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# Centroid moment tensor solutions for deep earthquakes predating the digital era: The historical dataset (1907–1961)

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**Abstract**

We present a catalogue of 35 centroid moment tensor solutions for deep earthquakes ($h \geq 300$ km), covering the years 1907–1961, and obtained by applying the inversion algorithm routinely used in the Harvard CMT project to analog records obtained from archived collections of historical seismograms. While the catalogue does not achieve completeness, it provides new insight into as many significant historical events as could be obtained given the available data. © 1998 Published by Elsevier Science B.V. All rights reserved.

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*Keywords:* Centroid; Earthquakes; Digital era

## 1. Introduction

We refer to Dziewonski et al. (1997) for the most recent update of the Harvard CMT catalogue, and additionally to Dziewonski et al. (1995) for a complete set of references to the 60 CMT reports published by the Harvard group over the past few years. A similar catalogue for deep events of the WWSSN era (1962–1976) was published earlier (Huang et al., 1997). We also refer to the latter article for a discussion of the rationale behind this research, and to Huang et al. (1994) for an explanation and test of the feasibility of inverting for the moment tensor of deep earthquakes using a dataset consisting of a very limited number of narrow-band records (potentially using a single station). The present report is the final step of this project. A discussion of the geophysical implications of the results of this experiment is given in a companion paper (Huang and Okal, 1998).

## 2. Methodology

When working with historical seismograms, a number of problems at all steps of the process conspire to give the resulting dataset a somewhat ad hoc character and in particular to prevent the completeness (above a certain moment threshold) which we had achieved in the WWSSN study. These problems can be classified roughly into three categories: the existence and availability of records, the documentation of recording characteristics, and the uncertainty surrounding hypocentral parameters. A full

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description of these issues is discussed in the work of Huang (1996).

### 2.1. Targeting the stations

Most records used in this work came from the archives of the California Institute of Technology in Pasadena, the Seismological Observatory in Uppsala, Sweden, and the microfilmed collection of historical seismograms maintained by the US Geological Survey in Denver. In very general terms, the types of records available for this study can be summarized as follows (backwards in time).

- From 1957 to 1961, Press–Ewing records from the International Geophysical Year [IGY] deployment are usually available; their characteristics are generally comparable to post-1961 long-period WWSSN seismograms.

Table 1
Inverted centroid parameters (left)

| No. | Centroid parameters | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Date | | | Time | | | | Latitude | | Longitude | | Depth | |
| | D | M | Y | h | m | s | $\delta t_0$ | $\lambda$ | $\delta\lambda_0$ | $\phi$ | $\delta\phi_0$ | h | $\delta h_0$ |
| 201 C | 25 | 5 | 1907 | 14 | 2 | 26.0 ± 2.0 | 18.0 | 52.50 | 1.00 | 152.00 | 5.00 | 547.7 ± 17.0 | −52.3 |
| 202 A | 28 | 4 | 1911 | 9 | 53 | 10.4 ± 0.9 | 16.4 | −9.50 | −9.50 | −71.20 | −0.20 | 556.8 ± 6.5 | −43.2 |
| 203 A | 23 | 4 | 1915 | 15 | 29 | 22.4 ± 0.7 | 4.4 | −8.10 | −0.10 | −70.71 | −2.71 | 612.0 ± 6.2 | −38.0 |
| 204 C | 21 | 6 | 1916 | 21 | 32 | 53.7 ± 1.1 | 23.7 | −28.50 | 0.00 | −63.00 | 0.00 | 647.1 ± 10.3 | 47.1 |
| 205 A | 17 | 1 | 1922 | 3 | 50 | 36.6 ± 1.4 | 3.6 | −3.80 | −1.30 | −71.94 | 1.00 | 663.7 ± 1.1 | 13.7 |
| 206 B | 4 | 5 | 1924 | 16 | 51 | 47.7 ± 1.5 | 4.7 | −21.40 | −0.40 | −178.49 | −0.49 | 528.3 ± 11.2 | −31.7 |
| 207 B | 29 | 3 | 1928 | 5 | 5 | 7.7 ± 1.4 | 4.7 | 31.35 | −0.35 | 138.20 | 0.00 | 428.2 ± 8.1 | 18.2 |
| 208 C | 2 | 6 | 1929 | 21 | 38 | 35.7 ± 2.9 | 1.7 | 33.80 | −0.70 | 137.12 | −0.13 | 366.7 ± 16.8 | 6.7 |
| 209 A | 9 | 1 | 1932 | 10 | 21 | 53.3 ± 0.6 | 11.3 | −6.08 | 0.12 | 154.44 | −0.06 | 371.4 ± 4.5 | −8.6 |
| 210 B | 11 | 8 | 1937 | 0 | 55 | 58.2 ± 1.0 | 4.2 | −6.65 | −0.40 | 116.29 | −0.21 | 612.0 ± 0.0 | 2.0 |
| 211 B | 21 | 4 | 1939 | 4 | 29 | 20.1 ± 2.8 | 16.1 | 47.60 | 0.10 | 139.75 | 0.00 | 525.4 ± 25.9 | 5.4 |
| 212 C | 20 | 7 | 1939 | 2 | 23 | 5.2 ± 2.1 | 5.2 | −22.58 | −0.58 | −179.02 | 0.48 | 605.9 ± 17.7 | −44.1 |
| 213 B | 25 | 5 | 1944 | 1 | 6 | 48.5 ± 0.9 | 11.5 | −21.58 | −0.08 | −179.17 | 0.33 | 626.6 ± 8.0 | −13.4 |
| 214 B | 11 | 1 | 1946 | 1 | 33 | 36.2 ± 1.4 | 7.2 | 44.56 | 0.56 | 130.12 | 0.62 | 573.5 ± 21.2 | −6.5 |
| 215 A | 27 | 1 | 1948 | 11 | 58 | 36.4 ± 0.5 | 8.4 | −19.92 | 0.58 | −178.21 | −0.21 | 619.4 ± 4.5 | −10.6 |
| 216 A | 28 | 2 | 1950 | 10 | 21 | 9.6 ± 0.8 | 12.6 | 45.82 | −0.18 | 143.55 | −0.45 | 338.9 ± 4.3 | −1.1 |
| 217 B | 9 | 7 | 1950 | 4 | 40 | 13.8 ± 0.8 | 9.8 | −8.45 | −0.45 | −70.16 | 0.59 | 649.0 ± 7.6 | −1.0 |
| 218 A | 14 | 8 | 1950 | 22 | 51 | 35.2 ± 0.8 | 11.2 | −27.49 | −0.24 | −62.88 | −0.38 | 612.0 ± 6.1 | −18.0 |
| 219 B | 22 | 9 | 1950 | 23 | 55 | 45.2 ± 1.5 | 13.2 | −17.52 | 0.08 | −177.13 | −0.03 | 429.1 ± 8.1 | 16.1 |
| 220 A | 11 | 7 | 1951 | 18 | 21 | 55.2 ± 0.7 | 3.2 | 27.50 | 0.00 | 139.50 | 0.00 | 478.8 ± 5.9 | −1.2 |
| 221 C | 30 | 5 | 1955 | 12 | 32 | 1.9 ± 1.9 | 20.9 | 24.50 | 0.00 | 142.45 | −0.05 | 551.6 ± 11.2 | −18.4 |
| 222 B | 6 | 8 | 1955 | 8 | 31 | 35.4 ± 1.9 | 7.4 | −20.98 | 0.02 | −177.62 | 0.38 | 344.2 ± 10.9 | −15.8 |
| 223 C | 1 | 2 | 1956 | 13 | 41 | 44.3 ± 2.9 | 0.3 | 19.25 | 0.25 | 145.25 | −0.25 | 390.7 ± 17.1 | 20.7 |
| 224 A | 18 | 2 | 1956 | 7 | 34 | 25.9 ± 0.7 | 6.9 | 30.08 | 0.18 | 138.14 | −0.36 | 480.4 ± 5.3 | 0.4 |
| 225 A | 23 | 5 | 1956 | 20 | 48 | 44.4 ± 0.5 | 16.2 | −15.41 | 0.00 | −178.73 | 0.00 | 435.8 ± 2.5 | 39.8 |
| 226 A | 17 | 7 | 1956 | 7 | 34 | 11.8 ± 1.0 | 4.8 | −7.04 | −0.04 | 126.15 | −0.35 | 438.3 ± 7.7 | −11.7 |
| 227 A | 3 | 1 | 1957 | 12 | 48 | 35.1 ± 1.3 | 5.1 | 43.85 | 0.00 | 130.63 | 0.00 | 573.4 ± 9.6 | −19.6 |
| 228 A | 16 | 4 | 1957 | 4 | 4 | 4.1 ± 0.5 | 1.1 | −4.35 | 0.33 | 107.30 | 0.14 | 635.6 ± 4.4 | 89.6 |
| 229 A | 28 | 9 | 1957 | 14 | 20 | 7.7 ± 0.6 | 7.7 | −20.48 | 0.00 | −178.51 | 0.00 | 578.2 ± 3.9 | 29.2 |
| 230 B | 26 | 7 | 1958 | 17 | 37 | 11.6 ± 1.0 | 2.6 | −13.50 | 0.00 | −69.00 | 0.00 | 592.0 ± 5.8 | −28.0 |
| 231 A | 15 | 1 | 1959 | 21 | 20 | 34.0 ± 1.1 | 6.1 | −25.68 | −0.15 | 179.97 | 0.10 | 494.4 ± 10.8 | 25.4 |
| 232 A | 15 | 9 | 1959 | 11 | 5 | 49.7 ± 0.4 | 13.5 | −21.93 | −0.05 | −179.40 | 0.06 | 597.3 ± 2.8 | 11.3 |
| 233 A | 3 | 9 | 1960 | 12 | 41 | 33.0 ± 0.3 | −1.9 | −6.10 | 0.00 | 154.50 | 0.00 | 420.3 ± 2.1 | −36.7 |
| 234 A | 8 | 10 | 1960 | 5 | 53 | 7.0 ± 0.4 | 5.9 | 40.23 | 0.23 | 129.98 | 0.28 | 616.1 ± 2.8 | 8.1 |
| 235 B | 19 | 8 | 1961 | 5 | 10 | 10.1 ± 1.5 | 20.6 | −10.90 | −0.10 | −70.90 | 0.10 | 619.5 ± 9.3 | −29.5 |

- In the 1940s and 1950s, the best records, when available, are from the Benioff instruments (1–90 and strainmeters at Pasadena, and some exported Benioff seismographs at other sites).
- For even older events, the only records available for processing are usually from the original Wiechert and Galitzin deployments. Among Wiechert seismographs, the Uppsala instrument has a particularly long period, superbly organized archives, and meticulously documented calibration records, which made it one of our preferred sources. Some very valuable seismograms also came from early Galitzin instruments deployed in Russia (until 1916; the Soviet Union starting in the mid-1920s), whose records are available from the microfilmed collections.

Instrument response information, a crucial ingredient for this project, was obtained preferably from careful calibrations either regularly documented (e.g.,

Table 1 (continued)
Inverted centroid parameters (right)

| Half Drtn | Scale Factor $10^{ex}$ | Principal axes | | | | | | | | | Best double-couple | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T-axis | | | N-axis | | | P-axis | | | $M_0$ | Plane 1 | | | Plane 2 | | |
| | | $\sigma$ | $\delta$ | $\xi$ | $\sigma$ | $\delta$ | $\xi$ | $\sigma$ | $\delta$ | $\xi$ | | $\phi_s$ | $\theta$ | $\lambda$ | $\phi_s$ | $\theta$ | $\lambda$ |
| 23.5 | 27 | 4.29 | 5 | 313 | −1.17 | 17 | 45 | − 3.12 | 72 | 206 | 3.7 | 25 | 42 | −116 | 238 | 52 | −68 |
| 9.4 | 27 | 4.06 | 11 | 94 | −0.74 | 0 | 4 | −3.32 | 79 | 273 | 1.5 | 184 | 34 | −90 | 4 | 56 | −90 |
| 11.8 | 26 | 1.33 | 4 | 242 | −0.06 | 8 | 152 | −1.27 | 81 | 0 | 1.3 | 340 | 41 | −78 | 145 | 50 | −100 |
| 14.8 | 26 | 5.91 | 1 | 90 | −1.26 | 37 | 0 | −4.65 | 53 | 181 | 5.3 | 212 | 55 | −43 | 330 | 56 | −136 |
| 9.4 | 27 | 7.86 | 20 | 287 | −1.62 | 17 | 191 | −6.24 | 63 | 63 | 9.4 | 44 | 30 | −53 | 183 | 67 | −109 |
| 11.8 | 26 | 6.11 | 21 | 318 | −1.00 | 29 | 61 | −5.12 | 52 | 198 | 5.6 | 8 | 35 | −148 | 251 | 72 | −59 |
| 9.4 | 26 | 3.25 | 3 | 359 | 1.97 | 56 | 94 | −5.23 | 34 | 267 | 4.2 | 49 | 64 | −157 | 308 | 69 | −28 |
| 9.4 | 26 | 2.45 | 27 | 84 | 0.12 | 34 | 333 | −2.57 | 44 | 203 | 2.5 | 223 | 35 | −17 | 327 | 80 | −124 |
| 11.8 | 26 | 2.36 | 6 | 91 | 0.60 | 14 | 183 | −2.96 | 75 | 338 | 2.7 | 166 | 41 | −112 | 14 | 53 | −72 |
| 8.3 | 26 | 5.46 | 24 | 280 | −0.85 | 16 | 183 | −4.61 | 61 | 62 | 5.0 | 39 | 25 | −51 | 177 | 70 | −107 |
| 8.3 | 26 | 5.53 | 3 | 234 | −2.40 | 56 | 139 | −3.13 | 34 | 326 | 4.3 | 4 | 64 | −23 | 105 | 69 | −152 |
| 8.3 | 26 | 2.69 | 35 | 97 | −0.74 | 54 | 266 | −1.95 | 5 | 3 | 2.3 | 134 | 62 | 157 | 235 | 70 | 30 |
| 10.5 | 26 | 11.33 | 15 | 151 | −1.40 | 23 | 55 | −9.93 | 62 | 271 | 10.6 | 270 | 36 | −49 | 43 | 63 | −116 |
| 10.5 | 26 | 2.54 | 50 | 128 | −0.92 | 16 | 18 | −1.62 | 35 | 276 | 2.1 | 315 | 18 | 26 | 200 | 82 | 106 |
| 10.5 | 26 | 4.28 | 19 | 212 | 1.40 | 51 | 96 | −5.68 | 32 | 315 | 5.0 | 349 | 52 | −10 | 86 | 82 | −142 |
| 23.5 | 27 | 4.74 | 42 | 39 | −1.77 | 22 | 150 | −2.97 | 40 | 260 | 3.9 | 57 | 22 | 177 | 150 | 89 | 68 |
| 8.3 | 26 | 1.96 | 6 | 111 | 0.06 | 10 | 20 | −2.02 | 78 | 231 | 2.0 | 213 | 40 | −74 | 12 | 52 | −103 |
| 11.8 | 26 | 5.62 | 34 | 229 | −0.10 | 18 | 332 | −5.51 | 50 | 84 | 5.6 | 268 | 20 | −155 | 155 | 82 | −72 |
| 8.3 | 26 | 1.81 | 42 | 90 | −0.15 | 16 | 194 | −1.66 | 44 | 300 | 1.7 | 109 | 16 | −176 | 14 | 89 | −74 |
| 8.3 | 26 | 4.58 | 8 | 343 | 1.85 | 35 | 79 | −6.44 | 54 | 242 | 5.5 | 40 | 48 | −141 | 281 | 62 | −49 |
| 9.4 | 26 | 7.80 | 22 | 298 | −1.66 | 20 | 37 | −6.13 | 59 | 164 | 7.0 | 356 | 29 | −135 | 224 | 70 | −69 |
| 8.3 | 26 | 1.99 | 39 | 280 | −0.69 | 35 | 155 | −1.31 | 31 | 40 | 1.6 | 75 | 36 | 8 | 338 | 85 | 126 |
| 8.3 | 26 | 1.57 | 7 | 262 | −0.02 | 8 | 171 | −1.55 | 79 | 34 | 1.6 | 1 | 38 | −77 | 165 | 53 | −100 |
| 13.2 | 26 | 8.92 | 4 | 331 | 1.80 | 36 | 64 | −10.72 | 54 | 236 | 9.8 | 29 | 52 | −139 | 270 | 59 | −47 |
| 14.8 | 27 | 2.44 | 36 | 305 | 0.56 | 22 | 51 | −3.00 | 46 | 166 | 2.7 | 337 | 23 | −165 | 234 | 84 | −68 |
| 8.3 | 26 | 2.01 | 28 | 148 | 0.58 | 52 | 280 | −2.58 | 24 | 45 | 2.3 | 185 | 52 | 177 | 277 | 88 | 38 |
| 8.3 | 26 | 2.69 | 23 | 138 | −0.44 | 30 | 34 | −2.26 | 51 | 259 | 2.5 | 270 | 35 | −29 | 25 | 74 | −121 |
| 10.5 | 26 | 2.07 | 1 | 204 | 1.04 | 14 | 113 | −3.11 | 76 | 297 | 2.6 | 307 | 46 | −70 | 100 | 48 | −109 |
| 14.8 | 27 | 1.56 | 24 | 79 | 0.16 | 24 | 180 | −1.72 | 55 | 309 | 1.6 | 130 | 30 | −143 | 8 | 73 | −65 |
| 14.8 | 27 | 2.85 | 32 | 219 | −0.54 | 19 | 321 | −2.31 | 51 | 77 | 2.6 | 262 | 22 | −151 | 145 | 80 | −70 |
| 4.8 | 25 | 4.23 | 50 | 55 | −1.02 | 16 | 165 | −3.21 | 36 | 266 | 3.7 | 49 | 17 | 155 | 163 | 83 | 74 |
| 4.8 | 25 | 6.19 | 44 | 95 | −1.28 | 14 | 199 | −4.91 | 42 | 303 | 5.6 | 105 | 14 | 176 | 199 | 89 | 76 |
| 5.3 | 25 | 4.44 | 31 | 222 | 0.66 | 21 | 118 | −5.11 | 51 | 0 | 4.8 | 359 | 24 | −27 | 114 | 79 | −112 |
| 5.3 | 26 | 2.16 | 43 | 129 | −0.17 | 18 | 22 | −2.00 | 41 | 275 | 2.1 | 295 | 18 | 3 | 202 | 89 | 108 |
| 8.3 | 27 | 3.25 | 4 | 232 | 0.27 | 2 | 142 | −3.52 | 86 | 27 | 3.4 | 324 | 41 | −87 | 140 | 49 | −92 |

Uppsala) or specifically compiled (Pasadena; H. Kanamori personal communication to E.A. Okal, 1991). We also used the extensive compilations by McComb and West (1931) and Charlier and van Gils (1953).

Unfortunately, one of the most poorly known parameters for these very early seismograms is the exact time correction to be effected. This information was often lost in the archiving and microfilming process. It then becomes impossible to use seismograms from different stations since the inversion procedure uses phase as well as amplitude information and thus, most of the historical inversions were performed with a single station.

An additional aspect of the uncertainties inherent in instrument responses is that, when the relative gains at two or more stations happen to be erroneous, the performance of the inversion drops significantly, and in particular, the orientation of the inverted focal mechanism can be substantially affected. If the single-station inversion is performed, the moment can be inaccurate, but the geometry of rupture is robust.

As a result of these limitations, and as discussed more in detail in the work of Huang et al. (1994), we then find it necessary to constrain the epicenter of the event, since a dataset limited to a single station cannot resolve all CMT parameters. This in turn requires an accurate epicenter, which in most cases necessitates a relocation effort based on arrival times published in the International Seismological Summary. These relocations were performed using the interactive algorithm of Wysession et al. (1991); we also benefited from a number of solutions obtained by Engdahl et al. (1997), using a new algorithm taking into account later phases such as *pP*, *sP*, and *PcP*.

### 2.2. Targeting the events

We extracted from the National Earthquake Information Center file all deep events ($h \geq 300$ km) occurring between 1900 and 1961 with at least one listed magnitude above a threshold $M_{\mathrm{thr.}} = 6.8$ (1900–1957) or $M_{\mathrm{thr.}} = 6.5$ (1958–1961), the lower figure reflecting the introduction of the more sensitive IGY Press–Ewing instruments. Of the 116 earthquakes thus extracted, 62 events yielded at least two records of potentially usable quality. We did not seek to obtain records of the deep 1954 Spanish earthquake, which was the subject of a comprehensive study by Chung and Kanamori (1976); this event was characterized by the combination of a relatively large moment and extreme complexity in the source. As discussed later, our experience with other complex events clearly meant that we could not expect to improve on these authors' solution.

For the remaining 54 earthquakes, seismograms were either unavailable or of a quality deemed unsuitable for the inversion of the relevant mantle phases. This includes, in particular, the Japanese earthquake of 21 January 1906, studied by Abe (1985) who assigned it a moment of only $1.5 \times 10^{27}$ dyn cm despite reported magnitudes of 8.0 (Gutenberg and Richter, 1954) or even 8.4 (Richter, 1958). Even in more recent instances, several seismograms were of such small amplitude as to raise significant doubt about their reported magnitudes (Fiji, 26 September 1946; Kuriles, 17 November 1957).

### 2.3. Inversion at constrained epicenters

As mentioned earlier, we must rely on single-station inversions for the historical events considered in this study. Although previous studies (Ekström et al., 1985; Huang et al., 1994) have demonstrated that single-station CMT analysis can provide accurate estimates of scalar moment and faulting geometries for large earthquakes, this procedure requires that the epicenter be constrained during the inversion. While such a constraint acts to stabilize the inversion and in particular improves the resolution of the scalar moment, it brings in the additional problem of the influence of an inaccurate epicenter, which could either destabilize the inversion or yield inaccurate source parameters, leading to erroneous geophysical interpretations.

In order to alleviate this problem, we adopted a grid-search strategy, in which CMT inversions are calculated systematically at a number of regularly spaced epicenters, extending typically over 150 km, and with the central location generally being the best available relocation. For each constrained epicenter, the root-mean-square ratio (RMS) of the misfits between the observed and synthetic seismograms, and the inverted focal depth are used to evaluate if the inversion result is stable and reliable. Further details and examples of the procedure are given in the work of Huang (1996). Whenever the patterns of variation of the RMS, inverted depths and focal mechanisms with epicentral location exhibited significant instability, the inversion effort was abandoned and the event discarded from the final catalogue.

An interesting aspect of the grid-search strategy is that, for very old events, it can be used as a relocation tool. It has been our experience that the combination of inadequate (in particular undamped) instrumentation with imprecise clock readings, makes it impossible to obtain reliable relocations based on available bulletin listings of presumed *P* wave arrivals. Indeed, on one occasion (Sea of Okhotsk event of 25 May 1907), a special request to the ISC to reprocess the available list of arrivals resulted in a failure to obtain convergence of their algorithm to a definite solution (R.D. Adams, personal communica-

Table 2
Inverted moment tensors

| No. | Scale | Elements of moment tensor | | | | | |
|---|---|---|---|---|---|---|---|
| | $10^{ex}$ | $M_{rr}$ | $M_{\theta\theta}$ | $M_{\phi\phi}$ | $M_{r\theta}$ | $M_{r\phi}$ | $M_{\theta\phi}$ |
| 201 C | 27 | −2.89 ± 4.68 | 1.20 ± 2.35 | 1.70 ± 6.94 | 0.85 ± 1.97 | 0.11 ± 1.06 | 2.77 ± 5.15 |
| 202 A | 27 | −3.05 ± 0.90 | −0.72 ± 0.32 | 3.77 ± 1.05 | −0.09 ± 0.34 | −1.38 ± 0.29 | 0.33 ± 1.06 |
| 203 A | 26 | −1.24 ± 0.34 | 0.22 ± 0.15 | 1.02 ± 0.43 | −0.23 ± 0.17 | 0.09 ± 0.16 | −0.57 ± 0.39 |
| 204 C | 26 | −3.44 ± 0.82 | −2.47 ± 0.70 | 5.91 ± 1.45 | 1.63 ± 0.46 | −0.13 ± 0.32 | 0.09 ± 0.82 |
| 205 A | 27 | −4.24 ± 1.84 | −1.07 ± 0.74 | 5.31 ± 2.36 | 0.04 ± 0.79 | 4.51 ± 0.63 | 2.77 ± 2.52 |
| 206 B | 26 | −2.64 ± 2.62 | 1.05 ± 1.62 | 1.59 ± 4.07 | 3.69 ± 1.23 | 0.98 ± 0.90 | 3.52 ± 2.50 |
| 207 B | 26 | −0.27 ± 2.46 | 3.24 ± 1.79 | −2.96 ± 4.18 | 0.23 ± 0.71 | −3.33 ± 0.60 | 0.26 ± 2.45 |
| 208 C | 26 | −0.69 ± 2.96 | −1.03 ± 1.34 | 1.72 ± 4.23 | 1.34 ± 0.72 | −1.48 ± 0.51 | 0.30 ± 2.35 |
| 209 A | 26 | −2.69 ± 0.41 | 0.39 ± 0.17 | 2.30 ± 0.46 | −0.85 ± 0.19 | −0.52 ± 0.15 | −0.05 ± 0.58 |
| 210 B | 26 | −2.72 ± 2.27 | −0.90 ± 2.10 | 3.61 ± 0.47 | −0.35 ± 0.60 | 3.69 ± 0.66 | 1.24 ± 3.11 |
| 211 B | 26 | −2.61 ± 1.10 | 0.01 ± 0.27 | 2.60 ± 1.15 | −0.56 ± 0.45 | 0.19 ± 0.38 | −4.00 ± 1.51 |
| 212 C | 26 | 0.40 ± 2.87 | −1.91 ± 3.00 | 1.51 ± 5.84 | −0.31 ± 1.07 | −1.60 ± 0.54 | 0.35 ± 1.48 |
| 213 B | 26 | −7.27 ± 2.99 | 7.78 ± 2.03 | −0.51 ± 1.31 | −2.82 ± 0.94 | −5.01 ± 0.99 | 4.96 ± 4.55 |
| 214 B | 26 | 0.88 ± 0.72 | −0.37 ± 0.48 | −0.51 ± 0.28 | −1.09 ± 0.27 | −1.67 ± 0.29 | 0.64 ± 0.98 |
| 215 A | 26 | −0.28 ± 1.00 | 0.73 ± 0.67 | −0.45 ± 0.47 | −3.01 ± 0.29 | −1.79 ± 0.30 | −3.69 ± 1.52 |
| 216 A | 27 | 0.65 ± 0.67 | 0.39 ± 0.82 | −1.04 ± 0.24 | 2.62 ± 0.21 | −2.62 ± 0.23 | −1.64 ± 0.80 |
| 217 B | 26 | −1.91 ± 0.99 | 0.27 ± 0.49 | 1.64 ± 0.60 | 0.20 ± 0.19 | −0.52 ± 0.19 | 0.67 ± 1.51 |
| 218 A | 26 | −1.46 ± 1.35 | 1.53 ± 0.78 | −0.07 ± 0.91 | −2.00 ± 0.46 | 4.67 ± 0.46 | −1.70 ± 2.05 |
| 219 B | 26 | −0.01 ± 0.80 | −0.34 ± 0.51 | 0.35 ± 0.39 | −0.37 ± 0.22 | −1.63 ± 0.22 | −0.34 ± 1.13 |
| 220 A | 26 | −3.47 ± 0.67 | 3.67 ± 0.65 | −0.20 ± 0.22 | 2.20 ± 0.25 | −3.39 ± 0.28 | 1.95 ± 0.85 |
| 221 C | 26 | −3.59 ± 5.44 | −0.92 ± 3.71 | 4.51 ± 8.87 | 3.47 ± 2.38 | 3.47 ± 1.40 | 3.07 ± 4.98 |
| 222 B | 26 | 0.21 ± 0.85 | −0.90 ± 0.59 | 0.70 ± 0.53 | 0.03 ± 0.36 | 1.47 ± 0.41 | 0.51 ± 0.98 |
| 223 C | 26 | −1.47 ± 0.87 | −0.03 ± 0.62 | 1.50 ± 1.38 | −0.26 ± 0.85 | 0.35 ± 0.38 | −0.19 ± 0.81 |
| 224 A | 26 | −6.29 ± 0.71 | 5.85 ± 0.75 | 0.44 ± 0.40 | 3.83 ± 0.40 | −4.68 ± 0.50 | 5.03 ± 0.93 |
| 225 A | 27 | −0.66 ± 0.28 | −0.65 ± 0.21 | 1.30 ± 0.14 | 2.23 ± 0.11 | 1.16 ± 0.10 | 0.18 ± 0.39 |
| 226 A | 26 | 0.36 ± 0.44 | 0.06 ± 0.44 | −0.42 ± 0.14 | −1.33 ± 0.21 | 0.52 ± 0.22 | 1.82 ± 0.56 |
| 227 A | 26 | −1.07 ± 0.69 | 1.01 ± 0.59 | 0.06 ± 0.21 | −0.65 ± 0.23 | −1.62 ± 0.22 | 1.46 ± 0.99 |
| 228 A | 26 | −2.86 ± 0.43 | 1.85 ± 0.32 | 1.01 ± 0.17 | −0.47 ± 0.18 | −0.87 ± 0.15 | −0.48 ± 0.56 |
| 229 A | 27 | −0.88 ± 0.39 | −0.04 ± 0.28 | 0.92 ± 0.22 | −0.45 ± 0.13 | −1.19 ± 0.14 | −0.52 ± 0.57 |
| 230 B | 27 | −0.68 ± 0.93 | 0.92 ± 0.42 | −0.24 ± 0.57 | −1.38 ± 0.32 | 1.79 ± 0.32 | −1.04 ± 1.39 |
| 231 A | 25 | 1.29 ± 0.64 | −0.31 ± 0.49 | −0.98 ± 0.41 | 1.54 ± 0.36 | −3.16 ± 0.40 | −0.93 ± 0.84 |
| 232 A | 25 | 0.73 ± 0.49 | −1.83 ± 0.38 | 1.11 ± 0.28 | −1.28 ± 0.19 | −5.24 ± 0.19 | −0.59 ± 0.74 |
| 233 A | 25 | −1.82 ± 0.45 | −0.08 ± 0.48 | 1.90 ± 0.20 | −4.07 ± 0.20 | 1.09 ± 0.24 | −1.40 ± 0.55 |
| 234 A | 26 | 0.13 ± 0.21 | 0.32 ± 0.18 | −0.45 ± 0.10 | −0.82 ± 0.09 | −1.80 ± 0.09 | 0.51 ± 0.29 |
| 235 B | 27 | −3.49 ± 1.20 | 1.37 ± 0.43 | 2.12 ± 1.04 | −0.38 ± 0.79 | 0.29 ± 0.51 | −1.43 ± 0.85 |

tion, 1995). On the other hand, the grid-search procedure can occasionally identify a zone of latitudes and longitudes where the CMT inversion converges to an acceptable solution. In the case of the 1907 earthquake, we are driven to a solution further East (Huang, 1996), and in the case of the 1911 Peruvian event, we move the reported epicenter about 800 km to the South (Huang et al., 1994).

### 2.4. Quality control

In order to counter the limited amount of data available for historical earthquakes, a number of a posteriori checks were devised.

- In a number of cases, we were able to gather good quality records of *P* or *S* waveforms, while for a number of reasons, the full seismogram could not

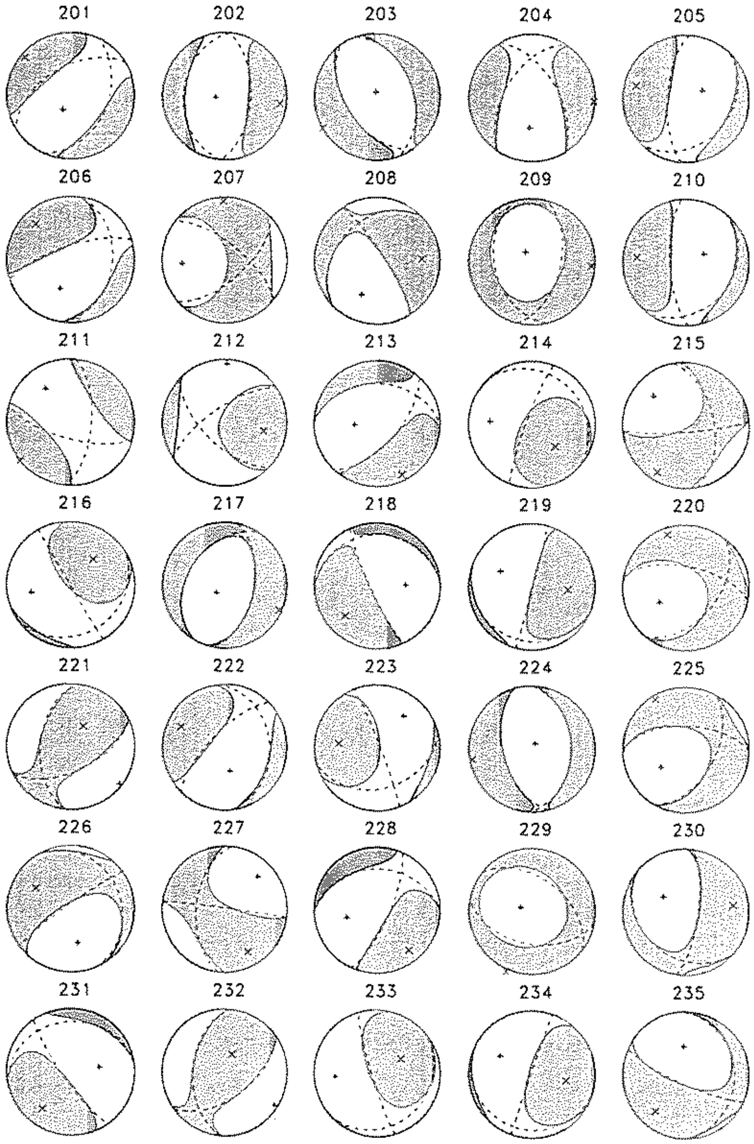

Fig. 1. Equal-area representation of the moment tensors listed in Table 2. Solid lines are the projections of the nodal surfaces of the full moment tensors; dashed lines represent the fault planes of the best double-couples, as listed in the last columns of Table 1. The compression and tension axes are shown by plus signs and crosses, respectively.

be inverted (e.g., high-frequency instrument; or only one component available). In such instances, body-wave forward modeling (Stein and Wiens, 1986) was applied to verify the general shape and amplitude of the body phases at a station not used in the inversion.

- On other occasions, we verified the polarity of body phases (*P*, *pP*, *S*, *SKS*, etc.) at stations not used in the inversion but for which we had gathered good-quality records of those arrivals.
- Whenever possible, and in order to verify the general order of magnitude of the inverted scalar moment, the inverted record was compared to a series of recent records obtained for post-1976 earthquakes in a comparable geometry and on the same instrument. This technique, which borrows directly from the general concept and philosophy of a 'magnitude' measurement, was made possible mostly by the continued operation of the Benioff and Press–Ewing instruments at Pasadena into the early 1990s.

## 3. Results

Among the 62 earthquakes whose records were subjected to inversion, 12 showed significant complexity in their waveshapes, 13 more led to unstable inversions, and two (the New Zealand events of 09 September 1953 at 282 km and 12 October 1958 at 270 km) converged above 300 km depth and were consequently dropped from the catalogue. Thus, the final historical CMT catalogue contains 35 deep earthquakes.

The source parameters and moment tensor solutions of these 35 historical deep events are presented in Tables 1 and 2. Events are numbered starting with 201, to prevent confusion with our WWSSN results. The format of the tables is similar to those in the work of Huang et al. (1997), and in the regular reports by Dziewonski et al.; a full description is given in the work of Dziewonski et al. (1987). The entries for the precision of the epicentral coordinates $(\lambda, \phi)$ have been dropped, since in all cases, the epicenter was constrained during the inversion. An additional entry in the first column is the quality of the solutions, expressed as A (excellent), B (good), or C (fair). This quality was assigned in two steps: first, on the basis of the variance reduction in the inversion, of the robustness of the inversion with respect to a change of epicenter, and of the quality of the verification tests described above. Second, we computed for each event the relative error $E$ as defined by Frohlich et al. (1997), and assigned a rating of A for $E < 0.5$; B for $0.5 \leq E < 1$ and C for $E \geq 1$. The lower of the two ratings was then kept.

Table 3
Events for which an inversion was attempted, but could not converge

| Date | NEIC hypocenter | | | Magnitude | Remarks |
|---|---|---|---|---|---|
| D M Y [H:mn] | Latitude (°N) | Longitude (°E) | Depth (km) | | |
| 22 05 1909 | −18 | −179 | 550 | 7.9 | |
| 21 08 1910 | −17 | −179 | 600 | 7.3 | |
| 25 02 1915 | −22 | −179 | 600 | 7.3 | |
| 31 07 1917 | 42.5 | 131 | 460 | 7.5 | |
| 04 06 1929 | 6.5 | 124.5 | 380 | 7 | |
| 26 05 1932 | −25.5 | 179.25 | 600 | 7.9 | See Okal (1997) |
| 16 04 1937 | −21.5 | −177 | 400 | 8.1 | Depth unresolvable (Okal, 1992) |
| *Doublets* | | | | | |
| 06 07 1959 (09:10) | −26.5 | −61 | 600 | $6\frac{3}{4}$ | |
| 06 07 1959 (09:23) | −26.5 | −61 | 600 | $6\frac{7}{8}$ | |
| 31 08 1961 (01:48) | −10.7 | −70.9 | 626 | $7\frac{1}{8}$ | |
| 31 08 1961 (01:57) | −10.5 | −70.7 | 629 | $7\frac{1}{2}$ | |

Table 4
Other (non-CMT) solutions published in the literature

| Date | Hypocenter | | | Published solution | | | | | Equivalent moment tensor ($10^{27}$ dyn cm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| D M Y | Latitude (°N) | Longitude (°E) | Depth (km) | $M_0$ ($10^{27}$ dyn cm) | $\phi_s$ (°) | $\delta$ (°) | $\lambda$ (°) | Ref. | $M_{rr}$ | $M_{\theta\theta}$ | $M_{\phi\phi}$ | $M_{r\theta}$ | $M_{r\phi}$ | $M_{\theta\phi}$ |
| 21 01 1906 | 33.8 | 137.5 | 340 | 1.5 | 208 | 80 | 85 | a | 0.51 | −0.22 | −0.22 | −0.64 | −1.25 | −0.64 |
| 18 12 1921 | −4.11 | −72.04 | 630 | 1.2 | 44 | 30 | 337 | b | −0.41 | −0.36 | 0.76 | −0.53 | 0.83 | 0.18 |
| 26 05 1932 | −24.97 | 178.34 | 560 | 3.4 | 330 | 68 | 310 | c | −1.81 | 2.21 | −0.40 | 0.23 | −2.03 | −1.80 |
| 29 03 1954 | 36.98 | −3.54 | 630 | 7.0 | 2 | 89 | 95 | d | 0.24 | 0.04 | −0.29 | 0.25 | 6.96 | 0.60 |

References: a: Abe (1985); b: Okal and Bina (1994); c: Okal (1997); d: Chung and Kanamori (1976).

Fig. 1, analog to Fig. 1 of Huang et al. (1997), presents the dataset in the familiar beach ball format.

### 3.1. The case of events with complex rupture

We list, for reference in Table 3, the set of 12 earthquakes for which significant complexity prevented a satisfactory inversion of the dataset. In two instances, these earthquakes are doublets of events with comparable magnitudes, occurring within a few minutes of each other. The remaining eight earthquakes are older events (1937 and earlier; four prior to 1920); in principle, and as discussed recently by Russakoff et al. (1997) in the case of the 1970 Colombian earthquake, it may be possible in such cases to overcome the difficulty by moving the entire inversion to a lower frequency, thereby rendering it less sensitive to the complexity of the source. This procedure turned out to be unfeasible in the case of historical earthquakes, due to the poor response of the ancient instruments at the typical periods required (200 s or greater).

Perhaps the most important such case is that of the deep Tonga earthquake of 26 May 1932, which was given a magnitude of 7.9 by Gutenberg and Richter (1954). In an independent study, Okal (1997) confirmed that the main shock consisted of at least three subevents and used forward modeling and spectral analysis techniques to propose a focal mechanism featuring down-dip compression and to evaluate the moment of this earthquake at (3 to 5) $\times 10^{27}$ dyn-cm, making it comparable to the deep Fiji earthquake of 09 March 1994, but considerably smaller than the South American giants of 1970 and 1994.

In the case of the 1954 Spanish earthquake, we refer to the study by Chung and Kanamori (1976), who documented a complex downward propagating rupture lasting about 30 s for a total seismic moment estimated at $7 \times 10^{27}$ dyn cm. As in the case of the 1906 Japanese and 1921 Peruvian earthquakes, and because their parameters were not obtained through application of the CMT algorithm, we do not include the 1932 Tonga and 1954 Spanish events in the catalogue in order to preserve the latter's homogeneity. Rather, in Table 4, and for reference, we list the moment tensors equivalent to the solutions obtained in those independent studies.

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## References

Abe, K., 1985. Re-evaluation of the large deep earthquake of January 21, 1906. Phys. Earth Planet. Int. 39, 157–166.

Charlier, C., van Gils, J.-M., 1953. Liste des Stations Séismologiques Mondiales. Observatoire Royal de Belgique, Uccle.

Chung, W.-Y., Kanamori, H., 1976. Source process and tectonic implications of the Spanish deep earthquake of March 29, 1954. Phys. Earth Planet. Int. 13, 85–96.

Dziewonski, A.M., Ekström, G., Franzen, J.E., Woodhouse, J.H., 1987. Centroid moment tensor solutions for January–March 1986. Phys. Earth Planet. Int. 45, 1–10.

Dziewonski, A.M., Ekström, G., Salganik, M.P., 1995. Centroid moment tensor solutions for October–December 1994. Phys. Earth Planet. Int. 91, 187–201.

Dziewonski, A.M., Ekström, G., Salganik, M.P., 1997. Centroid-moment tensor solutions for April–June 1996. Phys. Earth Planet. Int. 102, 11–20.

Ekström, G., Dziewonski, A.M., Steim, J.M., 1985. Single station CMT: application to the Michoacan, Mexico earthquake of September 19, 1985. Geophys. Res. Lett. 13, 173–176.

Engdahl, E.R., van der Hilst, R.D., Buland, R.P., 1997. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull. Seismol. Soc. Am., submitted.

Frohlich, C.H., Coffin, M.F., Massell, C., Mann, P., Schuur, C.L., Davis, S.D., Jones, T., Karner, G., 1997. Constraints on Macquarie Ridge tectonics provided by Harvard focal mechanisms and teleseismic earthquake locations. J. Geophys. Res. 102, 5029–5041.

Gutenberg, B., Richter, C.F., 1954. Seismicity of the Earth. Princeton Univ. Press, Princeton, NJ, 310 pp.

Huang, W.-C., Centroid-moment tensor inversions of analog seismograms from deep earthquakes (1907–1976), 1996. PhD Dissertation, Northwestern University, 193+ xviii pp.

Huang, W.-C., Okal, E.A., 1998. Centroid moment tensor solutions for deep earthquakes predating the digital era: discussion and inferences, Phys. Earth Planet. Int., 106, pp (this issue).

Huang, W.-C., Ekström, G., Okal, E.A., Salganik, M.P., 1994. Application of the CMT algorithm to analog recordings of deep earthquakes. Phys. Earth Planet. Int. 83, 283–297.

Huang, W.-C., Okal, E.A., Ekström, G., Salganik, M.P., 1997. Centroid-moment-tensor solutions for deep earthquakes predating the digital era: the WWSSN dataset (1962–1976). Phys. Earth Planet. Int. 99, 121–129.

McComb, H.E., West, C.J., 1931. List of seismological stations of the world, 2nd edn. Natl. Res. Council and Natl. Acad. Sci., Washington, DC, 119 pp.

Okal, E.A., 1992. Use of the mantle magnitude $M_m$ for the reassessment of the seismic moment of historical earthquakes: II. Intermediate and deep events. Pure Appl. Geophys. 139, 59–85.

Okal, E.A., 1997. A reassessment of the deep Fiji earthquake of 26 May 1932. Tectonophysics 275, 313–330.

Okal, E.A., Bina, C.R., 1994. The deep earthquakes of 1921–1922 in Northern Peru. Phys. Earth Planet. Int. 87, 33–54.

Richter, C.F., 1958. Elementary Seismology. Freeman, San Francisco, CA.

Russakoff, D., Ekström, G., Tromp, J., 1997. A new analysis of the great 1970 Colombia earthquake and its isotropic component. J. Geophys. Res. 102, 20423–20434.

Stein, S., Wiens, D.A., 1986. Depth determination for shallow teleseismic earthquakes: methods and results. Rev. Geophys. 24, 806–832.

Wysession, M.E., Okal, E.A., Miller, K.L., 1991. Intraplate seismicity of the Pacific Basin, 1913–1988. Pure Appl. Geophys. 135, 261–359.