit, suggesting complete reflection of the acoustic energy that reached it.

The layer was not continuous in elevation; rather, it was characterized by rapid changes in elevation from being exposed at the riverbed at one location, and then plunging to depths of ~20’ below the riverbed over a horizontal distance of 100’ or less (Figures 6, 7). In several regions, R01 appeared below the riverbed as a smudged surface that cut through overlying stratigraphy to come within a few feet of the riverbed (Figures 6,7), and was often exposed on adjacent, shore-parallel survey lines.

To see these variations in elevation more clearly, the depth below the riverbed of R01 was gridded in Matlab using a nearest neighbor algorithm with a search radius of 250 ft, and a smoothing interval of 8 cells (Figure 8). Although smoothing the data risks losing some of the more dramatic changes in R01 elevation change below the riverbed, it also reduces vertical errors generated by the digitization process (see Chapter 3, below). Overall, R01 was either exposed at the riverbed, or within ~6 ft of the riverbed: (1) near RM54, north of the town of Cape Girardeau, MO; (2) between RM 51 & 52, at Cape Girardeau, MO; and (3) along the right bank near RM49; and (4) between RM 46-43.5, near Thebes, IL. R01 was not observed in the sub-bottom data along the left bank between RM 49 and 46.5, or in regions near RM 50 (Figures 1, 8).

Figure 7. Example of buried rock and overlying stratigraphic layers in an: (A) un-interpreted seismic profile; and (B) interpreted image of the seismic profile (orange line, R01).

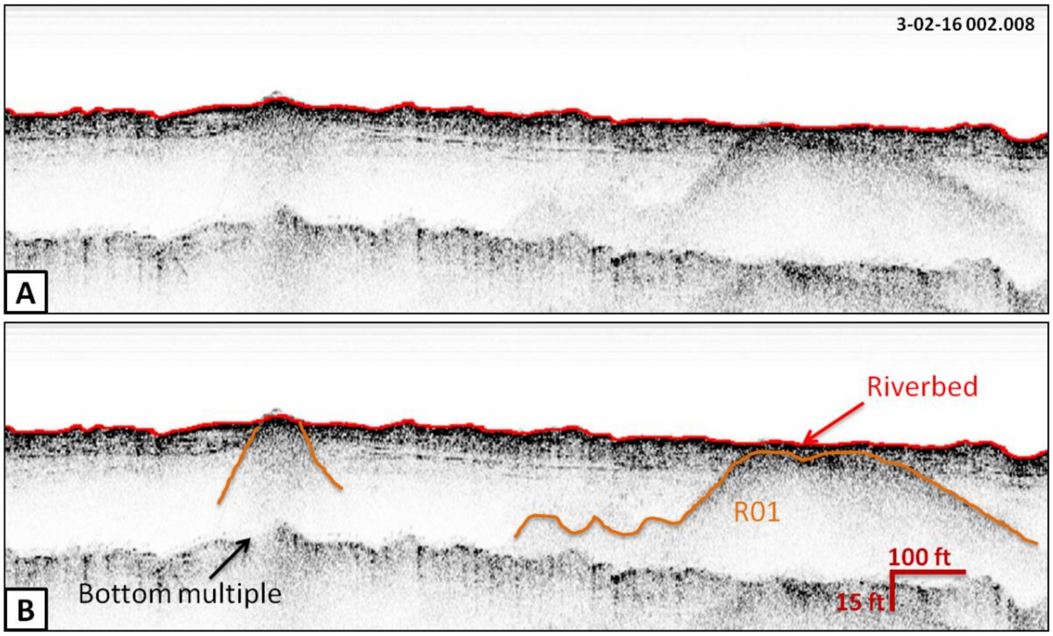
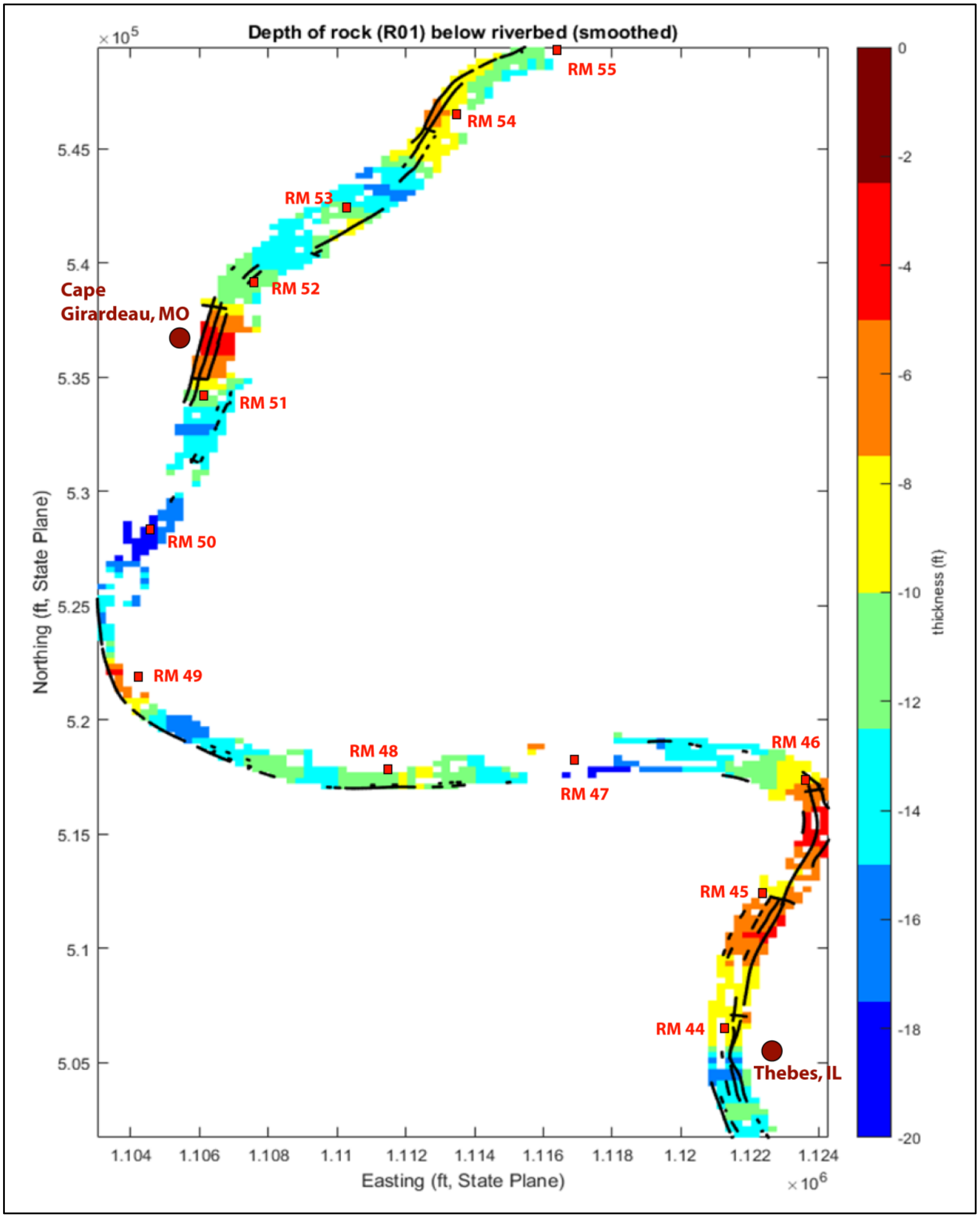


Figure 8. Depth of the rock unit R01 under the riverbed in feet. Regions where the rock was outcropping on the riverbed are delineated by black lines.



R02

A secondary, discontinuous reflection surface was noted throughout the study region and, where confidently identified, digitized as R02 (Figure 9). This surface was relatively flat-laying and found, on average, approximately 6 ft below the riverbed. Near the surface, it occasionally exhibited bowties, indicating strong reflectance of the acoustic energy back to the towfish. However, unlike R01, reflection surfaces were mapped below R02, indicating that R02 is composed of less-dense material than R01 (e.g., sediment vs. rock; Figure 10). Where R02 met R01, the R02 unit stopped at the vertical rise of R01, suggesting latter formation/deposition than R01 (i.e., that R02 is stratigraphically younger material). In many stretches of the study area, however, the distinct acoustic contrast of R02 with other sedimentary units became less clear in one of two ways: (1) observation of multiple reflection surfaces having similar acoustic signatures (Figure 11a) or (2) R02 showing a change in acoustic signature along the sub-bottom profile (Figure 11b), suggesting either change in the geologic material comprising the sedimentary unit or a lack of acoustic penetration into the riverbed. R02 was not digitized in these regions. The depth below the riverbed of R02 was gridded in Matlab using nearest neighbor with a search radius of 250 ft and a smoothing interval of 8 cells (Figure 12). Accordingly, the gridded surface of R02 shows significant data holidays (white areas) in between regions of mapped sediment (Figure 12).

Figure 9. Example showing the base of mobile sand in an (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile (green line, R02).

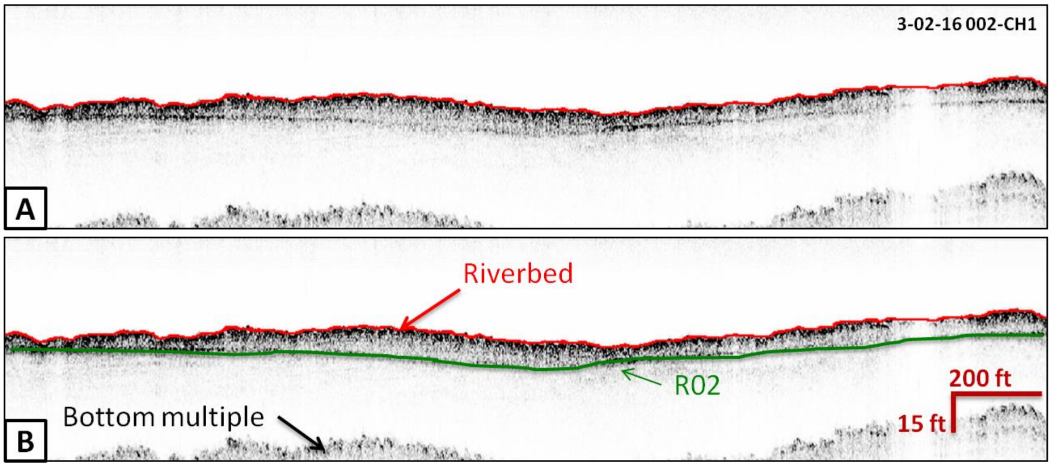


Figure 10. Example of the base of the mobile sediment layer overlying the subsurface rock in (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile (rock: orange R01; mobile sediment base: orange R02).

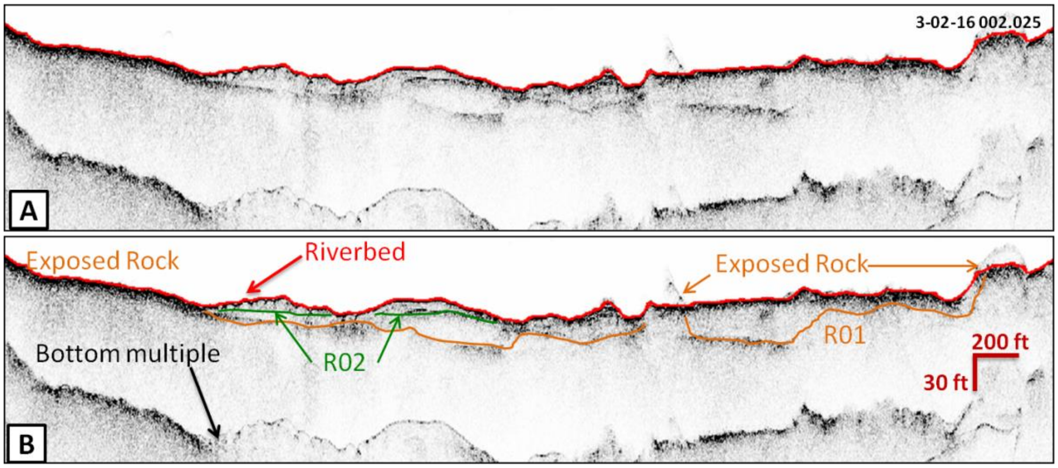


Figure 11. Upper two panels show an example of multiple intersecting layers with the same acoustic signature as R02 in (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile. Lower two panels show an example of the R02 reflection surface being lost due to absorption of the acoustic signal in (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile.

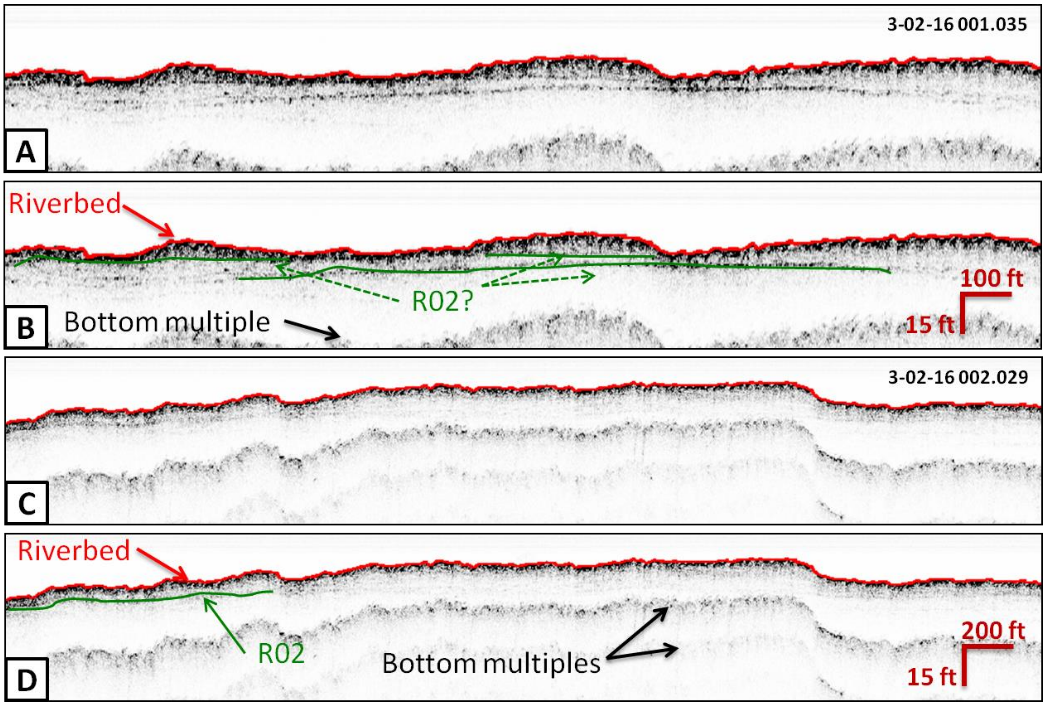
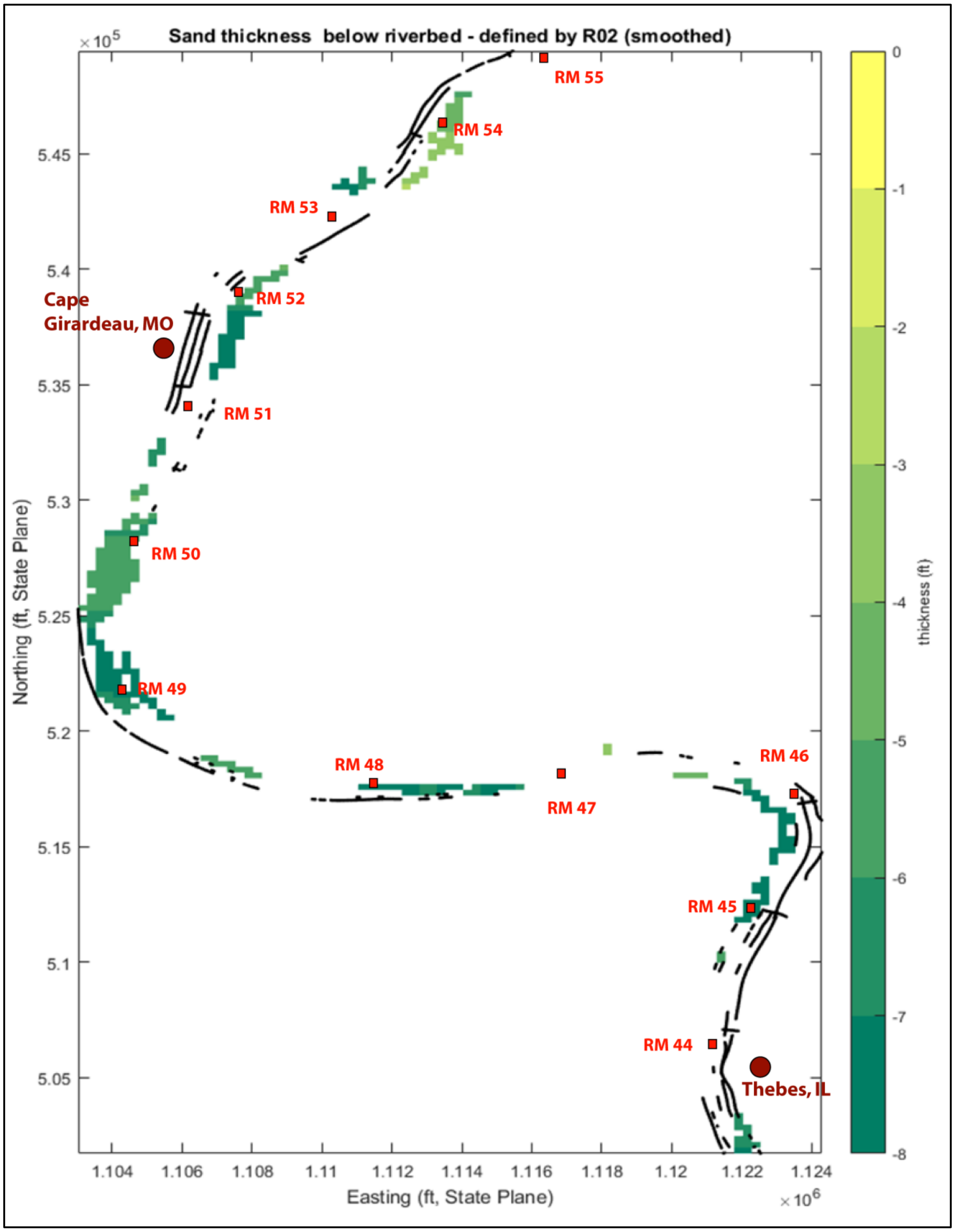


Figure 12. Depth of the interpreted base of the mobile sand wave layer, R02, under the riverbed in feet. Regions where the rock was outcropping on the riverbed are delineated by black lines.



Horizontal and vertical error

Data were collected using an Applanix POS system recording real-time Real-Time Kinematic (RTK) corrections. The horizontal error associated with RTK corrections is generally less than 1 ft. In addition, the location of the towfish was most likely not centered directly below the Global

Positioning System (GPS) antennae, but that offset was not provided to CHL. On an average survey vessel, that offset is usually approximately 2-4 ft, though applying those numbers here is pure speculation. Accordingly, a maximum horizontal error of 4 ft should be assumed.

Vertical error in the seismic profile is dependent on (1) the assumption of a standard speed of sound of 1485 m/s (assuming freshwater and an average water temperature of 20 °C) and (2) errors in digitization by the processor. Speed of sound, the rate at which sound travels through a sedimentary unit, is a function of the sediment's density, porosity, grainsize, temperature, and mineralogy and is higher in coarse-grained, sandy sediments vs. finer-grained, muddy sediment. Despite these variations, overall the speed of sound in sediment of all types has been determined to be very similar to the speed of sound in water (usually 1%-3% less in sediment than in water (e.g., Shumway 1960; Hamilton 1963, 1965; Gorgas et al. 2002; Yang and Tang 2017). This translates to a potential maximum vertical error of <0.5 ft, but many researchers have suggested that the effect is so minimal for stratigraphic purposes that it can be neglected altogether (e.g., Hamilton 1972; Kibblewhite 1989; Bowles 1997; Buckingham 1997; Gorgas et al. 2002). A greater source of vertical error is inherent in the digitization process. Chesapeake Technology SonarWiz uses sophisticated algorithms to identify the sediment-water interface and auto-digitize the riverbed. The process is not perfect and requires visual inspection to ensure that the software does not erroneously identify water column noise (such as a school of fish) as the riverbed. Subsequent digitization of underlying reflection surfaces are completed by hand, and slight variations in the position of the mouse will also introduce vertical errors. The error in vertical elevation is directly related to subtle variations in each digitized point as entered by the processor, and thus is different for every given project. For this project, the difference in elevation between subsequent *horizontal* digitized points was determined on multiple regions for 12 seismic lines and averaged 0.78 ft, with a standard deviation of 0.57 ft. Note that these errors can compound. Accordingly a vertical error of ~2 ft should be considered when evaluating these data. This error would persist even if the data were further rectified to known datum (i.e., to a rectified bathymetric survey).

4 Discussion

Applicability in riverine environments

One of the overarching goals of this effort was to determine the suitability of acoustic chirp reflection technology to map subsurface indurated and rock units in the Mississippi River. Although chirp data have been collected successfully in riverine environments, the specific goals of this application differ from what has been conducted before in similar environments. In addition, the cost to acquire chirp technology and the extensive training/educational requirements of data collection personnel and data interpretation personnel are significant and support a proof-of-concept survey.

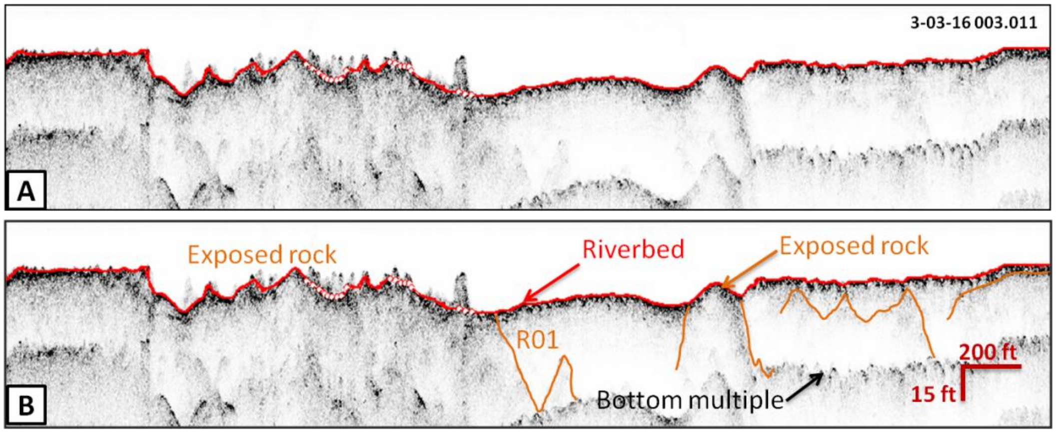
All 83 survey lines collected were suitable for importation and processing, and all contained usable sub-bottom data. Although there were limitations with the chirp frequency used on any given sonar line, and the overall transmitting power of the towfish (discussed in more detail below), the data yield a map of the underlying shallow stratigraphy of the Mississippi River. Data collection was completed in 3 days, not including mobilization/demobilization time, indicating this was a quick and thus economically viable mapping technique, especially given that bathymetric data could be collected simultaneously. The river conditions did not preclude the collection of quality data, and the final survey line plan shows minimal deviations from the planned survey, suggesting navigability of the survey lines around shallow regions and/or vessel traffic was excellent. Overall, this dataset indicates that, with some future modification of equipment and survey execution, shallow acoustic chirp geophysical surveys show great potential for the mapping of subsurface stratigraphy in the Mississippi River.

Interpretation of R01

R01 is interpreted to represent the irregular, pinnacle-like rock frequently exposed in the Mississippi River. The acoustic signature of this surface, including the acoustic bowties seen where it closely underlies the riverbed, the acoustic transparency below it, and the smudged appearance it has at depth, strongly supports interpretation of this unit as rock. In addition, the irregular, pinnacle-like nature of the outcropping rock continues below the surface, strongly suggesting this unit is not sedimentary but rather is lithified rock that has been subsequently folded and faulted (Figures 6, 7, 10).

The discontinuous nature of R01 is likely related to several factors. The primary factor is the irregularity of the rock surface. At the riverbed, R01 exhibits significant vertical relief, often in the form of steep pinnacles, and similar relief is observed in the subsurface formation (Figure 13). On many of the seismic lines, R01 plunges below the penetration limit of the towfish used (Figures 7, 10; see below for further discussion of that issue). The rock formations in the vicinity of Cape Girardeau are also faulted in many regions, meaning that the elevation of the R01 formation at any one location is not always spatially consistent. Finally, the cross-shore width of any one elevation of R01 was only ~100 ft. Given that the survey lines were spaced ~300 ft apart, this complicates extrapolation of this highly irregular surface between each survey line.

Figure 13. Example of highly variable surface elevation in exposed and buried rock at Cape Girardeau: (A) un-interpreted seismic profile and (B) interpreted image of the seismic profile (orange line, R01).



Despite these limitations, the general nature of R01 is clearly discernible from the data. Overall, R01 is highly irregular and found throughout the study area. In three major regions, R01 is within 10 ft of the riverbed (near RM 54, 51.5, and 43.5-46; Figure 8), representing a potential hazard for transiting vessels depending on sand mobility and river stage. To better illustrate the regions where R01 might present a hazard to navigation, a hazard map was generated for the region based on the gridded data (shown in Figure 8) and is presented in Figure 14. On this map, everywhere that R01 was mapped within 10 ft of the riverbed is shaded in gray, and the red lines that overlay the gray regions indicate exposed rock. Regions where R01 was mapped between 10 to 15 ft from the riverbed are shaded in yellow, and regions where R01 was only mapped at depths of 15 ft or more below the riverbed are shaded in green. Note that the spacing of the survey lines was insufficient to fully characterize the small-scale variability in R01, and thus additional, small-scale patches of shallow R01 might exist outside of the gray and yellow regions, but were not mapped. In addition, very small near-surface pinnacles of R01 were likely smoothed out in the gridding process. Despite these limitations, the hazard map is useful for identifying regions in the study area with greater potential navigability hazards than other regions.

Note the significant data holidays (white regions) along the northern shoreline between RM 47-48 on Figure 14, as well as along the western shoreline between RM 49.5-51. Figure 1 indicates that chirp data were collected in these white regions, so the lack of subsurface R01 is not due to a lack of data. Instead, these regions where characterized by very dense acoustic returns (hard, surficial geology), as evident in the nearly acoustic-transparency of the profile below the surface (Figure 15). Faint reflection surfaces are visible below the riverbed but are not coherent enough to be identified. The shape of the riverbed and the faint reflection surfaces below it suggest the sediment here is very hard and dense, likely sand in the form of sand waves. These data suggest that the towfish used lacked the ability to transmit an acoustic pulse through the entire sand layer, and this challenge is explored more in Chapter 4, below.

Figure 14. Hazard map for sub-surface R01 in the study area, shown as depth below the riverbed (thickness) in feet. Red lines indicate outcrops of R01 at the riverbed surface. White areas indicate data holidays.

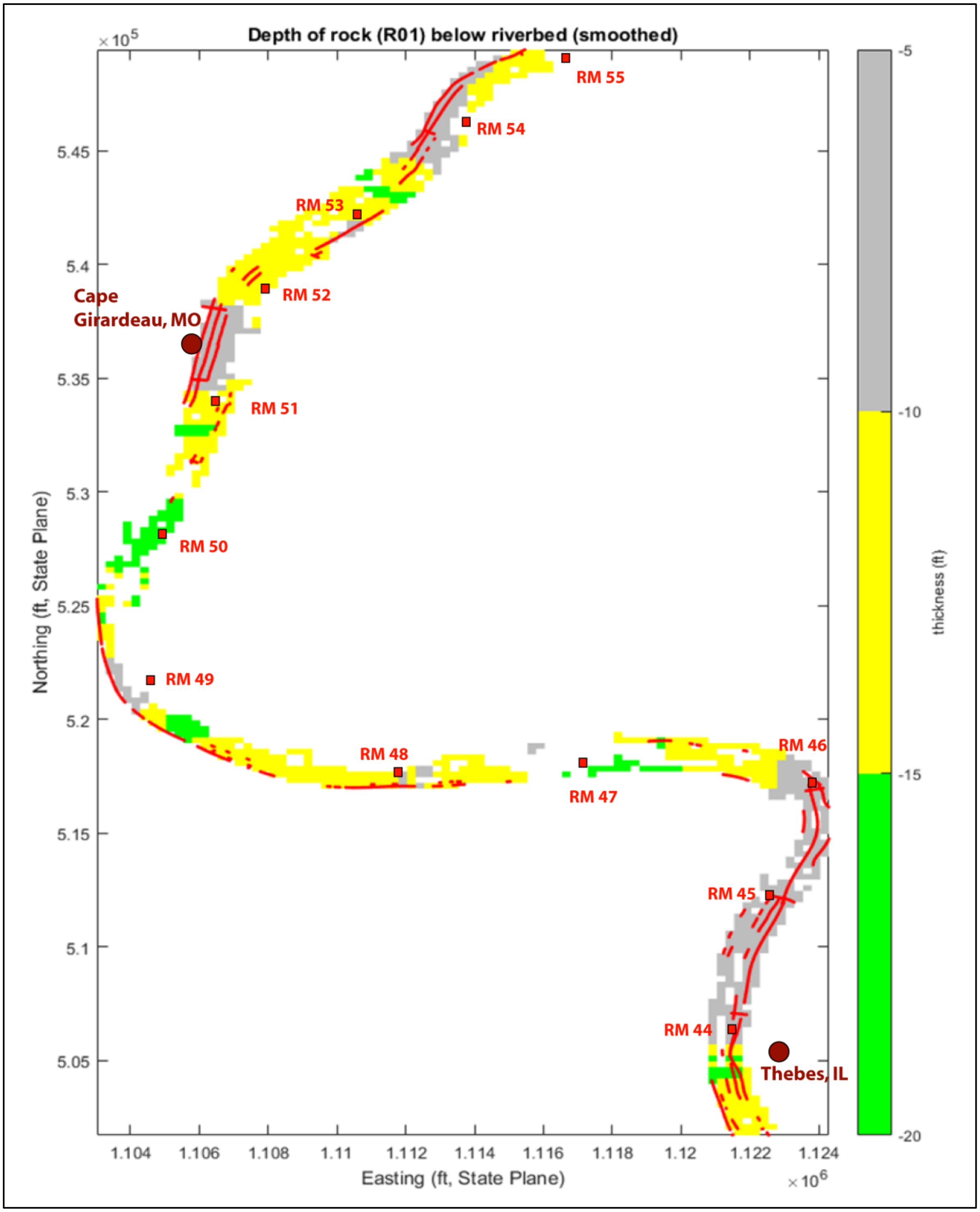
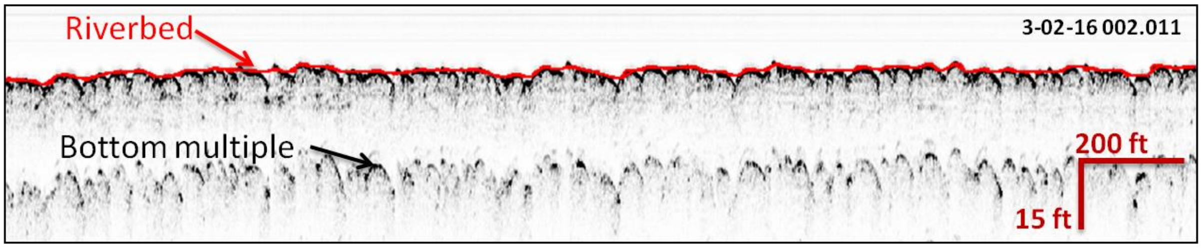


Figure 15. Example of an acoustically transparent profile underneath dense (hard) sediment. The morphology of the riverbed (sand waves) and the bowties suggest the surface was composed of very hard sediment, which reflected most of the acoustic energy. However, faint reflection surfaces are mapped below the surface, indicating that the riverbed here is not composed of rock. Accordingly, this is interpreted to represent a surficial deposit of sand overlying finer-grained (less dense) material.



Interpretation of R02

In addition to mapping the basement rock of a region (here, R01), acoustic chirp reflection technology can be used to produce stratigraphic maps of underlying sediment layers. A secondary goal of this effort was to identify the base of the mobile sediment layer of the Mississippi River in this location. Mobile sediment can take many forms, including mobile sand ripples or waves, as well as fluid mud layers. Without sediment cores, interpreting various reflection surfaces as the contact between sand and mud, or mud and gravel, etc., is tenuous at best.

The Cape Girardeau sub-bottom data clearly show not only multiple layers of sediment below the riverbed in many places but also the presence of sand waves over much of the study area (e.g., between RM 47-48.5; Figures 11, 15). The interpretation that the surface is sand is based on (1) the bathymetry of the riverbed showing undulations in depth consistent with sand waves, (2) the strong acoustic reflection and occasional bowties associated with the surface of the riverbed indicating dense (hard) material, and (3) the mostly acoustically transparent profile beneath the sand waves, indicating much of the acoustic energy was reflected back to the towfish (Figures 10, 11, 15). A discontinuous but coherent reflection surface (R02) was discernible in much of this region (Figure 12) and likely represents an indurated, erosion-resistant surface on which the sand waves are migrating. This reflection surface was mapped, on average, within ~6 ft of the riverbed (Figure 12), suggesting the sand deposit comprising the waves averages 6 ft in thickness. Note that in some regions, multiple reflection surfaces were observed that could represent the base of the migrating sand waves (e.g., Figure 11b), complicating the interpretation of R02 over the entire study area. This likely reflects multiple indurated sedimentary units below the riverbed and would be consistent with the complex geology of the region. Arbitrarily selecting one of the reflection surfaces as R02 is presumptive, however, without sediment cores to groundtruth the different layers. In addition, in some regions multiple reflection surfaces were noted without the presence of sand waves (Figure 4), likely reflecting multiple fine-grained sedimentary deposits, as the greater penetration of the acoustic energy is indicative of less-dense sediment. Identifying which of these reflection surfaces represents the base of a mobile fine-grained layer is not possible without sediment cores; however, these data do provide guidance for core collection if absolute identification of the base of the various mobile sediment layers in this region is needed.

Data holidays vs. lack of signal penetration

Large swaths of the study area provided limited geophysical data — either in the identification of the subsurface elevation of R01 or in the identification of the base of the mobile sediment layer(s) known as R02. These data holidays are most clearly seen as white regions in Figures 8, 12, and 14. Multiple factors can result in partial or complete data holidays during a geophysical survey, including (1) lack of coverage (e.g., a planned survey line was altered due to unexpected bathymetric hazards and/or to avoid transiting vessels), (2) too high of an acoustic pulse used (e.g., a higher pulse was used to improve minimal layer resolution with a trade-off in signal penetration), (3) insufficient record length during collection (e.g., the acoustic pulse used was low frequency enough to penetrate to the needed depths, but either the vessel moved too quickly or the towfish did not listen long enough between pulses to hear the slower, deeper returns), or (4) lack of signal penetration due to insufficient towfish transmittal power.

In the case of this study, the transited survey lines as shown in Figure 1 show very few large deviations from shore-parallel tracks, suggesting that the first factor, lack of coverage, is likely not a factor here. Although it has been previously noted that the spatial extent of the features being mapped is smaller than the survey line spacing (e.g., ≤100 ft vs. ~300 ft, respectively), the gridding algorithms used to generate Figures 8, 12, and 14 eliminate any data holidays that would result from that gap, at a potential trade-off of accuracy. Accordingly, survey line spacing is not considered to be a significant factor in the existence of the observed data holidays.

The other three factors described above are a function of the user-determined settings at the time of collection, as well as vessel survey speed. If the user selected a higher frequency pulse to better delineate the near-surface stratigraphy, the higher frequency would also not penetrate very far into the riverbed, and the result would be the acoustically transparent seismic profiles seen, for example, in Figures 9 and 11. Alternatively, the user might have selected a lower frequency pulse to enhance signal penetration (e.g., Figures 4, 10), but if the pulse rate or record length were set high, there would be insufficient listening time by the towfish in between each acoustic pulse to record the longer return times associated with reflections from greater depths, resulting in low resolution near the surface and little or no return from depth. Although it is clear from the variable appearance of the data during processing that settings were adjusted over the course of the survey, without a log of the user-selected settings, it is impossible to definitively identify when those factors impacted data collection and thus resulted in data holidays. In addition, the vessel survey speed was not noted, so it cannot be determined if the vessel was towing the receivers too quickly to receive the deeper returns.

The final factor that can result in data holidays is a lack of sufficient transmitting power by the towfish to penetrate deep enough into the riverbed's stratigraphy to reflect off of deeper layers. As detailed in the Methods section above, the EdgeTech 3100p (216s) has a typical maximum working penetration of ~15 ft in sand (~80 ft in mud), and this reflects, on average, the typical penetration seen below the sand waves in this region (~6-8 ft for underlying sediment; ~12-15 ft for underlying rock). R01 was mapped at depths of up to ~20 ft under the riverbed in some locations, but (1) most of the deeper rock was observed underlying finer-grained, less-dense sediment (e.g., acoustically absorbent material such as that seen in Figures 6 and 7), and (2) rock provides a powerful acoustic return (100% of the transmitted signal) that is often reflected at the maximum penetration depth of a pulse and towfish (e.g., ~15-22 ft, Figure 10). The transmit power of an acoustic reflection chirp towfish is created by piezoelectric ceramic plates, which generate an acoustic pulse. Larger (and heavier) ceramics generate higher transmit powers (louder sounds) and lower frequencies (enhancing penetration at the cost of resolution) but also greatly increase the size and weight of the towfish. As an example, the EdgeTech 3100p (216s) utilized in this study weighs ~170 pounds (lb) in air and as such, is portable and easily towed by a small vessel or mounted on a towing plate. In contrast, the EdgeTech 3200

(512i), which has the potential to penetrate up to 60 ft of sand in ideal conditions, weighs ~550 lb in air and requires either a large, deep-draft vessel to safely tow or a sophisticated mount on a smaller towing vessel to manage safely. The data collected here suggest that greater penetration is needed to map the deeper stratigraphy of R01 and the full spatial extent of R02. It is possible that improved signal penetration could be achieved with the EdgeTech 3100p (216s), using the lowest available frequency and a correspondingly low pulse rate as well as a slower survey speed to maximize deeper returns. Most likely, however, a different towfish will be needed to reliably collect data at depths greater than ~8-10 ft under sand.

5 Conclusions

Overall, the geophysical surveying conducted in 2016 in the vicinity of Cape Girardeau, MO, successfully demonstrated the applicability of shallow acoustic chirp sub-bottom profiling for mapping the stratigraphy underlying the Mississippi River. Over 77 miles of chirp sub-bottom data were collected between RM 55 and 43, and the data collected were sufficient to delineate regions of significant subsurface hazards in the form of shallow, buried rock that can potentially and ephemerally be exposed in the riverbed, representing a hazard to navigation. Although the survey line spacing precluded a highly detailed and accurate map of rock elevation at the resolution of the feature being mapped, it clearly identified the spatial extent of the more hazardous regions of the study area, allowing for more focused and cost-effective future surveying. In addition, the data were able to partially identify the spatially varying base of the mobile sand layer along approximately one-half of the study area, potentially providing more accurate bedload volume calculations for the region.

Significant data holidays were noted in the underlying rock maps and in the delineation of the base of the mobile sediment layers. These holidays are most likely due to limitations in user settings during the initial data collection, as well as power limitations inherent in the towfish utilized for the survey. In addition, the spacing between the survey lines was greater than the spatial extent of the features being mapped, with the result that although the gridded data provide an excellent overall view of the subsurface elevation of the underlying rock in this region, the exact elevation below the riverbed at any one location is not accurate, and the gridded elevation can vary by several feet from the actual elevation. Despite this, the data clearly identify the more hazardous regions of the river, allowing for prioritization of future work.

The region would benefit from additional surveying. A larger, lower-frequency towfish would provide greater penetration along any one survey line. In addition, subsequent surveys to accurately map the specific elevation of the underlying rock for navigation and/or removal purposes would need a survey line spacing that is closer than the spatial extent of the features being mapped. A trained geologist and geophysicist would be critical during subsequent data collection efforts, as that individual is trained to recognize geologic variability as presented in geophysical data in real time and to adjust a survey line plan’s spacing and/or orientation to accurately map the stratigraphy in question. These accurate data would then benefit by being rectified to a standard vertical datum such as North American Vertical Datum of 1988 by rectifying them with bathymetric data collected with RTK-GPS. From such data, a detailed elevation map (with error) could be generated for the region in question.

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Appendix: Sub-Bottom File Metadata

The table below lists file-specific importation and interpretation information for each sub-bottom profile collected in support of this project.

Note the following:

HardB: Indicates outcropping rock on the seismic profile.
R01: Interpreted buried rock.
R02: Interpreted base of mobile sand layer.

Line Name	% Import	Bttm Track Settings	Shore Orientation	Reflectors
3-01-16 001.002	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.003	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.004	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-01-16 001.005	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.006	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.007	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB
3-01-16 001.008	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.010	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.011	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-01-16 001.012	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R02
3-01-16 001.013	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01, R02
3-01-16 001.014	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01, R02
3-01-16 001.015	70%	Blnk 2.0; Dur 10, Thres 7	perpendicular	HardB, R01
3-01-16 001.016	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01, R02
3-01-16 001.017	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01
3-01-16 001.018	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-01-16 001.019	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.020	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01
3-01-16 001.021	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R02
3-01-16 001.022	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.023	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-01-16 001.024	70%	Blnk 2.0; Dur 10, Thres 7	parallel	R01, R02

Line Name	% Import	Bttm Track Settings	Shore Orientation	Reflectors
3-01-16 001.025	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.026	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-01-16 001.027	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-01-16 001.028	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.029	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-01-16 001.030	70%	Blnk 2.0; Dur 10, Thres 7	perpendicular	HardB, R01
3-01-16 001.031	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01, R02
3-01-16 001.032	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.033	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.034	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.035	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.036	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-01-16 001.037	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	R02
3-01-16 001.038	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01
3-02-16 002-CH1	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-02-16 002.001	70%	Blnk 2.0; Dur 10, Thres 7	parallel	R01, R02
3-02-16 002.002	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01
3-02-16 002.003	70%	Blnk 2.0; Dur 10, Thres 7	parallel	R01, R02
3-02-16 002.004	70%	Blnk 2.0; Dur 10, Thres 7	parallel	---
3-02-16 002.005	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R02
3-02-16 002.006	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	R01, R02
3-02-16 002.007	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-02-16 002.008	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-02-16 002.009	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01
3-02-16 002.010	70%	Blnk 2.0; Dur 10, Thres 7	parallel	---
3-02-16 002.011	70%	Blnk 2.0; Dur 10, Thres 7	parallel	---
3-02-16 002.012	70%	Blnk 2.0; Dur 10, Thres 7	parallel	R01
3-02-16 002.013	70%	Blnk 2.0; Dur 10, Thres 7	perpendicular	HardB, R01
3-02-16 002.014	70%	Blnk 2.0; Dur 10, Thres 7	parallel	R01, R02
3-02-16 002.015	70%	Blnk 2.0; Dur 10, Thres 7	parallel	---
3-02-16 002.016	70%	Blnk 2.0; Dur 10, Thres 7	parallel	---
3-02-16 002.017	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-02-16 002.018	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02

Line Name	% Import	Bttm Track Settings	Shore Orientation	Reflectors
3-02-16 002.019	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-02-16 002.020	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	R01
3-02-16 002.021	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-02-16 002.022	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-02-16 002.023	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-02-16 002.024	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-02-16 002.025	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-02-16 002.026	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01
3-02-16 002.027	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	R01, R02
3-02-16 002.028	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-02-16 002.029	70%	Blnk 2.0; Dur 10, Thres 5	parallel	R01, R02
3-02-16 002.030	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-02-16 002.031	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-02-16 002.032	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB
3-02-16 002.033	70%	Blnk 2.0; Dur 10, Thres 7	perpendicular	HardB, R00
3-02-16 002.034	70%	Blnk 2.0; Dur 10, Thres 7	perpendicular	HardB, R01
3-03-16 003-CH1	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01, R02
3-03-16 003.001	70%	Blnk 2.0; Dur 10, Thres 7	parallel	HardB, R01
3-03-16 003.002	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-03-16 003.003	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-03-16 003.004	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB
3-03-16 003.005	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01
3-03-16 003.006	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-03-16 003.007	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01, R02
3-03-16 003.009	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-03-16 003.010	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R01
3-03-16 003.011	70%	Blnk 2.0; Dur 10, Thres 5	parallel	HardB, R02
3-03-16 003.012	70%	Blnk 2.0; Dur 10, Thres 5	perpendicular	HardB, R01, R02

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms

Acronyms and Abbreviations

ft	foot(feet)
FM	frequency-modulated
FY	fiscal year
GPS	Global Positioning System
in.	inch(es)
kHz	kilohertz
lb	pound(s)
m/s	meters per second
MVS	St. Louis District
RM	river mile
RTK	Real-Time Kinematic
SAJ	Jacksonville District
USACE	US Army Corps of Engineers

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Shallow acoustic reflection (chirp) data have been utilized to map the elevation of underlying stratigraphy in a wide range of aqueous environments. Of particular concern in riverine regions is the elevation of near-surface underlying rock that, if exposed during normal migration of sedimentary bedforms, can cause grounding and damage to vessels transiting the region during periods of low water. Given the ephemeral nature of the rock's exposure, traditional surveying methods are insufficient to map rock when it is covered by a thin veneer of sediment, increasing the potential hazard. Accordingly, the US Army Corps of Engineers, St. Louis District, (MVS) explored the use of chirp sub-bottom surveys to identify buried rock within the Mississippi River in the vicinity of Cape Girardeau, MO, and Thebes, IL. Hazard maps showing the distribution of buried rock were generated, and the base of the mobile sediment layer was identified where possible. These data will allow MVS to accurately identify potentially hazardous regions during periods of low water. Although the study did not result in the complete mapping of all near-surface geologic hazards, regions that warrant further study are identified, and modifications to the original survey plan are provided to improve the accuracy of future data collection efforts.

15. SUBJECT TERMS
Fluvial geomorphology, Geophysical surveys, Mississippi River, River channels, Rocks, Sedimentation and deposition

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