Making Non-Digitally-Recorded Seismograms Accessible Online for Studying Earthquakes

W. H. K. Lee and R. B. Benson

Foreword Instrumental observations of earthquakes using the available technology at different times have been carried out over the past 120 years at either single seismic stations or networks of various sizes, from local to global scales. Before the 1980s, almost all seismograms were recorded on paper or photographic medium. Due to wars or neglects, many of these analog (or non-digitally recorded) seismograms had been lost, or are deteriorating and disappearing in a rapid rate.

This article is intended to summarize the authors' efforts to rescue and preserve seismograms, and to post non-digitally recorded seismograms and related research materials online for free access by anyone, anywhere. We also included some background information about observational seismology and constructions of online archives of old seismograms by others.

1 Introduction

Seismology became a quantitative scientific discipline after instruments were developed to record seismic waves in the late 19th century (Dewey and Byerly 1969; Agnew 2002). Earthquake seismology is essentially based on field observations. The great progress made in the past several decades has been primarily due to increasingly plentiful, high-quality digital data that have been archived in open and readily accessible archives designed exclusively for this purpose (see e.g., Ahern 2003). Our ability to collect, process, and analyze earthquake data has been accelerated by advances in electronics, communication, computers, and software, and is no longer limited by communication and technical difficulties that hampered scientists in the early years of seismology.

Historically, instrumental observations of earthquakes using the available technology at different times have been carried out over the past 120 years at either single seismic stations or networks of various sizes, from local to global scales (see e.g., Lee 2002). The observed data have been used, for example, (1) to compute

W. H. K. Lee
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, USA
e-mail: lee@usgs.gov

J. Fréchet et al. (eds.), *Historical Seismology*,

the source parameters of earthquakes, (2) to determine the physical properties of the Earth's interior, (3) to test the theory of plate tectonics, (4) to map active faults, (5) to infer the nature of damaging ground shaking, and (6) to carry out seismic hazard analysis. Constructing a satisfactory theory of the earthquake process has not yet been achieved within the context of physical laws. Good progress, however, has been made in building a physical foundation of the earthquake source process, partly as a result of research directed toward earthquake prediction. All of this effort has been hinged on reliable data access.

However, the instrumental record of earthquakes collected over the past 120 years is too short for reliable seismic hazard assessments and therefore, non-instrumental observations of earthquakes in the past must be utilized as much as possible. For example, Jean Vogt (1979) led an in-depth research program for revising French earthquake catalogs to better understand the seismicity near nuclear power plants in France, as required by the French government for safety considerations. The importance of historical records about earthquakes is well-recognized as shown in many articles of this volume. Semi-quantitative analysis of earthquake intensity data has been practiced for many decades in preparing seismic hazard maps (see, e.g., Frankel et al. 2000; Musson and Cecic 2002; Giardini et al. 2003). In addition, extending our knowledge about earthquakes by means of archaeological and paleoseismogical methods and techniques have been pursued by many scientists as summarized, for example, by Nur (2002) and by Grant (2002), respectively.

This article is intended to summarize the authors' efforts (in the past three decades) to rescue and preserve seismograms, and in particular, to post non-digitally recorded seismograms and related research materials online for free access by anyone, anywhere. We also included some background information about observational seismology and constructions of online archives of old seismograms by others.

2 Seismographs for Monitoring Earthquakes

Besides geodetic data (see, e.g., Feigl 2002), the primary instrumental data for the quantitative study of earthquakes are seismograms, records of the ground motion caused by the propagation of seismic waves generated by earthquakes. Seismograms are written by seismographs, instruments that detect and record ground motion with timing information. A seismograph usually consists of three components: (1) a seismometer that responds to ground motion and produces a signal proportional to acceleration, velocity, or displacement over a range of input motions in amplitude and in frequency; (2) a timing device; and (3) a recording device that writes seismograms (ground motion plus time marks) on papers or on electronic storage media. An accelerograph is a seismograph designed to record the time history of acceleration of strong ground motion on scale. Most modern seismographs are velocigraphs recording the time history of ground velocity (see e.g., Wielandt 2002 for a discussion of seismometry). A seismic network (or array if sensors are in close proximity to one another) is a group of seismographs that are "linked" to a central headquarters. The link is by mail or telegrams in the early days or simply by manual collecting of the records, and by various methods of telemetry since about 1950s. When we speak of a seismic station, it may be an observatory with multiple instruments in special vaults, or a small instrument package buried in a remote unmanned site.

2.1 Early Years

In the beginning of instrumental seismology, observatories with various types of seismographs operated independently. The observatories were linked by mail, which could take months. Many seismological studies require seismograms or their readings from multiple stations. For example, arrival times of seismic waves from at least four well-distributed stations are needed to locate an earthquake satisfactorily. Even after one managed to get a few seismograms, it was difficult to work with records from different instruments with poorly synchronized time until after about 1930.

In the late 19th century the need for standardization and for data exchange was recognized by G. Gerland, J. Milne, and E. von Rebeur-Paschwitz. With the support of the British Association for the Advancement of Science, over 30 Milne seismographs were placed at locations throughout the British Empire beginning in the late 1890s, and seismogram readings were reported to Milne's observatory at Shide on the Isle of Wight, England. A global earthquake summary with seismogram readings was issued by John Milne beginning in 1899, as shown in Fig. 1 by Milne (1900). These summaries are now known as the "Shide

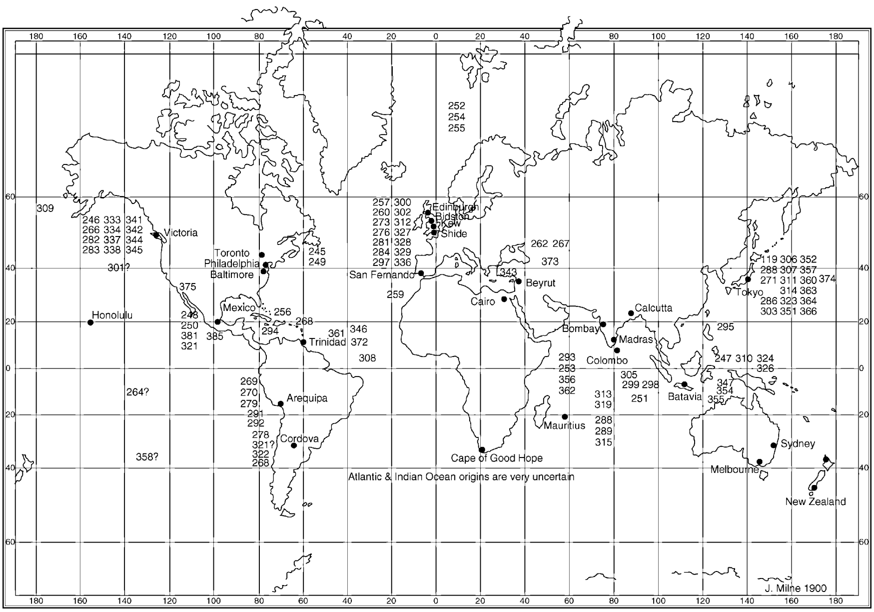


Fig. 1 Global earthquakes and seismograph stations in 1899, as published in Milne (1900). Numbers refer to earthquakes listed in Milne's catalogue and show approximate positions

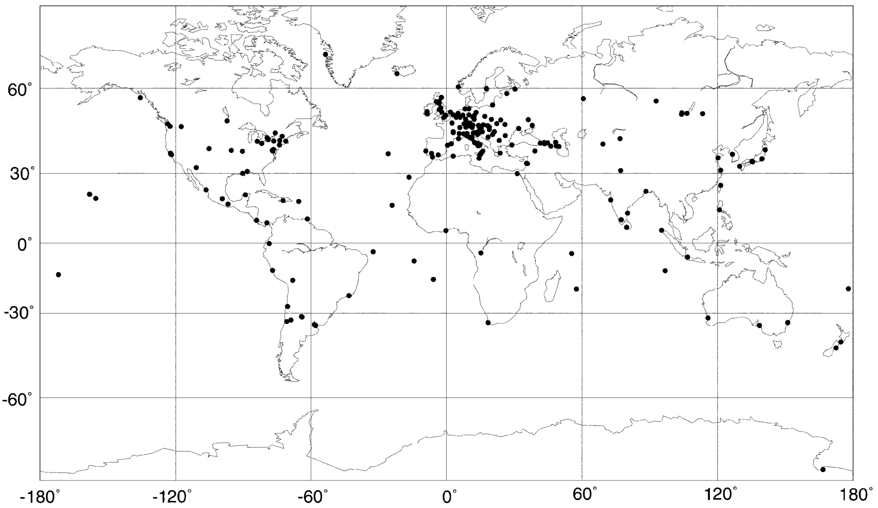


Fig. 2 A map showing all seismographic stations for which we could locate seismic bulletin materials with earthquake observations from before 1921 (from Schweitzer and Lee 2003)

Circulars" (Schweitzer and Lee 2003). Milne seismographs were soon superseded by more advanced instruments, and the Headquarters of the International Association of Seismology was established in Strassburg im Elsass (now, Strasbourg, France) by 1904 (Adams 2002).

Seismographs for recording teleseisms were installed at many observatories, especially meteorological and astronomical observatories. By 1920, about 250 seismic stations were established (although some operated only briefly), as shown in Fig. 2. The early enthusiasts included academic professors, Jesuits, and gentleman scientists. Revolutions and wars, however, frequently disrupted progress, especially in collecting and distributing earthquake information, during the first half of the 20th century.

2.2 WWSSN and ESSN

In the late 1950s, attempts to negotiate a comprehensive test ban treaty failed, in part because of perceptions that seismic methods were inadequate for monitoring the underground environment for nuclear testing (Richards 2002). The influential Berkner report of 1959 advocated major support for seismology (Kisslinger and Howell 2003). As a result, the World-Wide Standardized Seismograph Network (WWSSN) was created with about 120 continuously recording stations, located over much of the world (except China and USSR) in the early 1960s (Oliver and Murphy 1971), as shown in Fig. 3. Each WWSSN station was equipped with identical sets of short-period and long-period three-component seismographs and accurate chronometers. Seismograms were sent to the United States to be photographed

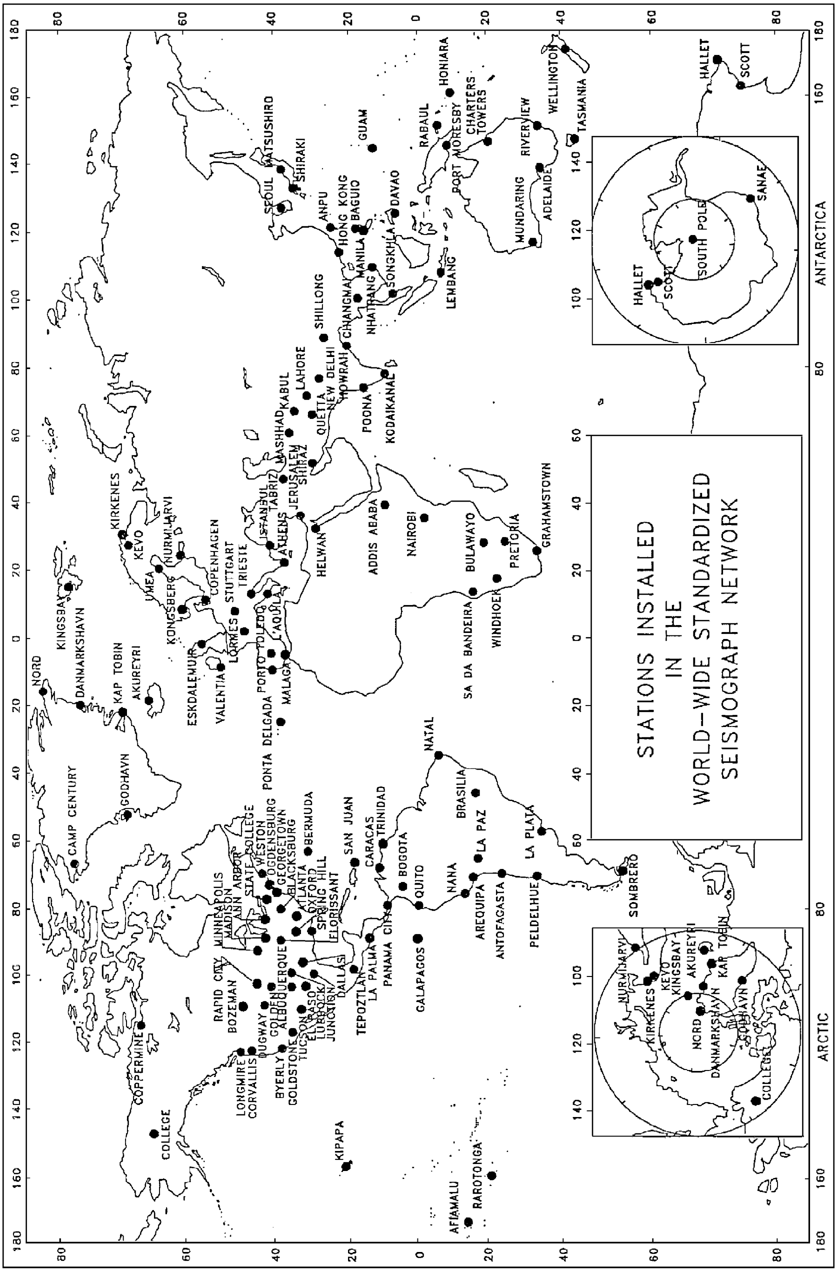


Fig. 3 Stations installed in the World-Wide Standardized Seismograph Network (WWSSN) in the 1960s

onto 70-mm film chips for distribution (about $1 per chip). This network is credited with making possible rapid progress in global seismology and with aiding the plate-tectonic revolution in the earth sciences in the late 1960s (Sykes 2003).

At about the same time, the Unified System of Seismic Observations (ESSN) of the former USSR and its allied countries was established for monitoring earthquakes, consisting of almost 100 stations equipped with Kirnos short-period, broadband (1–20 s displacement sensing), and long-period seismographs, as shown in Fig. 4 (Shishkevish 1974).

Despite its great success, the WWSSN declined after the mid-1970s. By then it had produced about 4 million seismograms, far more than seismologists could efficiently process and analyze. After about 10 years of operation, funding for the WWSSN began to disappear. The initial cost was funded by the U.S. Defense Advanced Research Projects Agency (DARPA), which emphasized research and not long-term operation. Funding for continuing the WWSSN was then left to the National Oceanic and Atmospheric Administration (NOAA) and subsequently to the U.S. Geological Survey (USGS). Because of statutory restriction, the USGS could not support global stations outside the United States. Although the U.S. National Science Foundation (NSF) did pick up the funding for supporting foreign stations for some time, NSF also wanted to avoid funding any ongoing seismic networks. In addition, the emphasis in seismology at the USGS was shifting to earthquake prediction, then considered a new and promising venture. Earthquake prediction, however, turned out to be far more difficult than anticipated (e.g., Kanamori 2003).

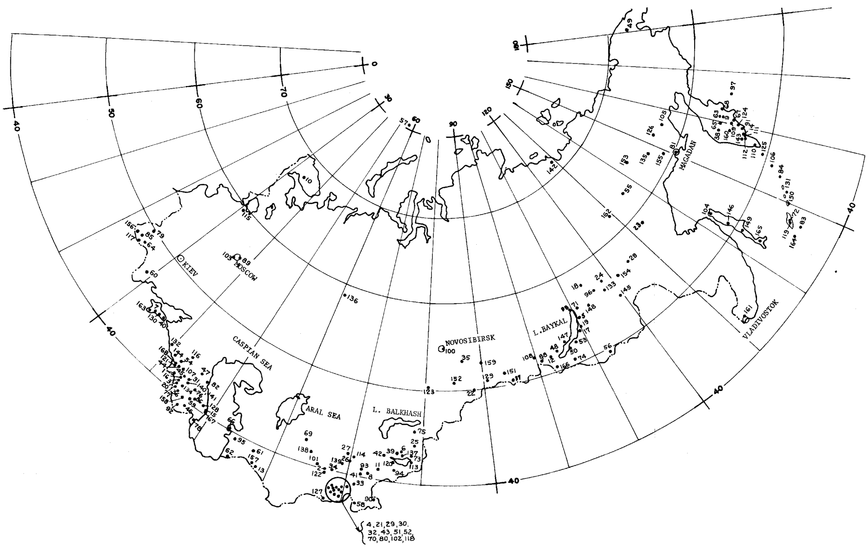


Fig. 4 Location of seismographic stations in the USSR (from Shishkevish 1974). Station names corresponding to the numbers shown can be found in Shishkevish 1974 (p. 10)

2.3 The Digital Revolution and the GDSN

Because analog (i.e., non-digitally recorded) seismograms have a low dynamic range (about 3 orders or less in amplitude) and must be digitized for computer processing, some seismologists recognized that "digital" instrumentation should be developed to achieve a much higher dynamic range, and for ease of computer processing. Many scientists and engineers in other disciplines had already been making great advances in that direction because of the emerging digital technology in the 1970s. Seismologists had long recognized that the tandem use of short-period and long-period instruments was needed to avoid the natural seismic noise (see Webb 2002). They realized that a new global seismic network should be built with (1) broadband, high-dynamic range seismographs, (2) digital electronics, (3) communication by telemetry or a mass storage medium, and (4) processing by computers.

The introduction of electronic force feedback to sealed inertial seismometers (Melton 1976; Wielandt and Streckeisen 1982) together with the application of high-resolution analog-to-digital converters made it possible to construct broadband, large dynamic-range seismograph systems. Many of the WWSSN stations were replaced by broadband digital systems starting in the 1980s (Hutt et al. 2002). A global digital seismic network has emerged since the 1980s under the guidance of two effective organizations: the international Federation of Digital Broadband Seismographic Networks (FDSN), and the Incorporated Research Institutions for Seismology (IRIS). Digital seismograms recorded by stations worldwide are now readily available via the Internet from the IRIS Data Management Center (DMC) within tens of minutes of a $M \approx 5.7$ (all depths, or $\mathrm{M} = 5.5$ for events $> 100\,\mathrm{km}$ depth) or larger earthquake occurring anywhere in the world (Ahern 2003), as well as, for example, through the European ORFEUS center at De Bilt, the Netherlands, the GEOFON center at the GeoForschungsZentrum, Potsdam, Germany, the Programme GEOSCOPE at the Institut de Physique du globe de Paris, France. Large strides have been made in networking these data centers, as well, so that data can be accessed transparently through web or imbedded interfaces, eliminating the need to know the specific location of waveform data in these distributed archives.

3 Microfilming Historical Seismograms of the World

Before the digital era (prior to 1980), seismograms were usually recorded locally on paper (a common size is about 30 cm by 90 cm) every day. There are usually 6 seismograms at a given station: east-west, north-south and vertical components for both long-period and short-period seismometers. Because of their size and fine resolution, seismograms were not easily reproducible until the 1960s. Consequently, seismologists must spend large amounts of time and effort to collect seismograms for their studies of earthquakes that occurred before the WWSSN era (i.e., before

1963). Many seismograms have been lost because of two World Wars and numerous political disturbances, and also because of poor storage conditions for preservation.

As noted by Kanamori (1988), "... old seismograms, if properly interpreted, provide invaluable information on earthquakes in the past, and every effort should be made to save them, ..." Because modern digital seismograms cover only about the last 25 years, the analog seismograms collected during the first 100 years of observational seismology are very valuable for seismological research, especially in characterizing seismicity for seismic zonation, probabilistic seismic hazard analysis, and earthquake prediction research (Lee et al. 1988).

3.1 Preservation and Distribution of Historical Seismograms

In early 1977, W.H.K. Lee and J.F. Lander prepared a report, "A plan for establishing an international library of significant seismograms", and asked the International Association of Seismology and Physics of the Earth's Interior (IASPEI) to consider endorsing such a project. Lee and Lander's proposal was well received at the IASPEI General Assembly in August, 1977. Subsequently, IASPEI passed the following resolution:

> ...it is essential that seismograms of significant earthquakes be systematically collected and preserved by making photographic copies at observatory sites, and be made available through the World Data Centres. IASPEI urges that seismological observatories around the world cooperate with a copying programme....

Following up on this resolution, the IASPEI Sub-Commission on Data Exchange established a working group for copying historical seismograms with Jorgen Hjelme as Chairman. In 1978, W.H.K. Lee obtained funding from the U.S. Geological Survey to begin the Historical Seismogram Filming Project in collaboration with the World Data Center A. These early efforts are summarized in Meyers and Lee (1979).

3.2 Working Group on Historical Seismograms

In July 22–24, 1981, the United Nations Educational, Scientific and Cultural Organization (UNESCO) sponsored a meeting of experts on historical seismograms during the IASPEI General Assembly in London, Ontario, Canada. A joint IASPEI/UNESCO Working Group on Historical Seismograms was established with W.H.K. Lee as its chairman. The proceedings of this meeting were summarized in a UNESCO report released in September, 1981, which was included in Lee et al. 1988 (pp. 6–10).

In December 20–22, 1982, the Working Group convened a regional workshop at the Earthquake Research Institute, University of Tokyo, Japan. The primary purposes of this Workshop were (1) to gain interest and cooperation from Asian seismological observatories, and (2) to evaluate the existing seismograms recorded by the Asian observatories. Six technical sessions were held with over 50 participants. The proceedings of this meeting were summarized in a report to UNESCO in March, 1983, which was included in Lee et al. 1988 (pp. 11–13).

In August 18–19, 1983, the Working Group convened a workshop in conjunction with the IASPEI General Assembly in Hamburg, Germany. This Workshop was organized to discuss the status of historical seismic data for Latin America and Europe. It was divided into six sessions with a total of 29 presentations from representatives of 19 countries and 4 international organizations. The proceedings of this meeting were summarized in a report to UNESCO in October, 1983, which was included in Lee et al. 1988 (pp. 13–15).

In addition to microfilming pre-1963 seismograms, the Working Group was actively engaged in organizing auxiliary earthquake information (such as station bulletins), and promoting research in studying instrumental and pre-instrumental earthquakes. Consequently, the name of the Working Group was changed to "Historical Seismograms and Earthquakes". The status of the Historical Seismogram Filming Project was presented by Glover and Meyers (1988) and appeared earlier in more detail in Glover et al. (1985). In brief, over 500,000 seismograms and station bulletins from 450 stations around the world were microfilmed. Countries that participated include China, Egypt, Germany, India, Japan, Philippines, Peru, USA, and USSR.

Unfortunately, the main source of funding to microfilm seismograms worldwide was terminated by the U.S. Geological Survey at the end of 1985, and no other funding source was found to replace it. The Working Group came to a halt and was disbanded after a book describing this effort was published (Lee et al., 1988).

4 Scanning WWSSN Seismograms

The World-Wide Standardized Seismograph Network (WWSSN) was fully operational in 1963 under the auspices of the U.S. Coast and Geodetic Survey (USCGS). Each WWSSN station consisted of 3 short-period (SP) and 3 long-period (LP) seismometers, recording apparatus, radio-synchronized crystal clock, and calibration controls (WWSSN 1964; Oliver and Murphy 1971). Typically, six 300 mm × 900 mm seismograms were produced each day (3 SP and 3 LP). Data were originally recorded on photographic paper mounted on rotating drums, and later (1980s) on heat sensitive paper. The rotation rate of the SP drums was one revolution every 15 min, resulting in a 60 mm/min chart speed (1 mm/s). The rotation rate of the LP drums was one revolution per hour, resulting in a 15 mm/min chart speed. Note that some of the LP records in the early 1960s were recorded at 30 mm/min. There are minute marks on the records (an offset in the traces of 2-s duration every minute). The time marks were recorded using the NIST WWVB broadcast signal, and typically have an accuracy of better than 100 milliseconds. Hours are marked with a 5-s offset, with no offset on the 0, 6, 12, and 18 h UTC.

The original photographic records were photographed using 70 mm film and stored by station and year on 70 × 120 mm film chips (one seismogram per film chip). Lamont-Doherty Earth Observatory and the USGS Albuquerque Seismological Laboratory (ASL) each hold a complete film chip set of the WWSSN seismograms. The slow degradation of these film chips, however, prompted a pilot scanning project.

4.1 First Rescue Attempt of WWSSN Seismograms

The idea of scanning the WWSSN film chips within the USGS came about in 1996 by Charles R. Hutt. A limited amount of USGS "data rescue" funding was used to perform some test film-chip scans. Direct scans of the 70 mm film chips were found possible if one used scanners having a resolution of at least 3200 dpi. One of the original ideas was to also digitize the waveforms on the scanned images, but this was judged to be too expensive. In late 1998, two high-resolution scanners were purchased to scan as many film chips as possible with the available funding. The main events of interest at the time were underground nuclear tests, along with some earthquakes. The event list was chosen in consultation with other government agencies and researchers interested in the project, resulting in scanning about 30,000 film chips of 156 nuclear events and 78 earthquakes.

The film chips are black and white and were scanned with a resolution of 3200 dpi. This is equivalent to scanning the original 300 $\times$ 900 mm seismogram at 394 dpi (the seismogram image on the film chip is approximately 8 times smaller than the original seismogram). The image has been cropped to exclude areas on the film chip which do not contain the image of the original record, but includes the record stamp containing station name, component, start and stop date and time of the record, and magnification. Because the primary selection was on U.S. nuclear explosion events, the 78 selected earthquakes were made for comparison purposes, and thus are not necessarily of primary interest to earthquake seismologists. In 2004, it was agreed that the IRIS Data Management Center would be the perpetual archive for these and other image files of non-digital recorded seismograms (see Section 5.1 for a description).

4.2 Second Rescue Attempt of WWSSN Seismograms

In fiscal year 2004, the International Council of Scientific Unions (ICSU) provided modest funding to the USGS to scan some WWSSN film chips. The USGS provided a similar amount of "in-kind" support (film-chip storage, work space, management oversight, etc.). A total of 10,548 film chips were scanned for 117 selected earthquakes on the basis of interest to earthquake seismologists. Due to funding limitations, seismograms from only 38 out of 123 WWSSN stations were selected.

The earthquake selection was made by W.H.K. Lee, starting with the Centennial Earthquake Catalog of Engdahl and Villasenor (2002) and selecting the largest earthquakes down to magnitude of 6.9 for the time period from 1962 to 1974. He then considered earthquakes that killed a lot of people from Utsu's deadly earthquakes list (Utsu 2002), and added some smaller events of seismological interests. Since this initial list had about 250 events, Lee sorted them by Flinn-Engdahl regions (FER) (Flinn et al. 1974) and chose at least one event (the largest if more than one is available) in each region.

Because the list contains 151 earthquakes, about 50% more than that could be scanned, Lee circulated the list to about 20 earthquake seismologists worldwide for comments and suggestions. Since no one proposed to delete any earthquakes on the list, Lee downsized the list by choosing fewer events after 1970. The final list of 117 earthquakes selected for the USGS/ICSU scanning project is given in Table 1. The station selection was made by C.R. Hutt so that stations are well-distributed globally, in addition to being either the current digital GSN stations or reasonably proximal to one (distance indicated in the table, if applicable), and a listing of the selected WWSSN stations is given in Table 2.

5 The SeismoArchives Project

In the past decade, modern information technology (including the World-Wide Web and the Internet) has made it possible to archive large volumes of data with back-end data storage for easy online search and access. Therefore, we take one step beyond scanning and preserving occasional analog seismograms. A new project termed the "SeismoArchives" utilizes these new technologies to make scanned seismograms and related materials readily accessible as online source material, suitable for research. The primary goal of the SeismoArchives project is to create online seismogram archives of significant earthquakes of the world. Unfortunately, because no funding is yet available for constructing these SeismoArchives, we depend on volunteers and donations of data files and/or financial support for scanning analog seismograms that date back as far as 1882.

These analog seismograms (about 50 millions pieces) have been disappearing at an alarming rate. We are now concentrating on preserving a small fraction of the seismograms recorded by the World-Wide Standardized Seismograph Network (Oliver and Murphy 1971) in the 1960s and 1970s (about 4 million seismograms on 70 mm film chips), and of the seismograms microfilmed by the Historical Seismogram Filming Project (Glover and Meyers 1988) in the 1980s (about 0.5 million seismograms on microfilms for earthquakes prior to 1963).

5.1 The IRIS Data Management Center

The Data Management Center (DMC) of IRIS is hosted by the University of Washington's Earth and Space Sciences Program in Seattle, Washington, USA. The IRIS DMC receives seismic data from nearly 100 networks worldwide. It archives more than 40 years of digital data, although almost most of them are from the past

Table 1 Selected earthquakes for the USGS/ICSU scanning project

Year	Mo	Dy	Hr:Mn	Lat	Long	Depth	Magnitude	FER	Deaths	Place/Name
1962	3	7	11:01	19.10	145.23	640	6.9 Mw	HRV	216	
1962	3	17	20:47	10.80	−43.30	15	7.0 mB	ABE1	403	
1962	4	12	0:52	38.07	142.74	24	7.2 Mw	P&S	228	
1962	5	11	14:11	17.18	−99.64	35	7.3 Mw	P&S	59	
1962	5	21	21:15	−20.00	−177.37	437	7.5 Mw	HRV	181	
1962	7	26	8:14	7.49	−82.78	23	7.2 Mw	P&S	83	
1962	8	3	8:56	−23.28	−68.01	113	7.2 mB	ABE1	123	
1962	9	1	19:20	35.56	49.81	19	6.9 Ms	ABE1	347	12225 Iran: Qazvin
1962	12	8	21:27	−25.81	−63.27	588	7.2 Mw	HRV	129	
1963	3	26	9:48	−30.11	−177.53	35	7.4 Mw	P&S	178	
1963	4	16	1:29	−1.13	128.00	34	7.2 Mw	P&S	267	
1963	4	19	7:35	35.63	96.96	15	6.9 Ms	ABE3	325	
1963	7	26	4:17	42.04	21.38	0	6.1 M	Utsu	383	1070 Macedonia: Skopje
1963	8	15	17:25	−13.71	−69.32	549	7.7 Mw	HRV	118	
1963	9	15	0:46	−10.47	165.76	35	7.5 Mw	P&S	184	
1963	9	17	19:20	−10.28	165.41	29	7.5 Mw	P&S	184	
1963	10	13	5:17	44.76	149.80	26	8.5 Mw	KANA	221	Kuril Is.
1963	10	20	0:53	44.76	150.56	27	7.9 Mw	P&S	222	
1963	11	4	1:17	−6.73	129.68	35	7.8 mB	ABE1	280	
1963	11	9	21:15	−8.98	−71.53	577	7.7 Mw	HRV	113	
1963	12	15	19:34	−4.76	108.05	666	7.1 Mw	HRV	275	
1963	12	18	0:30	−24.77	−176.51	35	7.7 Mw	P&S	171	
1964	2	6	13:07	55.64	−156.07	3	7.1 Mw	P&S	17	
1964	3	28	3:36	61.01	−147.62	6	9.2 Mw	KANA	2	131 Great Alaska EQ
1964	4	23	3:32	−5.42	133.93	5	7.1 Mw	P&S	204	
1964	4	24	5:56	−5.06	144.27	105	6.9 mB	ABE2	202	
1964	5	26	10:59	−56.24	−27.63	116	7.5 mB	ABE1	153	
1964	6	16	4:01	38.43	139.22	10	7.6 Mw	P&S	226	26 Japan: Niigata
1964	9	12	22:07	−49.07	164.39	27	6.9 Ms	ABE1	166	
1964	10	18	12:32	−7.18	123.80	581	7.0 Mw	HRV	280	

1964	11	17	8:15	−5.75	150.72	50	7.1 Mw	P&S	192	
1965	1	24	0:11	−2.45	125.96	28	8.2 Mw	P&S	270	71 Indonesia: CeramSea
1965	2	4	5:01	51.21	178.49	28	8.7 Mw	KANA	6	Aleutian Is.
1965	3	14	15:53	36.40	70.71	209	7.5 mB	ABE1	718	
1965	3	28	16:33	−32.49	−71.21	71	7.4 mB	ABE1	135	337 Chile: La Gigua
1965	4	29	15:28	47.31	−122.33	66	6.5 mb	ISC	29	USA: Puget Sound
1965	8	11	3:40	−15.47	166.98	17	7.2 Mw	P&S	186	
1965	8	11	22:31	−15.79	167.25	46	7.6 Mw	P&S	186	
1965	8	23	19:46	16.17	−95.84	10	7.4 Mw	P&S	60	
1965	9	12	22:02	−6.47	70.74	29	7.0 UK	BRK	426	
1965	11	13	4:33	43.84	87.75	51	7.0 UK	B&D	332	
1966	3	4	23:58	−38.70	178.00	33	6.2 M	NZ	160	NZ: Gisborne
1966	3	20	1:42	0.84	29.86	15	7.2 UK	B&D	567	200 Uganda/Zaire
1966	6	7	13:59	11.30	139.63	49	7.1 UK	B&D	209	
1966	6	15	1:32	−10.11	161.02	13	7.3 Mw	P&S	193	
1966	8	19	12:22	39.16	41.57	17	6.8 M	Utsu	366	2517 Turkey: Varto
1966	10	17	21:41	−10.79	−78.68	34	8.1 Mw	KANA	115	110 Peru: Lima
1966	10	19	8:01	−1.58	−15.39	19	7.0 UK	B&D	407	
1966	12	28	8:18	−25.50	−70.65	30	7.7 Mw	P&S	122	
1967	2	9	15:24	2.89	−74.80	41	7.2 Mw	P&S	103	98 Colombia
1967	2	15	16:11	−9.12	−71.32	600	7.0 Mw	HRV	112	
1967	3	13	16:06	−40.19	−74.84	23	7.3 UK	BRK	143	
1967	7	22	16:56	40.62	30.74	4	7.4 Mw	P&S	366	173 Turkey: Mudurnu
1967	7	30	0:00	10.55	−67.31	23	6.5 M	Utsu	97	240 Venezuela: Caracas
1967	11	23	8:35	14.44	51.98	12	7.0 UK	B&D	415	
1967	12	10	22:51	17.39	73.77	4	6.4 Ms	ISC	314	180 India: Koyna
1967	12	21	2:25	−21.86	−69.94	44	7.4 Mw	P&S	123	
1967	12	27	9:17	−21.21	−68.18	116	7.0 mB	ABE1	124	
1968	1	15	2:01	37.78	13.03	3	6.5 M	Utsu	398	231 Italy: ValdeBelice
1968	2	19	22:45	39.37	24.94	8	7.2 Mw	P&S	365	

Table 1 (continued)

Year	Mo	Dy	Hr:Mn	Lat	Long	Depth	Magnitude	FER	Deaths	Place/Name
1968	4	1	0:42	32.48	132.19	29	7.5 Mw	P&S	236	
1968	5	16	0:49	40.90	143.34	26	8.2 Mw	KANA	229	52 Japan: Tokachi-oki
1968	5	16	10:39	41.59	142.78	11	7.8 Mw	P&S	224	
1968	5	23	17:24	−41.74	172.12	46	7.2 Mw	P&S	162	NZ: Inangahua
1968	5	28	13:27	−2.92	139.40	63	7.2 mB	ABE1	197	
1968	6	19	8:13	−5.55	−77.15	17	6.9 Ms	ABE1	111	46 Peru: San Martin
1968	8	1	20:19	16.38	122.07	52	7.7 Mw	P&S	249	207 Philippines(Luzon)
1968	8	3	4:54	25.64	128.46	29	7.1 Mw	P&S	238	
1968	8	10	2:07	1.42	126.25	19	7.6 Mw	P&S	266	
1968	8	14	22:14	0.06	119.69	17	7.3 Mw	P&S	265	392 Indonesia(Celebes)
1968	8	18	18:38	−10.20	159.95	542	7.3 Mw	HRV	193	
1968	8	31	10:47	34.03	58.96	11	7.2 Mw	P&S	348	15000 Iran: Dasht-i Biyaz
1968	10	7	19:20	26.29	140.68	518	7.3 Mw	HRV	212	
1968	10	23	21:04	−3.37	143.31	9	7.1 Mw	P&S	200	
1969	1	30	10:29	4.76	127.43	73	7.1 mB	ABE1	263	
1969	2	11	22:08	41.42	79.23	13	7.1 UK	B&D	320	
1969	2	28	2:40	35.91	−10.57	21	7.8 Mw	P&S	739	
1969	3	29	9:16	11.91	41.21	35	6.3 M	Utsu	558	40 Ethiopia: Sardo
1969	7	18	5:24	38.41	119.45	10	7.2 Mw	P&S	658	
1969	8	11	21:27	43.47	147.81	45	8.2 Mw	KANA	221	Kuril Is.
1969	8	17	20:14	24.84	−109.68	32	7.2 UK	B&D	49	
1969	11	21	2:05	1.97	94.57	10	7.6 Mw	P&S	705	
1969	11	22	23:09	57.72	163.59	9	7.8 Mw	P&S	218	
1969	12	25	21:32	15.72	−59.64	11	7.2 Mw	P&S	92	
1970	1	8	17:12	−34.88	178.85	207	7.0 mB	ABE1	179	
1970	1	10	12:07	6.78	126.68	59	7.3 Ms	ABE1	259	
1970	3	28	21:02	39.17	29.54	24	7.4 UK	B&D	366	1086 Turkey: Gediz EQ
1970	4	7	5:34	15.77	121.65	29	7.2 Mw	P&S	249	Philippines: Luzon
1970	4	12	4:01	15.08	122.01	15	7.0 Ms	USCGS	248	
1970	4	29	14:01	14.45	−92.76	50	7.3 Mw	P&S	69	

1970	5	14	18:12	43.09	47.06	11	6.6 M	Utsu	337	many Russia: Dagestan
1970	5	31	20:23	−9.24	−78.84	73	7.9 Mw	KANA	109	66794 Peru: Peru EQ
1970	6	11	16:46	−59.41	159.22	15	7.3 Mw	P&S	167	
1970	6	15	11:14	−54.36	−64.11	3	7.0 Ms	USCGS	148	
1970	7	25	22:41	32.24	131.67	45	7.0 Mw	P&S	235	
1970	7	30	0:52	37.83	55.88	9	6.6 Ms	USCGS	341	220 Iran: Karnaveh
1970	7	31	17:08	−1.48	−72.55	644	7.5 mB	ABE1	103	
1970	8	30	17:46	52.34	151.61	649	7.3 Mw	HRV	663	
1970	12	10	4:34	−4.07	−80.66	19	7.1 Mw	P&S	110	81 Peru/Ecuador
1971	1	10	7:17	−3.23	139.74	55	7.7 Mw	P&S	201	
1971	2	09	14:01	34.40	−118.39	5	6.4 M	Utsu	43	58 USA: San Fernando
1971	5	22	16:43	38.86	40.53	4	7.0 M	Utsu	366	995 Turkey: Bingol
1971	7	14	6:11	−5.51	153.90	44	8.0 Mw	P&S	190	
1971	7	26	1:23	−4.88	153.18	37	8.1 Mw	P&S	190	
1971	12	15	8:29	56.02	163.17	21	7.8 Mw	P&S	218	
1972	1	25	2:06	22.55	122.32	10	7.5 Mw	P&S	243	
1972	2	29	9:23	33.37	140.88	58	7.5 Mw	P&S	211	
1972	4	10	2:06	28.41	52.78	5	6.9 Ms	NEIS	353	5010 Iran: Ghir EQ
1972	6	11	16:41	3.86	124.23	329	7.8 Mw	HRV	262	
1972	7	30	21:45	56.69	−136.09	7	7.6 Mw	P&S	20	
1972	12	23	6:29	12.35	−86.12	6	6.2 M	Utsu	75	6000 Nicaragua: Managua
1973	6	17	3:55	43.22	145.74	43	7.8 Mw	P&S	224	
1973	9	29	0:44	41.90	130.97	569	7.8 Mw	HRV	659	
1973	10	6	15:07	−60.95	−21.62	15	7.5 Ms	ISC	732	
1974	5	8	23:33	34.57	138.77	11	7.2 UK	B&D	230	30 Japan: Izuhanto−oki
1974	7	4	19:30	45.18	93.93	15	7.5 UK	B&D	334	
1974	12	28	12:11	35.02	72.90	13	6.2 M	Utsu	710	5300 Pakistan: Pattan

Table 2 Selected WWSSN stations for the USGS/ICSU scanning project

Number	Code	Latitude	Longitude	Location	Digital station
0011	ARE	−16.46	−71.49	Arequipa,	Peru NNA
0038	ESK	55.32	−3.21	Eskdalemuir,	Scotland ESK
0078	NNA	−11.99	−76.84	Nana,	Peru NNA
0001	AAE	9.03	38.77	Addis Ababa,	Ethiopia FURI
0005	AFI	−13.91	−171.78	Apia,	Western Samoa AFI
0112	ANP	25.18	121.52	Anpu,	Taiwan TATO
0009	ANT	−23.70	−70.42	Antofagasta,	Chile LVC
0021	BOG	4.62	−74.07	Bogota,	Columbia BOCO
0026	CHG	18.79	98.98	Chiengmai,	Thailand CHTO
0028	COL	64.90	−147.79	College,	Alaska COL,COLA
0030	COR	44.59	−123.30	Corvallis,	Oregon CSR
0031	CTA	−20.09	146.25	Charters Towers,	Australia CTAO
0033	DAV	7.09	125.57	Davao,	Philippines DAV
0042	GIE	−0.73	−90.30	Galapagos Islands,	Ecuador PAYS
0044	GUA	13.54	144.91	Guam,	Marianas Islands GUMO
0048	HNR	−9.43	159.95	Honiara,	Solomon Islands HNR
0070	KBS	78.92	11.92	Kingsbay,	Spitsbergen KBS
0052	KEV	67.76	27.01	Kevo,	Finland KEV
0053	KIP	21.42	158.02	Kipapa,	Hawaii KIP
0055	KON	59.65	9.63	Kongsberg,	Norway KONO
0064	MAT	36.54	138.21	Matsushiro,	Japan MAJO
0072	MUN	−31.98	116.21	Mundaring,	W. Australia NWAO (142 km)
0074	NAI	−1.27	36.80	Nairobi,	Kenya NAI, KMBO
0073	NAT	−5.12	−35.03	Natal,	Brazil RCBR (40 km)
0086	PMG	−9.41	147.15	Port Moresby,	New Guinea PMG
0093	QUI	−0.20	−78.50	Quito,	Ecuador OTAV (49 km)
0095	RAR	−21.22	−159.77	Rarotonga,	Cook Islands RAR
0099	SBA	−77.85	166.76	Scott Base,	Antarctica SBA
0102	SE0	37.57	126.97	Seoul,	Korea INCN (31 km)
0106	SJG	18.11	−66.15	San Juan,	Puerto Rico SJG
0108	SPA	−90.00	0.00	South Pole,	Antarctica SPA, QSPA
0113	TAU	−42.91	147.32	Hobart,	Tasmania TAU
0119	TUC	32.31	−110.78	Tucson,	Arizona TUC
0122	WEL	−41.29	174.77	Wellington,	New Zealand SNZO (6 km)
0123	WES	42.38	−71.32	Weston,	Massachusetts HRV (24 km)
0124	WIN	−22.57	17.10	Windhoek,	Namibia TSUM (375 km)
0096	RCD	44.08	103.21	Rapid City,	S. Dakota RSSD (67 km)
0101	SCP	40.80	−77.87	State College,	Pennsylvania SSPA (18 km)

25 years. It also includes the large temporary network archive of the IRIS PASSCAL Program data (http://www.iris.edu/about/PASSCAL/). It is responsible for the long-term (perpetual) archive and distribution of all IRIS generated data, and is the primary archive for the FDSN (http://www.fdsn.org/). The funding for IRIS comes from the National Science Foundation (through its Division of Earth Sciences), and acts in a leadership role to create a perpetually viable, openly accessible archive for seismic data. The DMC is the core component of the IRIS Data Management System (for more information, refer to http://www.iris.edu/).

The IRIS DMC mission is accomplished by creating a data management system suitable for archiving and processing of requests. This is enabled by providing the hardware and software infrastructure that includes a StorageTek Powerderhorn tape-based silo with a capacity of 1.2 petabytes, as well as currently keeping all data in an online RAID (redundant array of independent disks) filesystem to enable fast access. The policy employed is that 4 copies of the data are archived, including off-site copies, creating a redundant, fail-safe environment, and data are transcribed to new media every 4 years to keep technology current, and acts a read-back mechanism that provides a periodic verification of the holdings.

Since 1992 the quantity and diversity of data managed by the IRIS Data Management System continues to grow exponentially. The DMC currently (2007) manages data from 96 different permanent seismic networks, primarily in real-time, around the globe, and manages data from more than 165 temporary experiments. For the current, dynamic list of FDN approved network codes that shows current data availability at the DMC, refer to http://www.iris.edu/mda. Permanent networks includes the IRIS Global Seismographic Network (GSN), the International Federation of Digital Broad-Band Seismograph Networks (FDSN), and regional networks that contribute data to the IRIS archive or have open access to their data sets.

The primary function of the IRIS DMC is to archive and disseminate digital seismic data from modern instruments that began recording earthquakes after 1980 (Ahern 2003). In 2004, the IRIS DMC began hosting the SeismoArchives, which consist of scanned seismic data recorded by the older instruments from the 1880s to 1980, i.e., a period of about 110 years during which seismograms were recorded on papers and microfilms. This activity is in collaboration with the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the U.S. Geological Survey. Others are encouraged to collaborate as well.

5.2 Contents of the SeismoArchives Online

A stack of seismograms in the form of scanned raster-image files is not easy to use for research unless the seismograms can be quickly collated, viewed, and have some supporting documentation and metadata available. Technology has existed for the past decade to scan analog seismograms and related materials (e.g., maps, field notes, papers, and reports) into computer readable files, and the World-Wide Web provides easy access to these files online via the Internet. SeismoArchives at the IRIS DMC (http://www.iris.edu/seismo/) leverages modern information technology for archiving and disseminating historical seismograms and related materials. At present, there are 4 major sections: (1) Archives by Individual Earthquakes, (2) Archives by Stations, (3) Archives by Special Projects, and (4) Background Materials.

Each individual earthquake archive (http://www.iris.edu/seismo/quakes/) contains seismograms as well as supporting materials and links to appropriate files (if any) stored in the “Background Materials”. Some collections of seismograms created for certain specific projects are archived under “Archives by Special Projects”.

In 2007, W.H.K. Lee established seismograms archives for “Reference Stations of the World” at http://www.iris.edu/seismo/stations/. These Reference Stations are strategically located seismographic stations with relatively long duration of operation, and every effort is being made to scan the available seismograms and related materials (with the cooperation of the host stations). So far, Reference Stations include: (1) San Juan, Puerto Rico, (2) Honolulu/Kipapa, Hawaii, (3) College, Alaska, (4) Tucson, Arizona, (5) Albuquerque, New Mexico, (6) Weston Observatory, Massachusetts, and (7) Observatorio San Calixto, La Paz, Bolivia. We hope more seismographic stations will agree to become Reference Stations and make efforts to scan their seismograms and related materials.

In the section on “Background Information”, (http://www.iris.edu/seismo/info/), digital image-files of papers, books, reports, photos, and maps are archived in order to provide useful background information for the scanned seismograms. At present, this section is being developed and is far from being complete. It has (1) Historical Information: early developments in seismology, especially about instrumentation; (2) Seismographic Stations: catalogs of historical and WWSSN stations that contain detailed station information; and (3) Books and Reports: some valuable publications. Although most existing files are “borrowed” from the supplementary materials (on CD-ROMS) of the “International Handbook Earthquake and Engineering Seismology” (Lee et al. 2002; 2003), we plan to include additional materials over time, including the Handbook’s “errata and addenda”. We also encourage all seismologists to contribute their data files and related information that are relevant to the scanned seismograms.

The effort to preserve WWSSN and historical seismograms and related materials online is an immense task both in terms of human labor and computer resources, and the authors’ goal is to solicit contributions so that redundant search-and-discover operations are eliminated and the collection can grow and remain viable for generations to come.

At the time of writing this article, 30 earthquake archives are available online at various stages of construction, and about 100 more archives are in waiting. We realize that the scanned seismograms are just the first step. We hope users of these image files will convert them to digital data files, and make the digitized seismograms available through the SeismoArchives. Certainly a long-term goal is to be able to supply appropriate metadata, like gain information, etc., and information related to this would be very useful.

6 Other Projects for Archiving Seismograms

So far, we have described the efforts in archiving analog seismograms online taken by the authors and their USGS colleagues. Many other projects for archiving analog seismograms online have been and are being conducted by several institutions around the world. We will briefly describe three examples.

6.1 The SISMOS Project

The SISMOS Project started in 2001 at the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy. It involves scanning, archiving and distribution of historical seismograms, bulletins and other related material from the Italian observatories dating back to 1895 (Michelini et al. 2005). The scanned images of seismograms are available online at 200 dpi resolution for viewing, and are also available at 600 or 1024 dpi resolution upon request. This library contains over 3 terabytes of data volume currently, and growing. For more details, please visit their website at: http://sismos.rm.ingv.it/.

In addition, software for digitizing scanned seismogram images has been developed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy (Pintore et al. 2005). It is called "Teseo" and is free available at: http://sismos.ingv.it/teseo/. The SISMOS scanning laboratory is one of the Trans-National Access facilities of the European Union's NERIES project. Under the NERIES project, funding is available for visitors to have historical seismograms scanned and to learn how to use the Teseo vectorization software.

6.2 The EuroSeismos Project

The EuroSeismos Project is being conducted by the Working Group on the History of Seismometry of the European Seismological Commission. It has been supported financially mainly by INGV and has relied on the SISMOS facility for scanning paper seismograms. As of early 2007, more than 25,000 historical seismograms recorded by observatories of 30 countries in the Europe-Mediterranean region are available online. For more details, please visit their website at: http://storing.ingv.it/es_web/.

6.3 The Caltech Scanning Project

The Seismological Laboratory of California Institute of Technology (Caltech), Pasadena, California, has scanned 12,223 pre-digital analog seismograms 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 at the Data Center of the Southern California Earthquake Center through a search tool at: http://www.data.scec.org/research/scans/. Additional information on this project is available online under the following headings: (1) List of local $M>3.5$ events (1963–1992), (2) File format and naming convention, and (3) A primer on how to read drum seismograms.

7 Some Sample Analog Seismograms

In this section, we present some sample seismograms that had been scanned to illustrate the progressive improvements of earthquake observations over the years. The

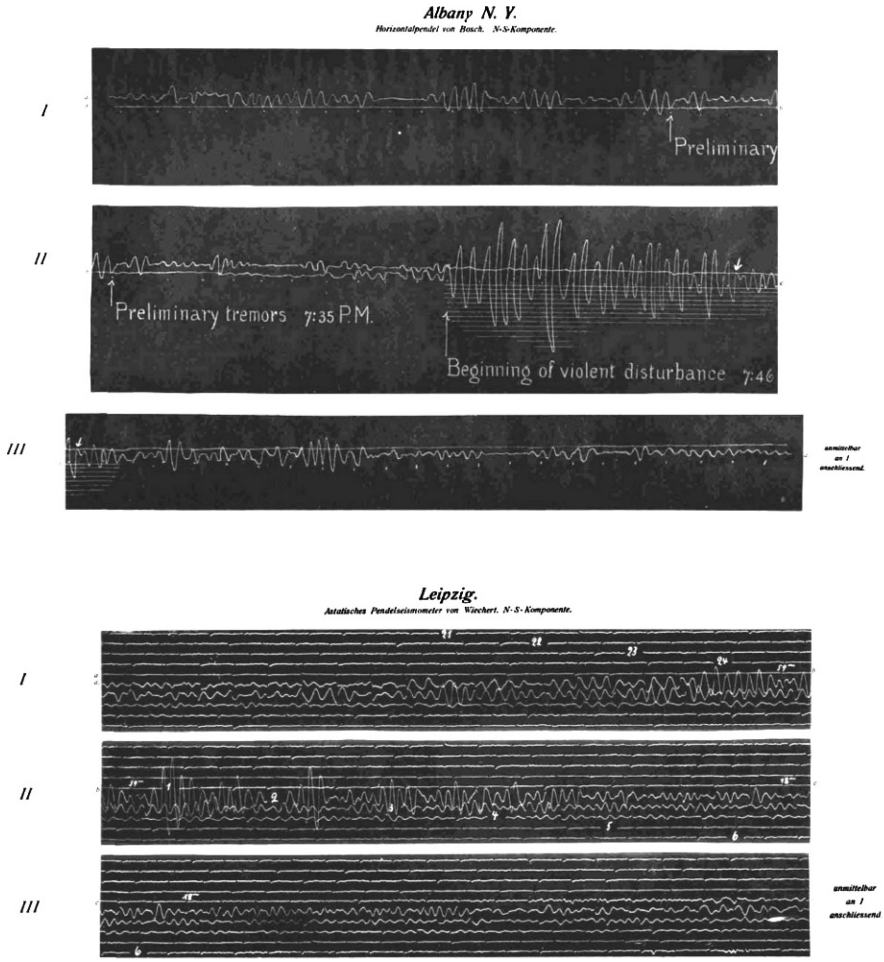
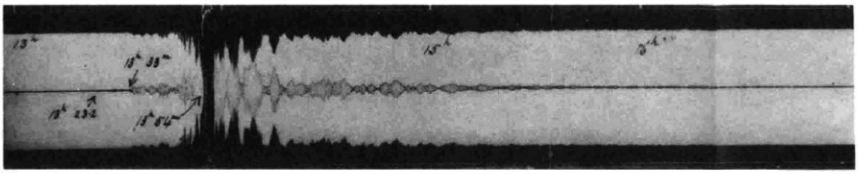


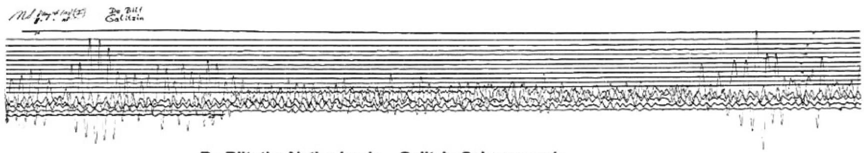
Fig. 5 Sample seismograms recorded on smoked paper. See text for explanation

first-generation seismographs are mechanical instruments with low magnifications of ground motions and recorded either on smoked paper or photographic paper. Figure 5 shows two seismograms of the 17 August, 1906 Valparaiso (Chile) earthquake. The first seismogram was recorded by the N–S component of a Bosch-Omori seismograph at Albany, N.Y., and the second seismogram, the N–S component of a Wiechert seismograph at Leipzig, Germany. Since these seismograms were too wide to fit the publication size of Rudolph and Tams (1907), each was cut into 3 sections. However, smoked paper seismograms are difficult to scan and most will be worse than these samples, as shown in: http://www.iris.edu/seismo/quakes/1906valparaiso/pdf/.

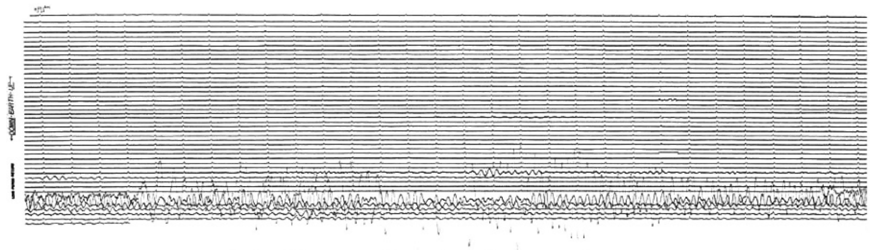
Figure 6 shows 4 seismograms that were recorded on photographic paper. The first seismogram was recorded by a Milne mechanical seismograph for the 18 April,



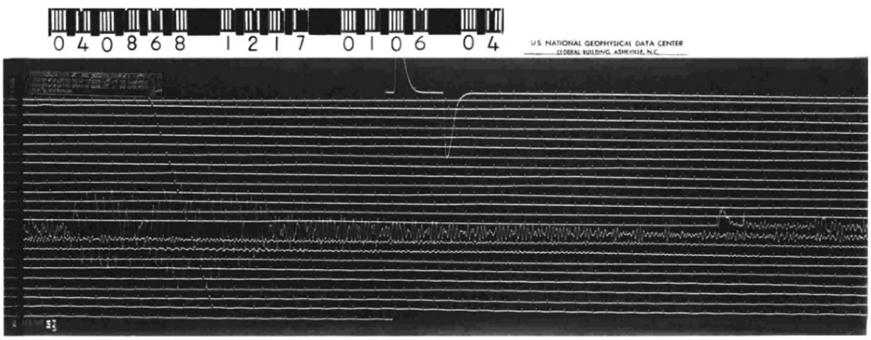
PAISLEY. SCOTLAND. Milne Seismograph. (*From photographic copy.*)



De Bilt, the Netherlands. Galitzin Seismograph.



Weston Observatory, USA. Benioff Seismograph.



San Juan, Puerto Rico. WWSSN Long-Period Seismograph.

Fig. 6 Sample seismograms recorded on photographic paper. See text for explanation

1906 San Francisco (California) earthquake at Paisley, Scotland. It is difficult to digitize from such an image because of the small time resolution, but most seismograms for the first decade of instrumental seismology were recorded by Milne seismographs. The second seismogram in Fig. 6 shows the 8 August, 1946 Mona Passage (Puerto Rico – Dominican Republic) earthquake recorded by the electromagnetic Galitzin seismograph at De Bilt, the Netherlands. The third seismogram in Fig. 6 shows the 28 June, 1944 Mexico-Guatemala earthquake recorded by the electromagnetic Benioff seismograph at the Weston Observatory, Massachusetts, USA. The fourth seismogram in Fig. 6 shows the 9 April, 1968 Borrego Mountain (California) earthquake recorded by a WWSSN electromagnetic seismograph at San Juan, Puerto Rico. All these electromagnetic seismographs belong to the second-generation of seismic instruments. After the 1960s, electronic seismographs were developed leading to digital, on-scale recordings of seismic waves. These electronic seismographs became the dominant seismic instruments for observing earthquakes starting in the 1980s.

Although seismic signals recorded by electromagnetic seismographs on photographic paper have a dynamic range of about 1000, they constitute the instrumental earthquake records we have from about 1910–1980. Although these analog seismograms are far inferior to the modern digital seismograms (with a dynamic range better than 1,000,000), we can still retrieve many useful information from them as shown by Kanamori (1988).

8 Discussion

The number of scanned images of the WWSSN and historical seismograms currently in the SeismoArchives is barely over 1%, numbering only approximately 50,000 out of a total of about 4 million available WWSSN film chips and about 0.5 million available on microfilms of historical seismograms. Nevertheless, it is a good first step toward preservation of these valuable seismograms. W.H.K. Lee volunteered to perform some quality assurance tasks and to prepare the prototype web pages of the current 30 "earthquake archives". The staff of the IRIS DMC provided the time necessary to post these earthquake archives online at the IRIS web site.

The hope is that institutions may be willing to fund scanning of analog seismograms that are of interest to them, and make the scanned image files available after their research interests are satisfied. So far, two institutions have provided modest funding for scanning specific sets of WWSSN seismograms: five Italian earthquakes by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy, and the 1964 Great Alaska earthquake by the URS Corporation of Pasadena, California.

At present, it costs about $2 US dollars to scan one WWSSN film chip and about $0.5 US dollars to scan one historical seismogram on microfilm roll. Projections suggest that it will cost a few million US dollars to scan a significant portion (e.g., 1 million) of the WWSSN and historical seismograms, and at least twice the amount of money (or equivalent volunteers' time) to perform quality assurance tasks and to prepare seismogram archives of earthquakes.

As we were preparing this manuscript in the fall of 2006, the USGS Albuquerque Seismological Laboratory began an 1-year project to scan and create images of about 60,000 WWSSN more seismograms in order to start constructing archives of "Earthquake Reference Stations": San Juan, Puerto Rico; and Honolulu/Kipapa, Hawaii (C.R. Hutt, personal communication, 2006). In addition, the National Earthquake Information Center (NEIC) of the USGS in Golden, CO scanned about

70,000 historical seismograms recorded at Tucson, Arizona (1926–1960); College, Alaska (1935–1956; 1959–1963), and San Juan, Puerto Rico (1946–1949; 1955–1963) (J.W. Dewey, personal communication, 2007). The USGS in Menlo Park began to scan about 15,000 historical seismograms recorded at San Juan, Puerto Rico (1926–1945; 1950–1954). As a result, we are expecting a significant increase in the number of scanned seismograms for SeismoArchives soon, and anyone can remain updated by referring to http://www.iris.edu/seismo/.

Acknowledgments We are indebted to C.R. "Bob" Hutt who provided the information for subsections 4.1 and 4.2. It was also Bob Hutt who kindly took over the WWSSN film chips collection from USGS Menlo Park in 1997 when the collection was to be discarded, and continuously makes efforts to scan the WWSSN seismograms. We thank Tim Knight of IRIS DMC for serving as webmaster for the SeismoArchives.

We wish to thank Carol Prentice and Chris Stephens for their comments and suggestions on the manuscript draft. We are grateful to Alberto Michelini and one anonymous reviewer for their critical reviews of the manuscript, and to Julien Frechet for his excellent editing of the manuscript.

Bibliography

Adams RD (2002). International seismology. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 29–37.

Agnew DC (2002). History of seismology. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 3–11.

Ahern TK (2003). The FDSN and IRIS Management System: Providing easy access to terabytes of information. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part B, pp 1645–1655.

Dewey J, Byerly P (1969). The early history of seismometry (to 1900). *Bull. Seism. Soc. Am.,* **59**, 183–227.

Engdahl ER, Villasenor A (2002). Global seismicity: 1900–1999. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 665–690.

Feigl KL (2002). Estimating earthquake source parameters from geodetic measurements. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 607–620.

Flinn EA, Engdahl ER, Hill AR (1974). Seismic and geographical regionalization. *Bull. Seism. Soc. Am.*, **64**, 771–993.

Frankel A, Mueller C, Barnhard T, Perkins D, Leyendecker E, Dickman N, Hanson S, Hopper M (2000). USGS national seismic hazard maps. *Earthq. Spectra*, **16**, 1–19.

Giardini D, Gruenthal G, Shedlock K, Zhang P (2003). The GSHAP global seismic hazard map. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part B, pp 1233–1239.

Glover DP, Meyers H (1988). Historical Seismogram Filming Project: Current status. In: Lee WHK, Meyers H, Shimazaki K (eds) Historical Seismograms and Earthquakes of the World, Academic Press, San Diego, pp 373–379.

Glover DP, Meyers H, Herrmann RB, Whittington M (1985). Inventory of filmed historical seismograms and station bulletins at World Data Center A, *World Data Center A Report SE-37*, 218pp, Boulder, CO.

Grant A (2002). Paleoseismology. In: Lee WHK Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 475–489.

Hutt CR, Bolton HF, Holcomb LG (2002). U.S. contribution to digital global seismograph networks. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 319–332.

Kanamori H (1988). Importance of historical seismograms for geophysical research. In: Lee WHK, Meyers H, Shimazaki, K (eds) Historical Seismograms and Earthquakes of the World, Academic Press, San Diego, pp 15–33.

Kanamori H (2003). Earthquake prediction: An overview. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology. Academic Press, San Diego, Part B, pp 1205–1216.

Kisslinger C, Howell BF (2003). Seismology and physics of the Earth's interior in the US (1900–1960). In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part B, p 1453 (full report on the attached CD #2).

Lee WHK (2002). Challenges in observational seismology. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 269–281.

Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) (2002). International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, 933pp. and 1 CD-ROM.

Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) (2003). International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part B, 1009pp. and 2 CD-ROMs.

Lee WHK, Meyers H, Shimazaki K (eds) (1988). Historical Seismograms and Earthquakes of the World, Academic Press, San Diego, 513pp. This book is freely available online at: http://www.iris.edu/seismo/info/publications/Lee1988.pdf.

Melton BS (1976). The sensitivity and dynamic range of inertial seismographs. *Rev. Geophys. Space Phys*., **14**, 93–116.

Meyers H, Lee WHK (1979). Historical Seismogram Filming Project: First progress report. *World Data Center A Report SE-22*, Boulder, CO, 68pp.

Michelini A, De Simoni B, Amato A, Boschi E (2005). Collecting, digitizing and distributing historical seismological data. *EOS* **86**(28), 12 July, 2005.

Milne J (1900). Fifth Report of the Committee on Seismological Investigations, British Association for the Advancement of Science, pp. 59–120, London. This report is freely available online at: http://www.iris.edu/seismo/info/historical/baas/BAAS1900.pdf.

Musson RMW, Cecic I (2002). Macroseismology. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 807–822.

Nur A (2002). Earthquakes and archaeology. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 765–774.

Oliver J, Murphy L (1971). WWNSS: seismology's global network of observing stations. *Science*, **174**, 254–261.

Pintore S, Quintiliani M, Franceschi D (2005). Teseo: A vectoriser of historical seismograms. *Comput. Geosci.* **31**, 1228–1285.

Richards P.G. (2002). Seismological methods of monitoring compliance with the Comprehensive Nuclear Test-Ban Treaty. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 369–382.

Rudolph E, Tams E. (1907). Seismogramme des nordpazifischen und südamerikanischen Erdbebens am 16. August 1906,. International Association of Seismology, Strassburg.

Schweitzer J, Lee WHK (2003). Old seismic bulletins: A collective heritage from early seismologists. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 1665–1723.

Shishkevish C (1974). Soviet seismographic stations and seismic instruments, Part I and Part II. *Report R-1240-ARPA*, Rand Corp. Santa Monica, CA.

Sykes LR (2003). Seismology, plate tectonics and the quest for a Comprehensive Nuclear Test Ban Treaty: A personal history of 40 years at LDEO. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part B, pp 1456–1457.

Utsu T (2002). A list of deadly earthquakes in the world: 1500–2000. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 691–717.

Vogt J (1979). Les tremblements de terre en France. Memoire BRGM No. 96, 220pp, Orleans.

Webb SC (2002). Seismic noise on land and on the seafloor. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 305–318.

Wielandt E (2002). Seismometry. In: Lee WHK, Kanamori H, Jennings JC, Kisslinger C (eds) International Handbook of Earthquake and Engineering Seismology, Academic Press, San Diego, Part A, pp 283–304.

Wielandt E, Streckeisen G (1982). The leaf-spring seismometer: Design and performance. *Bull. Seism. Soc. Am.*, **72**, 2349–2367.

WWSSN (1964). Handbook: World-Wide Standard Seismograph Network, Acoustic and Seismics Laboratory, Institute of Science and Technology, University of Michigan, Ann Arbor, 500pp. This publication is freely available online at: http://www.iris.edu/seismo/info/stations/WWSSN1964.pdf.