Note on the Propagation Velocity of the Formosa Earthquakes of 1906 and 1908.

By

F. OMORI, Sc. D.,

Member of the Imperial Earthquake Investigation Committee.

With Plates XIII, XIV, and XV.

CONTENTS.

1. ***Introduction.*** The present paper is a note on the rate of propagation within the epicentral distance of about 3,000 km of the 1st. preliminary tremor of the four strong Formosa earthquakes in 1906 and 1908. The velocity calculation has been made according to the "direct" as well as to the "difference" method*; the seismic waves being supposed to be propagated along or parallel to the great circles of the earth. For the sake of comparison are also considered the Calabrian earthquake of Sept. 8, 1905, the Geiyo (Aki-Iyo) earthquake of 1905, and the Omi (Central Japan) earthquake of 1909.

* See the "Bulletin," Vol. I, No. 1.

The times of occurrence of the different Formosa and Japan earthquakes are given in the 1st Normal Japan Time, or the mean civil time of longitude 135° east of Greenwich. Following notations are used :—

v_1 = Velocity of propagation corresponding to the commencement of the earthquake motion.
T_0 = Time of earthquake occurrence at the origin (epicentre).
t_1 = „ „ „ „ at a given observing place.
x = Epicentral (arcual) distance.

The geographical positions of the different stations, whose observations have been utilized in the deduction of the propagation velocity of the Formosa and Japan earthquakes, are as follows :—

Station.	Latitude, N.	Longitude, E.
Mizusawa.	39° 08′ —″	141° 07′ —″
Tokyo (Seismological Institute)	35 42 29	139 45 53
Osaka.	34 42 —	135 31 —
Kobe.	34 41 —	135 11 —
Taichu.	24 09 —	120 42 —
Manila.	14 34 41	120 58 33

2. *Formosa earthquakes of April* 14, 1906. (See Figs. 1 and 2, Pl. XIII.) The present author has experienced the severe Kagi (Formosa) earthquake of April 14, 1906, in the city of Taichu at an epicentral distance of about 90 km, and determined with a fair accuracy the time of occurrence in the above-named place to be $8^h\ 52^m\ 22^s$ am. In the early morning of the same day, there was another shock nearly equal in extension, whose

time of occurrence observed at the meteorological observatory of Taichu was, with proper corrections, $4^h\ 18^m\ 20^s$ am. These two earthquakes, which may be regarded as belonging to the series of seismic manifestations following the great destructive shock of March 17th in the same year, originated about 10 miles to the south of the centre of the latter, probably in the vicinity of the town of Tenshiko, at about $\varphi = 23°\ 25'$ N, $\lambda = 120°\ 30'$ E.

The following table gives, for the different stations, the epicentral distance,* the time of occurrence and the velocity v_1 calculated by the "direct method."

FORMOSA EARTHQUAKES OF APRIL 14, 1906.

Origin..... $\varphi = 23°\ 25'$ N, $\lambda = 120°\ 30'$ E.

1st Earthquake..... $T_0 = 4^h\ 18^m\ 00^s$ am.

2nd „ ..... $T_0 = 8\ \ 52\ \ 00$ am.

Station.	Epicentral Distance.	Time of Occurrence. (1st Normal Japan Time).		v_1 (Direct method).	
		1st Eqke.	2nd Eqke.	1st Eqke.	2nd Eqke.
Taichu.	90 km.	$4^h18^m20^s$ am.	$8^h52^m22^s$ am.	— km/sec.	— km/sec.
Manila.	983	19 56	53 52	8.48	8.78
Kobe.	1889	21 50	56 08	8.28	7.60
Osaka.	1922	21 51	56 14		
Tokyo.	2300	22 20	56 46	8.84	8.04
Mizusawa.	2611	22 58	57 12	8.77	8.37
			Mean.....	**8.59**	**8.20**

* In the "Bulletin," Vol. I, No. 2, the epicentral distance of Tokyo has by an unfortunate mistake been taken to be 1710 km, instead of 2300 km. The result given there was accordingly entirely wrong.

The mean values of the velocity v_1 calculated according to the "direct method" are for the two earthquakes respectively 8.59 and 8.20 km per sec., with the average of 8.39 km per sec.; the limits of the epicentral distance being about 1000 km (Manila) and about 2600 km (Mizusawa).

3. *Kagi* (*Formosa*) *earthquake of march* 17, 1906. (See Fig. 3.) The origin of this destructive earthquake was a zone extending in a WSW and ENE direction having its centre in the vicinity of the town of Baishiko, at $\varphi = 23^\circ\ 35'$ N, $\lambda = 120^\circ\ 32'$ E.* The approximate time (T_0') of occurrence at the origin may be estimated from a comparison with the earthquakes of April 14 in the same year (§ 2). Thus, it will be observed that the epicentral distance of Manila in the cases of the earthquakes of April 14, was practically equal to that in the case of the earthquake of March 17. Now, assuming a transit velocity of the preliminary tremor to be 5 km per sec. for the epicentral distance of 90 km between Taichu and the earthquake origin, the times of occurrence of the two earthquakes at the origin itself were probably as follows :—

(1) $8^h\ 52^m\ 04^s$ am. (2) $4^h\ 18^m\ 02^s$ am.

The differences between these and the times of occurrence at Manila, the station nearest to the origin, are :—

(1) $1^m\ 48^s$
(2) 1 54 } ..... *mean*, $1^m\ 51^s$

Applying this result to the case of the earthquake of March 17 the approximate time of occurrence at the origin may be estimated from the Manila observation to be about $7^h\ 42^m\ 49^s$ am.

---

* An account of this earthquake is given in the "Bulletin," Vol. I, No. 2.

FORMOSA EARTHQUAKE OF MARCH 17, 1906.

Origin..... $\varphi=23°\ 35'$ N, $\lambda=120°\ 32'$ E.

Approximate $T_0=7^h\ 42^m\ 49^s$ am.

Station.	Epicentral Distance.	Time of Occurrence. (1st. N. J. T.)
Manila.	1000 km	$7^h\ 44^m\ 40^s$ am.
Kobe.	1877	46 25
Osaka.	1903	46 37
Tokyo.	2286	47 18

4. *Formosa earthquake of Jan.* 11, 1908. (See Fig. 4.) This earthquake shook strongly the south-eastern part of the island of Formosa, the origin being probably in the Taito longitudinal valley*. The time of occurrence at the epicentre, roughly estimated from that at Manila as in the preceding §, is found to be $0^h\ 35^m\ 10^s$ pm.

FORMOSA EARTHQUAKE OF JAN. 11, 1908.

Origin.....$\varphi=23°\ 37'$ N, $\lambda=121°\ 15'$ N.

$T_0=0^h\ 35^m\ 10^s$ pm.

Station.	Epicentral Distance.	Duration of Preliminary Tremor.	Time of Occurrence. (1st N. J. T.)
Manila.	1000 km	$4^m\ 18^s$	$0^h\ 37^m\ 01^s$ pm.
Osaka.	1844	4 49	38 37
Tokyo.	2235	3 56	39 11
Mizusawa.	2544	—	39 45

* See the "Bulletin", Vol. II, No. 2.

5. *Geiyo (Aki-Iyo) earthquake of June 2, 1905.* The Geiyo earthquake of June 2, 1905, which shook strongly the two provinces of Aki and Iyo, originated in the Inland Sea, the position of the seismic centre being, according to Dr. A. Imamura, at $\varphi=34°\ 8'$ N, $\lambda=132°\ 24'$ E. From the observations at the different meteorological observatories in and near the meizoseismal district, the time of occurrence at the epicentre may be estimated to be *about* $2^h\ 39^m\ 30^s$ pm. The values of the velocity v_1 calculated according to the "direct method" are given below.

GEIYO (AKI-IYO) EARTHQUAKE OF JUNE 2, 1905.

Origin.....$\varphi=34°\ 8'$ N, $\lambda=132°\ 24'$ E.

$T_0=2^h\ 39^m\ 30^s$ pm.

Station	Epicentral Distance.	Duration of Preliminary Tremor.	Time of Occurrence. (1st N. J. T.)	v_1 (Direct method.)
Kobe.	264 km	— sec.	$2^h\ 40^m\ 12^s$ pm.	6.29 km/sec.
Osaka.	292	25	40 21	5.73
Tokyo.	693	93	41 16	6.54
Mizusawa.	954	—	41 42	7.22
Manila.	2457	—	44 23	8.40

6. *Omi earthquake of Aug. 14, 1909.* The earthquake of Aug. 14, 1909, shook violently the north-eastern part of the province of Omi, causing the loss of 41 lives. The origin seems to have been situated among the mountains in the vicinity of the Torahime village, at about $\varphi=35°\ 30'$ N, $\lambda=136°\ 20'$ E. The time of occurrence at the epicentre was approximately about $3^h\ 30^m\ 40^s$ pm.

OMI EARTHQUAKE OF AUG. 14, 1909.

Origin.....$\varphi=35°\ 30'$ N, $\lambda=136°\ 20'$ E.

Approximate $T_0=3^h\ 30^m\ 40^s$ pm.

Station.	Epicentral Distance.	Time of Occurrence. (1st N. J. T.)
Tokyo.	311 km	$3^h\ 31^m\ 38^s$ pm.*
Mizusawa.	584	32 15
Manila.	2783	36 17

(* According to the observation with Omori hor. pend. tromometer at the Central Meteorological Observatory.)

7. *Calabrian earthquake of Sept.* 8, 1905. Prof. G. B. Rizzo gives in his work "Sulla velocità di propagazione delle onde sismiche del terremoto della Calabria del giorno 8 Settembre, 1905," a very valuable and elaborate discussion of the propagation velocity of the Calabrian earthquake of 1905. The following table embodies part of the results obtained by Prof. Rizzo, and relates to the different stations whose epicentral distance was below 2500 km.

CALABRIAN EARTHQUAKE OF SEPT. 8, 1905.

Probable $T_0=2^h\ 43^m\ 11^s$, Central Europe Time.

[*According to Prof. G. B. Rizzo.*]

Station.	Epicentral Distance.	v_1 (direct-method)	t_1
Messina.	84 km	— km/sec.	$1^h\ 43^m\ 17^s$
Catania.	174	6.0	43 30
Caggiano.	200	3.5	44 09

Station.	Epicentral Distance.	v_1 (direct method)	t_1
Ischia.	274 km	7.6km/sec.	1h 43m 47s
Rocca di papa.	434	9.0	44 00
Mean.	**354**	**8.3**	**43 54**
Urbino.	616	11.3	44 07
Siena.	640	10.7	44 05
Athens.	673	9.2	44 04
Carloforte.	677	9.4	44 04
Florence.	682	8.1	44 34
Quarto-Castello.	688	8.8	44 29
Pola.	698	6.8	44 52
Fiume.	727	6.7	45 00
Belgrade.	757	5.7	45 25
Triest.	783	7.7	44 56
Venice.	798	12.1	44 16
Laibach.	798	12.1	44 19
Padua.	811	8.0	44 55
Temesvar.	879	8.1	45 00
Salò.	883	8.2	45 00
Pavia.	920	8.1	45 01
Turin.	981	8.2	45 12
Mean.	**765**	**8.8**	**44 40**
O'-Gyalla.	1020	9.4	45 00
Kremsmuenster.	1037	6.9	45 43
Vienna.	1048	8.3	45 18
München.	1098	7.3	45 43
Hohenheim.	1232	8.2	45 42
Strassburg.	1274	12.5	44 56
Cracow.	1287	9.3	45 05
Heidelberg.	1297	8.6	45 40

Station.	Epicentral Distance.	v_1 (direct method)	t_1
Plauen.	1336 km	8.5km/sec.	1h 45m 08s
Tortosa.	1347	8.0	46 00
Jena.	1393	8.3	46 02
Leipzig.	1421	8.2	46 05
Goettingen.	1492	7.8	46 22
Mean.	**1253**	**8.6**	**45 36**
Potsdam.	1526	8.0	46 22
Uccle.	1618	7.9	46 38
Hamburg.	1703	7.7	46 55
Shide.	1896	8.5	46 47
Kew.	1900	8.3	47 00
S. Fernando.	1979	7.9	47 04
Batum.	1998	8.5	47 11
Mean.	**1803**	**8.1**	**46 51**
Coimbra.	2104	8.6	47 03
Liverpool.	2178	9.1	47 02
Dorpat.	2306	8.4	47 51
Achalkalaki.	2336	8.1	47 58
Upsala.	2341	8.5	47 50
Edinburgh.	2376	8.2	48 00
Paisley.	2426	8.8	47 08
Tiflis.	2447	8.1	48 23
Moscow.	2464	8.0	48 19
Mean.	**2331**	**8.4**	**47 44**

The mean values of the velocity v_1 (direct method) obtained by properly grouping the 48 stations given in the above table, whose epicentral distance varied from 273 km (Ischia) to 2464 km (Moscow), are as follows :—

Group.	Number of Stations grouped together.	Mean Epicentral Distance.	v_1 (direct method).
(i)	2	354 km.	8.3 km/sec.
(ii)	17	765	8.8
(iii)	13	1253	8.6
(iv)	7	1803	8.1
(v)	9	2331	8.4

The values of the velocity v_1 for the groups ii and iii are greater than those for the other groups. We are, however, not warranted to conclude from this that the velocity was really maximum at the epicentral distances corresponding to the groups ii and iii, as these latter include a number of those time observations which were probably not perfectly correct, and which gave exceptionally high values of the velocity varying from 10 to 12.5 km per sec.

8. ***Velocity v_1 calculated by the "difference method."*** The mean values of the velocity v_1 for the different earthquakes calculated according to the "difference method" by Least Squares are as follows :—

Earthquake.	Limits of epicentral distance (x).	Relation between epicentral distance x and the time interval $y(=t_1-T_0)$	v_1 (difference method).
2 Formosa Eqkes of April 14, 1906.	$90^{km}-2611^{km}$	$x^{km}-8.55\,y^{sec.}+62^{km}=0$	**8.55** km/sec.
Formosa Eqke of March 17, 1906.	1000–2286	$x-8.08\,y-103=0$	8.08
Formosa Eqke of Jan. 11, 1908.	1000–2544	$x-9.45\,y+64=0$	9.45
Geiyo Eqke of June 2, 1905.	264–2457	$x-8.87\,y+175=0$	8.87
Omi Eqke of Aug. 14, 1909.	311–2783	$x-8.92\,y+224=0$	8.92
Calabrian Eqke of Sept. 8, 1905.	273–2331	$x-8.43\,y-12=0$	**8.43**

The results for the two Formosa earthquakes of April 14, 1906, and the Calabrian earthquake of Sept. 8, 1905, are based on the observations more numerous, and may be regarded as being more accurate, than those for the remaining earthquakes. Calculating the average value we find :—

v_1 (difference method) = **8.66** km/sec.

for....90 km $< x <$ 2783 km.

9. ***Velocity v_1 calculated by the "direct method."*** The following table gives the values of the velocity v_1 calculated by the " direct method " for the different earthquakes, in each of which the time (T_0) of occurrence at the origin is more or less accurately known.

Epicentral Distance.	v_1 (direct method)			Mean.	
	2 Formosa Eqkes of April 14, 1906.	Geiyo Eqke.	Calabrian Eqke. of 1905.	Epicentral Distance.	v_1
278 km	— km/sec.	6.01 km/sec.	— km/sec.	**316** km	**7.16** km/sec.
354	—	—	8.3		
693	—	6.54	—	**729**	**7.67**
765	—	—	8.8		
954	—	7.22	—		
983	8.63	—	—	**1063**	**8.15**
1253	—	—	8.6		
1803	—	—	8.1		
1899	7.92	—	—	**1871**	**7.99**
1922	7.95	—	—		
2300	8.44	—	—		
2331	—	—	8.4	**2425**	**8.45**
2457	—	8.40	—		
2611	8.57	—	—		

The mean value of the velocity v_1 thus varies, for the epicentral distances of about 300 to 2500 km, from 7.16 to 8.45 km per sec., giving the general average of **7.88** km per sec. This latter value is 0.78 km less than the average velocity v_1 calculated by the "difference method" (§ 8).

10. *Comparison of the rate of propagation of the Formosa earthquakes with that of the Calabrian earthquake of* 1905. The time interval $(t_1 - T_0)$ taken by the seismic waves of the four Formosa earthquakes in travelling the different epicentral distances (x) are given in the following table.

Eqke. / Epicentral Distance.	April 14, 1906; 4.18 AM.	April 14, 1906; 8.52 AM.	March 17, 1906.	Jan. 11, 1908.	Mean. Epicentral Distance.	Mean. Time Interval.
983 km	1m 56s	1m 52s	m s	m s	983km	1m 52s
1844	—	—	—	3 27		
1877	—	—	3 36	—		
1889	3 50	4 08	—	—	1892	3 51
1903	—	—	3 48	—		
1922	3 51	4 14	—	—		
2235	—	—	—	4 01		
2286	—	—	4 29	—	2280	4 24
2300	4 20	4 46	—	—		
2544	—	—	—	4 35	2589	4 55
2611	4 58	5 12	—	—		

For the Calabrian earthquake of 1905, the relation between the

epicentral distance (x) and the time interval ($t_1 - T_0$) are as follows :—

Group of the stations (§ 7)	Epicentral distance $= x$.	Time interval $= t_1 - T_0$.
i	354 km	0^m 43^s
ii	765	1 29
iii	1253	2 25
iv	1803	3 40
v	2331	4 33

As is illustrated in Fig. 5 (Pl. XV), the relation between the epicentral distance x and the time interval ($t_1 - T_0$) is almost identical for the Formosa earthquakes and for the Calabrian earthquake, implying the approximate equality of the rate of propagation in the cases under consideration. It is hereby to be noticed that with respect to the Calabrian earthquake, all of the stations, whose observations have been utilized in the calculation of the velocity (§ 7), are in Europe; the earthquake motion reaching, therefore, the different places by essentially continental paths. Again, the seismic waves originating in Formosa are propagated to the Main Island (Japan) and to Manila by paths, which lie under the shallow seas in the immediate vicinity of the south-eastern coast of Asia, and which my be regarded also as being of a continental nature. The approximate identity for the Formosan and Calabrian earthquakes of the relation between the epicentral distance x and the time interval ($t_1 - T_0$) is probably due to the similarity of the nature of the paths of

seismic propagation. As will be seen from Fig. 5, the distance and time relation for the Geiyo earthquake is, for the value of x from 1500 to 2500 km, close enough to that in the cases above considered.

Formosa Earthquakes. Relation between the Time of Occurrence and the Epicentral Distance.

Fig. 1. Earthquake of April 14, 1906; $4^h\ 18^m$ am.

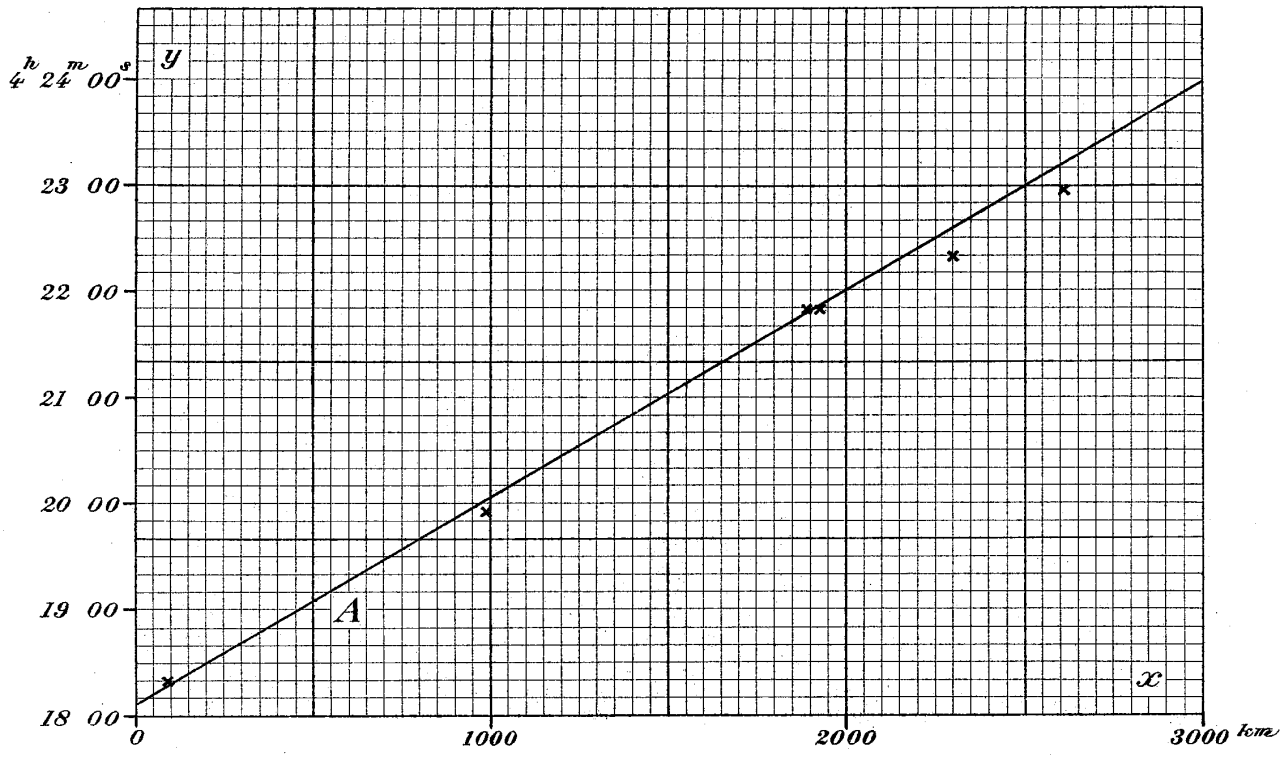
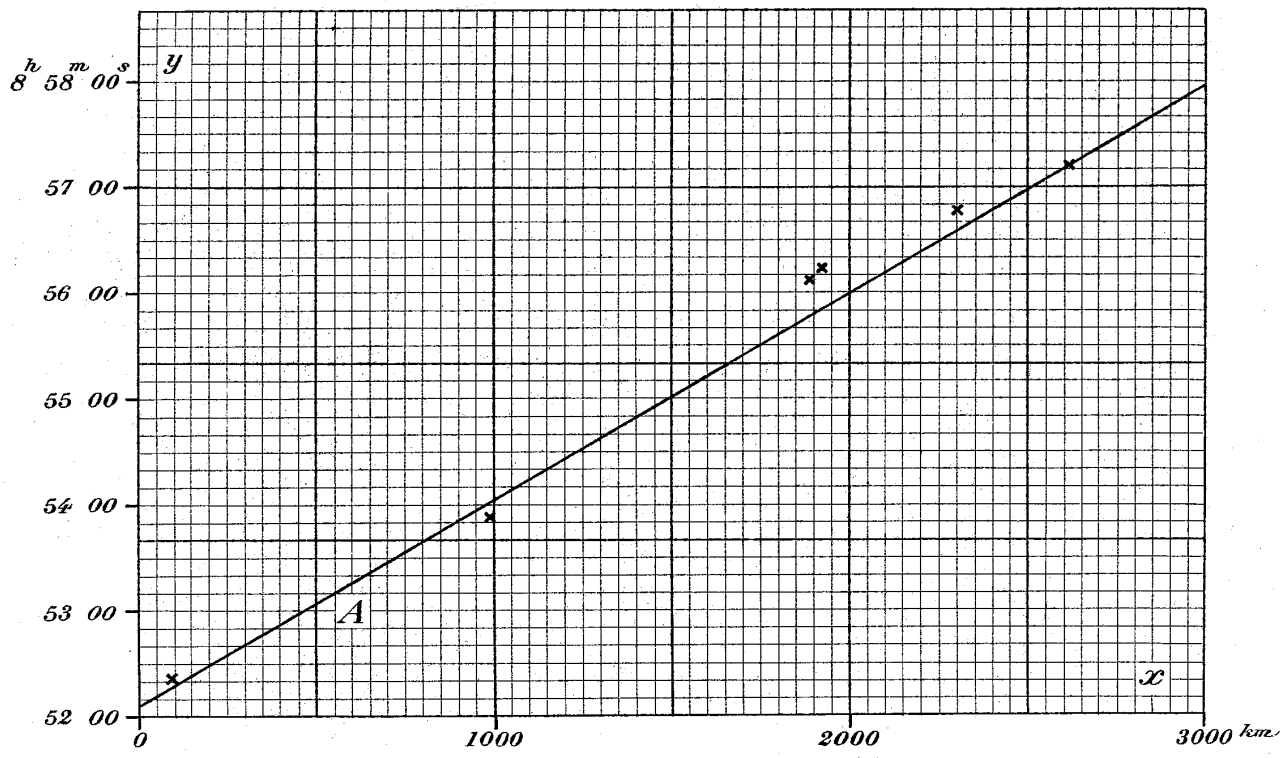


Fig. 2. Earthquake of April 14, 1906; $8^h\ 52^m$ am.



Formosa Earthquakes. Relation between the Time of Occurrence and the Epicentral Distance.

Fig. 3. Earthquake of March 17, 1906.

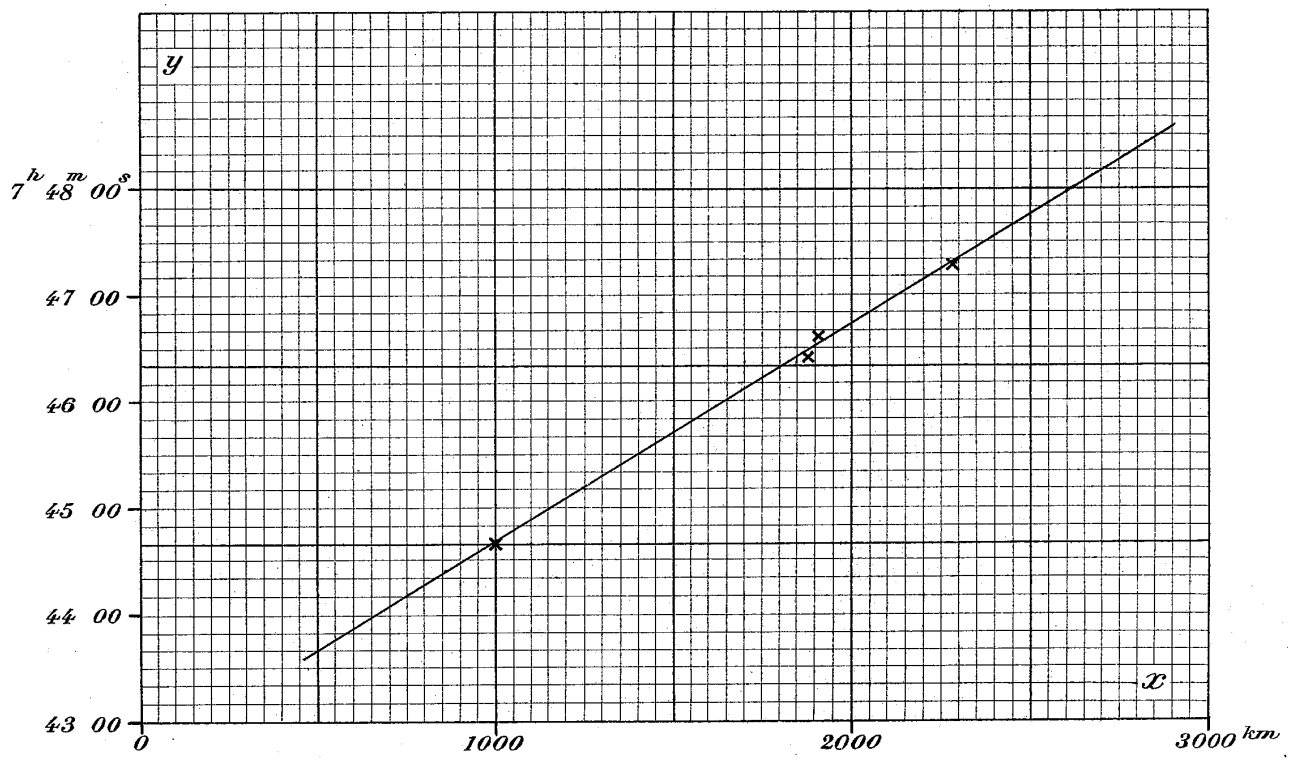


Fig. 4. Earthquake of Jan. 11, 1908.

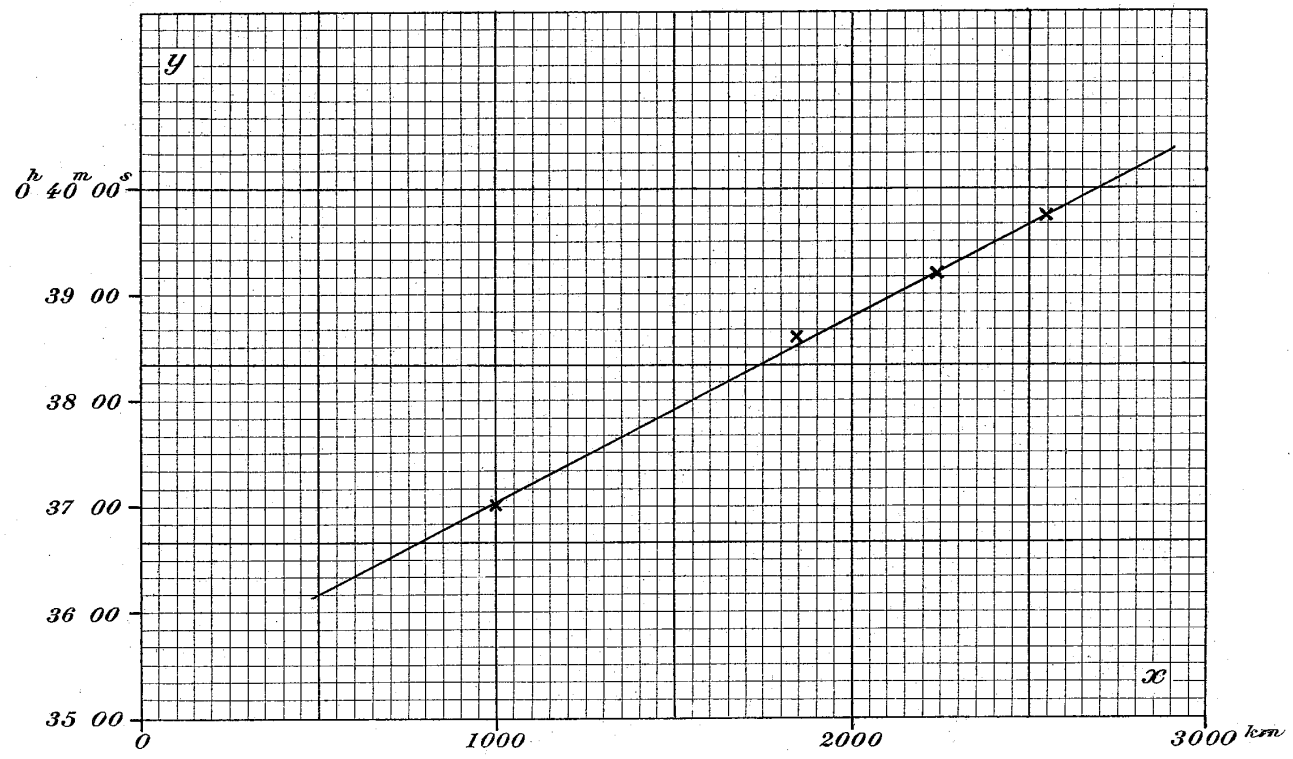


Fig. 5. Relation between the Time of Occurrence and the Epicentral Distance.