Mapping the floor of Lake Powell: Preliminary discussion of CHIRP data along the San Juan Sediment Delta

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Senior Integrative Exercise
17 March 2019

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ABSTRACT
Lake Powell began to fill with water and sediment in 1963 and reached full capacity in 1980. Previous studies have documented the presence of trace metals and other contaminants in the sediment deltas of the reservoir. Although very little is known about the volume and distribution of sediment and contaminants. This study uses seismic reflection profiles to inform core site selection for a larger project that aims to determine the extent of heavy metal contamination in Lake Powell. I divided the San Juan delta of Lake Powell into six distinct sections based upon interpreted sediment thickness from the seismic profiles and from the lake-floor gradient along the delta. Twelve sites for prospective coring were identified through analysis of the CHIRP seismic reflection data which was collected longitudinally along the delta. I identified six locations for coring, in each section of the delta, where sediment is likely representative of the section. The remaining six locations are particularly thick sediment packages within each of the six delta divisions. I also propose four preliminary sediment facies within the delta: rock outcrops, alluvial deposits, post-impoundment sediment deposits, and bedrock.

This study provides an initial analysis of the shape and composition of the San Juan sediment delta to inform further study of the deltaic deposits.

Keywords: seismic reflection; sedimentation; delta, reservoir; Lake Powell
INTRODUCTION

Lake Powell reservoir straddles the border between Utah and Arizona. The reservoir is fed by the Colorado and the San Juan Rivers. These rivers make up the two primary arms of the lake (Fig. 1). The Glen Canyon Dam, which was completed in 1964, impounds the water of Lake Powell. The Glen Canyon Dam was authorized by Congress in 1956 to provide water storage to the Upper Colorado River Basin which includes Wyoming, Utah, Colorado, and New Mexico. It took seventeen years for the reservoir to reach full pool at 3700 feet (1128 meters) above sea level, making Lake Powell the second largest man-made reservoir in the United States (Pratson et al., 2008).

As the reservoir began to fill with water in 1963, the basin also began to infill with sediment. Deltas have been growing beyond the mouths of both the San Juan and Colorado Rivers which account for 90% of the sediment input into Lake Powell (Potter and Drake, 1989; Ferrari, 1988). The San Juan and Colorado deltas are constantly changing and evolving due to active sediment deposition and erosion. Fluctuating lake levels, climate, and hydrology affect the volume and distribution of sediment along the delta and within the reservoir. When lake levels change, the sediment within the deltas are often reworked into different parts of the reservoir.

In addition to sediment and water, the San Juan River has transported mine-impacted water into the reservoir from mining districts in the upper Animas watershed of southwestern Colorado. A 2015 incident at the Gold King mine in the Animas watershed released an abundance of contaminants, including aluminum, iron, manganese, lead, copper, arsenic, zinc, cadmium, and mercury, that ultimately flowed into the San Juan River (U.S. BOR, 2015). This incident sparked conversation over the fate of
contaminants in the San Juan and Colorado River basin. The sediment of the San Juan delta, Lake Powell, are likely the repository of the persistent mining waste. As the sediment deltas are constantly being reworked, waste contaminants in the delta can be released into the water and become potentially harmful to humans, plants, and animal species (Hart et al. 2005; Potter and Drake, 1989; Vernieu, 1997).

Prior work on deltaic sediment in Lake Powell has identified the presence of heavy metals in the Colorado, San Juan, and Escalante deltas (Hornewer, 2014; Hart et al., 2005). The first major study of sediment composition in Lake Powell by Hart et al., (2005) was conducted on three sediment cores collected by the US. Geological survey in 2001 on the Colorado sediment delta. The authors found the presence of trace elements, organic compounds, and radionuclides in the deltaic sediment, but the chemical analyses of the cores did not show unusual concentrations of trace elements for delta sediments. However, the concentration of certain trace elements increased downstream and at depth within the core. The three core samples collected for this study were only about 4 meters in length, of up to 20 meters of available sediment, and sampled from a 10 kilometer long portion of the over 50 kilometer delta. Therefore, the scope of the study was limited in all three dimensions of the delta, and does not provide complete evidence that there are not dangerous volumes of contaminants in the Colorado sediment delta.

Expanding upon the Colorado deltaic sediment study, a 2014 U.S. Geological survey study obtained three sediment cores on the San Juan River delta and three sediment cores on the Escalante River delta (Hornewer, 2014). Major and trace elements were detected at greater than “reporting levels” within both deltas (Hornewer, 2014). The 2014 Hornewer study used the same core retrieval method as used by Hart et al. (2005).
Both previous studies of the primary sediment deltas within Lake Powell are limited in scope spatially and in terms of sediment volume. Though the sediment cores of previous studies provide initial insight into the sediment and water chemistry of Lake Powell, the coring method and limited scope does not lend itself to regional mapping of sediment distribution and composition throughout the reservoir.

The purpose of this study is to use compressed high-intensity radar pulse (CHIRP) data collected along transects of the San Juan delta of Lake Powell in order to determine the structure and thickness of the subsurface delta to (1) guide future core site selection and (2) inform further research into the relationship between stratigraphy, trace metal deposition, and possible re-mobilization of sediment. In this paper, I will discuss the shape of the sediment delta as imaged by the CHIRP data and propose twelve locations for coring: six locations with the thickest sediment and six locations with average sediment thickness and stratigraphy.

GEOLOGIC SETTING

In Glen Canyon National Recreation Area more than 3,000 meters of bedrock is exposed, spanning 300 million years of geologic history (Anderson, 2010). The bedrock is predominantly sandstones and mudstones and ranges from Late Pennsylvanian to Holocene in age. Approximately 5.5 million years ago, Tertiary-Quaternary uplift of the Colorado Plateau led to the dramatically carved canyons of the southwestern United States that we are familiar with today (Lucchitta, 1979). The uplift of the Colorado Plateau led to the integration of upper basin drainages to the lower basin drainages that flowed to the Gulf of California (Lucchitta, 1989; Young and Spamer, 2001).
Subsequently the Colorado River and its tributaries, including the Green, Escalante, Dirty Devil, and San Juan Rivers, sliced through the plateau’s strata creating Glen Canyon.

At the turn of the 20th century, water became an increasingly valuable resource in the west. A shift from mining to agriculture led to aggressive land grabs in search of increased water resources. Conflict between Colorado River Basin states (Colorado, New Mexico, Utah, Wyoming, Arizona, California, and Nevada) was at an all-time high as the states debated who had rights to the water in the basin. The Colorado River Compact signed by the basin states in 1922 resolved the differences between the Upper (Colorado, New Mexico, Utah and Wyoming) and Lower (Arizona, California and Nevada) basins. The Compact divided the water of the Colorado River basin between the Upper and Lower basins and set a requirement that the flow of water not be depleted above Lee’s Ferry, Arizona (National Research Council, 1987). In 1946, the Bureau of Reclamation completed a report that provided a suggestion for a scheme of control that would ensure the Upper basin satisfied the necessary required water delivery amount to the Lower basin in the form of “holdover reservoirs” which included Lake Powell (United States).

Construction of the Glen Canyon Dam began in 1956, the same year that a water diversion plan for the Colorado River was authorized by congress (Chidsey, 2000). The Colorado River’s uncontrollable and unpredictable water discharge was transformed by the construction of the dam. Not only could flooding and destruction from the river be controlled, but a reliable, essential water and power source was established for the American southwest. Today, the Glen Canyon Dam is operated by the US Bureau of Reclamation, who control water intakes and releases. Water storage and release is dictated by the Colorado River Storage Project (CRSP), which regulates the flow of the
Colorado River to provide water for consumptive use, flood control, agriculture, and hydropower (United States Congress, 1956). It took 7 years and 272 million dollars to complete the 216 meter tall engineering wonder (Potter and Drake, 1989).

Lake Powell reached full pool, at an elevation of 1,128 meters, for the first time in 1980 (Anderson, 2010). The reservoir has a capacity of 33 billion cubic meters at full pool, making it the second largest man-made reservoir in the United States after Lake Mead (Pratson et al., 2008). Lake Powell is over 300 kilometers long with a shoreline of about 3,060 kilometers, approximately the distance from Seattle to Detroit (Potter and Drake, 1989).

The two major tributaries to Lake Powell are the Colorado and San Juan Rivers. The Colorado arm extends nearly 300 kilometers from the dam in Page, Arizona during full pool, and the San Juan arm extends approximately 200 kilometers from the dam (Ferrari, 1988). Water levels in Lake Powell are in a constant flux. In the spring, the reservoir is filled with runoff and snowmelt from the Upper Colorado River basin which causes lake levels to rise. During the summer and fall months, demand for water increases and therefore the water levels decrease. When lake levels change, sediment that has accumulated at the base of the reservoir in the form of sediment deltas change as well. During periods of drought, the deltas are incised which causes remobilization of sediment into the water and further down the delta. Therefore the shape of the delta is in constant flux.

Both the Colorado and San Juan Rivers develop sediment deltas that account for 90% of the sediment input into the lake (Potter and Drake, 1989; Ferrari, 1988). The San Juan delta began developing in 1963, when the reservoir began to fill and sediment was
prevented from passing beyond the dam (Potter and Drake, 1989). Because the canyon walls of the reservoir on the San Juan arm are so narrow, sediment essentially moves down the delta and is prevented from moving laterally. Because of this constrained behavior, the deltas of Lake Powell are essentially two dimensional (Pratson et. al., 2008).

**San Juan Delta Contamination**

Lake Powell and the San Juan sediment delta are relatively well constrained systems where the inputs and outputs of water and sediment are well documented because the basin moved from open to closed after the completion of the dam in 1963. The suspended sediment of the San Juan River originates from highly erodible geologic material and contains contaminants from agricultural, industrial, natural, and municipal sources (Vernieu, 1997). There are detailed climatic, hydrologic, and historic records that can be used to inform the study of this newly closed basin. The historic data includes mining incidents and human activities that contribute to pollution in the San Juan River basin. There is a long history of mining contamination from operating, old, and abandoned mines throughout southwestern Colorado and northwestern New Mexico that contribute to the San Juan River. The San Juan sediment delta is a potential sink for contaminants in Lake Powell. The fine grained material of the delta contains a large volume of clay minerals which are also active sites for ion exchange or chemical absorption of metals, nutrients, and other pollutants that are in turn deposited into the delta (Vernieu, 1997). Intermittent monitoring and sampling of the delta has been conducted, and trace elements and radionuclides have been documented in the sediment (Horneuer, 2014). The volume and distribution of sediment and contaminants in Lake
Powell is of special interest to Glen Canyon National Recreation Area (Glen Canyon NRA) resource managers, as large volumes of contaminants in the delta could pose health risks for wildlife and humans, while also negatively impacting water users downstream of Lake Powell, such as Lake Mead.

On August 5, 2015, 3 million gallons of wastewater was released from the Gold King mine in Silverton, Colorado (EPA, 2015). The initial release of contaminants, including aluminum, iron, manganese, lead, copper, arsenic, zinc, cadmium, and mercury, flowed into Cement Creek which then flows into the Animas River and eventually joins the San Juan River 215, kilometers away from the mine (U.S. BOR, 2015). This incident sparked conversation and concern over the transport and fate of contaminants in the San Juan River basin, especially since most of the sediment is ultimately being deposited in the San Juan sediment delta in Lake Powell.

SEISMIC SURVEY

In the fall of 2017, the US Geological Survey Utah Water Science Center collected 92 kilometers of seismic-reflection data concurrently and georegistered with multibeam sonar data in the San Juan River and Colorado River arms of Lake Powell. A compressed high intensity radar pulse (CHIRP) system, Edgetech 424, was used to collect sub-bottom geophysical profiles along eight transects. The CHIRP system is a form of seismic reflection where a ‘swept’-frequency signal in the form of an acoustic pulses (“chirps”) are emitted from a transducer array that also receives the reflected signals.

When a pulse is sent out from the transducer, it travels down the water column until the “chirp” hits some form of sediment layer. Once the chirp contacts sediment,
some acoustic energy is reflected back towards and collected by the transducer. Changes in physical properties in the subsurface cause acoustic energy to be reflected back to the surface (Hart, 2000). Different materials reflect varying amounts of acoustic energy to the transducer based upon the rock’s inherent density multiplied by its velocity.

CHIRP systems are useful for high-resolution mapping of relatively shallow deposits, as the high frequency range allows for penetration into the sub-surface and detection of stratigraphy. When the chirp acoustic signal contacts bedrock or well consolidated sand, the majority of the chirp energy is reflected back and no distinct acoustic signature is detected. When the chirp acoustic signal contacts deltaic sediments, some of the energy continues to travel through the delta. Each change in the physical properties of the subsurface generates a reflection of energy back to the transducer (ie. the change from sand to mud to silt). The San Juan sediment delta consists of primarily soft, wet, poorly consolidated sediments. Therefore, the CHIRP system is able to detect changes in stratigraphic sequences within the delta.

Previous study of the San Juan delta focused on the shallow water regions at the upstream part of the delta. The box core method used in the 2014 USGS study limited the water depth at which they could retrieve core samples to no more than 25 meters. For the 2018 USGS coring operation of the San Juan and Colorado deltas, shallow water locations were inaccessible and a minimum water depth of 5 meters was required to accommodate the barge, drill rig, and anchoring equipment. The coring could also be conducted at much greater depths along the deltas.

The seismic profiles collected before the coring operation were collected along transects where water depth would likely be feasible for coring. The lake level at the time
of CHIRP data collection was at an average of 1105 meters above sea level during November and December of 2017. The CHIRP data of the eight San Juan River transects were processed by Rob Baskin of the USGS Utah Water Science Center. All processed files were converted into SEG-Y format. The eight transects of CHIRP lines along the San Juan River delta are the basis of my study.

**Processing and Interpretation**

For this study, I imported the SEG-Y traces into the IHS Kingdom Suite: seismic and geological interpretation software package. Each SEG-Y trace was imported as a 2D SEG Y File with Coordinates. The datum elevation for the project was set at 1105 meters, the average elevation of the surface of Lake Powell in October and November 2017. I assume a sound velocity and seismic datum velocity of 1500 m/sec in water and unlithified sediment thickness calculations. Using the standard values for SEG-Y format data, the shotpoint starts in byte 9 for the traces, with the start time byte location in the trace header set at 109. The shotpoint format, x-coordinate format, and y-coordinate format were set as 32bit, and I changed the output data format to be 32bit.

Once the eight lines were imported into the Kingdom program, they were ready for interpretation. Once the lines were imported into the Kingdom program I began my interpretations. The first of eight lines did not provide reliable or readable data, and it was therefore removed from interpretations. For the remaining lines, I used the horizon picking tool to pick the water sediment interface as the first dark, straight line I encountered on the way down from the water surface (blue lines in Fig. 2). In locations where the first “surface-like” acoustic signature I encountered was foggy, curved, or indistinguishable, I did not identify it as the sediment top/water bottom horizon. I set the
line contrast to a resolution that clearly showed alterations from white and black and worked with a vertically exaggerated image of about 1 to 7. I also interpret the sediment-bedrock interface, but this horizon was more difficult to consistently define (orange lines in Fig. 2). I use the crisp black line visible above where the image faded to white or a cloudy black. If I could not see at least one transition from black line, to white line, back to black line, then I did not include the section in the sediment bottom/ bedrock top horizon.

Once all delta interpretations were complete, I exported the line data into .csv files for each of the seven transects on the San Juan delta. In order to create a continuous delta shape, I connected the seismic transects end to end in the overlapping area. I removed the areas in which the transects overlapped, and chose the line that made the data the most continuous. In the end, I have 77,818 data points along the San Juan River which represents about 50 kilometers of downstream sediment deposition.

RESULTS

The elevation of the lake floor and the pre-impoundment surface along the seismic reflection surveys is shown in Figure 4. The difference between the two lines is the thickness of post-impoundment sediment. These surfaces are derived from interpreted water-bottom and sediment-bottom surfaces. The irregularities of the pre-impoundment surface result from the seismic tracks diverging from the thalweg of the submerged San Juan River as well as the tracks crossing over rock outcrops.

I identified four different lake-floor types using the seismic reflection data: rock outcrops, alluvial deposits, post-impoundment sediment deposits, and bedrock (Fig. 3). The rock outcrops, bedrock, and alluvial deposits predate Lake Powell and the post-
impoundment sediments have accumulated since the completion of the Glen Canyon Dam.

**Delta Divisions**

I divided the delta longitudinally into separate sections so that coring sites could be selected at locations that are representative of the entire delta. I created the divisions A through F based upon interpreted sediment thickness from the seismic profiles and from the lake-floor gradient along the delta (Fig. 4). Figure 5 provides a breakdown of average sediment thickness and maximum thickness of each section based upon interpretation of lake-floor surface and pre-impoundment surface.

Each section of the delta has a distinct lake-floor gradient, thickness, and consistency that differentiates it from other sections of sediment within the delta (Fig. 4). The first section, A, is characterized by a very uniform sediment thickness and gentle lake-floor gradient. The average sediment thickness in section A is 7.06 meters and has very little variations (Fig. 6). Moving further up the delta, there is an abrupt change in sediment thickness between sections A and B, even though the sections have similar average thickness (Fig. 6). Section B has a similar average thickness, 7.37 meters, but there is much greater variation in thickness than section A (Figs. 4; 5). The large fluctuation in sediment thickness is what makes section B distinct from section A. Transitioning from section B to C, there is a steep jump in lake floor elevation (Fig. 6). Section C has the thickest post-impoundment sediment of the delta at an average of 13.46 meters, and up to 40 meters thick (Fig. 5). The thick packages of post-impoundment sediment in section C abruptly thin to an average thickness of 2.40 meters at the transition to section D (Fig. 4). The abrupt change in sediment thickness is similar to the
transition from section A to section B as seen in Figure 6. In section D, the sediment remains a relatively consistent thickness with some gradual thinning of sediment upstream (Fig. 4). At the transition from section D to section E, the lake-floor gradient steepens and the post-impoundment sediment remains less than 4 meters thick throughout section E (Fig. 4). Section E is uncharacteristically thin. In most of the section it is difficult to identify any acoustic signatures of sediment. The final section of the delta, section F, is furthest upstream from the dam. It is characterized by highly variable post-impoundment sediment thickness that is 3.82 meters thick on average (Fig. 7). The lake-floor gradient remains steep like in section D, and eventually transitions to being close to horizontal at the upstream end of the transect.

**Representative Average Locations**

Using the seismic reflection data, I identified six locations in each section of the delta in which sediment is likely representative of that section by choosing locations where the sediment package is the average thickness (Fig. 7). In sections A, B, D, and E, the average sediment thickness is found in areas where there are acoustically homogenous and flat lying sediment deposits that span wide areas, greater than 200 meters wide. In sections, C and F, have highly variable thicknesses which makes it difficult to isolate large locations where the package is a representative average. The pre-impoundment surface is highly variable in sections C and F and in the CHIRP examples of average sediment thickness, the acoustic reflectors are not completely flat lying (Figs. 4; 7).
**Thickest Delta Locations**

I also identified 6 locations of particularly thick sediment packages in each of the 6 divisions (Fig. 8). The thickest sediment packages range from 3.84 meters thick in section E to 40.11 meters thick in section C (Fig. 5). In five of the six delta divisions, the thickest sections occur in short anomalously thick intervals (Fig. 8). Section E is the only section where the thickest package of sediment appears to be a gradual increase in sediment and not an abrupt jump in thickness (Fig. 8).

Sections A and E have maximum and average thicknesses that are close to one another in thickness. There is not much variation in these two sections. Section A is a uniformly thick section that has strong acoustic reflectors that are continuous throughout most of the section. Section E has little variation, but that is due to the fact that there is little to no visible sediment in this area of the delta.

**Anomalous sediment behavior**

Additionally, there are locations in the seismic transects where the sediment deposits are not flat-lying or continuous and exhibit anomalous behavior (Fig. 9). For example, in some locations the sediment onlaps (Fig. 9a, Fig. 9b). The strong acoustic reflectors have a gentle to flat lying dip and are banked up against a steep and clouded reflector. Moving up the steep reflector, the sediment packages thin and eventually terminate. The steep and clouded reflector is likely the top of a basement spire or pinnacle that was submerged when the reservoir flooded. Another example of anomalous behavior occurs when the sediment drapes the pre-impoundment slopes and the reflectors remain parallel and constant thickness (Fig. 9c, Fig. 9d). When the slope steepens, the
sediment reflectors terminate oblique to the steep reflector as opposed to onlapping the surface.

There are also locations in the seismic profiles with anomalously thick sediment packages bounded by vertical transitions (Fig. 10). These include some of the thickest locations along the delta (Fig. 8). It is unexpected that the change in thickness is so abrupt and sharp. Variations in sediment thickness are expected within the delta due to irregularities of the pre-impoundment surface, but one would expect the surface to gradually undulate as opposed to the sharp, straight transitions that are seen in the data (Fig. 10).

**DISCUSSION**

**Prospective Coring Locations**

The San Juan delta can be divided into six sections based upon differences in lake-floor gradient, sediment thickness, and sediment consistency. I believe these divisions are representative of different depositional environments encountered throughout the delta. The pre-impoundment surface of the San Juan River, the geomorphology of the area, lake levels, and water inflow all influence the distribution and structure of sediments in Lake Powell. I propose twelve prospective coring locations which would recover sediment that is representative of different depositional environments along the San Juan arm.

Six of the twelve prospective coring locations consist of the thickest packages of sediment in each section, A through F (Fig. 4). These locations are likely characteristic of environments in which larger volumes of sediment are being deposited on the delta due to external factors such as canyon wall width and amount of depositional energy or
locations in which pre-dam sediment is preserved. The thickest sediment locations are of high priority because they would not only provide the most sediment for the amount of time required to core, but they would also provide the highest temporal resolution of the sediments. This is assuming that the more sediment there is, the more depositional history is documented.

In five of the six thickest locations, sections A, B, C, D, and F, I believe that some of the acoustic reflectors are pre-dam sediments that are overlain by deltaic deposits (Fig. 8). I interpret the locations in which there is a sharp transition into thicker sediment packages that are flat-lying and have strong acoustic signatures as a transition into pre-dam alluvium (Fig. 10). In Figure 10, the transect is likely crossing the pre-dam channel of the San Juan River, and the additional sediments that suddenly appear are historic fluvial deposits below the sediment deposited in the reservoir. These deposits of pre-dam sediments are known to exist in Lake Powell, but their extent and distribution are relatively unknown (Miser, 1924). The pre-dam sediments would have likely contained contaminants related to historic mining in the Upper Animas watershed, and therefore it would be important to retrieve the underlying alluvial sediment for analysis.

In addition to the thickest sediment packages, I propose six additional coring locations that would retrieve sediment that is representative of the majority of the delta (Fig. 7). I determined one location in each of the six sections along the delta. Though it is important to have the most sediment, the goal of the coring project with the USGS is to understand the composition and distribution of contaminants throughout the entire delta. Obtaining cores that have average sediment volumes may provide better insight as to the
distribution and volume of contaminants as opposed to focusing on areas of thick, but often anomalous deposits.

**Preliminary Interpretations of Sediment Distribution and Deposition**

My analysis of the seismic transects have resulted in preliminary sediment facies characterization and an initial determination of the factors that influence sediment deposition throughout the delta. I believe that the geomorphology of the San Juan arm and the flow of the river strongly influence the deposition and distribution of post-impoundment sediment and that this sediment is constantly being reworked. On the other hand, I believe that the historical alluvial deposits have remained relatively stable since the construction of Glen Canyon Dam and are found as buried paleochannels underneath deltaic deposits. The acoustic signature of sediment deposits suggest various facies within the delta, but the way in which the sediment behaves within the delta could also suggest something about timing and mechanism of deposition.

Section E is the portion of the delta in which little to no sediment is found (Fig. 4). In a typical delta setting, there would not be locations in which a segment of the delta was almost entirely bypassed by sediment. One would expect the delta to be relatively uniform with decreasing sediment thickness as it moves down the delta. Therefore, something along the San Juan arm must be causing the sediment to jump section or deposit unexpectedly small volumes of sediment, or the seismic transect is following an area of the river that is not representative of the delta. The lack of sediment likely corresponds with entrance into a large bay on the San Juan. In this portion of the delta, the canyon walls are between 600 meters to 2000 meters wide. Comparatively, further downstream the canyon walls are between 200 to 400 meters apart. This means that in
section E the sediment is able to disperse laterally as opposed to the typical one-dimensional movement down the delta through confining canyon walls. It therefore makes sense that the sediment in section E is so thin that it is barely visible in the seismic data because it is being dispersed throughout a larger area (Figs. 7; 8). I conclude that channel width is a factor that influences the volume of sediment deposition throughout the San Juan delta. There are other locations along the San Juan arm in which the canyon walls widen to create a bay, but there is not an appreciable drop in sediment thickness.

Draping sediments could be interpreted as fine grained material that is settling to the bottom of the lake and mantling the topography (Fig. 9). In this environment, the flow of the San Juan River channel likely does not have a strong influence on the sediment deposition. In contrast, I believe the onlapping sediment could be deposits that have been reworked by changing water levels and the flow of the San Juan River. The fact that the sediment was able to climb up highly sloping topography suggests that some mechanism was mobilizing the sediment. Many of the onlapping deposits only lap up one side of the sloping surface and not the other. In Figure 2, the sediment onlaps from right to left in the direction of water flow onto a bedrock mound, but does not downlap on the other side of the mound. The fact that onlapping occurs in the direction of water flow in the delta suggests that the flow of the river is dictating sediment deposition and structure within the delta.

I believe that in certain locations, the seismic transects provide enough information to differentiate between pre-dam alluvium and post-impoundment sediment. The locations in which there is a sharp transition downward to thicker sediment packages that are flat-lying and have strong acoustic signatures is a transition into pre-dam
alluvium (Fig. 10). The acoustic reflectors of the alluvium in these locations are flat-lying and parallel to the bedrock reflectors, which suggests that the deposits have not been extensively reworked (Fig. 3).

**Future Work**

The results of this study are limited by the extent of the seismic data due to the fact that the CHIRP data provides only a single profile along the length of the delta. In the future, it would be useful to acquire additional seismic surveys to make the stratigraphic information pseudo-3D. Seismic profiles perpendicular to the river channel would enable one to extrapolate data laterally, though it is likely that in narrow canyons the delta sediments will be uniform across the channel because the sediment is constrained by the canyon walls.

Additionally, it would be useful to correlate the seismic profiles with bathymetric data of the San Juan arm of Lake Powell to give context to sediment behavior and anomalous data. Recent bathymetric data could be layered on top of pre-dam topography to develop a 3D model of sediment build-up in the reservoir. This model would be useful in explaining or confirming strange behavior within the profile such as locations where there is a sudden jump from thin to thick sediment packages. The more ways in which the 2D seismic profiles can be put into context of the 3-dimensional system, the easier it will be to interpret the sediment behavior. The bathymetric data would also be a useful tool for quantifying the volume of sediment impounded in the reservoir.

Another application of the seismic data is the possible correlation between seismic amplitude and grain size (Twitchell, 2005). Once the sediment cores are split, sampled, and catalogued, it is possible that lithologic and grain size changes in the cores
could be correlated to reflection amplitudes. If this correlation exists, seismic amplitudes can be used as a proxy for mapping grain size distribution along the seismic transects (Twitchell, 2005). Another parallel that could be drawn using the seismic reflection amplitudes is contamination with grain size. Often contaminants are found in fine grained, clay rich deposits. Therefore, if amplitude can be a proxy for grain size, it could also be a proxy for mapping contaminant distribution throughout the deltas.

CONCLUSION

As the climate of the Southwest changes and demands for water increase, it is necessary for water management in the region to adjust to lower water volumes, especially in large reservoirs such as Lake Powell. With that, it is essential to study and understand sediment sources, sediment transport, and sediment accumulation within Lake Powell as it affects management decisions and the lifetime of the reservoir. This project provides an initial analysis of the shape and structure of the San Juan sediment delta in order to inform core retrieval locations. These findings can be incorporated with further analysis of the sediment cores to understand the volume, distribution, and extent of potential metal loads in the delta.

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Figure 1: Map showing location of study area and CHIRP seismic transects, San Juan River, Lake Powell, Utah.
Figure 2: Screen capture of IHS Kingdom Suite Software. Seismic transect 11f3, shotpoints 1110.0 - 2200.0, is shown with interpreted horizons. The blue line is the water bottom/sediment top surface. The orange line is the sediment bottom/bedrock top horizon. These horizons are exported as .csv files with three columns; line number, shot location, TWT value.
Anomalous increase in parallel, flat lying reflectors. The transition from bedrock to sediment is sharp and vertical.

<table>
<thead>
<tr>
<th>CHIRP example</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td><img src="image" alt="Strong upper reflector" /></td>
<td>Strong upper reflector that is clouded on slopes. Defines steep, irregular topography.</td>
<td>Rock outcrops or highly sloping bedrock.</td>
</tr>
<tr>
<td><img src="image" alt="In the white box" /></td>
<td>In the white box: strong upper reflector with parallel sub-bottom reflectors. Area is acoustically homogenous.</td>
<td>Homogenous sediment that was deposited post-im-poundment.</td>
</tr>
<tr>
<td><img src="image" alt="Strong, thick bottom reflector" /></td>
<td>Strong, thick bottom reflector with clouded black dots that fade down profile.</td>
<td>Bedrock material.</td>
</tr>
<tr>
<td><img src="image" alt="Anomalous increase" /></td>
<td>Anomalous increase in parallel, flat lying reflectors. The transition from bedrock to sediment is sharp and vertical.</td>
<td>Pre-dam alluvial deposits in a former channel.</td>
</tr>
</tbody>
</table>

Figure 3: Four different lake floor types derived from the seismic reflection data.
Figure 4: Profile along the San Juan delta from the northeastern most point of the seismic CHIRP profiles to the confluence of the San Juan arm with the Colorado. The profile shows the elevation (above sea level) of the pre-impoundment surface and the elevation of the lake floor at the time of the CHIRP survey in 2017. The dashed black line is the lake level, 1105 meters above sea level, at the time of data collection. The lake floor profile and pre-impoundment profile are derived from interpretation of the seismic profiles. The delta is divided into 6 distinct sections, A through F, that vary in lake-floor gradient(slope) and sediment thickness.
Figure 5: Average and maximum thickness of sediment in each section (A-F) of the San Juan delta. The x-axis is the different sections and the y-axis is sediment thickness in meters. The values are extrapolated from interpreted lake-floor surface and pre-impoundment surface.
Figure 6: (a) Seismic transect showing the transition from section A to section B of the delta. There is a jump from thicker sediment in A to thinner sediment in B. (b) Interpreted seismic line showing seismic sequences; acoustic basement (white), sediment (orange), and strong acoustic reflectors (black lines). The abrupt change in sediment thickness is characteristic of other transitions throughout the delta. (c) Seismic transect showing the transition from section B to C of the delta. Basement elevation below the delta sediments decreases downstream from C to B (d) Interpreted seismic line showing seismic sequences; acoustic basement (white), highly sloping bedrock, and sediment (orange). The transition from section B to C is a jump in elevation of about 30 meters.
<table>
<thead>
<tr>
<th>Delta Section</th>
<th>CHIRP Representative Example</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>![Image A]</td>
<td>Average thickness of the lowest portion of the delta is 7 meters. This section is defined by a uniform thickness and gentle slope of the delta profile.</td>
</tr>
<tr>
<td>B</td>
<td>![Image B]</td>
<td>Average thickness of this portion is 7.3 meters. There is increased variation and the thickness undulates which makes it distinct from A.</td>
</tr>
<tr>
<td>C</td>
<td>![Image C]</td>
<td>Average thickness of portion C is 13.5 meters. This portion of the delta is highly variable and therefore it is difficult to find a location that is representative of the average. The dotted box depicts the average thickness.</td>
</tr>
<tr>
<td>D</td>
<td>![Image D]</td>
<td>Average thickness of portion D is 2.39 meters. This section is similar to section A with a uniform thickness and gentle lake-floor gradient.</td>
</tr>
<tr>
<td>E</td>
<td>![Image E]</td>
<td>Average thickness of portion E is 1.85 meters. The delta has little to no visible sediment for much of the section and has a steep lake-floor gradient.</td>
</tr>
<tr>
<td>F</td>
<td>![Image F]</td>
<td>Average thickness of portion F is 3.92 meters. The thickness of this section is highly variable and the lake-floor gradient is moderate.</td>
</tr>
</tbody>
</table>

Figure 7: Areas of representative average post-impoundment thickness identified from the CHIRP profiles. 100 shotpoints is approximately 67 meters in distance. The average vertical exaggeration (VE)≈5. Flow direction is right to left.
<table>
<thead>
<tr>
<th>Delta Section</th>
<th>CHIRP Example</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Maximum thickness = 11.16 meters. The bottom of the thickest portion looks like a trough that is filled with sediment.</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Maximum thickness = 17.50 meters. There are strong top and bottom reflectors with an area of acoustically transparent sediments at the thickest location.</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Maximum thickness = 40.11 meters. Similar to section A, the thickest portion of sediment looks like a trough that is filled with sediment. This is the thickest portion of the entire delta imaged by the CHIRP data.</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Maximum thickness = 12.15 meters. The thickest location abruptly terminates with sharp, straight cut-offs on both sides.</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Maximum thickness = 3.84 meters. This section of the delta has acoustically homogenous sediment that is hardly visible. The top reflector is strong.</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Maximum thickness = 16.53 meters. Similar to section D, the thickest location abruptly appears and is defined by vertical sides. The lower reflectors are relatively weak.</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Areas of thickest sediment from each division of the delta in the CHIRP transects. 100 shotpoints is approximately 67 meters in distance. The average vertical exaggeration (VE)~5. Flow direction is from right to left.
Figure 9: (a) Seismic transect showing onlapping sediment onto an acoustic basement (AB) spire. (b) Interpreted seismic line showing seismic sequences; acoustic basement (white), sediment (orange), and strong acoustic reflectors (black lines). The reflectors onlap onto the spire because the sediment thins upslope. (c) Seismic transect showing draping sediment. (d) Interpreted seismic line showing seismic sequences; acoustic basement (white), highly sloping bedrock, and sediment (orange). The strong reflectors mantle basement topography. The dark arrow is water flow direction.
Figure 10: Seismic profile showing a sharp jump in sediment thickness. (a) conceptual map view of seismic line. The dark blue is the submerged river channel of the San Juan river, pre-dam. The light blue is the current extent of the San Juan arm. X - X’ is the path of the seismic transect. (b) CHIRP line with abrupt jump in sediment thickness. There are strong parallel reflectors throughout the profile. (c) Interpreted line showing strong seismic reflectors and acoustic basement (AB). The jump in sediment thickness represents the pre-dam channel of the San Juan.
REFERENCES CITED


Lucchitta, I., 1979, Late cenozoic uplift of the southwestern Colorado Plateau and adjacent Lower Colorado River region: Tectonophysics, v. 61, no. 1, p. 63-95.


