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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.