WORKSHOP REPORT

Securing Legacy Seismic Data to Enable Future Discoveries

September 18-19, 2019

Albuquerque, New Mexico

NSF-1917159

Organizing Committee

Lorraine Hwang, UC Davis, *Chair*

Tim Ahern, IRIS *emeritus*

Cynthia Ebinger, Tulane University

William Ellsworth, Stanford University

Garrett Euler, Los Alamos National Lab

Emile Okal, Northwestern University

Paul Okubo, HVO US Geological Survey, *retired*

William Walter, Lawrence Livermore National Laboratory

Contact: Lorraine J. Hwang, ljhwang@ucdavis.edu

One Shields Avenue

University of California, Davis 95616

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Executive Summary

On September 18-19, 2019 a workshop on *Securing Legacy Data to Enable Future Discoveries* was held in Albuquerque, New Mexico engaging 29 researchers representing universities, national laboratories, and governmental agencies that included 4 international and 10 early career participants. The need and funding for this workshop grew out of a June 2018 event focused on legacy seismic data organized by the National Academy of Science Committee on Seismology and Geodynamics (NAS COSG), which sparked interest at both at the National Science Foundation and U.S. Geological Survey. The NAS COSG event identified a number of technical as well as financial challenges in trying to collect and build the datasets necessary to address key problems spanning large time periods that require legacy data. Not only are such datasets essential to evaluate global change in microseisms and extend time series of precursory phenomena, they are a crucial first step toward machine learning and other data intensive processing. Regardless, critical paper and magnetic tape records are at risk of loss or severe degradation.

Presentations and discussions at the meeting were organized in three main themes: science drivers, data preservation, and future directions. Through a series of presentations by the participants, the workshop reviewed examples of tectonic, volcanic, national security and climate science questions that can best be addressed using legacy data. Next the workshop reviewed past and ongoing legacy data preservation efforts in the US and internationally, enabling participants to consider best practices. This second theme included a number of different software products to better scan analog legacy data. Several large-scale international scanning and digitizing projects, such as by Instituto Nazionale di Geofisica e Vulcanologia in Italy, SISMOMEx by the Universidad Nacional Autónoma de México, and Harvard University were described in detail. These efforts show that with sufficient resources, significant volumes of analog data can be preserved and securely archived. However, these efforts are currently only addressing a small fraction of the available high-value, legacy data worldwide.

The workshop participants identified opportunities to coordinate activities internationally to achieve consensus on metadata standards. Initially, 39 metadata elements were identified. These elements can be grouped into 6 broad categories that parameterize the data including: 1) Time of Data, 2) Station/Channel, 3) Sensor, 4) Recording System, 5) Image File, and 6) Other. Participants were surveyed as to whether these elements should be required, recommended, optional, or omitted. Post-workshop, 20 additional metadata elements were contributed to the list. To reach consensus and maximize the utility of these efforts, additional vetting by the international community is warranted.

At the end of the workshop, a list of next steps for legacy data activities was developed and summarized below:

Analog holdings catalog. Create an inventory of analog seismic data holdings to identify current resources, connect potential users to resources, and aid in metadata discovery.

Publications database. Create a database of research publications that use analog data as a resource to other researchers, inspire new studies, and provide evidence to the importance of this data.

Data Availability. Develop policies to encourage legacy data submission to data centers working with existing centers on sustainable financial models.

Standards. Begin work on creating FAIR compliant metadata standards to enable federated discovery and access. Establish best practices and standards for imaging and digitizing, learning from established projects.

Pilot Project. Identify existing repositories to pilot federated data search and access utilizing proposed metadata standards, and retrieval of multiple data and metadata types. A pilot study will help to demonstrate the data's value, enable consensus on standardization, and advance data processing workflows.

Future Research. Identify strategies to enable future research through open source and standardization of both data and software. Identify targeted campaigns with specific research objectives defining the high priority science questions such as the identification of key stations to conduct imaging of all records and the identification of specific earthquakes for historical analysis.

New Technologies. Identify enabling technologies to reduce human intervention in the end-to-end process of creating research ready, time series data.

Other Communities. Attract a broader scientific community to apply seismological data in nontraditional research domains and communities with similar needs in preserving analog time series data.

Outreach. Create a larger community of users through outreach at all career levels.

Introduction

New seismological data mining methods are supporting discoveries and cross-disciplinary research across Earth system science. Such research is challenged by the relatively short time period of observation for which digital records are readily available. Historical data, recorded on paper and other physical media, potentially extend the time period of Earth observation to many decades. However, if such data are to be preserved and made available digitally to harness the data revolution, there are compelling challenges. The historical data is largely siloed; data are only available to scientists who can commit to traveling to specific archives or from archives capable of serving data requests. In addition, some of the physical media have been damaged or lost and/or at risk of losing stewardship. If converted to digital media, these collections conservatively represent upwards of 100's of petabytes of raw data. As a generation of scientists retires, both the data itself and the expertise required to use it are in danger of being lost.

In confronting this challenge, the first U.S. workshop focused on seismic legacy data was held September 18-19, 2019 in Albuquerque, New Mexico. The need and funding for this workshop grew out of a June 2018 session organized by the National Academy of Science Committee on Seismology and Geodynamics (NAS COSG) focusing on legacy seismic data.[1] The NAS COSG event identified technical as well as financial challenges in trying to collect and build the datasets necessary to address key problems that span large time periods that require legacy data. Building these data sets is not only a crucial first step toward machine learning and other data intensive processing but is urgently needed before critical paper and magnetic tape records are lost. The session showed the need for a more focused workshop addressing legacy data preservation and understanding its modern usage in research and development resulting in funding by NSF EarthCube for the September 2019 workshop.

The *2019 Securing Legacy Seismic Data to Enable Future Discoveries workshop,* engaged 29 researchers (including 4 international and 10 early career) representing universities, scientific consortia, national laboratories, and governmental agencies (Appendix A). Over two days, the participants discussed the science drivers, new and old, and the state of preservation of collections worldwide (Appendix B).[2] This workshop was the first to focus on creating the framework to enable the availability of digitally imaged legacy seismic data. A primary focus of discussions was the identification of necessary metadata. Previous efforts have largely been siloed with little discussion on standards and how the collections can meet modern data principles such as FAIR[3]; that the data be Findable, Accessible, Interoperable and Reusable as promoted by FORCE11[4]. Wilkinson et al., 2016 provides

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[1] http://dels.nas.edu/resources/static-assets/besr/miscellaneous/COSG/COSG-6-5-18.pdf
[2] Presentations are available on the workshop website. https://geodynamics.org/cig/events/calendar/2019-seismic-legacy/).
[3] https://www.force11.org/group/fairgroup/fairprinciples
[4] https://www.force11.org

guidance for data management and stewardship in the modern digital ecosystem but this must also be supplemented with domain requirements and leverage existing standards and infrastructure that the community has built over the last several decades.

Building upon community interests, the workshop activities were designed to lay the foundation to make progress on two broad goals:

> Goal 1: Work towards developing the framework for preservation of analog seismic data. This includes recommendations for prioritizing scanning efforts, defining metadata and data imaging standards to improve discovery and (re)use, and identifying the associated technical and social challenges.
>
> Goal 2: Create an interdisciplinary network of data, domain, and computational scientists to facilitate management, federated access, and use of digitally imaged legacy data.

In the report the following terms are used:

- Legacy seismic data. Any raw data or derived data products not originally captured in digital form. This may include station event bulletins and additional seismic information, non-digital media e.g. paper, magnetic tape, or analog film.
- Digital image, image, or scan. Legacy data that has been scanned or photographed and represented in a standard image file format.
- Vectorization. The process of converting a seismogram into a digital time series.
- Digital time series. A regularly spaced series of points that represents the seismogram after vectorization.

It is important to note that *preservation* may also include the safe storage of the physical records themselves, the act of scanning into a digital format, and vectorization. Each step holds different importance and priorities as discussed below in more detail.

Value of Historical data

In numerous cultures world-wide, earthquake lore spans centuries. Seismology began its transformation into a modern observational science during the mid- to late-19th century, when the first seismographs were built and installed, notably, in parts of Europe and Japan - regions known for volcanic as well as earthquake activity. Researchers from UC Berkeley installed the first seismographs in the western hemisphere in 1887 (Litehiser, 1989). Seismographs afforded the ability to record and preserve for later study details of ground motions generated from earthquakes and other sources. Subsequent efforts to understand these recordings drove the development of the theoretical underpinnings of wave propagation and solid mechanics transforming seismology into its somewhat uniquely quantitative position among the Earth sciences.

The earliest seismographs, triggered into operation by significant shaking, wrote data onto paper or glass plate recording media. In the early years, the smoked paper surfaces were etched by a stylus. Later seismographs recorded to thermographic, light sensitive, and photographic papers. As interests in seismology grew, seismographs were eventually operated continuously. Seismographic recordings resulted in collections of hard-copy seismograms, most typically large sheets of paper (~30x90cm) that recorded ground motions registered for a single instrument on a single day. Specific monitoring requirements would call for other recording formats like reels of microfilm, FM tapes, scrolling chart papers, or recording more than a single instrument or a different length of record onto a single physical record. Significant expansion during the 1960s and 1970s of seismographic monitoring at global and regional scales [e. g., Lee and Stewart, 1981] resulted in a corresponding increase in the number of collected seismograms.

Historical seismograms, as continuous recordings of ground motions spanning decades, and in many cases approaching a century from numerous sites around the world, comprise unique geophysical datasets that are invaluable complements to modern, continuously-recorded digital seismograms. They are the only quantitative data extant from past earthquakes, allow studies of phenomena over a longer time span, foster the development of new methods, and confirm new insights.

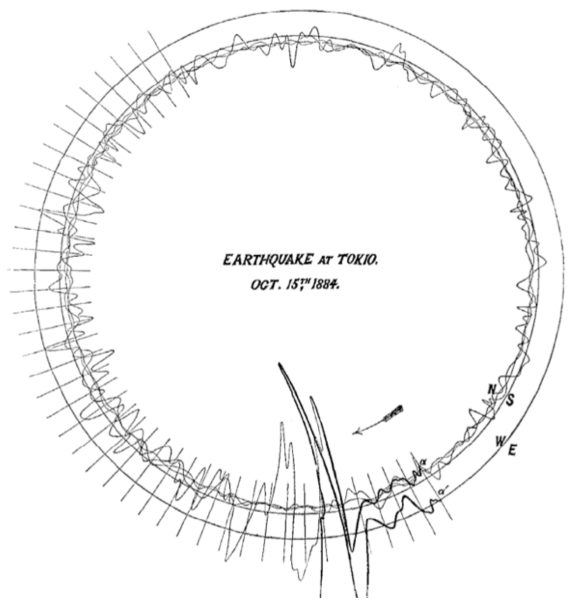

Figure 1. One of the earliest surviving seismograms captures strong motion data from the Tokyo, Japan earthquake of October 4, 1884. Time marks appear at 1 second intervals. Note the clear S-wave arrival at an S-trigger time of 4 seconds. Ewing (1885) estimated a peak velocity of 3.7 cm/s, the duration of the strong motion at 10 seconds and also noted the long persistence of shaking.

Traditional and Emerging Uses of Historical Data

The analog era in seismology lasted for more than a century, from the first recording of an earthquake in Japan (Figure 1) by one of the earliest functional seismometers by John Ewing in 1881 (Ewing, 1881; Matsu'ura et al., 2020; Satake et al., 2020) to the deployment of modern digital seismic networks as early as the 1970s. The study of seismograms from the analog era developed our basic knowledge of the Earth including its radial structure, tectonic plates, distribution and rate of seismicity, size of earthquakes, mechanics of fault slip, etc. Progress in the digital era has, of course, greatly refined our knowledge of Earth structure, fault zones, earthquake dynamics, while also leading to the discovery of new phenomena, such as tectonic tremor (Obara, 2002) and the development of new methods, such as recovery of the Green's tensor from the ambient seismic field (Shapiro and Campillo, 2004).

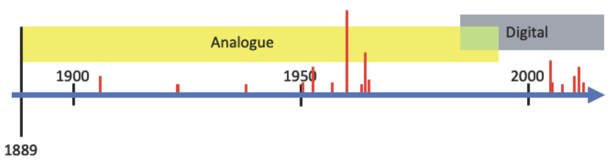

Figure 2a. Seismic moment release from earthquakes beginning from the analog era. Courtesy of M. Ishii.

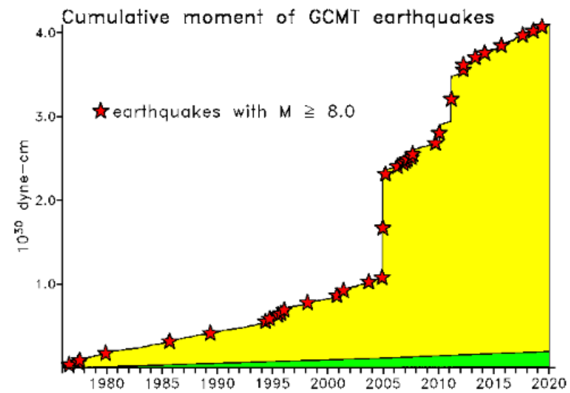

Figure 2b. Cumulative moment of earthquakes since 1976. Downloaded 24 January 2020 from globalcmt.org.

Despite the improvements in data quality, station density and availability, much of what we know about natural and man-made hazards and comes from the pre-digital era (Figure 2). Seismogram analysis, when combined with pre-instrumental historical accounts and paleoseismic investigations plays a central role in seismic hazard analysis in many regions of the world. Basic issues of earthquake rates, expected magnitudes, and recurrence intervals depend on the accurate assessment of past events. Notably the systemic determination of global centroid moment tensors (M>5.5) began in the year 1976 (Figure 2b) (Dziewonski et al., 1981; Ekstrom et al., 2012).

Figure 1. Analysis of the MW 6.8 Prince William Sound earthquake of March 25, 1932 by Doser and Brown (2001). Observed seismograms (top) and synthetic seismograms (bottom). Labels shown below seismograms refer to station code and waveform type (pz, vertical P; pr, radial P; sh, transverse S; pp, PP phase). Vertical scales show seismogram amplitudes in cm. Inset source time function plots have amplitudes of 10^{18} N m/sec. First motion data that were used to help constrain the inversion process are shown.

Consequently, much sound and socially relevant science remains to be done with pre-digital seismograms (Batlló et al., 2008). For example, time series recovered by digitization of paper and film records can be well-matched by synthetics and used to determine accurate earthquake locations, focal mechanisms and even moment rate through comparison with analog records such as in the case of historical activity in Prince William Sound, Alaska before the 1964 earthquake (Figure 3; Doser and Brown, 2001). Our ability to do more with pre-digital data continues to advance thanks to improvements in Earth models on local, regional and global scales, and improved methods for computing synthetic seismograms.

Tsunamigenic earthquakes represent a particularly important class of earthquakes that benefit from modern analysis. A recent re-evaluation of the 1933 Sanriku, Japan earthquake and tsunami using a variety of historical seismograms for the mainshock and aftershock adds new detail to the mechanism of the event, including the possible activation of high-angle east-dipping normal faults in addition to long-assumed west-dipping faults (Uchida et al., 2016). Similarly, reanalysis of the 1941 Andaman earthquake helped explain why no significant tsunami was reported for this M8.1 event (Okal, 2018) and reanalysis of the 1932 Manzanillo mainshock-aftershock led to further understanding of tsunami generation for this sequence (Okal and Borrero, 2011). Important questions about other tsunamigenic earthquakes, such as the 1957 Alaska event, remain targets of opportunity for improved modeling of old data.

Seismic hazard assessment provides the underpinnings for seismic safety provisions of building codes for both critical and ordinary structures, and guides risk reduction and resiliency planning. Earthquake catalogs underpin forecast models for the rate of seismicity and are usually the most important information used to construct a probabilistic seismic hazard analysis. Accurate earthquake magnitudes are essential for this purpose. Using modern methods, historical catalogs can be significantly improved, but only through access to waveforms and station metadata. It is worth noting that the 2800x magnification of the Wood-Anderson seismograph (foundation of local magnitude, M_L) was found to be too high by 1/3 by Uhrhammer and Collins (1990). After correction for the change, earthquakes in southern California, for example have moments 1/3 larger than previously determined which has a profound effect on the seismic moment rate and estimates of moment deficit in hazard models.

Assessment of volcanic hazards shares many of the same needs – and opportunities – with earthquake hazard assessment. The 2018 eruption of Kilauea in Hawaii was unprecedented in the 200+ year history of observations (Wright and Klein, 2014), and serves as a reminder of the importance of systematic cataloging of volcanic activity. A growing body of observations suggest that imminent eruptions are heralded by recognizable changes in seismic wave speeds measured from analyses of ambient seismic noise (Brenguier et al., 2008). The emerging understanding of the importance of volcano-tectonic earthquakes for forecasting eruptions (White and

McCausland, 2016) points to the need for better catalogs of volcano-related and unrelated seismicity, especially where populations are at risk from explosive volcanism, lahars, tsunamis, and similar hazards. Despite the large number of submarine volcanoes, submarine eruptions had remained largely undetected until new tools were developed (e.g., Tepp et al., 2019). Historical records provide a means to obtain a longer, and consistent database required to constrain hazards to shipping and to understand fundamental Earth processes.

Human induced earthquakes caused by petroleum extraction, enhanced geothermal system development, salt dome mining, and the construction of high dams have disrupted the conventional wisdom of seismic hazard in many locations around the world, and in particular in the central U.S. (e.g., Ellsworth et al., 2015; Nayak and Dreger, 2014). Long seismicity records are needed to assess the change in hazard and to identify factors that make some project sites riskier than others. Unfortunately, more attention has been given to reporting teleseismic phases than local events at many observatories and as a consequence the answers to pressing questions of background seismicity rates remain locked in the original seismograms.

Large-scale atmospheric nuclear explosions were only recorded on analog media. Since most nuclear testing ceased with signing of the Comprehensive Nuclear-Test-Ban Treaty in 1996 (Figure 4), these unique data provide key information to improved nuclear monitoring methods and yield estimates. Data from free-field and free-surface ground motion records from U.S. underground nuclear testing (e.g., Perret and Bass, 1975; Patton, 1990; Deupree et al., 1991) are currently being recovered to study non-linear wave propagation, rock damage, and spall and how these processes affect the elastic wavefield, and hence, energy release.

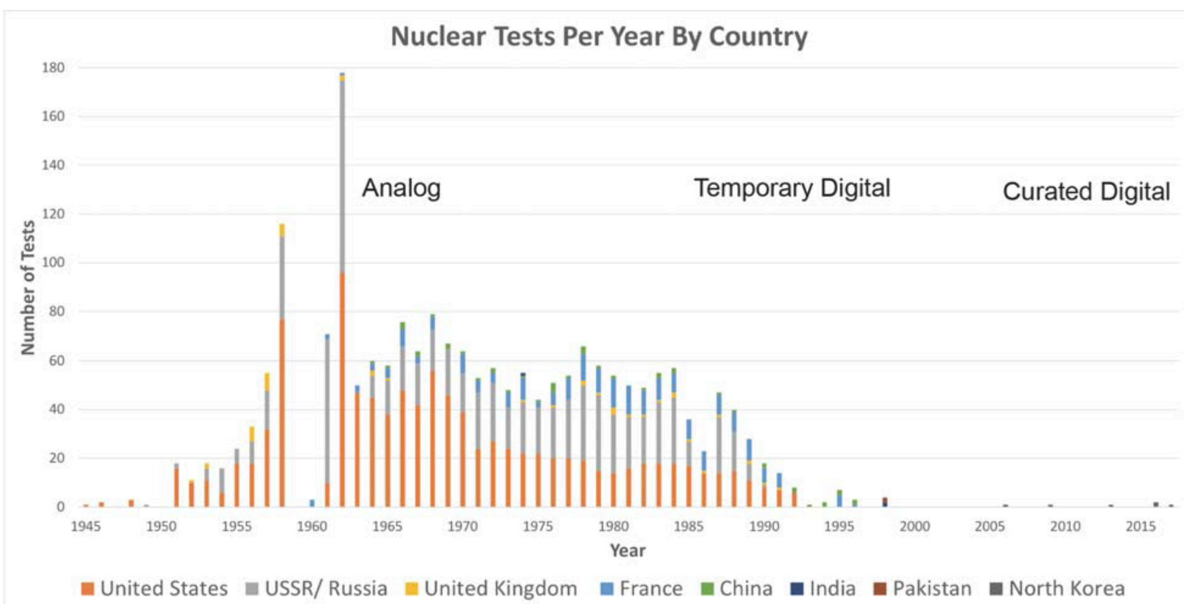

Figure 4. Number of nuclear tests per year by country from 1945 to 2017. The vast majority of nuclear testing took place in the analog and temporary digital era. This figure is based on publicly available data at: www.armsconrol.org/factsheets/nuclearteststally.

Seismic activity rates are not the only feature of the Earth that change with time. It has become clear in recent decades that seismic velocities can change as a consequence of seismic shaking, pressurization from magmatic and industrial fluid injection, and from fault movement. Seismic evidence also points to the super-rotation of the inner core (Song and Richards, 1996), which raises the prospect that evolutionary changes occurring in the outer core or in the mantle could someday be detected using seismic methods. Recordings of earthquakes, explosions and the ambient field all provide the essential data for understanding temporal changes in the Earth. Successful measurement requires precisely curated, ground motion time series data. While we sometimes take timing for granted in the era of GPS/GNSS and high-accuracy local clocks, time keeping of legacy data faces many challenges (Agnew, 2020).

The seismogram encodes a wealth of information about Earth structure that can be used to study the source using approaches such as template matching (Shelly et al., 2007) and path dependent approaches such as coda interferometry (Snieder, 2006). Even when precise timing is an issue, waveform similarity can be used to identify repeating earthquakes and other phenomena from well-curated seismograms (Figure 5). Repeating earthquakes play an important role in the current debate about the role of aseismic slip in the earthquake nucleation process (e.g., Bouchon, et al., 2019; Ellsworth, 2019) as well as volcano-tectonic activity (e.g., Oliva et al., 2019).

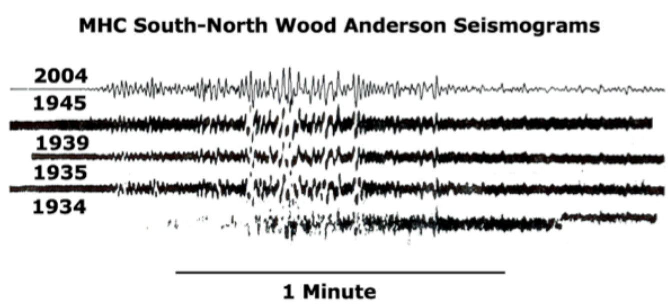

Figure 5. Seismograms of a repeating M_L 4.2 Parkfield, California earthquake recorded at the Mt. Hamilton (MHC) seismic station. This earthquake was a foreshock to the 1934 mainshock, a late aftershock in 1935, occurred at times unrelated to larger earthquakes in 1939 and 1945, and was an aftershock in 2004. Optical Wood Anderson

There is clearly great potential for using pre-digital seismograms to address a host of identified problems of Earth structure and dynamics. But there is also great potential to use the century plus of instrumental seismograms to tackle emerging issues of climate change such as changes in storm intensity (Aster et al., 2010; Ebeling, 2012; Sufri et al., 2014; Koper, 2013; Gerstoft and Tanimoto, 2007) and glacial retreat to name but two (Ekstrom et al., 2006; Nettles and Ekstrom, 2010) as well as in the application of new and emerging methods such as machine learning for traditional problems (Kong et al., 2018; Ross et al., 2019; Wang et al., 2019).

Preservation and Access

Seismograms have been recorded on an astonishingly wide range of media, with each new generation of instrumentalists leveraging the latest technology to improve the fidelity of the seismogram. From the earliest surviving recordings of scratch marks on a lampblack coated surface and photographic paper to digital tapes and disks, the challenges for preservation of data are numerous.

Early efforts summarized by Lee and Benson (2008) concentrated on rescue efforts for “important” earthquakes; it is less obvious today what wiggles in the seismogram will be important in the future. Keeping continuous data rather than just data around particular events enables future discoveries. Modern methods generally require information on the response characteristics of the record, emphasizing the involved task of metadata preservation and access, as well as knowledge of the Rube Goldberg-esque mechanical systems for transferring mass movement onto paper.

Many of the data preservation efforts in the U.S. from the 1970s and 1980s made photographic copies of original paper records. While this preserves the data, it makes access no better than for the original. In addition, some of these records on microfilm have begun to deteriorate or have been threatened by disposal (Okal, 2015; See supplemental material). Recently, universities and research organizations world-wide have begun or have completed ambitious scanning projects transforming paper records into digital images making them more widely accessible. See Appendix C. These preservation projects of pre-digital era seismograms set a standard that the U. S. should carefully consider as a model for going forward.

Digital storage is cheap in comparison to physical storage. In spite of these costs, as much is practically possible, all original data should be kept (Figure 5). Caveats to this are data that contain no identifying marks. In addition, some data may have deteriorated beyond usability. Criteria in each case may change with time with improvement in methods and technologies. In fact, scanning everything immediately may not be a priority as such improvements may produce better quality scans faster, and hence, cheaper.

Figure 5. The SISMOMex project aims to scan all 310,000 seismograms that have been moved to an ambient storage facility. The seismograms are protected from the sun and moisture. The area is fumigated yearly to prevent fungus and insect proliferation. The catalog of records has been integrated into the UNAM’s ALEPH system with the help of their university’s library. Courtesy of X. Perez-Campos.

Prioritization should be given to preserve collections at risk. Microfilm, FM tapes, digital objects as well as paper are subject to “rot”. Microfilm decays. In some cases, it becomes unreadable due to the lack of access to equipment or the deterioration of the medium itself e.g. film become brittle, chemical deterioration destroys the image. FM tapes suffer from sticky tape syndrome as their binders deteriorate. Digital objects are subject to degradation if not properly maintained. High quality paper so far has been the most robust storage media. However, Institutions may no longer have the capacity to safely store original records. Identifying at risk collections on the institutional, national, and global scale and raising the awareness of their value is of prime concern.

Current digital preservation projects employ a range of practices in scanning and products provided. In producing digital images, projects have used large format scanners, flatbed scanners, and photographic methods either contracting to private companies or using institutional resources. High resolution formats are typically tiff with some projects providing lower resolution copies and/or .jpgs for reviewing. High resolution copies are either available for download or by request. For stations HRV, digitized time series in SAC format are available for some records. Additional metadata information is also available.

Projects also engaged archivists. In these cases, archivists provided valuable expertise in restoration of records (Ishii et al., 2015) and cataloguing (See Appendix C. SISMOMex). Archivists bring valuable experience in best practices for scanning[5] as well as modern practices in accessing digital archives.

No agreement exists on standards or guidelines for processing these data. Scan quality is a balance between minimum fidelity to the data driven by the instrument response, and the costs of scanning and storing at higher resolution. Once scanned, several methods exist to convert scanned images to digital time series (Bartlett et al., 2018; Bogiatzis and Ishii, 2018; Pintore et al., 2005). These methods still require a great deal of human intervention especially for complex records or records with poor data quality. Improved methods in the future may not only produce higher fidelity time series data but also automate more processes. Producing such data should not be a community priority but as researchers digitize data for their own uses, they should be encouraged to deposit these to an open access repository. Lastly, benchmarking these software using pairs of records recorded digitally and by analog methods and as analyzed by different operators would lead to a better understanding of both systematic and unsystematic errors.

The larger issue of metadata standardization is discussed in the following section.

The Need to Standardize Metadata

The community is at a critical juncture in which it is estimated that we will begin losing institutional knowledge of the necessary metadata in 5 to 10 years as aging network operators and scientists with long-term involvement with these networks and the data the networks generated, will retire. In order to ensure continuity and consistency in data preservation projects, it is important that this knowledge is captured, and standards are established, ideally before significant work begins. This will ensure high quality products and comprehensive

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[5] https://www.archives.gov/preservation/technical/guidelines.html

capture of key information. High-quality metadata will enable professional curation of products resulting from preservation projects. Standards are needed in the initial capture stage such as well-defined and consistent analog to digital conversion parameters regarding the capture of images (e.g. scanning parameters) or analog to digital conversion (e.g. sample rates, bits of resolution, etc.). It is also essential that the types of metadata captured are consistent across projects with all required metadata captured and made available through standardized mechanisms.

By identifying and enforcing key metadata, it will allow centers managing these products to develop uniform tools that can discover data products and return legacy data in formats that are useful and with enough metadata to ensure the usability of the data.

The workshop contained several sessions dedicated to metadata. Prior to the workshop several individuals that had been involved in one or more legacy data preservation projects were contacted and asked to identify key types of metadata they had captured as part of those projects. Approximately 10 projects participated. Not too surprisingly, the types of metadata collected for each of these projects had some overlap in metadata (e.g. station name, geographical location) but there was a great deal of heterogeneity in other metadata collected. There were more differences than similarities in the overall metadata captured.

Workshop participants articulated a need to identify core metadata for legacy data. Metadata discussed not only included traditional metadata but metadata about the scanning and vectorization process as well. A key artifact of this workshop is the identification of metadata that should be 1) required, 2) recommended, or 3) optional and could be provided if captured. Perhaps equally useful is the identification of some metadata that was sometimes captured but likely was not deemed to be essential metadata for all legacy data rescue projects.

If an effective project to capture and manage legacy data is ever funded, it would be necessary to agree on metadata that should be captured during the preservation process. The availability of required and recommended metadata early in the process will allow systems to be developed that enable FAIR (Findable, Accessible, Interoperable, Reusable) data (Wilkinson, 2016).

Experience within the International Federation of Digital Seismograph Networks (FDSN) has demonstrated the importance of standards development in order to manage diverse collections in a distributed system. The federated system of FDSN Data Centers is a mature system that allows access to time series data across the FDSN members that are geographically distributed across the globe. By putting metadata standards into place early in the legacy data effort it will allow holdings adhering to the FAIR principles to be managed by and using financial resources from a wide collection of organization, those that are responsible for the networks that originally recorded the data in most cases. This is viewed to be superior to any system that would rely on just one entity system and one funding organization and would increase the viability and sustainability of such a project.

Metadata Elements

During the review of previous projects and drawing upon current state of the art in managing digital data, we identified 39 metadata elements to consider. These elements can be grouped into 6 broad categories that parameterized the data: 1) Time of Data, 2) Station/Channel, 3) Sensor, 4) Recording System, 5) Image File, and 6) Other. See Table 1.

Table 1. Surveyed Metadata Elements.

Metadata Element	Description	Units or Format
Time of Data (3)		
Start Time	The time of the first sample in the image.	YYYMMDDTHH:MM:SS.FFFF
End Time	The time of the last sample in the image.	YYYYMMDDTHH:MM:SS.FFFF
Time Correction	Any time correction applied to the data.	YYYYMMDDTHH:MM:SS.FFFF
Station/ Channel (11)		
Latitude	Latitude using WGS84 datum.	SEED format convention
Longitude	Longitude using WGS84 datum.	SEED format convention
Elevation	Elevation above (+) or below (-) sea level.	real in meters
Depth of sensor below ground surface	Depth below ground surface at specified longitude and latitude.	real in meters
Network Name	network to which the station belongs (e.g. WWSSN, GSN, EREBUS).	text
FDSN Network Code	FDSN network code (use SS if not associated with a network)	text
Site Name/Station Name	Site name (e.g. Albuquerque, New Mexico, USA).	text
IR Station Code	Station's code in the International Registry (ISC).	text
Channel/component	Channel code as in SEED format.	text as in SEED Manual Appendix A
Open Date	Date when station was opened.	YYYYMMDDTHH:MM:SS.FFFF
Close Date	If closed, Date when station was closed. Leave empty if still operating or not known.	YYYYMMDDTHH:MM:SS.FFFF
Sensor (7)		
Type of sensor	type of sensing instrument (e.g. Streckheisen STS-2, Benioff)	text

Sensor serial number	Manufacturer's serial number of seismometer, if known’	text
Free period	The free period of the instrument.	real in seconds
Damping constant	The instrument's damping constant.	real dimensionless
Horizontal 1 dip/azimuth	The dip/azimuth of the first horizontal.	SEED convention
Horizontal 2 dip/azimuth	The dip/azimuth of the second horizontal.	SEED convention
Vertical dip/azimuth	The dip/azimuth of the vertical channel.	SEED convention
Recording System (4)		
Type of recording system	The type of recording system (e.g. Teledyne helicorder).	text
Recording system serial number	Manufacturers serial number, if known.	text
Scale/gain/amplification	Scale or gain factor (scaler)	real dimensionless
Period of scale/gain	Period at which the gain is valid.	real in seconds
Image file (12)		
Date of Scanning	The date the image was scanned.	YYYYMMDDTHH:MM:SS.FFFF
Resolution	The resolution of the scanned image.	pixels per meter
Vertical pixels	The number of pixels in the vertical dimension.	number of pixels
horizontal pixels	The number of pixels in the horizontal dimension.	number of pixels
Image format	The image file type.	e.g. heic, jpeg, jpeg-2000, openEXR, pdf, png, tiff in ASCII
image size	The total size of the image in bytes.	integer
Analog image length	Length of the original document.	real in meters
Analog image width	Width of the original document.	real in meters
Color depth	The color depth of the scanner, if applicable.	integer
Original recording type	Photographic paper, drum recordings (smoke, hot stylus, ink)	text
Location of original record	Country, state or province, city, institution, room of original analog document when scanned.	text

Contact information of owner	Contact information for the original owner of the data.	text
Other (2)		
Notes and Comments	Optional Notes and/or Comments.	text
Date of metadata creation	The date and time when the metadata was created or last updated.	YYYYMMDDTHH:MM:SS.FFFF

Identifying Important Metadata Elements

During the workshop all participants were asked to consider each of the 39 metadata elements and identify which of the following categories each element belonged (Table 2).

Table 2. Element Categories.

Category	Meaning
Required	The metadata element should be required and to values verified before submission for management at a data center.
Recommended	The metadata elements should be provided if the information is easily available.
Optional	The metadata element should be totally optional.
Omitted	The metadata elements should not be requested or managed by a data center.

Elements identified as **Required** would have to be submitted with the legacy data. Systems that manage search and discovery would assume that this metadata is available to use as a search parameter.

Elements identified as **Recommended,** would be used to refine searches if they are available. While not required for submission to a data center, these metadata elements could increase the power and flexibility of a search.

Elements identified as **Optional** would be kept with the legacy data and can be provided but would not be used for search or increased flexibility.

Elements identified as **Omitted** would not be managed by data centers in any way. These elements will not become part of any standard.

Responses for most all metadata fields surveyed were either **Required** or **Recommended**. None polled as **Omitted** and only metadata fields associate with serial numbers polled highly for **Optional.** Surprisingly was the split in votes between **Required** and **Recommended** for some fields. This may be a stronger indication of intended use and/or experience in using data of these types. Results of the survey are given in Appendix D.

The survey focused on search and discovery of assets and should not be considered a complete list of descriptive metadata necessary for research uses of the data. For example, specific information, for some recording systems are not captured such as pen length arm and drum speed that would be necessary to accurately account for these distortions.

Post Workshop

Workshop attendees were requested to make comments about definitions of the 39 elements presented at the workshop and also were allowed to make suggestions for more metadata elements. There were 20 requests from 8 different workshop participants to consider modifications of the definitions of the current metadata elements in the survey or to consider adding new elements (Table 3).

Table 3. Additional Metadata Elements

Possible Additional Metadata Element	Description	Units or Format
DOI	Authoritative Resource Identifier for Scanned Image.	DOI
DOI	Authoritative Resource Identifier for Original Recording.	DOI
Timing drift	Estimated drift or error in time progression.	[+/-] seconds
Contrast Ratio	Estimate or specification of ratio of light to dark intensity.	float ratio to 1
Pen radius	Length of the pen arm from pivot to marking tip (optional).	mm
Drum surface velocity	Scrolling speed of the drum surface (optional).	mm/s
Trace direction	Direction of flow of the seismogram (optional).	L-R (left to right), R-L, U-D (up to down), D-U
Phase markings	Indicate true if phase notations were placed in the image.	True/False
Occlusions	Indicate true if tears or other flaws obscure trace data.	True/False
Condition	An index to indicate the condition of the image	e.g. SSIM
Earthquake signal	Indicate true if an earthquake signal is present	True/False
Timemark Format	Positive real to indicate length of vertically offset timemark negative real to indicate length of gapped timemarks, null to indicate no timemarks.	real numbers (pixels?)

Source of information	Information about source of metadata entered - e.g., lat/lon adopted from a published source, or response assumed based on X information or publication. Optional or recommended.	text
Nature of instrument	Logical variable: either mechanical (e.g., Wiechert) or electromagnetic (e.g., Golitsyn). This logical variable would control the instrument constants (T, V, epsilon; or Tp, hp, Tg, hg, mu, Vmax).	
Polarity of recording	Either ground motion up = up on paper or down on paper.	
Sensor	Include poles/zeros from the damping and free-period. This would allow for NRL type responses and would avoid developing new types of metadata as you could put most information into blockette 53.	
Drum radius	The drum radius is necessary to apply corrections.	real (mm or cm)
Associated bulletin	In case of earthquake trace, the time of the phases present on the seismogram may have been reported in the station bulletin or elsewhere. If true, provide bulletin name, url or DOI if published	if True, provide url or DOI of the bulletin.
Vectorized_trace	This field to be added if the trace has been vectorized. Provide the url/DOI where it can be obtained.	if True, provide url or DOI of the vector trace.
date-time of time-correction	Necessary, together with tabulated time-correction and timing-drift, to calculate correction for time of data-sample.	Same as for other date-time metadata.

Based on the results of the metadata survey, the next activity will be to incorporate the new or modified elements into an updated survey and submit it to the FDSN mailing lists for broader consideration This will ensure broad international consensus and set the stage for an eventual endorsement of the metadata elements needed for legacy data. After receiving results back from this larger survey, a working group will be able to identify **Required, Recommended,** and **Optional** metadata for legacy data.

Use Cases

Workshop attendees were requested to describe how they would want to discover and use legacy data. These use cases describe not only how the data would be accessed and used, but also how the system should respond, including expected outputs and error messaging. In this context, use cases were of interest to ensure the necessary metadata is being collected and that any systems designed to access data, leverage the available metadata.

For this exercise, attendees were asked to provide a summary of their use case, describe the workflow, conditions, expectations, and requirements. In all, seven use cases were completed which can be categorized as follows:

- **Multi-decadal studies.** Studies over large time spans to understand regional seismicity or changes in Earth properties on a global scale.
- **Historic events**. Re-analysis of historical events e.g. earthquakes and volcanic eruptions using modern analyses.
- **Climate change.** Investigating changes in storm intensity over time.
- **History of science.** Understanding the development of instrumentation and the development of observational seismology.

See Appendix E.

Repositories and Inventory

Further waiting or delaying preservation of the physical media puts these resources at risk. What to preserve and estimates of the resources necessary to ensure their continuity are needed but are difficult to make without knowing the scope and status of collections worldwide. A large number of collections of scanned images were identified at the workshop, but it is clear that the worldwide collection of non-scanned images is much larger. To understand the scope of the effort to capture legacy data using standard digitizing techniques and standard metadata, it will be necessary to survey our community to produce an inventory of as many collections of legacy data as possible. For collections not necessarily at risk, this helps to establish decision-making, preservation priorities and enables the ability to assess the uniqueness of the dataset.

A starting place in defining the inventory of legacy data collections is to approach the membership of the FDSN to help identify legacy data collections known to its members. Once completed, information about additional collections can be solicited through the International Association of Seismology and Physics of the Earth’s Interior (IASPEI). Collection of basic metadata and standardization of indexing will be helpful in defining the scope of the problem related to legacy data, inform proposals to funding agencies, and help safeguard collections around the world.

Appendix C lists the collections of imaged records both presented at this workshop and those currently known to this effort.

Next Steps

Workshop participants discussed and proposed several activities that would increase awareness of research enabled by the use of legacy data and available resources. Standardization was emphasized both to guide preservation and to enable sharing.

Next steps include:

Analog holdings catalog. Create an inventory of analog seismic data holdings to identify current resources, connect potential users to resources, and aid in metadata discovery. Necessary information includes the institution responsible for the data, network name, station metadata, data types, and the condition of the collection. Legacy data includes not only the data e.g. paper, tapes, digital signal, or images but data products such as station catalogs and other historical artifacts.

Publications database. Create a database of research publications that use analog data as a resource to other researchers, inspire new studies, and provide evidence to the importance of this data.

Data Availability. Develop policies to encourage legacy data submission to data centers working with existing centers on sustainable financial models.

Standards. Begin work on creating FAIR compliant metadata standards to enable federated discovery and access. Establish best practices and standards for imaging and digitizing learning from established projects.

Pilot Project. Identify existing repositories to pilot federated data search and access utilizing proposed metadata standards, and retrieval of multiple data and metadata types. A pilot study will help to demonstrate the data's value, enable consensus on standardization, and advance data processing workflows.

Future Research. Identify strategies to enable future research through open source and standardization of both data and software. Identify targeted campaigns with specific research objectives defining the high priority science questions e.g. identify key stations to conduct imaging of all records and specific earthquakes for historical analysis.

New Technologies. Identify enabling technologies to reduce human intervention in the end-to-end process of creating research ready, time series data.

This includes:

- image capture. Faster and cheaper ways to image the data would increase the ability of repositories to make these available over the internet.

- image compression. Smaller files decrease storage costs and download times.
- time series creation. Identifying new algorithms and techniques e.g. machine learning to reduce human intervention would speed-up the conversion process and improve reproducibility.

Other Communities. Attract a broader scientific community to apply seismological data in nontraditional research domains and communities with similar needs in preserving analog time series data. Potential research applications include, tsunamis, geomagnetic field, ocean sciences, glaciology, climate change, civil engineering especially countries not belonging to COSMOS[6] and not contributing events to the Next Generation Attenuation databases[7], and natural resource extraction. In addition, techniques could be transferable to other analog time series observations. Lastly, archivists, historians, and the image processing community both contribute to the preservation of these data and broaden its impact. Leverage professional societies and international organizations in engaging these communities.

Outreach. Create a larger community of users through outreach at all career levels (Figure 6). Continued visibility of legacy data in the form of workshops, special issues, special interest groups, and sessions at professional meetings. Focusing on specific topics will attract new participants and advance progress on identified issues.

Figure 6. Researchers from Harvard University are working with High Schools in Japan to digitize seismograms and interest students in careers in seismology. Picture here are student from the Miyazaki Prefectural Nobeoka High School. Courtesy of T. Lee and M. Ishii.

The vision outlined above is to create a community and the infrastructure necessary to enhance the preservation, access, and usage of analog seismic data. Knowledge of this resource is essential in describing current holdings and identifying the metadata necessary to find data and make them available to modern research techniques. Lowering the barriers to usage includes easing access and creating the tools necessary to transform the data to digital forms, whether as scanned images or a digital time series, in making them accessible to modern seismic

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[6] Consortium of Organizations for Strong Motion Observation Systems
[7] See: https://peer.berkeley.edu/peer-strong-ground-motion-databases

analysis methods. Building a community of users includes inspiring early career researchers through an NSF Research Experiences for Undergraduates program, leading special sessions at professional meetings on research uses, volunteering to be an Editor of a special issue, or teaching workshops on tools and methods. Only good stewardship by the community will secure these primary observations for future generations and preserve our scientific heritage. We invite you to join the effort to safeguard this resource and make it FAIR for current and future generations of earth scientists.

Conclusions

As we are faced with unprecedented changes to climate, understanding the deeper patterns and trends in natural systems through time have taken on new importance (Research Data Alliance, 2019). The call to reuse data is driven not only by economics but also by the recognition of their uniqueness (observations of natural systems are not repeatable) and scientific value in enhancing current understandings as well as potential new discoveries especially in the era of big data. These data are part of the historical record and our scientific heritage (American Geophysical Union, 2019) not only in explicitly recording earth observations but implicitly recording, and thus providing the evidence that addresses the manner in which science was conducted. The importance of these efforts was affirmed at the 2017 IASPEI meeting in Kobe, Japan, with the following unanimous resolution:

> *IASPEI strongly encourages efforts to conserve archives of analogue seismograms, metadata and seismological bulletins, making them usable by future generations of Earth scientists.*

A small number of institutions are leading the way in their efforts to preserve these data and make them accessible to a wider international community. Projects at these institutions provide a model and experience to draw upon on the end-to-end process from conservation, archival, digital preservation, digital repository through online access. Such knowledge will benefit FAIR data practices and the establishment of standards throughout the process to enable **F**indable, **A**ccessible, **I**nteroperable, and Reusable legacy seismogram data.

"… old seismograms, if properly interpreted, provide invaluable information on earthquakes in the past, and every effort should be made to save them, regardless of their quality, from possible loss and to make copies in an easily readable form." Hiroo Kanamori (1988)

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Appendix A. Participants

Ana Aguiar, Lawrence Livermore National Laboratory+

Tim Ahern, IRIS Data Services*

G. Eli Baker, Air Force Research Laboratory

Josep Batlló, Institut Cartografic i Geologic de Catalunya (ICGC)

Allison Bent, Natural Resource Canada

Daniel Burk, Michigan State University

James Dewey, U.S. Geological Survey

James Dixon, USGS Fairbanks

Diane Doser, University of Texas at El Paso

Cynthia Ebinger, Tulane University

Bill Ellsworth, Stanford University*

Garrett Euler, Los Alamos National Laboratory*+

Leila Honarbakhsh, University of Louisiana at Lafayette+

Lorraine Hwang, University of California, Davis*

Rebecca Koskela, DataONE, University of New Mexico

Thomas Lee, Harvard University+

Mairi Litherland, New Mexico Bureau of Geology+

Alberto Michelini, Istituto Nazionale di Geofisica e Vulcanologia *virtual*

Gabriele Morra, University of Louisiana at Lafayette

Meredith Nettles, Columbia University

Emile Okal, Northwestern University*

Paul Richards, LDEO, Columbia University

Adam Ringler, USGS+

Jesus A Perez Santana, Universidad Naciónal Autonoma de México *virtual*

Justin Sweet, IRIS PASSCAL+

Paul Viskovic, GNS Science+

William Walter, Lawrence Livermore National Laboratory*

Kaiwen Wang, Stanford University+

Brian Young, Sandia National Laboratories+

*organizer

+early career

Appendix B. Agenda

Day 1. Enabling Future Discoveries. Wednesday, 18 September 2019

Morning - Franciscan Ballroom

8:15A

0. Introduction to the workshop *Leader: Lorraine Hwang*

0.1 COSG *Bill Walter & Cynthia Ebinger*

0.2 Participant Introductions

8:45A

I. Research Uses of Seismic Data *Moderator: Bill Walter*

I.1 Emile Okal (Northwestern U.). 1907, 1915, 1941: Examples of the critical value of historical seismograms for the study of subduction processes

I.2 Diane Doser (UT El Paso): Waveforms and beyond: Analysis of seismogram, phase and intensity data for M 6-7 pre-digital earthquakes

I.3 Meredith Nettles (Columbia U.): Analysis of unusual earthquakes using 'legacy' data

1**0:20A** Break

10:40A (cont) *Moderator: Garrett Euler*

I.4 Paul Richards (Lamont-Doherty Earth Observatory): Work Done, and Work Still Needed, to preserve and make usable the analog seismograms of nuclear test explosions conducted in all environments

I.5 Brian Young (Sandia Nat. Lab.): Importance of Legacy Data for National Security

I.6 Ana Aguiar (Lawrence Livermore Nat. Lab.): A New Seismic Catalog in the Caucasus Using Digitized Legacy Data

1.7 Daniel Burk (Michigan State U.): Restoration and Recovery of Historical Seismic Records from the Former Soviet Union

1**2:30p Lunch** - Pavillion

Afternoon

1:40P

II. Creating Discoverable Data Sets *Moderator: Tim Ahern*

II.1 Rebecca Koskela (DataONE): Creating Discoverable Data Sets

II.2 Andrew Bartlett (Retriever Technology): SKATE, A Web-based Seismogram Digitization Tool

II.2 Alberto Michelini (INGV): Historical Seismogram Analysis, *virtual*

II.3 Thomas Lee (Harvard U.). The Potential of Analog Seismograms for Science and Education

3:10P Break

4:00P *Moderator: Cynthia Ebinger*

III. Lightning Talks (60 min)

1. Adam Ringler (U.S. Geological Survey): Calibration Analysis of ALQ
2. Mairi Litherland (New Mexico Bureau of Geol.): Analog seismic data from the New Mexico Tech Seismological Observatory
3. Thomas Lee (Harvard U.): Relative Time Corrections for Digitized Analog Records
4. Allison Bent (Nat. Res. Canada): Status of the Canadian Archive
5. Paul Viskovic (GNS Science): One million paper seismograms from New Zealand, Antarctica and the Pacific.
6. Jim Dixon (U.S. Geological Survey): Archival efforts at AVO and AEC.
7. Garrett Euler (Los Alamos National Lab): Our Legacy Data Can Help Us Monitor for Nuclear Explosions

Discussion/Day 1 Wrap-up

5:45P End Day 1

Day 2. Securing Legacy Seismic Data. Thursday, 19 September 2018

8:15A

IV. Data Preservation *Moderator: Emile Okal*

IV.1 Josep Batllo (Institut Cartografic i Geologic de Catalunya): Dealing with Old Seismic Data: Something Like a SWOT

IV.2 Josep Batllo (Institut Cartografic i Geologic de Catalunya): A.Geophysical Data National Archive of IGN-Spain, B. Preserving Analogue Seismograms of Regional Networks and Other Documents. Experience at the Institut Cartografic i Geoloic de Catalunya

IV.3 Jesus A Perez Santana (UNAM): The Mexican Sismoteca Nacional Online: preservation and dissemination of historical data on seismograms 1904-2000 *virtual*

IV.4 Jim Dewey (U.S. Geological Survey): Legacy data holdings at the U.S. Geological Survey in Colorado.

9:50A BREAKOUT *Leader: Lorraine Hwang*

Strategy for selecting data for rescue

10:30A Break

10:45A

Report Back

V. Metadata *Moderator: Lorraine Hwang*

V.1 Tim Ahern (IRIS DS *emeritus*): Metadata Collected by Legacy Data Rescue Projects

V.2 Daniel Burk (MIchigan State U.): MSU's Analog Digitization Challenges

11:45A BREAKOUT *Leader: Tim Ahern*

Tim Ahern: A Strawman for Legacy Data Metadata from Using International Input

Noon Lunch - Pavillion

Afternoon

1:00P Metadata Polling *Leader: Tim Ahern*

Tim Ahern: Identifying Metadata Element Importanc

1**:30P BREAKOUT** *Leader: Tim Ahern*

Tim Ahern: Use Cases for Legacy Seismic Data

1:50P Applications in Machine Learning *Moderator: Bill Ellsworth*

VI.1 Kaiwen Wang (Stanford U.). Image-Based Processing Methods in Develocoder Films Using Machine Learning: Application to the Rangely Earthquake Control Experiment

VI.2 Gabriele Morra (UL Lafayette). Convolutional Neural Network Detects Strombolian Eruptions at Mount Erebus, Antarctica

3:00P Roadmap for Future Activities *Moderator: Bill Walter*

4:00P Adjourn

Appendix C. Preservation Projects

PROJECTS PRESENTED AT WORKSHOP

Representatives from the following projects presented at the workshop. Below are short summaries of their projects augmented from other sources.

HRV (Lee et al., 2019)

Rescue and conservation efforts of seismograms from the Harvard-Adam Dziewonski Observatory (HRV) are detailed in an article by Ishii et al. (2015) and on their website: http://www.seismology.harvard.edu/HRV/archive.html.

In addition, more information about the HRV stations and their metadata can be found online: http://www.seismology.harvard.edu/hrv.html

Harvard Library preservationists were engaged in the process of restoring, cleaning, and flattening the seismograms. 15% of the approximately 12,000 seismograms from 1933-1953 were recoverable. The collection was transferred to proper archival boxes and currently are at the Harvard Archives.

Several techniques to image the records were investigated including photographic and conventional copying. Both were unsatisfactory as the former required perfectly flattened seismograms and the latter resulted in the seismogram being imaged in parts due to their unusual size (not desirable).

The best method tested was the use of a feed through, large format scanner. Seismograms were enclosed in Mylar to protect both the seismogram and the scanner. The scanner had the additional benefit of providing further flattening of the record. Images were scanned at different resolutions depending on the scanner used and whether the front or back side of the record was scanned. The most recent scans used 1200 dpi color (24 bit) on the front (~1.6 GB) and 400 dpi grayscale (8 bit) on the back (~60 MB) and saved as TIFF and reduced JPEG files. High resolution scanning (front side) took ~5 min. Total archive size is > 41 TB.

Images (~10,200 seismograms, 20,400 files) are readily available for download from their website: http://www.seismology.harvard.edu/HRV/scanned_images.html

A vectorization project using DigitSeis is underway. These seismograms in SAC format are also available for download through the above link.

The project requests citation to Ishii et al., 2015 if any of the images are used.

IGN-Spain (Batlló, 2019a)

The preservation objections of the Geophysical Data National Archive of IGN-Spain are to:

- Collect all analog geophysical data produced at IGN Observatories along their history
- Catalog and store them for preservation, maintaining adequate environmental conditions for its correct conservation
- Digitize important documents
- Disclosure of its content, providing information to [*sic*] scientific community

The collection includes seismic and geomagnetic data on a variety of media e.g. smoked paper, photographic paper, thermal paper, ink records, and microfilm in a variety of sizes from 40cm to 2.6m in length. Records include bound and unbound documents such as bulletins, telegrams, assembly instructions of historic instruments and observatory memories.

Most of the data has been catalogued and a digitization project is being carried out. The digitization project includes:

- Seismic bulletins of Toledo and Tenerife Observatories
- Photographs, slides, and glass plates
- Analog seismograms of Toledo, Alicante, Malagal, and Santiago Observatories that meet the magnitude criteria
- Books containing associated information.

Imaging of data was performed by an external company with the following specifications:

- High resolution planetary scanner
- A0 or double A0 size
- 300 dpi real optical resolution
- Without degradation or deformations at edges and corners
- Absorption systems or glasses, depending on the type of original
- Full image of the seismic band including annotations on margins
- Master files in TIFF format without compression

Present state of digitization project (2019):

- 54.000 analog seismograms digitized
- 17,000 book pages digitized
- 8 TB of data obtained

Request for data can be made to: archivo.geofisico@fomento.es

See also Supplemental Material: The ICGC Actions for the Preservation of Catalan Seismological Heritage.

Institut Cartogràfic i Geològic de Catalunya (Tordesillas et al., 2019)

Stations EBR and FBR in the Catalan Seismic Network have been operating since 1904 and 1906, respectively. Additional stations (AVN, CAD, EROG, FONT, MRB, OLT, SOR, VIH) were added to the network in the mid to late 1980's. These seismograms were recorded on thermal paper.

Plans are to scan the entire collection of records from EBR and FBR.

Seismograms were cleaned, placed in a protective sleeve and scanned using a feed through scanner at 1200 dpi grayscale. Seismograms whose original size is 600x360mm were imaged to typically a 458 MB file. Scanning was done by an external contractor.

A complete listing of scanned records and more information can be found through their website:

> http://www.icgc.cat/en/Public-Administration-and-Enterprises/Services/Earthquakes/Seismic-information-and-maps-collections/Analog-seismograms

Thumbnails are available for viewing and high/max resolution images may be requested. The original documents are the property of ICGC and the use of these digitized versions is freely allowed for non-lucrative study or investigation purposes as long as the responsible institution is properly cited (ICGC, 2000). Approximately 40,000 scanned records are available.

Other material scanned and available online include seismological bulletins, seismicity catalogs, and other reports and documentation.

Original records are kept at their respective observatories.

See also Supplemental Material: The ICGC Actions for the Preservation of Catalan Seismological Heritage.

Istituto Nazionale di Geofisica e Vulcanologia (Michelini *et al.,* 2019)

The SISMOS project at INGV scanned all papers records recorded by the Italian seismological observatories since early 1900. INGV is also engaged in scanning paper records from the European seismological observatories. There are more than 120,000-200,000 seismograms recorded in over 300 stations mainly of euro-Mediterranean area, over a period from 1895 to 1984 (1990) from ~1,000 earthquakes.

The original project used large format, flatbed scanners. New equipment is currently being acquired.

The records are imaged at 1016 dpi, ~320 MB per component. For the Italian observatories, if only "noise" was present, these were scanned at low resolution 400 records @400 dpi. Lower resolution, 200 dpi is used for previewing. 600 dpi records are available for direct download at: http://seismogramrequest.rm.ingv.it/

Total archive size is ~ 50 TB.

Very few records have been vectorized.

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SISMOMex (Pérez-Campos *et al.*, 2019)

The SISMOMex project represents the search, recovery, organization, collection and dissemination of all the information located and processed on the subject of seismology and related areas published in any format (printed, multimedia, etc.) in the country and abroad, that speaks about Mexico at different academic levels from 1904-2015. The project aims to scan historical seismograms containing the most important earthquakes at national and global levels, as well as the 15,000 oldest seismograms in the collection.

In 2009, moving the collection of ~310,000 seismograms stored at Tacubaya to UNAM took 6 months. Conserving the collection - classifying, organizing, boxing (1,220 boxes), and shelving took an additional 2 ½ years. The collection occupies ~120m^2 at an ambient air facility that is fumigated each year.

Records are from the Servicio Sismological Nacional (SSN) collection and from Oaxaca (OXX), Popocatepelt (PPM), Santa Fe, Jal (SFJ); Acapulco, Gro (ACX); and San Cristobal Chis (SCZ).

Digitization began in 2015 using a large format, flatbed, feed through scanner. Records are prioritized as: by request from a researcher, earthquakes with M>6.0, and oldest first. Currently 12,000 seismograms have been scanned. Seismograms were scanned at 300 and 600 dpi and stored in .pdf and .jpg format. Scanning required 5 min plus an additional 10 min to index the image into the database.

The following metadata is recorded:

- Corporate author: that in this case is the National Seismological Service.
- Name of the station: place of the Mexican Republic from where the registration was taken.
- Station code: Short ID of the station name

- State: State of the Mexican Republic where the registration station is located.
- Physical description: details of the document (e.g. one sheet, incomplete sheet, etc.).
- Date of Recording: day, month and year of beginning of the recording of the information in the seismogram.
- Recording Time: hour, minute and second when the registration process begins.
- Date of End of Recording: day, month and year of completion of the registration of the information on the seismogram.
- Time of End of Recording: hour, minute and second when the registration process ends.
- Component: type of seismogram Vertical, North-South, East-West
- Notes: complementary data of the document.
- Link: URL to the image of the seismogram in PDF format.

Data is being quality controlled and will be available through an ALEPH database system built for libraries. Current for records, contact: ssndata@sismologicao.unam.mx

Website: http://bcct.unam.mx/sismoteca/

United States Geological Survey (Ringler *et al.*, 2019)

See also Lee and Benson (2008) and Alejandro et al., (2018)

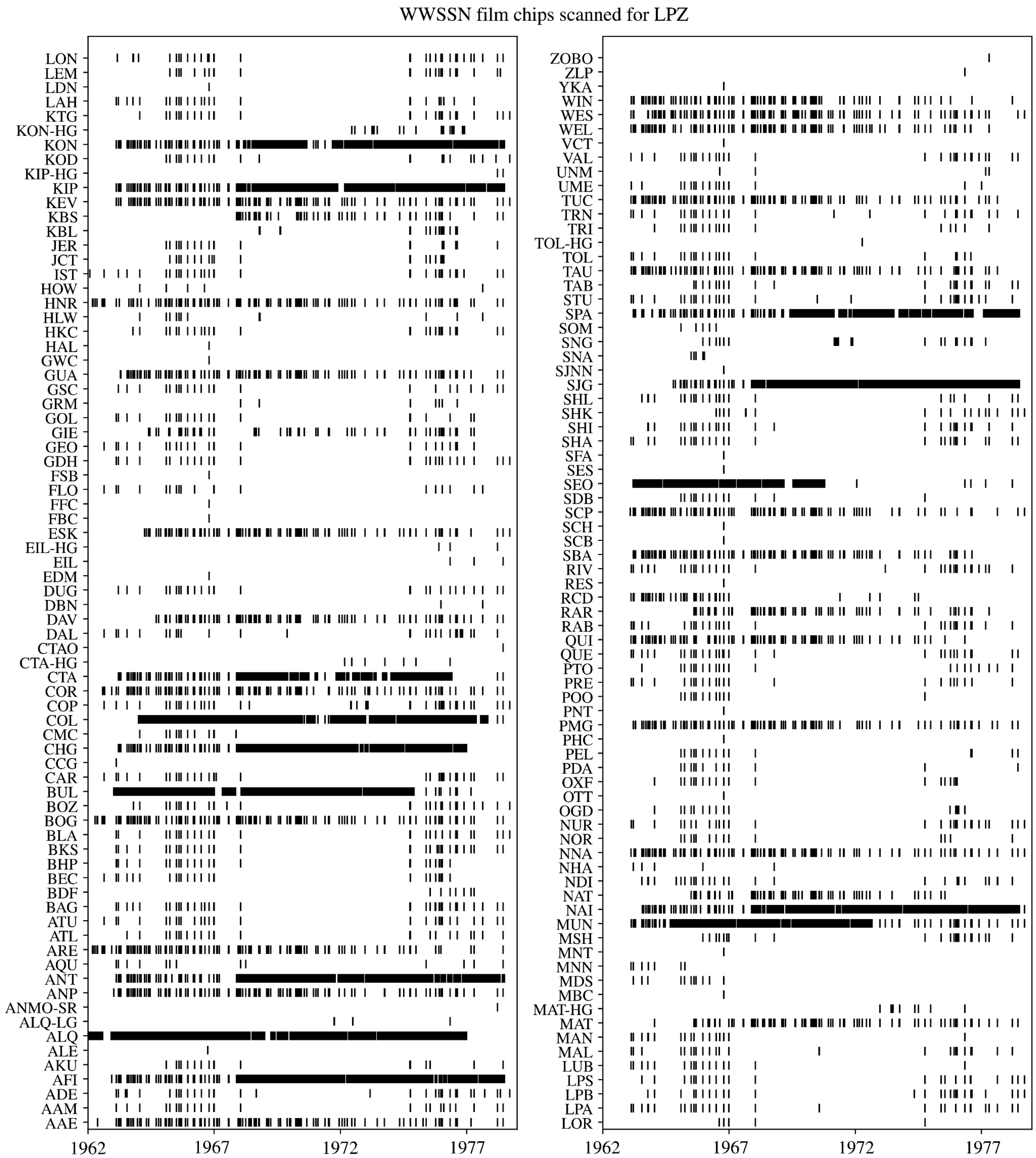
The Albuquerque Seismic Laboratory currently maintains a complete collection of microfilms from the WWSSN (~3.7 million). Records are stored in cabinets in shipping containers onsite. Approximately 5% (189,182 records) of the collection has been scanned and shipped to the IRIS Data Management Center (DMC). Scans of the 70mm x 120mm film chip, completed by private contractors, are 3200 dpi grayscale (8bit) in TIFF file format. Resolution is equivalent to 394 dpi.

The complete collection totals 7.61 TB has been shipped to IRIS DMC. It contains 156 nuclear events, 153 earthquakes, four reference stations (SJG, KIP, COL, and ALQ) and 244 film chips from part of the Canadian network.

For more information and access to part of the collection: http://ds.iris.edu/ds/products/filmchip/

IRIS DMC requests that the film chip data product be cited if used (IRIS DMC, 2011).

See also Supplemental Material: Analog records held in the Seabury Collection, Northwestern University, 5 March 2019.



Station film chip scans by day for all WWSSN stations and the Canadian network stations for the long-period vertical component (channel: LPZ). Each tick mark represents a single film chip that has been scanned. From Alejandro et al., (2018)

Central Asia (Burk et al., 2019a, Burke et al. 2019b)

Restoration and Recovery efforts in Central Asia are led by Michigan State University (MSU). MSU's mission is to facilitate scientific cooperation between the seismic institutions of states of the Former Soviet Union, as well as with institutions within the international community through the Seismic Cooperation Program (SCP).

The Probabilistic Seismic Hazard Analysis (PSHA) Project for Central Asia includes collaborators from the Institute of Seismology, Kyrgyzstan; Kazakhstan Seismological Expedition, Kazakhstan National Data Centre, IG and Institute of Geology, Earthquake Engineering, and Seismology, Tajikistan. The project goal was to provide a unified seismic bulletin.

As part of this project both event data and station metadata were compiled. The station database includes station code, network code, location, instrument type, open/close date, and a link (if possible) to a document containing a station passport. Most are currently basic text files, but some are full documents including photographs and calibration information. Eventually as the information is retrieved, the passport will contain poles & zeros for channel response.

Restoration efforts include peaceful nuclear explosion (PNE) seismogram digitization via the Wavetrac software and stored as miniSEED. Central Asia historical strong motion digitization and Kazakhstan DSS profile magnetic tape recovery. The DSS profile archive in Kurchatov holds ~6500 magnetic tapes (only ~2000 are labeled), 225 paper folders with metadata, and >300,000 paper seismograms. Digitization of these records is in progress.

Recording of PNEs was to photosensitive paper. A scan resolution less than 600 dpi was insufficient to capture accurately higher frequencies (>1 Hz), e.g.

600dpi * (30mm/minute/25.4inches) /60 sec = 11.8 dots per second

This is less than a 6 Hz. However. to obtain adequate amplitude resolution a 5x oversampling ratio is required. Hence, the realized resolution is closer to 1 Hz

Contrast control was also very important for faded and faint traces. The vectorization process included corrections for variable drum speeds and curvilinear motion of the recording device. Signal up to 5-8Hz were recoverable.

Currently 10% of MSU holdings have been digitized.

See also Supplemental Material: A New Seismic Catalog in the Caucasus Using Digitized Legacy Data.

OTHER PROJECTS

The following lists projects reported elsewhere including Lee and Benson (2008), Okal (2015), and Okal (2017) or as noted. The list should not be considered complete.

Stations

BAT

Batavia/Jakarta. >500 digital pictures of seismograms 1910.04.12 – 1935.12.29

Canberra

Canberra, Australia. Scanning project on hold.

CGH/CTO

Cape Town, South Africa. Scans from 1920-1947.

GTT

Gottingen. Microfilms at USGS Golden of M≥7. Scans at Northwestern.

HON/KIP

Honolulu/Kipapa, Hawaii. Scanning project initiated 2017. Recordings exist 1912-2013 (~ half million seismic records). Records were safely evacuated to Hilo due to damage to the observatory during the 2018 Kilauea eruptions (Okubo, *personnel communication)*

See: http://www.bigislandvideonews.com/2017/05/06/volcano-watch-stacks-of-paper-quake-records-tranformed-into-digital-squiggles/

https://hilo.hawaii.edu/depts/geology/documents/SeismicArchive.pdf

MIZ

Mizusawa, Japan. Scans of entire collection dating back to 1905 available on DVD at Tohoku University.

SJG, SJP, VQS

San Juan, Puerto Rico. 550 seismograms scanned as part of the "Reference Stations of the World" project (1926-1945, 1946-1949; 1950-1954, 1955-1963).

See: https://ds.iris.edu/seismo-archives/stations/

https://ds.iris.edu/seismo-archives/stations/puerto_rico/

WES

Weston, Massachusetts. 2600 seismograms were scanned from the station at Weston Observatory, covering the years 1936–1977.

Events

Japan

Currently constructing databases of digitized historical records and seismogram images for the 1923 Kanto, 1944 Tonankai, and 1946 Nankai earthquakes. (Murotani et al., 2020)

IRIS SeismoArchives

The project includes archives by individual earthquakes, archives by stations (see below), archives by special projects, and background information. The endowed earthquake archives include seismograms, selected information, and references to scientific publications.

See: http://ds.iris.edu/seismo-archives/
http://ds.iris.edu/seismo-archives/quakes/

Networks

Carnegie Institution: AKU, CUS, DTM, TRU, TCC, KMU, SWU, AMT, PMG

From Supplemental Material: Digitization of Carnegie Analog Broadband Seismograph Tapes

Between 1965 and 2003, the Carnegie Institution of Washington operated a network of 9 broadband seismograph stations spread over the world. The instruments recorded data to analog magnetic tapes, which were preserved to this day in reasonably good condition thanks to storage in a magnetically shielded room that was specifically designed for this purpose. …

The final primary data products are properly time stamped miniSEED files to be archived at the IRIS Data Management Center (DMC). In addition, we are planning to archive the raw digitized HDF5 files, so that future researchers have the option to reprocess this dataset from scratch if they so desire. All paper-based field notes are scanned to PDF files a subset of the metadata found within is retyped into machine readable format.

See also: Golden et al., 2020

China

Early stage seismograms from China are scarce. The existing analog seismograms written on smoked or photographic paper have survived damage from the passage of time, war, and social unrest. Instrumentation from 1904-1949 included Omori, Wiechert, Galitzin, and Galitzin-Wilip. Beginning in 1976, seismograms were preserved on microfische. 540 of these records have been scanned and published on CD ROMs (Department of Monitor and Prediction in CEA, 2005a,b,c).

TABLE 2
Microfiches and Scanning of Seismograms

Number	Name	Code	Instruments	Microfiche Time Period	Scanning Time Period and Number
1	Xujiahui	ZS	Omori	19060413–19131231	19060413–19111014, 7
			Wiechert	19090418–19131231	19090511–19480303, 153
			Galitzin	19150305–19400931	19150428–19410516, 22
			Galitzin–Wilip		19190724–19380907, 17
2	Dalian	DR	Omori	19380201–19431231	19180907–19431201, 63
			Wiechert	19301226–19450909	19310127–19450628, 150
3	Qingdao		Wiechert		19120325–19251007, 17
4	Chongqing		Ni		19431022–19460508, 46
5	Shuijing		Ni(I)		19470327–19481224, 65

(Wang, 2020)

Icelandic Meteorological Office

From their website: http://seismis.hi.is./

A project to make historical seismograms from stations in Iceland available in digital form was initiated in 2017 by Sigurdur Jakobsson and Pall Einarson, with an initial grant from Eggertssjódur, and the plan is to transfer all analog seismograms to a digital form before the end of 2020. Recording of analog seismic records in Iceland began in 1910 when the first seismograph was installed in Reykjavík. The number of seismic stations increased greatly in the 1970s and reached a maximum in the late 1980s. Digital recording began in 1990 and since 2010 all seismic recording is digital. Jpg files (300dpi, original size 435 x 945 mm) of analog seismograms will be stored on a server at the Institute of Earth Sciences, University of Iceland, and are made available to the public on this webpage. The original seismograms are stored in the Icelandic National Archives.

As of October 4, their website lists 110,564/300,00 *est.* seismograms available. High resolution waveforms are on the order of 4-8 Mb each (Einarsson and Jakobsson, 2018).

Japan

High resolution scans of the Wakayama microearthquake network (3 stations, ~12,650 records from 1928-1968) and the tsunami waveform archive (~3100 records) on Japanese tide gauges from large earthquakes between 1911 and 1996 available through the ERI website. (Satake et al., 2020)

See: http://wwweic.eri.u-tokyo.ac.jp/wakayama/

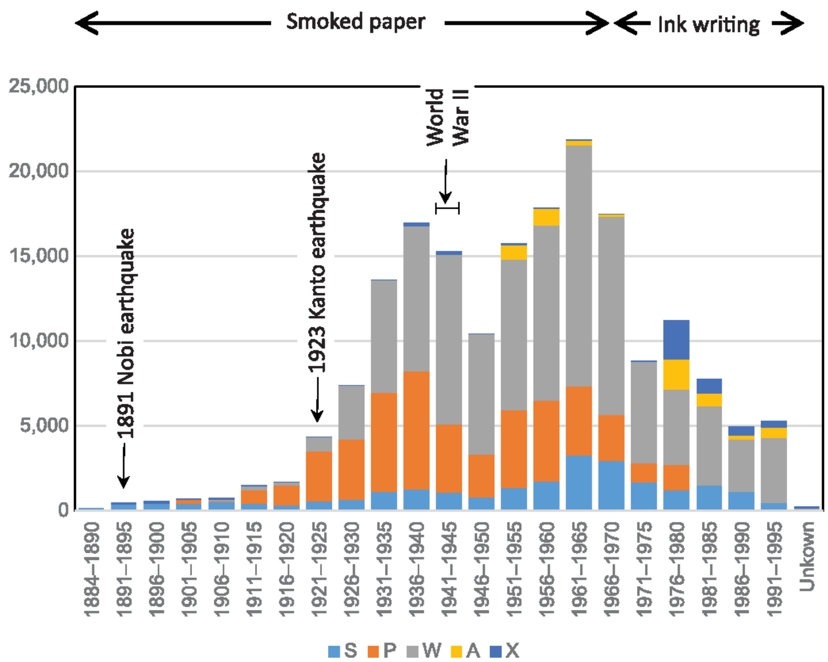
http://wwweic.eri.u-tokyo.ac.jp/tsunamidb/index.html

Japan Meteorological Agency

Seismograph based observations began in 1884 at the Tokyo Meteorological Observatory the predecessor to the Central Meteorological Observatory which in 1956 became the Japan Meteorological Agency (JMA). Digital recordings began in the 1990s. Analog recordings exist on smoked paper and ink. Analog recordings from 1988-2007 were initially archived on microfilm. Inconsistencies were discovered in the archiving of the microfilms that required checking phase picking records. Not all records exist today due to damage from sunlight, use, and or mold. Seismograms from all stations for destructive earthquakes $M \geq 6$ were scanned. In addition, scans were made of records with event amplitudes greater than 1mm for strong-motion type instruments and 10mm for the Wiechert seismograph. Prioritization for scanning was given to smoked paper records.

Seismograms were scanned using flatbed color scanners. Images were saved as 8-bit color TIFF with some color tuning for faint records. Original files are ~200 MB (400 dpi) and ~400 MB (500 dpi) and then compressed as JPEG2000 when added into the database. As of March 2019, over 185,000 images from 113 stations have been scanned. Seismograms can be retrieved from the JMA and searched by date, station name, and component. Low resolution thumbnails (~1-2 MB) are available for preview. The project requests that digital waveform data produced from these records be donated back to the project for reuse by others.

See the Headquarters for Earthquake Research Promotion (HERP) data retrieval system of the JMA at: http://www.susu.adep.or.jp/



The number of digital image files of scanned seismograms in 5 year intervals. Seismographs are classified into five groups by their magnification.

(Furumura et al., 2020)

Leo Brady Network

The Leo Brady Seismic Network (originally the Sandia Seismic Network) was established in 1960 by Sandia National Laboratories in order to monitor underground nuclear tests at the Nevada National Security Site (formerly named the Nevada Test Site). This project has digitized tapes from 592 underground nuclear tests. (Young and Abbott, 2020)

Ohio Geological Survey

From Fox (2019):

The Ohio Geological Survey (OGS) is the current proprietor of eighty-three years' worth of analog seismic records of the Jesuit Seismological Association, recorded at the John Carroll University (JCU) near Cleveland Ohio. The collection contains records from the 80-kg Wiechert seismograph spanning the years 1909 to 1947. JCU then installed two long-period horizontal and one short-period vertical Sprengnether instruments. The Sprengnether instrument records contain traces from July 1947 to 1986. In 1986 a multi-station network of short-period L4 seismometers were used until the end of operations in 1992. The Ohio Seismic Network saved these paper recordings from destruction and has housed them at the H.R. Collins Laboratory in Delaware, OH since 1999.

Recent preservation grants have been obtained by OGS through which the archiving, detailed cataloging and preservation work has begun. Phase-I was completed in mid-2018 and it is anticipated that two more phases will be required to complete the project. Over 100,000 seismograms are currently in the inventory and are nearly complete. The records have not been inventoried in detail but appear to be continuous from the early 1920's through 1931. From 1931 – 1936 JCU was in the process of moving locations, so no records exist during this time. Work has begun listing the significant global, regional and local earthquakes contained in the collection, which are recognized in the traces. Digital scanning has begun on select seismograms and the entire collection is available in-person to interested researchers. This presentation covers the history, current inventory, progress and plans for this rare collection.

Southern California Seismic Network: BAR, PAS, RVR, TIN, GSC

12,223 scanned images of pre-digital analog recordings of major earthquakes recorded in Southern California between 1963 and 1992. Scanned images of paper records for M>3.5 southern California earthquakes and several significant teleseisms are available for download via SCEDC (BAR, PAS, RVR, TIN, GSC), and specific instruments (Wood-Anderson, 1–90, 30–90, and the WWSSN long-periods at GSC)

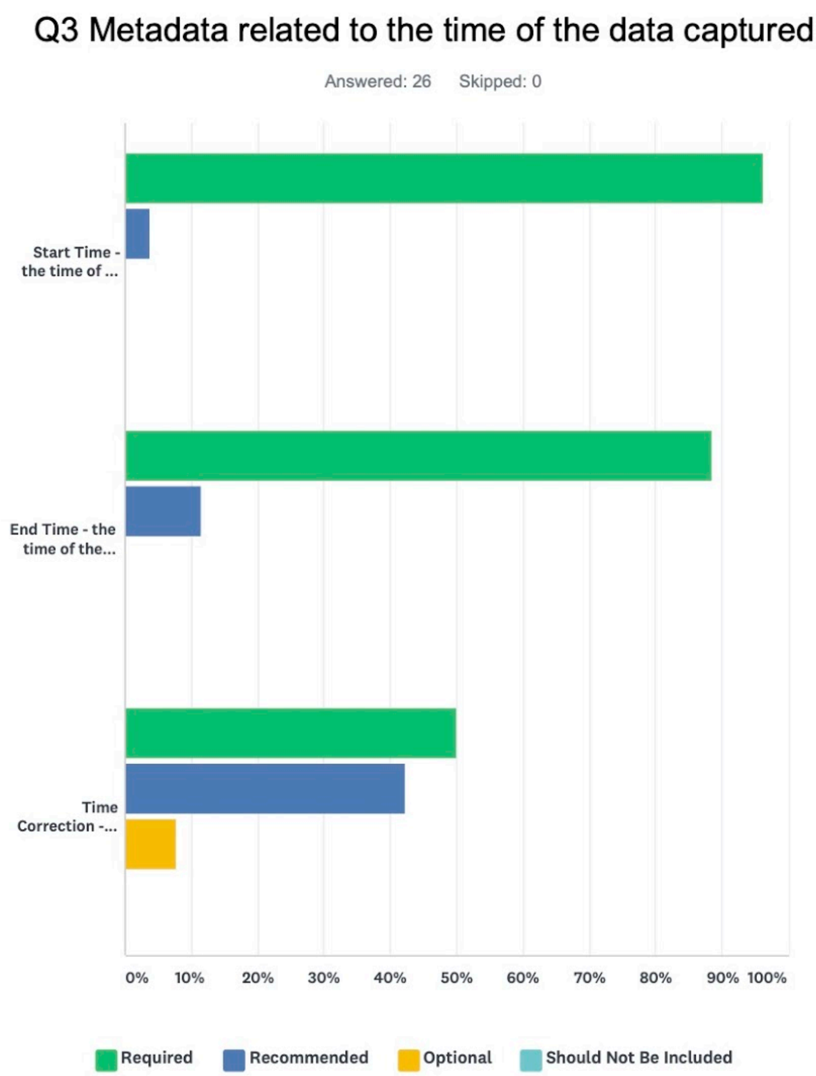
See: https://scedc.caltech.edu/research-tools/seismograms.html

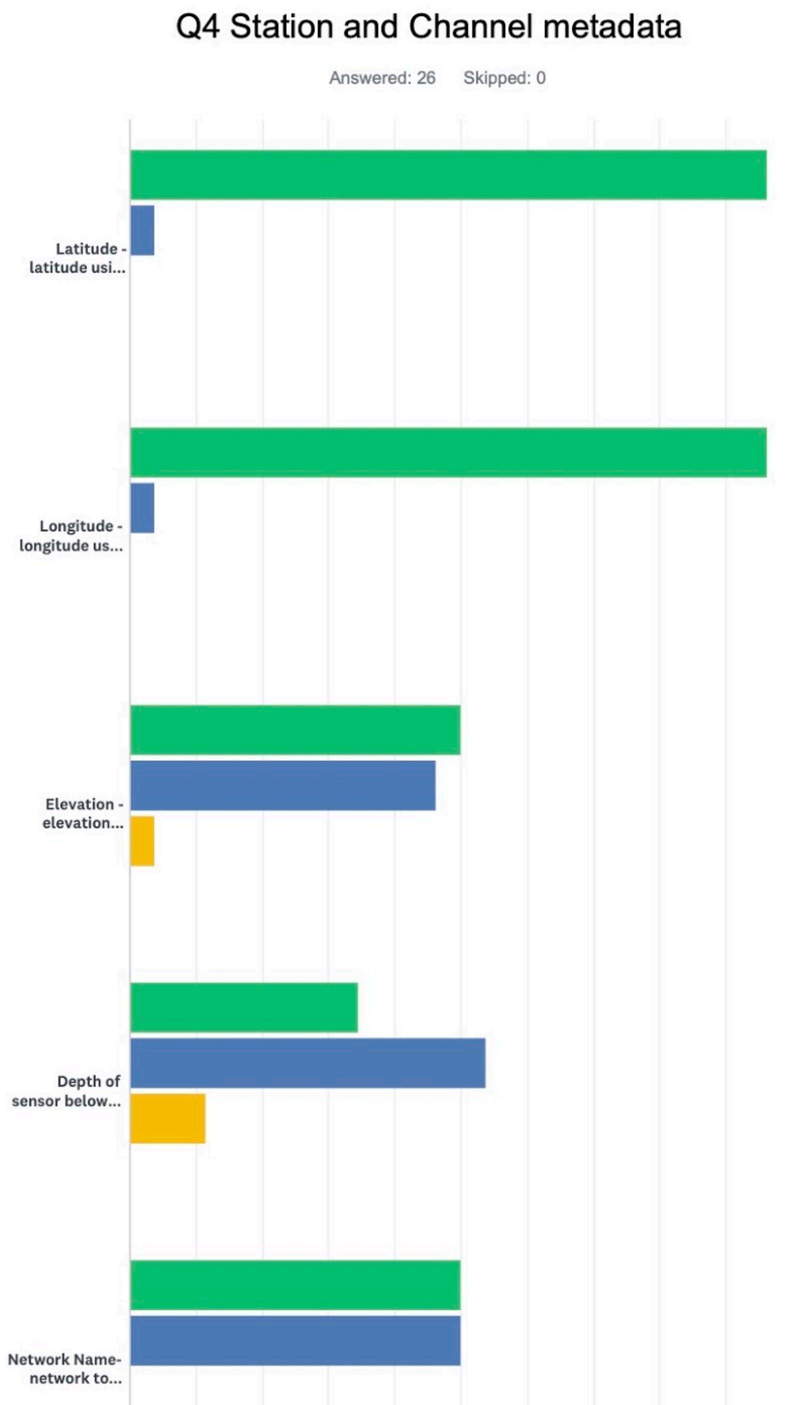
Seismological Laboratory, California Institute of Technology

Select images (~70,000) from 1928-1936 and special collections were scanned by Google in collaboration with UC Santa Cruz as part of the Google Books project.

See: http://ds.iris.edu/seismo-archives/projects/
http://ds.iris.edu/seismo-archives/projects/caltech_archive/

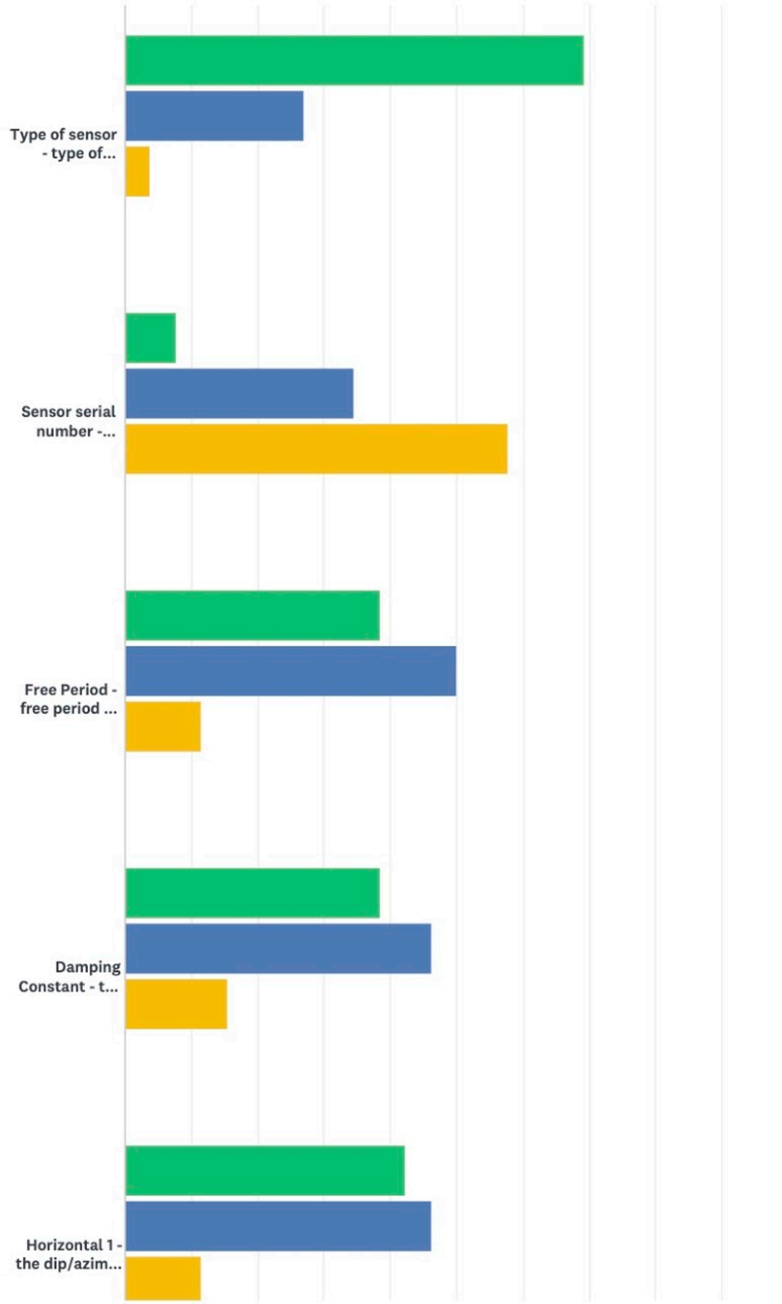
Appendix D. Results of Metadata Survey




Q4 Station and Channel metadata
Answered: 26 Skipped: 0
Latitude - latitude usi...
Longitude - longitude us...
Elevation - elevation...
Depth of sensor below...
Network Name- network to...

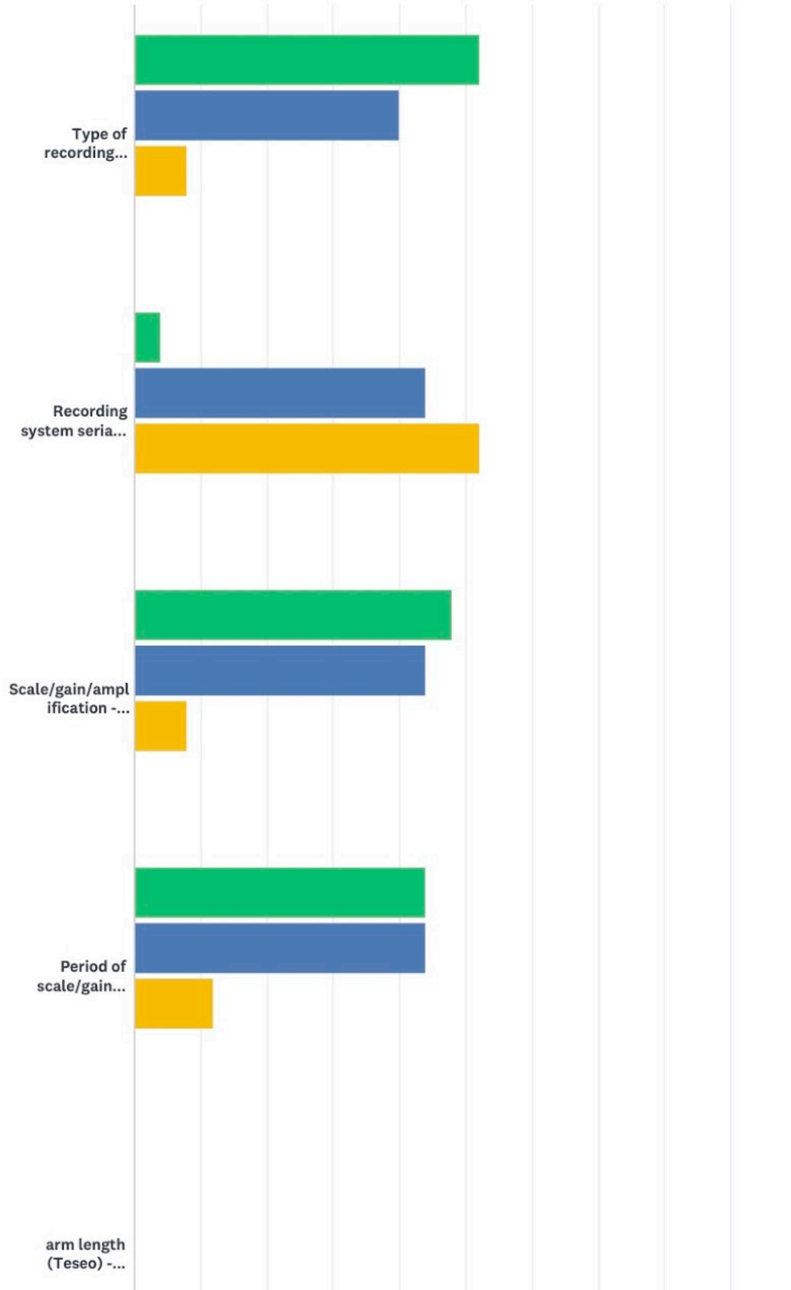
Q5 Sensor Metadata

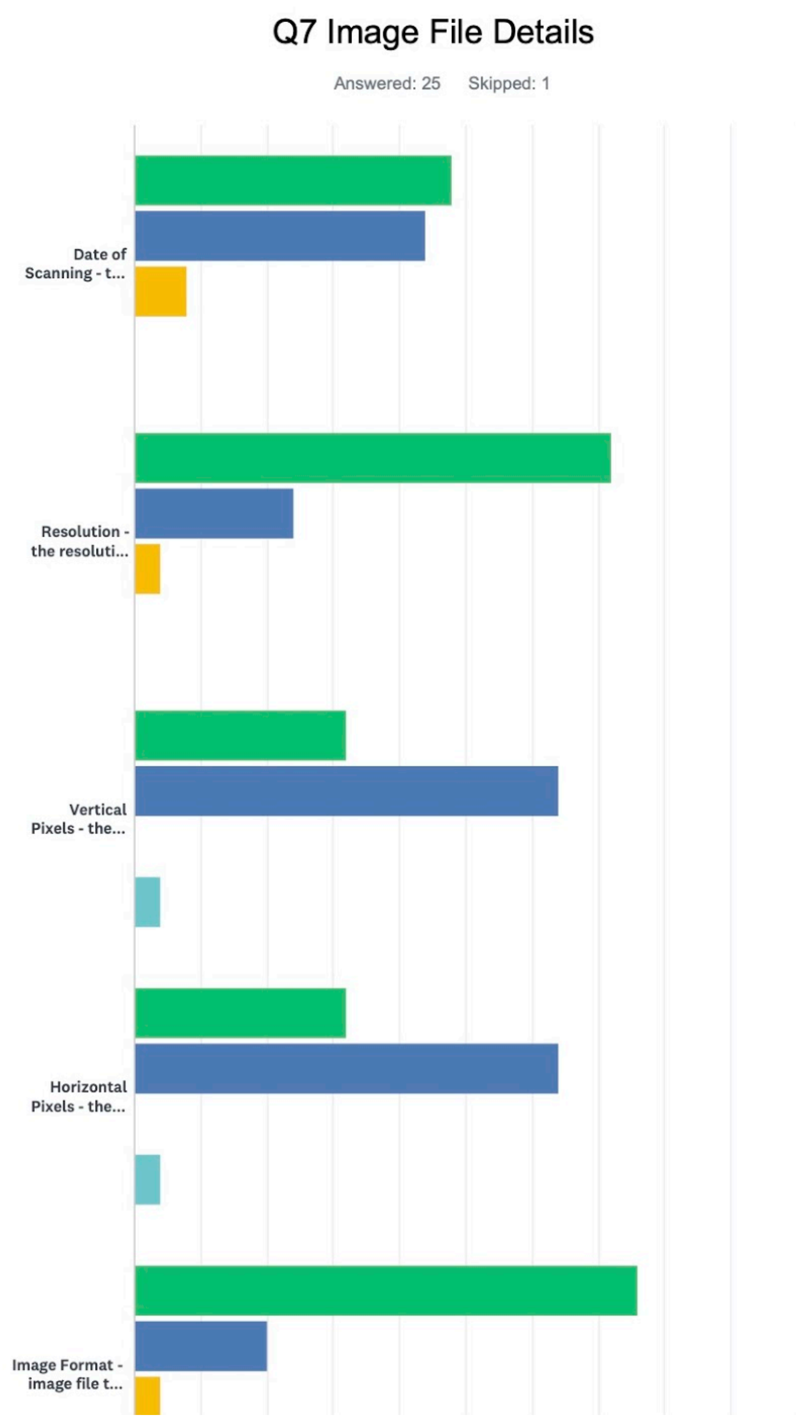
Answered: 26   Skipped: 0



Q6 Recording System Metadata

Answered: 25 Skipped: 1





Q7 Image File Details
Answered: 25 Skipped: 1
Date of Scanning - t...
Resolution - the resoluti...
Vertical Pixels - the...
Horizontal Pixels - the...
Image Format - image file t...

Appendix E. Use Case Summaries

A template was provided to participants to describe use cases for analog seismic data. Use cases provides a narrative of how a researcher or other users would interact and use the data and could include processes such as search, access, data reduction, and data manipulation to achieve stated research objectives. The purpose of the exercise was to inform the software and metadata requirements for the development of infrastructure necessary to enable FAIR data.

Benioff Search *contributed by Jim Dewey*

Summary:

> Writing a summary of the Benioff seismometer and will be looking for examples. Looking more for a record of examples but would like to digitize the images to look at spectra for different types of events recorded on a Benioff seismometer. I would only want digitized records.

Search Workflow:

> Specific instrument type e.g. Benioff seismometer
>
> Digitized records

Use:

> > Spectral analysis

Investigation of 1970s Mauna Loa and Kilauea Eruptions *contributed by Thomas Lee*

Summary:

> The 1970s mark both the last eruptions of Kilauea in the summit area (Mauna Ulu) before the near continuous 1984-2018 eruptions, and the last time Mauna Loa erupted. These events are only recorded in the analog and are crucial to understanding the volcanic systems of Hawai`i. While there was certainly analysis done at the time of these events, our understanding would likely see great benefit from a revisiting these records with modern analysis techniques.

Katmai Eruption *contributed by Jim Dixon*

Summary:

Want to see what data would exist for this event in early June.

Search Workflow:

*S*earch for wide-world for records on June 6-9

Postconditions:

Data shown to be available or not. It would be useful to know if the scanned image has already been digitized to prevent me from repeating the effort. I would not expect this to be tagged as an already identified event.

Storm Strength Analysis From Analog Record Noise *contributed by Thomas Lee*

Summary:

The Northeastern United States typically has several nor'easter storms per year, and there has been much investigation regarding whether climate change has had an effect on the characteristics of these storms. Studies have shown that the strength of microseisms induced by oceanic waves increases with the strength of storms and hurricanes. This effect can be leveraged along with the long time-span of analog records at the HRV station at Harvard, MA to compare storm strength estimates from the 1930s and 1940s with storm strength estimates computed in the same way today. This will allow for a quantitative analysis of changes in storm strength in the last 80 years.

Precondition:

Digitization of sufficient HRV records to cover periods coinciding with historic nor'easters. Identification of sources that list the time and locations of historic nor'easters.

Use:

Spectral analysis

Multi-decadel Modal Studies *contributed by Robert Casey*

Summary:

Considering a hypothetical use case where the S(0) and higher geoid modes need to be studied for the past century.

Preconditions:

Need to find very low period data covering different parts of the globe for an extended period of time. Data needs to be digitized such that a sample rate of 1/10 or 1/100 SPS data can be retrieved. The largest difficulty is the file count that must be traversed, as opposed to the sheer volume of data returned.

Postconditions:

Modal studies of the earth can be conducted in a far more historical perspective than has been possible before. The possibility of discovering patterns in the ringing of the planet may become clearer with more data to work from. The nature of the mantle and core may be further revealed in the flexion studies that result.

Workflow:

Search for historical data from equidistant stations around the globe that have a long period of run time.

Find references to images that may be located at various data centers. Use a federated catalog reference.

Pull back the images and apply digitization, decimation, and ground motion conversion.

Apply decimated data to modal studies.

Exceptions:

There may be large gaps in datasets. How much can this be remedied?

It may be difficult to derive consistent ground motion from all stations.

It may take a lot of I/O and processing time just to preprocess the data.

Requirements:

There needs to be a sufficient continuity of data from enough stations to affect a clear progression of global motion. This requires at least a handful of equidistant stations to have long runs of viable data.

Study of Historical Earthquakes in a Region *contributed by Diane Doser*

Summary:

Download seismograms for one or more events to model body or surface waveforms (long period records) and check short period instruments for first motion information

Preconditions:

Need to search specific times/days for the earthquakes of interest. Need to check distribution of stations (azimuthal coverage), also need to know lat/long of stations so one can compute distances and see if certain phases are suitable for modeling.

Postconditions:

Collection of scans from stations that can be digitized and analyzed using a variety of waveform modeling techniques.

Search Workflow:

Look for stations that record an earthquake on a certain date.

Get list of available stations plus information on types of instruments (long period versus short period, components)

Next would do a calculation of the distances and azimuths of the stations from event of interest (this could be done off-line, not necessary to do on-line)

Based on distances and azimuths select stations of interest

It would be nice at this point if we could view thumbnails of the scans (for example, we may find the seismogram is too noisy to use and would search for another possible station)

It would also be helpful to know if there are other data (like instrument responses) before committing to download scan.

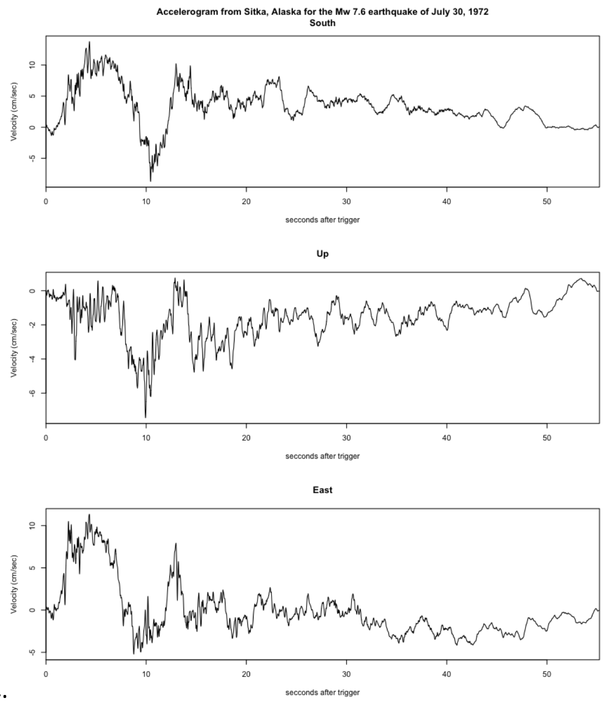
Once stations with reasonable looking thumbnails are noted, download the scans

From there use software of choice for digitizing.

Exceptions:

I would think people could mistype dates or actual station name. I think a simple error response would be sufficient for these.

Applying Modern Methods to the 1972 Sitka, Alaska Earthquake *contributed by Bill Ellsworth*



Summary:

The M_w 7.6 Sitka, Alaska earthquake of July 30, 1972 ruptured a segment of the Queen Charlotte/Fairweather fault, filling a major seismic gap. Little is known, however, about the extent of the rupture, including its endpoints. The goal of this study is to assemble global recordings for kinematic and back projection analysis of the rupture. A key question is if the rupture was supershear over any of its length.

Preconditions:

Availability of data from stations within the teleseismic P- and S-wave window (~30 to 85 degrees) and at regional distances. Availability of data from strong motion instruments at near and regional distances. Particular value in data from networks that can be used as arrays to track radiated energy in space and time.

Workflow:

1. Determine availability of seismic recordings that may be suitable for analysis

2. Review images of recordings to determine suitability of data.

3. Obtain high-resolution scans of acceptable data.

4. Extract time series from scanned images.

5. Apply instrument corrections to obtain calibrated ground motion.

6. Perform kinematic rupture inversion.

7. Use dense array observations (e.g. Northern California Seismic Network) for back projection and comparison with kinematic models.

Exceptions:

Potential need to request original records or copies from individual network operators for custom scanning.

Potential need to improvise instrument corrections using relative calibration methods.

Requirements:

Data must be capable of resolving relative time to 0.2 s and frequencies in the 0.1 – 2 Hz band.