

# GPR on a High Mountain Lake, Colorado, USA

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## Abstract

Many GPR reflection profiles were collected using a canoe on a freshwater lake in the Rocky Mountains. Excellent radar wave penetration was measured, using both 270 and 400 MHz antennas. Reflection traces were placed into space using GPS and individual profiles were interpreted, with the lake bottom and other reflections digitized for three-dimensional mapping. It was found that the lake was composed of more than six sub-basins, which were bounded by glacial moraines and large bedrock slump blocks. Each basin contained a different sediment package with a unique depositional history. One small basin was chosen for coring, and a buried soil unit was encountered, corresponding to a distinct reflection in GPR profiles. This soil horizon was created during a drying episode about 8,000 years ago when this part of the lake was drained of water.

## Introduction

A high altitude lake in the Colorado mountains was explored with GPR in order to determine the thickness of the sediment packages and the extent of the lake-fill. This was done to target areas for coring, from which pollen was extracted to study changes in the flora over millinea, and from those data determine climate changes. It was known that South Mesa Lake was formed at the end of the last Ice Age, about 12, 000 years ago. The basin that presently contains a lake that filled a depression produced by a small mountain glacier, with the dam for the present lake created by a moraine that was formed as the glacier receded. This area today is called the Grand Mesa area of the Rocky Mountains (Figure 1).



**Figure 1:** Location of S. Mesa Lake, Colorado

The lake today is bounded on the south by large angular boulders, which were deposited on that margin of the lake by mass wasting events such as slumps and landslides, likely beginning as the glacier melted. On the north the lake is also bounded by rubble, but in this case mostly glacial till. A moraine of very large boulders and cobbles dams the basin on the west.

Nothing was known about the lake sediment prior to the GPR survey. As the water is very clear, cursory analysis of the lake bottom showed some higher areas in the middle of the lake, whose origin was somewhat of a mystery. It was hypothesized that the lake today may actually be a few smaller basins, bounded by these mid-lake high areas. The shallow areas were thought to be large slump units of boulders and other angular rocks that came from the steep side of the valley on the south (Figure 2).

### **Data collection**

Ropes that are typically used for waterskiing as they float on the water surface, were stretched across the lake to provide linear transects for a canoe, which contained the GPR system (Figure 2). The beginning and end of each transect was located using GPS. People on each end of the rope moved it about every 10 meters, attempting to keep the lines parallel.

Every 10 meters along the transect ropes red plastic flags were woven into the rope as distance markers. These were used to place fiducial marks as data were collected (Conyers 2023), so that reflection traces could be normalized for distance variations between these marks.



**Figure 2:** Collecting GPR in a canoe, following a water-ski rope, which floats on the surface.

Both 270 and 400 MHz GSSI antennas were used for collection, with a SIR-3000 control unit. A manual mark “clicker” was connected to the antenna to place the fiducial marks within the recorded data stream. Data were collected in time, with 3 traces recorded per second. The canoe was paddled at a constant rate from the beginning to end of each transect with the first fiducial mark placed at location 0



that was about 5-10 meters from the shore. In this way the canoe could be given a “running start” to provide a consistent speed along each transect.

With both antennas the trace collection time-window was 410 nanoseconds, which is approximately 7 meters of distance using an RDP of 80 for fresh water. The RDP for the saturated lake sediments was lower, averaging about 50-60. All traces were defined by 512 digital samples. Each profile contained between 600 and 1100 traces, depending on the transect length and the rate that the canoe was paddled during collection.



**Figure 3:** The 270 MHz antenna on the canoe bottom, with the control system resting on it.

Three people were required in the canoe during collection. One to paddle at a constant rate, one to watch the data as it was being recorded, and to hold the manual marker button and place fiducial marks in the data, and one person to watch when the antenna crossed over one of the red flags at each 10-meter distance (Figure 4).



**Figure 4:** Placing manual marks in the data string every 10 meters along the rope.

The GPS locations for the beginning and end of each profile were then placed into GIS, and straight lines were drawn between them (Figure 5). A program was written in DOS to find the manual fiducial marks in each profile (recorded at trace #2), and to then “rubber sheet” the traces equally between these marks to more accurately located the reflections in space. Using UTM’s the GIS software was used to create UTM locations for each of the 10-meter spaced fiducial marks, and from that give each trace (after rubber sheeting normalization) a location in space (Figure 5). In this way all traces had a unique location, from which computer mapping of the thickness of the sediments and the bottom of the lake could be obtained.

These GPR data were collected and processed in 2007, before the industry had good “real time” integration methods for GPS points to be assigned to the recorded the radar wave traces. Today there are software programs and collection methods that can do this without necessitating following ropes, making marks and adjusting all in a GIS platform for spatial corrections (Conyers 2023: 42). One could potentially just paddle around the lake in a random way and collect reflection traces in a continuous but curving pattern, and then place all into space very quickly. Amplitude maps could be made of that type of dataset but creating linear 2-D reflection profiles would be much more difficult.



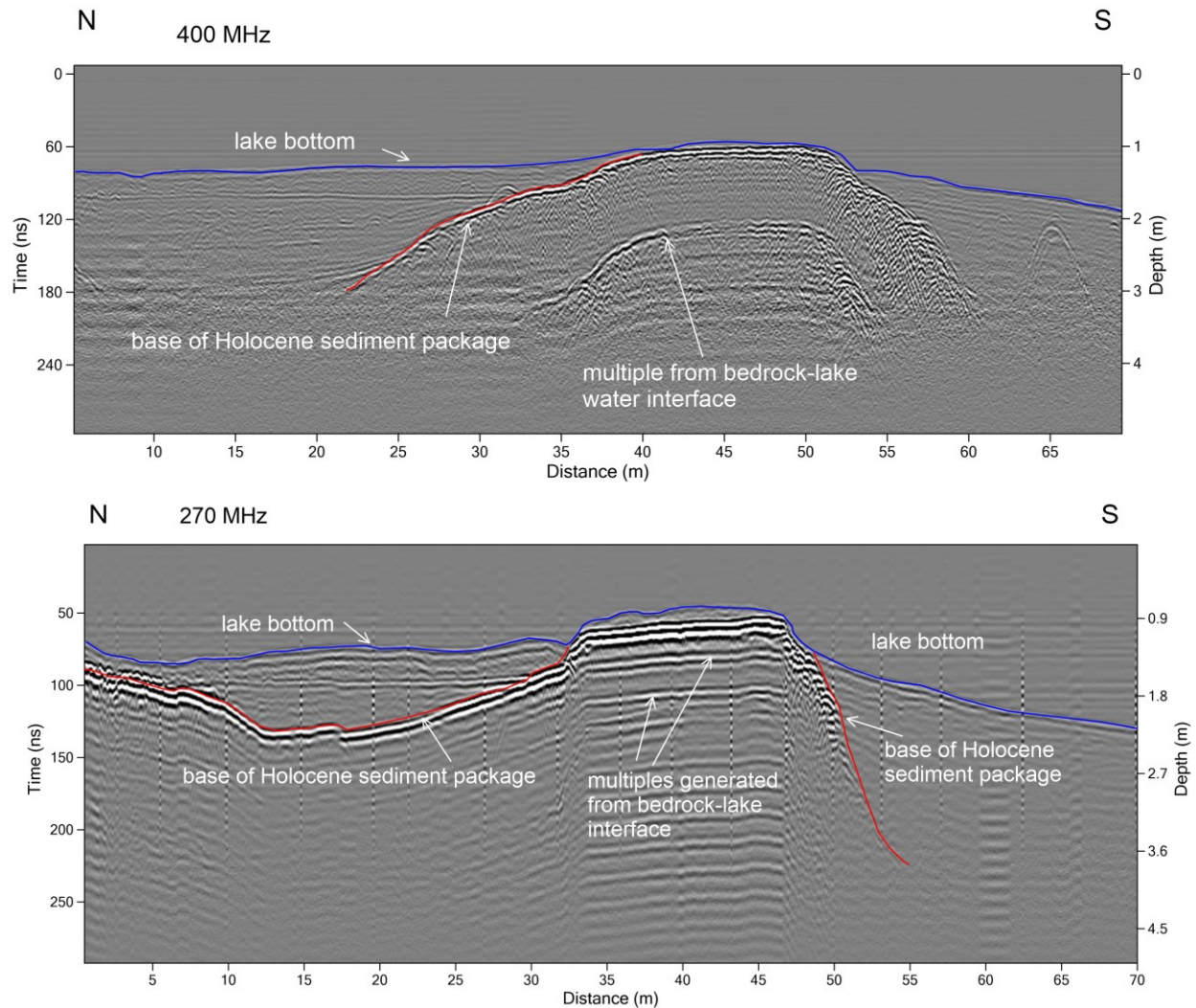


**Figure 5:** Placement of the GPR transects after correction for locations, where GPS points were located at the beginning and end of each transect.

### Data analysis

Once all the transects had been put into space, each profile, which had location information attached to it, could be viewed in two-dimensions (Figure 6). A variety of very interesting features were immediately visible in the lake, the most notable being large pieces of bedrock many tens of meters across that separated basins of sediment. The lake bottom produced a distinct reflection, and many other reflections were visible from stratigraphic interfaces within the lake sediment.

These bedrock features are very highly reflective, often producing multiple reflections as radar energy reflects first from the bedrock surface. The first arrival, measured in time and converted to depth, is the actual depth of the top of the stone feature (Figure 6). Some of the radar energy that travels that path is reflected again from the bottom of the canoe, travels back into the lake to be reflected again from the bedrock, producing a second reflection. Sometimes this happens numerous times (Figure 6) depending on the shape of the rock feature. Two examples from 400 and 270 MHz waves demonstrate the way multiple reflections are recorded. When the bedrock surface has a flat top, but its sides are very steep, only the horizontal surface produces the multiples (270 MHz reflections in Figure 6). If the bedrock surface is curved and its sides slope gently with depth, the whole of the upper bedrock produces a multiple reflection (400 MHz reflections in Figure 6).



**Figure 6:** Comparison of 400 MHz and 270 MHz profiles collected over the same bedrock feature in the lake, but about 10 meters apart. The 400 MHz energy penetrated to about 2 meters in the lake-bottom sediment, with very good resolution. The 270 MHz energy was capable of about 4-5 meters of depth penetration, but with much less resolution of the stratigraphy. Both center-frequencies generated multiple reflections (in very different ways) from the bedrock-lake bottom interface.

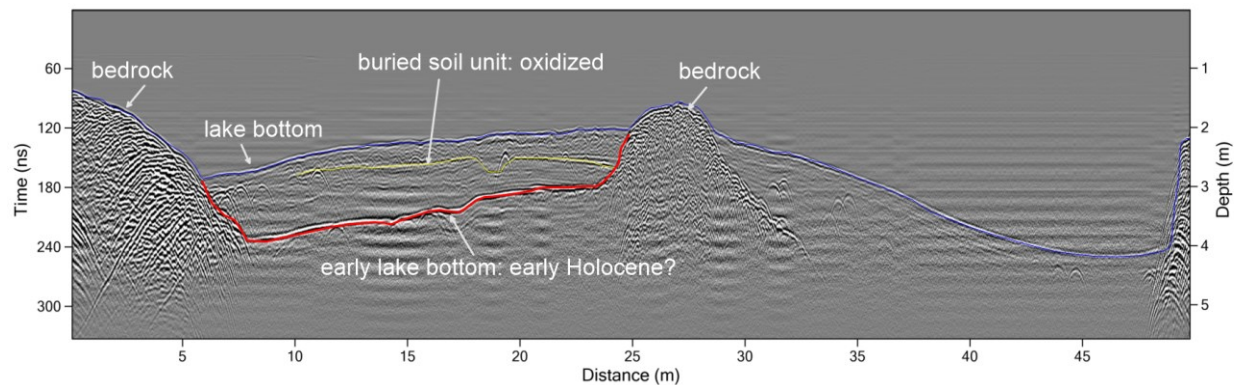
The 400 MHz waves produced reflection profiles with much greater resolution than the 270 MHz but were only capable of transmitting energy about 2-3 meters into the lake sediment (Figure 6). This frequency was suitable for defining shallow stratigraphic layers, but not the base of what is thought to be the complete sediment package (covering most of the Holocene period of deposition).

The 270 MHz data when processed into profiles showed the complete sediment thickness (Figure 6) of what is the post-glacial deposition (covering most of the Holocene or about 12,000 years). These frequency profiles were most useful in producing maps of the total sediment thickness in the lake. The 400 MHz profiles were very useful in defining the total sediment thickness in smaller sub-basins of the lake where the total sediment thickness is only about 1-1.5 meters (Figure 7).

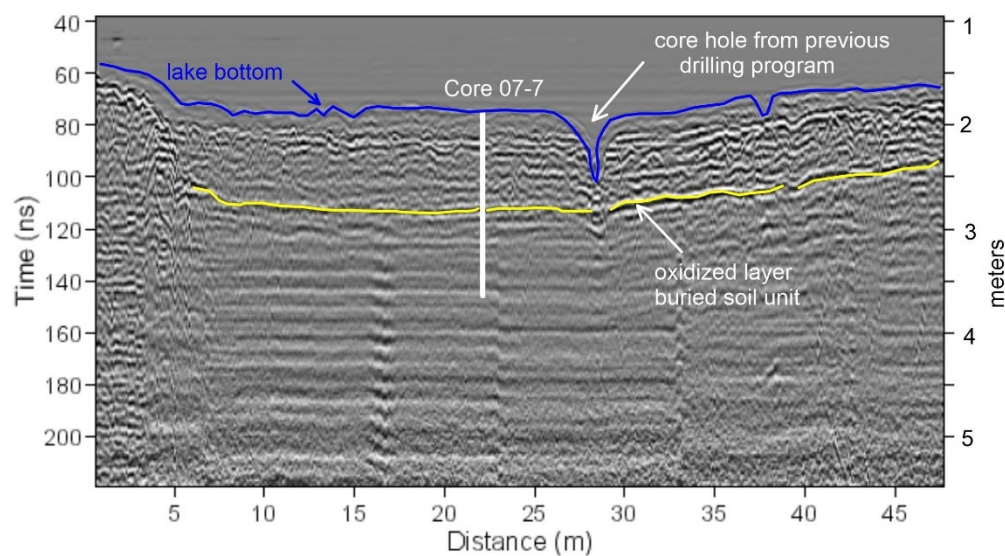
One small sub-basin of the lake was of particular interest as it was hypothesized to contain a fairly thin sediment package, which it was hoped would contain a record of pollen that spans the whole of the

Holocene (Figure 7). A core was recovered from sediment in this small basin and it was discovered that a reddish oxidized layer, which corresponds to a high amplitude reflection visible with GPR (Figure 8). This layer corresponds in age to the early part of the Holocene when the climate was hotter and drier than today (about 8-6k years ago). This small basin in the lake must have dried up during this time and terrestrial soils were formed on the exposed lake sediment, which produced this reddish soil unit. The climate then became wetter, and the small basin re-filled, burying this soil unit with more lake deposits.

This climate variation is very interesting for western Colorado as it appears to document that this Altithermal Period affected high-altitude lakes in the same way that it did along the Rocky Mountain Front Range and the Great Plains (Davis, 1988).



**Figure 7:** A bedrock feature, which is likely a very large slump block deposited in the basin at the end of the last Ice Age, creates a dam for sediment. The lake is divided into separate basins from these slump blocks. One layer within the Holocene sediment is of interest (in yellow) as it is a buried soil unit during a period when this area of the lake dried out and soil formed.

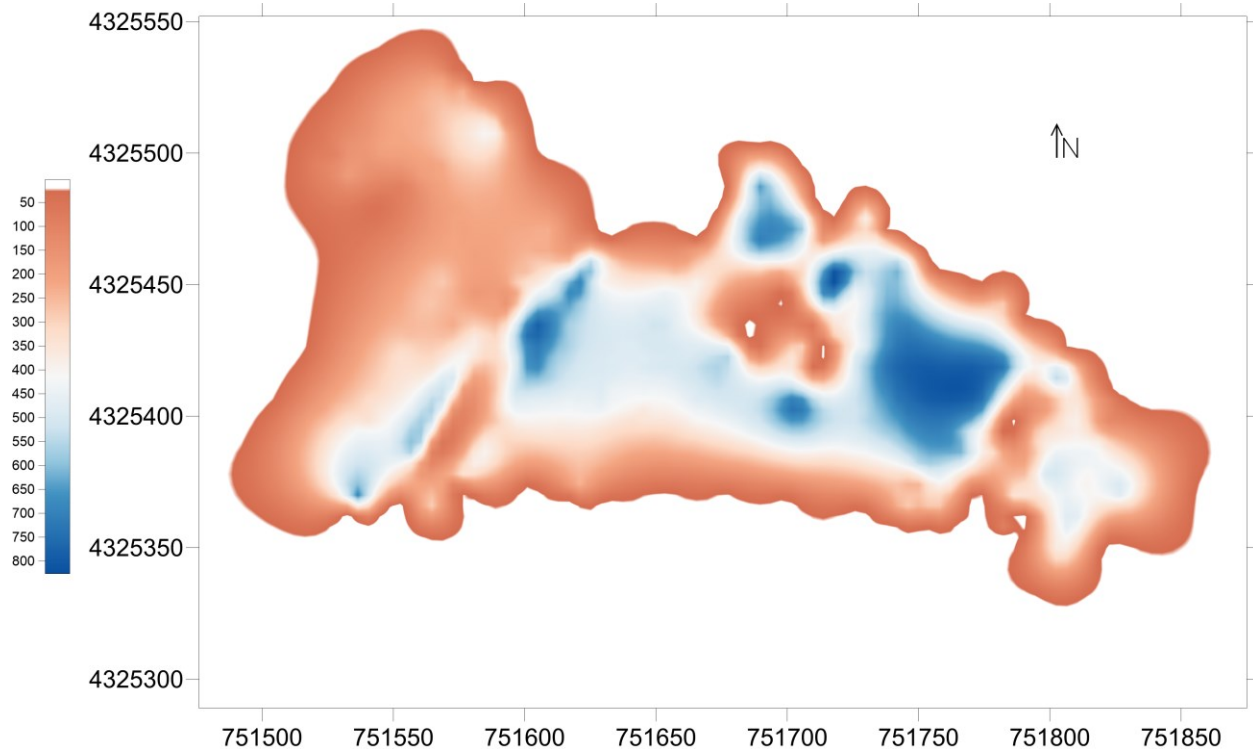


**Figure 8:** A core was placed in a location to intercept the yellow GPR reflection, which was determined to be an oxidized (reddish colored) buried soil from the Early to Mid-Holocene Altithermal, which was a time of relative warming and drying in the Rocky Mountains.



## Overall lake analysis

The 400 MHz reflection profiles were excellent at producing very high-resolution reflections from the lake bottom sediments. Each profile was interpreted, and the depth of the lake was digitized. Those depth values, whose x and y values were plotted as UTM values from the GIS analysis were imported into one spreadsheet and mapped (Figure 9). In this depth map there can be seen 5 major sub-basins where the water is the deepest. Some are deeper areas are bounded by large bedrock masses, as can be seen in the reflection profiles (Figures 6 and 7). Others are bounded by linear shallow areas (on the east and west), which may be glacial recessional moraines.



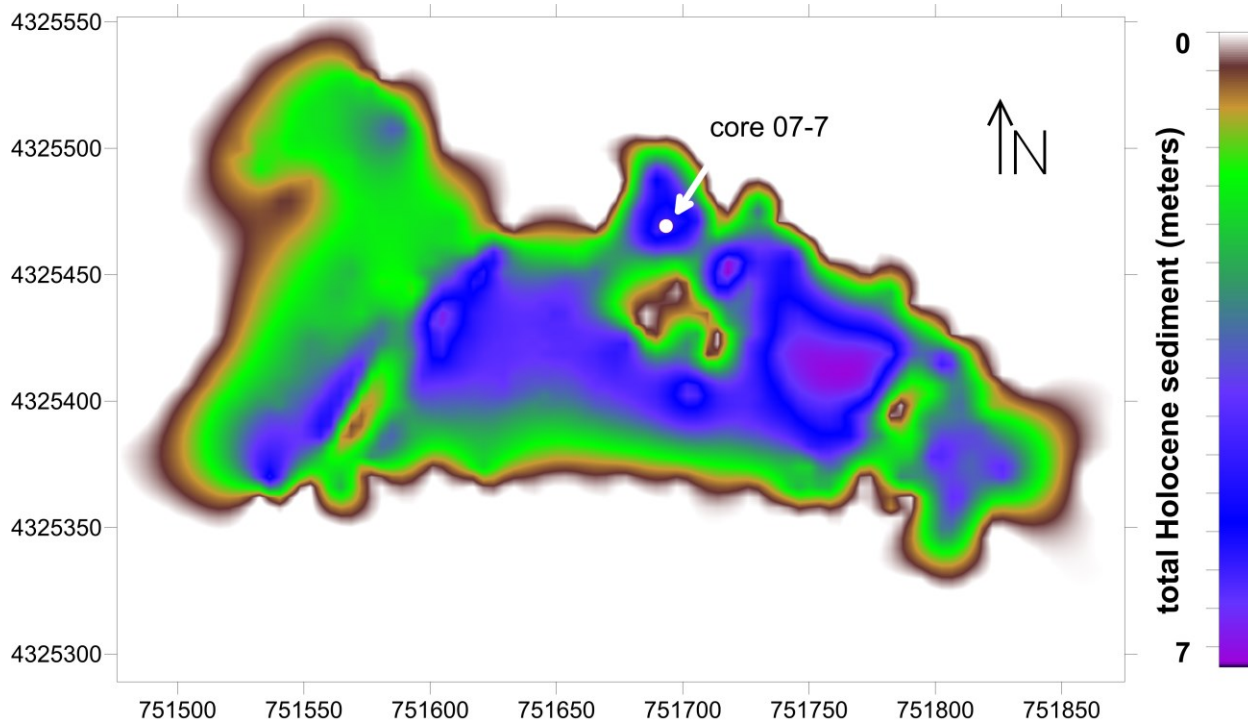
**Figure 9:** Depth of the water in South Mesa Lake.

The 270 MHz profiles, which display reflections as deep as 6-7 meters in the lake sediment, were used to produce a map of the overall thickness of the sediment. That sediment is likely Holocene in age, deposited after ice in the valley had completely melted (Figure 10). This thickness map (termed an isopach map by geologists) mostly mimics the lake bottom depth map.

This is not surprising, as the lake basin was available for water filling soon after the glaciers melted. One moraine to the west was the dam for the lake, but the GPR mapping shows that there were possibly two other moraine barriers within the lake proper. It is not known when the large bedrock blocks were deposited, but they were likely brought into the basin in landslide events. If those landslides or slumps occurred soon after the glacial ice melted, then the South Mesa lake when it was initially filled with water (and slowly with sediment) was originally segregated into many smaller basins. Over time with rising water levels and sediment influx, the lake became one large basin that we see today. Each of the smaller basins within this lake, however, retained their shape as originally created soon after the glacial ice melted. Each has its own unique depositional history, as demonstrated by the core in the northernmost small basin (Figure 10) where the buried soil horizon was cored. That small basin may



have been one of the sub-basins that dried out, as it had restricted water flow from the rest of the lake, as can be seen in the sediment thickness map.



**Figure 10:** Sediment thickness map at South Mesa Lake.

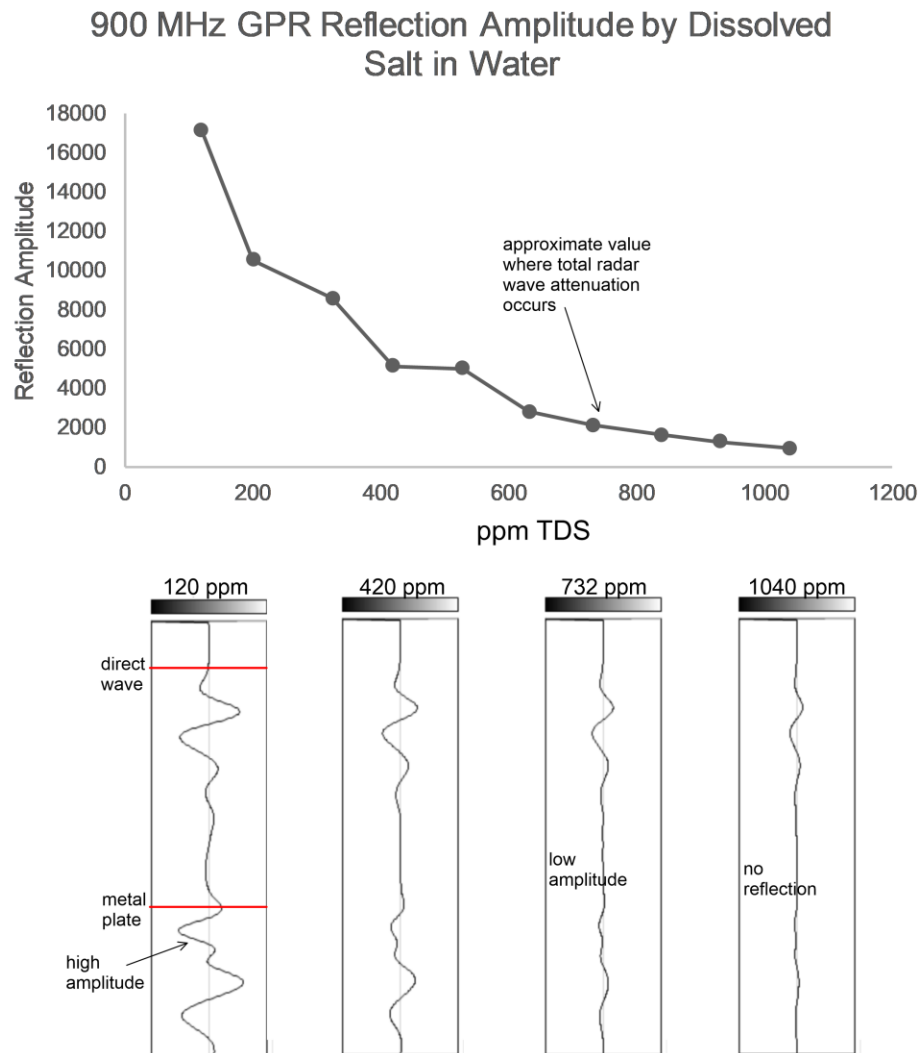
## Conclusions

The GPR mapping of this high-altitude lake in western Colorado demonstrated how this method can be used for geological and environmental studies. It was very useful in understanding the history of this lake after the end of the last Ice Age. It was found that the lake morphology was much more complicated than anticipated, with many sub-basins and varying thickness of sediment. These sub-basins were originally formed by glacial moraine deposits and modified by large slump or landslide blocks brought into the lake soon after the ice melted.

It is important to take into consideration how important water chemistry is for GPR. Here at S. Mesa Lake the water was extremely fresh, with very low total-dissolved solids (lower than 100 mg/L-or parts per million-ppm). Andrew Bair and I did a study of GPR variability with salinity in 2018. We placed a metal pie pan in a large plastic barrel of water in our lab and filled it with water directly from the tap using Denver City water. The city of Denver water supply has dissolved solids that usually fluctuate between 50 and 150 ppm. We measured the dissolved solids in the water at 120 ppm. A 900 MHz antenna was then floated in a plastic wash basin on the top of the water in the barrel and single traces were collected (Figure 11). Table salt was added to the water, mixed, and the test was performed at increasing salinities. The amplitude of the reflected wave from the pie pan at the bottom of the barrel was measured at each test (with gains held steady throughout).

Just a small increase in the salinity (measured in total dissolved solids) affects the amplitude of the reflected wave in a dramatic way. By the time the water salinity increased to 200 ppm the reflected wave amplitude had decreased by half. By 400 ppm it had decreased by about 68%. The amplitude of the reflected wave was still visible in the reflection traces at 700-800 ppm but had totally disappeared by 900 ppm. Freshwater is generally defined as water with less than 1,000 ppm total dissolved solids and drinking water for human consumption is generally acceptable at less than about 500 ppm. A general

rule-of-thumb for GPR utility in lakes, therefore, is that if you can drink the water, you can probably get good GPR results!



**Figure 11:** An analysis of GPR utility in water as a function of total dissolved solids, as a measure of salinity.

The use of GPR on lakes has been limited, perhaps because of a misplaced idea that water is bad for GPR in general. It is not as long as the water is fresh. But care must be taken when collecting and interpreting data from lakes, as radar waves will travel very slowly in fresh water. Water has an RDP of 80, which translates to a very slow radar wave velocity (the slowest of any medium). In air a radar wave will travel about 1.2 meters in 10 nanoseconds (two-way travel time, as we usually measure with GPR). That same wave in fresh water will only travel about 18 cm in the same time (an 85% decrease in velocity). This needs to be considered when calibrating radar control systems, and the time-window needs to be opened for elapsed time that is much higher than we usually encounter in most ground. At S. Mesa Lake we experimented with many different time-windows and decided on 410 nanoseconds to record all the reflected waves necessary and still define those waves with the programmed samples per trace.

It is a puzzle why GPR has not been used more to explore for shipwrecks or other cultural features in lakes. Perhaps people are not used to using this technology? Harry Jol, (at Univ. Wisconsin, Eau Claire) used GPR on lakes there to map logs that were harvested for timber more than 100 years ago and were



lost during transport from one side of the lake to the other in rafts (Jol and Albrecht, 2004). This shows that wood will reflect very well when buried by lake sediment. Why shouldn't timber boats?

### **Acknowledgments**

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