Quantitative Analysis of Early Seismograph Recordings

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Foreword Seismograms are the most comprehensive and quantitative documents of ground motion produced by earthquakes. First preserved records account for more than 100 years of instrumental seismology already, outperforming the time-span covered by modern broad-band seismic networks. But their uniqueness, as a document, prior to the generalization of massive methods of copy and distribution, limits the usability and availability of the earliest seismograms for research purposes. Contemporaneous analysis of old seismograms predated fundamental developments in quantitative seismology, as well as the digital revolution, suggesting the reanalysis of these unique and valuable records with modern seismological tools for the direct calculation of earthquake source parameters, at least for the most relevant events.

However, this is not straightforward: Early seismograms have been recorded at instruments with low dynamic range and narrow frequency band. Many times the complementary information required to process the records and to recover ground displacement, like instrument calibration and time accuracy, has been lost or is doubtful. In fact, procedures to make old seismograms useful for quantitative analysis are, in many aspects, similar to those needed to process and to use old macroseismic information. The present contribution reviews the main topics and methodologies leading to a proper use of old seismograms and related documents, including the location and distribution of the original seismograms and recording system information, as well as the sequence from the original paper seismogram to digital ground displacement, involving digitization, trace correction and deconvolution of the instrument response. We discuss the potential and the limitations of such treatments, and review some applications of recovered records in retrieving earthquake source parameters through full waveform analysis.

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1 Introduction

Seismograms can be regarded as the most comprehensive and quantitative documents of the ground motion produced by earthquakes, and are the basis of the large majority of earthquake studies. Only the availability and constant improvement of quantitative data made possible the development of seismology as a quantitative science. Modern seismology has produced a huge variety of methodologies and tools, many of which have become standard, to investigate earthquake source characteristics, seismic wave propagation and earth structure from waveforms recorded in digital form. Many of such calculations are performed on a routine basis by different agencies on global and regional scale.

But seismograms much older predate these relatively recent developments. First preserved records date from the end of the XIX century, accounting already for more than 100 years of instrumental seismology. Those old records were not obtained, evidently, in digital form: they are analogue records. Many times we call them historical seismograms or, simply, old seismograms, for all records before the 1960s, when standardizing efforts like the WWSSN deployment and the related system of microfilming and distribution, and other parallel initiatives around the world, made seismograms more easily available for researchers. Early records are unique documents preserved mainly on paper. Up to now, and mainly for technological reasons, it has not been easy the archiving, copying and distribution of these seismograms, but many of the original recordings are still preserved today. Actually, also WWSSN microfilms and analogue tape recordings fall within the scope of this article, in the sense that they require digitization and dedicated pre-processing.

But, are these records important to present seismology? The answer is definitely yes. But it is a conditional one, with many similarities to the importance of old macroseismic data to modern seismology. The main interest to use old records arises from the uniqueness of each earthquake. Earthquakes nucleate at some place and time, and rupture propagates according to instantaneous conditions along a fault. Among them, the largest earthquakes – either in a regional or global context- are particularly interesting because they are the most exceptional ones over the long-term earthquake cycle and often absent over the only two decades for which we dispose of modern-standard broad-band recordings, while on the other hand they are the most relevant to characterize seismic hazard and strain release. Kanamori (1988) proposed an exhaustive list of general research topics for which we apparently depend on the evaluation of old seismograms: (1) Global seismicity and (2) subduction zone seismotectonics, (3) Rupture process of large earthquakes, (4) Study of seismic gaps, (5) Regional seismotectonics, (6) Seismic moment release, (7) Strong motion seismology, (8) Tsunami earthquakes and (9) Unusual events in general.

The interest and willingness to preserve the quantitative documents of the Earth's physical activity and processes comes from far, even it was often an oscillating consciousness. One of the important results of the International Geophysical Year (IGY) of 1956–57 was the creation of the "International Data Centers", envisaged as depositories of the large amount of data necessary to study the Earth. Similar initiatives took off in other fields. Of our interest, for its global character, is the organization and management of the WWSSN data centre, in charge of the centralization and distribution of the recorded seismograms over the world. Also, in the 80s, following the resolutions approved by the IASPEI and the task of the IASPEI/UNESCO Working Group on Historical Seismograms, the World Data Centre A (WDC-A) started collecting, microfilming and archiving of seismograms recorded before 1963 (Glover and Meyers 1982, 1988 and references therein). More recently, applying the modern digital facilities, other efforts to store copies of the old seismograms as images in digital format have been undertaken. Among them, we may point to the SISMOS and the EUROSEISMOS projects at European scale (Michelini et al. 2005). Also Lee impulses a project to digitize part of the microfilm chips of the WWSSN (see Lee and Benson, this volume).

If we are interested to study an old earthquake, we face the necessity to use old records. At a first glance, it looks like it involves only the digitization of the relevant portions of the waveforms in the old recordings, and to process those time series with the available tools. But, at this point, problems arise. Among them, it can be mentioned that old seismograms have been recorded with narrow-band, low-range instruments, now technologically surpassed and let behind. Many times the complementary information (metadata) required to process the records and to recover ground displacement, like instrument calibration and time accuracy, has been lost or is doubtful. Even, sometimes, the physical support of the record, the paper itself, is in poor conditions and physical restoration of the document is needed (Ferrari and Roversi Monaco 2005). In few words, the use of historical waveforms is not straightforward. In fact, procedures to make old seismograms useful for earthquake analysis (restoration, metadata, study of the context) are, in many aspects, similar to those needed to process and to use old macroseismic information.

In the next sections we report some of our own experience in processing and evaluating this particularly challenging kind of data, and summarize other efforts within the seismological community to use early waveforms for the quantitative analysis of seismic sources. The present contribution reviews the main topics and methodologies leading to a proper use of old seismograms and related documents, including the location and distribution of the original seismograms and recording system information, as well as the sequence from the original paper seismogram to digital ground displacement, involving digitization, trace correction and deconvolution of the instrument response. We discuss the potential and the limitations of such treatments, and show the performance of recovered records of ground displacement in analyzing earthquake source parameters.

2 Early Seismic Sensors and Recording Systems

The beginning of quantitative recording of earthquake ground motion is more related to the solution of technical problems that of scientific ones. Even though the nature of earthquakes sources and shaking was not well understood, it was known from old times that a suspended mass (a pendulum) oscillates with earthquakes.

Also, a propagating nature of earthquake disturbances was crudely assumed since the second half of the XVIII century (see, for example, Agnew 2002, for a short sketch of the history of seismology). Problems arise when we try to keep a record of the motion of the suspended mass. As ground motions are often small, it will be also necessary some kind of amplification and the whole system should be very sensitive and stable at the same time. These problems impeded the recording of ground motion generated by earthquakes prior to the second half of the XIX century, when technical solutions became available and first recording tests took place. Italian Filippo Cecchi's instrument of 1875, with separate record of the two horizontal components, can be considered the first modern seismograph. Milne, Ewing and others were recording earthquakes in Japan already in 1881 (Dewey and Byerly 1969). After these firsts records of near earthquakes have been obtained, Ernst von Rebeur-Paschwitz (1889) discovered the possibility to record major earthquakes also at teleseismic distances. As early as 1895, J. Milne, under the auspices of the British Association for the Advancement of Sciences, deployed the first world seismographic network. But, unfortunately, the seismograms of these Milne pendulums, recorded on photographic paper at too slow speed (1–4 mm/min), are useless for waveform studies, because consecutive wiggles are drawn one onto another and only the seismogram envelope is preserved.

At the beginning of the XX century, a number of new seismological observatories began recording earthquakes, forming an early, however sparse and heterogeneous seismic network. Instrument design includes purely mechanical sensors, transferring pendulum motion continuously onto smoked papers, as the Bosch-Omori seismographs (Batlló et al. 2004) or the Wiechert instruments (Wiechert 1904). The last ones became soon a de-facto standard and the most widely distributed instruments, at least for the purpose of recording relatively long period motion, up to the IGY. A second group of widely used instruments couple the pendulum with a galvanometer, record ground motion electromagnetically via induced currents, and keep a photographic record (Galitzin 1914). In fact, electromagnetic instruments are more sensitive than mechanical ones but, again, technical problems (like the demagnetization of transducer magnets and the difficulties to manage photographic records) delayed its generalization until the 50s. Figure 1 shows the world distribution of seismic stations around 1909–10. To collect old waveforms for an individual earthquake, we may consider database facilities like EUROSEISMOS, a request – or the inspection of seismogram archives- at seismic observatories or their successor organizations, and sometimes even high-quality reproductions of seismograms in the contemporaneous scientific literature.

An important feature of early seismographs, severely complicating the analysis of old recordings, is the diversity of instruments. Existing networks were instrumented very heterogeneously, and even a same type of instrument was operated under different settings from one observatory to another. This diversity arises mainly from two reasons. First one is that the basic principles of earthquake recording were not definitely established and many "trial and error" experiments were going on. Second one is due to the limited bandwidth and range of the instruments, as discussed later. No recording configuration was able to record all signals of interest,

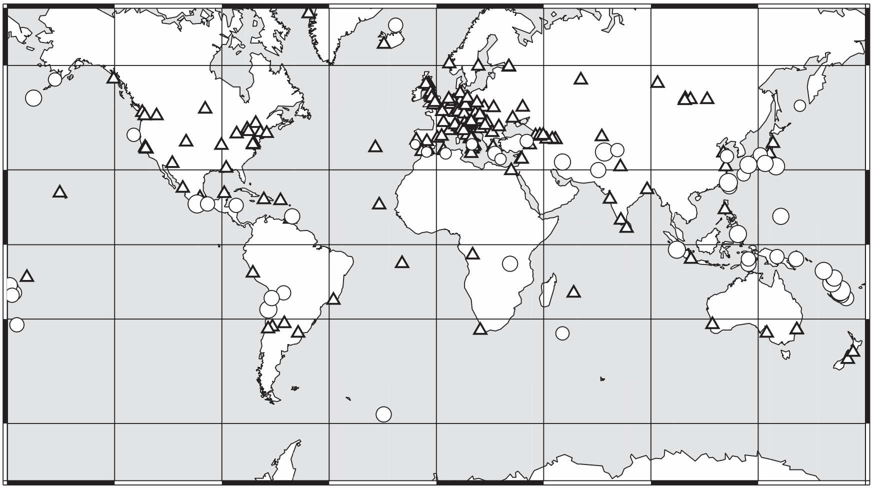

Fig. 1 Worldwide distribution of seismic stations (*triangles*) from Schweitzer and Lee (2003) complemented with data from Merlin and Somville (1910) and magnitude 6+ earthquakes (*circles*, from Gutenberg and Richter 1954), for the years 1909–1910. Around 150 seismological stations were operative at that time, but, on a first sight, only for approximately fifty of them seismograms are available (IASPEI Working Group 2006)

and different purposes resulted in different recording parameters. Therefore, the study of an event recorded in old seismograms implies to deal with many different kinds of records, with different dimensions, diverse recording speeds, and different instrument transfer functions. Consequently, the recovering and consideration of related metadata, describing the mode of operation of the recording system, is an issue as important as the recovering of the seismogram itself. Of main importance are the free period, the damping, the magnification and the orientation and polarity of the recording system. Often, these instrument characteristics may be recovered from contemporaneous bulletins and station books, or from daily calibration pulses included on many old seismograms. This kind of signals, the recording of an electromagnetic or mechanical kick to the oscillating mass, permit to obtain directly damping from the decay of the calibration pulse, as well as the free period in case of undercritical damping of the system.

3 Conservation, Digitization and Restitution of Analog Recordings

The reanalysis of arrival times, polarities and amplitudes contained in old station bulletins is fundamental to our knowledge on old earthquakes (e.g. Abe 1981, Dineva et al. 2002), and the qualitative assessment of waveform similarity and a trivial comparison of the raw amplitudes can even lead to a quite robust estimation of the relative size of nearby earthquakes recorded at the same (or nearby) stations (e.g. Kanamori et al. 2006). Here, however, we centre our interest in the investigation of full waveforms preserved on old seismograms, which can, in general, give us a more complete picture of the earthquakes process. Consequently, the objective is to convert our analogue record, supported on paper, to a digital time series of seismic ground motion, ready to use for any of our waveform analysis tools. The first step of such a procedure, just like for the purpose of conservation and digital storage of old records, is the scanning of the seismogram as a raster image.

The first key decision is the dpi density the raster image should be acquired to preserve the resolution of the original seismogram. The answer is tied to the dimensions of the trace to be extracted: It is unlikely to find traces thinner than 0.1 mm on smoked paper. To have a good definition of the trace on a digitalized image, we should have at least 3 pixels covering the thickness of the trace (i.e. 762 dpi). Such a resolution allows to properly defining the centre of the trace. In the case of photographic paper records, line width is much larger, and just half this estimate is enough. SISMOS and EUROSEISMOS projects adopted a basic scanning density of 1,016 dpi, this is, 4 pixels in 0.1 mm, for all records.

As seismograms are always monochrome records (black on white for photographic records, white on black on smoked papers, a unique color on white in the case of ink paper records) grayscale scanned images are enough to keep the information about the trace without any loss of resolution. For the case of film scanning, dpi density should be adjusted to the scale of the filmed seismogram to maintain the resolution of the original image. Such parameters (1,016 dpi, grayscale) impose the record dimensions: For the example of a WWSSN record (900 $\times$ 300 mm) the scanned image size will be $\sim$440 MB. The efficiency of file compression algorithms depends on the image characteristics, and is usually good only for photographic or ink recordings. Only recently, image processing with standard PC's, and the management of databases containing thousands of these files at large facilities has become functional. Finally, prior to trace extraction, it is useful to optimize the characteristics of the raster image enhancing the contrast, brightness and other parameters adjustable within standard image processing software.

Following, the waveform of the seismic trace of interest (usually just a fragment of the section contained in the image) must be extracted and pre-processed for further seismic analysis. This involves the digitization itself and several steps of trace correction. On early studies involving the use of digitized old seismograms, the digitization of the trace was performed from the original records, or enlarged copies obtained with photographic techniques, with digitizing tables (ex.: Adams and Allen 1961, Howell 1966, Wickens and Kollar 1967, Batlló et al. 1997). Even, some studies used digitized points obtained directly on the seismograms measuring with a rule (Samardjieva et al. 1997). Actual procedures typically avoid the use of special hardware and involve the use of computer software to extract the traces from the scanned images. Several commercial or freeware programs, not specially designed for seismological purposes, are available for this step. Most of them involve the manual picking of points. Whichever will be the program, control on the original scale of the record, i.e., accurate control of the exact coordinates of the picked digitization points, must be carefully maintained.

Also, some specific programs have been developed for this purpose (among others: Teves-Costa et al. 1999, Baskoutas et al. 2000, Liu et al. 2001). The most comprehensive and "up to date" are SeisDig (Bromirski and Chuang 2003) and TESEO (Pintore et al. 2005). Both are intended for general distribution. In most cases, totally automatic digitization of the seismograms has shown, up to now, extremely problematic. Main problems are interruptions on the trace lines, the variation of the contrast of the image from one part to another and the continuous crossover of lines. The use of a semiautomatic digitization scheme, where the user has the possibility to feed back with the algorithm, allowing the redrawing of wrong sectors of the acquired trace or editing of points, is currently the best option when image quality is quite good. Otherwise, a purely manual digitization is not more time consuming than any semiautomatic procedure. Figure 2 shows a scanned and processed seismogram. As it can be seen, small dimensions and frequency contents are important handicaps for its digitization.

After a series of points on the seismic trace has been extracted, several corrections are necessary to convert it into a ready to process description of ground motion. They depend on the type of seismograph and on some specific technical problems of each one, and can be grouped into geometrical corrections, timing corrections and instrument corrections.

Arm length correction and skew correction as geometrical corrections depend on the geometrical characteristic of the recording seismograph and are implemented analytically, point by point. They should be applied only to records on mechanical seismographs. The correction for arm length arises from the conversion of the motion of the inertial mass of the mechanical seismographs into a rotational motion through the use of levelers. The recording arm, with the stylus attached to it, moves on an arc of circumference over the recording drum. If the longitude of the arm and its angle from the vector of angular velocity on the drum are known, the curvature of the record can be immediately corrected, point by point (Cadek 1987, Samardjieva et al. 1997). Schlupp (1996) refines this correction taking into account the dimensions of the drum where the record was wrapped.

Record skew correction, also known as the detrending of the zero-line, are necessary when the equilibrium point of the inertial mass is such that the recording arm does not stand parallel to the vector of angular velocity (Crouse and Matuschka 1983). Figure 2 shows an example of arm length and skew correction. Problems may arise when the equilibrium point of the inertial mass changes during the event recording, as shown by Inoue and Matsumoto (1988) in the case of strong motion records. In this case, a particular analysis and correction is needed, though sometimes high-pass filtering may reduce the impact of those instabilities. Figure 3 shows an example of this problem. It is possible, but uncommon, to find skew in photographic records. It is due to misalignments between the recording drum and the light spot projection system.

Corrections of time marks present more difficult problems. They haven't direct analytical solution and some hypotheses should be made to process the record. Time marks are present in almost all old seismograms. They are introduced in the record in three ways:

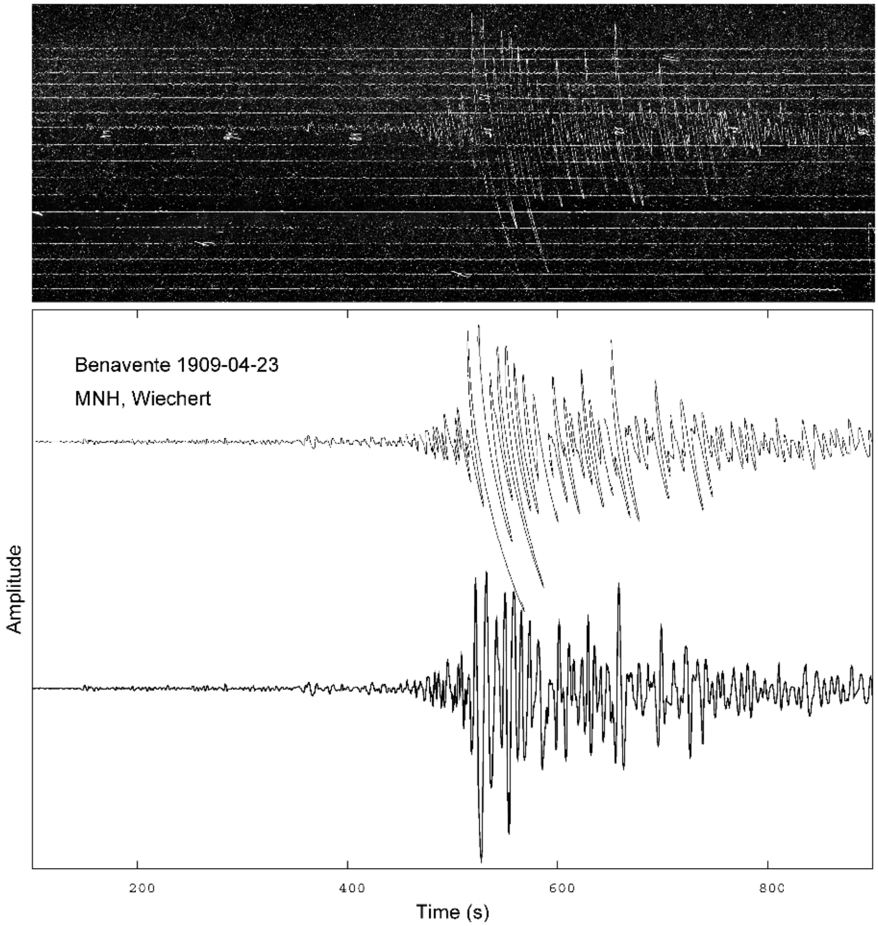

Fig. 2 *Top*: Scanned image of the record of the N–S component of the Wiechert seismograph at Munich seismic station for the 23 April 1909 Benavente earthquake, near Lisbon. *Upper trace*: Raw digitized record. *Lower trace*: The same record corrected for arm length curvature and skew. Note how the time mark (minute 50 in the seismogram image), clearly visible in the raw digitized record at about 530 s, in this case remains almost invisible after geometrical correction

– With an additional stylus, external to the recording stylus. They do not introduce distortion on the record, but absolute timing problems may arise due to parallax.
– Directly on the record: an electromagnet shakes the stylus or interrupts the record. In both cases, part of the record is lost. In some cases (low frequency motion) it is possible to ignore them. Schlupp (1996) introduced and tested linear predictive filter to successfully reconstruct part of the missing signal after interpolation.
– Finally, an electromagnet displaces the record line. The displaced fragment should be reintegrated to the "unaltered" trace.

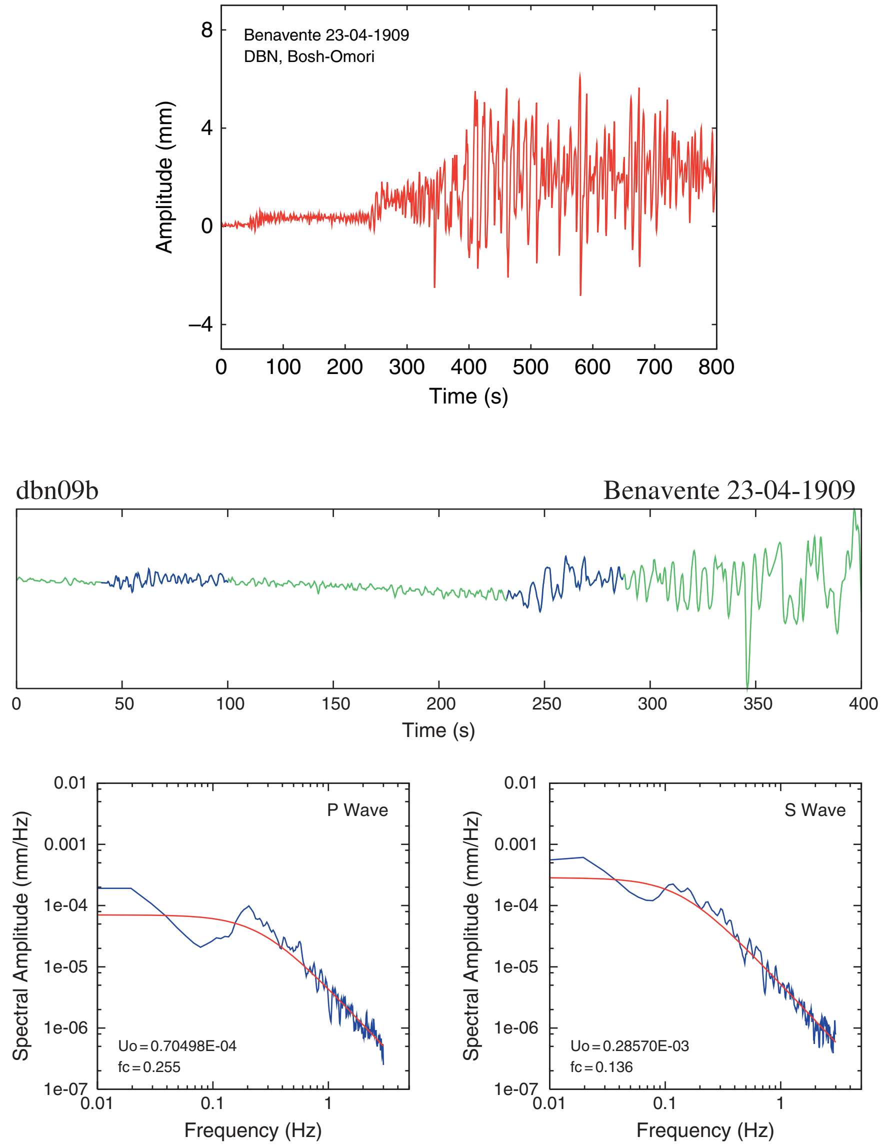

Fig. 3 (**a**) Digitized record of the Bosch-Omori seismograph at De Bilt seismic station for the 23 April 1909 Benavente earthquake, near Lisbon. It is clearly seen how a displacement of the equilibrium centre of the recording mass occurs during the P and S wave arrivals. Note also the whole dimension of the record, peak to peak maximum amplitude is just 15 mm. In the horizontal scale 100s are equivalent to 25 mm. (**b**) Even though mass displacement is noteworthy, after HP filtering (Butterworth filter at half the free period of the instrument) the P and S wave spectra give reasonable results

While bothersome for the retrieval of waveforms, time marks are essential to control the record speed and convert distance on the seismograms to differences in time. Especially for uneven recording speed or for distorted raster images of seismogram sections (e.g. due to the process of photographic reproduction), time marks are key to recover the time series. Between time marks, fluctuations of the recording drum angular velocity may distort the apparent frequency contents of the record. As the real instantaneous velocity of the drum is unknown, Herrmann (1987) suggested interpolating linearly between time marks. After these corrections are applied, the records can be interpolated to a constant sampling rate.

After such preprocessing, the signal amplitude is still given in counts, and we need to deconvolve the proper instrument response to restitute actual ground displacement. The instrument transfer functions are defined by design characteristics as are the damping and the magnification of the system, the free period of the pendulum, and the free period of the coupled galvanometer in case of electromagnetic recording systems. Above the free period of the instruments, the magnification drops rapidly, following a ω^{-2} slope for purely mechanical sensors, and a ω^{-3} slope for electromagnetic sensors (e.g. Kanamori 1988, Batlló 2004). Below the free period, nominal sensor sensitivity is nearly flat for purely mechanical sensors and drops proportional to ω for electromagnetic sensors. Near the free period, the response curve is conditioned by the damping of the pendulum motion. Some of the earliest instruments are essentially undamped except of friction effects, making a stable restitution of ground motion problematic. The removal of the instrument response through deconvolution is a task performed by many standard seismic processing tools. Though most of them do not contemplate the responses of old mechanical and electromagnetic instruments directly, it is possible to introduce the response as a series of poles and zeroes (Scherbaum 1996, Batlló and Bormann 2000, Batlló 2004).

For mechanical instruments a further problem arises. The inscription system (leveler contacts and stylus) presents a non negligible amount of dry friction. Dry friction is a dissipative force and introduces a loss of signal energy. It is a problem that, even early acknowledged (Reid 1925), still needs further studies to properly characterize its importance. Also, sometimes, mainly for some mechanical instruments, the transfer function may not be exactly linear (Herak et al. 1997, Ritter 2002). To complete our description of possible pitfalls, we recall that even idealized instrument transfer functions may be inappropriately estimated, since instrumental parameters are sometimes insufficiently documented (if at all) in contemporaneous sources, and furthermore may be subject to temporal drifts and fluctuations. Especially damping on mechanical seismographs may depend on the daily variations of room temperature. This type of uncertainties is particularly critical for the restitution of intermediate period waveforms (e.g. Rodgers 1968, Stich et al. 2005). Given the uncertainties of estimated transfer functions and the potential instabilities of deconvolution, a more stable alternative for waveform modeling may be applying the convolution of the corresponding instrument response to the synthetic Green functions instead (e.g. Kikuchi et al. 2003, Ichinose et al. 2003), or – in case we want to compare two real seismograms recorded with different instrument response- the re-convolution of the records with the interchanged instrument responses (Rivera et al., 2002). In both cases the resulting traces are directly comparable since they correspond both to the same transfer function.

4 Inversion of Source Parameters from Historical Seismograms

Digitized and corrected time series from old seismogram recordings can –in principle – be used in any state-of-the-art digital inversion procedure to derive point source seismic source parameters or the distribution of rupture parameters over a finite fault. However, there are evident differences between modern recordings of the seismic wavefield at dense networks of modern-standard accelerometers or very broadband velocity sensors with force feedback technology and 24 bit digitizing systems (Wielandt 2002), and sparse early XX century recordings. Beneath station coverage, the main limitation is due to the small dynamic range and bandwidth of early instruments. The dynamic range is nominally limited between the most tiny amplitude differences we can resolve and digitize on analogue recordings, about 0.2–0.3 mm under most favourable conditions, and the full width of the recording medium, which does not exceed 30 cm. This corresponds to about 60 dB. To translate this into the language of the digital seismologist: The double amplitude of digitized waveforms is intrinsically limited to 1,000 meaningful counts, which would be equivalent to the performance of a 10 bit digitizer. Considering the enormous amplitude range of seismic ground motion in nature, only for small subsets of earthquake magnitudes and epicentral distances the input signal could be recorded appropriately at those instruments. In practice, the dynamic range will be even smaller due to background noise at the low end, or due to nonlinearity and imaging issues at the high end of the recording range.

The frequency bandwidth of early instruments is conditioned by the free period of the pendulum, as well as the free period of the coupled galvanometer where applicable. By early XX century standards, long period recording meant free periods for either seismometer or galvanometer to be 10–25 s at horizontal components, and less for vertical sensors (e.g. Kanamori 1988, Batlló 2004). For longer periods, the decrease of instrument magnification is proportional to ω^{-2} for mechanical sensors, and ω^{-3} for electromagnetic sensors, usually corresponding to just the same decay of dynamic range for the longer period component of recorded ground motion (12 dB/octave and 18 dB/octave, respectively). At the high frequency end, bandwidth is practically limited at about 1–4 Hz by an instrument-specific ratio between the effective pen width and the velocity of the recording media: high frequency wiggles in quick succession may be drawn onto one another and cannot be distinguished readily anymore. In this case, aliasing effects may be introduced into the digitized waveforms (c.f. Scherbaum 1996), and recordings with too low drum speed are not suitable for digital waveform analysis.

Teleseismic recordings of early XX century recordings are a comparably reliable source of information. Teleseismic body waves with periods of a few seconds carry a lot of information on the source process and are recorded with low distortion in the flat part of the instrument response. Teleseismic body wave arrivals for large events can be picked rather accurately, overcoming the notorious timing inaccuracies of early seismographs, and permitting a consistency check between the assumed component polarities and the direction of the incident ray. Consequently, many studies focused on modelling or inverting teleseismic body waves to constrain the orientation of faulting, scalar seismic moment, and source time histories (e.g. Singh et al. 1984, Stein et al. 1988, Doser 1992, Doser et al. 1999, Alvarado and Beck 2006). A combination of teleseismic data and either geodetic leveling data or observed surface faulting was used to obtain finite slip distributions for several large earthquakes (e.g. the 1906 San Francisco earthquake by Wald et al. 1993; the 1923 Kanto earthquake by Wald and Somerville 1995; the 1905 Mongolian earthquakes at Tsetserleg and Bolnay by Schlupp and Cisternas 2007, and the 1944 Tonankai earthquake by Ichinose et al. 2003). Many of those results are highly relevant for science and society, such as the fault dimensions of early XX century subduction earthquakes in Japan or Mexico.

When historical teleseismic waveforms are on scale and well resolved, the long period component may be input into routine schemes for global source parameter retrieval, as shown by Okal and Reymond (2003), who use long period (100–200 s) mantle Love and Rayleigh waves to invert for the seismic moment tensor of the 1938, Mw 8.5 Banda Sea earthquake from the azimuthal pattern of spectral amplitudes, or Huang et al. (1998), who systematically applied the Harvard centroid moment tensor technique (Dziewonski et al. 1981) to a global set of 35 pre-WWSSN deep earthquakes (depth 330–670 km, Mw 6.3–7.9), benefiting from the comparably even resolution of moment tensor elements and simple excitation kernels for deep focus events.

For local and regional distance recordings, the small range, bandwidth, and station sparseness may introduce more severe complications in the analysis of historical waveforms. Strong ground motion is off scale, except for few purpose-built low gain instruments that may have recorded near-regional P waves of large earthquakes (Kikuchi et al. 2003, Ichinose et al. 2003). The limited frequency bandwidth affects the reliability of restituted long period ground motion, and source analysis must be often based on shorter period components that do not account for the entire source process and, furthermore, are severely influenced by small-scale heterogeneity affecting regional wave propagation. Two strategies to stabilize source retrieval suggest the use of as unaltered historical recordings as possible, that is substituting the deconvolution of the instrument response from the target waveforms by the corresponding convolutions (see previous section and Rivera et al. 2002, Kikuchi et al. 2003, Ichinose et al. 2003), or the direct processing of individual un-rotated horizontal component seismograms instead of the usual radial and transverse waveforms (Stich et al. 2005), to avoid distortions introduced by rotation of pairs of horizontal historical seismograms with incorrect alignment, uneven drum speed, and imprecise instrumental correction.

Comparably stable approaches for analysing regional historical data include the retrieval of scalar seismic moment from displacement amplitude spectra (e.g. Teves-Costa et al. 1999, Pino et al. 2000), or seismic moment rate from empirical

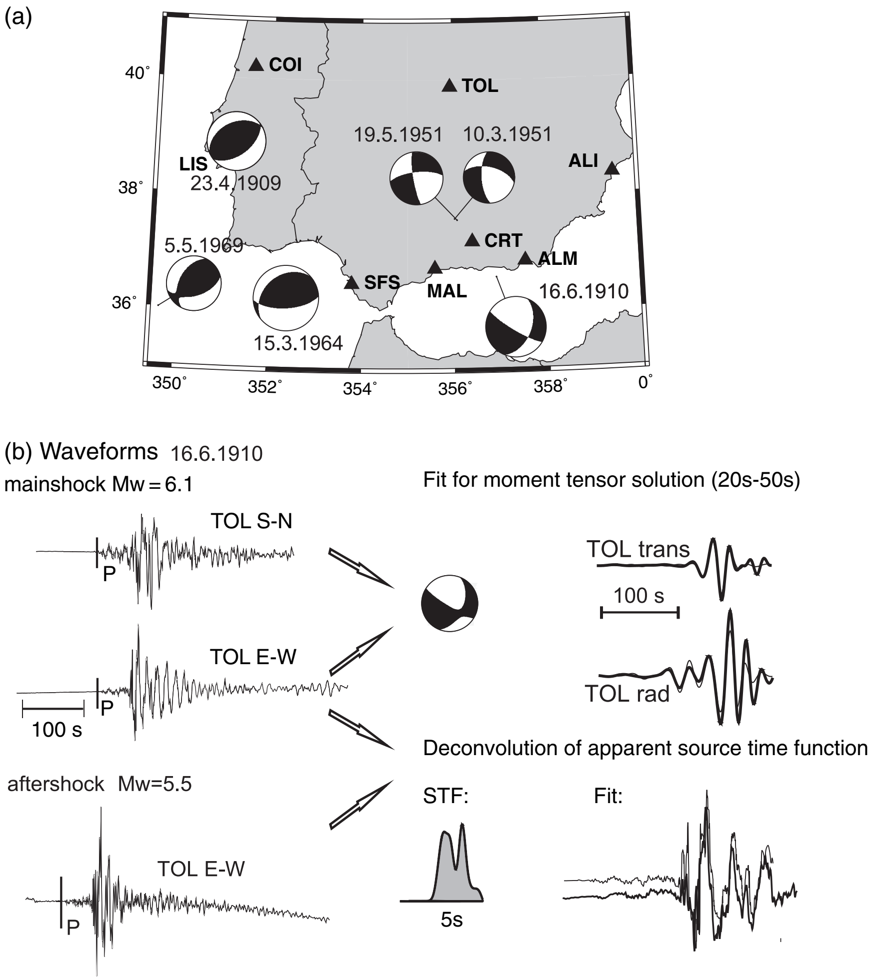

Fig. 4 (**a**) Map showing early seismic observatories (*triangles*) and regional moment tensor estimates from digitized analogue data for the south of the Iberian Peninsula (Pondrelli et al. 1999, Stich et al. 2003, 2005, Batlló et al. 2008), showing a NE–SW orientation of P-axes and a change in faulting style from east to west consistent with source estimates from modern broad band data (Stich et al. 2006). (**b**) Waveform examples for the 16 June 1910 Adra earthquake recorded at station TOL, showing original seismograms after geometrical corrections (*left*), moment tensor fits to intermediate period waveform (*upper right*, the inversion is based on 5 stations altogether, Stich et al. 2003), and waveform fits and apparent source time functions from aftershock deconvolution (*lower right*)

Green functions analysis based on aftershock waveforms (Stich et al. 2003, Batlló et al. 2008, Fig. 4). Forward modeling of sparse regional waveforms can provide valuable insight into focal mechanisms (Baroux et al. 2003), and slip distribution in the case of large events like the Mw 7.1, 1908 Messina Strait earthquake (Pino et al. 2000). Time domain moment tensor inversion of regional historical intermediate period waveforms led to useful source approximations for the largest instrumentally recorded shallow earthquakes that hit Portugal, Spain and France, respectively (Mw 5.5–6.1, Stich et al. 2003, 2005, Fig. 4), showing good consistency with modern seismotectonic studies. For later decades, technical advances including the densification of networks and the deployment of electrodynamic instruments in addition to existing mechanical systems, permitted moment tensor inversion for smaller earthquakes in areas of comparably dense station coverage, e.g. the case of a Mw 5.2 and 5.3 earthquake doublet in 1951 in southern Spain (Batlló et al. 2008, Fig. 4), or small to moderate (Mw 4.5–5.6) aftershocks of the 1952 Kern County earthquake in California (Dreger and Savage 1999).

5 Conclusions

In the early XX century, fundamental concepts of seismic source physics, such as the double couple model for the equivalent body forces of a shear dislocation, were yet to be discovered, as well as the benefits of computer technology and digital signal processing. Fundamental advances of scientific theory and methodology should lead themselves to a reprocessing and reinterpretation of previously obtained data, which is especially true for analog seismograph recordings. To date, most of the instrumental era in seismology predates the invention of digital recording systems and processing schemes, containing the larger share of all moderate and large earthquakes for which waveform information may be available. Large earthquakes, either in a regional or global context, are the rarest events within the seismic cycle, and may be of particular interest, although sometimes their analysis from historic recordings may be hampered by the small dynamic range (causing nonlinearity or clipping of the signal) or the narrow bandwidth (with the instruments being not sufficiently sensitive to long period signals, leading to an underestimation of the total source duration and seismic moment). The characterization of source properties from recorded waveforms of early XX century earthquakes may provide key information for very diverse topics such as regional tectonics and strain accumulation, the identification and kinematics of individual seismogenic faults, earthquake recurrence and seismic hazard, tsunami generation, or the benchmarking of contemporaneous magnitude estimates or earthquake parameters derived from macroseismic observations.

Pointed reasons strongly sustain the need to reanalyze the seismograms of past conspicuous events. The use of such records for seismic research may expand considerably the instrumental period of earthquake seismology. But such reanalysis is not straightforward. Especially dedicated procedures should be taken into account, from restoration of the physical support to the search and recovery of the metadata accompanying the old seismograms to be processed. It is necessary to recover, at least, the information concerning the transfer function, orientation, and polarity of the recording instrument from seismic bulletins, photography and other contemporaneous documents. In the previous sections the acquisition of analogue records obtained from old seismograms, its special characteristics and processing and some possibilities they offer for actual research have been reviewed. Special attention has been paid to the processing procedures, from the scanning of the record image to the generation of a digital seismogram useful for modern seismic analysis tools. Often, the older the seismogram, the more critical is the accurate control of issues like image resolution and adequate instrument performance, complicating the whole procedure. All these factors point to the conclusion that image acquisition and the consecutive digitization and restitution of ground displacement is, in general, a time consuming process. This limits the scope of the different campaigns developed at several institutions to recover and make available those records. Despite those difficulties, the reprocessing of old seismograms for inversion of source parameters can – and did- yield results highly relevant for science and society.

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Bibliography

Abe K (1981) Magnitudes of large shallow earthquakes from 1904 to 1980. *Phys. Earth Planet. In*. 27: 72–92.

Adams WM and Allen DC (1961) Reading seismograms with digital computers. *Bull. Seism. Soc. Am*. 51: 61–67.

Agnew DC (2002) History of Seismology. In: Lee WHK, Kanamori H, Jennings PC and Kisslinger K (eds) *International Handbook of Earthquake & Engineering Seismology*. Academic Press, Amsterdam, pp 3–11.

Alvarado P and Beck S (2006) Source characterization of the San Juan (Argentina) crustal earthquakes of 15 January 1944 (Mw 7.0) and 11 June 1952 (Mw 6.8). *Earth Planet. Sci. Lett*. 243: 615–631.

Baroux E, Pino NA, Valensise G, Scotti O and Cushing ME (2003) Source parameters of the 11 June 1909, Lambesc (Provence, southeastern France) earthquake: A reappraisal based on macroseismic, seismological, and geodetic observations. *J. Geophys. Res*. 108: 2454, doi:10.1029/2002JB002348.

Baskoutas IG, Kalogeras IS, Kourouzidis M and Panopoulou G (2000) A modern technique for the retrieval and processing of historical sesimograms in Greece. *Nat. Hazards* 21: 55–64.

Batlló J, Susagna T and Roca A (1997) A processing system for old records of regional earthquakes: Analysis of the 19th November 1923 earthquake in the Pyrenees. *Cahiers du Centre Européen de Géodynamique et de Séismologie* 13: 149–157.

Batlló J and Bormann P (2000) A catalog of old Spanish seismographs, *Seismol. Res. Lett*. 71: 570–582.

Batlló J (2004) *Catálogo – Inventario de Sismógrafos Antiguos Españoles*. Instituto Geográfico Nacional, Madrid, 414pp.

Batlló J, Clemente C, Pérez-Blanco F, and Vidal F (2004) Reconstruction of a Bosch-Omori Seismograph. *Nuncius* 19: 701–711.

Batlló J, Stich D, Palombo B, Macià R and Morales J (2008) The 1951, Mw 5.2 and 5.3, Jaén (S-Spain) earthquake doublet revisited. *Bull. Seism. Soc. Am*., 98: 1535–1545.

Bromirski PD and Chuang S (2003) *SeisDig User's Manual*. Scripps Institution of Oceanography, San Diego, 28pp.

Cadek O (1987) Studying earthquake ground motion in Prague from Wiechert seismograph records. *Gerl. Beitr. Geoph.* 96: 438–447.

Crouse CB and Matuschka T (1983) Digitialization noise and accelerograph pen offset associated with Japanese accelerograms. *Bull. Seism. Soc. Am*. 73: 1187–1196.

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

Dineva S, Batlló J, Mihailov D and van Eek T (2002) Source parameters of four strong earthquakes in Bulgaria and Portugal at the beginning of the 20th century. *J. Seismol.* 6: 99–123.

Doser DI (1992) Historic earthquakes and an assessment of source parameters along the San Jacinto fault system. *Bull. Seism. Soc. Am*. 82: 1786–1801.

Doser DI, Webb TH and Maunder DE (1999) Source parameters of large historical (1918–1962) earthquakes, South Island, New Zealand. *Geophys. J. Int.* 139: 769–794.

Dreger D and Savage B (1999) Aftershocks of the 1952 Kern County, California, earthquake sequence. *Bull. Seism. Soc. Am.* 89: 1094–1108.

Dziewonski AM, Chou T-A and Woodhouse JH (1981) Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *J. Geophys. Res.* 86: 2825–2852.

Ferrari G and Roversi Monaco C (2005) Restoration and conservation of the Scientific documentation of seismology. http://storing.ingv.it/es_web/Data/restoration/restoration.html (10 October 2006).

Galitzin B (1914) *Vorlesungen über Seismometrie*. B.G. Täubner, Leipzig and Berlin.

Glover DP and Meyers H (1982) Historical Seismogram Filming Project: Fourth Progress Report. *Report SE-33*, *World Data Center-A for Solid Earth Geophysics*, Boulder, CO, 54pp.

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

Gutenberg B and Richter CF (1954) *Seismicity of the Earth and Associated Phenomena*. Princeton University Press, Princeton.

Herak M, Allegretti I, and Duda SJ (1997) Calibration of Vicentini seismographs and magnitude determination for the 1906 San Francisco earthquake on the basis of Zagreb seismogram. *Cahiers du Centre Européen de Géodynamique et de Séismologie* 13: 177–184.

Herrmann RB (1987) *Computer Programs in Seismology. Volume II*. Department of Earth and Atmospheric Sciences, Saint Louis University, St. Louis.

Howell BF (1966) Simple digitizer for paper seismograms. *Bull. Seism. Soc. Am*. 56: 605–608.

Huang WC, Okal EA, Ekström G and Salganik MP (1998) Centroid moment tensor solutions for deep earthquakes predating the digital era: The historical dataset (1907–1961). *Phys. Earth Planet. In.* 106: 181–190.

IASPEI Working Group (2006) IASPEI Working Group on Seismological Archives. http://www.quakes.bgs.ac.uk/iaspei/iaspei_wg_files.htm (10 October 2006)

Ichinose GA, Thio HK, Somerville PG, Sato T and Ishii T (2003) Rupture process of the 1944 Tonankai earthquake (Ms 8.1) from the inversion of teleseismic and regional seismograms. *J. Geophys. Res.* 108(B10): 2497, doi:10.1029/2003JB002393.

Inoue R and Matsumoto T (1988) Digitization and Processing of the J.M.A. Strong Motion Records in the Period of 2 to 20 sec. from Nine Great Earthquakes. In: Lee WHK, Meyers H and Shimazaki K (eds) *Historical Seismograms and Earthquakes of the World*. Academic Press, San Diego, pp 390–400.

Kanamori H (1988) Importance of Historical Seismograms for Geophysical Research. In: Lee WHK, Meyers H and Shimazaki K (eds) *Historical Seismograms and Earthquakes of the World*. Academic Press, San Diego, pp 16–33.

Kanamori H, Miyazawa M and Mori J (2006) Investigation of the earthquake sequence off Miyagi prefecture with historical seismograms. *Earth Planets Space* 58(12): 1533–1541.

Kikuchi M, Nakamura M and Yoshikawa K (2003) Source rupture processes of the 1944 Tonankai earthquake and the 1945 Mikawa earthquake derived from low-gain seismograms. *Earth Planets Space* 55: 159–172.

Lee WHK and Benson RB (2008) Making non-digitally-recorded seismograms accessible online for studying earthquakes. This volume, 403–427.

Liu Z, Wang W, Zhang R, Yu N, Zhang T and Pan J (2001) A seismogram digitization and database management system. *Acta Seismol. Sin.* 14: 333–341.

Merlin E and Somville O (1910) *Liste des observatoires magnétiques et des observatoires séismologiques*. Bruxelles, Hayez, 192pp.

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

Okal EA and Reymond D (2003) The mechanism of great Banda Sea earthquake of 1 February 1938: Applying the method of preliminary determination of focal mechanism to a historical event. *Earth Planet. Sci. Lett.* 216: 1–15.

Pino NA, Giardini D and Boschi E (2000) The December 28, 1908, Messina Straits, southern Italy, earthquake: Waveform modeling of regional seismograms. *J. Geophys. Res.* 105: 25473–25492.

Pintore S, Quintiliani M and Franceschi D (2005) Teseo: A vectorizer of historical seismograms. *Comp. Geosci.* 31: 1277–1285.

Pondrelli S, Ekström G, Morelli A and Primerano S (1999) Study of Source Geometry for Tsunamigenic Events of the Euro-Mediterranean Area. In: *International Conference on Tsunamis*, UNESCO books, Paris, pp. 297–307.

Rebeur-Paschwitz E (1889) The Earthquake of Tokio, April 18, 1889. *Nature* 40: 294–295.

Reid HF (1925) The influence of friction on seismographs, *Bull. Seism. Soc. Am.* 15: 222–241.

Ritter RR (2002) On the recording characteristics of the original Wiechert seismographs at Göttingen (Germany). 6: 477–486.

Rivera L, Sieh K, Helmberger D and Natawidjaja D (2002) A comparative study of the Sumatran subduction-zone earthquakes of 1935 and 1984. *Bull. Seism. Soc. Am.* 92: 1721–1736.

Rodgers PW (1968) The response of the horizontal pendulum seismometer to Rayleigh and Love waves, tilt, and free oscillations of the earth. *Bull. Seism. Soc. Am.* 58: 1384–1406.

Samardjieva E, Payo G, Badal J and López C (1997) *Catalogue of Digital Historical Seismograms (1912–1962)*. Instituto Geográfico Nacional, Madrid, 60pp + 244 plates.

Scherbaum F (1996) *Of Poles and Zeros: Fundamentals of Digital Seismology*. Kluwer, Dordrecht, The Netherlands.

Schlupp A (1996) *Néotectonique de la Mongolie Occidentale analysée à partir de données de terrain, sismologiques et satellitaires*. PhD thesis, ULP, Strasbourg, 270pp.

Schlupp A and Cisternas A (2007) Source history of the 1905 great Mongolian earthquakes (Tsetserleg, Bolnay). *Geophys. J. Int.* 169: 1115–1131.

Schweitzer J and Lee WHK (2003) Old Seismic Bulletins to 1920: A Collective Heritage from Early Seismologists. In: Lee WHK, Kanamori H, Jennings PC and Kisslinger K (eds): *International Handbook of Earthquake & Engineering Seismology*. Academic Press, Amsterdam, pp 1665–1725.

Singh SK, Domínguez T, Castro R and Rodríguez M (1984) P-waveform of large, shallow earthquakes along the Mexican subduction zone. *Bull. Seism. Soc. Am.* 74: 2135–2156.

Stein S, Okal EA and Wiens DA (1988) Application of Modern Techniques to Analysis of Historical Earthquakes. In: Lee WHK, Meyers H and Shimazaki K (eds) *Historical Seismograms and Earthquakes of the World*. Academic Press, San Diego, pp 85–104.

Stich D, Batlló J, Morales J, Macià R and Dineva S (2003) Source parameters of the 1910 Mw=6.1 Adra earthquake (southern Spain). *Geophys. J. Int.* 155: 539–546.

Stich D, Batlló J, Macià R, Teves-Costa P and Morales J (2005) Moment tensor inversion with single-component historical seismograms: The 1909 Benavente (Portugal) and Lambesc (France) earthquakes. *Geophys. J. Int*. 162: 850–858.

Stich D, Serpelloni E, Mancilla F and Morales J (2006) Kinematics of the Iberia-Maghreb plate contact from seismic moment tensors and GPS observations. *Tectonophysics* 426: 295–317.

Teves-Costa P, Borges JF, Rio I, Ribeiro R and Marreiros C (1999) Source parameters of old earthquakes: Semi-automatic digitization of analog records and seismic moment assessment. *Nat. Hazards* 19: 205–220.

Wald DJ, Kanamori H, Helmberger DV and Heaton TH (1993) Source study of the 1906 San Franciso earthquake. *Bull. Seism. Soc. Am.* 83: 981–1019.

Wald DJ and Somerville PG (1995)Variable-slip rupture model of the great 1923 Kanto, Japan, earthquake: Geodetic and body-waveform analysis. *Bull. Seism. Soc. Am.* 85: 159–177.

Wickens AJ and Kollar F (1967) A wide range seismogram Digitizer. *Bull. Seism. Soc. Am*. 57: 91–98.

Wiechert E (1904) Ein astatisches Pendel hoher Empfindlichkeit zur mechanischen Registrierung von Erdbeben. *Beiträge zur Geophysik* 6: 437–450.

Wielandt E (2002) Seismometry. In: Lee WHK, Kanamori H, Jennings PC and Kisslinger K (eds): *International Handbook of Earthquake & Engineering Seismology*. Academic Press, Amsterdam, pp 283–304.