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THE JULY 9 AND 23, 1905, MONGOLIAN EARTHQUAKES: A SURFACE WAVE INVESTIGATION [1]

EMILE A. OKAL

Seismological Laboratory, California Institute of Technology, Pasadena, Calif. 91125 (USA)

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Synthetic Love wave seismograms for a series of reasonable models of the catastrophic earthquakes of July 1905 in Mongolia are generated and compared to observed data, to help constrain the source parameters suggested from older field reports. The most probable models suggested are pure strike-slip, striking N280°E, dipping north 50° to 90°, with an eastward rupture on the order of 200 km for the first event and 300 km for the second one. A seismic moment of 3–8 × 10^{28} dynes cm, together with a redetermined M_s value of 7.9 ± 0.2 clearly give the first event an "interplate" behavior, consistent with actual theories of Chinese tectonics. Although figures are less accurate, the second event ($M_0 \simeq 5 \times 10^{28}$; $M_s \simeq 8.25$) probably falls into the same category.

1. Introduction

During the summer of 1905, two major earthquakes occurred along the Bolnai fault (also known as the Khangai fault in the U.S.S.R), in northern Mongolia, at 14 days' interval: event I, on July 9, 1905 *, was followed on July 23 * by event II, a seemingly larger earthquake. Both shocks were reported felt over several millions square kilometers, and motivated an extensive field survey by Voznesenski, resulting in a series of reports and maps [1,2].

In view of the recent interest in Chinese tectonics in relation with the Himalayan collision [3,4], it is important to evaluate the focal mechanism of the larger earthquakes which have happened in this area. A previous study of the 1957 Gobi-Altai earthquake [5] resulted in low values of apparent stress and stress drop, revealing the "interplate" behavior of this event in the sense of the study by Kanamori and Anderson [6]. This confirmed the fact that the left-lateral motion involved in this event is a major process in plate tectonics, as described by Molnar and Tapponnier [4], and possibly giving birth to a new Chinese plate.

The magnitude estimates which have been given for the 1905 Mongolian events vary largely, partly due to the use of several magnitude scales [7], and also due to the use of records from old Milne instruments of unknown precision [8]. A detailed discussion of the magnitude determinations of older events can be found in Geller and Kanamori [9]. However, since the adoption of a standardized surface wave magnitude [10], it is important to re-estimate old events in that scale, especially in view of a possible quantitative reassessment of the high intensity of seismic activity at the turn of the century.

Therefore, the object of this paper is two-fold: (1) to get an understanding of the seismotectonics involved in the 1905 events and to analyze them in the general pattern of Asian tectonism, and (2) to give an estimate of the magnitude of these earthquakes, on a scale allowing easier comparisons with recent events.

2. Data

Requests were sent to seismic stations all over the world, with a surprisingly good turnout of usuable

[1] Contribution 2755, Division of Geological and Planetary Sciences, California Institute of Technology.

* In the Gregorian calendar. Dates in the Julian calendar (used in Russia at the time of the events) are respectively June 26 and July 10.

answers. Table 1 lists the material obtained from various agencies.

Most of the data pertaining to seismotectonics of Mongolia is reported in Florensov and Solonenko's study of the Gobi-Altai earthquake [11], where they quote data from Voznesenski's archives. The basic pieces of information from their report are:

(1) The Bolnai fault is identifiable for at least 500 km, a fact later confirmed by satellite photographs (see Fig. 1)

(2) Surface rupture associated with the 1905 earthquakes is continuously present for at least 350 km along the Bolnai fault.

(3) Event I occurred in the eastern part of the ruptured fault, and caused much damage in the Tsetserleg area, north of the fault.

(4) No evidence for any substantial vertical displacement, anywhere on the fault, was reported, at least at the time the report was published.

This last situation clearly restricts the mechanism to pure horizontal strike-slip. In the absence of any usable record of body waves, the following models, derived from this descriptive data and the general seismotectonics of the area, will be used as a source of synthetic seismograms: *strike*, 80–110°; *dip*, 50–90° to –50°; *slip*, 0°; *fault length*, 100–200 km (event I), 250–400 km (event II). A step function source, propagating at a velocity of 3.5 km/s, will be assumed. The depth of the events remains unknown, as it could not be derived from the usual study of pP, sP, etc. By comparison with the Gobi-Altai earthquake [11], the depth was fixed at 15 km, and the study was restricted to longer periods ($T > 75$ seconds), less sensitive to crustal effects, in order to minimize the influence of depth.

3. Surface wave study

Records available for a study of wave shapes are extremely few. None of the instruments used at the time were sensitive enough to provide usable records of multiple Love or Rayleigh waves; yet, most of them went off-scale for the fundamental R_1. Therefore, the Love wave G_1 is the only recoverable phase. Only the

TABLE 1

Seismic data available for the study of the 1905 Mongolian events

Station	Instrument	Seismogram		Bulletin	
		event I	event II	event I	event II
Bombay, India	Colaba EW	√	√		
Bombay, India	Milne	√	√		
Budapest, Hungary	Bosch-Omori			√	
Cartuja, Spain	Vicentini SP	√			
Christchurch, New Zealand	Milne	√	√		
Firenze, Italy	Omori	√	√	√	√
Göttingen, Germany	Wiechert	√	√		
Kew, England	Milne	√	√		
Leipzig, Germany	Wiechert			√	√
Melbourne, Australia	Milne	√	√		
Ogyalla, Hungary *	Bosch-Omori			√	√
Paisley, Scotland	Milne	√	√		
Ponta Delgado, Azores	Milne	√	√		
Tacubaya, Mexico	Omori	√			
Uccle, Belgium	Rebeur			√	√
Urbino, Italy **	Agamemnone			√	√
Strassburg, Germany ***				√	√

* Now Hurbanovo, Czechoslovakia.
** Includes various Italian stations.
*** Now Strasbourg, France; worldwide bulletin; no amplitudes reported.

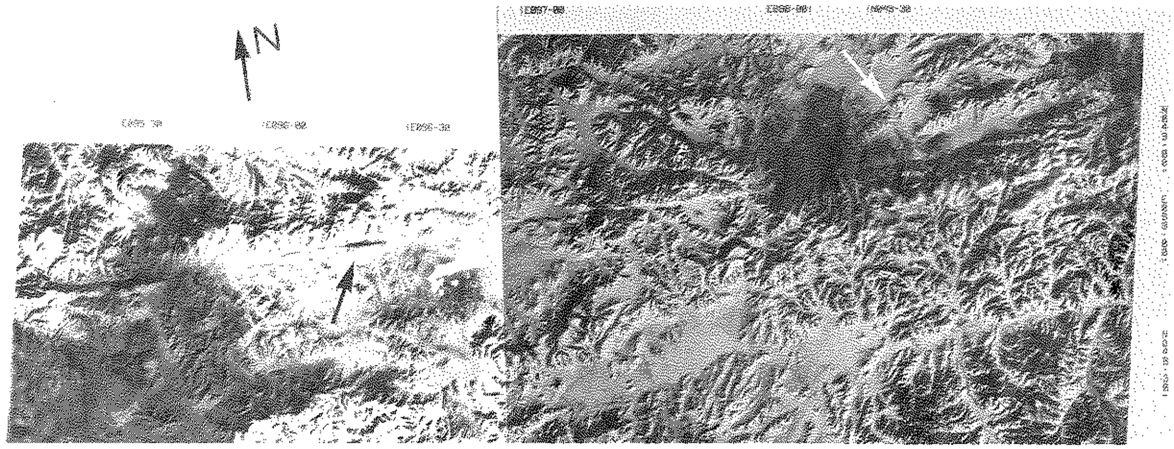

Fig. 1. Satellite view of the Bolnai fault area in northern Mongolia. The black arrow points to the Bolnai fault, the white one to the Tsetserleg fault. This figure is a composite of ERTS photographs E 1519-03510-7 and E 1502-03570-7.

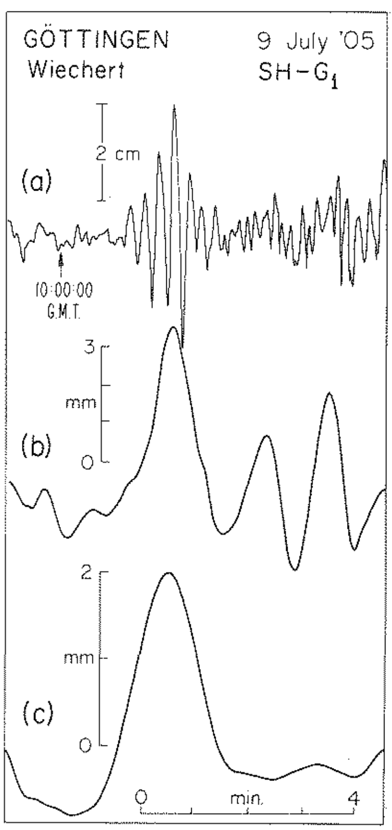

Fig. 2. Experimental records of G_1 at Göttingen for event I: (a) original SH trace; (b) filtered at T = 30 seconds; (c) filtered at T = 75 seconds.

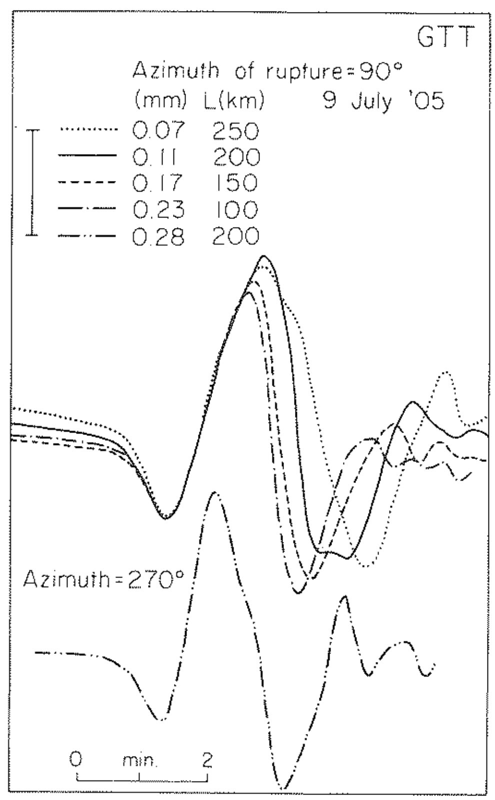

Fig. 3. Synthetics for G_1 at Göttingen for event I. The focal mechanism is a pure vertical strike-slip along an E–W plane. Upper trace: eastward rupture for l = 100–250 km, with amplitude scaling (in mm) for the various traces; lower trace: westward rupture for l = 200 km. A common moment of 10^{28} dynes cm is assumed in all cases.

Wiechert instrument, with its high damping constant ($\epsilon = 5.3$), retains a good sensitivity at longer periods, and therefore, only the G_1 records at Göttingen, Germany (GTT) could finally be usefully analyzed.

Event I, 9 July 1905. The observed G_1 trace is shown in Fig. 2a, after rotation into SH polarization. Fig. 2b, c shows the same trace, once low-pass filtered at $T = 30$ and 75 seconds, respectively. Synthetic seismograms, also filtered at $T = 75$ seconds, were obtained using the technique of Kanamori [12–14]. Fig. 3 shows a selection of synthetics for a number of rupture lengths. In this geometry, the dip angle and the strike of the fault do not affect the shape of the wave, while the direction and length of rupture have a major influence. However, no substantial influence of the rupture length on the waveform was found for a westward rupture, up to a length of 350 km. Therefore, only a sample curve (for a length of 200 km) of westward rupture, is shown in Fig. 3. By comparing Figs. 2c and 3, we can conclude that the rupture propagated eastward, presumably over a distance of 200 ± 30 km, for a rupture velocity of 3.5 km/s. Such an eastward propagation is in agreement with witness reports, quoted from Voznesenski by Florensov and Solonenko [11], and is similar to the rupture process of the Gobi-Altai earthquake [5]. It also helps in defining the epicenter of the earthquake: as suggested by Florensov and Solonenko on the basis of deformation data, Gutenberg and Richter's [8] location (49°N, 99°E) should be moved westward to 98°E, or even 97°E, to allow for an eastward rupture of 200 km. The epicenter could possibly lie at the branching point of the Tsetserleg fault (see Fig. 1 and [2]).

Event II, 23 July 1905. Results of a similar study for the second earthquake are shown in Figs. 4 and 5. As can be seen, the quality of the signal is lower, and it contains more longer periods. However, it is again possible to rule out a westward rupture and the most probable mechanism is an eastward rupture of 300 ± 50 km.

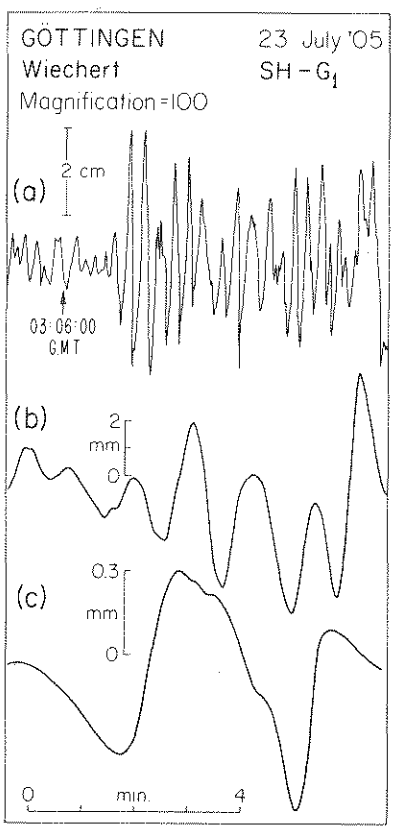

Fig. 4. Experimental records of G_1 at Göttingen for event II: (a), (b) and (c) as in Fig. 1.

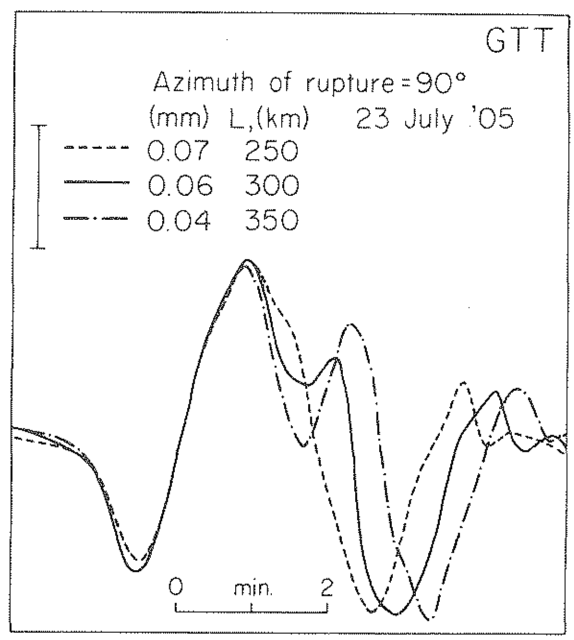

Fig. 5. Synthetics for G_1 at Göttingen for event II. Same focal mechanism as in Fig. 3. Eastward rupture for l = 250–350 km. Traces for westward ruptures are identical to the one shown in Fig. 3. A common moment of 10^{28} dynes cm is assumed in all cases.

This asks for an initial epicenter at the west end of the rupture, around 94–95°E. (The possibility of a bilateral faulting was also contemplated, but gave a very poor fit to the data.)

4. Magnitude and moment

Magnitude determinations for the 1905 events in Mongolia are reported by Gutenberg and Richter [8] ($8\frac{1}{4}$ for both events), and by Richter [7, p. 711] (event I: $M = 8.4$; event II: $M = 8.7$). A redetermination was made, using data shown in Table 2, and the "Prague formula" [10]:

$$M_s = \log_{10}(A/T) + 1.66 \log_{10}\Delta + 3.3$$

Magnification and damping constants not reported in available station bulletins were taken from the "Report on the California Earthquake of April 18, 1906" [15], and used on the assumption of good stability in time for the mechanical instruments in use in the 1900's.

The average magnitude obtained for event I is $M_s = 7.9 \pm 0.2$. Most of the stations report off scale maximum amplitudes for event II. However, a comparison between Milne records for both events at Bombay, Ponta Delgada, Christchurch and Paisley, suggests that corresponding phases are 2–3 times larger in amplitude for the second event. Therefore a very tentative value of $M_s = 8.25$ is proposed.

These figures are much lower than those published by Richter [7] and, in the case of event I, by Gutenberg and Richter [8]. This study provides a sample qualitative evaluation of the deviation between the various scales used by these authors, and the presently used M_s scale. An extensive comparison of various magnitudes for a large number of other earthquakes is given by Geller and Kanamori [9].

Moment values for event I, as determined from the surface wave study in section 2, are shown in Table 3, for various values of dip angle and azimuth of fault. As can be seen, the azimuth has a major influence on the moment, whereas the dip angle does not. Reports of damage north of the Bolnai fault [2] ask for a fault plane dipping north. In view of the topographic layout of the Bolnai fault, the most probable value of the seismic moment of event I is $(5.5 \pm 2.5) \times 10^{28}$ dynes cm. For event II, a similar value of 5×10^{28} dynes cm is suggested from Fig. 5, although this value is much less accurate than for event I.

The moment of event I translates into an apparent stress $\eta\bar{\sigma}$ of only 1–4 bars, using Kanamori and

TABLE 3

Value of seismic moment for a number of models of event I (an eastward rupture of 200 km is always assumed)

Strike azimuth (deg.)	Dip angle (deg.)	Moment (dynes cm)	Apparent stress (bars)
80	90	1.43×10^{29}	0.937
90	90	8.8×10^{28}	1.52
100	90	3.5×10^{28}	3.83
110	90	2.0×10^{28}	6.7
100	–50	4.5×10^{28}	3.0
100	–70	3.7×10^{28}	3.6
100	70	3.6×10^{28}	3.7
100	50	4.7×10^{28}	2.85

TABLE 2

Amplitude data used in magnitude determination of event I

Station	Distance	Instrument	High-frequency gain	Damping constant ϵ	Amplitude (mm)	Magnitude M_s
Budapest	50.8	Bosch-Omori	9	1.17	152	8.05
Cartuja	69.5	Vicentini SP	155	–	60	7.7
Leipzig	52.8	Wiechert	240	3.0	1.14 *	7.86
Göttingen	52.9	Wiechert	198	5.3	>97	>7.76
Ogyalla	50.1	Bosch-Omori	10	1.17	132	7.94

* Ground motion.

Anderson's results on rupture parameters [6]. Although no precise data on the area of rupture, and consequently on stress drop $\Delta\sigma$, is available, this apparent stress can be compared with results from the Gobi-Altai event and several other major shocks in Central Asia [5]. Even within the range of uncertainty event I exhibits rupture properties which let it qualify for interplate behavior, along with such earthquakes as the 1965 Rat Island, 1968 Tokachi-Oki, and 1969 Kurile events, which have the closest moments and magnitudes, as opposed to, say, the 1969 Portuguese earthquake ($M_s = 8.0; M_0 = 6 \times 10^{27}$ dynes cm). It is suggested that event II ($M_s = 8.25; M_0 = 5 \times 10^{28}$ dynes cm) has a similar behavior.

5. Conclusion

A study of event I yields: $M_s = 7.9 \pm 0.2; M_0 = (3-8) \times 10^{28}$ dynes cm, and clearly agrees with the previous study of the Gobi-Altai earthquake, suggesting a major tectonic rupture process between China and Eurasia, as proposed by Molnar and Tapponnier [4].

The magnitude value obtained for event I ($M_s = 7.9$) suggests that magnitude estimates in Gutenberg and Richter's "Seismicity of the Earth" may be 0.3–0.4 units larger than present-day M_s values, for that magnitude range. Estimates of M by Richter could be 0.5 units larger than M_s.

Results for event II are much less accurate, but do not disagree with the main conclusions of this paper.

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