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Magnitudes of Major Volcanic Earthquakes of Japan 1901 to 1925

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Abstract

Instrumental magnitudes are determined for major volcanic earthquakes that occurred in Japan in the early years of modern seismology. The calculation of M_S (surface-wave magnitude) is based on the method devised recently by the present author and the instrumental records of undamped, long-period Omori seismographs. In case of a great eruption of the Sakurajima volcano of 1914, many shocks of M_S 5.2 or less preceded the eruption, and a destructive shock of M_S 7.0 occurred on January 12, about 10 hours after the eruption had started. Several strong shocks frequently occurred near the Asama volcano during the explosive period from 1909 to 1914, most of which show no special correlation, in proximate time, with the individual eruptions; the largest of these was on February 22, 1916, of M_S 6.3. An eruption of the Usu volcano of 1910 was preceded by many small shocks, the largest of which was M_S 5.1. This shock occurred on July 24, 30 hours before the initial explosion.

1. Introduction

In a recent study[1] the present author devised a method of a consistent assignment of instrumental magnitudes for local earthquakes that occurred in Japan in the early years of modern seismology. Records of undamped, long-period Omori instruments were used, and the Moscow-Prague formula was employed considering periods as well as amplitudes. The scale was adjusted to coincide with the surface-wave magnitude defined by Gutenberg[2] on the basis of the data of the Gutenberg-Richter's unpublished original work-sheets for *Seismicity of the Earth*[3]. The results were successfully applied to many damaging earthquakes that occurred in Japan from 1901 to 1925. In the present paper this new method is applied to the determination of magnitudes for volcanic earthquakes that occurred from 1901 to 1925 in the vicinity of the Sakurajima, Asama, and Usu volcanoes, Japan. These three volcanoes were very active in the early years of this century, and many earthquakes occurred in the volcanic areas before or during the explosive period. No instrumental magnitudes have been given for these shocks, except

for the Sakurajima shock of January 12, 1914, to which Gutenberg and Richter[3] assigned magnitude 7.

2. Method

For the determination of instrumental magnitudes of volcanic earthquakes, we use the result of Abe[1] who made possible a consistent assignment of surface-wave magnitudes for local earthquakes by using undamped, long-period instruments. Since the details are given in Abe's paper, the method will be briefly outlined in the following.

Calculation of magnitudes is based on the procedure proposed by Vanek et al.[4] and Abe and Kanamori[5]. The formula employed is:

$$M_s = \log \frac{A}{T} + 1.66 \log \Delta + 3.3 + C \tag{1}$$

where M_s is the surface-wave magnitude which is logically consistent with the original scale defined by Gutenberg[2], A is the single horizontal component of the maximum ground amplitude, in microns, of surface waves, T is the period in sec, Δ is the epicentral distance in degrees, and C is the station correction. M_s is the arithmetic mean of the values from each component. Note that A is neither total nor combined horizontal amplitude. In this paper the notation M_s is used as the surface-wave magnitude determined by the present method, unless otherwise stated. According to Abe[1], the maximum amplitudes and periods are taken from station bulletins, various reports and reproduced seismograms from the Osaka Meteorological Observatory at Osaka and the Imperial University of Tokyo at Tokyo, Japan. At these two stations, long-period Omori instruments were operated in the early years of this century. The natural period and the static magnification were around 25 sec and 20, respectively. Since the Omori instruments had no special damping mechanism in those days, the station corrections given by Abe[1] are applied for each station. Fig. 1 shows the location of the seismographic stations and the volcanoes concerned here.

The epicenter data are taken from catalogues of Central Meteorological Observatory[6] and Usami[7]. The epicenters in these catalogues were mostly located on the basis of macroseismic data with an error probably not exceeding 10 km. This amount of error does not greatly affect the general precision of the results. For earthquakes which are not listed in the catalogues, either the center of volcanic activity or the epicenter of main shock is used for

the calculation of epicentral distances. Even in this case the location error dose not much exceed 10 km.

In view of the imperfect data in the early years of this century, the magnitude estimate is subject to numerous uncertainty, and the general precision of results is not quite so high as that for latest earthquakes. However, the magnitudes derived from the present method appear to be dependable to better than 1/4 unit, as was demonstrated in the previous study.

Fig. 1 The volcanoes and seismographic stations.

3. Results

3.1 Sakurajima Volcano

The Sakurajima volcano is located in south Kyushu, Japan: 31.6°N, 130. 7°E. A great eruption of this volcano occurred in January, 1914, following the great outbreak of 1779. The details of this eruption are given by Omori[8]. Following is the brief summary.

From the night of January 10, 1914, earthquakes were felt with increasing frequency in the Sakurajima island. More than 20000 people living in the island became alarmed and many fled from the island. The maximum frequency of earthquakes was attained between the night of the 11th and the next morning. On the morning of the 12th, at about 8 a.m., a column of white smoke was seen rising from the west side of the volcano, and at about 10 a.m. explosive eruptions began. The eruption cloud attained at a height of over 6000 m with lightening flashes through dense cloud. At 6:28 p.m. in the evening a strong earthquake took place and caused severe damage to the

city of Kagoshima and the Sakurajima island. Around 1 a.m. of the 13th the eruption was particularly violent, but in the afternoon the violence was greatly diminished. On the succeeding evening a lava flow began to issue from the east and west flanks, and gradually flowed down into the sea. By January 29 the eastern flow connected the island with the mainland 400 m apart, and the Sakurajima island was converted into a peninsula. The total volume of lava extruded was 1.56 km^3.

The bottom trace in Fig. 2 shows the daily number of earthquakes recorded at the Nagasaki Meteorological Observatory[8]. At Nagasaki, 150 km north of the Sakurajima island, Omori horizontal tromometers were operated, and 44 shocks were registered during the period from January 9 to 20. The maximum frequency of shocks was attained on January 11, but the earthquake activity fell off rapidly after the eruption had started.

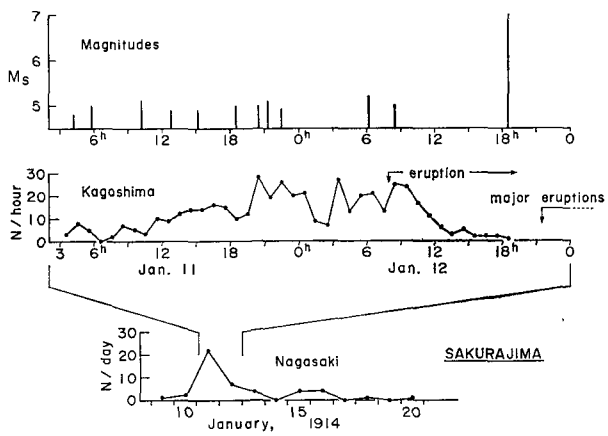

Fig. 2 Magnitudes of major earthquakes and the number of earthquakes near the Sakurajima volcano.

The middle trace in Fig. 2 shows the hourly number of earthquakes recorded at the Kagoshima Meteorological Observatory on January 11 and 12[8]. This observatory, 10 km west of the volcano, operated Gray-Milne seismographs having a starter mechanism and a pointer magnification of about 5. The hourly frequency was gradually increased from the early morning of the 11th, but was decreased rapidly in the afternoon of the 12th.

Table 1 lists 14 major shocks to which M_s can be assigned by the present method. Most of these shocks have magnitude near 5. For smaller shocks,

Table 1. Magnitudes of major earthquakes at Sakurajima.

Year	Date	Time (JST)	M_K	M_S	Remarks
1914	January 11	04:03		4.8	
		05:09		5.0	
		10:03		5.1	
		12:48		4.9	
		15:01		4.9	
		18:29		5.0	
		20:29		5.0	
		21:14		5.1	
		22:29		4.9	
	January 12	06:09		5.2	
		08:33		5.0	
		18:28	6.2	7.0	Damage[1]
	January 13	16:10		4.6	
	April 22	15:27		5.0	

[1] In the Kagoshima city, 13 persons were killed and 39 houses were totally collapsed.

the amplitudes are too small to record legibly at far distances. Of 14 major shocks, 10 occurred before the initial explosion. The largest shock of the series took place on January 12 at 6 p.m.: in the city of Kagoshima it was most violent and took over 13 lives. As is shown in Fig. 2, this largest shock occurred immediately before the intensity culmination of the explosions and one day before the commencement of the lava outflow. The epicenter and focal depth have been estimated to be 31.6°N, 130.6°E, and 13 km, respectively[8], but the accuracy is not very high in view of the poor quality of the instrumental data obtained in the 1910's.

In June and July, 1913, half a year prior to the Sakurajima eruption, locally damaging earthquakes occurred near Ijuin, about 20 km west of the volcano. There were two large shocks in the group, on June 30, of M_s 5.8[1]. It is presently unknown whether this activity shows a special correlation with the eruption.

3.2 Asama Volcano

Mount Asama is located in central Japan: 36.4°N, 138.5°E. Active repeatedly in historic times, it experienced a great eruption in 1783. In this eruption a great volcanic avalanche occurred and buried some villages; for example, the village of Kamahara-mura was entirely buried and of a population of 597, 477 were killed. The death toll was placed at 1151 people.

The details of the activity in the early years of this century are given in enormous papers of Omori[9]. The brief summary is given in the following. The Asama volcano became active after 1909 and moderate explosions lasted with varying intensity until 1914. During this active period strong explosions were often accompanied by a loud detonation which was heard to distances of 200 km, and by a dense explosion cloud which spread abundant ashes over a wide area. In case of strong explosions, clouds sometimes reached a height of 7500 m above the mountain top. The explosions were particularly strong on January 29, May 31, December 7, 1909, December 2, 1910, May 8, October 22, December 3, 1911, December 14, 1912, June 17, August 12, 1913, January 29, March 3, 1914. The year 1913 was the most explosive period. In these explosions no lava flows were produced, but "bread crust" bombs and incandescent fragments of lava were often scattered over the crater rim and the immediate surroundings. After 1915 the volcano became quiet. During the explosive period, many earthquakes, several of which were very strong, originated in the vicinity of the volcano.

The bottom trace of Fig. 3 shows the yearly number of the observed explosions[10]. The frequency of the explosions was predominantly increased during the period from 1911 to 1914.

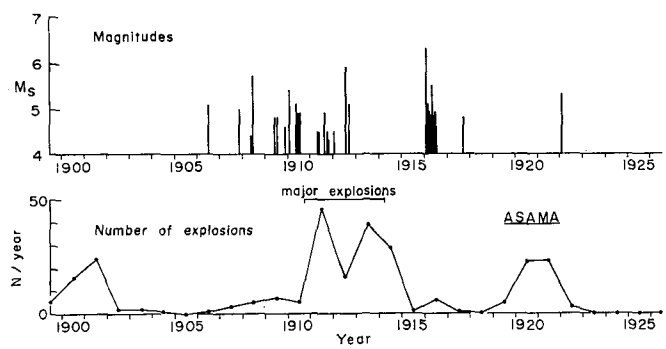

Fig. 3 Magnitudes of major earthquakes and the number of explosions near the Asama volcano.

Table 2 lists 29 shocks to which magnitudes can be assigned. These shocks are of magnitude 4 1/2 or more, and probably occurred within a radius of 20 km from the crater: according to Central Meteorological Observatory[6] the shocks of June 22, 1906, December 10, 1907, June 11 and 12, 1909,

Table 2. Magnitudes of major earthquakes at Asama.

Year	Date	Time (JST)	M_K	M_s	Remarks
1906	June 22	02:28	5.5	(5)	
1907	December 10	00:39	5.0	5.0	
1908	May 10	11:57	5.1	4.4	
	May 26	09:07	5.8	5.7	Damage[1]
1909	June 11	23:16	5.8	4.8	
	June 12	11:06		4.8	
	December 7	19:44		4.6	Eruption[2]
1910	January 22	15:03	6.5	5.4	
	May 7	08:01	6.0	5.1	
		08:19		4.9	
		11:07		4.9	
1911	April 2	22:30	5.6	4.5	
	April 9	06:33	5.0	(4 1/2)	
	July 24	09:09	5.1	4.9	
	October 5	23:52	4.9	(4 1/2)	
	October 6	08:50	5.0	4.3	
1912	January 14	14:41	5.0	4.5	
	July 16	07:46	6.2	5.9	Damage[3]
	August 17	23:22	5.7	5.1	Damage[4]
1916	February 22	18:12	6.0	6.3	Damage[5]
		20:31	5.5	5.1	
		18:32		4.9	
		18:44		4.8	
		20:40		5.0	
	February 23	00:32		4.8	
		03:03		4.9	
		03:08		4.6	
1917	September 12	05:03		4.8	
1922	January 9	08:49		5.3	

1) Several cracks, 10 to 20 meters in length, and the fall of rock fragments around the crater.
2) A strong eruption, putting forests on fire, followed this shock, 1 1/2 minutes later.
3) Appreciable cracks at the crater rim and landslides at Kibayama.
4) Slight damages to buildings, embankments, roads, and stone-framed retaining walls at Ueda.
5) Seven houses collapsed and landslides at Tsumagoi.

January 22, 1910, and August 17, 1912, occurred near the base of the volcano, and the others occurred near the crater. Some strong shocks had their own aftershock series.

Most of the major shocks show no special correlation, in proximate time, with the individual explosions; only the earthquake of December 7, 1909, occurred 1 1/2 minutes prior to the strong explosion[11]. No major shocks

occurred in 1913. This year was the most explosive period since the great eruption in 1783[9].

Of 29 major shocks, the largest shock was on February 22, 1916, of M_s 6.3. This shock was felt severely at the northern region of Asama. The second largest shock of July 16, 1912, was very strong near the crater. The shock of May 26, 1908, is considered to be similar in intensity to the shock of July 16, 1912[9].

The late Dr. Kawasumi previously determined magnitudes from reported seismic intensities[6]. In the column of M_K of Table 2, those magnitudes are listed in comparison with M_s. On average, M_K is found to be larger by 0.5 than M_s. This difference is consistent with that obtained for major Japanese shocks[1]. Considering this result, M_K minus 0.5 is given for three shocks of June 22, 1906, April 9 and October 5, 1911, to the nearest quarter unit, owing to the lack of the instrumental data for these shocks.

3.3 Usu Volcano

Mount Usu is located in south Hokkaido: 42.5°N, 140.8°E. A major eruption of this volcano occurred in 1910, following the eruptions of 1822 and 1853. The eruption of 1910 was preceded by a notable foreshock activity [12),13)]. From July 21, 1910, 4 days before the first eruption, earthquakes were felt near Usu with increasing frequency. As the frequency continued to increase in a marked way, the inhabitants at the immediate base of the mountain began to leave their homes. On July 23 a local police issued compulsory measures of evacuation. The maximum frequency of earthquakes was attained on July 24. On the 24th and 25th strong shocks occurred and caused minor damage. On July 25 at about 10 p.m., the initial explosion occurred near Kompira-yama on the northern flank of the volcano. This explosion threw out ashes and rock fragments in a small area. Explosions similar to the first lasted intermittently until the end of 1910, forming 45 explosion craterlets whose diameters varied from 30 to 250 m[12]. None of the explosions was of great magnitude. No lava flows were produced. On the other hand, a place near Nishi-maruyama on the northern flank was gradually uplifted with an average rate of 1.55 m per day since the initial explosion, and a new mountain (cryptodome) was formed there by the early November[12]. The actual amount of elevation was 155 m above the former level.

The bottom trace of Fig. 4 shows the 6-hourly number of earthquakes

recorded at Sapporo which is located 70 km northeast of the volcano[12]. Long-period Omori instruments were operated there, but unfortunately the data of amplitudes have not been available. According to Omori[12], the earthquakes observed at Sapporo were most numerous during the period from 6 p.m. on the 24th to 9 a.m. on the 25th, and during the next 13 hours, at the end of which the eruption began, the earthquake activity fell off rapidly.

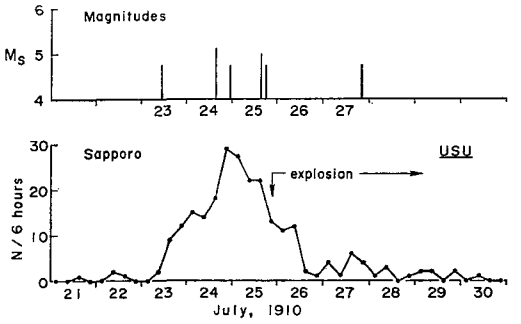

Fig. 4 Magnitudes of major earthquakes and the number of earthquakes near the Usu volcano.

Table 3. Magnitudes of major earthquakes at Usu.

Year	Date	Time (JST)	M_K	M_S	Remarks
1910	July 23	11:16		(4 3/4)	
	July 24	15:49	6.5	5.1	Damage[1]
		23:01		(4 3/4)	
	July 25	16:40		(5)	Damage[2]
		18:27		(4 3/4)	
	July 27	20:40		(4 3/4)	

1) In Abuta, two brick-framed warehouses had serious cracks in the walls and were partially destroyed.

2) In Abuta, a small stone building and a stone monument were overthrown.

The surface-wave magnitude can be assigned only to the damaging shock of July 24, of M_s 5.1. This value is significantly different from M_K from the intensity data (Table 3); here note that the large deviation from M_K is also found for the Sakurajima shock (Table 1). For the other shocks of Usu, magnitudes were estimated from the amplitudes recorded at Hakodate and Mizusawa in comparison with the amplitudes of the largest shock of M_s 5.1.

At Hakodate and Mizusawa (Fig. 1), Gray-Milne seismographs and tromometers were operated, respectively. These estimates are very rough, since the instruments were significantly different from the long-period Omori instrument. In Table 3 the magnitudes thus estimated are given to the nearest quarter unit in parentheses. Earthquakes to which M_s can be assigned by this method is roughly for M_s greater than 4 3/4.

In view of the macroseismic data, it is almost certain that the second largest shock of July 25 was not larger than the largest shock of July 24. These two shocks occurred 30 and 5 hours prior to the first eruption, respectively, and both were felt severely at Abuta, 5 km west of Usu, where some structures were damaged[13].

In 1977 the Usu volcano erupted again near the summit, not far from the site of the 1910 eruption, and many earthquakes have occurred there[14]. The Sapporo Meteorological Observatory (SMO) have assigned local magnitudes to major volcanic shocks on a routine basis, using the standard procedure adopted by the Japan Meteorological Agency (JMA), that is, the formula devised by Tsuboi[15]; therefore, the SMO scale is logically consistent with the JMA scale. There were 16 shocks of the largest magnitude 4.3 during the period from August, 1977 to October, 1978[16]. For a comparison of the SMO scale with the present scale, M_s is determined for the 16 largest shocks by using the method employed here and the instrumental records obtained at SMO. The instruments used are the 59-type horizontal seismographs with natural periods of 5 sec. The station correction is neglected in equation (1). The average of M_s thus calculated is 4.34 ± 0.04; in this calculation the average period of surface waves is 2.6 ± 0.4 sec. It is found that the magnitude given by SMO is not different from the value derived from the present procedure, and the two scales appear to be consistent with each other. This result is not surprising in view of the fact that Tsuboi's formula is almost equivalent to equation (1) for short periods of a few seconds and relatively small distances. From this comparison, it is safely concluded that the large shocks in 1910 are greater, in magnitude, than the largest shocks in 1977 and 1978.

4. Conclusion

On the basis of instrumental records, the surface-wave magnitudes are determined for major volcanic earthquakes which occurred near the Sakurajima, Asama and Usu volcanoes during the period from 1901 to 1925. Among these volcanic shocks the largest shock was on January 12, 1914, of magnitude 7.0

which occurred in the vicinity of the Sakurajima volcano. The results obtained here supplement the previous magnitude catalogue[1] of major earthquakes which occurred in Japan in the early years of this century.

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