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Historical seismograms: Preserving an endangered species

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ABSTRACT

The youth of seismology as a science, compared to the typical duration of seismic cycles, results in a relative scarcity of records of large earthquakes available for processing by modern analytical techniques, which in turn makes archived datasets of historical seismograms extremely valuable in order to enhance our understanding of the occurrence of large, destructive earthquakes. Unfortunately, the value of these datasets is not always perceived adequately by decision-making administrators, which has resulted in the destruction (or last-minute salvage) of irreplaceable datasets.

We present a quick review of the nature of the datasets of seismological archives, and of specific algorithms allowing their use for the modern retrieval of the source characteristics of the relevant earthquakes. We then describe protocols for the transfer of analog datasets to digital support, including by contact-less photography when the poor physical state of the records prevents the use of mechanical scanners.

Finally, we give some worldwide examples of existing collections, and of successful programs of digital archiving of these valuable datasets.

1. Introduction

This paper examines efforts and challenges related to the preservation and conversion into the digital age of world-wide archives of historical seismograms, broadly defined as predating the onset of digital recording in the 1970s. The value of these precious datasets stems from the relative youth of observational seismology as a science, as compared to typical estimates of the seismic cycle along any given fault. As detailed below, the former started in 1889, and the first waveforms available for modern quantitative interpretation date back to approximately 1902, meaning that as of today, seismogram archives span at best about 110 years for great earthquakes, much less for smaller ones. By contrast, typical recurrence times of major earthquakes at subduction zones are estimated to be on the order of one to several centuries. Thus, the record of observational seismology clearly undersamples the seismic cycle, the situation being made even worse by the fact that earthquake recurrence at any given plate boundary is far from periodic, but rather takes place in a capricious, unpredictable way even among the greatest known earthquakes [3,38,14].

In this respect, a seismologist studying a given tectonic province, especially from exclusively digital data, could be compared to a meteorologist attempting to study the occurrence of hurricanes with at most a few months' worth of observations, or to an early astronomer using less than one month of observations to understand the phases of the moon.

In addition, events such as the 2004 Sumatra and 2011 Tohoku earthquakes have led to a re-examination and abandonment of the concept of a maximum earthquake predictable in a subduction zone based on simple plate tectonics parameters [57]. Rather, a precautionary approach now suggests that all subduction zones may have the capacity to host mega earthquakes [61,41], illustrating once again the danger of an undersampling of the world's seismicity by the relatively short record of digital seismometry.

2. A short perspective on the history of seismometry

In order to illustrate the value of historical seismograms and the need for their preservation, it is worth recapping briefly the principal developments in the history of seismometry. A general review of its early stages can be found, *e.g.*, in Dewey and Byerly [15] and Lee and Benson [39], to which the reader is referred for ampler details. As mentioned above, the first instrumental record of a distant earthquake to be identified as such is generally recognized as von Rebeur-Paschwitz' [64] observation on 17 April 1889 of a Japanese earthquake on horizontal pendulums at Potsdam and Wilhelmshaven, built to function as modern day tiltmeters, *i.e.*, to record deviations in the local vertical.

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The earliest seismometers such as Milne's [43] instrument suffered from being undamped, and their waveforms are not suitable for modern interpretation. After the introduction of damping, the many instruments developed by the pioneers of seismometry generally fell under two categories: the mechanical seismometer, of which the most successful example is Wiechert's [65] instrument, and the electromagnetic seismograph, pioneered by Prince B.B. Golitsyn, as reviewed for example by Galitzin [21].[1]

In the context of the present paper, we will focus on the Wiechert and Golitsyn instruments, on account of the remarkable success that these two scientists (or associates after Golitsyn's untimely death in 1916) had in deploying (in modern lingo, we would say "marketing") their instruments worldwide, thus building early, if informal, networks of relatively well standardized seismographs. For example, McComb and West's [42]compilation lists no fewer than 96 stations worldwide equipped with Wiechert instruments and 32 with Golitsyn systems.

- *The Wiechert mechanical seismometer* functioned as a displacement sensor at high frequencies, and as an accelerometer at long periods, with typical short-period magnifications of between 100 and 200. The free period of the pendulum, controlling the "corner frequency" of its response curve, was usually between 4 and 10 s, exceptionally up to 13 s. Recording was by means of a stylus writing on smoked paper laid onto a helicoidal drum which provided a time axis to the seismogram. The resulting seismograms are generally 90 cm in length. These characteristics make the Wiechert seismograms particularly valuable for the teleseismic study of earthquakes in the magnitude range $M \geq 7$. The robustness of the instrument is illustrated by the fact that several original Wiechert seismographs functioned without major interruption until the 1980s (Zagreb) and 1990s (Uppsala), and even to this day following some restoration (Zagreb). Fig. 1 shows a typical example of teleseismic body-wave recording on a Wiechert vertical instrument.
- By contrast, *the Golitsyn electromagnetic seismograph* uses a velocity sensor, since the voltage and hence the current generated into its electrical circuit are proportional to the velocity of the coil in the field of the magnet. The galvanometric recording system allows much increased amplifications, typically reaching 2000, but the latter are peaked over a narrow band of frequencies, with the low-frequency response of the system falling as ω^3, as opposed to ω^2 for the mechanical instruments. Standard Golitsyn instruments usually featured pendulum and galvanometer periods on the order of 10 to 25 s. Recording was on photographic paper, which has the advantage of better physical preservation with time, but generates fainter traces when a large signal amplitude reduces the time of exposure under the fast-moving light spot. These characteristics make the Golitsyn system particularly valuable for the teleseismic study of earthquakes in the range $6 < M < 7.5$; at higher magnitudes, the signal either goes off-scale or is simply lost. Fig. 2 shows a typical example of two teleseismic recordings on a Golitsyn horizontal instrument.

Later progress in instrumental seismometry is perhaps best exemplified by the works of V.H. Benioff, who strived to improve Golitsyn's concept of the electromagnetic seismograph by separating the pendulum and galvanometer free periods, thus building some superb instruments which can be regarded as prototypes of today's broadband systems. The most remarkable one is undoubtedly the "1–90" seismometer developed in the early 1930s (with definitive periods $T_p = 1$ s, and $T_g = 90$ s, for the pendulum and galvanometer, respectively, and a maximum gain of 2000), which allows quantitative studies of waveforms of both short-period *P* waves and mantle surface waves. However, very few such instruments were built, and they were largely confined to the Southern California network, and to a few North American stations, such as Tucson ($T_g = 77$ s) and Weston ($T_g = 60$ s).

In the 1950s, F. Press and W.M. Ewing developed an improved version of the Golitsyn concept, into a long-period system with $T_p = 30$ s; $T_g = 90$ s [53]. A dozen such instruments were deployed world-wide at the start of the International Geophysical Year in 1957. Their records are archived at the Lamont-Doherty Earth Observatory of Columbia University (LDEO), and played a crucial role in the source study of the great Chilean earthquake of 22 May 1960 [13].

2.1. The World-Wide Standardized Seismograph Network (WWSSN)

In 1958, the Conference of Experts in Geneva examined the feasibility of seismic verification of a possible Partial Nuclear Test Ban Treaty, eventually signed by the United States, the United Kingdom and the Soviet Union in 1963. In the Western world, verification of the treaty was assisted through deployment of a "World Wide Standardized Seismograph Network", initially under funding by the Defense Advanced Research Projects Agency of the US Department of Defense. The stations were equipped with short-period instruments along Benioff's [5] design, standardized at $T_p = 1$ s; $T_g = 0.75$ s, and long-period Sprengnether systems adapted from the Press-Ewing design ($T_p = 30$ s (15 s after 1965); $T_g = 100$ s). The WWSSN was complemented with a network of about 40 Canadian stations, operating slightly different instruments ($T_g = 75$ s).

The WWSSN constituted the first truly centralized, standardized seismic network attempting world-wide coverage. It featured about 120 stations, but significant coverage gaps in Africa, and of course during the cold war over China, the Soviet Union and Eastern Europe. The data, consisting of six components per station per day, were available as individual 70-mm microfilm chips, or on rolls of 35-mm microfilm, the latter inherently more cumbersome to use. A detailed description of the history of the WWSSN is given by Lee and Benson [39].

The sudden availability of continuous, high quality, essentially worldwide, seismological data produced nothing short of a revolution in observational seismology in the mid 1960s. One must never forget that the fundamental concepts of ocean-floor spreading, continental drift and eventually the plate tectonics paradigm were formulated without knowledge of the geometry of major earthquakes at plate boundaries. In this context, the WWSSN data could be used for an *independent verification* of the proposed theory, superbly achieved in the landmark papers by Sykes [63] and Isacks et al. [30]. In a nutshell, these papers upheld the concept of transform faults as proposed by Wilson [66], and the overthrusting mechanism of subduction earthquakes at oceanic trenches, as earlier hinted by Plafker [52] based on geodetic observations following the 1964 Good Friday earthquake. It should also be remembered that the concept of moment tensor inversion of seismic waveforms was developed by Dziewonski and Gilbert [17] and Gilbert and Dziewonski [22], based on extensive datasets painstakingly hand-digitized from WWSSN records of the 1963 Peru, 1964 Alaska and 1970 Colombia earthquakes.

It follows that a gold mine of information must remain untapped to this day in film chips of events from the 1960s and 1970s which have not been individually studied.

In the 1970s, digital converters were developed and mated to the WWSSN instruments, resulting in their upgrade to (and

[1] While the correct transliteration of the author's name from Russian is "Golitsyn", the forms "Galitzin" and "Galitzine" have been widely used in the Western world.

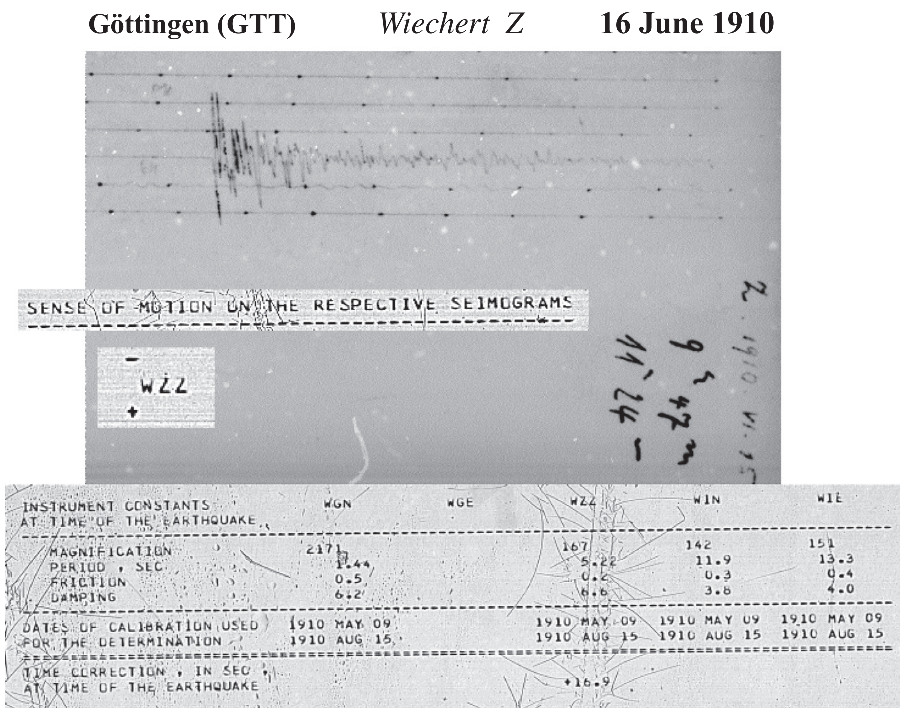

Fig. 1. Typical example of Wiechert seismogram. Vertical record at Göttingen (GTT; $A = 143°$) of the PKP-wave group from the large intermediate earthquake of 16 June 1910 in Vanuatu ($M_{PAS} = 8.6$; probably an excessive value). This record was scanned from the microfiche collection owned by the US Geological Survey in Golden (see Section 6). Note the remarkable metadata reproduced on each microfiche and documenting the response and polarity of the various instruments. This allows a definitive interpretation of the *PKP* wave as "anaseismic" (first motion up, or away from the source).

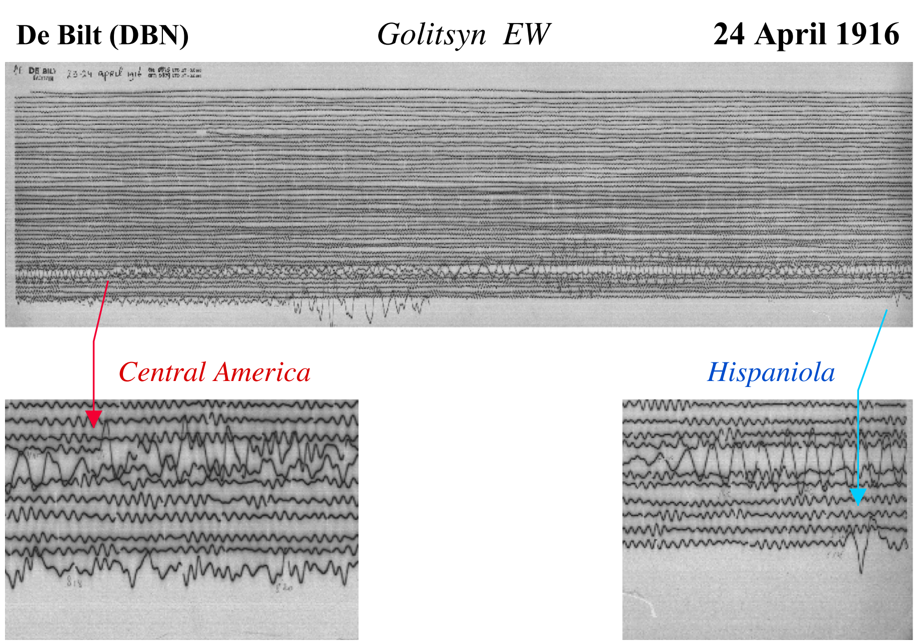

Fig. 2. Typical example of Golitsyn seismogram. This horizontal (East–West) record at De Bilt (DBN) was scanned at the KNMI facility. It features two events separated by 3.5 hours, the first one in the Dominican Republic ($M_{PAS} = 7.2$), the second one at the Nicaragua-Costa Rica border ($M_{PAS} = 7.3$). The close-up boxes show that the polarities of first arrivals (to East or anaseismic in both cases) are perfectly resolved. Note also the strong mantle Rayleigh waves of the second event, just before the record ends.

eventual replacement by) the so-called SRO, HGLP and DWWSSN systems. The demise of analog recording, and more generally of the WWSSN, was becoming inevitable, notably as funding for the maintenance and operation of the network became scarcer [39]. As a cost-cutting measure, it was decided, starting in July 1978, to discontinue the production of 70-mm film chips, in favor of microfiches regrouping 24 seismograms (four days of data). Unfortunately, the optical quality of the reproduction suffered significantly in the process, and some of resulting microfiches suffer from distortion which could affect the interpretation of the longest-period part of the seismic spectrum. The use of excellent optics in any filming or scanning program is a perhaps trivial requirement, which however is worth re-emphasizing. Additionally, the absence of adequate printers capable of reproducing real-size seismograms from the post-1978 WWSSN microfiches rendered the use of those records much more difficult. These problems actually fed back into an accelerated demise of the WWSSN. In the 1980s, the network was replaced by the digital Global Seismograph Network, under the auspices of IRIS [59].

3. The value of historical seismograms in quantitative earthquake source studies

Seismology has traditionally consisted of investigating both earthquake sources and the internal structure of the Earth. As discussed, *e.g.*, by Kanamori [36], it is clear that the added value of historical seismograms relates fundamentally to the former family of studies, which can contribute critically to our understanding of the dynamics of the plate tectonics system, and more generally of the Earth's internal engine. Thirty years later, and in this general context, the value of seismogram archives can be illustrated best by an examination of the presently available dataset of earthquake source mechanisms and moment tensors. We summarize here the recent work of Lee and Engdahl [40], who present an exhaustive discussion of moment tensors, our goal being to stress the fundamental role that collections of historical seismograms still have to play in the quest for an improved and enlarged dataset of moment values.

- The GlobalCMT project, presently run at LDEO, has compiled about 40,000 CMT solutions (or on the order of three per day), forming a homogeneous catalog of source mechanisms which extends back to 1977 [18 and subsequent updates]. Additional solutions were obtained for the year 1976 [19], but that dataset does not share the same level of completeness, on account of the sparse repartition of digital stations for that year.
  While many future studies will undoubtedly explore more in detail the source properties of literally hundreds of earthquakes from the era of digital seismology (post-1976), it can be stated that the seismological community possesses an adequate waveform dataset at both permanent and temporary stations, superbly accessible through a network of data centers, such as IRIS, GEOSCOPE, GEOFON, to name a few.
- For the WWSSN years (1962–1975), a large number of focal mechanisms have been published based mostly on first motion data, and targeted moment tensors have been obtained (by inversion or other methods). Indeed, the WWSSN contributed the data used in the landmark studies which proved the feasibility of retrieving seismic moments, either through a grid search among direct syntheses, or by formal inversion [1,2,31,32,22].
  Lee and Engdahl [40] list approximately 800 moments compiled from the literature for that period. However, the diversity of methodologies used in their computation gives their catalog a heterogeneous character and suggests that in the future, many more studies will continue to take place of earthquakes from the WWSSN era (1962–1975) through quantitative processing of their waveshapes.
- For the approximately 60 years between 1904 and 1962, only about 200 seismic moment values are listed by Lee and Engdahl [40], and among them, only one fourth achieve a "B" quality ranking indicating a resolved moment tensor. In addition, many of the relevant studies were carried out at relatively high frequencies, *e.g.*, on body waves, casting doubt on how representative of their static values those moment estimates may be. As such, our quantitative understanding of the Earth's seismicity during those decades remains approximate. Particularly worrisome in this respect and as detailed by Lee and Engdahl [40], is the trend consisting of expressing conventional magnitudes (M_s, m_b, or "Pasadena" magnitudes M_{PAS} compiled in the 1940s and 1950s by Gutenberg and Richter [26]) as "moment magnitudes", the so-called "proxy-M_w" [16], based on scaling laws that the relevant earthquake may or may not have followed. In principle, the use of the symbol M_w should certify that it represents the interpretation, in terms of a magnitude, of a *bonafide* seismic moment computation, as originally defined in Kanamori's [35] "charter" paper on the moment magnitude M_w. While the use of the word "proxy" is probably meant to underscore this reservation, it remains misleading to re-interpret other magnitudes as M_w, since this stamp of quality control is actually absent, but could be suggested by the use of the symbol M_w, its "proxy" qualifier facing the danger of being simply omitted in less-than-careful retranscriptions of catalogs. Such an approach would for example lead the unsuspecting scientist to suggest that earthquakes violating scaling laws (*i.e.*, those exhibiting a significant difference between conventional and moment magnitudes) became more frequent after the 1960s! This led Lee and Engdahl [40] to exclude "proxy-M_w" values from their catalog of "reliable" seismic moments.
  Consequently, it remains particularly important to continue the computation of genuine values of seismic moments (then, and only then, to be expressed as true moment magnitudes) from historical earthquakes. We are helped in this respect by the fact that robust moment tensors can be obtained from relatively sparse datasets. Buland and Gilbert [9] showed that it is at least theoretically possible to invert a single, non-naturally rotated horizontal record into the full time history of the moment tensor, and Ekström et al. [20] demonstrated that it was feasible to invert a static moment from a three-component record at a single digital broad-band station. Of course, the situation deteriorates when working with analog data (WWSSN or older), since the narrower response of the instruments acts as a *de facto* filter on the dataset and reduces its resolution. However, we showed in Huang et al. [27] that in the case of non-shallow earthquakes, the excitation of overtones may overcome this difficulty, to the extent that deep events (conventionally taken as $h > 300$ km) can be inverted from a single station, while intermediate ones (conventionally $70 \leqslant h \leqslant 300$ km) may require as few as three stations. Based on this remark, we were able to invert 104 deep and 76 intermediate moment tensor solutions for the WWSSN period and 35 more deep solutions from the pre-WWSSN era [28,29,11], all included and given a B_+ quality ranking in Lee and Engdahl's [40] compilation.
  Our inability to invert intermediate-depth solutions from the pre-WWSSN era stems from the combination of the need for several stations, and of clock uncertainties, the latter affecting the relative phase information between stations, and thus preventing the inversion. This situation obviously worsens in the case of shallow events, which would require an even greater number of stations to compensate for the lack of overtone excitation. However, based on an original remark by Romanowicz and Suárez [56], Reymond and Okal [54] have shown that moment tensor inversion from a sparse dataset remains possible by inverting only the spectral amplitude information at each station, after discarding the spectral phase. Note that ignoring the spectral phase of the inverted data results in a double $\pm 180^\circ$ indeterminacy on strike and slip angles, which can usually be lifted using first motion polarities at critical stations. Based on this remark, a number of successful inversions of historical events were performed, including the resolution of the case of the 1906 "twin eights" (two magnitude 8 events occurring within 30 minutes of each other on 17 August 1906, at opposite ends of the Pacific Ocean), the large Banda Sea event

of 1938, the 1956 Amorgos earthquake in the Aegean Sea, and several events in the Mariana Trench, where we documented significant undersampling of the seismicity by the digital record [48,45,49,50].

Finally, and even when the scarcity of data precludes the formal inversion of a moment tensor, historical seismograms may provide critical, if more classical, information, such as polarities of first motion. Fig. 3 [46] provides a spectacular example, which proved crucial in understanding the tectonic regime of the large intraplate earthquake of 11 September 1921, off the coast of Java.

In conclusion, these examples reaffirm, if need be, the invaluable character of historical seismograms, in particular from the pre-WWSSN era, in our quest for a more quantitative understanding of the seismicity of the planet.

4. Challenges and methods of seismogram preservation

Once a collection of historical seismograms has been identified, the first challenge in its preservation consists of maintaining the awareness of its curators for its unique scientific value. While "scientific curators" (*i.e.*, observatory directors) are usually enthusiastic supporters of the collections, they are often engaged in a tug-of-war with "administrative curators", *i.e.*, business managers, motivated by the admittedly legitimate goal of modernization of institutional infrastructures under the general umbrella of cost-cutting efforts. The key to a harmonious collaboration in this respect resides in the education of administrators as to the value of the collections. This can involve some level of publicizing the use of seismograms, notably by researchers from other institutions. In practice, the easier the access to the collection, the better chances it has of surviving: removing its holdings to distant commercial storage will make it significantly more difficult to use in scientific projects, thereby reducing its utilization, further affecting the perception of its scientific value, and accelerating its eventual demise. In the same spirit, an archiving facility should provide an adequate on-site means, either analog or preferably digital, of copying records for the visiting scientist; unfortunately, some collections which are truly superb in terms of their holdings, fail in this respect.

In the present state of information technology, and as part of a general strategy of seismogram preservation, it is desirable to transfer existing collections onto some form of digital support. This is nothing short of a gargantuan project, merely on account of the extraordinary volumes of data involved. In particular, this effort becomes more difficult in the case of the best collections, which are expected to contain a greater volume of archives. At present, the choice technology appears to be large-scale scanners. At a scanning rate of ~900 bpi, a typical seismogram requires about 300 Mbytes of storage, and scanning the entire collection of a large observatory which may house several million seismograms will quickly reach the PetaByte (10^{15} bytes) level, significantly larger than the present complete holdings of the IRIS data center. Such projects are also labor intensive, since they involve manual handling of the individual seismograms, not to mention the need for a critical organization of the metadata for each individual file, as well as a general episode of quality control. In this respect, scanning projects can be easier to achieve at observatories with smaller collections, and/or located in developing countries allowing lower labor costs.

In this context, a common practice is to effect a selection of records to be processed, most often based on a magnitude threshold, as discussed for example by Lee and Benson [39]. While this may constitute the only feasible strategy under existing budgetary and manpower constraints, the ultimate goal of a preservation effort should be the transfer of the complete collection to digital format, including those seismograms perceived as containing only "noise". After all, one scientist's noise may be the next one's signal, as forcefully demonstrated by the recent explosion in studies based on the processing of so-called "seismic ambient noise" e.g., [58,8].

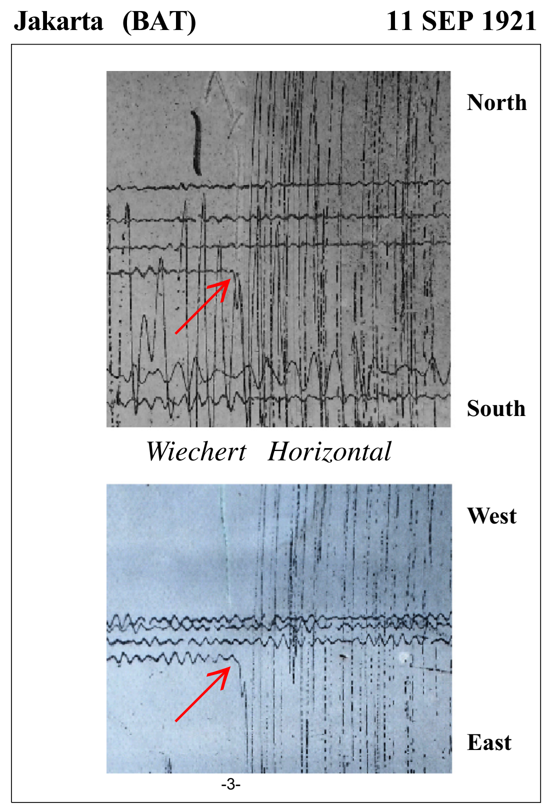

Fig. 3. First motion arrivals on the Wiechert instrument at Jakarta (ex-Batavia; BAT) from the South of Java earthquake of 11 September 1921 [46]. This spectacular arrival (to Southeast, "kataseismic", or back towards the source) helped resolve the focal mechanism of this event, which could not be interpreted as a classical subduction interplate thrust earthquake.

As described below, in the case of the Jakarta archives, the situation is occasionally made more difficult by the physical state of the original seismograms, which may have become so brittle as to disallow the use of a scanner's automatic feeder.

Before waveform data can be processed as time series on digital computers, there remains the overwhelming step of transforming a seismogram image into a time series sampled at a regular time step. This process of digitizing (sometimes referred to as "vectorization") has been implemented for decades on hand-digitizing tables. Algorithms have been developed to possibly automate the process [51], the main difficulty being the recovery of continuous time series in scrambled seismograms, where several traces (corresponding to subsequent hours in the record) are often intertwined, due to the large excursions of the signal during the recording of great earthquakes. An additional problem is the selection of an appropriate time sampling for the final time series, since the latter depends *a priori* on the nature of the research project involved. For example, the investigation of a *T* wave recorded by a land seismic station (in the geometry of a distant precursor to the CTBTO's "T-phase stations" [44]) may require a time sampling of 0.05 s, which is unlikely to be provided by an automatic digitization program, tuned for traditional P-wave studies requiring a step no finer than 0.25 s, while it remains possible on a hand digitizer, after some customized enlargement of a scanned seismogram. In this context, it might be argued that there will always be room for a personal approach to the digitization of historical events by individual researchers.

4.1. Further challenges

Even when seismograms have been identified, and possibly copied digitally, a number of significant challenges persist which may inhibit their scientific use.

4.1.1. Instrument responses

Perhaps unexpectedly, our experience has been that the question of the instrument response is usually relatively easy to resolve, as early observatories carried regular calibration tests, whose results were themselves systematically archived (*e.g.*, the Wiechert system at Uppsala was calibrated at least twice a year from 1905 to 1959). Among the several catalogs of instrument responses, the most exhaustive are McComb and West's [42 and Charlier and van Gils' [10], as well as Kawasumi's [37] for Japanese stations.

4.1.2. Location

As surprising as it may sound, a further problem involves station locations. For example, we recently discovered that the Cape Town, South Africa station was moved in 1934 from the Royal Observatory of the Cape of Good Hope (CGH) to the Department of Mathematics of Cape Town University (CTO, only less than 2 km away), but then again in 1950 and more significantly to Hermanus (HER), ~90 km to the East, while all records were filed at the Silverton office of the Council for Geosciences under the label "Hermanus". Obviously, this error could have crucial implications in the study of regional historical seismicity.

4.1.3. Orientation and Polarity

Unfortunately, some records do not list the component (*e.g.*, North-South *vs.* East-West) of the seismogram, let alone its polarity of recording (*e.g.*, North *vs.* South up on the paper). Often times, the former can be asserted from the polarization at the receiver (P as opposed to S waves, Love as opposed to Rayleigh, etc.). The latter is obviously a crucial parameter for the interpretation of first motions. It can occasionally be reconstructed from the examination of contemporaneous events with known focal mechanisms, but this level of forensic interpretation is not totally foolproof: while the polarity of a mechanical instrument is expected to be robust, it would have been reasonably easy to switch two wires in an electromagnetic seismograph, especially during the early phases of its development.

We wish to stress that the resulting metadata (location, orientation, polarity and instrument response) should be scrupulously included as part of any digital archiving of historical seismograms.

4.1.4. Lost records

Finally, an extremely frustrating but inescapable fact is that the records of many significant earthquakes, which presumably had been used by individual scientists (including through loans of originals at times when copying facilities were few, impractical and expensive), are all too often missing from the collections. While in some instances, this may have resulted from an "act of God" (a worldwide collection of records from the 1960 Chilean earthquake, which had been on loan to Chilean scientists, was destroyed in a fire in Santiago shortly thereafter), in most cases, one can only blame unprofessional negligence on the part of scientists who failed to return, or simply refile, the relevant records upon completion of their work.

5. Past global preservation projects

5.1. The WWSSN dataset

Complete collections of WWSSN film chips were purchased through standby orders by a number of government and academic institutions, primarily in the United States. Unfortunately, budgetary constraints often dictated cutbacks expressed for example as a magnitude filter, the resulting collection comprising only those days when a sufficiently large earthquake had occurred (*e.g.*, $M \geqslant 6$, with some exceptions such as nuclear blasts, for the Caltech archives after June, 1970).

A history of efforts for the preservation of WWSSN collections (and their partial scanning) is given by Lee and Benson [39], to which the reader is referred. We address here the question of the existence and preservation of complete collections, not affected by magnitude filtering.

In this context, the main challenge to the scientific community is presently to ensure that the very few remaining WWSSN collections are preserved and do not fall prey to the axe of administrators seeking cost-cutting measures and unaware of the exceptional value of these admittedly "old-fashioned" datasets. As a very unfortunate example, the entire collection of WWSSN film chips owned by the Central Branch of the US Geological Survey at the Denver Federal Center was shredded in the late 1990s, after business administrators at the Center argued that they could no longer afford the "costs" associated with maintaining the collection in a couple of rooms in the attic of one of the buildings of the Center.[2] In what could have been a similar fate, and as described by Lee and Benson [39], the 70-mm film chip collection held at the Western Branch of the US Geological Survey in Menlo Park was saved from shredding through the efforts of Dr. C.R. Hurt and is preserved at the Albuquerque Seismological Laboratory of the US Geological Survey, where access is however more difficult.

In 2014, and to our knowledge, it is believed that two complete collections of WWSSN data remain archived and in principle reasonably accessible to scientists: a 70-mm film chip collection, owned by LDEO, which is presently in remote storage, and a collection on 35-mm rolls, at the Western Branch of the US Geological Survey in Menlo Park. Incidentally, a remarkable aspect of the LDEO collection is that it had been manually re-sorted by day, not by station-month, immensely facilitating the extraction by the individual scientist of all seismograms pertaining to a particular event, including nowadays from the remote storage facility.

Northwestern University (Evanston, Illinois) holds more than 3 million WWSSN seismograms including the full collection originally owned by the California Institute of Technology, which was kindly transferred to Northwestern when threatened with disposal and destruction (shredding), and then merged with our own holdings in 2010. As a result, the Northwestern collection is believed complete for the years 1963-June 1970, and features both complete time series at a selection of-55 stations from July 1970 to 1978, and records at all functioning stations for earthquakes with $M \geqslant 6$ for July 1970-1978. A selection of microfiched records of the rapidly dwindling WWSSN network is also available for 1978-1987. The Northwestern facility comprises a large scale reader-printer allowing the routine reprinting of seismograms from 70-mm film chips at 175% of their original scale. Access is open by simple prior appointment for any colleague in the seismological community.

5.2. Historical, pre-WWSSN archives

Following the successful investigation of seismic sources from WWSSN waveforms, a number of individual studies showed that earlier seismograms could be similarly processed e.g., [33,34,60,62], and the value of a systematic effort towards preservation and compilation of historical seismograms became self-evident.

[2] Several years later, during a visit to the Center, the author was able to access the attic and verify that the rooms in question remained empty...

As detailed in Glover and Meyers [24], a resolution for the preservation of historical seismograms was passed during the 1977 General Assembly of IASPEI, and the Historical Seismogram Filming Project [HSFP] took place in the 1980s, targeting the records of approximately 30 stations worldwide, with the products made available through World Data Center-A for Solid Earth Geophysics. A dozen stations were earmarked for filming of the complete time series, while the rest were filmed only on days with sufficiently large earthquakes [39].

These datasets are archived as 35- or 16-mm film rolls, of which reasonably complete collections are presently available at the Western (Menlo Park) and Central (Golden) branches of the US Geological Survey. A developing problem is that the film, now 30 years old, is becoming brittle, and the rolls are starting to tear when processed through the automatic feeders of modern reader-scanners.

Particularly valuable among these records are those of the Omori instruments at Hongo (Tokyo), going back nominally to 1899, the Wiechert instruments at Abuyama (starting 1929), the Bosch–Omori and Wenner instruments at San Juan, Puerto Rico (starting 1926), the Milne-Shaw instruments at Honolulu (starting 1921), and the seismograms of the Southern California network operated by the California Institute of Technology (1923–1962; see below).

A project to scan HSFP records from a number of critical stations (San Juan, Honolulu, College, Tucson, Weston, La Paz), and deposit the files on the website of the IMS data center was started by W.H.K. Lee in 2007 [39]. Unfortunately, this so-called SeismoArchives project has been idled by lack of funding; so far, only about 550 San Juan seismograms for the years 1930-32 and 1943-1946 are available on the IRIS website, at www.iris.edu/-seismo/stations/puerto_rico/SJP_San_Juan.

The HSFP holdings also comprise a number of Russian/ex-Soviet stations, from Pulkovo in the suburbs of St. Petersburg, to Vladivostok in the Far East. The collection is event based; the instruments were generally built on the Golitsyn concept, but to save photographic paper, both horizontal components were often recorded on the same sheet, with a slight vertical offset, and a difference in the intensity of the light spot; this can make it very difficult to use such valuable records for research. Most Russian stations started recording in the late 1900s or early 1910s, but operations were interrupted for about ten years after the 1917 revolution and ensuing civil unrest. Miraculously, the station at Yekaterinburg (Sverdlovsk from 1924 to 1991; SVE) apparently kept recording continuously during this period.

Unfortunately, the filming project could not be completed at several originally targeted stations, such as Helwan, Egypt.

6. A few examples of recent, individual archiving and preservation efforts

In the following paragraphs, we describe several preservation projects of which we are presently aware. This list is by nature incomplete, and does not pretend to be exhaustive. It is hoped that the present paper can serve the purpose of opening a forum for sharing information about existing collections and projects.

6.1. North America

6.1.1. Pasadena

Even though its first seismometers were deployed relatively late, in 1922, the Seismological Laboratory of the California Institute of Technology became a cradle of seismometry in the 1930s, as Benioff developed not only variants to the Golitsyn concept [7], but also a full line of strainmeters [6], of which Fig. 4 shows an example of recording for the great 1938 Banda Sea earthquake. In addition, many instruments were deployed at satellite locations in Southern California, some of them sharing the technological state-of-the art of the Pasadena systems (*e.g.*, the “1–90” seismometers at Riverside and Tinemaha).

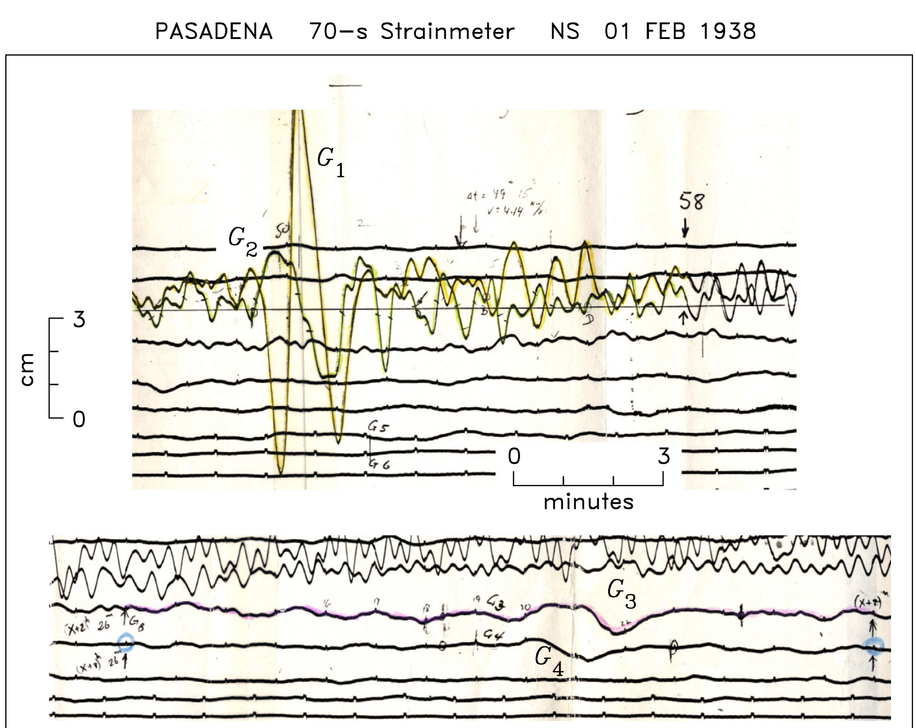

Fig. 4. Pasadena strainmeter record of the great Banda Sea earthquake of 01 February 1938. This record shows four successive passages of mantle Rayleigh waves, at periods reaching 180 seconds, which were all used for moment tensor inversion by Okal and Reymond [48].

The Caltech records for 1923–1962 were filmed as part of the HSFP [25], and the microfilms are available at the US Geological Survey Centers in Menlo Park and Golden. However, the satellite station holdings (*e.g.*, La Jolla, Santa Barbara, Mount Wilson) are not available in Golden. Furthermore, not all components of the experimental systems that Benioff was developing were filmed.

After 1962, the Caltech records were not filmed, but a selection of records were scanned and are archived at the Data Center of the Southern California Earthquake Center, at www.data.scec.org/research/seismograms.html.

They consist of seismograms of local earthquakes ($M_L > 3.5$) and of a few large teleseismic events, for 1963–1992. Unfortunately, this collection is limited to five stations (BAR, PAS, RVR, TIN, GSC), and to specific instruments (Wood-Anderson, 1–90, 30–90, and the WWSSN long-periods at GSC), even though further developments had led to superb instruments [23], such as the "Number 33" ultra-long period, low gain vertical seismometer, whose records remain invaluable notably for the study of mantle Rayleigh waves (Fig. 5).

Under the leadership of Professor Emily Brodsky (University of California at Santa Cruz), earlier historical Pasadena seismograms were scanned by GoogleBooks, and deposited on the website of the IRIS Data Management Center, at www.iris.edu/seismo/projects/caltech_archive.

Unfortunately, this ambitious project was terminated after approximately 70,000 scans of records from the years 1926, 1928–1932, 1937–1938, largely duplicating the dataset microfilmed under the HSFP. Additionally, the individual files containing the seismograms are not labeled in a searchable way, which makes their scientific use particularly cumbersome.

All the Caltech paper collections were slated for shredding in 2011 (including the majority of the post-1962 records from the unique very-long-period instruments, and from satellite stations), but eventually, and with only one week to spare, they were accepted by the State Archives in Sacramento, California. While they are presently being filed and as such not accessible, at least, they should be preserved for the foreseeable future.

6.1.2. Harvard

A superb project is presently being carried out at Harvard University by Professor Miaki Ishii. It consists of scanning and posting to the web the complete collection of archived seismograms of the Harvard Observatory (starting in 1933), only those dates with sufficiently large signals having been archived. The instruments are primarily Benioff short- and long-period, with Milne-Shaw and Wood-Anderson seismometers in the early years. Particularly remarkable in this project is the quality of the physical preparation of the seismograms (often times in very poor material condition) before scanning. At present, the holdings contain 16,000 scans for the years 1936–1953, and are available at www.seismology.harvard.edu/HRV/archive.html.

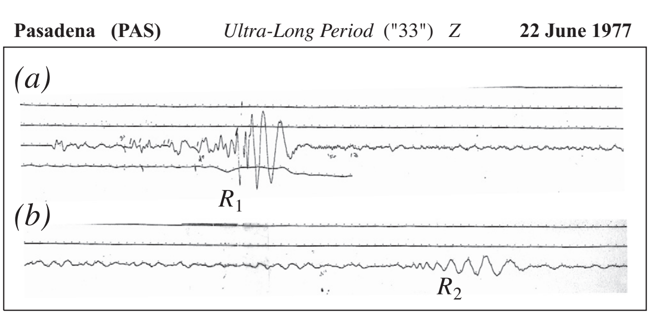

Fig. 5. Pasadena record of the intermediate-depth Tonga earthquake of 22 June 1977 on the ultra-long period "Number 33" vertical seismograph, (*b*) is the continuation of (*a*) to the right. Both frames are 40 minutes in length. Note the remarkable recording of the inverse dispersion of mantle Rayleigh wave packets R_1 and R_2 in the period range 50–250 s. Such records also have exceptional educational value in the classroom.

6.1.3. Weston

As part of a joint project between Boston College and the US Geological Survey, a total of 2600 seismograms were scanned from the station at Weston Observatory, covering the years 1936–1977. It is proposed to eventually deliver these files to the IRIS data center, as part of the SeismoArchives project described above (W.H.K. Lee, pers. comm., 2014).

6.1.4. Other sites

While many superb collections exist at observatories with a long tradition in observational seismology (*e.g.*, Berkeley, Saint Louis), we are not aware of any project aimed at archiving the records in a digital format. Canadian seismological archives are embedded in the National Archives of Canada in Ottawa, and we are not aware of on-site scanning facilities, let alone of a systematic scanning project.

6.2. Europe

Among the many historical stations in Europe, the Royal Netherlands Meteorological Institute (KNMI) in De Bilt probably holds the largest and most complete collection of Golitsyn records, starting in 1912 (as well as earlier records from other instruments). It benefits from easy access and the availability of a large scanner allowing an easy transfer to a digital image format.

Excellent collections of European Wiechert archives are available (among others) at Uppsala (where unfortunately access has become restricted, and no scanning facilities are available), Göttingen and Zagreb. All Göttingen records of events with a reported magnitude $M \geqslant 7$ (starting in 1903) were microfiched under a project led by Prof. S.J. Duda (Hamburg University), and their collection distributed. It is available at the Central Branch of the US Geological Survey in Golden. An example of record is given in Fig. 1.

6.2.1. The SISMOS project (INGV, Rome)

Under Project SISMOS and, later, EuroSeismos, the Istituto Nazionale di Geofisica e Vulcanologia has scanned an estimated 152,000 historical seismograms from Italian observatories, as well as about 25,000 records of Euro-Mediterranean earthquakes at Euro-Mediterranean stations. The database is presently (2014) being reorganized, with the aim of providing access to low resolution (200 bpi) scans directly online, and to the full high resolution scans (600 to 1024 bpi) through customized requests.

As part of the SISMOS project, the digitizing software "Teseo" was developed by Pintore et al. [51].

6.3. Africa

6.3.1. Council for Geosciences, Pretoria

The Silverton (Pretoria) branch of the Council for Geosciences (South Africa) holds a large collection of analog seismograms, including the Milne-Shaw instrument operated at Cape Town between 1920 and 1938. These records have recently been scanned (I. Saunders, pers. comm., 2014); they are particularly valuable given the scarcity of stations in that part of the world.

6.4. Eastern Asia and Australasia

6.4.1. Mizusawa, Japan

The Mizusawa Observatory was founded in 1899 as one of the six stations of the International Latitude Project, all deployed along a common latitudinal small circle of the Earth (39°08′N). An Omori "tromometer" (a mechanical instrument with an exceptionally long pendulum period $Tp = 36$ s (North–South component) and 16 s (East–West)) was installed at the Observatory in 1902. Records have now been systematically scanned on more than 600 DVDs, and a full collection is archived at the Observatory, with copies available at Tohoku University in Sendai.

6.4.2. Canberra, Australia

A superb, if somewhat ambitious, project of scanning an estimated 3 million seismograms was undertaken starting in 2010 at the headquarters of Geoscience Australia in Canberra, including Wiechert records of the Riverview (Sydney) observatory, which started operations in 1909, and Milne-Shaw records from Perth (starting 1923) and Melbourne (starting 1900). Unfortunately, funding difficulties have temporarily halted the project.

6.4.3. Lower Hutt, New Zealand

The central office of GNS in Lower Hutt holds seismological archives including New Zealand stations such as Wellington (Milne-Shaw, started 1924), Christchurch (Golitsyn, started 1931), and Apia, a station originally built when [Western] Samoa was a German colony, with Wiechert instruments deployed as early as 1904 [4]. These superb holdings are easily accessible, but unfortunately no scanning facilities were available as of our last visit in 2011.

6.4.4. Jakarta, Indonesia

The regional center of the Indonesian Bureau of Meteorology, Climatology and Geophysics (BMKG) at Ciputat in the suburbs of Jakarta, holds the archives of historical seismograms recorded in Indonesia. Most valuable among them are about 70,000 Wiechert records of the Jakarta (ex-Batavia) station, going back to 1910. This is a particularly crucial dataset, given the absence of nearby stations in that part of the world. Unfortunately, the smoked paper records are suffering from acidification of the paper, making them so brittle that they often tear upon handling, however careful the operator may be; it is simply out of question to consider any form of mechanical scanning, which would hasten their further decomposition. Under a generous pilot grant from the Earth Observatory of Singapore, we have recently explored the possibility of systematically filming the seismograms, using a high-quality digital camera [47]. Despite several initial challenges, we were able to obtain more than 500 digital copies of seismograms over a window of eight working days; capacity building through the training of BMKG staff suggests that the effort can be pursued in the forthcoming months. This project, depicted in Fig. 6, has established a contact-less alternative to scanning for seismograms in poor physical conditions.

6.4.5. China

We note the publication, in Chinese, of a total of approximately 600 selected seismograms of Chinese earthquakes, recorded mostly at Zi-ka-Wei, and at Dalian, Qingdao, Chongqing and Nanjing, from 1906 to 1948 [12], this publication including a CD-Rom which allows their detailed examination. This would suggests that records, including those of teleseismic events, may have been preserved and systematically archived.

6.5. Present gaps

Among regions known to have hosted early seismological stations, which for example reported regularly to the ISS, but whose archives, if they still exist, are not readily accessible, a flagrant geographic gap is the Indian subcontinent, where a large number of instruments (primarily Milne-Shaw) were deployed in the 1920s at Colaba, Hyderabad, Kodaikanal, Dehra Dun, etc.

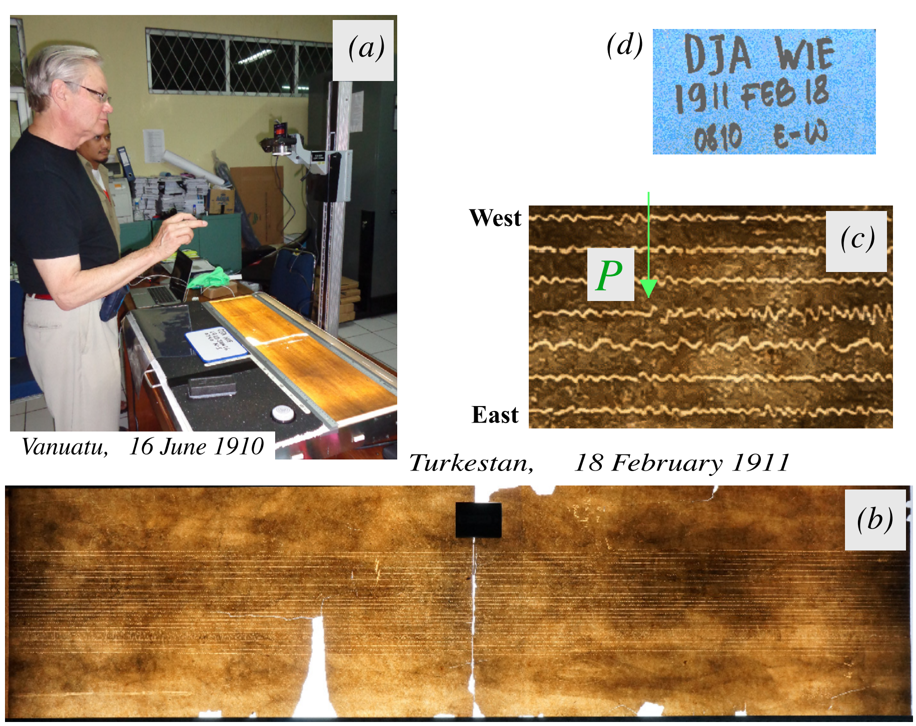

Fig. 6. Preserving fragile seismograms by digital photography, Ciputat, Indonesia, July 2014. (*a*): Physical set-up of the photographic protocol (Dr. Stephen H. Kirby, Operator). The smoked paper seismogram is illuminated through a light table. Note the tears, in particular in the center part where the record had been stored folded in two. The remaining gap has been adjusted based on time marks to provide continuity of the time axis. Note the metadata label photographed jointly with the seismogram. (*b*): Example of scanned record for the earthquake of 18 February 1911 in Turkestan. Note again the large tears and missing fragments of the original seismogram. (*c*): Close-up of *b*, zooming on the *P*-wave arrival, demonstrating the feasibility of retrieving definitive first-motion information (in this case to West, kataseismic). (*d*): Close-up of metadata label giving date, time (local) at beginning of trace (0610 GMT+7), station (DJA, ex-BAT), instrument (Wiechert), and component (E–W).

Similarly, archived data are extremely scarce in Africa, where reputed seismic stations had been deployed *e.g.*, at Algiers and Tamanrasset, Algeria, and Tananarive, Madagascar; unfortunately, nothing is known of the existence and location of any possible archives. On the other hand, the Helwan, Egypt records (Milne-Shaw, starting 1921) are reported to be archived locally (N. Melis, pers. comm., 2014), as are those of the more recent station at Lwiro (DR Congo; starting 1953) (T. Camelbeeck, pers. comm., 2014). They could constitute a priority for scanning or digital filming, as would the superb collection of analog records known to exist at La Paz, Bolivia, of which only a small fragment is available on microfilm under the HSFP.

6.6. Event-based collections

Finally, an alternative strategy has been the collection and digital archiving of seismograms from different sources, pertaining to events specially targeted by individual scientists. To some extent, and as described above, this philosophy has guided the efforts of the SCEC project for the post-1962 Pasadena archives, or the SISMOS project at the INGV. Another recent example is the remarkable dataset of seismograms from Eurasian nuclear explosions recently gathered by Richards et al. [55]. These data are exceptionally valuable since, contrary to earthquake data and in the context of the Comprehensive Nuclear-Test Ban Treaty, it would be expected and hoped that they will not be reproduced in the future.

7. Conclusion and recommendations

- Despite the superb quality of the digital networks deployed since the mid-1980s, historical seismograms constitute an irreplaceable dataset for the quantitative investigation and understanding of the planet's long-term seismicity. Most of the analytical methods used routinely in the processing of modern digital data were actually developed using analog data and, notwithstanding certain operational challenges, they can be, and have been successfully, extended and adapted to historical seismograms.
- The need for the preservation of seismogram archives, as well as their easy access by the scientific community, were recognized since the late 1970s, and the HSFP was at the time a state-of-the-art approach towards this goal. The resulting datasets have been critical in many studies of historical earthquakes, which have shed significant new light notably on several aspects of the subduction process. In view of the typically long earthquake cycles, the critical study of large historical events remains of primary importance, not only to global geophysicists, but also to communities as diverse as earthquake engineers, civil defense authorities, and the insurance industry.
- The explosive nature of recent progress in information technology now warrants the transfer of seismological archives to digital formats, which will ease their use by seismologists, thereby enhancing the visibility of these invaluable datasets. In addition to being relatively more cumbersome to use, the analog datasets of microfilms produced under the HSFP are now facing a potential physical deterioration which will only accelerate in the predictable future. While we have no knowledge of the life expectancy of digital datasets produced under presently available technologies, it would be expected that protocols will be available for back-up and transfer onto newer digital supports to be developed in the future, given the increasingly large amount of data being generated by the operation of the present permanent and portable arrays.
- Technologies exist for the smooth transfer of analog seismograms to digital formats. Commercially available scanners, complemented by image editing software, now allow the routine extraction and retrieval of waveforms even from seismograms with extremely poor contrast. For those analog seismograms whose physical state has deteriorated to the extent that scanning is no longer an option, our pilot program at the Ciputat, Indonesia archives has shown that photography with a high-quality digital camera is a viable option.
- However, historical collections of original seismograms remain under threat, as they can be perceived as obsolete and useless by "lay" individuals outside the scientific community, rightfully sensitive to the progress represented by the new digital networks, but unfamiliar with both the generally long duration of seismic cycles and the absence of strict repeatability in their occurrence. These characteristics warrant the study of as many large seismic events as possible, including historical earthquakes, which makes the preservation of any existing seismological archives an absolute priority for the seismological community. The examples of the WWSSN collection at the Denver Federal Center, which fell victim to alleged administrative cost-cutting, or even of the superb dataset at Pasadena, which was saved from shredding only at the last minute, should not be repeated.
- The few examples given in Section 6 illustrate how individual projects at various observatories can lead to the successful digital archiving of original analog seismograms. It is undeniable that such projects bear some cost, which does inhibit their development, but the alternative, *i.e.*, maintaining strictly analog collections, especially when no scanning facilities are available on-site, leads inescapably to more difficult, and thus less frequent use by the scientific community, and hence to a reduced perception of their value, and an increased threat to their preservation.
- On a number of occasions, individual programs have successfully scanned entire collections of historical seismograms (*e.g.*, Mizusawa, Cape Town). While the value of this approach cannot be questioned since a myriad of unsuspected signals of unique value may be hidden, if not buried, in what most observational seismologists might regard as mere noise, the economics of limited resources will most often dictate the limitation of digital conversion to a number of targeted seismograms, as was the case of our pilot program in Jakarta [47]. In particular, financial support for such targeted "good" projects will obviously be easier to raise from funding agencies, private stakeholders or benefactors, who would otherwise balk at the scope of a "perfect" one involving complete collections. There remains the fact that, for each new collection to be preserved, the selection of targeted events over and beyond the use of a simple magnitude threshold, will be a frustrating, perhaps agonizing, process, which will have to involve the broadest possible community, in the fields of science, engineering, civil defense, government and industry.
- As mentioned earlier, the list of projects examined in Section 6 is far from exhaustive; we call on our colleagues at seismological observatories worldwide to widely publicize the quality of their archives, as well as every effort made for their preservation and their transfer to digital supports.

Acknowledgments

First and foremost, the scientific community should be grateful to the individual operators of historical stations, most of them anonymous, and all now bygone, whose professional devotion has built over the years the invaluable collections mentioned herein. Similarly, seismological archives would not exist without a continuing commitment from the present curators of the collections.

At my *alma mater*, the California Institute of Technology, I am particularly grateful to Professor Donald Helmberger, and then Director Jeroen Tromp, who arranged the salvage and transfer of the WWSSN collection to Northwestern University, where Associate Deans Marvin Lofquist (now retired) and Joel Trammell secured floor space for the collection, and the Office of the Vice President for Research helped fund the acquisition of a modern reader-printer.

I thank Willie Lee for many discussions over the past few years on the subject of historical records, for his indefatigable efforts which led to the miraculous salvage of the Caltech paper collection, and for many constructive comments during the preparation of this report.

I am particularly grateful to Professor Kerry Sieh, Director of the Earth Observatory of Singapore, for funding the pilot program of digital photography at Jakarta, and to Steve Kirby for collaboration in Ciputat in July 2014.

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Finally, I thank Bernard Minster, for inviting me to write up the present contribution, and Paul Richards and another reviewer for constructive comments on the original version of the paper.

References

[1] Aki K. Generation and propagation of G waves from the Niigata earthquake of June 16, 1964. Part I: a statistical analysis. Bull Earthquake Res Inst Tokyo Univ 1966;44:28–72.
[2] Aki K. Generation and propagation of G waves from the Niigata earthquake of June 16, 1964. Part II: estimation of earthquake moment, released energy, and stress-strain drop from the G-wave spectrum. Bull Earthquake Res Inst Tokyo Univ 1966;44:73–88.
[3] Ando M. Source mechanism and tectonic significance of historical earthquakes along the Nankai Trough, Japan. Tectonophysics 1975;27:119–40.
[4] Angenheister GH, Reilly WI. History of the Samoan observatory from 1902 to 1921. Rept Wellington Geophys Div Dept Sci Ind Res 1978;134:36. Wellington.
[5] Benioff H. A new vertical seismograph. Bull Seismol Soc Am 1932;22:155–69.
[6] Benioff H. A linear strain seismograph. Bull Seismol Soc Am 1935;25:283–309.
[7] Benioff H. Earthquake seismographs and associated instruments. Adv Geophys 1955;2:219–75.
[8] Bensen GD, Ritzwoller MH, P Barmin M, Levshin AL, Lin F, P Moschetti M, et al. Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements. Geophys J Int 2007;169:1239–60.
[9] Buland RP, Gilbert JF. Matched filtering for the moment tensor. Geophys Res Lett 1976;3:205–6.
[10] Charlier C, van Gils J-M. Liste des stations séismologiques mondiales. Observ Roy Belgique Uccle 1953.
[11] Chen P-F, Nettles M, Okal EA, Ekström G. Centroid moment tensor solutions for intermediate-depth earthquakes of the WWSSN-HGLP era (1962–1975). Phys Earth Planet Inter 2001;124:1–7.
[12] China Earthquake Administration, Album of historical seismograms recorded in early Chinese seismographic stations, 3 vol., Seismology Press, Beijing, 2002 [in Chinese with 1 CD-Rom].
[13] Cifuentes IL, Silver PG. Low-frequency source characteristics of the great 1960 Chilean earthquake. J Geophys Res 1989;94:643–63.
[14] Cisternas M, Atwater BF, Torrejon F, Sawai Y, Machuca G, Lagos M, et al. Predecessors of the giant 1960 Chile earthquake. Nature 2005;437:404–7.
[15] Dewey J, Byerly P. The early history of seismometry (to 1900). Bull Seismol Soc Am 1969;59:183–227.
[16] Di Giacomo D, Bondar I, Storchak DA, Engdahl ER, Bormann P, Harris J. ISC-GEM: global instrumental earthquake catalogue (1900–2009), III. Re-computed M_s and m_b, proxy M_w, final magnitude composition and completeness assessment. Phys Earth Planet Inter 2015;239:33–47.
[17] Dziewonski AM, Gilbert JF. Observations of normal modes from 84 recordings of the Alaskan earthquake of 1964 March 28. Geophys J Roy Astron Soc 1972;27:393–446.
[18] Dziewonski AM, Chou A-T, Woodhouse JH. Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J Geophys Res 1981;86:2825–52.
[19] Ekström G, Nettles M. Calibration of the HGLP seismograph network, and centroid moment tensor analysis of significant earthquakes of 1976. Phys Earth Planet Inter 1997;101:219–43.
[20] Ekström G, Dziewonski AM, Stein JM. Single-station CMT: application to the Michoacan, Mexico earthquake of September 19, 1985. Geophys Res Lett 1986;19:173–6.
[21] Galitzin Fürst BB. Die elektromagnetische Regiestriermethode, Comptes Rendus Séan. Commission Sismique Perm Acad Impér Sci St Pétersbourg 1908:1–106.
[22] Gilbert JF, Dziewonski AM. An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra. Philos Trans Roy Soc London 1975;278A:187–269.
[23] Gilman R. Report on some experimental long-period seismographs. Bull Seismol Soc Am 1960;50:553–9.
[24] Glover DP, Meyers H. Historical seismogram filming project: Current status. In: Lee WHK, Meyers H, Shimazaki K, editors. Historical seismograms and earthquakes of the world. San Diego: Academic Press; 1987. p. 373–9.
[25] Goodstein JR, Roberts P. Filming seismograms and related materials at the California Institute of Technology. In: Lee WHK, Meyers H, Shimazaki K, editors. Historical seismograms and earthquakes of the world. San Diego: Academic Press; 1987. p. 380–9.
[26] Gutenberg B, Richter CF. Seismicity of the Earth and associated phenomena. Princeton, N.J.: Princeton Univ. Press; 1954. 310 p.
[27] Huang W-C, Ekström G, Okal EA, Salganik MP. Application of the CMT algorithm to analog recordings of deep earthquakes. Phys Earth Planet Inter 1994;83:283–97.
[28] Huang W-C, Okal EA, Ekström G, Salganik MP. Centroid moment tensor solutions for deep earthquakes predating the digital era: The WWSSN years (1962–1976). Phys Earth Planet Inter 1997;99:121–9.
[29] Huang W-C, Okal EA, Ekström G, Salganik MP. Centroid moment tensor solutions for deep earthquakes predating the digital era: The historical dataset (1907–1961). Phys Earth Planet Inter 1998;106:181–90.
[30] Isacks BL, Oliver JE, Sykes LR. Seismology and the new global tectonics. J Geophys Res 1968;73:5855–99.
[31] Kanamori H. Synthesis of long-period surface waves and its application to earthquake source studies – Kuril Islands of October 13, 1963. J Geophys Res 1970;75:5011–27.
[32] Kanamori H. The Alaska earthquake of 1964: radiation of long-period surface waves and source mechanism. J Geophys Res 1970;75:5029–40.
[33] Kanamori H. Seismological evidence for a lithospheric normal faulting: The Sanriku earthquake of 1933. Phys Earth Planet Inter 1971;4:289–300.
[34] Kanamori H. Faulting of the great Kanto earthquake of 1923. Bull Earthquake Res Inst Tokyo Univ 1971;49:13–8.
[35] Kanamori H. The energy release in great earthquakes. J Geophys Res 1977;82:2981–7.
[36] Kanamori H. The importance of historical seismograms for geophysical research. In: Lee WHK, Meyers H, Shimazaki K, editors. Historical seismograms and earthquakes of the world. San Diego: Academic Press; 1987. p. 16–33.
[37] Kawasumi H. Seismology in Japan, 1939–1947. Bull Seismol Soc Am 1949;39:157–67.
[38] Kelsey HM, Nelson AR, Hemphill-Haley E, Witter RC. Tsunami history of an Oregon coastal lake reveals a 4600-yr. record of great earthquakes on the Cascadia subduction system. Geol Soc Am Bull 2005;117:1009–32.
[39] Lee WHK, Benson RB. Making non-digitally recorded seismograms accessible online for studying earthquakes. In: Fréchet J, Meghraoui M, Stucchi M, editors. Historical seismology. Berlin: Springer; 2008. p. 403–27.
[40] Lee WHK, Engdahl ER. Bibliographical search for reliable seismic moments of large earthquakes during 1900–1979 to compute M_w in the ISC-GEM Global Instrumental Reference Earthquake Catalogue. Phys Earth Planet Inter 2015;239:25–32.
[41] McCaffrey R. The next great earthquake. Science 2007;315:1675–6.
[42] McComb HE, West CJ. List of seismological stations of the world. Bull Natl Res Council Natl Acad Sci 1931;82:119. Washington, DC.
[43] Milne J. Seismology. Cambridge Univ. Press; 1898. 320 p.
[44] Okal EA. T-phase stations for the international monitoring system of the comprehensive nuclear-test ban treaty: a global perspective. Seismol Res Lett 2001;72:186–96.
[45] Okal EA. A re-evaluation of the great Aleutian and Chilean earthquakes of 1906 August 17. Geophys J Int 2005;161:268–82.
[46] Okal EA. The South of Java earthquake of 11 September 1921: a negative search for a large interplate thrust event at the Java Trench. Geophys J Int 2012;190:1657–72.
[47] Okal EA, Kirby SH. Digital filming of the seismograms held in the Jakarta archives: a pilot program. Eos Trans Am Geophys Un 2014;95(53):S13C–4460 [abstract].
[48] Okal EA, Reymond D. The mechanism of the great Banda Sea earthquake of 01 February 1938: applying the method of preliminary determination of focal mechanism to a historical event. Earth Planet Set Lett 2003;216:1–15.

[49] Okal EA, Synolakis CE, Uslu B, Kalligeris N, Voukouvalas E. The 1956 earthquake and tsunami in Amorgos, Greece. Geophys J Int 2009;178:1533–54.
[50] Okal EA, Reymond D, Hongsresawat S. Large, pre-digital earthquakes of the Bonin-Mariana subduction zone, 1930–1974. Tectonophysics 2013;586:1–14.
[51] Pintore S, Quintiliani M, Franceschi S. Teseo: a vectoriser of historical seismograms. Comput. Geosci. 2005;31:1277–85.
[52] Plafker GL. Tectonic deformation associated with the 1964 Alaska earthquake. Science 1965;148:1675–87.
[53] Press F, Ewing WM, Lehner F. A long-period seismograph system. Trans Am Geophys Un 1958;39:106–8.
[54] Reymond D, Okal EA. Preliminary determination of focal mechanisms from the inversion of spectral amplitudes of mantle waves. Phys Earth Planet Inter 2000;121:249–71.
[55] Richards PG, Sokolova IN, Kim W-Y, Mikhailova NM. A new database of digitized regional seismic waveforms from nuclear explosions in Eurasia. Eos Trans Am Geophys Un 2014;95(53). IN41B-3657, [abstract].
[56] Romanowicz BA, Suárez G. An improved method to obtain the moment tensor depth of earthquakes from the amplitude spectrum of Rayleigh waves. Bull Seismol Soc Am 1983;73:1513–26.
[57] Ruff L, Kanamori H. Seismicity and the subduction process. Phys Earth Planet Inter 1980;23:240–52.
[58] Shapiro N, Campillo M, Stehly L, Ritzwoller MH. High-resolution surface-wave tomography from ambient seismic noise. Science 2005;307:1615–8.
[59] Smith SW. IRIS: a university consortium for seismology. Rev Geophys 1987;25:1203–7.
[60] Stein S, Okal EA. Seismicity and tectonics of the Ninetyeast Ridge area: evidence for internal deformation of the Indian plate. J Geophys Res 1978;83:2233–45.
[61] Stein S, Okal EA. Ultra-long period seismic study of the December 26, 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process. Bull Seismol Soc Am 2007;97:S279–95.
[62] Stein S, Okal EA, Wiens DA. Application of modern techniques to analysis of historical earthquakes. In: Lee WHK, Meyers H, Shimazaki K, editors. Historical seismograms and earthquakes of the world. London: Academic Press; 1987. p. 85–104.
[63] Sykes LR. Mechanism of earthquakes and nature of faulting on the mid-oceanic ridges. J Geophys Res 1967;72:2131–53.
[64] von Rebeur-Paschwitz E. The earthquake of Tokyo, April 18, 1889. Nature 1889;40:294–5.
[65] Wiechert E. Ein astatisches Pendel höher Empfindlichkeit zur mechanischen Registrierung von Erdbeben. Gerlands Beitr Geophys 1904;6:435–60.
[66] Wilson JT. A new class of faults and their bearing on continental drift. Nature 1965;207:343–7.