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The 1909 Taipei earthquake—implication for seismic hazard in Taipei

Hiroo Kanamori,[1] William H. K. Lee[2] and Kuo-Fong Ma[3,4]

[1] *Seismological Laboratory, California Institute of Technology, Pasadena, CA* 91125, *USA. E-mail: hiroo@gps.caltech.edu*
[2] *U.S. Geological Survey, Menlo Park, CA* 94025, *USA*
[3] *Institute of Geophysics, National Central University, Chung-Li, Taiwan*
[4] *Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*

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SUMMARY

The 1909 April 14 Taiwan earthquake caused significant damage in Taipei. Most of the information on this earthquake available until now is from the written reports on its macro-seismic effects and from seismic station bulletins. In view of the importance of this event for assessing the shaking hazard in the present-day Taipei, we collected historical seismograms and station bulletins of this event and investigated them in conjunction with other seismological data. We compared the observed seismograms with those from recent earthquakes in similar tectonic environments to characterize the 1909 earthquake. Despite the inevitably large uncertainties associated with old data, we conclude that the 1909 Taipei earthquake is a relatively deep (50–100 km) intraplate earthquake that occurred within the subducting Philippine Sea Plate beneath Taipei with an estimated M_W of 7 ± 0.3. Some intraplate events elsewhere in the world are enriched in high-frequency energy and the resulting ground motions can be very strong. Thus, despite its relatively large depth and a moderately large magnitude, it would be prudent to review the safety of the existing structures in Taipei against large intraplate earthquakes like the 1909 Taipei earthquake.

Key words: Earthquake dynamics; Earthquake ground motions; Earthquake source observations; Seismicity and tectonics; Site effects.

GJI Seismology

1 INTRODUCTION

The 1909 April 14 Taiwan earthquake is often called the '1909 Taipei' earthquake. It caused 9 deaths, 51 injured, 122 houses destroyed, 252 houses half destroyed and 798 houses damaged (Taihoku Meteorological Observatory 1936, p. 149; hereafter this reference is abbreviated to Taihoku Obs., and 'Taihoku' is the Japanese name for Taipei) even though Taipei was not heavily populated in 1909. Taipei is now a large city with nearly 3 million people, and seismic hazard in the greater Taipei Metropolitan Area (TMA) is a matter of great concern, as discussed in detail by Wang (2008). The TMA now has a population of nearly 7 million, versus fewer than 0.5 million in 1910. Since earthquakes similar to the 1909 earthquake can have significant impact on the TMA, it is important to investigate this earthquake in as much detail as possible. Most information on this earthquake available now is from the written reports on its macroseismic effects and station bulletins.

A handwritten report (Kondo 1909) was issued by Kyujiro Kondo, Director of the Taihoku Meteorological Observatory, on 1909 May 1. This report was mostly reproduced in typeset print in the 1909 Annual Report of the Osaka Meteorological Observatory (1910), and the handwritten report was reproduced in Cheng *et al.* (1997). Kondo (1909) provided detailed seismological readings from the seismographic stations operating in Taiwan at the time, but the earthquake was just called the 'Northern Taiwan Strong Earthquake'. The hypocentral parameters were not included. An excerpt of the Osaka Meteorological Observatory (1910) on the 1909 Taipei earthquake, the Kondo (1909) original report, and many documents we used are now available online at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section. Unfortunately, the seismograms from these Taiwan stations seem to have been lost, and we could not find any of them despite our extensive search.

In view of the obvious importance of this event for assessing the shaking hazard in Taipei we collected historical seismograms of this event recorded outside of Taiwan, and investigated them in conjunction with other seismological data. We will show that the 1909 Taipei earthquake is a relatively deep intraplate earthquake, which occurred within the subducting Philippine Sea Plate beneath Taipei.

2 HYPOCENTRAL LOCATION

The first published epicentre coordinate (25°N, 121.5°E) appears to be the one on page 149 of the list of Taiwan earthquakes (Taihoku Obs. 1936), and it is the 'round off' coordinate of Taipei (25.033°N,

121.517°E). Gutenberg & Richter (1954, p. 269) put it at 24°N, 123°E, with a focal depth of 80 km, and $M = 7.3$. Gutenberg and Richter probably determined the epicentre using the traveltime data listed in the station bulletins with their standard relocation method (see Richter 1958, p. 693). An examination of Gutenberg Notepad (Goodstein *et al.* 1980) of this event (Appendix A, Fig. A3) showed that Gutenberg did not use any readings from the Taiwan stations. There was no indication how Gutenberg derived the focal depth of 80 km. No station bulletins we investigated so far contain any *pP* readings. We also found an error in the S–P time of Zikawei used by Gutenberg (106 s vs. 63 s from the Zikawei station bulletin), and we corrected it in our relocations. It is also unclear how $M = 7.3$ was estimated. Because of the poor quality of seismic data used, Gutenberg & Richter (1954) gave a quality rating of CCC which means that the errors in the epicentre location, the origin time and the depth are 3°, 12 s, and 80 km, respectively.

Hsu (1971) included this event in his Table 2, adopting the Taihoku Obs.'s (1936) epicentre, and the Gutenberg & Richter's (1954) focal depth and magnitude. Hsu (1971) relocated Taiwan earthquakes from 1936 to 1969, but did not relocate the 1909 earthquake. Wang *et al.* (2011) examined the published hypocentral locations of this earthquake in light of the present-day seismicity and the damage pattern of the 1909 event. They prefer the epicentral location given in Taihoku Obs. (1936), and the depth, about 80 km, given by Gutenberg & Richter (1954). Theunissen *et al.* (2010) presented a homogeneous earthquake catalogue with equivalent moment magnitude M_W higher than 7.0 in the area 119.5°E –123°E and 22°N–25.5°N for the period 1900–2007, but did not include the 1909 event.

We first attempt to relocate this event using a few teleseismic traveltime data and *S-P* time data. The arrival times were first collected from Kondo (1909), Gutenberg Notepads (Goodstein *et al.* 1980), and Shide Circulars (1900–1912); see Appendix A for details. Individual station bulletins were then used to add more data and to verify the arrival times listed in the Gutenberg Notepad. For relocation we use the JLoc method (Lee & Dodge 2007), which is an interactive, graphical grid-search software specially developed to locate old earthquakes that are poorly constrained by the arrival times. Before 1964, seismic stations were poorly distributed over the world (Lee & Benson 2008); the magnifications of seismographs were often too low to record global earthquakes clearly, and station clocks often required large time corrections (radio time signals started in the 1920s).

First we compare the location given in Gutenberg & Richter (1954) and that in Taihoku Obs. (1936). The Gutenberg & Richter's hypocentre solution (24°N, 123°E, 80 km) placed this event far from Taipei (in the southeast offshore of Taiwan, as shown in Fig. 1a), and is considerably different than the Taihoku Obs. (1936) location (25°N, 121.5°E). We use the JLoc program to perform a simple test to compare the rms residuals for the Gutenberg & Richter's location and Taihoku Obs.'s (1936) location using the same arrival time data set used by Gutenberg (except correcting his error in the *S-P* time at Zikawei). We selected two velocity models: the old standard of Jeffreys & Bullen (1940), and the new standard 'ak135' (Kennett *et al.* 1995). As shown in Table 1, the rms residuals for the Taihoku Obs. (1936) location are much smaller than those for the G-R location.

Next, we examine all the traveltime data we have collected. There are three types of arrival times: *P*, *S* and *S-P*. Kondo (1909) and some stations did not give *S* times explicitly, but just the *S-P* times. We also computed *S-P* times when both *P* and *S* arrival times are given in the station bulletins. We made several trials by using different subsets of data, and finally created the '090414best.PHA' file (see Appendix B). In this file we converted the observed arrival times at the stations into traveltimes by assuming an origin time of 19:53:42 to follow the data format of the International Seismological Summary (ISS 1918–1963).

We first attempt to determine a location with just the *P* times from TAP, ZKW, TTU, OSA, MZS, MAN, DJA & TIF, using a grid-search approach with a large volume (5° × 5°) and 300 km using the AK135 model (Kennett *et al.* 1995). The initial step size was 0.2°. After executing JLoc, we examined the residuals, selected the *P* and *S* times that have residuals <5 s, and ran JLoc again. Finally, we included the *S-P* times of local stations in Taiwan and ZKW (The *P* and *S* times at ZKW have large residuals, indicating that the clock at ZKW was not accurate. However, its *S-P* time appears accurate.). The final hypocentre is given as follows

Origin time: 1909/04/14 19:53:52.5
Latitude = 25.28°N, Longitude = 121.52°E, Depth = 75 km
rms = 1.31 s.

Detailed results are given in Table B1 of Appendix B, and Fig. 1 shows this solution with the O-C residual distribution. This solution also yields small rms residuals for the traveltime data used by Gutenberg.

Since the quality of old traveltime data is limited, we cannot expect to obtain accurate hypocentral parameters. Although we obtained our preferred solution, it is hard to assign an error bound. Nevertheless, based on the test with the Gutenberg Notepad data, the JLoc location using the selected *P* and *S-P* data, and the old result from Taihoku Obs. (1936), we prefer the location about 30 km north of Taipei, rather than the location given by Gutenberg & Richter (1954) which is nearly 200 km SE of Taipei and about 120 km offshore from the east coast of Taiwan. The strength of shaking at many locations in Taiwan reported in Kondo (1909) seems to rule out the location offshore of the east coast of Taiwan.

In this paper, we will use the hypocentre given above (i.e. Latitude = 25.28°N, Longitude = 121.52°E, Depth = 75 km), but fairly large uncertainties are inevitable as shown by the 2 s rms residual contour (see Fig. 1), which defines the limit within which the rms error in arrival times is less than 2 s. In Fig. 1(b), the rms residual contours are shown on map view at a depth of 75 km, longitude cross-section versus depth, and latitude cross-section versus depth, respectively However, we are encouraged by the quality of readings and seismograms recorded by five Taiwan stations in Omori (1905) for the Chiayi-Touliu earthquake on 1904 November 6 (04:25 local time). As we will discuss in more detail in Appendix A, we are confident in the arrival times reported by Kondo (1909), because the Gray-Milne seismographs in Taiwan were capable of recording impulsive arrivals and had time resolution of better than 1 s. Furthermore, telegraphic time signals from Taipei allowed all Taiwan stations to be on a common time base. We believe that the 2 s rms residual contour provides a reasonable bound of location error.

In Appendices A and B, we discuss the arrival times we collected for the 1909 Taipei earthquake, including the starting input file (090414best.PHA) for the JLoc software (Table B1). If a different hypocentre is to be considered, it can be tested against the observed arrival times. We also present a more detailed discussion on our approach to relocate the 1909 Taipei earthquake in Appendix A, with all source materials and derived data files archived at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section.

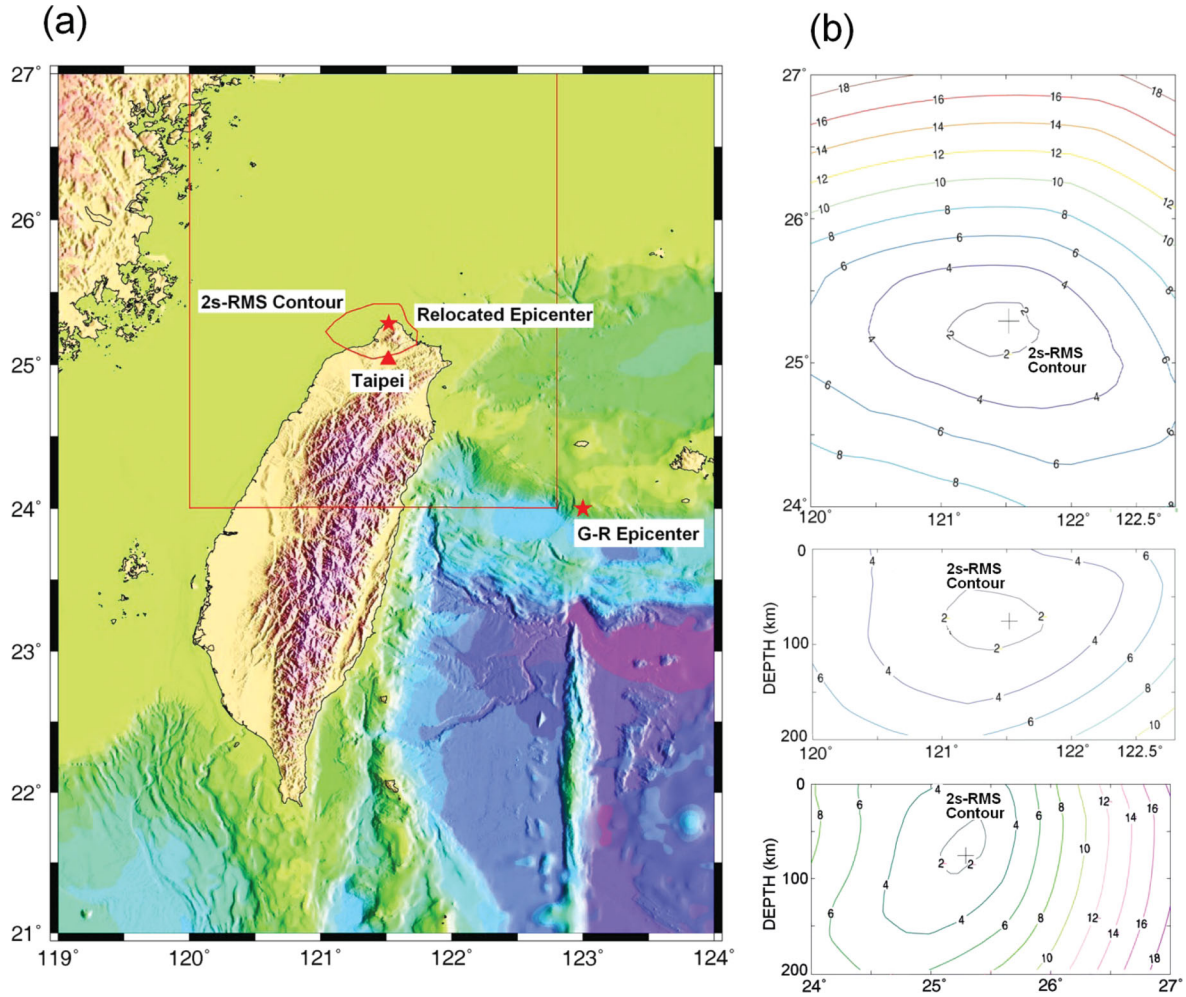

Figure 1. (a) Topographic map of the Taiwan region showing the relocated epicentre of the 1909 Taipei earthquake, with the 2 s rms residual contour shown as the red curve surrounding the relocated epicentre. The boxed area (enclosed by red lines) is the map view of a volume (extending to 300 km deep) in which rms residuals to the chosen stations were computed at step of 0.1° in latitude and longitude and of 5 km in depth. The 'Taihoku Epicenter' published by Taihoku Obs. (1936) is practically at the same location as Taipei which is shown as a red colour triangle (see text for explanation), and the 'G-R Epicenter' was published by Gutenberg & Richter (1954, p. 269). (b) The rms residual contours were drawn at 2s, 4s, 6s, . . . using the MATLAB software, showing in the map view (top panel), Depth versus Longitude cross-section (middle panel), and Depth versus Latitude cross-section (bottom panel).

Table 1. Comparison of traveltime rms residuals.

19090414Gutenberg.PHA (JB Model)							
Phase Data Source	Hypocentre Author	Date Year/Mon/day	OT Hr:Min:S	Latitude (° N)	Longitude (° E)	Depth (km)	rms (s)
Gutenberg NP	Gutenberg NP	1909/04/14	19:53:42.	24.0	123.0	80.0	10.486
Gutenberg NP	Taihoku-75	1909/04/14	19:53:53.	25.0	121.5	75.0	8.538
Gutenberg NP	Taihoku-100	1909/04/14	19:53:53.	25.0	121.5	100.0	8.724
Gutenberg NP	This study	1909/04/14	19:53:53.55	25.23	121.38	72.0	8.626
19090414Gutenberg.PHA (AK_135 Model)							
Phase Data Source	Hypocentre Author	Date Year/Mon/day	OT Hr:Min:S	Latitude (° N)	Longitude (° E)	Depth (km)	rms (s)
Gutenberg NP	Gutenberg NP	1909/04/14	19:53:42.	24.0	123.0	80.0	10.703
Gutenberg NP	Taihoku-75	1909/04/14	19:53:53.	25.0	121.5	75.0	8.376
Gutenberg NP	Taihoku-100	1909/04/14	19:53:53.	25.0	121.5	100.0	8.306
Gutenberg NP	This study	1909/04/14	19:53:53.55	25.23	121.38	72.0	8.339

3 GUTENBERG-RICHTER's MAGNITUDE

Gutenberg & Richter (1954) gave $M = 7.3$. The details are given in Gutenberg Notepads (Goodstein *et al.* 1980; *see* GutenbergNotePad_G-R80-805_TaipeiEQ.pdf at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section.), but interpretation of the information in the notepad is not straightforward, and some judgment is required. Following Abe (1984), we interpreted the Gutenberg Notepad

Table 2. Gutenberg Notepad m_B and M_S.

Station	Phase	m_B
Jena	*P*	7.2
Jena	*PP*	7.3
Jena	*S*	7.2
Strassburg	*P*	7.2
Strassburg	*S*	6.8
Göttingen	*P*	7.5
Göttingen	*PP*	7.4
Wien	*S*	7.5
Uppsala	*P*	6.9
Uppsala	*S*	7.0
Average		7.2
Station		M_S
Jena		6.9
Göttingen		6.8
Wien		6.7
Batavia		6.8
Hamburg		6.8
Cartuja?		6.7
Osaka		6.1
Pulkova		6.8
Average		6.7

entries for magnitude (as shown in Table 2), and conclude that Gutenberg estimated the body wave magnitude to be $m_B = 7.2$ which is consistent with what Abe (1981) lists for this event, $m_B = 7.1$, within the round-off error. The surface-wave magnitude M_S is 6.7. The magnitude $M = 7.3$ entered in Gutenberg & Richter's (1954) 'Seismicity of the Earth' book was probably derived from m_B using a conversion formula $M - m_B = (m_B - 7)/4$ which is slightly different from eq. (1) of Gutenberg & Richter (1956). Abe (1984) showed that this is the formula used for conversion of m_B in Gutenberg's Notepad to M listed in the 'Seismicity of the Earth' book (Gutenberg & Richter 1954).

It is still unclear how Gutenberg estimated the depth. We suspect that the relatively small $M_S = 6.7$ with respect to the large body-wave magnitude $m_B = 7.2$ led him to conclude that the event was deeper than a typical shallow crustal earthquake, and $H = 80$ km was considered reasonable for explaining the disparity between m_B and M_S given in Table 2.

Regarding the magnitude, we prefer to use m_B rather than the converted magnitude M. Utsu (2002a) and Bormann & Saul (2008) showed that m_B is essentially the same as M_W near $M_W = 7$. Thus, the m_B value listed in the Gutenberg Notepads can be taken approximately as M_W.

4 ESTIMATION OF FOCAL DEPTH AND MAGNITUDE FROM AVAILABLE SEISMOGRAMS

4.1 Available data

Table 3 lists the seismograms available to us for studying this earthquake. The quality varies from station to station, and the Göttingen Wiechert seismogram and the Hongo (Tokyo) Omori seismogram are of the best quality. The Strasbourg seismogram is qualitatively similar to that from Göttingen and the Mizusawa seismogram is qualitatively similar to that from Hongo. Thus, we will focus our analysis on the Göttingen Wiechert seismogram and the Hongo Omori seismogram, while referring to other seismograms qualitatively. Other seismograms are shown in Appendix C and Fig. C1.

We immediately noticed on these seismograms that surface waves are relatively small compared with body waves, especially on teleseismic records. From the large Gutenberg-Richter magnitude, $M = 7.3$, we initially expected fairly large surface waves; thus, the small surface waves on these records were somewhat surprising at first sight. However, as noted, this is probably what prompted Gutenberg to assign a fairly large depth to this event.

We investigate this question further by comparing the waveforms of these old records with those of more recent events for which high-quality broad-band records are available. We use several pairs of events (Table 4), each pair consisting of an event at a shallow depth and an event at a depth range from 40 to 100 km, in Japan and Taiwan, and compare the waveforms of these reference events with those observed at Hongo and Göttingen.

Most seismograms from the 1909 event have very small amplitudes, and the mechanism of the 1909 event is unknown. Furthermore, since all the seismograms are from narrow-band seismographs (natural periods between 10 and 30 s), it is difficult to model the waveforms in detail. Considering these difficulties, we take the approach similar to that used by Kanamori *et al.* (2010) for studying the 1907 Sumatra earthquake. We compare the old

Table 3. List of available seismograms for the 1909 April 14 Taipei Earthquake. V, Static Magnification; T, Natural period of pendulum; ε, damping ratio; h, damping constant.

Station	Seismograph	Constants
Göttingen	Wiechert EW	$V = 158$, $T = 13.6$, $\varepsilon = 4.0$
Strasbourg	Wiechert NS	$V = 180$, $T = 9.5$ s, $\varepsilon = 3.5$
Strasbourg	Wiechert EW	$V = 180$, $T = 9.5$ s, $\varepsilon = 3.5$
Hamburg	Wiechert EW	$V = 190$, $T = 10.7$, $\varepsilon = 5$
Hamburg	Wiechert NS	$V = 190$, $T = 10.7$, $\varepsilon = 5$
Hongo, Tokyo	Omori, 'Bido' (probably EW)	$V = 120$, $T = 12.5$ s, $h = 0.2$
Hongo, Tokyo	Omori, 'Kyoshitsu No. 3' NS	$V = 10$, period unknown
Hongo, Tokyo	Omori, 'kyoshitsu No. 1' EW	$V = 10$, period unknown
Mizusawa, Japan	Omori, EW	$V = 20$, $T = 30$ s
Mizusawa, Japan	Omori, NS	$V = 9$, $T = 30$ s
Nagano, Japan	Omori, EW	$V = 20$, $T = 30$ s Large friction
Related record		
Taiwan 1910 April 12		
Göttingen,	Wiechert, EW	$V = 147$, $T = 13.2$ s, $\varepsilon = 3.9$
Göttingen,	Wiechert, NS	$V = 142$, $T = 11.8$ s, $\varepsilon = 3.6$

Table 4. List of events.

Event	O.T.	M_W	Lat.	Long.	Depth	s/d/r
N-Iwate	7/23/2008 15:26:19.9	6.8	39.73	141.51	98.8	14/18/−75, 178/73/−95
Iwate-Miyagi	6/13/2008 23:43:45.3	6.9	39.03	140.85	12.0	17/42/87, 201/48/92
W-Tottori	10/6/2000 04:30:19.1	6.7	35.33	133.20	15.0	331/83/1, 241/89/173
Geiyo	3/24/2001 06:27:53.5	6.8	33.97	132.52	47.4	323/39/−121, 181/57/−67
Taiwan	10/15/2004 04:08:50.2	6.6	24.48	122.74	102.1	200/17/6, 104/88/107
Taiwan	12/18/2001 04:02:58.2	6.8	24.00	122.79	16.0	329/47/−135, 204/59/−53

Note: O.T. Origin time from NEIC PDE.
M_W, Lat., Long. and Depth are from the global CMT solution.
a/d/r: strike/dip/rake in degree from the global CMT solution.

seismograms for the 1909 event with the seismograms for recent reference events recorded with broad-band seismographs. To facilitate comparison we convert the broad-band seismogram of a recent event to equivalent Omori or Wiechert seismograms. We first remove the instrument response from the broad-band seismogram by deconvolution and then convolve the deconvolved seismogram with the response of either the Omori or Wiechert seismograph. We call these seismograms the converted Omori or Wiechert seismograms.

4.2 Estimation of depth

Our primary interest is to determine whether the 1909 Taipei earthquake is indeed a relatively deep event as inferred from Gutenberg Notepad. We first take the event pair in Taiwan listed in Table 4. One event (2001 December 18) is shallow ($H = 16$ km) with $M_W = 6.8$, and the other (2004 October 15) is deep ($H = 102.1$ km) with $M_W = 6.6$ (in this paper, 'deep' means a depth of 40–100 km.) The station we chose is TTO (Takato), one of the Japanese F-net stations, listed in Table 5. We converted the broad-band seismograms (Streckeisen STS-2) of the recent Taiwan events to equivalent Omori seismograms using the instrument constants of the Omori seismograph [Period (T) = 12.5 s, Magnification (V) = 120 and the Damping Constant (h) = 0.2]. Although the damping constant is not given for the Omori seismogram, we use $h = 0.2$ which we found appropriate for most Omori seismograms at Hongo (Kanamori *et al.* 2010). The results of comparison are summarized in Table 6. Figs 2(a) and (b) compare the observed Omori record at Hongo with the converted Omori seismograms for the shallow and deep events in Taiwan. Since the overall paths are about the same between the observed and the converted records, we can compare just the overall character of the seismograms, especially the amplitude ratio of the body wave group (from P to S) to the surface-wave train (300 s after the end of S-wave train). We denote this ratio by R_{b2s}. A visual comparison shows that $R_{b2s} = 0.70$, 0.72 and 0.23 for the observed, the deep event and the shallow event, respectively; the ratio for the deep event is very close to the observed.

Since this comparison is qualitative and the result from just one pair is not representative, we make similar comparisons for other event pairs. We cannot find any other good pairs of events in the magnitude range around $M_W = 7$ in the Taiwan region, but we can have similar event pairs in the Japanese region. In this case we use a reverse path, from Japan to Taiwan. We chose the seismograms recorded at station TATO in Taiwan (Table 5) for the two event pairs in Japan (Table 4). Fig. 2(c) compares the converted Omori seismograms for the event pair of the 2008 July 23 Northern Iwate earthquake ($M_W = 6.8$, $H = 98.8$ km) and the 2008 June 13 Iwate-Miyagi earthquake ($M_W = 6.9$, $H = 12.0$ km). The ratio R_{b2s} is 0.33 and 0.07 for the deep and the shallow event, respectively; the ratio for the deep event is closer to that of the observed, 0.7.

Fig. 2(d) compares the converted Omori seismograms for the event pair of the 2001 March 24 Geiyo ($M_W = 6.8$, $H = 47.4$ km)

Table 5. Station list.

Station Code	Latitude (°N)	Longitude (°E)	Elevation (m)	Station Name
TTO	35.8363	138.1209		Takato
TATO	24.9754	121.4881	53.0	Taipei
GOT	51.55	9.967		Göttingen
BFO	48.33190	8.33110	589.00	Black Forest Observatory,
HNG	35.708	139.767	9.	Hongo

Table 6. Amplitude data. R_{b2s} = amplitude ratio of body to surface wave, $\Delta M_w = \log(A_o/A_c)$. M_W = Estimated M_W.

Event	R_{b2s}	P-P amp (cm)	ΔM_W	M_W
Hongo Omori (observed)	0.70	4.2		
Taiwan (2004 October 15, deep), $M_W = 6.6$	0.72	1.46	0.46	7.1
Taiwan (2001 December 18, shallow), $M_W = 6.8$	0.23	18.4		
N-Iwate (2008 July 23, deep), $M_W = 6.8$	0.33	6.3	−0.17	6.6
Iwate-Miyagi (2008 June 13, shallow), $M_W = 6.9$	0.07	46.4		
Geiyo (2001 March 24), deep), $M_W = 6.8$	0.70	12.8	−0.48	6.3
W-Tottori (2000 October 6, shallow), $M_W = 6.7$	0.09	67.9		
Göttingen, Wiechert (observed)	0.75	0.40		
Taiwan (2004 October 15, deep), $M_W = 6.6$	0.43	0.11	0.56	7.2
N-Iwate (2008 July 23, deep), $M_W = 6.8$	1.1	0.64	−0.20	6.6
Geiyo (2001 March 24), deep), $M_W = 6.8$	0.30	0.65	−0.21	6.6

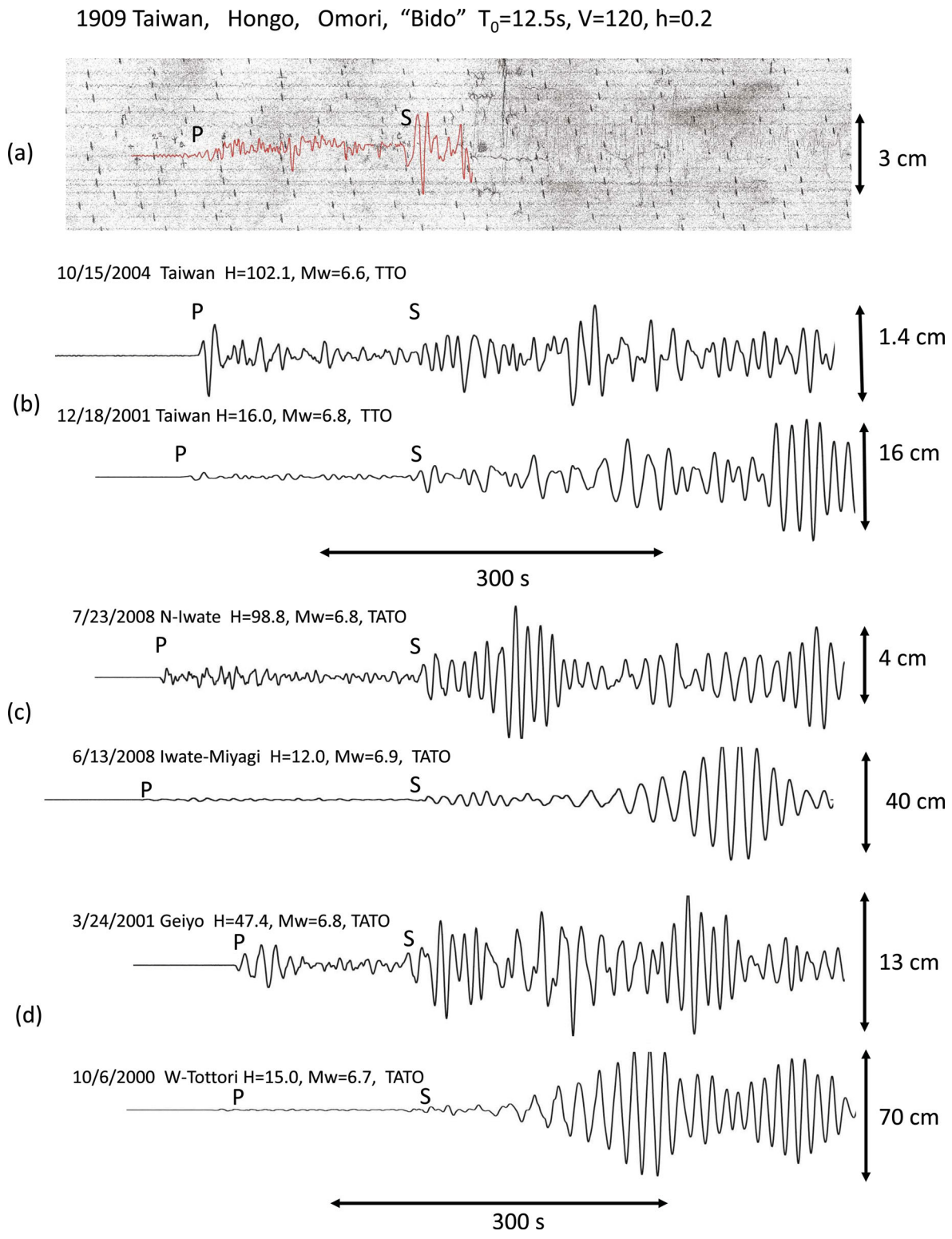

Figure 2. Comparison of the Hongo Omori seismogram of the 1909 Taipei earthquake with the converted Omori seismograms for three pairs of shallow and deep earthquakes. (a). Hongo Omori ('bido') EW component seismogram. (b). Converted Omori seismograms computed from broad-band seismograms of a pair of Taiwan earthquakes (top trace: deep, bottom trace: shallow) recorded at Takato (TTO). (c) Converted Omori seismograms computed from broad-band seismograms of the Northern Iwate, Japan, earthquake (deep) and the Iwate-Miyagi earthquake (shallow) recorded at Taipei (TATO). (d). Converted Omori seismograms computed from broad-band seismograms of the Geiyo, Japan, earthquake (deep) and the Western Tottori earthquake (shallow) recorded at Taipei (TATO).

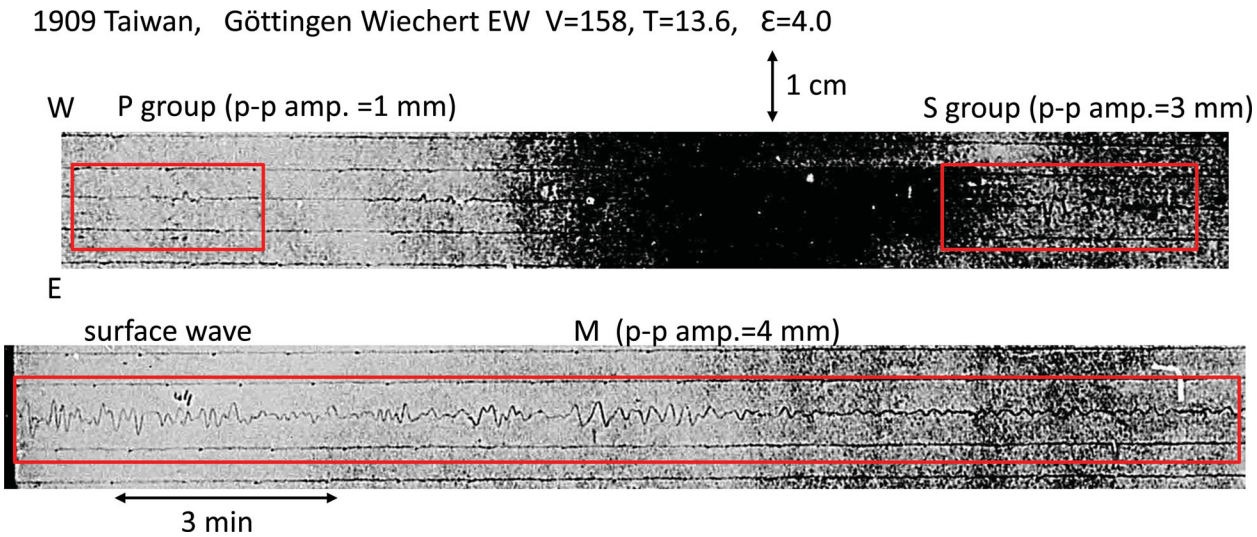

Figure 3. Göttingen Wiechert EW component seismogram of the 1909 Taipei earthquake.

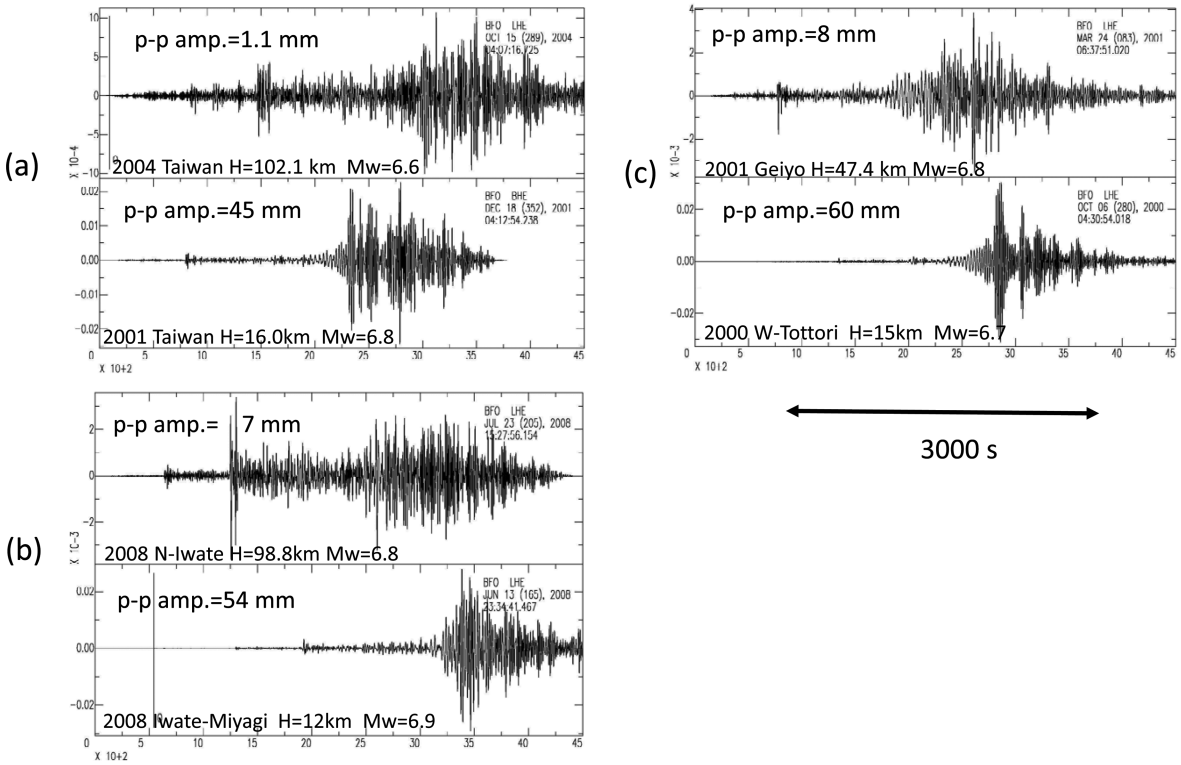

Figure 4. Converted Wiechert seismograms computed from the broad-band seismograms for the three pairs of events listed in Table 4 recorded at BFO. (a). Two Taiwan earthquakes (top panel: deep; bottom panel: shallow). (b). The N-Iwate earthquake (deep) and the Iwate-Miyagi earthquake (shallow). (c). The Geiyo earthquake (deep) and the Western Tottori earthquake (shallow).

and the 2000 October 6 Western Tottori ($M_W = 6.7$, $H = 15.0$ km) earthquakes. The ratio R_{b2s} is 0.70 and 0.09 for the deep and the shallow events, respectively; the ratio for the deep event is the same as that of the observed, 0.7.

Among all the seismograms we could find from stations at teleseismic distances, the Wiechert seismogram (EW component) recorded at Göttingen (Table 3) is of the best quality (Fig. 3), but even on this record the *P* wave is very small (peak-to-peak amplitude ≈1 mm), and the *S* wave is barely recognizable in the dark background (peak-to-peak amplitude ≈3 mm). The surface-wave trains are visible with a peak-to-peak amplitude of 4 mm. To interpret this record, we computed converted Wiechert seismograms for the three pairs of events we used for interpretation of the Hongo Omori seismogram. We used the broad-band seismograms recorded at the Black Forest Observatory (BFO) in Germany (Table 5). The results are shown in Fig. 4. For the three shallow events, the surface wave amplitude is at least 10 times larger than the body-wave amplitude, which is not what was observed for the 1909 earthquake. In contrast, the ratio R_{b2s} is 0.43, 1.1 and 0.30 for the three deep earthquakes, the Taiwan (2004 October 15), the N-Iwate (2008 July 23) and the Geiyo (2001 March 24) earthquakes, respectively. The observed ratio is 0.75, which falls in the range for

the converted records. Thus, we can conclude that the Göttingen Wiechert seismogram is much more consistent with those from the deep events.

4.3 Estimation of magnitude

We estimate the magnitude of the 1909 event from the ratio of the amplitude of the observed record and the converted record. Since the amplitude ratio of body to surface waves R_{b2s} strongly suggests that the 1909 Taipei earthquake is a relatively deep event, we use only deep reference events here for magnitude estimation. The definition of magnitude of old events is not straightforward, as discussed by Wang *et al.* (2011). As discussed earlier, the Gutenberg-Richter's $M = 7.3$ is derived from the body-wave magnitude m_B, in the sense of Gutenberg's unified magnitude. In this paper, we compare the observed peak-to-peak amplitude, A_o, with that of the converted record, A_c, computed for the reference event with a known M_W. Thus, although we cannot directly determine M_W of the 1909 event, we estimate M_W by adding log (A_o/A_c) to the M_W of the reference event.

For the 2004 deep Taiwan event, the *P-P* amplitude is 1.46 cm. Since the observed *P-P* amplitude at Hongo observed for the 1909 event is 4.2 cm, the ratio is $(A_o/A_c) = 2.9$, which translates to a magnitude of 7.0 for the 1909 Taipei earthquake. Since we are ignoring the effect of the radiation pattern in this comparison, this estimate should be taken only as a rough estimate.

We can perform a similar analysis using the reference events in Japan. However, we use a reverse path in this case and must assume that the amplitude of the converted seismogram of a Japanese event measured at a Taiwan station is approximately the same as that of a similar-sized Taiwan reference earthquake recorded at a station in Japan. We consider that this approximation is good enough for the purpose of our rough estimation of magnitude.

The maximum amplitude A_c is 6.3 cm for the 2008 N-Iwate earthquake (deep), and the ratio $(A_o/A_c) = 0.67$ leads to $M_W = 6.6$ for the 1909 Taipei earthquake. Similarly, from the maximum amplitude $A_c = 12.8$ cm and the ratio $(A_o/A_c) = 0.33$ for the 2001 Geiyo earthquake (deep), we can estimate the magnitude of the 1909 Taipei earthquake as 6.3.

From the *P-P* amplitude of the Göttingen Wiechert seismogram ($A_o = 4$ mm) and the *P-P* amplitudes of the converted Wiechert seismograms computed from the records at BFO for the 2004 Taiwan earthquake, the 2008 N-Iwate earthquake and the 2001 Geiyo earthquake, we can estimate the M_W of the 1909 Taipei event as 7.2, 6.6 and 6.6, respectively.

The values of M_W estimated from the deep earthquakes (Table 6) range from 6.3 to 7.2, and are slightly smaller than m_B listed in Gutenberg Notepad. Considering all the uncertainties associated with the m_B determinations, conversion of m_B to M_W, and the ambiguities in the estimation of M_W from the amplitudes of converted seismograms, we will use $M_W = 7$ in this paper with an approximate

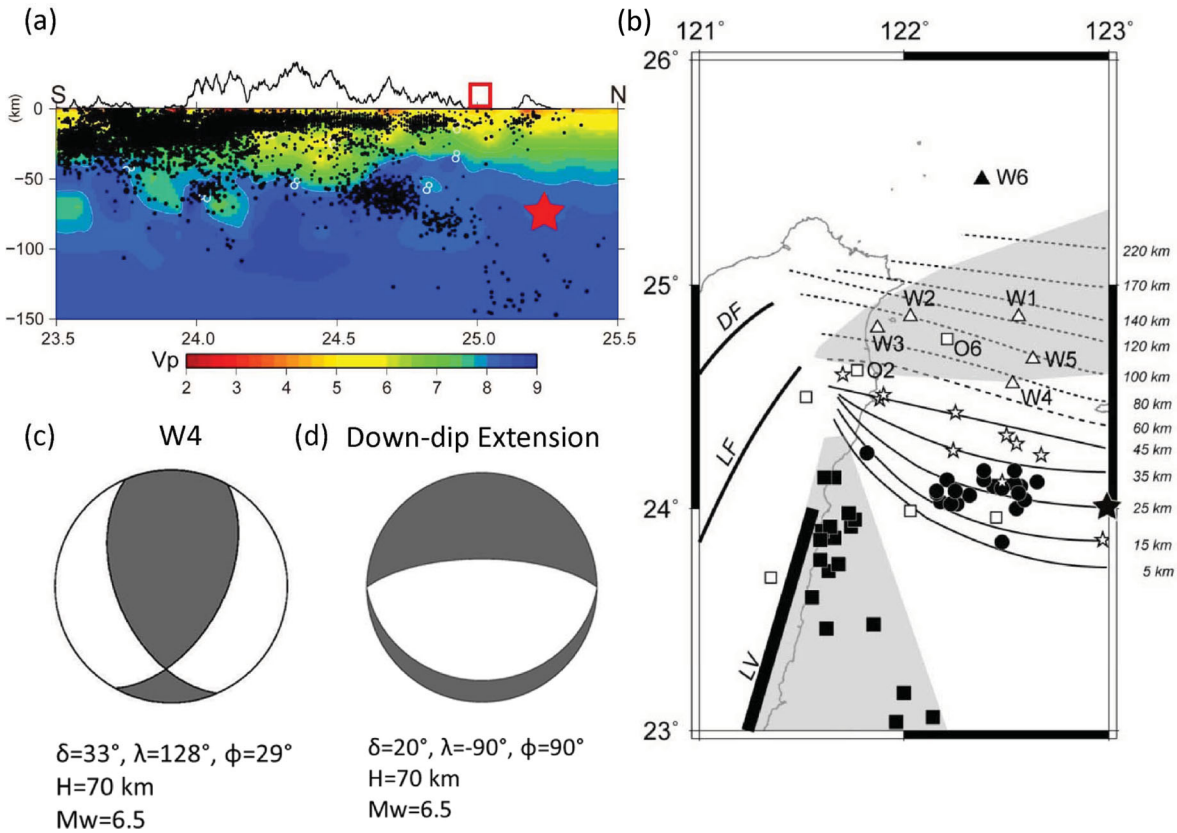

Figure 5. (a) A NS cross-section of seismicity and tomographic structure along the longitude of 121.5° in northwest Taiwan. This figure is made using the data published in Wu *et al.* (2009b). Open square indicates the location of Taipei and closed star indicates the hypocentre of the 1909 Taipei earthquake. (b) Locations of down-dip extension events W1 to W5, and normal-fault earthquakes, O2 and O6 (Kao *et al.* 1998). The contours on the right-hand side describe the subduction interface; LV is the Longitudinal Valley, LF is the Lishan fault and DF is the Deformation Front. They are some of the prominent tectonic features in Taiwan. [Fig. 5(b) was modified from fig. 2(b) of Kao *et al.* 1998]. (c) The mechanism of W4 event. (d) The EW striking down-dip extensional mechanism taken from the mechanism of the 2008 N-Iwate earthquake, and is rotated such that the *T*-axis is oriented in the north–south direction.

uncertainty of ±0.3, the average m_B taken from Gutenberg Notepad being given preference.

5 TECTONIC INTERPRETATION

Judging from the m_B versus M_S disparity noted in Gutenberg Notepad, *P* and *S-P* times, and comparison of the seismograms at Hongo and Göttingen with the converted seismograms for three pairs of deep and shallow events, we conclude that the 1909 earthquake is a relatively deep event, probably between 50 and 100 km, with an M_W around 7.0. Given the limited instrumental data available to us, we cannot determine more definite source parameters, but we believe that this qualitative conclusion is robust. We can go one step further by relating this event to the subducting plate structure beneath Taipei, although the tectonic setting is very complex (Wu *et al.* 2009a,b; Theunissen *et al.* 2010).

The epicentre of the 1909 Taihoku earthquake at 25.28°N and 121.52°E places this event near the western edge of the subducting Philippine Sea Plate (Fig. 5b). The hypocentre plotted on the N–S cross-section (Fig. 5a) appears considerably shallower than the subducting plate inferred from seismicity. However, allowing for the uncertainties in the hypocentral location and in the detailed plate geometry near the western edge, we conclude that the 1909 Taipei event probably occurred within the Philippine Sea Plate. Earthquakes of this type occur in many regions in the world. The three deep events we used for comparison (Taiwan (2004 October 15, $H = 102.1$ km, $M_W = 6.6$), N-Iwate (2001 July 23, $H = 98.8$ km, $M_W = 6.8$), and Geiyo (2001 March 24, $H = 47.4$ km, $M_W = 6.8$) are all of this type. We also note that another earthquake occurred in this general area on 1910 April 12. Gutenberg & Richter (1954) list this event as (O.T. 00:22:13, 25 1/2°N, 122 1/2°E, $H = 200$ km, $M = 7\frac{3}{4}$). Abe & Kanamori (1979) list $m_B = 7.6$ for the 1910

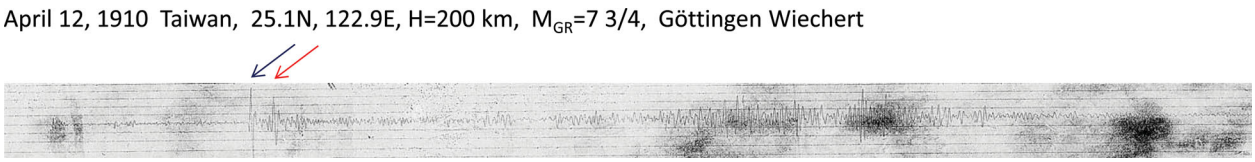

Figure 6. Wiechert seismogram for the 1910 April 12 Taiwan earthquake (25.1°N, 122.9°E, $H = 200$ km, $M_{GR} = 73/4$) recorded at Göttingen.

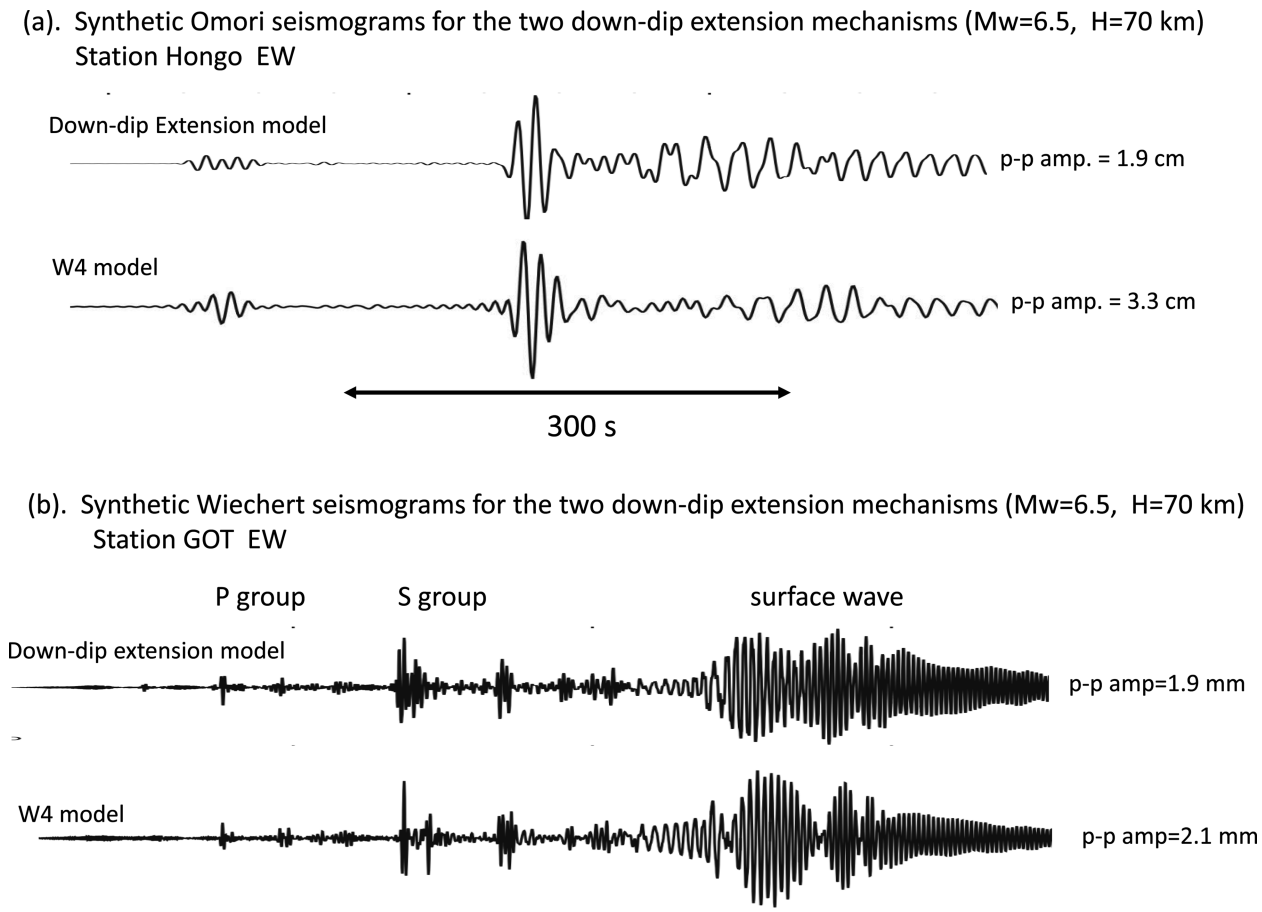

Figure 7. (a) Synthetic Omori seismograms ($V = 120$, $T = 12.5$ s, $h = 0.2$) computed for the two down-dip mechanisms shown in Fig. 5. The hypocentral parameters are (25°N, 121.5°E, $H = 70$ km, $M_W = 6.5$), and the station is Hongo. These seismograms are to be compared with the Omori seismogram at Hongo shown in Fig. 2(a). (b) Synthetic Wiechert seismograms ($V = 158$, $T = 13.6$ s, $\varepsilon = 4.0$) computed for the two down-dip mechanisms shown in Fig. 5. The hypocentral parameters are (25°N, 121.5°E, $H = 70$ km, $M_W = 6.5$), and the station is Göttingen. These seismograms are to be compared with the Wiechert seismogram at Göttingen shown in Fig. 3.

earthquake which was computed from the Gutenberg Notepad. We found a good Wiechert seismogram (EW) for this event recorded at Göttingen (Fig. 6). Although this event does not seem to be as close to Taipei as the 1909 event, it is much larger than the 1909 event. The report from the Taihoku Observatory (Taihoku Obs. 1910) includes a map showing the distribution of strong ground motion (Fig. D1). Almost the entire northern half of Taiwan is included in the area of strong ground motion. Although it is unclear exactly what 'strong' means here, in 1910, the intensity scale was expressed in seven levels (0–6), and 'strong' was used for Intensity 5, and the corresponding PGA is in the range from 80 to 250 cm s^{-2}. Gutenberg & Richter (1954) gave a depth of 200 km. A sharp pulse (red arrow on Fig. 6) following *S* (black arrow on Fig. 6) on the Göttingen record is most likely *sS*. The implied *sS*-*S* time, 70 s, gives a depth of 160 km, which agrees reasonably well with the Gutenberg and Richter's estimate, 200 km. The seismicity in this area shown by figs 2(a) and (b) of Kao *et al.* (1998) (also Fig. 5b in this paper) indicates that most events in this region are shallower than 130 km. At depths below 130 km, only one relatively small, $m_b = 5.5$, event, W6, is shown. Thus, the 1910 event at a depth of about 160 km with a large magnitude of $m_B = 7.6$ indicates that the subducted Philippine Sea Plate is capable of generating very large events even if the recent seismicity is very low. This means that even if the 1909 Taipei earthquake is the largest earthquake beneath Taipei in the last century, considering the relatively short instrumental data, we should not rule out the possibility of having even larger events beneath Taipei.

Kao *et al.* (1998) found several down-dip extension events (e.g. W1–W5 in Fig. 5b), and normal fault events (e.g. O2 and O6) in Fig. 5(b) to the east of the 1909 event. In general 'down-dip extension' events refer to those for which the *T*-axis is more or less in the down-dip direction of the Benioff-Wadati zone, but the *P*-axis can be in any orientation. In case of W2, W3 and W4 events in Kao *et al.* (1998), the *P*-axis is almost horizontal in the east–west direction. Thus, the mechanism is more like a NS striking thrust mechanism as shown in Fig. 5(c). In contrast, the N-Iwate event is also interpreted as a down-dip extension event, but in this case the *P*-axis is nearly vertical and the mechanism is a normal fault (Fig. 5d). Thus, it is difficult to infer a particular focal mechanism for the 1909 event even if it is a down-dip extension mechanism. Here, just to explore the possible types of mechanisms, we assume two mechanisms: one is the mechanism of W4 event (Fig. 5c), and the other is a N-Iwate type normal-fault (still down-dip extension) mechanism, rotated as shown in Fig. 5(d). Then, we computed synthetic Omori seismograms at Hongo and Wiechert seismograms at Göttingen using the two mechanisms, which are shown in Figs 7(a) and (b). These synthetic seismograms can be compared with the observed record shown in Fig. 2(a) (Hongo) and Fig. 3 (Göttingen). The synthetic seismograms for the two mechanisms are both similar to the observed record concerning the amplitude ratios of *P*, *S* and

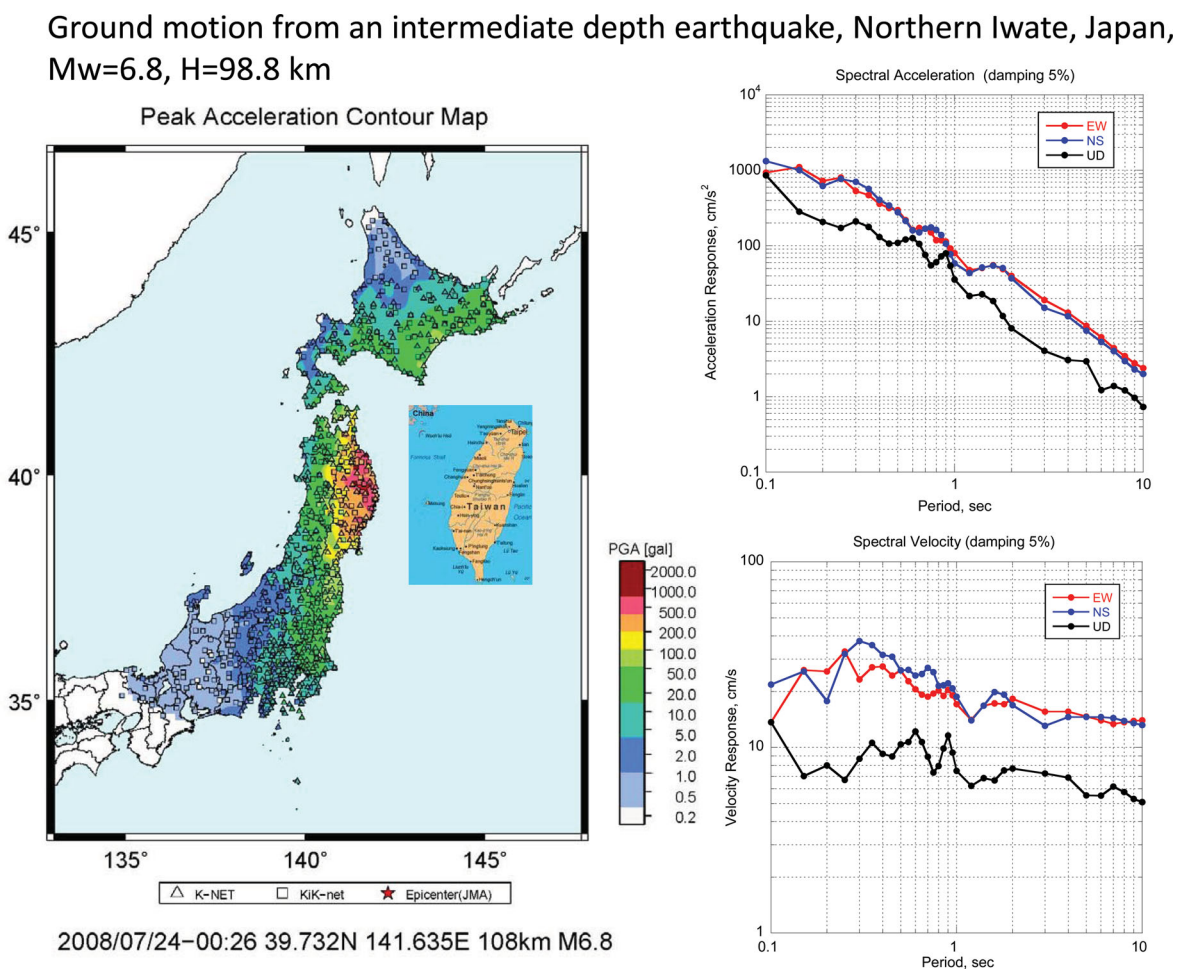

Figure 8. Peak ground accelerations, spectral velocity and spectral acceleration at a K-net station IWT016 for the 2008 Northern Iwate earthquake (http://www.kyoshin.bosai.go.jp/kyoshin/quake/).

surface waves. Thus, the types of down-dip extensional mechanisms considered here are compatible with the observation. Given the lack of any other obvious candidate mechanisms, we do not explore the issue any further, but if some other mechanisms are preferred in light of other tectonic considerations, they can be tested against the Hongo Omori and Göttingen Wiechert seismograms as is done here.

6 IMPLICATIONS FOR GROUND MOTIONS

During the 1909 earthquake, according to Osaka Meteorological Observatory (1910), very severe ground motion was felt in an area of about 80 km^2 near Taipei, and strong ground motion was felt in an area of about 750 km^2 north of Taichung. Also, the description in the local newspaper suggests very severe ground motion near Taipei, but it is difficult to quantitatively estimate the strength of shaking.

As we discussed above, the 1909 earthquake is most likely an intraplate earthquake such as the 2008 N-Iwate earthquake, and the 2001 Geiyo earthquake. Thus, it is useful to take the ground motion data for the 2008 N-Iwate and the 2001 Geiyo earthquakes as a proxy for ground motions to be expected from the 1909 type earthquake. As shown in Figs 8 and 9, these earthquakes, despite a modest $M_W = 6.8$, produced very strong shaking in the epicentral areas. Figs 8 and 9 show the peak acceleration, spectral acceleration and spectral velocity for the 2008 N-Iwate earthquake and the 2001 Geiyo earthquake. According to Suzuki *et al.* (2009), for the 2008 N-Iwate earthquake, the Japan Meteorological Agency (JMA) observed a maximum seismic intensity of six (approximately IX on the modified Mercalli intensity scale). The maximum acceleration recorded by the two nationwide strong-motion networks, K-NET and KiK-net, was larger than 1000 cm s^{-2} at the KiK-net surface station, IWTH02; a peak ground acceleration larger than 500 cm s^{-2} was recorded at the other 11 stations. The peak ground-motion velocity exceeded 25 cm s^{-1} at six stations. For the 2001 Geiyo earthquake, the peak ground-motion acceleration exceeded 500 cm s^{-2} at eight stations and the peak-ground-motion velocity exceeded 25 cm s^{-1} at 11 stations.

We could not find any seismograms from which we could estimate the strength of ground motion near Taipei, but the report from the Osaka Meteorological Observatory describes the ground motion at Keelung and Taipei measured from the strong motion records. According to this report, the maximum ground motion displacement measured on the strong-motion record at Keelung was 6.1 cm at a period of 1.3 s, from which the maximum acceleration was estimated at 67 cm s^{-2}. Similarly, the maximum acceleration at Taipei was estimated at about 70 cm s^{-2} at a period of 1.2 s. However, these estimates cannot be interpreted as PGA used in the modern practice, because the ground-motions were measured with the Omori strong-motion seismograph, which is a mechanical seismograph (flat displacement response at short period) with a natural period of about 5 s (Hamada 2007) rather than an accelerograph (flat acceleration response). At regional distances, PGA usually occurs at a period of 0.2 to 0.3 s on accelerograms, not at 1 s as was observed in Taipei and Keelung. To investigate this difference, we performed

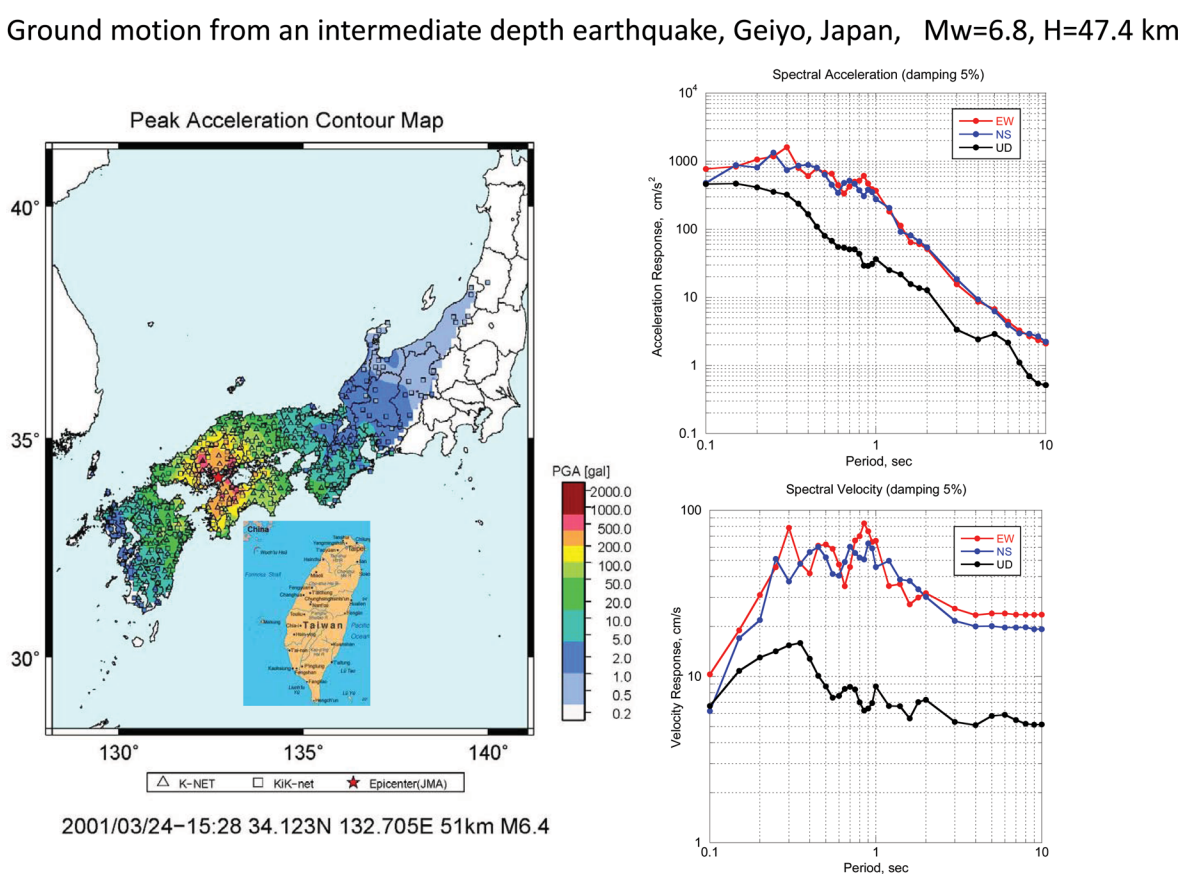

Figure 9. Peak ground accelerations, spectral velocity and spectral acceleration at a K-net station HRS019 for the 2001 Geiyo earthquake (http://www.kyoshin.bosai.go.jp/kyoshin/quake/).

the following numerical test using the accelerogram of the Geiyo earthquake recorded at a K-NET station, Hiroshima (HRS019), the response spectrum of which is shown in Fig. 9. This record has a PGA of 410 cm s^{-2} at a period of 0.3 s. We computed the displacement from it and convolved it with the Omori instrument response (period = 5 s, damping ratio = 8, magnification = 1). The maximum displacement occurs at a period of about 1s with an amplitude of 2.05 cm. Then, we computed the maximum acceleration from it using the same method as was used in the Osaka report and obtained 100 cm s^{-2}, which is about 1/4 of the PGA. Although the damping factor and the natural period of the Omori strong-motion seismograph are somewhat uncertain, using slightly different damping and period does not affect the result significantly. This difference is due to the difference in the period where the acceleration was measured. The maximum acceleration thus measured is about the same as the acceleration spectral response at 1 s for this record as shown on Fig. 9. If we apply this factor of four difference between the maximum acceleration around 1 s and PGA to the Taipei and Keelung estimates, the estimated PGAs are about 280 and 270 cm s^{-2} for Taipei and Keelung, respectively.

However, since the difference between the maximum acceleration and PGA depends on the frequency characteristics of the record, and the description in Osaka Meteorological Observatory (1910) on how the maximum accelerations were estimated is somewhat ambiguous, these values should be taken with caution.

7 CONCLUSION

The 1909 Taipei earthquake is most likely an intra-plate earthquake, which occurred within the subducting Philippine Sea Plate beneath Taipei at a depth of about 75 km (possible range is from 50 to 100 km). The epicentre is located at 25.25°N and 121.38°E, which is very close to that given by Taihoku Obs. (1936). Our preferred estimate of the magnitude is $M_W = 7 \pm 0.3$. We found that the arrival-time readings from Taiwan stations (as reported locally) are reliable in general, and thus these readings will be useful for relocating earthquakes occurring in the Taiwan region before 1964.

Even if the magnitude is only moderately large, intraplate events in other regions suggest that these events are enriched in high-frequency energy and the resulting ground motions can be very strong. Also, even if the 1909 Taipei earthquake is the largest event near Taipei during the last century, we should not rule out the possibility of even larger events within the subducting Philippine Sea Plate beneath Taipei.

The population density in the TMA has increased by more than tenfold since 1909, and instead of mostly one-story houses in scattered villages and towns in 1909, we now have multistory buildings, especially in Taipei City and nearby towns as illustrated in Fig. 10.

For comprehensive ground motion hazard assessment in Taipei, the amplification effect of the Taipei basin needs to be considered. Considering the vast difference in the living environment and the construction practice in Taipei between 1909 and the present, it would be prudent to review the current preparedness in Taipei against large intraplate earthquakes like the 1909 Taipei earthquake.

It is unfortunate that we could not find any 1909 Taipei earthquake's seismograms from the Taiwan local stations. We have to depend on the arrival-times and amplitudes/periods given in the Kondo (1909) report. If we had access to the original seismograms, we would have been able to better assess the accuracy of these measurements, thereby enabling us to have better estimates of the uncertainties in the hypocentre location and the ground-motion parameters. This demonstrates the importance of preserving old seismograms, especially from local stations.

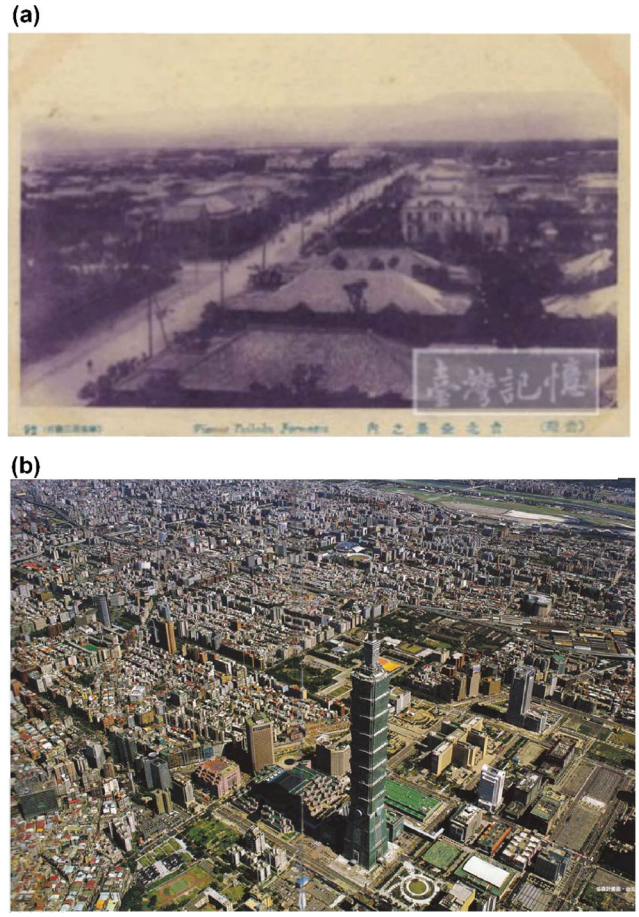

Figure 10. Taipei in 1900s and in 2010.

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APPENDIX A: SOURCE MATERIALS FOR STUDYING THE 1909 TAIPEI EARTHQUAKE

In Appendix A, we will discuss the source materials for studying old earthquakes, such as the 1909 Taipei event. Many source materials and data files used in this paper are archived in online at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section.

A major obstacle in studying old earthquakes is the difficulties in obtaining their seismograms and related seismic station bulletins/reports. An earlier attempt in the late 1970s to preserve the old seismograms and related materials could manage to microfilm only about 0.5 million seismograms (before 1964) out of a total of over 20 millions existing seismograms at that time (Lee *et al.* 1988). Since then, many seismograms have been lost or have become difficult to access. As a result, the microfilms from this Historical Seismogram Filming project (https://www.openseismo.org/Public/Lee/Historical_Seismogram_Filming_Project/) have become a major resource for old seismograms.

Since 2004, the SeismoArchives project of the International Association and Physics of the Earth's Interior (IASPEI) (http://www.iris.edu/seismo/) is an attempt to preserve paper seismograms and related materials and make them available online (Lee & Benson 2008), but the progress is slow due to the lack of funding. We hope that institutions and funding agencies will increase support to make old seismograms and station bulletins available online.

A1 Seismographic stations at the time of the 1909 Taipei earthquake

According to Schweitzer & Lee (2003), there were about 100 seismographic stations at the time of the 1906 San Francisco earthquake. H. F. Reid attempted to collect the available seismograms and related information right after the earthquake, and published an atlas of seismograms with detailed instrumentation information in Reid (1910). Three major seismograph types available in those days were Milne ($V \approx 5$, $To \approx 20$ s), Omori ($V \approx 20$, $To \approx 25$ s) and Wiechert ($V \approx 150$, $To \approx 15$ s), where V is the static magnification, and To is the natural period. Besides low magnification, Milne seismographs suffered from lack of damping and the small record size with a slow film speed, 1 mm/60 s. This means that the reading error in arrival times is about 10 s at best, and thus Beno Gutenberg ignored the readings from Milne seismograms in Gutenberg & Richter (1954). The paper speed of the Omori and Wiechert seismographs was typically 1 mm/4 s, so that arrival times could be read to about 1–2 s. These three seismograph types were designed to record teleseismic earthquakes, but for regional and local earthquakes, shorter natural period and higher magnification are necessary.

Fortunately, all the Taiwan stations in 1909 were equipped with the Gray-Milne (also called 'G.M.E' or 'Ordinary') seismograph. Thanks to Nobuo Hamada, the history of the Taiwan

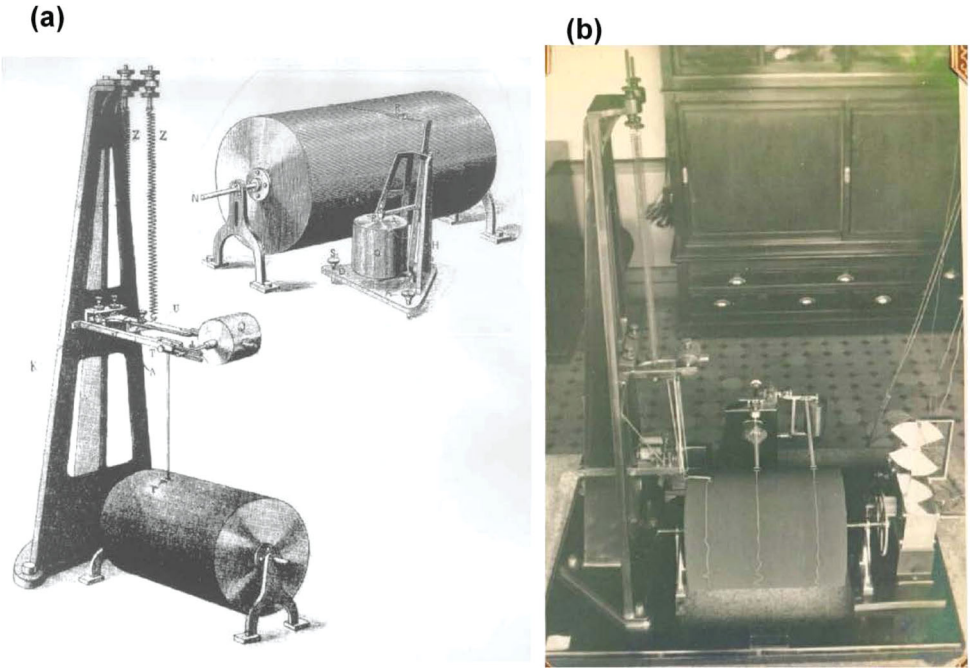

Figure A1. (a) Sketch of Gray-Milne seismographs, which appeared in the Manual of Seismological Observation Practice of the Central Meteorological Observatory. (b) Gray-Milne seismograph at Okayama Local Meteorological Observatory. This figure is extracted from a file on the CD-ROM of Hamada (2007).

seismographic stations was translated and revised from Hamada (2007), and is available online as a PDF file at: http://www.iris.edu/seismo/quakes/1909Taiwan/TaiwanStationInfo-by-Hamada_Revised.pdf. The Gray-Milne seismograph was designed for recording local earthquakes by Gray and Milne and improved by Omori. Bracket pendulum was used for horizontal component as shown in Fig. A1, and a seismoscope was used for triggering drum rotation when an earthquake was detected. Pendulum mass was about 2 kg, and the natural period was about 3 s. The magnification was 5–6 for the horizontal components, and about 10 for the vertical component. The speed of the recording paper was 1 mm/4 s, so that arrival times could be read to better than ±1 s for impulsive arrivals.

A2 Seismograms for the 1909 Taipei earthquake

Despite our search, we could not find any seismograms of the 1909 Taipei earthquake that were recorded in Taiwan. However, Gray-Milne seismograms and arrival-time readings for the Chiayi-Touliu earthquake on 1904 November 6 (04:25 local time) was published by Omori after his visit to the epicentral area. Fig. A2 consists of three pages taken from Omori (1905) published in Japanese, and is taken from Schweitzer & Lee (2003, fig. 5). The upper two frames in Fig. A2 are seismic readings (from horizontal and vertical components) for eight earthquakes at the Tainan Observatory (an auxiliary station of the Taihoku Meteorological Observatory, and is located in the southwestern part of Taiwan). The main shock is the 7th earthquake listed in the readings (magnitude = 6.3 as

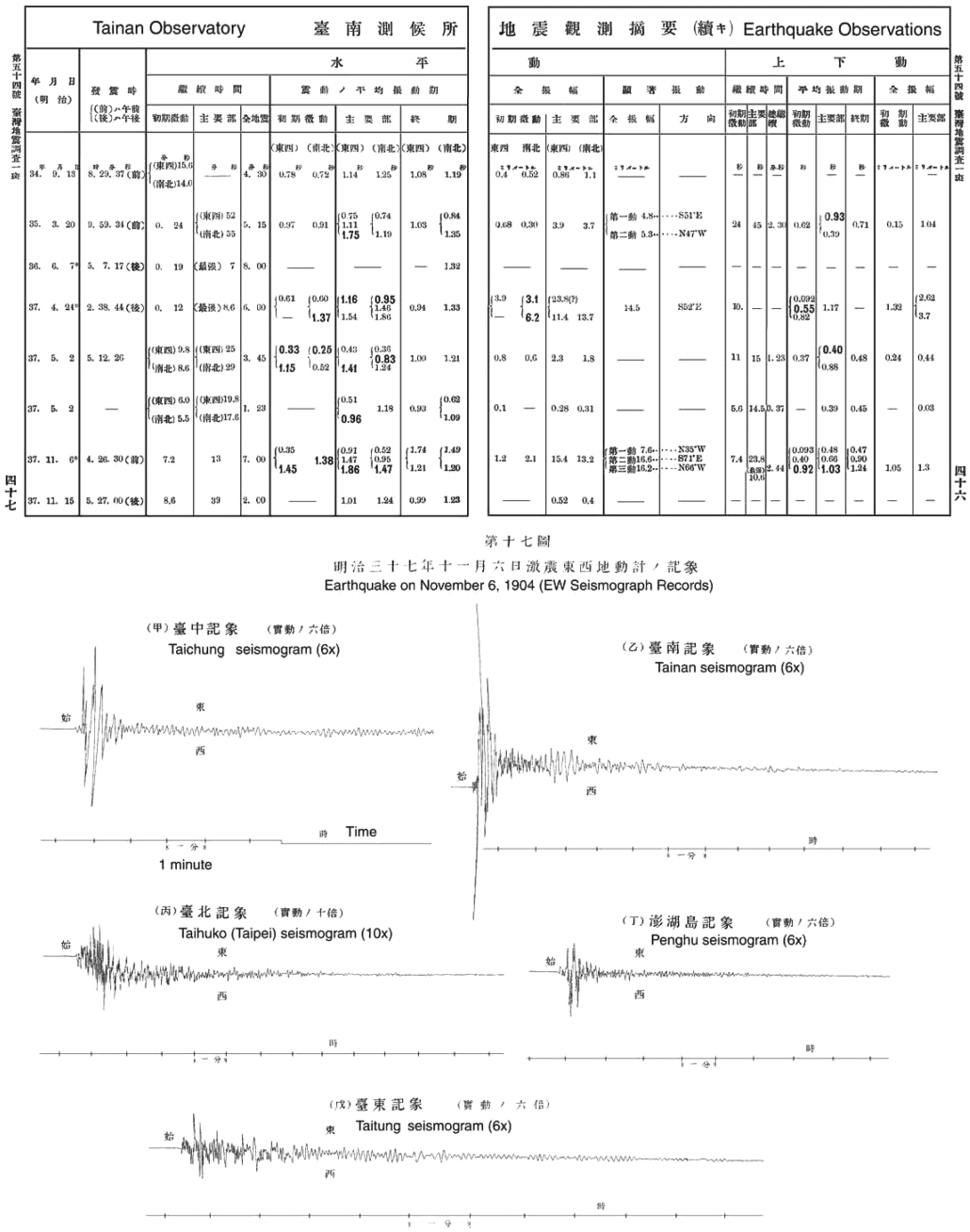

Figure A2. Readings and seismograms for the 1904 November 6 Chiayi-Touliu, Taiwan, earthquake (04:25 local time) extracted from Omori (1905).

given by Utsu (2002b)). Seismograms (east–west component) from Gray-Milne seismographs at five Taiwan stations (Taichung, Tainan, Taipei, Penghu and Taitung) for this earthquake are shown in the lower frame. From these 1904 seismograms, it is obvious that *P* and *S* arrivals could be read accurately throughout Taiwan for local earthquakes with magnitude of ≈6 or greater. Also, according to a survey by Wood (1921), stations in Taiwan had telegraphic timing service from Taipei, such that the Taiwan stations were on a common time base with Taipei. Therefore, we are confident in using the local arrival times for locating the 1909 Taipei earthquake, and also for locating any old Taiwan earthquakes if arrival times of Taiwan stations could be found.

A3 Station bulletins and reports for the 1909 Taipei earthquake

Because of the limited ability to reproduce the original (analogue) paper seismograms, seismologists had to describe their observations in words and numbers. By the early 1900s, first order features of the seismograms were deciphered. The recording instruments were able to produce seismograms in which one could distinguish between the onsets of all three-wave types (i.e. *P*, *S* and surface waves), and a common vocabulary for the description of these records was developed (Borne 1904). Unfortunately, not many of the early seismograms survived and very few are accessible today for re-analysis with modern techniques (Lee *et al.* 1988). The station bulletin publications about these early seismograms are therefore often the only source of information we have now. For the 1909 Taipei earthquake, we extracted arrival-time data from (1) Shide Circulars [ShideCirculars_19090414 TaipeiEQ.pdf], (2) Gutenberg NotePads [GutenbergNotePad_G-R80-805_TaipeiEQ.pdf], and some station bulletins [StationBullExcerpts_19090414_TaipeiEQ.pdf]. All the above-mentioned PDF files are available online at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section. We also take this opportunity to introduce the Shide Circulars and the Gutenberg NotePads below.

A.3.1 Shide circulars

In 1895, John Milne recognized not only the need to deploy seismographs worldwide to monitor earthquakes, but also to collect seismic readings for any cooperating stations so that a database could be made available for earthquake location and seismological research. The first 18 annual reports (1896–1913) of the Committee on Seismological Investigation of the British Association for the Advancement of Science (BAAS) were mostly written by John Milne; these reports chronicled the Committee's efforts in establishing the first worldwide seismograph network,

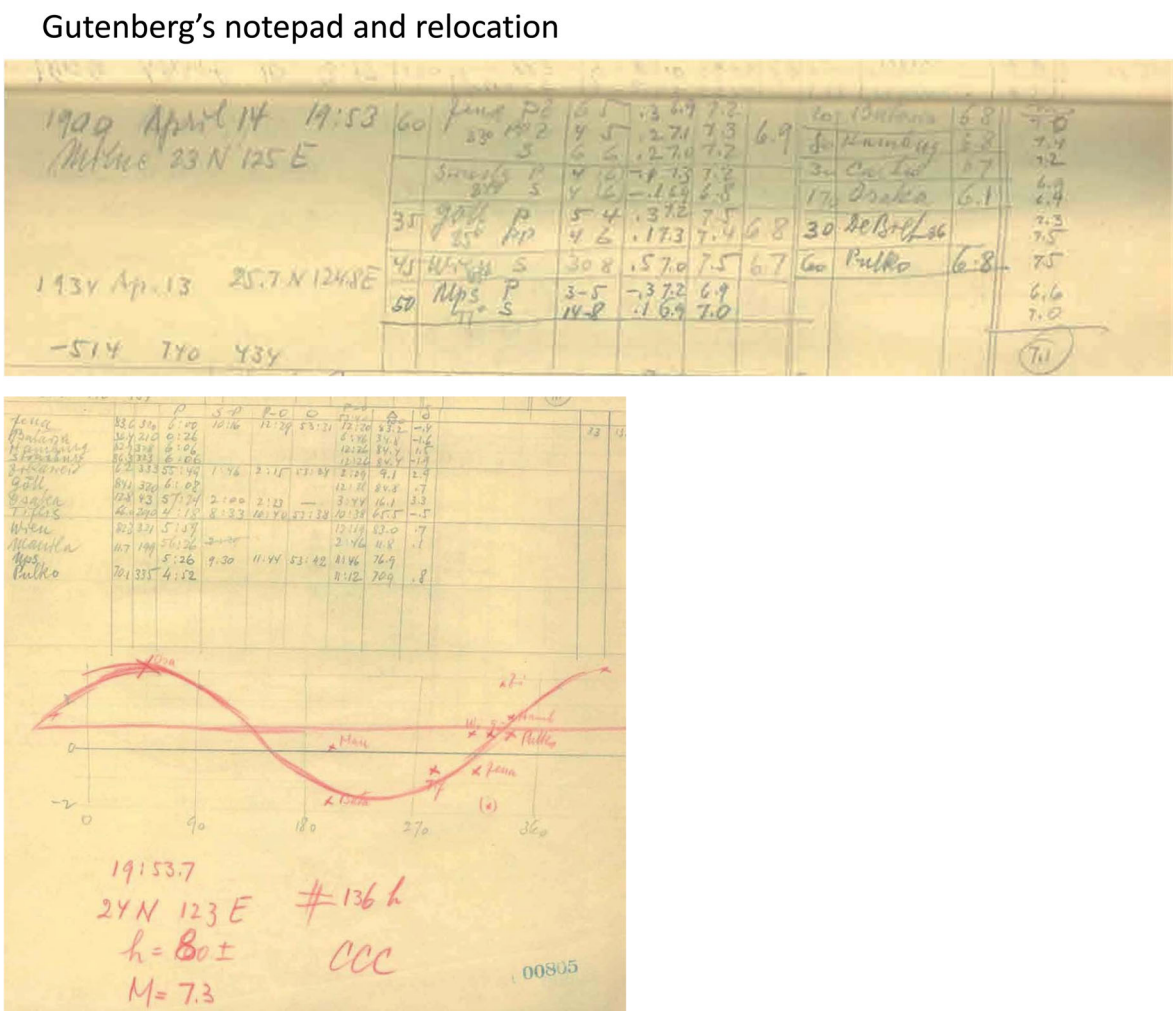

Figure A3. Gutenberg Notepad for the 1909 April 14 Taipei earthquake.

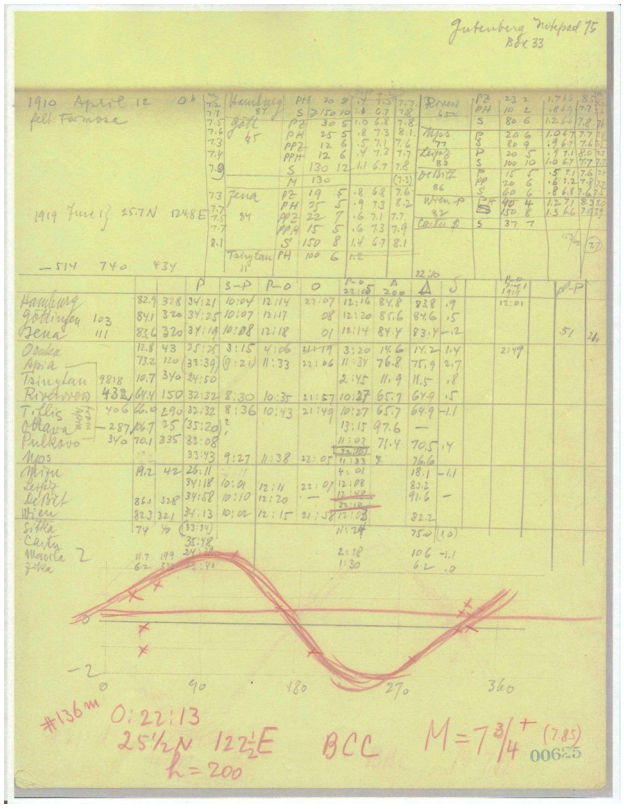

Figure A4. Gutenberg Notepad for the 1910 April 12 earthquake.

collecting the seismic readings and locating the earthquakes [http://www.iris.edu/seismo/info/historical/baas/ for free online access of these valuable reports]. In 1899, the seismic readings became too many to be published in the BAAS annual volumes; from then on, they were issued separately as supplement to the annual reports and called the 'Shide Circulars'. These circulars were collections of 'earthquake registers' from stations distributed worldwide and mostly equipped with the Milne type seismographs. The list of contributing seismic stations changed but during the time the total number of stations continually increased. The biannual 'Shide Circulars' contained, until the end of 1912, seismic readings from about 30 regularly reporting stations, almost all in the then British Empire. The complete set of 27 Shide Circulars are available online at: https://www.openseismo.org/Public/Lee/ShideCirculars/.

Despite Milne's urging, fewer than a third of all operating seismic stations worldwide participated in this project, as participation was only voluntary. Furthermore, the 'Shide Circulars' contained only onset time readings (and maximum amplitude and duration) from large earthquakes that were observed at several stations. Despite its obvious shortcomings, the Shide Circulars remain the only continuous compilation of the early station bulletins worldwide from 1899 through 1912, and total over 1,000 pages. Many of these early seismic stations are no longer in existence and their station bulletins are only accessible through the Shide Circulars. After Milne's death in 1913, the efforts were continued under Turner's leadership, eventually leading to publications of the 'International Seismological Summary' in 1918 (Schweitzer & Lee 2003).

A.3.2 Gutenberg notepads

In preparing the book 'Seismicity of the Earth' (Gutenberg & Richter 1954), Beno Gutenberg left behind a large numbers of note pads, which were subsequently microfilmed by Goodstein *et al.* (1980) into 116 microfiches, and the originals are archived at the Caltech Archive. The Gutenberg NotePads contain the original worksheets that Gutenberg used for the determination of the hypocentre and magnitude for each earthquake, including the arrival times and amplitude data that he copied from station bulletins and the International Seismological Summary (ISS, 1918-1963). Figs A3 and A4 show the pages of Gutenberg Notepad for the April 14, 1909 Taipei earthquake, and for the April 12, 1910 Taiwan earthquake, respectively. The top section is for magnitude determination and the bottom section, relocation of the epicentre. The Gutenberg NotePad for the 1909 Taipei earthquake is available online as a PDF file at: http://www.iris.edu/seismo/quakes/1909Taiwan/GutenbergNotePad_G-R80-805_TaipeiEQ.pdf.

APPENDIX B: ARRIVAL-TIME DATA AND COMPUTATIONAL PROCEDURE

Earthquake location procedures require (1) arrival times from stations that recorded the earthquake, (2) the station coordinates, (3) a velocity model, and (4) a computational procedure that 'fits' the observations to the model by a minimization criterion of the residuals (i.e., differences between the observed and the theoretical computed travel times from a hypocentre to the stations). Since station coordinates had been documented in Hamada (2007) and in the surveys of seismological stations (e.g., Wood 1921), they are accurate enough for use in locating the 1909 Taipei earthquake. Velocity models are also not a problem in locating old earthquakes as several good models are available in the JLoc software (Lee & Dodge 2007). Many files (and related files) used in this paper are documented online at: http://www.iris.edu/seismo/quakes/1909Taiwan/) under the 'Supplementary Sources' section.

B1 Arrival-time data

Preparing arrival time data for a given earthquake is fairly straightforward after the publication of the International Seismological Summary (ISS 1918–1963) starting in 1918 (Schweitzer & Lee 2003). However, except for 1904–1908 when compilations of arrival times for large earthquakes were published by the International Seismological Association (ISA 1904–1908), it is tedious to locate and extract arrival times from individual station bulletins worldwide. For the 14 April 1909 Taipei earthquake, Gutenberg listed in his Notepad P-arrival times for 12 global stations (with S-P times for 5 of them), but did not include any Taiwan local stations. Gutenberg also wrote down his hypocentre solution.

For completeness, we collected the arrival times of the 14 April 1909 earthquake from the following sources: (1) Kondo (1909), (2) Shide Circulars (British Association for the Advancement of Science 1900–1912) and (3) Seismological bulletins issued by individual stations worldwide. Several individual station bulletins were used to verify the Shide Circulars and the Gutenberg Notepad data. For documentation purposes, the excerpted materials for arrival-time data and the input data file for relocating the 1909 Taipei earthquake are available online at: http://www.iris.edu/seismo/quakes/1909Taiwan/ under the 'Supplementary Sources' section. The excerpted files are: (1) Kondo1909_TaihokuReport_TaipeiEQ.pdf, (2) Osaka1910_1909AnnRept_TaipeiEQ.pdf, (3) ShideCirculars_19090414_TaipeiEQ.pdf and (4) StationBullExcerpts_19090414_TaipeiEQ.pdf. The arrival-time data were then

Table B1. Relocation results for the 1909 Taipei Earthquake.*

Station	Code	Phase	Def	Time	RE	Lat.	Long.	Elev.	Delta	Azm.	Resid.
Keelung	tKLG	*S-P*	d	7.700	3	25.150	121.733	0.000	0.24	125.0	−0.67
Keelung	tKLG	*P*	n	−36.509	3	25.150	121.733	0.000	0.24	125.0	−47.91
Taihoku	tTAP	*S-P*	n	7.800	3	25.033	121.517	0.008	0.25	180.5	−0.63
Taihoku	tTAP	*P*	d	11.491	3	25.033	121.517	0.008	0.25	180.5	−0.00
Taichung	tTCU	*S-P*	d	15.700	3	24.150	120.683	0.077	1.36	214.1	−1.86
Taichung	tTCU	*P*	n	71.491	3	24.150	120.683	0.077	1.36	214.1	48.15
Penghu	tPNG	*S-P*	d	26.000	3	23.533	119.550	0.011	2.50	226.2	−3.53
Penghu	tPNG	*P*	n	24.491	3	23.533	119.550	0.011	2.50	226.2	−14.01
Taitung	tTTN	*S-P*	d	30.000	3	22.750	121.150	0.009	2.55	187.7	−0.00
Taitung	tTTN	*P*	n	73.491	3	22.750	121.150	0.009	2.55	187.7	34.39
Tainan	tTNN	*S-P*	d	31.400	3	23.000	120.217	0.013	2.57	207.9	1.17
Tainan	tTNN	*P*	n	102.491	3	23.000	120.217	0.013	2.57	207.9	63.11
Hengchun	tHEN	*S-P*	d	35.600	3	22.000	120.750	0.022	3.34	192.3	−2.98
Hengchun	tHEN	*P*	n	112.491	3	22.000	120.750	0.022	3.34	192.3	62.56
Zi-ka-wei	ZKW	*S-P*	d	63.000	3	31.183	121.433	0.007	5.87	359.3	−2.87
Zi-ka-wei	ZKW	*P*	n	116.491	3	31.183	121.433	0.007	5.87	359.3	32.12
Zi-ka-wei	ZKW	*S*	n	179.491	3	31.183	121.433	0.007	5.87	359.3	29.24
Manila	MAN	*P*	n	153.491	3	14.660	121.078	0.070	10.58	182.3	4.89
Tsingtau	xTTU	*P*	d	151.491	3	36.070	120.321	0.000	10.79	354.8	0.00
Osaka	OSA	*S-P*	n	120.000	3	34.678	135.522	0.013	15.30	49.0	−48.50
Osaka	OSA	*P*	d	211.491	3	34.678	135.522	0.013	15.30	49.0	0.00
Hongo	HNG	*P*	n	−10.509	3	35.708	139.767	9.019	18.80	52.2	−263.83
Hongo	HNG	*S*	n	−10.509	3	35.708	139.767	9.019	18.80	52.2	−473.67
Mizusawa	MZS	*P*	n	294.491	3	39.133	141.117	0.061	21.49	45.3	12.01
Calcutta	CAL	*P*	n	373.491	10	22.539	88.331	0.006	30.40	271.9	8.54
Batavia	DJA	*P*	n	393.491	3	−6.183	106.836	0.008	34.38	206.5	−6.23
Kodaikanal	KOD	*P*	n	475.491	10	10.233	77.467	2.345	44.31	258.4	−6.81
Bombay	BOM	*P*	n	517.491	10	18.896	72.813	0.006	45.36	272.2	−9999.99
Tiflis	TIF	*S-P*	n	513.000	3	41.717	44.800	0.399	63.99	306.0	2.72
Tiflis	TIF	*P*	n	625.491	3	41.717	44.800	0.399	63.99	306.0	0.17
Sydney	SYD	*P*	n	1141.491	10	−33.867	151.200	0.043	65.22	153.0	508.12
Pulkova	PUL	*P*	n	659.491	3	59.767	30.317	0.065	68.97	327.3	2.41
Honolulu	HON	*P*	n	1291.491	3	21.317	−158.060	0.000	72.85	74.0	610.87
Honolulu	HON	*S*	n	1291.491	3	21.317	−158.060	0.000	72.85	74.0	50.65
Beirut	xBei	*P*	n	607.491	10	33.900	35.467	0.030	73.20	300.1	−75.18
Uppsala	UPP	*S-P*	n	570.000	3	59.860	17.630	0.014	74.95	329.6	−1.56
Uppsala	UPP	*P*	n	693.491	3	59.860	17.630	0.014	74.95	329.6	0.59
Uppsala	UPP	*S*	n	1263.491	3	59.860	17.630	0.014	74.95	329.6	−0.97
Helwan-B	HLWB	*P*	n	691.491	10	29.858	31.342	0.116	77.92	297.5	−18.13
Potsdam	POT	*S-P*	n	603.000	3	52.380	13.068	0.080	80.64	324.0	1.74
Potsdam	POT	*P*	n	725.491	3	52.380	13.068	0.080	80.64	324.0	1.00
Potsdam	POT	*S*	n	1328.491	3	52.380	13.068	0.080	80.64	324.0	2.75
Wien	VIE	*P*	n	724.491	3	48.248	16.362	0.198	80.78	319.3	−0.74
Leipzig	LEI	*S-P*	n	606.000	3	51.335	12.392	0.113	81.53	323.3	0.24
Leipzig	LEI	*P*	n	787.491	3	51.335	12.392	0.113	81.53	323.3	58.31
Leipzig	LEI	*S*	n	1393.491	3	51.335	12.392	0.113	81.53	323.3	58.56
Hamburg	HAM	*P*	n	733.491	3	53.465	9.925	0.030	81.72	326.0	3.30
Graz	GRA	*S-P*	n	610.000	3	47.077	15.448	0.369	81.88	318.6	2.46
Graz	GRA	*P*	n	725.491	3	47.077	15.448	0.369	81.88	318.6	−5.55
Graz	GRA	*S*	n	1335.491	3	47.077	15.448	0.369	81.88	318.6	−3.08
Jena	JEN	*S-P*	n	616.000	3	50.952	11.583	0.193	82.16	323.3	7.06
Jena	JEN	*P*	n	727.491	3	50.952	11.583	0.193	82.16	323.3	−5.00
Gottingen	GTT	*S-P*	n	612.000	3	51.546	9.964	0.272	82.72	324.3	0.31
Gottingen	GTT	*P*	n	735.491	3	51.546	9.964	0.272	82.72	324.3	0.10
Gottingen	GTT	*S*	n	1347.491	3	51.546	9.964	0.272	82.72	324.3	0.41
DeBilt	DBT	*S*	n	1359.491	3	52.100	5.183	0.003	84.87	326.4	−9.16
Strassburg	STR	*P*	n	733.491	3	48.579	7.763	0.135	85.52	322.6	−16.12
Edinburgh	EDI	*P*	n	757.491	10	55.923	−3.186	0.125	86.32	332.5	3.91
Paisley	xPai	*P*	n	−412.509	10	55.850	−4.433	0.032	86.89	332.9	−1168.84
Shide	xSHD	*P*	n	487.491	10	50.700	−1.317	0.015	88.93	327.8	−278.57
Granda	GND	*S*	n	1432.491	3	37.200	−3.600	0.768	99.05	318.8	−64.56

Table B1. (*Continued*.)

Station	Code	Phase	Def	Time	RE	Lat.	Long.	Elev.	Delta	Azm.	Resid.
San Fernando	SFS	*P*	n	1477.491	10	36.466	−6.206	0.021	101.08	319.6	656.00
Cape Good Hope	CTO	*P*	n	3787.491	10	−33.950	18.450	0.100	113.93	242.4	2908.87
Pilar/Cordoba	PIL	*P*	n	1831.491	10	−31.668	−63.883	0.338	171.85	146.0	−9999.99

*Preferred solution: Origin Time: 1909/04/14 19:53:52.51;
Latitude: 25.2865°N; Longitude: 121.5193°E; Depth: 75.5 km.
Def: d = used for location; n = not used for location.
RE: An error estimate in s.
Time = Travel time in s.
Lat., Long. and Elev.: Station latitude and longitude in degrees, and elevation in km.
Delta: Epicentral distance in degrees.
Azm.: Azimuthal angle from epicentre to station in degrees measured clockwise from North.
Resid.: Traveltime residual in seconds. Resid. = −9999.99 means that the residual is too large to fit into the column.

prepared for inputting to the JLoc software as a text file called '090414best.PHA'.

B2 Computational procedure

Geiger (1912) introduced a rigorous method to locate an earthquake by applying the Newton-Gauss optimization procedure in minimizing the sum of the least squares of the residuals, but it was not practical until computers became generally available in the early 1960s. Lee & Stewart (1981) presented a detailed derivation of the Geiger's method and discussed its pitfalls. In brief, the Geiger method requires at least four stations surrounding the epicentre and at least one of the stations at epicentral distance comparable to the focal depth, or some depth-phase readings. It also assumes that the velocity model is realistic, and errors in station coordinates and in arrival times are small and Gaussian. Unfortunately for old earthquakes (especially those which occurred before 1930), it is easy for the Geiger's method to fail. Recently, several authors developed direct-search methods that improve earthquake relocation by 'brute force' computing [See Lomax *et al.* (2011) for technical details]. In particular, we used the JLoc software by Lee & Dodge (2007) for re-locating the 1909 Taipei earthquake as described in Section 2 of the text.

The results of the relocation are shown in Table B1, which also includes the essential input data used.

APPENDIX C: OTHER SEISMOGRAMS

Fig. C1 shows other seismograms collected in this study.

Record # 1 is from the archive of the Earthquake Research Institute, Tokyo University, and is listed as the record at the Seismological Institute (Kyoshitsu) at Hongo, Tokyo (No. 1909–63-313). It is labelled as an Omori NS component seismogram with a magnification of 10. Unfortunately, the pendulum period is not listed, but it is probably around 20 s. Because of the unknown period, we did not use this seismogram for the present analysis, but the general appearance, small surface waves compared with the *S* wave, is similar to that of other seismograms at Hongo.

Record #2 is the one we used. Although the component is not clearly listed, we judged it to be the EW component from its comparison with other records.

Record #3 is from the archive of the Earthquake Research Institute, and is listed as an Omori seismogram recorded at the Seismological Institute (Kyoshitsu) at Hongo, Tokyo, Japan, but the component, magnification and the pendulum period are not listed. Judging from its similarity to Record #2, it is probably similar to Record #2 with a lower magnification.

Record #4 is the Omori EW component seismogram from Mizusawa, Japan, with a magnification of 20 and a pendulum period of 30 s. Because of the low gain, the trace amplitude is very low, and we did not use this record for our analysis. However, the overall waveform is similar to Record #2.

Record #5 is the Omori NS component seismogram from Mizusawa, Japan, with a magnification of nine and a pendulum period of 30 s. Because of the low magnification, it is barely recognizable, and we could not use it for the analysis.

Record #6 is the Omori EW component seismogram from Nagano, Japan with a magnification of 20 and a pendulum period of 30 s. Because of the obviously large solid friction, this seismogram was not useable.

Record #7 is the Wiechert EW component seismogram recorded at Strasbourg with a magnification of 180, a pendulum period of 9.5 s, and a damping ratio of 3.5. Unfortunately, because of the fuzzy focus, we could not use this seismogram for analysis. However, the overall character of this seismogram is similar to that of the Göttingen seismogram shown in Fig. 3.

Record #8 is the Wiechert EW component seismogram recorded at Hamburg. At first sight, the appearance of this seismogram is very different from that recorded at Göttingen (Fig. 3). Surface waves with a period of 6–8 s with the trace amplitude of about 10 mm dominate the record. The old seismic station in Hamburg was located on the North German sedimentary basin, about 10 km thick, (Torsten Dahm, written communication 2011), and this large amplitude of relatively short-period surface waves is probably due to the site response. On the Göttingen seismogram shown in Fig. 3 the surface waves which yield the peak amplitude, marked by M, has a period of about 20 s. The surface wave with a period of 20 s on the Hamburg record does not seem to be anomalous, because Gutenberg gave the same surface-wave magnitude $M_S = 6.8$ for both Göttingen and Hamburg.

APPENDIX D: SHAKING DISTRIBUTION OF THE 1910 TAIWAN EARTHQUAKE

Fig. D1 shows the distribution of shaking caused by the 1910 Taiwan earthquake and was published in Taihoku Obs. (1910).

In 1910, the JMA intensity scale was expressed in seven levels (0–6), and 'Strong' was used for Intensity 5 ('cracks are expected on walls and . . . . . .'), and 'Strong (weak one)' was used for Intensity four ('vases will fall down. . . . . .').

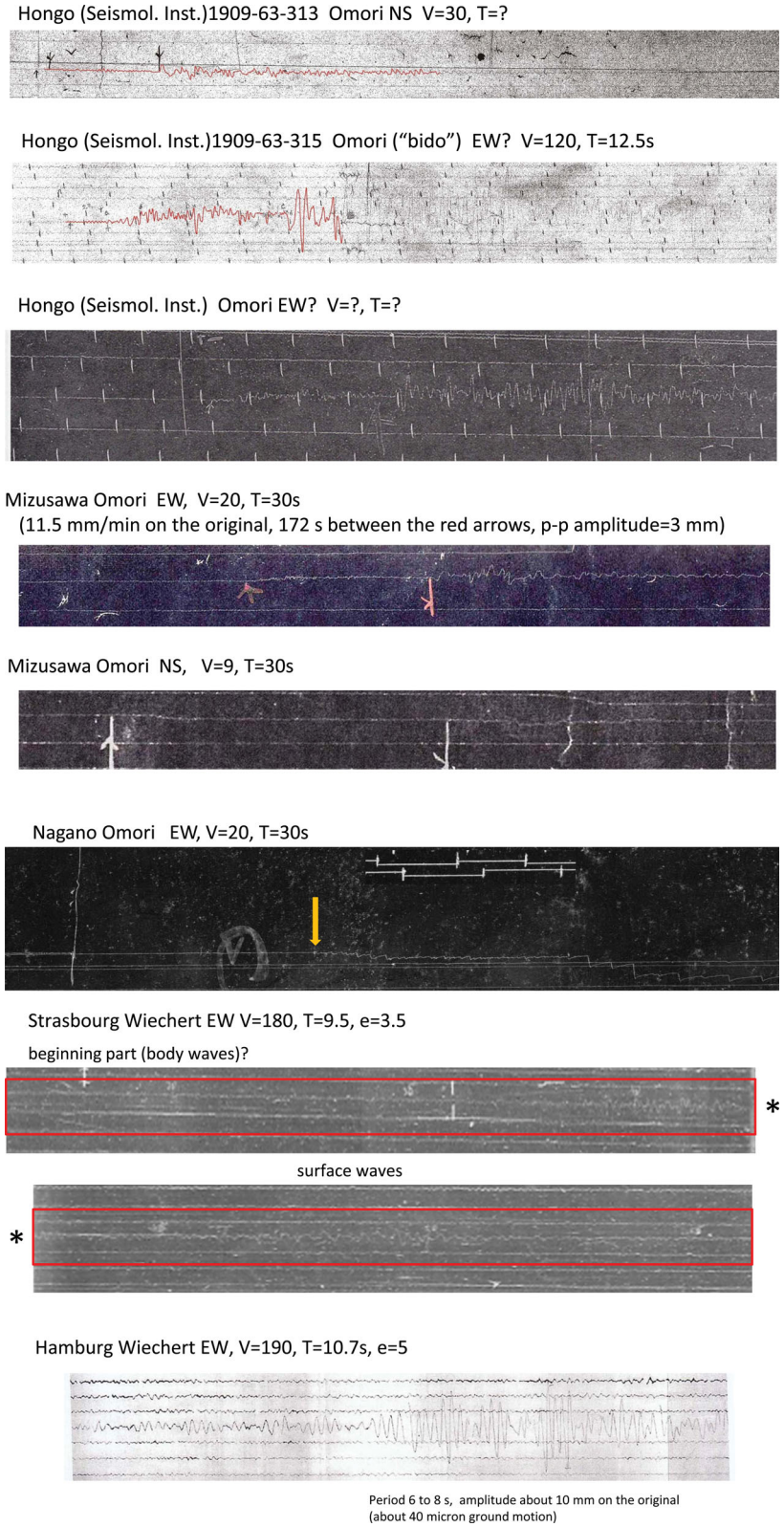

Figure C1. Other seismograms.

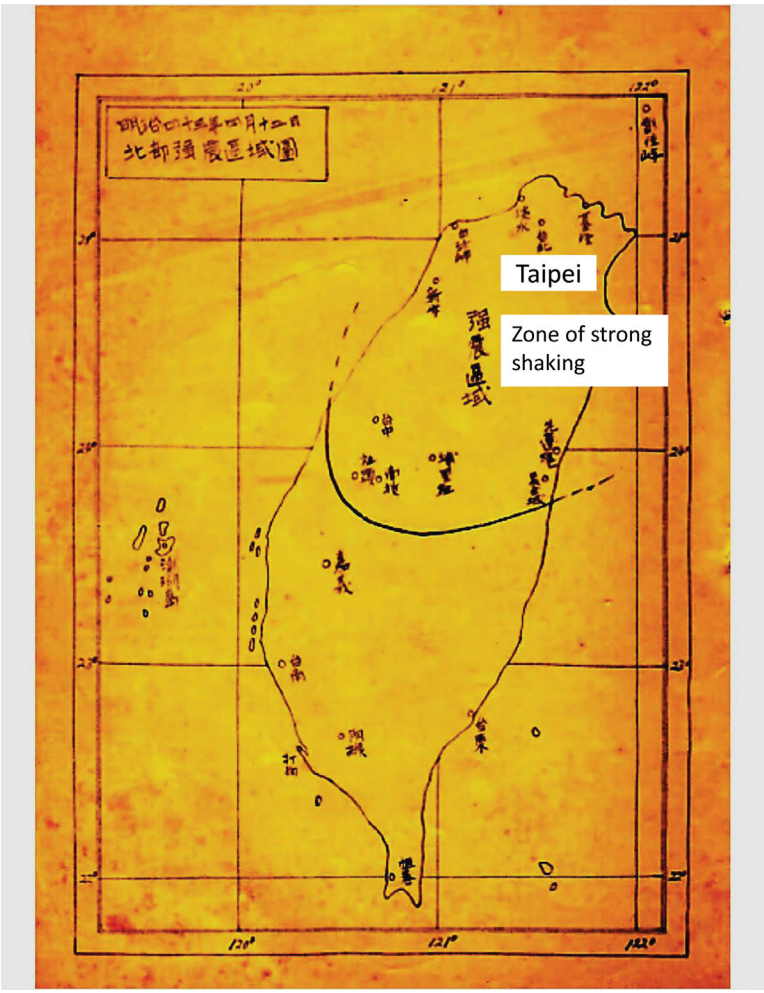

Figure D1. The distribution of shaking caused by the 1910 Taiwan earthquake and was published in Taihoku Obs. (1910).