Efforts to Recover and Digitize Analog Seismograms from Harvard-Adam Dziewoński Observatory

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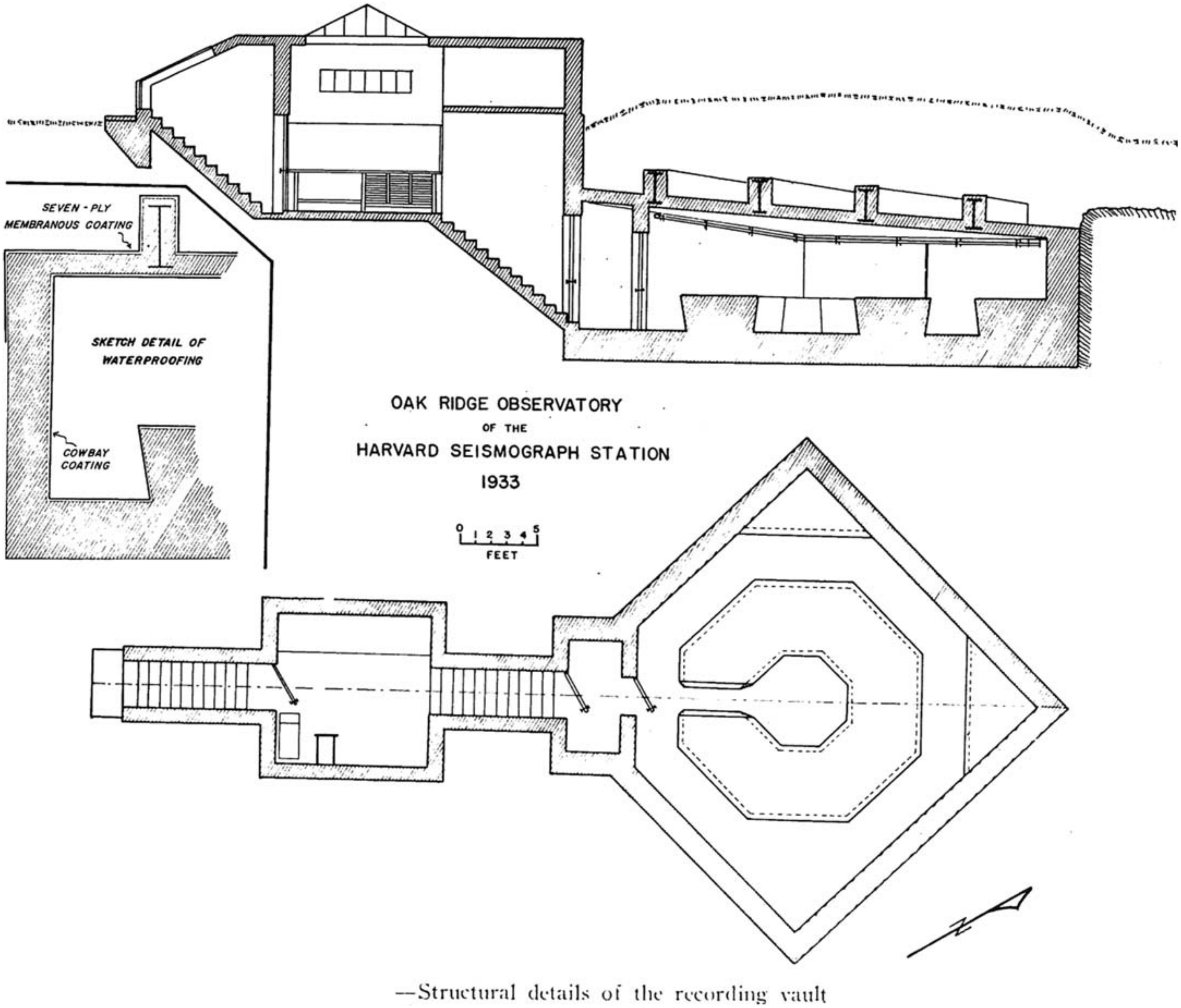
INTRODUCTION

The Harvard-Adam Dziewoński observatory is one of the oldest seismic stations academically established in the United States, and it is owned and maintained by Harvard University (Leet, 1934). It is currently one of the Global Seismic Network stations operated by the U.S. Geological Survey (USGS)'s Albuquerque Seismological Laboratory (network code IU) and is also used as a testing facility for new instruments by Quanterra, Inc. The digital data from the Harvard seismic station since 1988 are readily available to the scientific community through the Incorporated Research Institutions for Seismology Data Management Center and are widely used for various research purposes. The data from this station are known to be of high quality, partly because the instruments are housed in a vault that is about 4.5 m below ground, ensuring reduced surface noise and a stable environment (e.g., nearly constant temperature and humidity). In this manuscript, we focus on the analog data that have been collected at this station prior to 1988.

The vision of operating a high-quality seismic station is attributed to a Harvard professor, J. B. Woodworth, who began seismic instrumentation in 1908 (Leet, 1934). Initially, two Bosch–Omori 100 kg horizontal pendulum seismographs were installed in the basement of the Harvard Museum of Natural History building in Cambridge, Massachusetts, and the two instruments operated until 1928. Ground-motion monitoring continued at this location with two Milne–Shaw horizontal pendulum seismographs until April 1933. Only a handful of seismograms appears to have survived from this time period. In 1933, under the direction of L. Don Leet, a new seismic observatory (Fig. 1), one that is used today, was constructed at the Oak Ridge Observatory, also known as Harvard Astronomical Observatory, at Harvard, Massachusetts (note that this is about 40 km northwest of Cambridge, Massachusetts, where Harvard University is located). Instruments began recording ground motion at the new seismic station on 30 March 1933 (Leet, 1934). Continuous monitoring of ground motion was carried out for the next 20 years, until the end of July 1953. After this time, there are intermittent records from the 1960s and between 1989 and 1997. With limited maintenance and more than 60 years of operation, the station was in poor condition by 1996 (USGS trip reports, 1996, 2006). In 2007, the Department of Earth and Planetary Sciences, with generous contributions from USGS Albuquerque Seismological Laboratory and Quanterra, Inc., performed major renovation throughout the facility to bring the station up to modern standards. In 2009, to commemorate Adam M. Dziewoński's retirement and to acknowledge his great contributions to the scientific and Harvard communities, the station was renamed as Harvard-Adam Dziewoński Observatory.

SEISMOGRAMS

The seismometers at the Harvard station recorded many subtle signals of earthquakes and other ground motion, and they were used in contemporary research. For example, during 1934 and 1935, about 150 local disturbances were recorded on short-period components (Collins, 1937a). Many of these are thought to be from artificial blasts, but a considerable subset of these events appears to be from natural earthquakes. The locations of some of these earthquakes were determined, but about half are registered as being from unknown locations (Collins, 1937a). Another example of the quality and importance of the Harvard recordings is the signals associated with a sequence of events in New Hampshire. On 9 November 1936, there was a relatively large earthquake that was felt over a large area in northern New Hampshire and adjacent parts of Vermont (Collins, 1937b). This event was preceded by at least six events in 1935 and four in 1936 that are possibly foreshocks of the earthquake on 9 November 1936. None of these earthquakes is cataloged in the Earthquake Catalogue for New England and adjacent regions (1638–2014) provided by Weston Observatory (2014). Later in 1940, there were twin events near Ossipee that were the largest earthquakes in New Hampshire in the last century (Devlin *et al.*, 1942). These events and their aftershocks were clearly recorded at the Harvard station (Linehan and Leet, 1942), and various seismic phases from the mainshocks are easily discernible, allowing good estimates of the epicentral locations (Leet and Linehan, 1942). In addition to local earthquakes, signals from large teleseismic and regional earthquakes were observed. For example, there are 393 magnitude 7 or greater earthquakes between 30 March 1933 and 31 July 1953, including a magnitude 9 event in Kamchatka Peninsula on 4 November 1952 (Allen *et al.*, 2009; Fig. 2). With about 20 years of operation, the collection of analog data

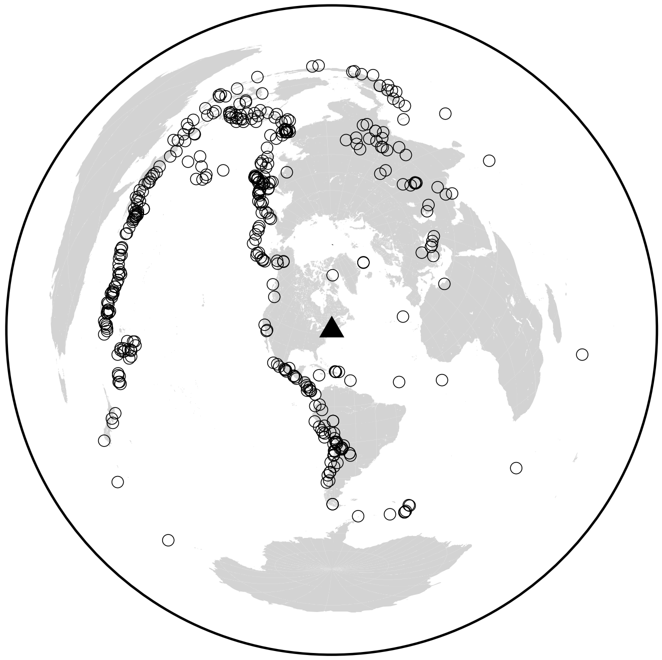


▲ **Figure 1.** Original plan of the HRV seismograph station from 1933 found in the archives at the Albuquerque Seismological Laboratory, U.S. Geological Survey (USGS) by C. R. Hutt. This plan has also been published in Leet (1934) as volume 24, plate 5. The above-ground brick building that exists today was added later to provide work space at the station.

produced at this station represents a wealth of data for seismological studies.

The ground motion was observed by different types of instruments at the station throughout its history. However, no record of station operation from the 1933–1953 period, such as a log book that may provide detailed record of instrument quality and operation, has been found. There are two primary publications that give information about instruments used at the station. The first, and the most important, is a *Bulletin of the Seismological Society of America* report by Leet on the "New recording vault of the Harvard seismograph station" (accepted in August 1933 for publication) that describes the station and instruments that were or were being planned to be deployed (Leet, 1934). The second source is a pamphlet, *Geophysics at Harvard*, which contains photographs and a brief description of the facility. The year of publication of this pamphlet is unknown, but based upon the dates of references cited, it appears to have been published in the early 1940s. A scanned copy of this pamphlet is available from the Harvard Seismology web page (http://www.seismology.harvard.edu/downloads/Geophysics_at_Harvard.pdf, last accessed November 2014).

Detailed day-to-day information, such as types of instruments and dates of operation associated with each seismogram, is inferred from stamped and hand-written data found on the back of each individual seismogram. These data are invaluable in identifying appropriate instrument, alignment, times of operation, and potential problems. Almost all seismograms have hand-written date, start/end times, instrument type,



▲ **Figure 2.** World map using the equidistant azimuthal projection showing the location of the Harvard-Adam M. Dziewoński observatory (black triangle) and epicenters of 393 earthquakes (open circles) with magnitude greater than or equal to 7 that occurred between 30 March 1933 and 31 July 1953 as given by the USGS PAGER-CAT (Allen *et al.*, 2009).

and alignment information that are typically located at the top right corner (Fig. 3a). On the top left corner, sheet number and start/end dates are stamped on almost all seismograms until mid 1948 (Fig. 3b). The sheet numbers are consecutive integers assigned to each day (with some exceptions). Some seismograms, especially during early years, contain data associated with instrument response (Fig. 3c) and time correction (Fig. 3d). According to Leet (1934), a standard E. Howard pendulum clock was used for timing, and its accuracy was "checked with NAA time-signals by means of a radio receiver mounted in the workshop." In addition, station location information is stamped on many records (Fig. 3e). Finally, additional information, both stamped (Fig. 3f) and hand-written (Fig. 3g), is found on a subset of seismograms.

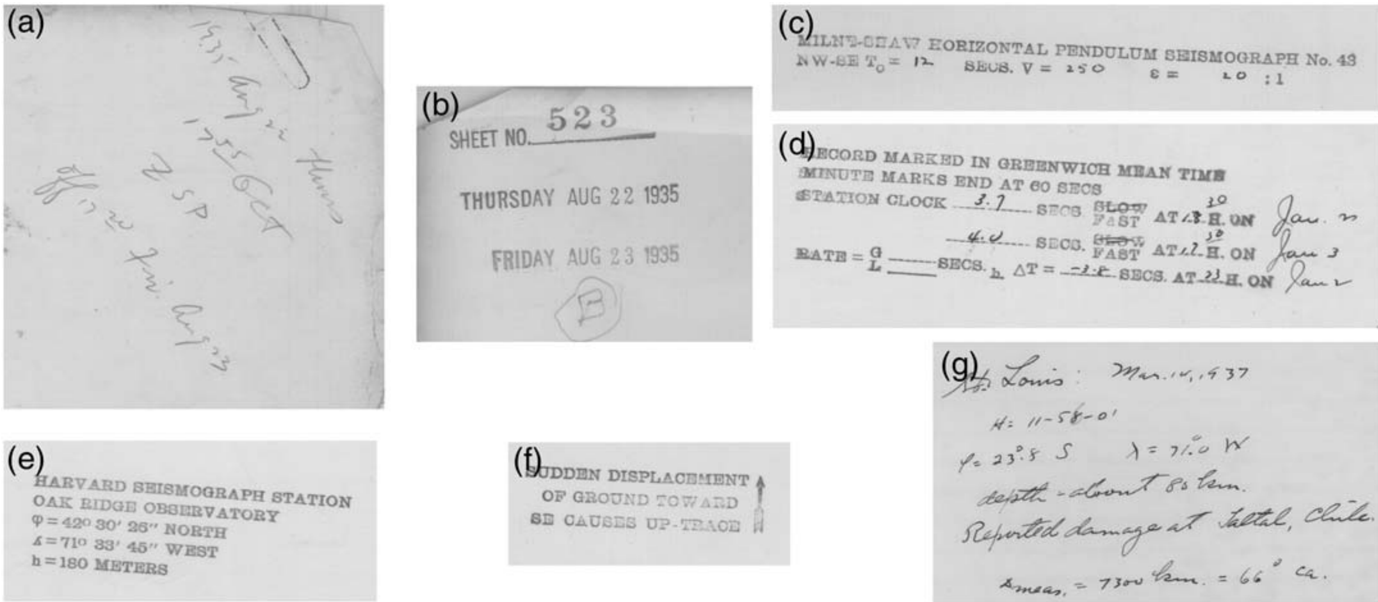
According to the collection of seismograms, between May 1933 and end of March 1935, there were six seismographs (Leet, 1934). The vertical motion was recorded by two Benioff vertical seismographs configured with short- and long-period galvanometers, and the horizontal motion was measured by two sets of two instruments, Milne–Shaw horizontal pendulum seismographs (numbers 43 and 44) and Wood–Anderson horizontal torsion seismographs. The Milne–Shaw seismographs, measuring the long-period horizontal motion, were aligned in northwest–southeast and northeast–southwest directions, whereas the Wood–Anderson seismographs, measuring the short-period motion, were aligned in east–west and north–south directions. These six instruments were replaced by six Benioff seismographs in April 1935, and the new instruments continued to monitor ground motion until July 1953 (Fig. 4; described in *Geophysics at Harvard*). A pair of instruments were used to measure vertical, east–west, and north–south motion, and each pair provided short- and long-period recordings. The seismogram collection from this period also includes some paper recordings of unknown origin. Some of these may have been recorded by the Leet seismograph, a three-component portable seismograph Leet developed (Leet, 1945).

The ground motion measured by the seismometers was transcribed onto photographic papers through galvanometers. In general, the photographic papers are about 36 inches wide and 14 inches high (with some exceptions). Usually, a single seismogram contains recording from a single instrument, but between 1936 and 1943, the long-period vertical and east–west components were printed on a single photographic paper with the vertical component occupying the top half and east–west component recorded on the bottom half. Typically, a fully recorded seismogram contains about 48 lines, and each horizontal trace corresponds roughly to one hour for long-period instruments or half an hour for short-period instruments. Minute marks are found at the end of each minute, and additional offsets are found for each hour on some seismograms. Overall, each seismogram contains a record of ground motion over one to two days. It appears that seismograms without significant events or microseisms have been discarded, especially during early years, and we estimate that there are about 12,000 seismograms that have been kept at the Harvard station.

Cleaning and Flattening

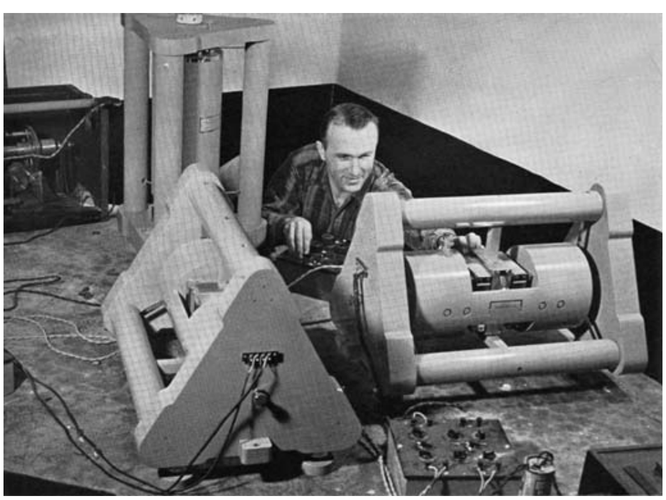
The analog seismograms had been stored in a large wooden cabinet at the station until 2007 when the station was renovated. The cabinet was located below the ground level, in the mezzanine level (Fig. 1), between the vault and the ground floor, and moisture and rodents damaged the contents of many drawers. The seismograms were in dire condition. Drawers with significant rodent activity contained droppings and carcasses, and the seismograms were damaged by bodily fluids and were eaten or shredded. These seismograms with rodent damage are darkened (reddish brown to black) as if they had been burnt, are fragile, and emit an unpleasant odor. Presence of moisture has caused seismograms to adhere to one another, and a subset has become powdery. Mold growth was observed for one drawer that appears to have been affected both by rodents and moisture. Even for drawers that survived in the best condition, the seismograms are soiled and the photographic surface has become damaged and vulnerable over the years. It was necessary to have the seismograms cleaned before anything could be done: they were in no condition to be digitized or curated as a library collection despite their historical and scientific value. Because of the biological contamination of the seismograms, all individuals working with them wore personal protection such as masks, nitrile gloves, and lab coats.

The best course to clean the seismograms was determined with in-house expertise in historical photographs available at the Weissman Preservation Center, Harvard Library. Loose soil and dirt are first removed using a soft brush. The photographic



▲ **Figure 3.** Some examples of information found on the back of seismograms. (a) Typical information that is found at the top right corner of almost all seismograms. This particular example indicates that the recording started on Thursday, 22 August 1935, at 17:55 GCT (Greenwich Civil Time, synonymous with Greenwich Mean Time) and ended on Friday, 23 August at 17:20. The phrase "Z SP" indicates that this is vertical-component recording of short-period instrument. (b) Typical information found at the top left corner of almost all seismograms until mid 1948 showing the sheet number (523), start date (Thursday, 22 August 1935), and end date (Friday, 23 August 1935). (c) Data associated with instrument response found on some seismograms. This example is for a Milne–Shaw seismograph. (d) Time correction information found on some seismograms. (e) Station location information. (f) An example of a stamped information indicating the direction of sudden offset. (g) An example of hand-written information about an earthquake that occurred in St. Louis on 14 March 1937. The seismic signal from this event is recorded on the front side.

side of the seismograms that are sensitive to abrasion is then cleaned using nonabrasive wipes. The back side with paper surface is less sensitive to abrasion and is cleaned using porous sponges used commercially for soot removal. Even though we aim to recover as many seismograms as possible, during this stage of cleaning, some records that have been hopelessly damaged are discarded. For example, if only a small portion of a seismogram remains with no discernible information about the type of seismogram on its back, the piece is discarded. We also remove parts that are powdery, shredded, or too darkened, to provide an acceptable working environment for the person cleaning them and to avoid having fragments fall off in subsequent stages. This type of damage typically occurs at the edges of a recording, and utmost care is taken to preserve as much of the traces and back-side information as possible.



▲ **Figure 4.** Photography of the vault in late 1930s showing three Benioff instruments and Don Leet (taken by Paul Donaldson and appears in *Geophysics at Harvard*, a booklet published sometime in the early 1940s).

Another problem is the tendency of the photographic surface, which is a gelatin emulsion, to swell with moisture and become prone to sticking to another seismogram in the stack. If the photographic surfaces are not badly damaged, drying the seismograms allows for separation of individual records. Some groups of seismograms were too strongly blocked or stuck together and did not separate after drying. We tested with exposure to humidity, and if that was not sufficient, immersion in water. For thick groupings, a few drops of Photoflo surfactant was added to the water to facilitate the penetration of water between the seismograms and speed the process. Because damaged gelatin emulsions are very sensitive to water and could easily dissolve and lift off, reducing exposure time to water is critical. These procedures successfully recovered a number of seismograms but could not separate those that were almost cemented together into a single block of paper mass. We also lost seismograms that crumbled upon removal from storage boxes and those that were too darkened to discern any writings or traces. We estimate that about 15% of the seismogram collection fall into these unrecoverable categories.

Even though seismograms filled individual drawers almost to the brim, they, nonetheless, acquired curvature over the years. This is mainly due to differences in the response of two surfaces (photographic versus paper) over time and to moisture. Every seismogram curls inward on the photographic side with different degrees of curvature. Those that were preserved well show little curvature whereas others can have edges rolling inward multiple times. This becomes an issue for the subsequent digitization procedure when good imaging of the seismograms requires relatively a flat surface. Therefore, we experimented with various approaches to flattening the seismograms. For example, flattening under heavy weights worked reasonably well, but it took a long time, and curvature returned quickly once the weight was removed. Any rapid uncurling method, such as rolling against existing curvature, can crack the photographic surface and should be avoided. The following procedure is found to be most effective. After the seismogram has been thoroughly cleaned, the curved edges are put against a corner (e.g., edge of a desk), and pressure is applied softly against the curl. Care must be taken to apply soft enough pressure to avoid surface cracking. This is repeated until the seismograms become relatively flat. The seismograms are then stacked until the height is about 1–2 cm and are sandwiched between two flat surfaces (e.g., hard archival-quality cardboard) that is about the same size as the seismograms themselves. This package is squeezed together by large binder clips that secure the edges. After a couple of weeks to a month, the seismograms become straight enough to be imaged. After digitization, the seismograms are boxed in properly fitted archival boxes that will keep the seismograms clean and flat. Plans are underway to store the original photographic seismograms in a controlled environment with cool temperature and low humidity.

Digitization

To make the analog seismograms readily accessible, we explored techniques to obtain digital images. Even though our ultimate goal is to convert the analog seismograms to digitized time series, in this manuscript, we focus on generating digitized images. Our efforts to trace the seismograms will be described elsewhere.

There are multiple options for producing digital images of the recordings. The first option investigated was to send the seismograms to the Harvard Library Imaging Services. A pilot photographing attempt involving five seismograms was carried out using a Betterlight Super 8k2 scanning back camera on a large copy stand. Unfortunately, for this approach, even slight curvature of the seismogram distorted the image, and it required too much effort to perfectly flatten each seismogram. An alternative imaging approach we investigated was the use of a conventional copy machine (we tested with Canon Image Runner 5065). This option provided the most convenient and economical imaging technique, but the seismograms must be imaged in parts due to their unusual size. The seismograms had to be either bent or cut into pieces, both of which are undesirable, and tracking different parts of the images and combining them to reconstruct a single seismogram was not simple.

The last, and most effective, option was a large-format scanner. At the time we were experimenting with imaging techniques, the Structural Geology group at the Department of Earth and Planetary Sciences at Harvard University owned an old large-format scanner, VIDAR PRO TruScan Titan Atlas. The seismograms can be imaged as a whole, and slight curvature did not create serious image distortion. The large-format scanner was, therefore, the chosen approach for imaging the seismograms. However, after scanning a little more than 1000 seismograms, the LED bulb of the scanner burnt out. Unfortunately, because this equipment was out of date, a replacement bulb was no longer available. Using internal funds, the Department of Earth and Planetary Sciences replaced the scanner with Contex HD Ultra i4250s in 2013, and scanning has been performed using the new scanner.

For scanning, a seismogram that has been thoroughly cleaned and flattened is placed inside a Mylar (transparent thin flexible polyester) enclosure to protect both the seismogram and the scanner. This ensures that any loose piece of seismogram will not get into the scanner, and any scratching that may result from the scanning procedure will be made on the enclosure rather than the seismogram itself. The enclosure does not alter image quality significantly, and it is extremely difficult to distinguish ones with and without the enclosure. Interestingly, the Mylar enclosure is also useful in determining when the scanner needs to be cleaned. When the scanner becomes dirty, colorful vertical bars appear in the space where there is only mylar, that is, in the gap between mylar enclosure and the seismogram. The bars often did not appear in the seismogram image part, but if the scanner is left uncleaned, the bars will begin to show on the images. The enclosure becomes too scratched and dirty after scanning about 100 seismograms and is replaced.

Seismograms from 1938 and most of 1939 have been scanned with the old VIDAR PRO TruScan scanner. The photographic side has been scanned at 800 dpi (highest resolution available) in color, and the paper side has been scanned at 400 dpi in black and white. The images are stored in Adobe Photoshop format (.psd). Depending upon the exposure and amount of data available, the image files containing the front side ranges between 100 and 600 MB, and the back side is typically 90 MB. For images with poor exposure or faint traces (often resulting from a significant event), the trace side is rescanned with a low image contrast, resulting in file sizes that are around 1 GB. Use of the new Contex HD Ultra scanner significantly improved image quality and scanning time. The front side is scanned at 1200 dpi in color, whereas the back side is scanned at 400 dpi in black and white. The old scanner took almost 15 min to scan the front side, but the current scanner, at higher resolution, takes about 5 min. Twelve hundred dpi is not the highest resolution available for the new scanner, but higher resolution requires too much scanning time per image. For example, increasing the resolution to 2400 dpi, a level higher than 1200 dpi, takes more than 30 min to scan a single seismogram. 1200 dpi also provides sufficient resolution for poorly exposed or thin traces, and no rescanning at a different setting is performed. The images are saved in the TIF format (.tif), and the file sizes for the front and back sides of a seismogram are typically around 1.6 GB and 60 MB, respectively. As of 1 July 2014, more than 8000 seismograms have been scanned.

With so many seismograms to scan, particular attention is paid to ensure that the scanned images (front and back) match the appropriate seismogram. One useful strategy is the file naming system. Each image file is named sXXXX_YYYY_MMDD_mmdd_II_CC_S.tif (or .psd for those in 1938 and 1939), in which XXXX corresponds to the sheet number, YYYY is the year of the start time, MMDD is the month and day of the start time, mmdd is the month and day of the end time, II is the instrument, CC is the alignment direction, and S is either f for front side or b for back side. For example, a filename s6588_1952_0308_0309_lp_ns_f.tif indicates that this is a seismogram (photographic side) of long-period north–south ground motion beginning on 8 March 1952 and ending on 9 March 1952 with sheet number 6588. Initially, including the sheet number in the filename appeared redundant because it corresponds to the beginning date, but this redundancy turned out to be effective at identifying typos and other careless errors in the filenames. We, therefore, stamped sheet numbers for a handful of seismograms up to mid 1948 that did not have the sheet number stamped on the top left corner. After mid 1948, no seismogram had a sheet number, and we calculated and stamped sheet numbers for all seismograms. Once a group of seismograms has been scanned, the images are checked on a computer in a different room. Filenames and consistency of images to physical seismograms are examined with visual inspection of the image files. If there are issues in the images, such as vertical lines, the file is discarded and seismogram is scanned again.

There are some seismograms that do not have enough information on the back to assign a filename. If either the start or end date and time are available, the missing date/time can be inferred from the traces using minute and hour marks. If dates are available but instrument type and component are not, we look for any hand-written information. Sometimes such information can be found on the front side of the seismogram. If no additional information can be found, then it is compared against other seismograms from the same date to identify the missing component that might correspond to the record in question. If the instrument type and component cannot be determined after these steps, then the traces are compared with those before and after the date to infer at least the instrument type (e.g., short versus long period). In cases in which no dates are found on a seismogram but the sheet number is available, we convert the sheet number to the start date. If neither dates nor sheet number is found, we search for any additional hand-written information on the photographic surface. If this is not available, sometimes we can guess the date. For example, if a seismogram is found within other seismograms recorded on 8 March, it is plausible that the date of the unknown seismogram is also 8 March. Any inferences made as to the time, instrument, and component of scanned images are noted and are made available with the scanned images.

One final potential complication is the determination of the top side of the image where the traces begin. In general, we use the orientation of the information on the back to infer which side is up. However, there are cases in which misorientation is suspected, requiring closer examination. Three properties are useful when determining the top side. One is the hand-written information on the photographic side. If this orientation is inconsistent with inferred orientation from the back side, the orientation based upon the front side is chosen. The second property is how the traces end at the sides of each seismogram. On one side, there is usually a white space before traces start, whereas on the other, the traces continue until the very end. The white strip usually occurs on one side (e.g., left) for some periods of time, and consistency of this side with the orientation inferred from the back information can be checked. If they are inconsistent, the last property, the offset of minute marks, is invoked. For a given instrument, the offset of minute marks is consistent over some time, that is, they are always offset above or below the main trace. If a seismogram from the same instrument and component can be found prior to or after the seismogram in question, the offset is used to infer the correct orientation.

CONCLUSIONS

This manuscript describes the collection of analog seismograms from Harvard-Adam Dziewoński Observatory (HRV, IU) between 1933 and 1953 and our attempts to retrieve as many seismograms as possible. During this time period, there were more than 400 global significant earthquakes listed in the National Oceanic and Atmospheric Administration (NOAA) Significant Earthquake Database (NOAA, 2014) and more than 400 earthquakes in the Northeastern United States and Southeastern Canada cataloged by the Weston Observatory (2014). The analog seismograms, therefore, contain a wealth of information and almost doubles the duration of the data holdings from the HRV station. Another advantage of this analog seismogram collection is that the instruments operated in the same vault as those reporting data today. This will allow comparison of digital and analog recordings for better estimation of information needed for analysis of the seismograms such as instrument response, alignment, and site correction.

The HRV analog collection from 1933 to 1953 consists of approximately 12,000 seismograms, of which 15% are estimated to be damaged beyond any possible recovery. As of 1 July 2014, about 85% of the seismograms have been cleaned, about 8000 seismograms have been scanned, and, of the scanned seismograms, about 5500 have been made available online. The scanned images can be accessed by anyone through the Harvard Seismology group webpage (http://www.seismology.harvard.edu/HRV/scanned_images.html, last accessed November 2014) and the status and other information about the archival project can be found on linked pages. The ultimate goal is to digitize these images into time series for use in research. Efforts are underway to develop MATLAB (http://www.mathworks.com/products/matlab/, last accessed November 2014) software that converts scanned images into time series with funding from USGS Earthquake Hazards Program. The digitization software will be reported elsewhere.

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