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8. *Seismometrical Re-Evaluation of the Great Kanto Earthquake of September 1, 1923.*

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Abstract

Old seismological data were used to re-evaluate the Great Kanto Earthquake of September 1, 1923. On the basis of reported P times at about one hundred stations the hypocenter parameters were determined as: origin time, $2^h58^m32^s$; latitude 35.4°N; longitude, 139.2°E; depth, 0 to 10 km. The above epicenter may be uncertain by ±15 km. The surface-wave magnitude was re-evaluated using seismograms from 17 stations. The average value of 8.16 was obtained.

1. Introduction

The Great Kanto (or Kwanto) Earthquake of September 1, 1923, is one of the most disastrous earthquakes in history. Although various aspects of this earthquake have been documented extensively in many publications [*e.g. Imperial Earthquake Investigation Committee*, 1925; *Imamura*, 1924; *Davison*, 1931] (see also *Usami and Tsuno* [1969] for other references), the location of hypocenter and the magnitude are still somewhat uncertain. *Imamura* [1924] placed the epicenter nearly in the middle of Sagami Bay (139.37°E, 34.98°N), while *Hirano* [1924] located it in the neighborhood of Lake Kawaguchi, about 60 km northwest of Imamura's epicenter. Other determinations [*e.g. Gutenberg and Richter*, 1954; *Matuzawa*, 1928; *Kunitomi*, 1930; *Turner*, 1927] placed the epicenter somewhere in between these two epicenters.

The magnitude (20 sec surface-wave magnitude or its equivalent) of this earthquake has been a matter of controversy. *Gutenberg and Richter* [1954] gave a value 8.3, while *Kawasumi* [1951], using macro-seismic data, estimated it at 7.9; the difference, 0.4, corresponds to an energy difference of a factor of 4. In view of its historic and tectonic importance, we re-evaluated this earthquake by using all the available seismological data and updated analysis techniques.

2. Hypocenter

The basic data used for the present relocation of the hypocenter

Table 1*a*. Station, latitude, longitude, reported *P* time, distance (in degree), azimuth at source (AZ.–1), azimuth at station (AZ.–2), and O-C residual. The hypocenter determined for case III is given. Stations with asterisk were not used for relocation.

GREAT KANTO EQRTHQUAKE, SEPT. 1, 1923 2H58M32.1S
35.38N +- 8KM, 139.18E +- 6KM, H=0.0KM RMS OF (O-C) = 3.7SEC

STATION	LAT. (DEG)	LONG. (DEG)	P-TIME H	M	S	DELTA (DEG)	AZ.-1 (DEG)	AZ.-2 (DEG)	O-C (SEC)
NUMAZU	35.10N	138.85E	2	58	39.0	0.39	224.1	43.9	-0.87
YOKOSUKA	35.32N	139.65E	2	58	40.0	0.39	99.2	279.5	0.11
MAEBASHI	36.40N	139.07E	2	58	42.2	1.02	354.9	174.8	-10.17*
TOKYO	35.68N	139.75E	2	58	44.0	0.56	56.8	237.2	0.77
KOHU	35.63N	138.57E	2	58	43.0	0.56	297.0	116.6	-0.31
KUMAGAI	36.15N	139.38E	2	58	51.0	0.79	12.1	192.2	3.18
TUKUBA	36.22N	140.10E	2	58	53.0	1.12	41.6	222.1	-1.05
MITO	36.38N	140.47E	2	58	56.0	1.45	45.9	226.6	-3.48
KANAZAWA	36.53N	136.65E	2	58	56.0	2.35	300.0	118.5	-16.58*
NAGANO	36.67N	138.20E	2	58	56.0	1.51	328.5	148.0	-4.39
TYOSI	35.73N	140.87E	2	58	57.0	1.42	75.1	256.1	-2.09
NAGOYA	35.17N	136.97E	2	59	2.0	1.82	263.9	82.7	-2.94
GIHU	35.40N	136.77E	2	59	2.0	1.97	271.3	89.9	-5.09
TAKAYAMA	36.15N	137.25E	2	59	3.0	1.75	296.6	115.5	-0.84
MATUMOTO	36.23N	137.97E	2	59	4.0	1.30	311.2	130.4	6.85
HUSIKI	36.78N	137.05E	2	59	10.0	2.22	309.7	128.4	-0.70
TOKUSIMA	34.07N	134.58E	2	59	10.0	4.01	252.2	69.6	-26.09*
TAKADA	37.10N	138.25E	2	59	10.0	1.87	336.6	156.1	4.33
TU	34.73N	136.52E	2	59	11.0	2.28	254.3	72.8	-0.51
HIKONE	35.27N	136.25E	2	59	14.0	2.40	268.1	86.5	0.76
NIIGATA	37.93N	139.05E	2	59	14.0	2.55	357.7	177.6	-1.41
YAGI	34.52N	135.80E	2	59	21.0	2.91	253.7	71.8	0.52
SENDAI	38.27N	140.90E	2	59	21.0	3.19	25.1	206.1	-3.56
KUMAMOTO	32.82N	130.70E	2	59	23.0	7.48	252.4	67.7	-62.19*
OSAKA	34.65N	135.53E	2	59	24.0	3.08	257.4	75.3	1.06
KOBE	34.68N	135.18E	2	59	26.0	3.35	259.2	76.9	-0.81
ISINOMAKI	38.43N	141.32E	2	59	30.0	3.50	28.7	210.0	1.17
KYOTO	35.02N	135.73E	2	59	33.0	2.85	263.7	81.7	13.39*
TOYOOKA	35.53N	134.82E	2	59	33.6	3.57	273.7	91.2	3.77
YAMAGATA	38.25N	140.35E	2	59	39.0	3.01	17.8	198.5	17.00*
MIZUSAWA	39.13N	141.13E	2	59	40.0	4.06	22.0	203.2	3.19
MIYADU	35.53N	135.20E	2	59	41.0	3.25	273.8	91.5	15.61*
TADOTU	34.28N	133.77E	2	59	42.0	4.59	257.7	74.7	-2.31
NEMURO	43.33N	145.58E	2	59	49.0	9.36	30.0	214.1	-62.24*
HIROSIMA	34.37N	132.43E	2	59	52.1	5.64	261.6	77.8	-7.14
OKAYAMA	34.67N	133.93E	2	59	55.0	4.36	262.1	79.1	13.83*
MATUYAMA	33.83N	132.75E	2	59	58.0	5.52	255.6	72.0	0.38
WAKAYAMA	34.23N	135.17E	3	0	2.0	3.49	252.0	69.8	33.17*
HAMADA	34.90N	132.07E	3	0	6.0	5.85	267.3	83.3	3.82
AKITA	39.72N	140.10E	3	0	10.0	4.39	9.3	189.9	28.47*
NAZE	28.38N	129.50E	3	0	11.0	10.78	232.4	47.3	-59.84*
HAKODATE	41.78N	140.72E	3	0	13.0	6.51	10.2	191.2	1.54
TITIZIMA	27.08N	142.18E	3	0	20.0	8.66	161.9	343.5	-21.63*
SIMONOSEKI	33.95N	130.93E	3	0	22.0	6.94	260.5	75.8	4.38
HUKUOKA	33.58N	130.42E	3	0	22.0	7.46	258.6	73.6	-2.78
OITA	33.23N	131.62E	3	0	24.0	6.62	253.3	69.0	10.99*
KURE	34.23N	132.57E	3	0	27.0	5.56	260.0	76.3	28.86*
SAGA	33.25N	130.30E	3	0	29.9	7.65	256.4	71.4	2.42
NAGASAKI	32.73N	129.87E	3	0	30.0	8.17	253.8	68.6	-4.74
KUSIRO	42.98N	144.40E	3	0	33.0	8.60	26.5	209.8	-7.81
KAGOSIMA	31.57N	130.55E	3	0	36.0	8.15	244.6	59.9	1.49
ITUHARA	34.20N	129.28E	3	0	41.3	8.23	264.6	79.0	5.72
HATIDYOZIMA	33.10N	139.83E	3	0	44.0	2.34	166.4	346.8	91.64*
OBIHIRO	42.92N	143.20E	3	1	0.0	8.15	21.3	203.8	25.57*
NAHA	26.20N	127.65E	3	1	19.0	13.48	230.4	44.5	-28.16*
ODOMARI	46.65N	142.77E	3	1	20.0	11.58	12.4	194.8	-1.61
MIYAZAKI	31.92N	131.43E	3	1	21.8	7.32	244.1	59.8	58.85*
ISIGAKIZIMA	24.33N	124.17E	3	1	40.0	17.03	233.8	46.3	-53.26*
DAIREN	38.90N	121.60E	3	1	49.0	14.46	289.2	98.6	-10.96*
SHANGHAI	31.19N	121.43E	3	2	15.0	15.42	259.3	69.6	2.41
KOSYUN	22.00N	120.75E	3	2	24.3	20.91	235.3	46.4	-54.37*

(to be continued)

(continued)

TAIHOKU	25.03N	121.52E	3	2	52.0	18.40	240.7	51.8	1.74
TAITO	22.75N	121.15E	3	3	13.0	20.13	236.1	47.3	2.46
TAITYU	24.15N	120.68E	3	3	13.8	19.54	240.1	50.8	9.90
HOKOTO	23.53N	119.55E	3	3	31.0	20.73	240.6	50.9	14.20*
TAINAN	23.00N	120.22E	3	3	39.0	20.60	238.3	49.0	23.52*
HONGKONG	22.30N	114.17E	3	4	0.0	25.40	245.9	53.6	-2.81
MANILA	14.58N	120.98E	3	4	11.0	26.39	222.9	35.1	-1.10
DEHRA DUN	30.32N	78.05E	3	6	25.0	50.90	282.6	67.2	-72.17*
CALCUTTA	22.53N	88.33E	3	6	49.0	45.84	268.0	62.0	-8.84
SIMLA	31.10N	77.18E	3	7	36.0	51.29	283.9	67.6	-4.41
BATAVIA	6.18S	106.84E	3	7	37.0	51.33	222.9	34.1	-3.55
MALABAR	7.22S	107.62E	3	7	41.0	51.76	221.4	33.0	-2.80
EKATERINBURG	56.83N	60.64E	3	8	5.0	55.20	319.0	77.2	-3.62
HONOLULU	21.32N	158.06W	3	8	17.0	56.14	86.6	299.0	1.04
SITKA	57.05N	135.33W	3	8	25.0	58.82	39.6	287.8	-9.21
BOMBAY	18.89N	72.82E	3	8	44.0	60.29	272.9	59.5	-1.00
COLOMBO	6.90N	79.87E	3	8	48.0	61.12	257.2	53.4	-2.80
ABISKO	68.34N	18.82E	3	9	28.0	67.55	339.7	49.7	-3.80
KODAIKANAL	10.23N	77.47E	3	9	30.0	61.13	261.8	55.3	38.76*
PULKOVO	59.77N	30.32E	3	9	36.0	68.69	329.1	56.1	-2.97
VICTORIA	48.41N	123.32W	3	9	40.0	68.98	45.1	299.8	-1.01
APIA	13.81S	171.77W	3	9	44.0	67.44	127.4	318.1	12.01*
BUDAPEST	47.49N	19.07E	3	9	46.0	81.64	323.6	45.6	-67.14*
RIVERVIEW	33.83S	151.16E	3	9	47.0	69.75	169.4	349.6	1.00
SYDNEY	33.83S	151.16E	3	9	48.0	69.75	169.4	349.6	2.00
MELBOURNE	37.83S	144.97E	3	9	54.0	73.03	175.2	355.1	-11.63*
TIFLIS	41.72N	44.80E	3	9	54.0	70.41	307.6	59.9	4.07
PERTH	31.95S	115.84E	3	9	55.0	70.46	200.9	20.1	4.58
ADELAIDE	34.93S	138.58E	3	10	0.0	69.94	180.5	0.5	12.71*
UPPSALA	59.86N	17.63E	3	10	1.0	73.64	333.4	46.5	-7.64
BERKELEY	37.87N	122.26W	3	10	15.0	75.17	54.1	303.3	-3.01
LICK	37.34N	121.64W	3	10	17.0	75.87	54.2	303.7	-5.25
SASKATOON	52.13N	106.63W	3	10	25.0	75.68	35.5	309.7	4.34
LEMBERG	49.83N	24.02E	3	10	33.0	77.64	323.1	49.2	1.39
BERGEN	60.40N	5.30E	3	10	37.0	77.35	338.5	37.1	7.27
HAMBURG	53.54N	9.98E	3	10	47.0	81.13	332.1	39.9	-3.34
BEIRUT	33.90N	35.47E	3	10	49.0	80.86	305.1	53.5	-0.42
VIENNA	48.25N	16.36E	3	10	54.0	82.38	325.5	43.9	-3.00
CHRISTCHURCH	43.53S	172.62E	3	10	54.0	84.23	156.2	333.1	-12.56*
BELGRADE	44.82N	20.45E	3	11	0.0	82.80	321.0	46.2	0.74
KEW	51.47N	0.31W	3	11	0.0	86.51	336.0	32.1	-17.69*
DYCE	57.22N	2.17W	3	11	1.0	82.17	339.9	31.0	5.36
DE BILT	52.10N	5.18E	3	11	2.0	84.07	333.5	36.2	-3.52
ZAGREB	45.82N	15.98E	3	11	4.0	84.32	324.0	43.4	-2.98
SARAJEVO	43.87N	18.43E	3	11	5.0	84.51	321.4	44.9	-3.06
WELLINGTON	41.28S	174.77E	3	11	6.0	82.98	153.8	331.4	5.70
EDINBURGH	55.92N	3.18W	3	11	8.0	83.57	339.8	30.1	5.09
UCCLE	50.80N	4.36E	3	11	9.0	85.42	333.2	35.6	-3.36
STRASBOURG	48.58N	7.77E	3	11	12.0	85.88	330.0	37.9	-2.68
HELWAN	29.86N	31.34E	3	11	13.0	86.10	304.0	51.2	-3.25
MOSTAR	43.35N	17.81E	3	11	14.0	85.19	321.3	44.4	2.64
INNSBRUCK	47.27N	11.40E	3	11	14.0	85.35	327.3	40.4	1.80
ZURICH	47.37N	8.58E	3	11	14.0	86.49	328.9	38.4	-3.85
STONYHURST	53.84N	2.47W	3	11	18.0	85.16	338.3	30.6	7.04
BIDSTON	53.40N	3.07W	3	11	18.0	85.72	338.4	30.1	4.22
W. BROMWICH	52.52N	1.98W	3	11	18.0	86.15	337.4	30.9	2.05
TUCSON	32.25N	110.83W	3	11	22.0	86.03	53.0	309.7	6.05
OXFORD	51.76N	1.25W	3	11	22.0	86.57	336.6	31.4	4.01
VENICE	45.43N	12.32E	3	11	23.0	86.33	325.6	40.9	6.01
PARIS	48.81N	2.49E	3	11	23.0	87.75	333.0	34.1	-0.77
ROCCA DI PAPA	41.76N	12.72E	3	11	28.0	88.91	323.0	41.1	-1.68
BESANCON	47.25N	5.99E	3	11	29.0	87.66	330.2	36.6	5.54
FLORENCE	43.78N	11.26E	3	11	31.0	88.08	325.1	40.2	5.50
TRAVNIK	43.22N	17.68E	3	11	33.0	85.35	321.3	44.4	20.83*
SINJ	43.74N	16.64E	3	11	47.0	85.50	322.2	43.7	34.09*
POMPEI	40.75N	14.50E	3	11	48.0	88.77	321.3	42.2	19.11*

Table 1*b*. Distance and Azimuth of stations located at distances larger than 90° (not used for relocation).

GREAT KANTO EARTHQUAKE, SEPT. 1, 1923 2H58M32.1S
35.38N +- 8KM, 139.18E +- 6KM, H=0.0KM RMS OF (O-C) = 3.7SEC

STATION	LAT. (DEG)	LONG. (DEG)	P-TIME H	M	S	DELTA (DEG)	AZ.-1 (DEG)	AZ.-2 (DEG)
PUY DE DOME	45.77N	2.97E	3	11	30.0	90.08	331.0	34.4
MARSEILLES	43.31N	5.39E	3	11	35.0	91.09	328.2	36.2
CHICAGO	41.78N	87.62W	3	11	42.0	92.06	33.1	323.4
ANN ARBOR	42.28N	83.58W	3	11	48.0	93.39	30.3	326.2
OTTAWA	45.39N	75.72W	3	11	49.0	93.64	23.8	332.1
TORONTO	43.77N	79.40W	3	11	48.0	93.76	26.9	329.3
BARCELONA	41.42N	2.13E	3	12	11.0	94.02	329.1	33.9
TORTOSA	40.82N	0.49E	3	12	4.0	95.20	329.8	32.8
NORTHFIELD	44.17N	72.68W	3	12	3.0	95.70	22.4	334.3
ITHACA	42.45N	76.49W	3	11	59.0	95.96	25.7	331.4
ALGIERS	36.80N	3.03E	3	12	8.0	97.43	325.9	34.8
HALIFAX	44.63N	63.60W	3	12	0.0	97.73	16.2	341.4
TOLEDO	39.88N	4.05W	3	12	5.0	97.80	332.3	29.6
GEORGETOWN	38.91N	77.07W	3	11	33.0	98.84	27.8	330.7
WASHINGTON	38.91N	77.07W	3	11	33.0	98.84	27.8	330.7
CHELTENHAM	38.73N	76.84W	3	12	43.0	99.08	27.8	330.9
COIMBRA	40.21N	8.42W	3	12	12.0	99.09	335.4	26.3
GRANADA	37.18N	3.60W	3	12	33.0	99.96	330.6	30.1
RIO TINTO	37.77N	6.63W	3	10	0.0	100.62	333.1	27.9
LISBON	38.72N	9.15W	3	12	32.0	100.67	335.3	25.9
SAN FERNANDO	36.46N	6.20W	3	12	28.0	101.61	332.1	28.3
AZORES	37.73N	25.68W	0	0	0.0	105.92	347.6	12.8
JOHANNESBURG	26.18S	28.07E	3	17	30.0	121.08	258.4	63.0
PORTO RICO	18.15N	65.45W	3	19	20.0	121.79	27.8	336.4
BALBOA HEIGHTS	8.96N	79.56W	3	20	0.0	122.63	47.3	322.6
ACCRA	5.53N	0.20W	3	20	0.0	124.09	308.4	40.0
CAPE TOWN	33.95S	18.45E	3	21	25.0	131.52	253.7	70.6
LA PAZ	16.50S	68.13W	3	18	27.0	146.93	59.4	312.9
LA QUIACA	22.13S	65.72W	0	0	0.0	150.91	65.4	306.7
ANDALGALA	27.59S	66.32W	0	0	0.0	152.51	77.4	296.0
MENDOZA	32.88S	68.82W	3	23	48.0	152.36	91.9	283.9
CIPOLLETTI	38.93S	68.13W	3	20	36.0	153.16	107.4	269.3
PILAR	31.67S	63.88W	0	0	0.0	160.43	85.7	287.1
LA PLATA	34.91S	57.93W	3	20	4.0	165.98	93.0	276.8
RIO DE JANEIRO	22.91S	43.17W	3	18	52.0	167.40	10.0	351.2

are included in Table 1*a*. The sources of these data are *Turner* [1927] (most of the stations farther than Hong Kong), *Kunitomi* [1930] (most of the Japanese data), and *Imperial Earthquake Investigation Committee* [1925] (used for supplementary purpose). The station co-ordinates are taken from *Wood* [1921], *International Seismological Summary* [1951], *Central Meteorological Observatory* [1934], and *Charlier and Van Gils* [1953]. The relocation was made by using reported *P* times (see Table 1*a*) at stations whose epicentral distances are less than 90°.

A standard hypocenter location program (similar to the one used by U.S. Coast and Geodetic Survey) was written and used with the J-B travel-time table [*Jeffreys and Bullen*, 1958]. The timing accuracy in the 1920's was obviously rather poor but it is extremely difficult to estimate the error at each station. Further, the detection of the first arrival at distant stations may have been very difficult with the classic low-magnification seismographs. In view of these considerations we made the relocation for five cases: (I) All the stations with Δ (distance) $\leq 90°$ are used. (II) All the stations with $\Delta \leq 90°$ except those whose O–C residual (observed minus computed P time) exceeds 30 sec are used. (III) Stations with $\Delta \leq 90°$ are used but the O–C threshold is set at 10 sec. (IV) Stations with $\Delta \leq 10°$, and the O–C threshold at 30 sec. (V) Stations with $\Delta \leq 10°$, and the O–C threshold at 10 sec. In effect, we had five different sets of data. The number of stations included in each set is shown in Figure 1. Also shown is the number of stations located in NE, NW, SW, and SE quadrants around the epicenter. The hypocenter relocation was made for each of these five different sets of station data. Although the quality of the data may be questionable, it is hoped that the results obtained for these different sets of data, when compared

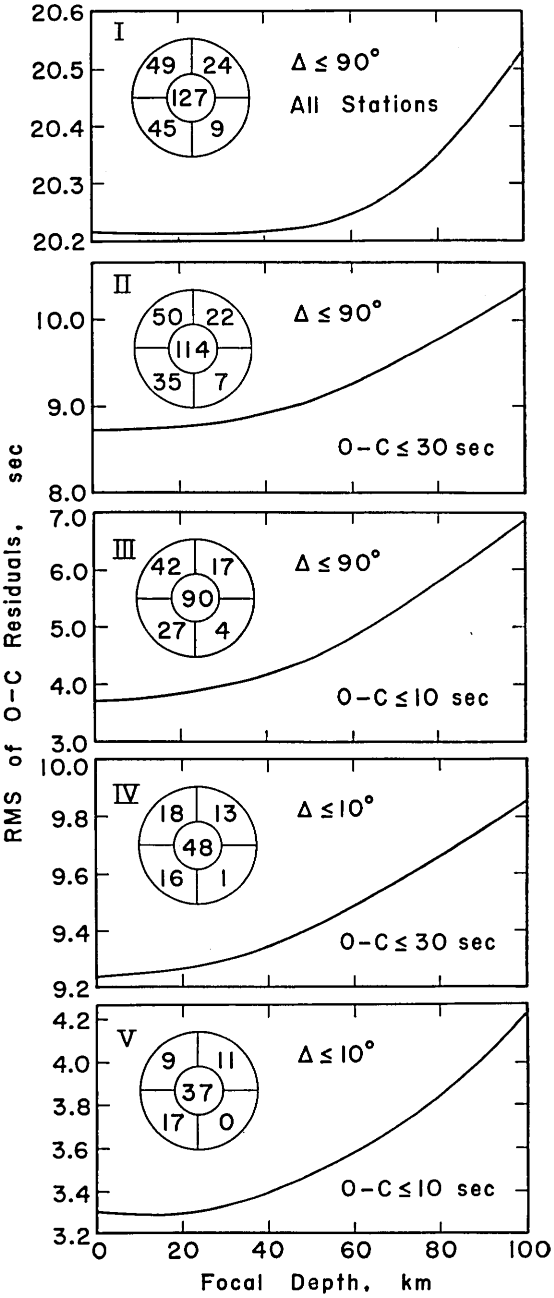

Fig. 1. Root-mean-square of O–C residuals as a function of focal depth. Results for five different cases are shown. Total number of stations together with the number of stations in NE, SE, SW, and NW quadrants is shown in the insert.

to each other, will give some measure of the reliability of the present relocation.

It is well-known that the ordinary hypocenter determination from P times alone cannot constrain the focal depth very well. This is particularly true when the reported P times are unreliable. Hence, we restrained the focal depth at 0, 20, 40, 60, 80 and 100 km and determined the epicenter co-ordinates and origin time for each depth, and calculated the root-mean-square (RMS) of the O–C residuals. The results are summarized in Figure 1 for the five cases. Evidently, in all cases, the RMS of O–C residuals increases as the focal depth increases. This common feature strongly favors, despite the relatively poor quality of the data, a shallow focal depth of this earthquake. The residuals at nearby stations provide a much stronger evidence for a shallow depth; at nearby stations an error in the focal depth shows up markedly in the O–C residuals as shown in Table 2 where the O–C residuals, for case III, at 6 nearby stations are listed for 4 focal depths. Note that the residuals systematically become very large as the focal depth increases. These observations lead to a conclusion that the focus of this earthquake is very shallow, probably not deeper than 10 km. We will therefore restrain the focal depth at 0 km in the following analysis. The epicenters determined for the five cases are shown in Figure 2 with standard errors. The epicenter determined for case I seems unacceptable because several stations which obviously misread the minute mark (see stations in Table 1*a* whose O–C is about ± 60 sec) are included. The results for cases IV and V may also be in error because of the lack of stations in the SE quadrant. It is known that an uneven azimuthal distribution of stations often results in a systematic error in the epicenter location. Cases II and III have a reasonably good azimuthal coverage of stations; the epicenters determined for these two cases are probably most reliable in the light of the available seismological data. Thus we conclude that the

Table 2. O–C residuals at nearby stations for 4 focal depths. The computation was made for case III.

Station	Δ deg.	O–C Res., sec			
		H=0 km	20	40	100
NUMAZU	0.39	−0.79	−4.38	−7.58	−18.05
YOKOSUKA	0.39	0.13	−3.49	−6.98	−18.17
TOKYO	0.56	0.74	−2.27	−4.82	−14.63
KOHU	0.56	−0.30	−3.10	−5.20	−13.29
KUMAGAI	0.79	3.15	0.81	−0.51	− 7.96
TUKUBA	1.12	−1.08	−1.61	−3.49	−10.72

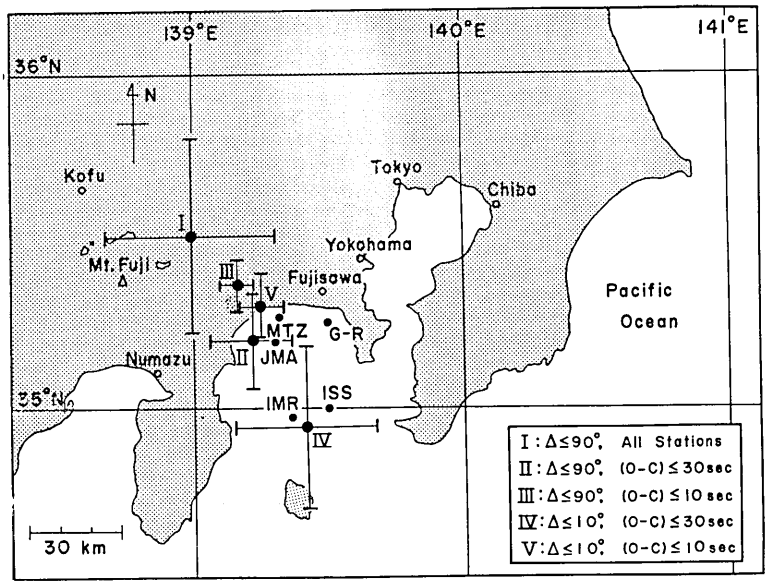

Fig. 2. Epicenters determined for five different cases. Epicenters determined by other investigators are included. MTZ (35.27°N, 139.33°E): *Matuzawa* [1928], G-R (35.25°N, 139.50°E): *Gutenberg and Richter* [1954], IMR (34.98°N, 139.37°E): *Imamura* [1924], ISS (35.0°N, 139.5°E): *Turner* [1927], and JMA (35.2°N, 139.3°E, see *e.g.* *Usami* [1966]).

initial break of this earthquake occurred nearly on the coast at a very shallow depth (less than 10 km). This epicenter is very close to that of *Matuzawa* [1928]. The uncertainty of the present determination of epicenter is probably about ±15 km. Tables 1a and 1b show the station data for the hypocenter for case III. The origin time estimated here is $2^h58^m32.1^s$. Since, at Tokyo, the time of commencement of P wave and S–P time are $2^h58^m44^s$ and 9.8 sec [*Matuzawa*, 1928] respectively, the origin time determined above is quite reasonable.

3. Magnitude

The determination of magnitude was made on the basis of the amplitude of surface waves. To do this we collected seismograms from the stations operated at the time of this earthquake. We requested 86 stations for the seismogram, and obtained response from 48 stations out of which 25 provided us with seismograms. Among these we used seismograms at the 17 stations listed in Table 3 for the magnitude determination. Two seismograms are reproduced in Figure 3. We used the standard formula as proposed by *Vaněk et al.* [1962]:

$$M = \log (A/T) + 1.66 \log \Delta + 3.3 ,$$

Table 3. Stations used for magnitude determination. *R*: Rayleigh Wave, *L*: Love Wave, *At*: Trace Amplitude, *A*: Amplitude of Ground Displacement, *T*: Period, *M*: Magnitude

Station	Δ (deg)	Azimuth (deg)	Back Azimuth (deg)	Component	R or L	At (mm)	A (μ)	T (sec)	M	Instrument
Riverview	69.8	170	350	NS	R	18	730	21	7.90	Wiechert
Uppsala	73.9	334	46	NS	R	61	1210	18	8.23	Wiechert
				EW	R	52	1680	20	8.33	Wiechert
Berkeley	74.9	54	303	NS	L	21	650	16	8.03	Bosch-Omori
Lick	75.7	54	303	NS	L	18	870	17	8.13	Wiechert
Wien	82.6	326	44	NS	R	55	1360	20	8.32	Wiechert
				EW	R	58	1960	20	8.48	Wiechert
Edinburgh	83.7	340	30	EW	R	30	530	17	7.98	Milne-Shaw
Zagreb	84.3	324	43	NW-SE	L	85	1200	17	8.35	Wiechert
				NE-SW	R	90	1800	20	8.45	Wiechert
Strasbourg	86.1	330	38	NS	R	69	700	13	8.25	Wiechert
Helwan	86.4	304	51	EW	R	30	490	21	7.89	Milne-Shaw
Oxford	87.0	337	31	EW	R	40	1330	25	8.25	Milne-Shaw
Ottawa	93.6	23	332	EW	R	33	810	20	8.18	Milne-Shaw
Barcelona	94.1	329	34	EW	R	13	730	15	8.27	Mainka
Georgetown	98.7	28	330	NS	R	2	210	18	7.69	Wiechert
Lisbon	100.8	335	26	NS	R	48	740	19	8.21	Wiechert
La Paz	149.2	60	312	NS	R	16	190	20	7.88	Mainka
								(Average)	8.16	

where M is magnitude, A is the maximum horizontal ground displacement in microns, T is period in second and Δ is the distance in degree. We measured the trace amplitude and the period of the largest wave group of either Love or Rayleigh waves on horizontal seismograms and estimated the ground displacement, A, by correcting for the instrument magnification and the polarization (the particle motion is assumed to be radial for Rayleigh waves, and transverse for Love waves). Although the wave group which gives maximum trace amplitude does not necessarily represent the maximum ground displacement, we believe that the above procedure gives a sufficiently accurate estimate of A. The distinction between Love and Rayleigh waves was made on the basis of the polarization and group arrival time. The group velocity curves for continental and oceanic paths compiled by *Oliver* [1962] were used to estimate the expected arrival time of Love or Rayleigh waves along mixed paths. The results are summarized in Table 3. The magnitude values scatter considerably around 8.2; this scatter reflects the azimuthal dependence of radiation pattern, error in the instrument calibration, error in the standard formula etc. Since a large number of stations are used here, the average value, 8.16, is probably very stable; inclusion of more stations would not change the average magnitude significantly. The standard formula used here has been calibrated in such a way that the resulting magnitude values agree, on the average, with those previously determined using slightly different formulas such as those introduced by *Gutenberg* [1945]. Hence, the magnitude determined here may be directly compared with those as given by *Gutenberg and Richter* [1954], and *Duda* [1965].

4. Conclusion

Old seismological data have proved to be very useful for a meaningful re-evaluation of the Great Kanto Earthquake. On the basis of a large amount of data the hypocenter parameters were determined as follows:

origin time, $2^h58^m32^s$; latitude, 35.4°N;
longitude, 139.2°E; depth, 0 to 10 km.

The above epicenter may be uncertain by ± 15 km. The surface-wave magnitude was re-evaluated using seismograms from 17 stations. The average value of 8.16 was obtained. No significant difference was found between the magnitudes determined from Love and Rayleigh waves. Tectonic and geophysical significance of this earthquake will be discussed in a separate paper.

Acknowledgment

We are much indebted to those seismological observatories who kindly responded to our inquiries and sent us the seismograms. All the seismograms collected for this study are copied and filed at the Earthquake Research Institute, the University of Tokyo.

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8. 関東大地震の震源とマグニチュード

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1923 年 9 月 1 日の関東大地震の震源とマグニチュードを再決定した．震源決定に用いた資料は International Seismological Summary や日本の文献に発表されている *P* 波の発震時で約 100 の観測点の値を用いた．再決定された震源要素は次の通りである．震源時: 02 時 58 分 32 秒，震央緯度: 35.4°N，震央経度: 139.2°E，深さ: 0～10 km．この震央の誤差は ±15 km 位である．マグニチュードの決定は，17 ケ所の観測所で記録された周期 20 秒程度の表面波の振幅を用いて行なつた．平均値として 8.16 が得られた．

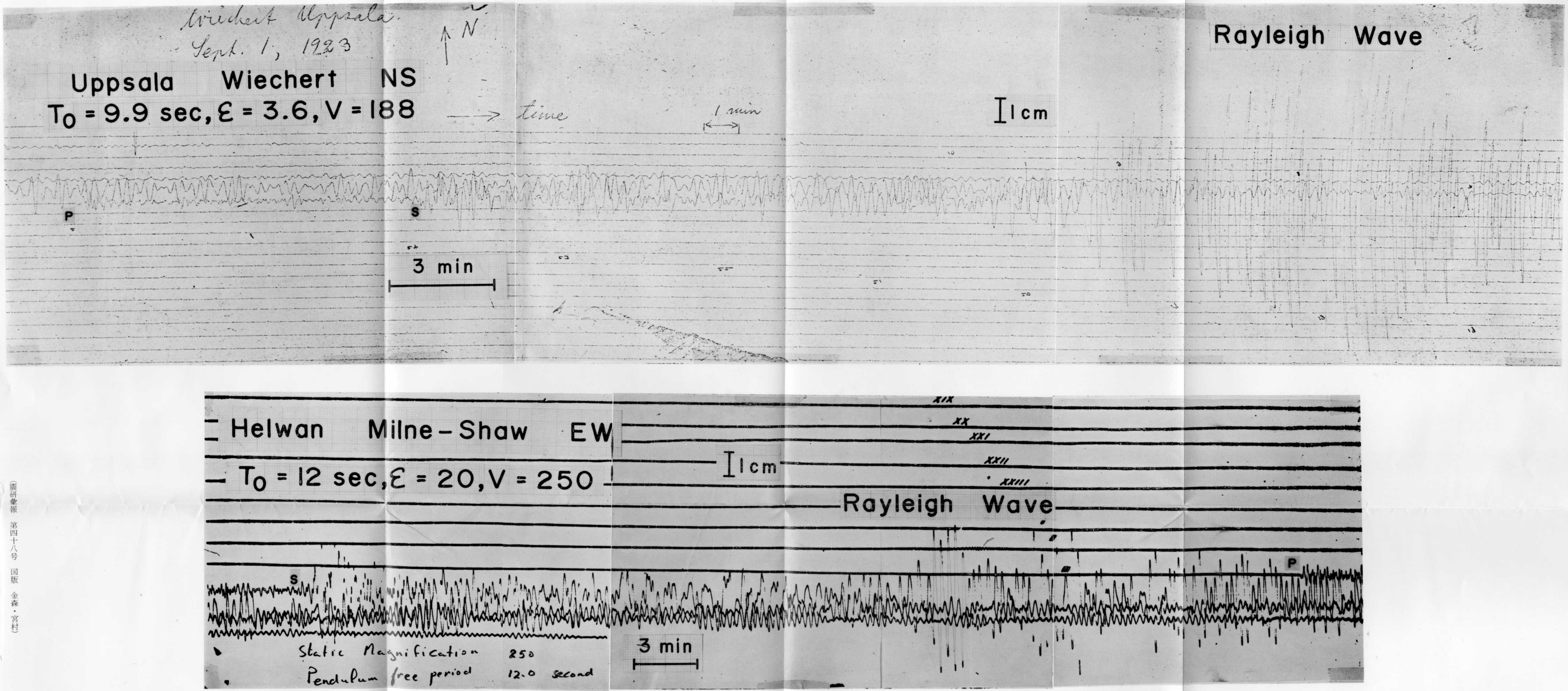

Fig. 3. Seismogram at Uppsala ($\Delta=73.9°$) and Helwan ($\Delta=86.4°$). For instrument constants, see *Elementary Seismology* by C.F. Richter (W.H. Freeman and Company, San Francisco, 1958) page 219.

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