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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

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ABSTRACT

Moment magnitude (M_W) determinations from the online GCMT Catalogue of seismic moment tensor solutions (GCMT Catalog, 2011) have provided the bulk of M_W values in the ISC-GEM Global Instrumental Reference Earthquake Catalogue (1900–2009) for almost all moderate-to-large earthquakes occurring *after* 1975. This paper describes an effort to determine M_W of large earthquakes that occurred *prior to* the start of the digital seismograph era, based on credible assessments of thousands of seismic moment (M_0) values published in the scientific literature by hundreds of individual authors. M_W computed from the published M_0 values (for a time period more than twice that of the digital era) are preferable to proxy M_W values, especially for earthquakes with M_W greater than about 8.5, for which M_S is known to be underestimated or "saturated".

After examining 1,123 papers, we compile a database of seismic moments and related information for 1,003 earthquakes with published M_0 values, of which 967 were included in the ISC-GEM Catalogue. The remaining 36 earthquakes were not included in the Catalogue due to difficulties in their relocation because of inadequate arrival time information. However, 5 of these earthquakes with bibliographic M_0 (and thus M_W) are included in the Catalogue's Appendix. A search for reliable seismic moments was not successful for earthquakes prior to 1904. For each of the 967 earthquakes a "preferred" seismic moment value (if there is more than one) was selected and its uncertainty was estimated according to the data and method used.

We used the IASPEI formula (IASPEI, 2005) to compute *direct* moment magnitudes ($M_W[M_0]$) based on the seismic moments (M_0), and assigned their errors based on the uncertainties of M_0. From 1900 to 1979, there are 129 great or near great earthquakes ($M_W \geqslant 7.75$) – the bibliographic search provided *direct* M_W values for 86 of these events (or 67%), the GCMT Catalog provided *direct* M_W values for 8 events (or 6%), and the remaining 35 (or 27%) earthquakes have empirically determined *proxy* M_W estimates. An electronic supplementary file is included with this paper in order to provide our M_0/M_W catalogue of earthquakes (1904–1978) from the published literature, and a reference list of the 1,123 papers that we examined.

1. Introduction

Seismic moment (M_0) is a fundamental parameter characterizing the "size" of an earthquake (Bormann et al., 2002). The International Seismological Centre (ISC) was funded by the GEM Foundation to deliver a reliable instrumental global earthquake catalogue (from 1900 to 2009) with relocated hypocenters and moment magnitudes.

Using digital seismograms, the Global CMT Project (http://www.globalcmt.org/) provides uniform seismic moment tensor solutions for many global earthquakes from 1976 to the present, and some selected events earlier. Since 1981, The National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS) has computed moment tensor solutions for all global moderate-to-large size earthquakes (Sipkin, 2002). At present, many websites have near real-time moment tensor solutions posted for online access and/or search. However, it is beyond the

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scope of this paper to discuss these resources, because almost all the posted online moment tensor solutions are for earthquakes from about 1990 to the present.

This paper describes an effort to collect determinations of seismic moment published by various researchers for individual large earthquakes from 1900 to 1979 in order to complement the GCMT seismic moments (1976–2009), and to allow for a small overlap with the GCMT Catalog, 2011. Preferred seismic moment values (with quality assessments) for the ISC-GEM Global Instrumental Earthquake Catalogue were selected and the moment magnitudes, $M_W[M_0]$, computed, with error assignments based on the M_0 quality assessments. The period from 1976 to 1979 has provided very favorable comparisons between the M_0 values in the GCMT Catalog (2011) and those calculated by other authors based on the assigned errors.

In the following sections, an approach for obtaining moment magnitudes, a brief history on seismic moment, the compilation procedure, the selection of preferred seismic moment values and their classification by quality, comments on the preferred seismic moment values, discussion, and conclusions, will be presented. An electronic supplementary file is included with this paper in order to provide our catalogue of the seismic moments and moment magnitudes of earthquakes (1904–1978) from the published literature, and a reference list of 1,123 papers that we examined.

2. An approach for obtaining moment magnitudes

An earthquake magnitude scale is intended to provide an objective measure of earthquake "size" that can be routinely carried out by a seismic network. Richter (1935) introduced the so-called "Richter magnitude", M_L, for *local* earthquakes in southern California using Wood-Anderson seismograms. For more distant earthquakes worldwide, Gutenberg (1945a,b) introduced the surface-wave magnitude (M_S) and the body-wave magnitude (m_B) for shallow events, and Gutenberg (1945c) m_B for deep events. Since then, many magnitude scales have been introduced. Utsu (2002) presented a concise summary for 12 commonly used magnitude scales with their defining equations, and made an extensive study of their relationships. Since seismic instrumentation has improved over time (see e.g., Lee and Wu (2009)), the practice of computing earthquake magnitudes has also changed. Before 1904, the first generation seismic instrumentation did not permit reliable magnitude calculations due to the small numbers of mostly undamped seismographs of low magnification (about 10×) deployed globally. From 1904 to the late 1950s, damped seismographs with higher magnification (about 100–1,000×) were developed and the number of seismic stations increased from about 100 to about 1,000 worldwide. Also, the infrastructure in seismology was developed for sharing seismic data (e.g., by publishing station bulletins and the International Seismological Summary). In fact, one of the first instrumental global earthquake catalogue with magnitudes (1904–1952) was published by Gutenberg and Richter (1954). A major advance in seismology was the establishment of the World-Wide Standardized Seismograph Network (WWSSN) of uniform short-period and long-period seismographs with over 100 stations by 1964, and a seismogram distribution system in microfilms. Up to the mid-1970s, seismic instruments were "analog" with limited dynamic range and narrow frequency response, making it difficult to use modern methods for determining earthquake moment from seismic waveforms.

The so-called "proxy" moment magnitudes can also be estimated empirically from conventional magnitudes, such as M_S and m_b. However, these *proxy* moment magnitudes should be used with caution for the following reasons: (1) M_W was introduced because of the "saturation" problem with conventional magnitudes, especially m_b. For example, the largest M_S observed was about 8.6. This means that one cannot obtain a reliable *proxy* M_W from M_S for the very large earthquakes (M_S greater than about 8.5). (2) Proxy moment magnitudes that are estimated from other magnitude scales are purely empirical and not based on any independent physical measurements. Nevertheless, it was decided that, in the absence of published moment magnitudes, *proxy* M_W estimates would be used as default values in the ISC-GEM Catalogue.

3. A brief history on seismic moment

Richter (1935) introduced the concept of *magnitude* for Southern California earthquakes, which he specifically related to a measurement (in physical units) of the Earth's ground motion, corrected for epicentral distance. In this landmark contribution, Richter recognized the empirical, somewhat *ad hoc* character of his approach, while expressing the hope that later developments would bring a theoretical legitimacy to what he envisioned would become a quantitative measurement of the energy released by the earthquake. Notwithstanding the extraordinary success of the application of the magnitude concept worldwide (Gutenberg and Richter, 1954), little progress was made in the ensuing years until an adequate physical model of the earthquake source became available and accepted.

Highlights in the developments of seismic moments include but are not limited to:

1. Vvedenskaya (1956) first proposed the concept of a double-couple system of forces. Steketee (1958a,b) applied dislocation theory to study a 3-dimensional fault.
2. Knopoff and Gilbert (1959) proved the representation theorem, namely that a dislocation occurring in an elastic material featuring a discontinuity along a fault can be replaced, in the limit of a point source, by a combination of forces in the form of a double-couple imbedded in a continuous medium.
3. Under the formalism of the double-couple, Haskell (1963, 1964) derived theoretical formulas for the excitation of Love and Rayleigh waves in layered media.
4. Aki (1966) performed the first determination of the seismic moment of an earthquake by applying Haskell's approach to the Niigata earthquake of 16 June 1964.
5. Saito (1967) soon used normal mode theory to extend Haskell's method to the more realistic case of a spherically stratified self-gravitating Earth. His results were used by Kanamori (1970a,b) to obtain seismic moment estimates for two very large events: the 13 October 1963 Kuril and 28 March 1964 Alaska earthquakes. Both Aki and Kanamori used a forward-modeling approach: they computed synthetic seismograms of mantle surface waves, and compared their amplitudes in the time domain to those of recorded seismograms worldwide, using trial and error to optimize the geometry of the double-couple, as well as the lateral dimensions of the source.
6. Gilbert (1971) provided a simple, elegant, formula for the excitation of a free oscillation of the Earth by any system of forces, proving in particular that a double couple of moment excites an Earth mode proportionally to its full scalar product with the eigenstrain of the mode at the location of the source. Gilbert (1973) showed that earthquake source parameters could be formulated as a *linear* inverse problem because the excitation of normal modes depends *linearly* on the elements of the seismic moment tensor. This set the stage for a possible direct inversion of the moment tensor from a large set of observed seismograms. Gilbert and Dziewonski (1975) tested this idea using digitized analog (WWSSN) seismograms from two large deep earthquakes