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1970 Flathead Lake Seismic Survey Geosciences

4-1-2017

A. Overview of the Flathead Lake Seismic Survey

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Digital Archive of the 1970 Flathead Lake Reflection Seismic Survey

By
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4-1-2017

Introduction

In this article, I attempt to give an overview of the contents of the 1970 Flathead Lake seismic survey digital collection. The collection is divided into two main groups of "books". The first group of books includes the sets of images scanned from paper documents relating to the 1970 survey. The scanning was done in 2006. The second group of books includes articles and data that relate to using digital seismic traces that I have derived from the original documents and from an orphan magnetic tape that was serendipitously found in 2006 at the United States Geological Survey (USGS) library at Woods Hole, MA. The content in this second group of books has been developed since 2006.

Each book in this archive has a narrative written by me. The narratives describe the contents of the respective books and, generally, expand on what is in this article. The narratives in the respective books are all labeled "Narrative by Robert W. Lankston". Authorship of the main content of a book, however, is attributed to whoever generated the content initially. For example, the actual field seismic sections in Book C are attributed to the co-principal investigators, Gary W. Crosby and Richard J. Wold. Authorship of Book H is attributed to Richard L Hess who digitized the archive magnetic tape. The dates for the respective books are when the content was originally generated. The pick list for the main content of a book always follows my narrative for that book.

This article and some of the narratives include hyperlinks to other parts of the collection. One map file, the scans of the seismic and bathymetric sections, and the digitized data in .wav format can be very large and take some time to download. Each computer installation will handle downloading and opening files from the links differently as a function of applications that are used and settings for those applications. In some cases, a requested file may be sent automatically to a download location on your computer. In other cases, you may have to specify the destination or specify an application that will open the file. Some files might be opened automatically with some predefined application without explicit user input.

References that are available online have their respective URL's listed with the attribution in the References Cited sections of the respective narratives. If you find a dead hyperlink in a narrative or article, please contact me at the email address on the website. If you have saved links from previous visits to this site, you may find that they are dead. Try going to the 1970 Flathead Lake seismic survey site and selecting the desired item from there.

Figure 1. Field party at Yellow Bay boat dock. Standing at left is Professor Crosby. Seated on the bow (holding line) is Ronald Friedel. The boat that the field crew is posed on was the survey boat. Richard Wold is the photographer and is not pictured. *(Image scanned from a slide provided by Richard Wold.)*

The 1970 Flathead Lake Seismic Survey

A reflection seismic survey was conducted on Flathead Lake during one week in August of 1970. The principal investigators were Gary W. Crosby of the University of Montana (UM) and Richard J. Wold of the University of Wisconsin-Milwaukee (UW-M). The field party (Figure 1) operated from The University of Montana research station at Yellow Bay.

In the mid-1960's, Wold and his technician, Ronald Friedel, assembled a system for recording seismic data in lakes. According to Friedel (2011), the system was utilized in surveying many of the large lakes in the western US during the late 1960's and early 1970's. Much of Wold's research and development was funded by the Office of Naval Research (ONR) (e.g., Wold, 1976). The 1976 Wold report to the ONR shows data from part of Line E of the 1970 Flathead Lake survey. In general, Wold was interested in the hardware aspects of the surveying (Wold, 2006), and his hardware evolved from the mid 1960's to the mid 1970's. For each lake survey, Wold would partner with a "local" geophysicist who was more interested in the geologic results than in the survey hardware, in this case Professor Crosby from UM.

Relatively little is now known about the recording system and field procedures for the 1970 survey. No field notes were included with the set of 1970 paper documents that were stored at

Figure 2. Performing maintenance on the air gun. The air gun is the metal device on the deck in the lower, center of the image. *(Image scanned from a slide provided by Richard Wold.)*

the University of Montana, Department of Geosciences, and memories have faded with the passage of time. Wold (1982) gave a few cursory comments on field equipment and operations in the only publication that gives any information on the equipment and field procedures of the 1970 survey. At the outset of this archiving process, Wold (2006) provided a few photographs of the components of the field system. In addition to information provided by Friedel (2011), Peter Simpkin (IKB Technologies Limited, Dartmouth, Nova Scotia) (2007), commented on the Gifft wet-paper chart recorder used during field operations.

Otis et al. (1977) used the same basic Wold-Friedel hardware, i.e., single channel analog recording on magnetic tape, in surveying Yellowstone Lake in 1973 and 1974. Otis et al. (1977) explicitly mention the survey boat speed of 9 km/hr with a shot interval of 4 s, which leads to a shotpoint interval of 10 m. The 4 s shot interval is obvious from the data digitized from the tape recovered from the USGS library. Combining the trace count in the field recorded seismic section for a given survey line, the line length measured on the track line map, and the time interval between the digitized traces indicates that the 9 km/hr speed was used in the Flathead Lake survey also.

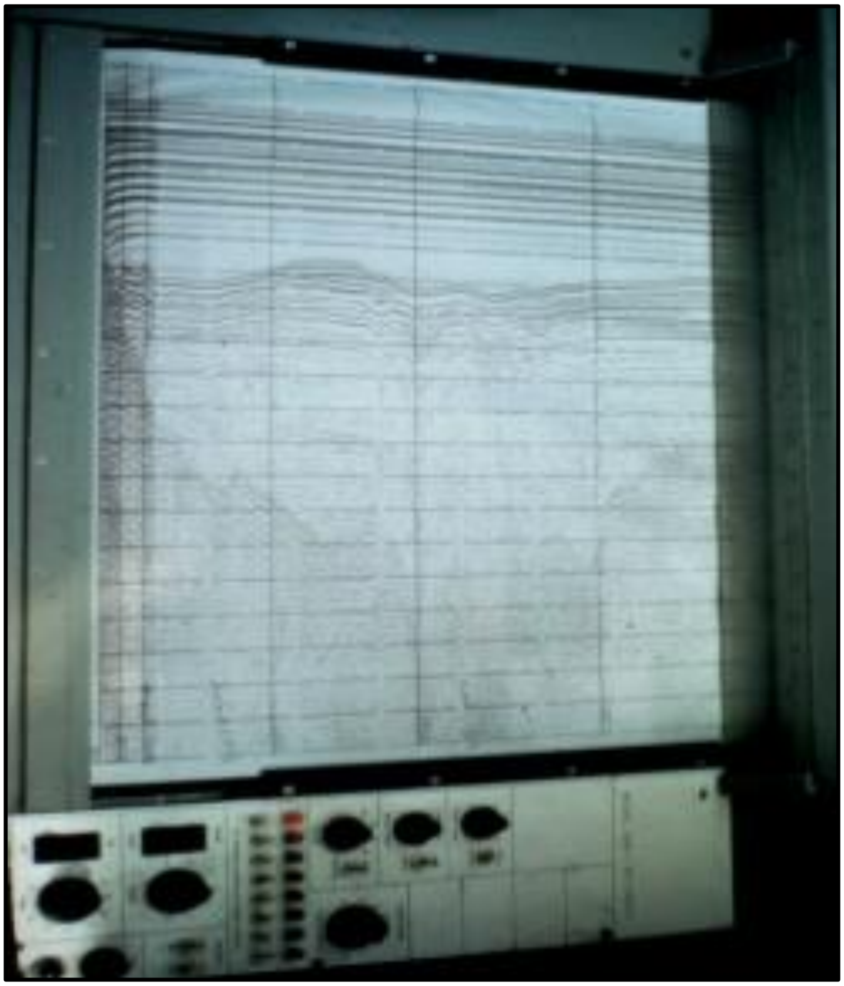

Figure 3. Gifft wet-paper recorder used for real time recording during seismic traverses. Wold's original photograph has been rotated and stretched slightly so that the view of the chart recording is as one would normally view the seismic section. In this view, the chart would be moving from the right of the image toward the left of the image as the traverse progressed. The display on the chart at the left of the image shows the recording at the start (north end) of Line R. The chart in this image can be compared to the surviving section for Line R in order to see the discoloration of the paper and dots with age. The vertical lines on the chart were triggered by the user. Each vertical line has an annotation written at the bottom of the chart. Most of these annotations indicate the time of sextant readings. This image shows approximately half of the Line R section. The "wet-paper" was coated with a conductive solution to provide the electrical ground for the current that burned the dots into the paper. The bathymetric recorder for this survey, by contrast, used a paper with a metallic coating. *(Image scanned from a slide provided by Richard Wold.)*

The Wold-Friedel seismic system employed for the Flathead Lake survey apparently included:

- a single channel hydrophone streamer with one or more hydrophone elements
- a 1 in^3 Bolt air gun (Figure 2) pressured to 2000 psi (14 MPa)

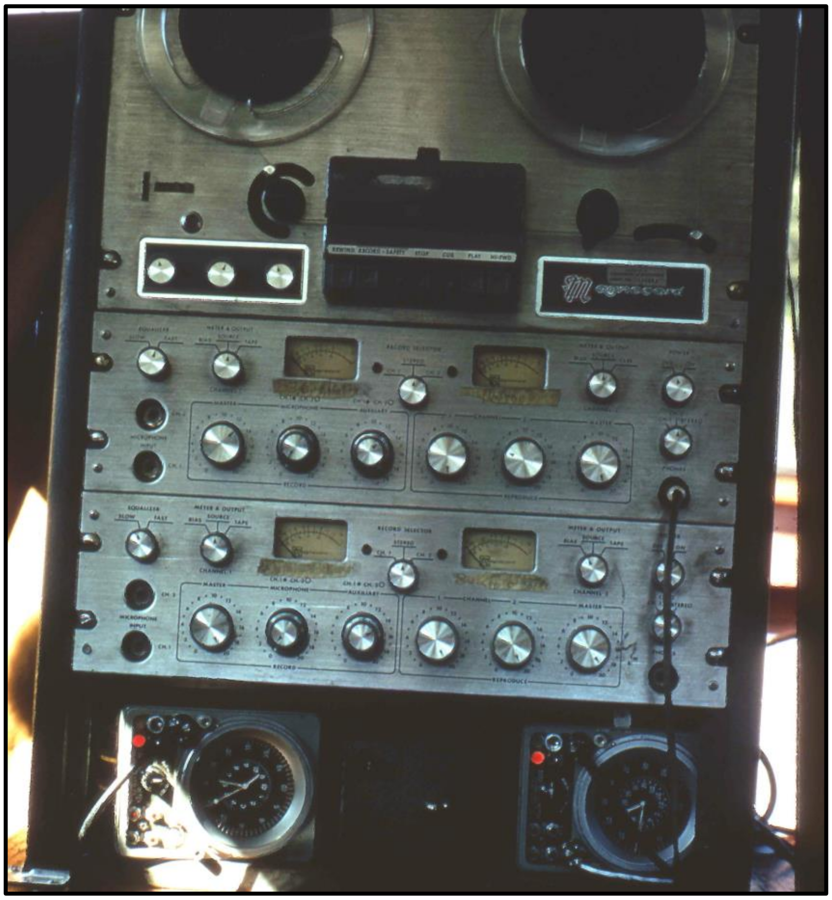

Figure 4. Magnecord 1024 stereo analog tape recorder. ***(****Image scanned from a slide provided by Richard Wold.)*

- a Gifft wet-paper chart recorder (Figure 3)
- a Magnecord 1024 studio-grade (according to Hess, 2006) stereo analog tape recorder (Figure 4)
- Swiss-made clocks for shot timing (Friedel, 2011) (Figure 4).

The stereo tape recorder (Figure 4) was not a common component of bathymetry and sub-bottom profiling systems of the late 1960's and early 1970's. This component allowed for the post-acquisition analog processing of the data that is mentioned by Wold (1982).

Typically, a tape record/playback deck would have been accompanied by one record/playback amplifier component. In this case (Figure 4), the rack was fitted with two record/playback amplifiers. If both of these units served to amplify the input from the hydrophone streamer, perhaps one routed the signal to the tape recorder, and the other routed the hydrophone signal to the Gifft chart recorder (Figure 3). Perhaps one amplifier was dedicated to field recording, and the other was dedicated to signal playback for the post-acquisition processing. Perhaps one amplifier unit was simply a spare.

The two Swiss-made clocks mentioned by Friedel (2011) are visible at the bottom of the image in Figure 4.

Figure 5. Shore-based theodolite station mentioned by Wold (1982). A notebook can be seen in the surveyor's left hand. The notes from any theodolite readings from shore or sextant readings from the survey boat are lost. *(Image scanned from a slide provided by Richard Wold.)*

The survey apparently recorded bathymetric data along with the seismic data, but a photograph of the bathymetric equipment was not in the set of pictures provided by Wold in 2006. Whether or not the bathymetric equipment was that used by Silverman during the 1960's is not known.

Wold (1982) states that determining the position of the survey boat while it was making a seismic traverse was based on sightings from pairs of shore-based theodolite stations. Figure 5 shows such a shore-based station, but no other information about this process is known. Use of a sextant for positioning is not explicitly stated by Wold (1982), and a sextant is not pictured in his set of photographs.

However, the actual field recordings from the lines in the southern part of the lake have hand written annotations (Figure 3) of when sextant readings were made from the boat, e.g., Line R. Lines A through G, in the northern part of the lake, do not have sextant annotations on the field recordings. Perhaps the theodolite positioning was used for these lines. Alternatively, perhaps the starting and ending points of the lines across open water were noted on a map, and the survey line was assumed to be straight between the two endpoints, i.e., neither sextant nor theodolite readings were made. No field notebook of sighting data has survived with the other documents. Otis et al. (1977) indicate that they made sextant readings from their survey boat on Yellowstone Lake when the boat was out of range of their microwave positioning system

On board the survey boat were a gasoline-powered air compressor for the air gun, two gasoline-powered electrical generators, and a voltage regulator to power the electronics. Figure 6 shows

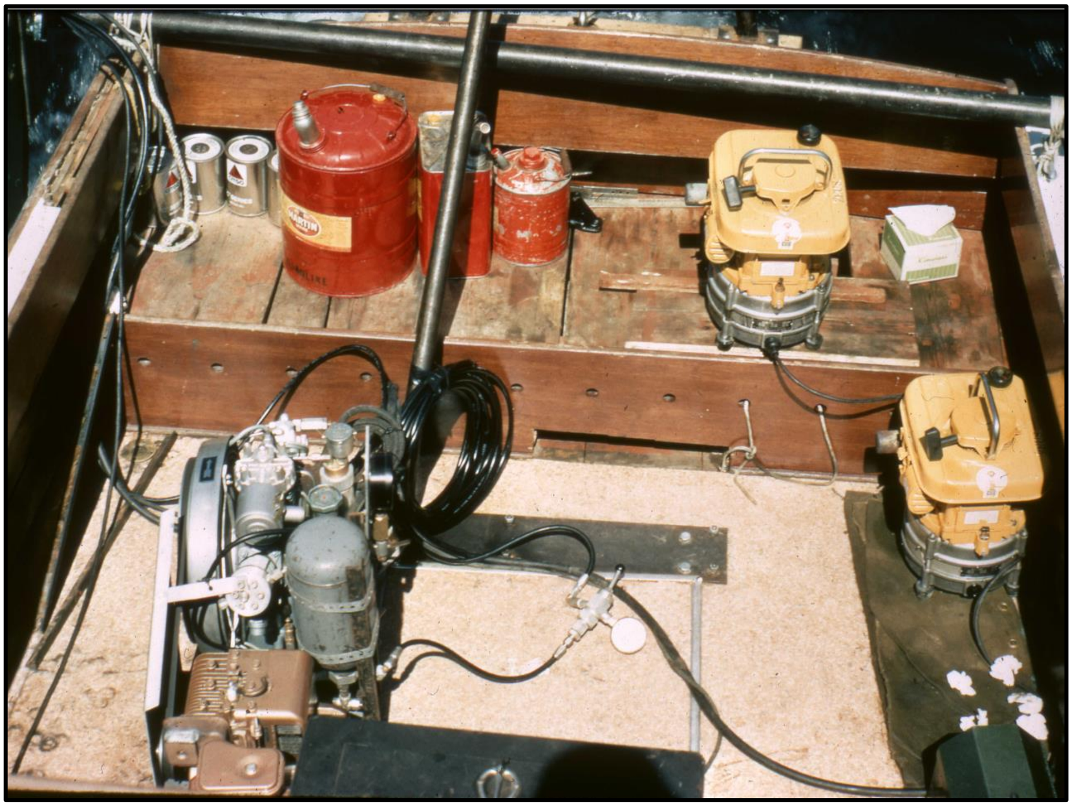

Figure 6. View of the stern of the survey boat. The gasoline powered air compressor is on the left in the foreground. The two yellow-topped devices on the right are the electrical generators. The survey boat must have been noisy during recording. At the bottom center of the image is the top of the automatic voltage regulator. Based on other Wold photographs, the pipe that is lashed to the gunwales (top of image) provided the towing points for the air gun (left side in the image) and the hydrophone streamer (right side in the image). The chart recorder and the tape recorder were probably inside the cabin of the boat (Figure 1). *(Image scanned from a slide provided by Richard Wold.)*

the stern of the survey boat with the air compressor, the two electrical generators, and the top of the voltage regulator.

With no field notes, we do not have much information on the source to hydrophone shooting geometry. The hand written annotation on the field recording at the start of Line A ("Hydro 50 ft") suggests that the hydrophone was deployed 50 ft (15.25 m) from the source. Of course, the distance could have been referenced to the towing point (Figure 6) at the stern of the survey boat and not to the air gun position. An annotation on Line J indicates that the source to receiver distance was increased to 100 ft (30.5 m). Later along Line J, an annotation indicates that the offset distance was reduced back to 50 ft (15.25 m). The increase in offset and the decrease in offset did not happen instantaneously, and the increase (and decrease) in offset with time is obvious in the field recording for Line J.

The field seismic system was evidently complemented by equipment for redisplaying the data from the field analog tapes and possibly applying some basic analog processing such as band pass filtering and automatic gain control (agc). The only explicit reference by Wold (1982) to post-acquisition processing of the Flathead Lake data is an acknowledgement to Sidney Prahl, a member of the 1970 field crew and a University of Montana graduate student at that time.

One can deduce that Wold played back the data from the field tapes and redisplayed them over a period of time after the 1970 acquisition because his report to the ONR (Wold, 1976) shows segments of Line E in several figures that were the results of experiments with chart recorders as late as 1973. Wold (1976) makes a passing reference to the use of agc and band pass filtering. Otis et al. (1977) mention only band pass filtering as a post-acquisition process for "field analysis" of seismic sections in their work three years after the Flathead Lake survey, which may suggest that the Flathead Lake post-acquisition processing did not include agc. The Otis et al. (1977) "field analysis" was apparently separate from their main analysis, which was based on traces digitized from their field tapes.

The redisplay system for the Flathead Lake data clearly used a chart recorder other than the Gifft wet-paper unit that was used in the field, possibly an EPC 4600 dry process recorder based on a reference in Wold (1976). Book C shows the field recordings. They have aged from the nominal black on white renderings seen in Figure 3 to the brown on orange displays in Book C. The redisplayed sections in Book E, however, are still nominally black dots on white paper. Other differences between the two sets of seismic sections, e.g., timing line intervals, can be seen. In both sets of seismic sections, time zero is not clear.

Use of the Data, 1970 to 2005

The original paper sections from the Gifft wet-paper seismic recorder and the bathymetry recorder and a set of seismic sections that resulted from redisplaying the data recorded on magnetic tape were stored in the University of Montana, Department of Geosciences for over 35 years after the survey was completed. The 1970 data in paper form appear to have been used as a guide for the 1980 seismic survey conducted by Jerry Kogan based on handwritten notes that were stored with the 1970 seismic sections. Scans of all of these documents are available in the various books of this archive.

Also stored with the data from the 1970 survey was a copy of a map that showed the bathymetry of the lake and the locations of the Wold-Crosby survey lines (Silverman et al, 1971). The surviving map is a blue line copy of what was a formally-drafted original, probably prepared on drafting film. The original is presumed to be lost, and the blue line copy that was stored with the seismic data is the only known large copy of the map. Arnold Silverman was a faculty member in the Department of Geosciences in the 1960's and 1970's. The second author of the map was David Pevear, a graduate student who worked occasionally with Silverman in the late 1960's to make bathymetry traverses across the lake. Sidney Prahl, the data processor mentioned by Wold (1982), was the third co-author of the map and, presumably, the actual map compiler and artist. The Silverman-Pevear bathymetry is augmented by depths provided by Prahl from the Wold-Crosby seismic or bathymetric data. The bathymetry in the Wold (1982) paper and in the Kogan (1980) thesis is that on the Silverman et al. (1971) map.

Kogan's (1980) survey focused on the sediments near the lake bottom while the 1970 survey focused more on the structure both in the lake sediments and at the surface of the Precambrian bedrock under the lake sediments (Wold, 1982). Aside from Wold's (1982) paper and the Kogan thesis, the only other significant use of the Wold-Crosby data appears to have been made by Michael Hofmann during his PhD research at UM (Hofmann, 2005). Some of the Hofmann research is available in professional journals, e.g., Hofmann et al. (2006).

While the Wold(1982) and Hofmann (2005) appear to be the only formal publications that relate to the 1970 survey, the 1980 notes document one other significant use of the paper documents. Other researchers probably perused the documents during this time period. One case is mentioned in the narrative for Book G, and Karl Mueller (2017) of the University of Colorado indicated that he reviewed the paper documents during his one year appointment to the UM Department of Geosciences faculty in the early 1990's.

Use of the Data, 2005 to 2017

I was a geology/geophysics graduate student at UM in the early 1970's, and I shared office space with Sidney Prahl. While I was aware of the Flathead Lake survey, I was not involved with the project. In 2005, I heard a lecture given by Michael Hofmann, who is mentioned above. I asked Hofmann whether or not the field tapes of the data still existed. I suggested that if the data did exist on tape, the data could be digitized and processed with modern software to make significant improvements over the paper images he had used during his dissertation research, i.e., Books C and E. The conventional wisdom in 2005 was that the paper sections were all that existed.

Wold's (1982) paper mentioned post-acquisition data processing, and that was the trigger in 2005 that started my quest to find the survey data on an electronic or a magnetic medium. The search for data in electronic or magnetic form was followed in 2006 by my initial efforts to preserve the1970 documents through the development of this archive.

I contacted Wold in early 2006 in an attempt to find the data on tape. Wold (2006) indicated that the field tapes had become lost over the years. Serendipitously, a tape, about which no one had any information other than it contained seismic data from Flathead Lake, was discovered in 2006 at the USGS library in Woods Hole, MA (Lankston, 2007). The USGS archive tape is obviously a derivative of the field tapes because of its width and reel size. Wold had worked for the USGS for a number of years after leaving the University of Wisconsin-Milwaukee and had, evidently, carried the Flathead Lake data with him to Woods Hole.

The USGS archivist checked the tape out to me in the spring of 2006, and thinking that the tape was digital, I tried to find a seismic contractor who could convert the data on the tape to a common seismic data exchange format such as SEG-Y and place the data on a DVD or a flash memory drive. Unfortunately, the tape was not in a standard seismic industry format.

Later, in the summer of 2006, I found an audio laboratory in suburban Toronto, ON, that is operated by Richard L Hess and that specializes in digitizing data from old analog tapes. With no information available about the tape, e.g., how many tracks it had, did the tape need to be rewound, was it an AM or FM recording, and so forth, Hess had to do some experimentation before being able to digitize the analog traces. To determine the number of tracks on the tape and to determine which tracks contained information, he used a process called "developing" (Figure 7). The Hess lab was able to digitize the analog tape, and Hess delivered .wav files of the various tape tracks. .wav files with 1 ms and 0.125 ms sampling are in Book H. .wav files with 48,000 Hz sampling, i.e., images of the tape tracks, are in the University of Montana, Maureen and Mike Mansfield Library, K. Ross Toole archive.

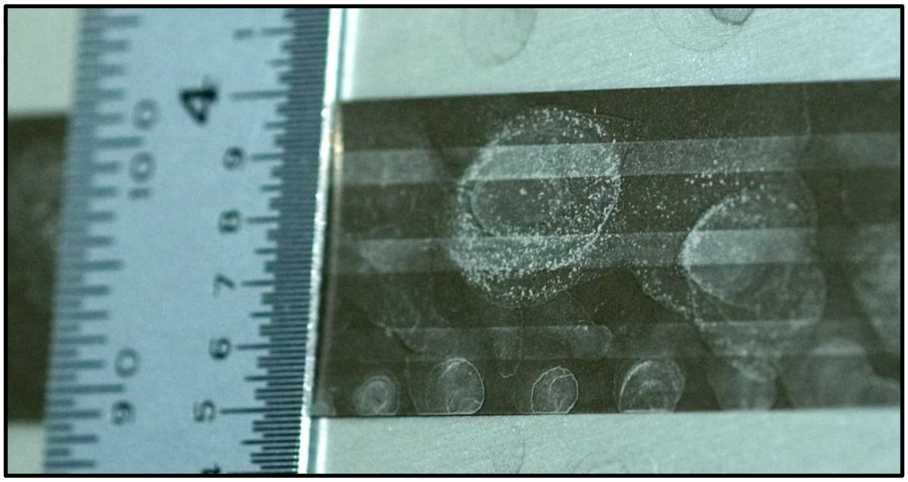

Figure 7. Tape "developing" to determine the number of tracks. An iron-rich solution was applied to a small segment of the tape. The tape recovered from the USGS has seven tracks, four dark bands and thee light bands. The three light bands have information recorded on them. In this case, this was beneficial because the playback machine had intercalated heads, i.e., tracks 1, 3, 5, and 7 were read from one head assembly while the data-bearing tracks (2, 4, and 6, the light tracks in the image) were read from the other head assembly (Hess, 2006). The 4 on the scale is inches. The tape is one half inch wide. *(Image provided by Richard L Hess)*

Unfortunately, of the 200 km of data recorded (Wold, 1982), the analog tape contains less than 60 km of data, i.e., the data from six nominally parallel traverses across the northern half of the lake (Lines A, B, C, D, E, and F). Nevertheless, this tape was a significant find.

The discovery and digitization of the USGS tape opened the door for initial redisplay of the data, e.g., in variable area or color-coded amplitude styles, and processing, e.g., filtering, agc, and deconvolution. Books H through L describe the processes of preparing and using the traces digitized from the USGS tape and the traces manufactured from the 1970-era redisplayed sections for use with modern seismic software. Book K gives an example of color-coded seismic section display and describes application of homomorphic deconvolution, a technique applied by Otis and Smith (1977) to the data that they collected in Yellowstone Lake (Otis et al., 1977).

During this time period (2005-2017), several UM Department of Geosciences undergraduates experimented with the digital traces. The first was Jenica Andersen, who made some initial displays of the digitized data for her 2007 UM Conference on Undergraduate Research (UMCUR) poster. In the spring semester of 2008, Daniel Aspden experimented with generating diffraction curves and comparing them to event patterns in real traces. In the fall semester of 2008, Benjamin Van den Bos experimented with removing multiples in the Line C data using gap deconvolution. In the fall of 2012, Evan Hanson worked with the embryonic, manual workflow for the image-to-data process. His work is noted on the 2013 UMCUR website, but no abstract, poster, or paper is posted. In the fall semester of 2014, Jensen White attempted to apply gap deconvolution to the traces resulting from the automated image-to-data process. During the spring semester of 2015, Christopher Casas used the traces from the image-to-data process and overlays of diffraction curves to demonstrate that events on Line R are primary reflections possibly indicating the collapse of lake sediments into voids left by the melting of stranded glacial ice blocks. The Casas poster was displayed at the 2015 UMCUR.

Evolution of the Digital Archive

About the time that the USGS tape was being digitized, summer 2006, I became interested in building physical and digital archives for the 1970 Flathead Lake seismic project. In the 2006-07 academic year, Jenica Andersen, then an undergraduate in the UM Department of Geosciences working under the direction of Marc Hendrix, Department of Geosciences faculty member, scanned all of the field sections, the redisplayed sections, the bathymetry recordings, the cross section sketches from the 1970-71 era, and the handwritten notes from the Kogan era. The documents were scanned at 600 dots per inch (dpi). For some reason, the Silverman et al. (1971) map did not get scanned during this episode.

In January of 2008, Andersen and I delivered the paper documents themselves, a DVD of the scans of the documents, and Hess' DVD's of the .wav files to the UM library to become the heart of the digital and physical archives of the 1970 Flathead Lake reflection seismic survey, i.e., this digital collection and the corresponding collection in the University of Montana, Maureen and Mike Mansfield Library, K. Ross Toole archive. In May 2008, the USGS library at Woods Hole transferred custody of the analog tape to the Toole archive. After the buildout of this digital collection, the Hess DVD's were placed in the Toole archive.

Neither a scan of the Silverman et al. (1971) map nor the map itself was in the package delivered to the library in 2008. The Silverman et al. (1971) map resurfaced in early 2011, and Hendrix and I delivered it to the Toole archive at the UM library. The map was scanned by the library for inclusion in the digital archive. This map is significant for defining the locations of Lines A and B in the Wold-Crosby survey. Wold (1982) does not show the locations of these two lines. Lines A and B were among those that Wold chose not to interpret because of poor data quality, and the line locations do not appear on his version (Wold, 1982) of the bathymetry and seismic line track map. However, these two lines are in the set of six for which data were preserved on the USGS archive tape. With modern data processing (Book J), some improvement in the 1970 redisplayed images of the subsurface (Book E) can be realized for those two lines.

I georeferenced the 2011 scan of the Silverman et al. (1971) map to a modern base in a geographical information system (GIS) and recovered the x-y coordinates of the end points and turning points of the lines and the locations of line intersections. I scaled the x-y coordinates for each trace from the end and turning points, and the UTM coordinates are now stored in the trace headers in the files in Books I and K.

For some time after the digital products were delivered to the library in 2008, the library was evaluating its options for a platform for an institutional repository. In the summer of 2011, a first pass at setting up the digital archive of the Flathead Lake seismic project was made on an experimental repository platform. The first pass was basically a bulk copy by the library staff of all of the digital files from those 2006 and 2008 DVD's to the repository server. The site was effectively unworkable because of the cryptic filenames assigned at the time of the document scanning in 2006. I rebuilt the archive in February of 2012 grouping like files into subdirectories and giving the files names that were less cryptic. I wrote narratives to explain the contents of each group of files.

With the introduction of ScholarWorks at the Mansfield Library in the fall of 2013, I migrated the 2012 site to the new platform. The "groups of files" mentioned above became stand alone "books", to use the ScholarWorks vocabulary, and my narratives introduced each book. The ScholarWorks platform provided much more metadata for the user to see.

In the migration to the ScholarWorks platform, my narratives, which had attempted to describe the various sets of images and data, had to be updated. I made edits to make clearer the authorship of the contents of the various books in the archive. In some cases, the authorship is speculative, and that is indicated where necessary. I down-sampled the scans of the various paper documents from 600 dpi to 300 dpi to reduce their size and to decrease their download time.

Since 2013, the various narratives have been updated as needed. I made significant changes to this document in early 2017 in order to include some of the photographs that Wold gave me in 2006 and to add hyperlinks to content in this collection and to significant resources outside of this archive, e.g., the Wold (1982) paper on the USGS publications website. I also reviewed the narratives for the various books in this collection in early 2017 and made updates and edits as necessary. The narrative texts are headed with the date that the editing was started. At the end of the narrative, however, is a time/date stamp that shows the actual latest update.

I have tried to keep the books in this archive in a somewhat temporal sequence. Books A through G include:

A. This document
B. Two versions of the Silverman et al. (1971) bathymetry and survey line map
C. The actual field recordings of the seismic data attributed to Richard Wold and Gary Crosby
D. The bathymetric recordings
E. The redisplayed seismic sections attributed to Sidney Prahl
F. The interpretation cross section sketches presumably generated by Prahl in the early 1970's
G. The handwritten notes from the Kogan era attributed to Anthony Qamar.

These books contain the scans of the surviving paper documents and represent the 1970 to 1980 era.

Following the surviving documents comes a set of books, i.e., H, I, and so forth, that attempt to present proof of concept techniques for using the data. The contents of these books have been developed since 2006.

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