Western Region Coastal & Marine Geology

The internal structure of sand bars on the Colorado River, Grand Canyon, as determined by ground-penetrating radar

U.S. Geological Survey Open-File Report 01-425

2001

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Contents:

Abstract

High-resolution, subsurface imagery from ground-penetrating radar (GPR) has revealed the internal structure of sand bars at seven sites on the Colorado River, Grand Canyon. Based on reconnaissance-level surveys, we recognized three stratigraphic units and several intervening unconformities. Unit A, which exhibits hyperbolic reflections and always occurs at the base of the section, is interpreted as bedrock and/or talus. Unit B is a commonly

observed sand deposit that overlies unit A and is characterized by reflections that gently dip down toward the river axis. Unit C is a sand deposit up to 2 m thick that always occurs at the top of the section and may represent a flood deposit from 1983. This study demonstrates the utility of GPR for non-destructive investigation of sand-bar thickness and the stratigraphic record of flood events in the Grand Canyon.

Introduction

The stratigraphy of sand bars in Grand Canyon is, to some extent, a long-term measure of hydrodynamics and sediment-supply conditions of the Colorado River below Glen Canyon Dam. The completion of the dam in 1963 reduced the size and frequency of floods on the Colorado River, and has greatly altered the deposition and erosion of alluvial sediment in downstream areas (Topping et al., 2000a, 2000b). Prior to dam construction, the river delivered large volumes of sediment to Grand Canyon, especially during powerful spring floods. Peak flows of up to 8500 m3/s episodically scoured sediment from the river bottom and deposited it along the river banks. The dam releases now seldom exceed 900 m3/s and transport only a small fraction of the the pre-dam volume of sand into Grand Canyon National Park. Sand bars have topographically adjusted to the infrequent, smaller floods (Andrews et al., 1999; Hazel et al., 1999) and reduced sediment supply. Systematic surveys that document those changes only began in 1974, and have been limited to a small number of sites (Howard and Dolan, 1981; Beus et al., 1985; Schmidt and Graf, 1990). Clearly though, the post-dam history of sand accumulation in the Grand Canyon is well preserved in the stratigraphic record.

This study examines the near-surface geology of sand bars in Grand Canyon (Fig. 1) with ground-penetrating radar (GPR). The high-resolution imagery of GPR is similar to seismic reflection data and provides an effective tool for mapping stratigraphic interfaces in unconsolidated fluvial deposits (e.g., Vandenberghe and van Overmeeren, 1999). Although GPR cannot resolve the finest details of bedform architecture, unconformities and other major bounding surfaces produce strong reflections that are readily observed in GPR data. Moreover, the depth of exploration with GPR is well below the depth typically reached by shallow trenches. The main objective of this project is to determine whether GPR profiles can be used to characterize patterns of subsurface reflections and provide information about the internal structure of alluvial deposits in the Grand Canyon. By examining the geometry of unconformities and intervening sedimentary structures, we can better understand the long-term depositional history of alluvial sediment, particularly the effects of large floods that were common in the past.

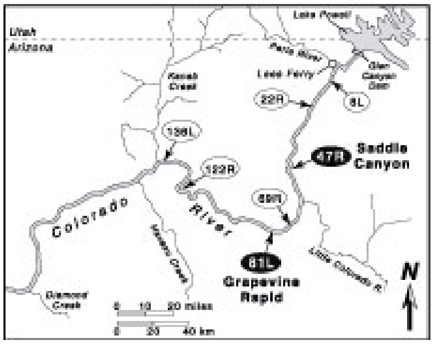

Figure 1 (52K)

Figure 1. Map of Colorado River downstream of Glen Canyon Dam, Arizona. Study sites are indicated by circled numbers (river mile) and the letter "L" (left bank) or "R" (right bank). This study focuses on sand bars at Saddle Canyon (mile 47R) and Grapevine Rapid (mile 81L).

Methods

Approximately 1.9 km of GPR profiles were collected from seven sites in the Grand Canyon (Fig. 1; Table 1),using a Sensors and Software pulseEKKO 100* system with a 1000 V transmitter. The lightweight, portable system is powered by 12 V batteries and primarily consists of a transmitter, receiver, electronics console, and laptop computer. Antennas are frequency specific and fall within the range of 10-1000 MHz. The transmitter generates pulses of high frequency electromagnetic energy, which propagate through the ground. Where the signals encounter an interface between electrically contrasting materials, part of the energy reflects back to the surface. The receiver antenna precisely measures the travel time of of the reflected signals, similar to seismic reflection techniques (Davis and Annan, 1989). All data are displayed in real time on the computer monitor and stored in raw form for later analysis. Post-processing procedures are similar to those used in processing of seismic reflection data.

Table 1. Summary of study sites and length of GPR profiles collected.

Site	River Mile	Deposit Type	GPR Profiles (m)
Badger Creek	8	separation	86
no name	22	reattachment	275
Saddle Canyon	47	reattachment	288
Basalt Rapid	69	channel margin	361
Grapevine Rapid	81	reattachment	283
122-Mile Creek	122	reattachment	254
no name	136	separation	217
TOTAL			1894

The GPR transmitter and receiver antennas were moved together in increments of 0.20 m (shot spacing) along a profile, providing continuous observations of subsurface structure. Shore-normal and shore-parallel profiles were collected at each site. Typically, the GPR collected 32 shots at each point and stacked them to improve the signal-to-noise ratio, and thus better define real reflections. Data were also collected in areas of shallow water by placing the antennas in water-tight housings and towing them behind a motorized raft at speeds of 1-2 km/hr. On water, the system was triggered at a set time interval of 0.5 s (2 Hz), thus shot spacing was determined by the speed of the vessel. Most GPR lines were shot several times with antennas of different frequencies (50, 100, 200, and 450 MHz). Common midpoint (CMP) surveys were also performed to determine the velocity of GPR through the sediment, which permitted the conversion of travel time to sand thickness. Topographic data were collected with a hand-held bubble level and stadia rod, and used to correct the GPR profiles. Geographic coordinates were determined with GPS for the start and end of each profile

Types of Alluvial Deposits

Three main types of sand bars exist in the Grand Canyon, including: 1) separation bars, 2) reattachment bars, and 3) channel-margin bars (Schmidt and Graf, 1990). Separation deposits accumulate in areas of low-velocity flow located at or near the upstream end of recirculation zones, and typically extend downstream from a debris fan at the head of a rapid. In this study, 303 m of GPR profiles were collected from two separation bars (Table

1).

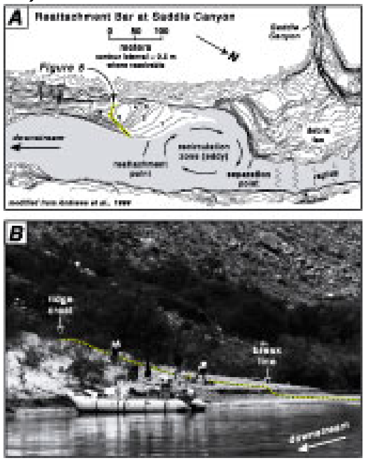

Figure 2 (192K)

Figure 2. Reattachment bar at Saddle Canyon. A) Topographic map of eddy-fan complex showing location of GPR profile in Figure 5. B) Photograph of sand bar also shows location of GPR profiles in Figures 5 and 6, which begin on the flat, emergent platform at right and cross the sandy ridge crest.

Reattachment deposits accumulate in primary eddies at the downstream end of recirculation zones (Fig 2), where flow directions are reversed and flow velocities are low (Rubin et al., 1990; Schmidt and Graf, 1990). These morphology of these deposits resemble a sandy spit with a relatively high, central ridge or mound that projects upstream and a return channel on the landward side of the bar. Daily and seasonal fluctuations in discharge have significant impact on the morphology of reattachment bars, which respond to changes in the size of recirculation zones (Rubin et al., 1990). Substantial reworking occurs during infrequent large floods. The deposits first erode as flow velocity increases, and then build higher as the eddy enlarges and the reattachment point migrates downstream at peak flow. In this study, 817 m of GPR profiles were collected at three reattachment bars (Table 1). Data from Saddle Canyon, a reattachment bar at river mile 47, are presented here.

Channel-margin bar deposits are most common where the river is relatively wide and recirculating currents do not normally detach from the bank (Schmidt and Graf, 1990). They may form where minor flow obstructions create recirculation zones along the river bank, but are not related to a well developed eddy-fan complex. "Typically, these deposits mantle bedrock rock or talus. At low discharges, bedrock or talus may exist between the deposit and the water's edge (Schmidt and Graf, 1990, p. 23)". This study examined channel-margin deposits at two sites (Table 1). Data from a channel-margin bar at river mile 81 above Grapevine Rapid (Fig. 3) are presented here.

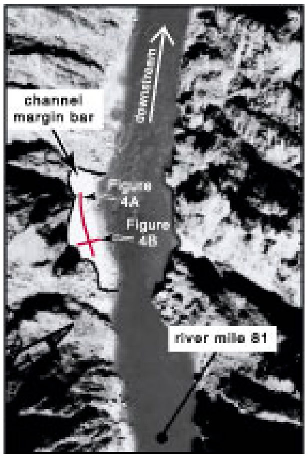

Figure 3 (38K)

Figure 3. Aerial photograph of sand bar at Grapevine Rapid. Dashed lines indicate location of GPR profiles in Figure 4. Air photo from Northern Arizona University web page (http://vishnu.glg.nau.edu/gces/studysites.html)

Description of GPR Units

GPR imagery consists of subsurface reflections that primarily arise when high-frequency electromagnetic signals encounter changes in degree of water saturation of sediment (Topp et al., 1980). These variations in water content are typically related to either changes in degree of saturation or differences in sediment texture. In this study, GPR reflections were recorded as shallow as 0.5 m and as deep as 7 m below the ground surface. We observed packages of relatively uniform reflections bounded by unconformities and recognized three GPR units following the methodology of Beres and Haeni (1991) and van Overmeeren (1998), a method that is similar to sequence-stratigraphic interpretation of seismic reflection data (e.g., Mitchum et al., 1977). The GPR units are defined on the basis of: 1) morphology of major bounding surfaces, 2) intensity, spacing, and coherence of internal reflections, 3) geometry or shape of a package of similar reflections, and 4) stratigraphic setting. We collected no cores and excavated no trenches in this project, but depend on earlier studies to confirm the GPR interpretations, where possible (Rubin et al., 1990, 1994a, 1994b).

Unit A was observed in approximately 25% of all profiles and exhibits an irregular upper surface that is characterized by a high-amplitude reflection (Fig. 4A). Large-scale hyperbolic reflections are common and imply the presence of relatively high-relief objects along the upper surface that act as point reflectors. These hyperbolic reflections are created when the diverging, cone-shaped beam of electromagnetic energy from the GPR encounters, for example, a bedrock pinnacle or boulder. Energy is not only reflected in the near-vertical plane, but is also reflected as the GPR system approaches, passes over, and moves away from such a positive-relief object, thus creating a reflection that takes the shape of an upside down "U", or hyperbola. Internal reflections in unit A range from absent (Fig. 4A) to chaotic (Fig. 4B), a variable that is largely dependent on the degree of heterogeneity of the sediment and the orientation of the profile. Unit A is always the lowermost unit and is interpreted as bouldery talus and/or bedrock. Partially buried boulders were observed in several locations where unit A approached the surface. The total thickness of unit A is not known, but seismic refraction and vibra-probe studies indicated that "bars are underlain by tens of meters of talus" and depths to bedrock range up to 45 m (Rubin et al., 1994a, p. 4).

Unit B is the most common unit in this study and exhibits a smooth upper surface that was observed in every GPR profile. Internal reflections are typically coherent, closely spaced, and laterally continuous. Depending on the orientation of a given GPR profile, the parallel reflections are flat-lying (strike section; Fig. 3) to gently dipping (dip section; Fig. 4). The two-dimensional GPR profiles also depict large-scale, clinoform reflections that are planar to slightly concave-upward and dip toward the river at apparent angles of 5 to 17 degrees (Fig. 5). Reflection patterns are complex and include subhorizontal reflections that truncate underlying, inclined reflections, perhaps representing minor unconformities. Unit B is the uppermost unit in all except one location and has a maximum observed thickness of 6 m. Unit B always overlies unit A, where present, and is interpreted as laminated to thick-bedded, alluvial sand. Cutbank exposures and trenches (Rubin et al., 1990, 1994b) confirm this interpretation.

Unit C was observed in only one location and exhibits a smooth upper surface that is coincident with the surface of the ground. Unit C is a draping, irregularly shaped deposit that lies along the flanks and under the crest of a sandy ridge at Saddle Canyon (Fig. 5). A highly reflective boundary at the base of unit C is slightly concave upward and smoothly increases in elevation from approximately river level to +3 m beneath the ridge crest. Landward of the ridge, this buried surface exhibits more irregular relief; low-lying areas may represent former channels. Unit C has a maximum observed thickness of approximately 3 m in the center and pinches out at the break line, adjacent to the river. Internal reflections are laterally continuous and approximately parallel to the upper and lower bounding surfaces. Unit C always overlies unit B and is interpreted as a sandy flood deposit.

Thickness of Sand Deposits

GPR data show wide variation in the thickness of subaerial sand deposits at Saddle Canyon and Grapevine Rapid - sand bars located 47 miles and 81 miles, respectively, downstream of Lees Ferry (Fig. 1). At Grapevine Rapid, a thin veneer of sand (unit B) overlies talus and/or bedrock (unit A) beneath upstream parts of the sand bar (Fig. 4). There is significant relief on the upper surface of unit A and, where that buried surface is topographically low, the overlying sand deposits are at least 4 m thick. Due to attenuation below that depth, the base of the sand was not imaged, so the observed thicknesses are minimum values. No cores or trenches were available for ground truthing the imagery. Anima (personal communication, 1999) vibra-probed this sand bar in 22 locations and measured an average sand thickness of 2.54 m.

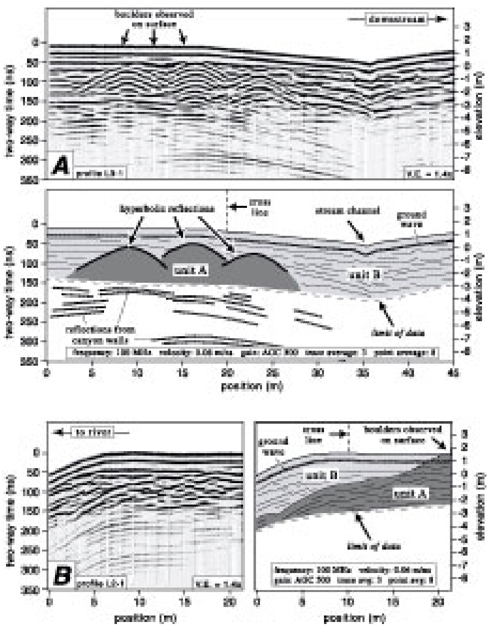

Figure 4 (180K)

Figure 4. GPR profiles on sand bar at Grapevine Rapid, collected with 100 MHz antennas. A) GPR profile oriented parallel to river; downstream direction is to the right. Hyperbolic reflections indicate presence of buried boulders at positions 5-25 m. B) GPR profile oriented perpendicular to river channel. Vertical, dashed line indicates where profiles cross. See Figure 3 for location of profiles

At Saddle Canyon, low-frequency GPR surveys indicate that sand deposits are at least 7 m thick beneath the crest of a sandy ridge (Fig. 5). The GPR reflection profiles here, as at Grapevine Rapid, provide only a minimum thickness because signal attenuation prevented detection of the base of the sand deposit. The base of the sand (unit B) is presumably underlain by talus or bedrock (unit A), but was not observed beneath the outer parts of the reattachment bar (i.e., closer to the main channel). It is unclear if unit A occurs in the more landward areas, where strong reflections may represent the base of the sand. Vibra-probing in 12 locations on this bar indicated an average sand thickness of 9.29 m (Anima, personal communication, 1999). Trenches or cores are needed to better interpret the origin of subsurface reflections in these two-dimensional profiles.

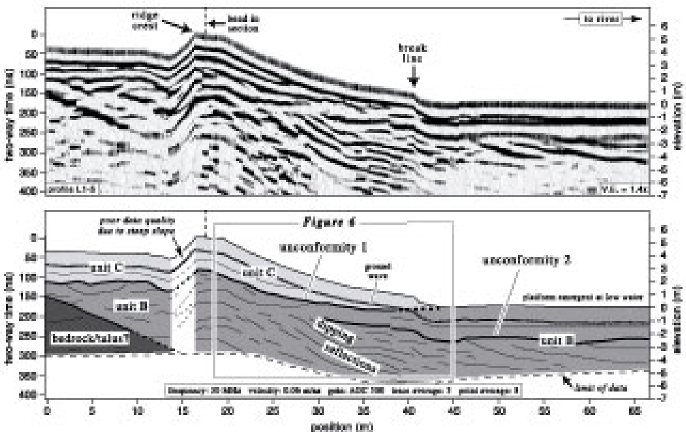

Figure 5 (88K)

Figure 5. GPR profile on sand bar at Saddle Canyon, collected with 50 MHz antennas. Profile is oriented perpendicular to river and crosses a linear ridge and return channel that were produced by the 1983 flood (see Figure 2). Depth of penetration varies from approximately 4 m on emergent platform (fully water saturated) to 7 m beneath ridge crest (drier sand). Beneath platform and flank of ridge, reflections gently dip toward the river (down to left) and are truncated by an angular unconformity. Box indicates section of profile that is replicated in Figure 6.

A Possible 1983 Flood Deposit

Sand bars contain a partial record of floods in the Grand Canyon. Large floods typically scour an unconformity into older material, then bury that erosional surface with up to several meters of new sediment (Rubin et al., 1990, 1994b; Schmidt and Graf, 1990; Andrews et al, 1999). In 1983, a flood of over 100,000 cfs lasted two months and was the largest since completion of Glen Canyon Dam. The magnitude of the flood was representative of pre-dam events and strongly impacted the topographic and stratigraphic evolution of sand bars (Andrews et al., 1999; Schmidt and Graf, 1990). However, the full impact is poorly documented due to lack of pre-dam, baseline data. We believe that the strong reflector separating units B and C beneath the sandy ridge at Saddle Canyon (Figs. 5 and 6) is an erosional surface created by the large 1983 flood. Unit C probably represents material deposited later in the same flood cycle. This conclusion is based on comparison with interpretations of trench observations (Rubin et al., 1994b).

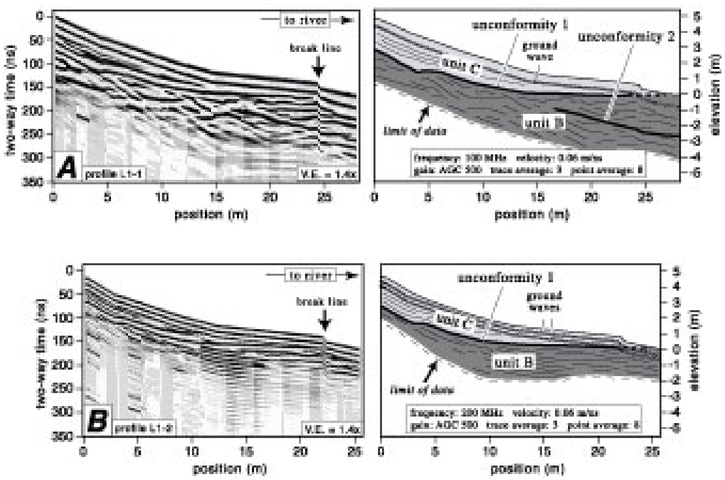

Figure 6 (92K)

Figure 6. GPR profiles on sand bar at Saddle Canyon, collected with A) 100 MHz and B) 200 MHz antennas along same trackline in Figure 5. Depth of penetration is less but these higher frequency surveys resolve finer details in upper part of section. Dipping reflections (down to right) are truncated by a strong, concave-up unconformity along flank of ridge. A smoothly curving, wedge-shaped deposit of sand (unit C) overlies the unconformity and is approximately 2 m thick in the center.

The elongate, sandy ridge at Saddle Canyon is a relic feature that rises about 6 m above the average level of the river, and is separated from the canyon wall by a low-lying channel on its landward side (Fig. 2A). Topographically high parts of the bar were last submerged by flood waters in 1983, but the 1996 flood also had significant impact (Andrews et al, 1999). The 1996 flood lasted 7 days and initially caused intense scour, but was followed by generally depositional conditions. This sequence of events was also observed at Carbon Canyon, another reattachment bar located downstream, where "During the initial hours of the flood...the existing reattachment bar was extensively scoured and the return-current channel enlarged. The outer or channelward half of the reattachment bar...also was extensively scoured (Andrews et al., 1999, p. 125)." The maximum depth of erosion was about 3 m and, after the initial period of scour, more than 2 m of sand accumulated on both sides of the bar top, causing the crest of the bar to broaden considerably (Andrews et al., 1999). The possible flood deposit, or unit C (Figs. 5 and 6), at Saddle Canyon is similar in thickness and also drapes over the bar crest of the bar. It is underlain by a strongly reflective surface, which probably represents the period of initial scour. Similarly, Schmidt and Graf (1990) reported evidence of significant erosion by the 1983 high flows, and noted that "...major truncation surfaces ... indicate that much of the sand in reattachment deposits is scoured, transported, and redeposited by high discharges (p. 21)." The well-documented response of sand bars in 1996 provides insight into the geomorphic effects of high-discharge events such as the 1983 flood, and aids our interpretation of GPR-based stratigraphic units.

Linking a particular deposit to an individual flood event is problematic. The 1983 flood produced deposits at several bars that exceeded several meters in thickness, too thick to trench (Rubin et al., 1994b). Unit C, the possible flood deposit at Saddle Canyon, is up to 3 m thick (Figs. 5 and 6). Was the entire volume of unit C deposited in a single event in 1983? Or is it the product of an earlier, pre-dam flood that was only modified by the 1983 event? Sediment texture can help determine if the deposit originated in 1983 or if it is an older deposit that predates Glen Canyon Dam. During pre-dam floods, the Colorado River typically carried a high suspended sediment load with abundant silt. Since completion of the dam, most suspended sediment settles out in Lake Powell. Releases of clear water contain little silt and, instead, principally mobilize well sorted sand that already exists in the river channel, and produce deposits of different texture than under pre-dam conditions (Andrews et al., 1999). The sediment of unit B, which underlies the flood deposit, is probably representative of deposition by the natural, undammed river. The contrast in sediment texture (i.e., high versus low silt content) may produce the strong reflections at the base of unit C that are observed on GPR profiles (Figs. 5 and 6). This high-amplitude reflection probably represents an erosional surface cut into older, pre-dam deposits.

Characterization of Alluvial Sediment with GPR

Dam construction on the Colorado River has reduced the supply of new sand to the Grand Canyon, so it is important to quantify and monitor the amount of sand that is stored in the system. This study demonstrates that GPR is an appropriate method for geophysical exploration of alluvial sediment in the Grand Canyon. Data collection is rapid and non-destructive, making GPR ideal for reconnaissance of large study areas and selection of sites for more intensive study. We recommend using antennas of different frequencies at sites of high value; replication of profile lines optimizes the utility of GPR imagery with a balance between penetration and spatial resolution of subsurface features. Information from trenches and cores are needed to confirm interpretations of GPR units, to correlate individual reflections with lithologic or textural changes, and to determine the depths and thicknesses of deposits.

GPR works best in coarse-grained, relatively dry sediment and therefore is not applicable at all sites. Low-frequency (50 MHz) electromagnetic waves can penetrate to depths of up to 47 m in dry sand and gravel (Smith and Jol, 1995). However, the presence of electrically conductive materials (e.g., clay-rich sediment or saline porewater) causes rapid attenuation of electromagnetic energy, and severely limits the depth of exploration with GPR. Although GPR can operate in shallow water (Beres and Haeni, 1991), we experienced high energy losses in eddy pools because the water was moderately conductive. The specific conductance of Colorado River water at Lees Ferry ranges from 550 to 750 uS/cm @ 25° C (U.S. Geological Survey, 2000). The depth of penetration was also limited in areas adjacent to the river, where the water table was at or near the surface (Fig. 5). At slightly higher elevations above the river, however, sediment was well drained and system performance greatly improved. Attenuation is less of a problem with lower frequency signals, but there is a concomitant decrease in the ability to resolve small features. Spatial resolution of reflectors in the ground depends on the antenna frequency and on electrical properties of the medium. In common geologic materials, the expected resolution is approximately 0.25 m for 200-MHz antennas, 0.50 m for 100-MHz antennas, and 1.0 m for 50-MHz antennas (Annan, 1999). Our experience indicated that the 50- and 100-MHz antennas were superior to the higher frequencies. The reflection data resolved individual beds in the shallow subsurface that were less than one meter thick, and provided good resolution to depths of up to 7 m below the ground surface.

Seismic reflection is similar in concept to GPR; both techniques depend on the detection of energy reflected from objects or discontinuities in the subsurface. Seismic methods operate at much lower frequencies (kHz range) than GPR (MHz range), and are able to map stratigraphic interfaces below the practical depths of GPR. The major advantage of seismic reflection is that water chemistry or the presence of clayey sediment does not adversely affect the transmission of acoustic energy. Data collection is slow and labor intensive, however, and the resolution of seismic data is much lower than GPR data. In addition, high-frequency GPR can resolve features less than 1 m below the surface, whereas ground waves often obscure the upper few meters of seismic reflection records.

Acknowledgments

We thank David Topping and the Grand Canyon Monitoring and Research Center (GCMRC) for the logistical support that made this project possible. Ingrid Corson, Robin Dornfest, Ted Melis, Keith Kohl, and Hank Chezar assisted with the heavy lifting of field operations. We especially thank expert boatman Dan Dierker for sharing his knowledge of the river.

References

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* This report is preliminary and has not been reviewed for conformity with U.S. Geological

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