Magnitude-Frequency Distribution of Slope Failures in Japan: Statistical Approach to a True Perspective on Volcanic Mega-Collapses

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Additional information is available at the end of the chapter

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Abstract

The relationship between magnitude and frequency of mega-collapses (i.e., sector collapses), mainly of volcanic edifices, in Japan is examined by using existing datasets for volcanic mega-collapses and smaller but more frequent events. Statistical analysis of these datasets showed that the magnitude-frequency distribution of slope failures with volumes greater than or equal to 10^7 m^3 can be expressed by a simple exponential function: $\log N(x) = a - bx$, where $N(x)$ is the cumulative number of mass-movement events with magnitude $\geq x$. When this function was fitted to the datasets, the slope coefficient, b, was 0.7 or 0.8. The frequency distribution of mega-collapses was similar to that of smaller (volume $>10^{5-6}$ m^3) events. Records from the past millennium in Japan suggest that this magnitude-frequency relationship may be applicable to the last several tens of thousands of years. Therefore, it is possible to predict event probability and the recurrence interval of events of a certain magnitude. In this way, mega-collapses with a volume of over 10^9 m^3 may be estimated to occur at least every 1000–2000 years somewhere in Japan. Therefore, mega-collapses in Japan should not be considered "rare"; rather, they are "normal" events on a geomorphological timescale.

Keywords: exponential regression, probability, recurrence interval, sector collapse, debris avalanche

1. Introduction

In recent years, terrestrial slope failure and rapid mass movement have been attracting increasing attention as disastrous geomorphic processes [1–3]. Rapid mass movements range from maximal events, such as the gigantic sector collapse of a volcanic edifice, to much smaller but more frequently observed slope failures. In a geomorphological context, it is important to critically examine the relationship between the magnitude and frequency of rapid mass-movement events to determine the relative contributions of large and small events to the denudation processes of mountains (including volcanoes) in an area of active uplift and denudation such as Japan (**Figure 1**) [4, 5].

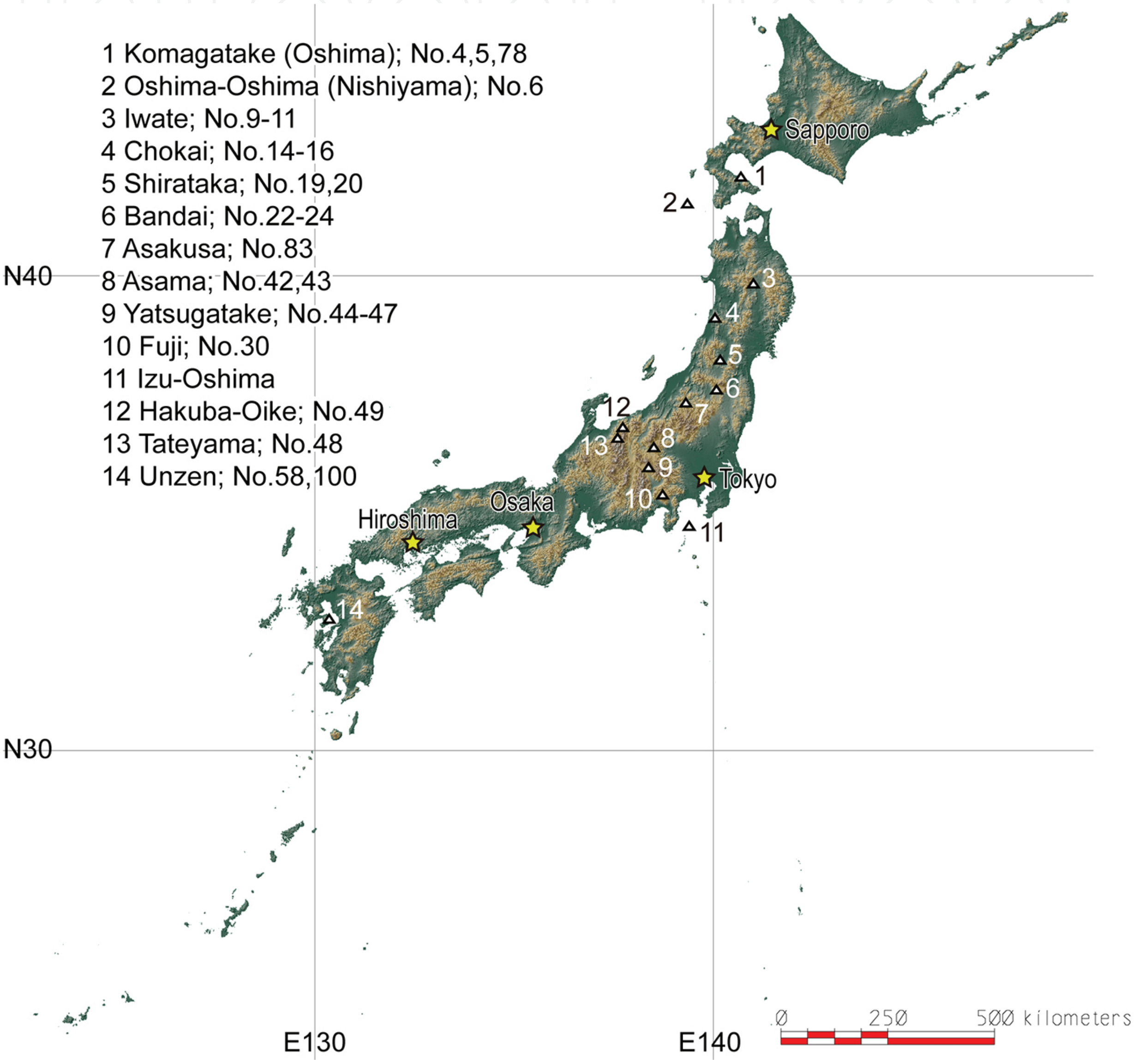

Figure 1. Topographic map of the Japanese islands, produced from DEMs of the Geospatial Information Authority of Japan, showing the locations of the volcanoes referred to in the text.

Many studies have investigated magnitude-frequency relationships of earth surface processes and landforms [6–10], the best-known example of which is possibly the Gutenberg-Richter equation in seismology. In geomorphology, the frequency distribution of landslides has often been analyzed because landslides can have significant impacts on human activities. In

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particular, studies have focused on the relationship between landsliding potential and geologic [8] or climatic conditions and changes [9]. In general, the frequency distributions of landslides and other mass movements are similar [10], and they can be simply expressed by the following exponential equation:

$$\log N(x) = a - bx \tag{1}$$

where $N(x)$ is the cumulative number of landsliding or mass-movement events with magnitude $\geq x$ and a and b are constants. Here, x is equal to $\log A$, where A is the landform area (e.g., landslide area).

By contrast, very few attempts have been made to investigate statistically the magnitude-frequency distribution of gigantic sector collapses of volcanic edifices [11], although Yoshida [12] has analyzed the magnitude-frequency distribution of hummocks on rockslide-debris avalanche deposits associated with volcanoes. Thus, the question of whether the relationship between magnitude and frequency of mega-collapses shows a similar trend to that observed for much smaller events remains unanswered.

One reason for this situation, of course, is the paucity of examples, because gigantic sector collapses occur much less frequently than small slope failures. Although mega-collapses have been qualitatively characterized as relatively low-frequency events [13, 14], it is important to assess the impact of mega-collapses (which are mainly volcanic) from a more rigorous geo-statistical viewpoint. Because the impact of an event is the product of its magnitude and frequency [10], despite their low frequency, mega-collapses can contribute substantially to long-term geomorphic changes and sediment transport to alluvial plains [14], and they also have the potential to cause greater disasters than smaller-scale events [1–3]. The accumulation of research results, particularly in the field of volcanology, has made it possible to analyze the relationship between magnitude and frequency of mega-scale mass movements by combining published datasets of magnitude-frequency distributions.

The aim of this chapter is to explore the characteristics of the magnitude-frequency distribution of mega-scale slope failures in Japan, which typically occur on the flanks of mature volcanoes [15]. These huge events (generally $>10^8$ m^3 in volume) are significant in terms of the geomorphic development of volcanic edifices and other mountains and the regions surrounding them, as shown by the catastrophic rockslide-debris avalanche event associated with the 1980 eruption of Mt. St. Helens [16, 17]. Here, to deepen our understanding of volcanic mega-collapses in Japan several datasets of mega-scale and smaller slope failures are examined statistically, and event probabilities and recurrence intervals are also discussed.

2. Data and methods

First, it is necessary to define "rapid mass movement" as used in this research. Mass movements include a variety of phenomena, which have been characterized by terms such as "creep," "fall," "topple," "slip," "avalanche," "slide," "flow," "heave," "sink," and "subsidence" [18–20]. Among these terms, slip, avalanche, and flow may denote rapid (e.g., 10^0–10^2 m/s or even faster if expressed as speed) mass movements in which the collapsed materials are transported relatively far from the source region in short time. Because in particular "slide" (landslides) can in fact describe both rapid and slow events, this study excludes selectively slow slides (landslides) (e.g., 10^0–10^5 cm/y) from rapid mass movements, unless the landslide mass is well segregated and the depositional area shows a hummocky terrain [21–24] as in the case of a debris avalanche. Mega-collapses of volcanic edifices can be considered slips or avalanches.

Given this criterion, three datasets were prepared as follows (**Table 1**):

In this chapter	Target	Original reference	No. of events analyzed in this study	Magnitude expression	Magnitude range	Notes
Table 2	Mega-collapses of Quaternary volcanoes	Yoshida (2010)	67	Volume	59 ≧ 10^8 m^3, 8 ≧ 10^7 m^3	
-	Large-scale collapses	Machida et al. (1987)	332	Depositional area	10^5–10^7 m^2	Of 333 recorded events
-	Rapid mass-movements during 1975–1983	Ohmori and Hirano (1988)	2083	Depositional area	10^3–10^7 m^2	1739 rocky mudflows, 344 steep slope collapses
Table 3	Estimates based on the empirical relationship between caldera area and (partly depositional) volume	-	36	Volume	>10^7 m^3	

Table 1. Datasets of rapid mass movements in Japan used in this study.

1. Mega-collapses of volcanic edifices in Japan reported by Yoshida [25], together with additional data retrieved by a literature search.

   In 2010, Yoshida [25] identified 58 mega-collapses in Japan with an estimated debris (or partly scar) volume greater than or equal to 10^8 m^3. Most of these events occurred in the Middle Pleistocene or later. The volume data of some of these events have been corrected on the basis of new data in this chapter. In addition, for the Kurumizaka debris avalanche (Oshima-Komagatake volcano; **Figure 1**), the author considered here as two events, the Shikabe and Onuma lobes. In addition, eight large collapses with a volume greater than or equal to 10^7 m^3 identified by an additional literature search have been integrated into the dataset. Thus, a total of 67 events were included in the dataset analyzed in this study

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(**Table 2**). Note that reference [25] includes only a very rough discussion of the magnitude-frequency relationship of mega-collapses.

2. Large-scale collapses in Japan compiled by Machida et al. [26]

Machida et al. [26] identified 333 large-scale collapses in Japan by examining aerial photographs and maps. For each event, they described the area of the collapse scar, the depositional area (i.e., the area covered by the collapse deposit), and the equivalent coefficient of friction. They did not report volumes, except for a few representative cases. The reported deformed (i.e., depositional) areas ranged from 10^5 to 10^7 m^2. They estimated that most of the identified events (74%) were associated with a volcanic edifice or a volcanic terrain. They also noted that the compiled events represented rapid mass movements, not slow sliding or creep events. In this chapter, the depositional area of each event is used as the measure of its magnitude.

3. Rocky mudflow and steep slope collapse data reported by Ohmori and Hirano [10], based on data for 9 years (1975–1983) originally compiled by the former Construction Ministry of Japan.

Ohmori and Hirano [10] aggregated the depositional area of three types of mass-movement events, which they called "landcreep" (1428 events), "rocky mudflows" (1739 events), and "steep slope collapses" (344 events), and examined the magnitude-frequency relationship of each type. In this chapter, only the rocky mudflow and steep slope collapse events are interpreted as rapid mass movements. Thus, the dataset analyzed in this study consisted of 2083 events that occurred in Japan during 1975–1983.

No.	Volcano	Debris avalanche	Age		Averaged age	Volume	Averaged volume	Caldera area	Caldera area to the three-halves power	References (for corrected and additional data; asterisks)
			×10^4 yBP	Recent event	×10^4 yBP	×10^8m^3	×10^8m^3	(×10^8m^2)	(×10^8m^3)	
1	Shiribetsu	Rusutsu	10–5		7.5	20	20	0.0228	34.50	
2	Yotei	Old-Yotei	4		4	13*	13			[27]
3	Usu	Zenkoji	0.8–0.7		0.75	10–20	15			
4	Komagatake (Oshima)	Kurumizaka (Shikabe)		AD 1640	0.0369	14.2-17.0	15.6	0.0551	129.23	
5	Komagatake (Oshima)	Kurumizaka (Onuma)		AD 1640	0.0369	3	3	0.0231	35.19	
6	Oshima-Oshima	Nishiyama		AD 1741	0.0268	24	24	0.0119	13.05	
7	Iwaki	Tokoshinai	65		65	13	13			

No.	Volcano	Debris avalanche	Age		Averaged age	Volume	Averaged volume	Caldera area	Caldera area to the three-halves power	References (for corrected and additional data; asterisks)
			$\times 10^4$ yBP	Recent event	$\times 10^4$ yBP	$\times 10^8 m^3$	$\times 10^8 m^3$	($\times 10^8 m^2$)	($\times 10^8 m^3$)	
8	Tashirodake	Iwasegawa	>2.5		2.5	1	1	0.0106	10.98	
9	Iwate	Aoyamacho	15		15	7.6	7.6			
10	Iwate	Oishiwatari-Koiwai	12		12	25	25			
11	Iwate	Hirakasa	0.6		5	2	2	0.0135	15.76	
12	Hachimantai	Matsuo	5		0.6	20–30	25			
13	Komagatake (Akita)	Sendatsugawa	2.2		2.2	>1	1			
14	Chokai	Kisakata	0.26		0.26	28.5	28.5	0.1393	519.98	
15	Chokai	West Chokai	9		9	14	14	0.0761	209.75	
16	Chokai	Yurihara	1.978		1.978	52	52			
17	Kurikoma	Sukawa	1.8–1.7		1.75	3.7	3.7			
18	Gassan	Sasagawa	<40–30		30	50 ± 30	50	0.1057	343.52	
19	Shirataka	Hataya	80		80	20	20			
20	Shirataka	Hariu	90		90	13	13	0.0687	180.21	
21	Zao	Sukawa	7		7	30	30	0.0341	62.88	
22	Bandai	Ura-Bandai		AD 1888	0.0121	4.9*	4.9	0.0262	42.34	[28]
23	Bandai	Biwasawa	0.25		0.25	1	1	0.0188	25.70	
24	Bandai	Okinajima	4.6–3.0		3.8	22.5*	22.5	0.0642	162.60	[29]
25	Nasu	Kannongawa	1.74		1.74	3	3	0.0050	3.55	
26	Nasu	Ofujisan	4–3		3.5	>10	10	0.0682	178.13	
27	Nyoho-Akanagi	Namekawa	15–12		13.5	7.9	7.9	0.0109	11.39	
28	Akagi	Nashigi	22		22	40–80	60			
29	Onoko	Hirasawa	>55		55	14	14			
30	Fuji	Gotemba	0.29		0.29	17.6	17.6	0.1005	318.45	
31	Myoko	Suginosawa	0.27		0.27	1	1	0.0081	7.23	
32	Myoko	Taguchi	0.9		0.9	2	2			
33	Myoko	Yashirogawa	1		1	5	5			

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No.	Volcano	Debris avalanche	Age		Averaged age	Volume	Averaged volume	Caldera area	Caldera area to the three-halves power	References (for corrected and additional data; asterisks)
			×10⁴ yBP	Recent event	×10⁴ yBP	×10⁸m³	×10⁸m³	(×10⁸m²)	(×10⁸m³)	
34	Myoko	Sekikawa	1.9		1.9	14	14	0.1154	392.17	
35	Myoko	Nihongi	4.5		4.5	3	3			
36	Myoko	Tagiri	9		9	3	3			
37	Kurohime	Nabewarigawa	4.3		4.3	8–10	9	0.0327	59.00	
38	Kurohime	Terao	25–15		20	50	50			
39	Iizuna	Koshimizu	20		20	5	5	0.0124	13.80	
40	Iizuna	Mure	23–22		22.5	30–50	40			
41	Yakeyama (Niigata)	Nishi-Onogawa	0.18		0.18	1	1	0.0154	19.17	
42	Asama	Kambara		AD 1783		1.38	1.38			
43	Asama	Okuwa-Maebashi	2.4		2.4	40	40	0.0336	61.59	
44	Yatsugatake	Otsukigawa		AD 888	0.1121	3.5	3.5	0.0283	47.68	
45	Yatsugatake	Nirasaki	24–20		22	90	90			
46	Yatsugatake	Aikigawa	80–100		90	1	1			
47	Yatsugatake	Kannonji	80–130		105	60	60			
48	Tateyama	O-Tombi		AD 1858	0.0151	1.3–2.7	2			
49	Hakuba-Oike	Hiedayama		AD 1911	0.0098	1.5	1.5			
50	Ontake	Kaida-Kisogawa	5		5	16–27	21.5			
51	Hakusan	Oshirakawa	0.44		0.44	1.2	1.2	0.0054	3.95	
52	Kyogatake	Karatanigawa	3–4		3.5	3	3	0.0075	6.45	
53	Takahiradake	Matsuzuka	13–80		46.5	1	1			
54	Takahiradake	Kannawa	13–80		46.5	5	5	0.0163	20.73	
55	Tobidake	Wakasugi	<7		7	1	1	0.0041	2.59	
56	Ojikayama	Higashiyama	<50		50	2	2			

No.	Volcano	Debris avalanche	Age		Averaged age	Volume	Averaged volume	Caldera area	Caldera area to the three-halves power ($\times 10^8 m^3$)	References (for corrected and additional data; asterisks)
			$\times 10^4$ yBP	Recent event	$\times 10^4$ yBP	$\times 10^8 m^3$	$\times 10^8 m^3$	($\times 10^8 m^2$)		
57	Noine-Hanamure	Tashiro	40	40	9	9				
58	Unzen	Mayuyama		AD 1792	0.0217	4.4	4.4	0.0140	16.63	
59	Kujyu	Matsunodai	1		1	1.5	1.5			
60	Tokachidake	Taisho		AD 1926		0.02–0.004*	0.012			[30]
61	Yakeyama (Akita)	—				0.051*	0.051			[30]
62	Nasu	Miyama	0.08–0.07			>0.1*	0.100			[30]
63	Hiuchigatake	Numajiri	0.8			0.3*	0.300			[30]
64	Kurohime	Komazume	1			0.2*	0.200	0.0037	2.22	[31]
65	Ontake	Denjo		AD 1984		0.34*	0.340	0.0058	4.37	[30]
66	Yufu	Tsukahara	0.2			0.4*	0.400			[32]
67	Mizuguchi-Kuraki	Tsue		AD 1596		0.3*	0.300	0.0012	0.40	[32]

Asterisks indicate corrected and additional data with the source (reference) of each of these collapses. See "References" of the last column.

Table 2. Mega-collapses of volcanic edifices in Japan.

To increase the number of mega-collapses (volume >$10^{7–8}$ m^3) in the dataset 1 as above, three procedures were used as follows:

a. In Japan, Inokuchi [13] recognized more than 100 mega-collapses, and Yoshida [25] identified 58 (reinterpreted here as 59) events with a volume greater than or equal to 10^8 m^3 by surveying the volcanic, geologic, and geomorphologic literature, including the catalog in reference [13]. Therefore, that leaves several tens of mega-collapses whose volume is unknown, even roughly.

b. Thus, to estimate the magnitudes of additional mega-collapses, topographic collapse features such as horseshoe calderas (amphitheaters) associated with these mega-collapse events were investigated. In some cases, the collapse landforms are almost completely preserved and in other cases, they are partly preserved. The relationship between the areal extent of the collapse feature to the three-halves power, based on the geometry, and the mega-collapse volume was examined for 33 events for which both the caldera area and collapse volume were known (**Figure 2**). As a result, the following positive empirical relationship was found:

$$V = 0.5299 (A^{1.5})^{0.6805} \tag{2}$$

where V is the volume and A is the caldera area. The correlation coefficient (R) is 0.78, which is quite high, indicating the applicability of Eq. (2) as a predictive one to estimate volumes from the caldera area.

c. Then, 36 events whose topographic characteristics suggest formation as a result of a catastrophic mega-collapse were identified, and their volumes were estimated by substituting caldera area for A into Eq. (2). For example, the caldera of Asakusadake volcano (No. 83) in northern Honshu (**Figure 1**) has an area of 0.0396×10^8 m^2; the caldera opens to the northwest, and a partly dissected hummocky terrain exists below the caldera opening (**Figure 3**). The event volume estimated with Eq. (2) is 10.33×10^8 m^3. The estimated volumes of all 36 events are given in **Table 3**, and these 36 events were added to the mega-collapse dataset compiled in reference [25]. Thus, the expanded dataset, including the eight events added above (see Eq. (1)) by a literature search, comprises 103 mega-collapses, most with a volume greater than 10^8 m^3.

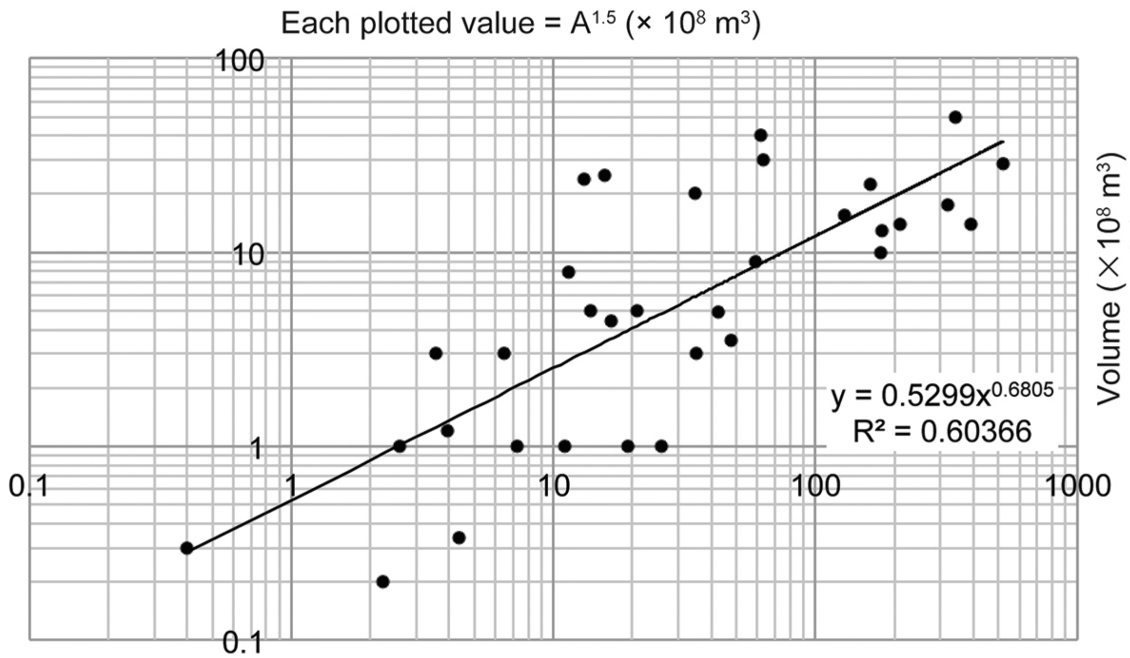

Figure 2. Relationship between event volume and caldera area to the three-halves power for 33 events.

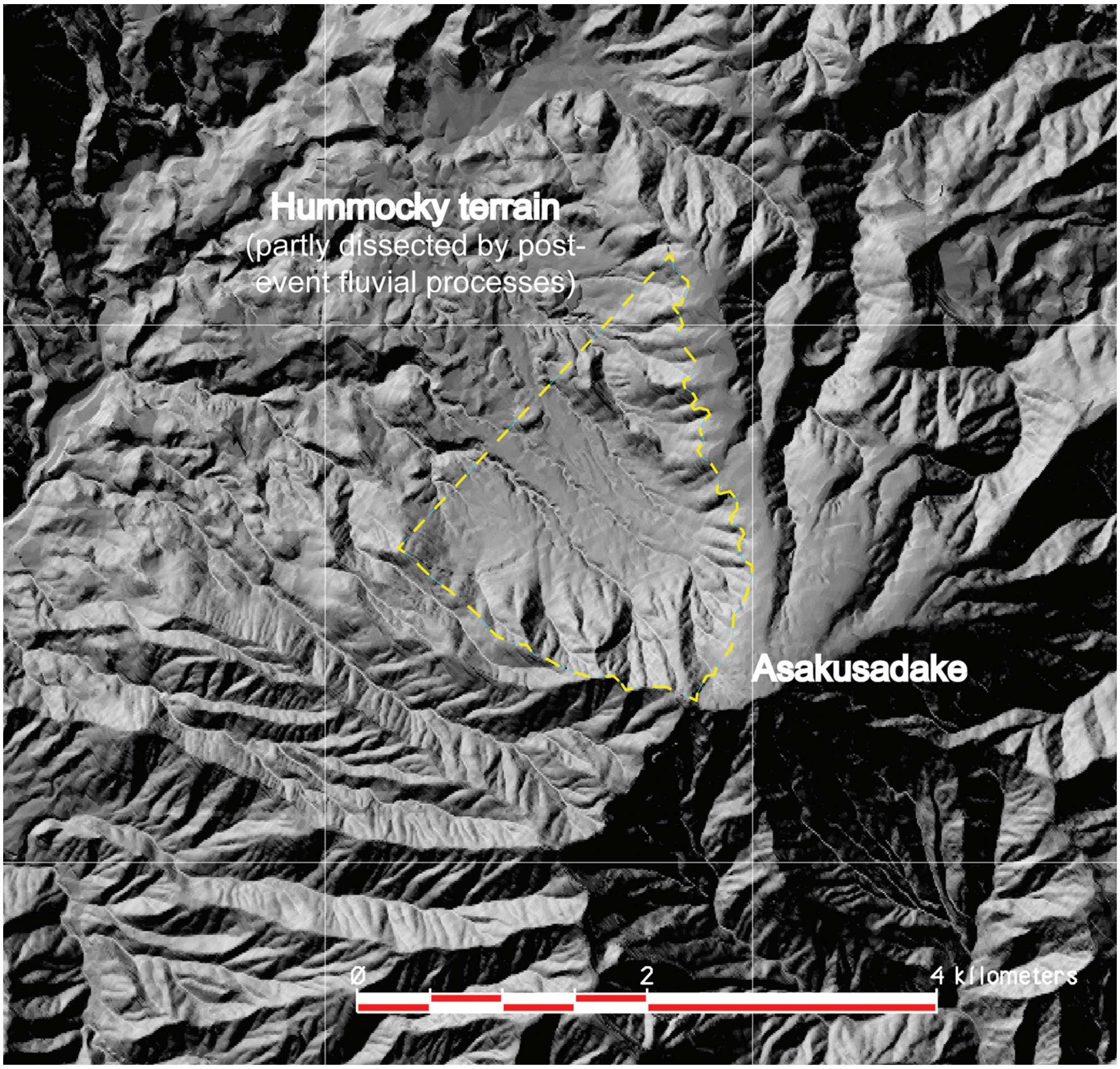

Figure 3. Topography around Asakusadake volcano, northeast Japan. The caldera scar, which opens to the northwest, is outlined by the dashed line. The base map is from 10-m-mesh data provided by the Geospatial Information Authority of Japan.

No.	Volcano		Caldera area ($\times10^8 m^2$)	Caldera area to the three-halves power ($\times10^8 m^3$)	Estimated volume ($\times10^8 m^3$)
68	Shiretoko		0.0090	8.56	2.28
69	Shiretoko-Chinishidake	(landslide?)	0.0295	50.73	7.67
70	Shiretoko-Onnebetsu	NW (landslide?)	0.0129	14.63	3.29
71	Shiretoko-Onnebetsu	E (landslide?)	0.0112	11.81	2.84

No.	Volcano		Caldera area (×10⁸m²)	Caldera area to the three-halves power (×10⁸m³)	Estimated volume (×10⁸m³)
72	Shiretoko-Iou		0.0189	26.06	4.87
73	Mashu		0.0096	9.37	2.43
74	Oakan		0.0192	26.57	4.94
75	Muine	West	0.0193	26.73	4.96
76	Muine	East	0.0075	6.55	1.90
77	Eniwa	NE	0.0033	1.90	0.82
78	Komagadake (Oshima)	Oshirogawa	0.0094	9.17	2.39
79	Esan	Es-3	0.0038	2.34	0.95
80	Mutsu-Hiuchigadake		0.0452	95.99	11.83
81	Zao	Kanno	0.0295	50.56	7.65
82	Hayama		0.1213	422.43	32.44
83	Asakusadake		0.0396	78.66	10.33
84	Nikko-Nantai		0.0110	11.53	2.80
85	Haruna	Miyukida	0.0167	21.52	4.28
86	Haruna	Jimba	0.0136	15.83	3.47
87	Hakone	Kamiyama	0.0069	5.77	1.75
88	Toshima		0.0050	3.52	1.25
89	Mikurajima		0.0223	33.24	5.75
90	Torishima		0.0034	2.01	0.85
91	Kurikoma	Tsurugidake A	0.0027	1.43	0.67
92	Madarao		0.0065	5.26	1.64
93	Tomuro		0.0043	2.82	1.07
94	Okinoshima	West (landslide?)	0.0049	3.45	1.23
95	Okinoshima	South (landslide?)	0.0013	0.46	0.31
96	Okinoshima	(landslide?)	0.0093	8.92	2.35
97	Sambe		0.0021	0.98	0.52
98	Yufu-Garandake		0.0018	0.75	0.44
99	Yufu-Kuehiranoyama		0.0029	1.56	0.72
100	Unzen	Shimabara	0.0057	4.26	1.42
101	Kirishima-Hinamoridake	Kobayashi	0.0508	114.40	13.33

No.	Volcano	Caldera area ($\times 10^8 m^2$)	Caldera area to the three-halves power ($\times 10^8 m^3$)	Estimated volume ($\times 10^8 m^3$)
102	Suwanosejima	0.0406	81.91	10.62
103	Akusekijima	0.0064	5.07	1.60

Table 3. Mega-collapse events whose volumes were estimated using Eq. (2).

3. Magnitude-frequency distribution of volcanic edifice mega-collapses

The magnitude-frequency distribution of 103 mega-collapses (dataset 1) was investigated. First, the event volumes were transformed to their common logarithm values (log$V$). Then, the magnitudes (log$V$ values) were grouped into bins of 0.4 (**Figure 4**). The resulting unimodal distribution resembles a log-normal distribution, especially if the smaller bins are ignored. In fact, the cumulative frequencies of events in the lower (smaller magnitude) bins are likely to be too low, a phenomenon known as rollover, which is often observed in, for example, landslide magnitude-frequency curves [33–35]. Thus, the magnitude-frequency distribution represented by the larger bins may be closer to the true distribution. However, the maximum magnitude of slope failures is necessarily limited by the slope length; thus, it is logically inappropriate to apply a log-normal distribution, which implies a maximum collapse of infinite volume [7]. Therefore, an exponential distribution (Eq. (1)) with constant b fitted to the distribution after excluding the five smallest bins affected by rollover. As a result, the fitted values of a and b were 7.14 and 0.64, respectively, and the correlation was high (R = -0.985) (**Figure 5**). Thus, the magnitude-frequency distribution of the mega-collapse dataset with log$V$ ≥8.0 can be explained by an exponential distribution with constants described above.

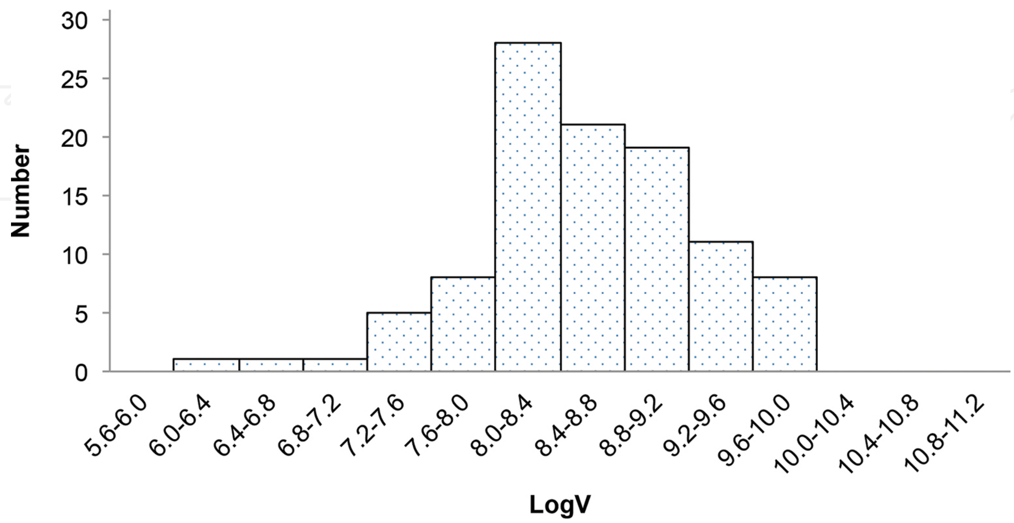

Figure 4. Magnitude (log$V$)-frequency histogram of 103 mega-collapses in Japan. The bin size is 0.4.

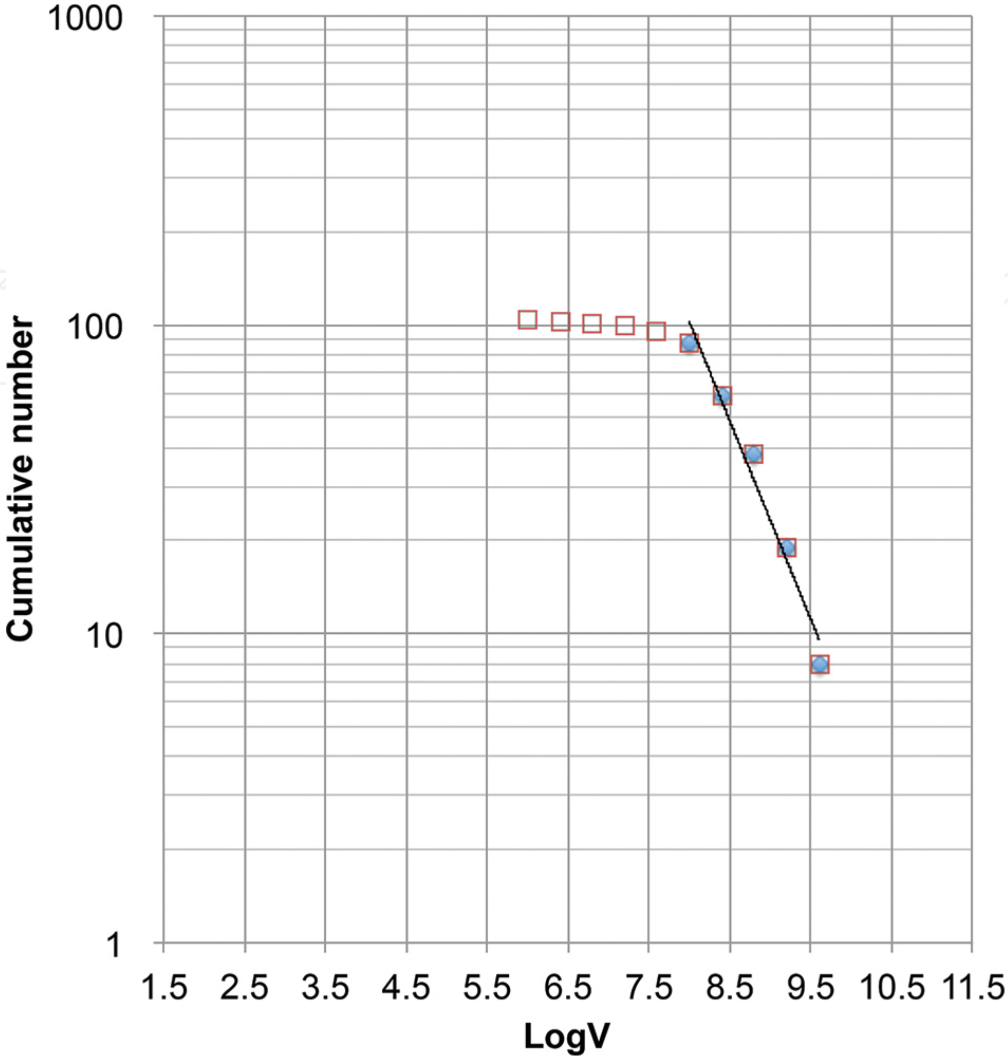

Figure 5. Regression analysis result of 103 mega-collapses in Japan, obtained by fitting Eq. (1) to the filled data points.

4. Magnitude-frequency distribution of large-scale collapses

Similarly, the magnitude-frequency distribution of large-scale collapses (but smaller than mega-collapses) in Japan compiled in reference [26] (dataset 2) was investigated. Because this dataset does not include individual volume data, the depositional area of each event ($10^{5–7}$ m^2) was used as its magnitude. Among the 333 events, the depositional area of one event was recorded as “0”; therefore, 332 events were used in this analysis. First, each depositional area was transformed to its common logarithm (log*A*). Then, the magnitudes (log*A* values) were grouped into bins of 0.2 (**Figure 6**). The resulting magnitude-frequency distribution is quite similar to that for the mega-collapse dataset (**Figure 4**). In a similar manner, Eq. (1) was fitted the distribution (after excluding the four smallest bins as affected by rollover; see Section 3). The resulting fitted values of *a* and *b* were 13.54 and 1.84, respectively, with a high correlation (R = -0.981) (**Figure 7**).

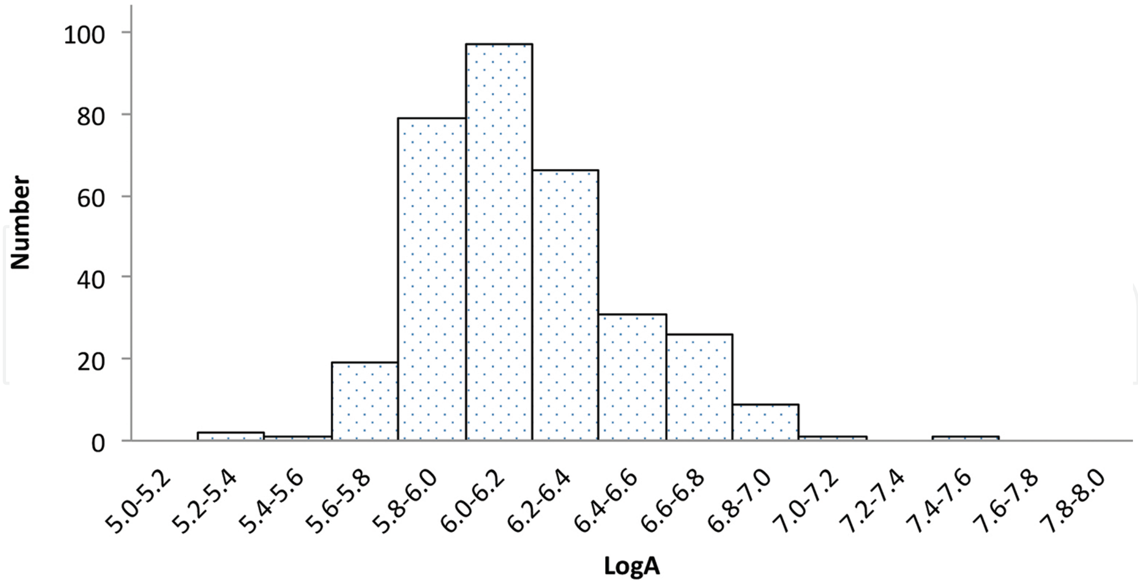

Figure 6. Magnitude (log*A*)-frequency histogram of 332 large-scale collapses in Japan. The bin size is 0.2.

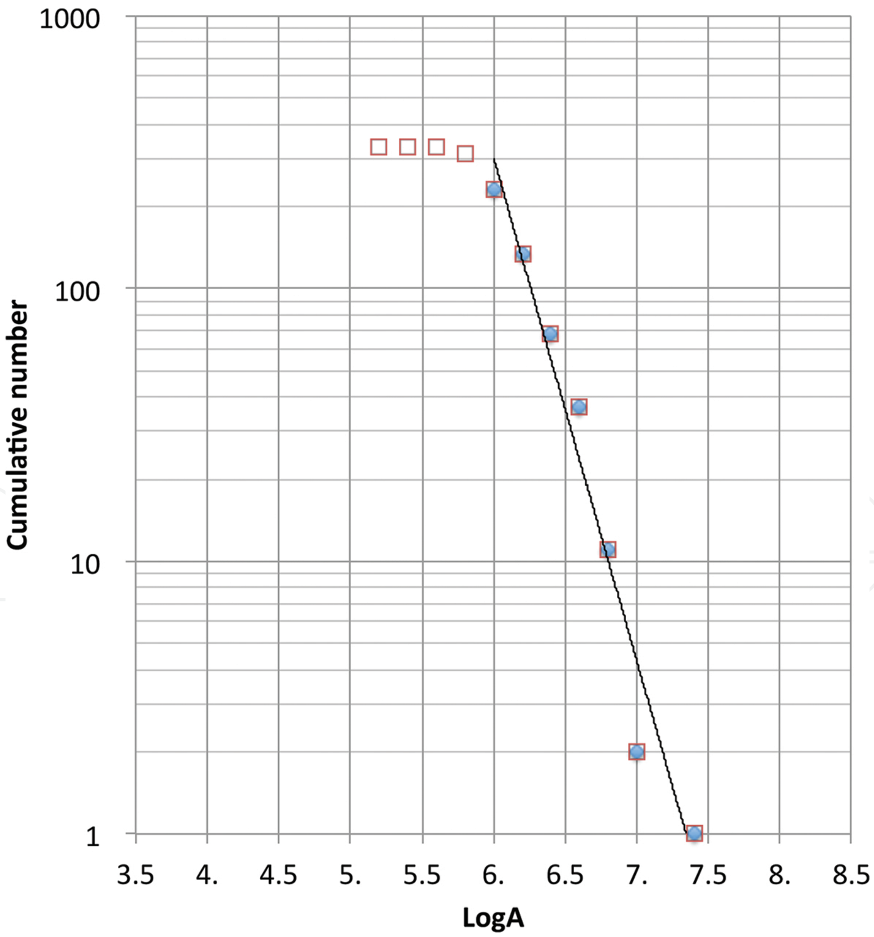

Figure 7. Regression analysis result for the 332 large-scale collapses obtained by fitting Eq. (1) to the filled data points.

5. Combined analysis of the large-scale collapse and mega-collapse datasets

The magnitude-frequency distributions of both the mega-collapse and large-scale collapse datasets are similar: the distribution is exponential even though magnitude is expressed as event volume in the former dataset and as event area in the latter. Therefore, it can be anticipated that if the two datasets are merged into a single combined dataset, then in the resulting dataset, magnitude and frequency should also show an exponential relationship. To determine whether this view is valid, the depositional area of each event was converted to its equivalent volume.

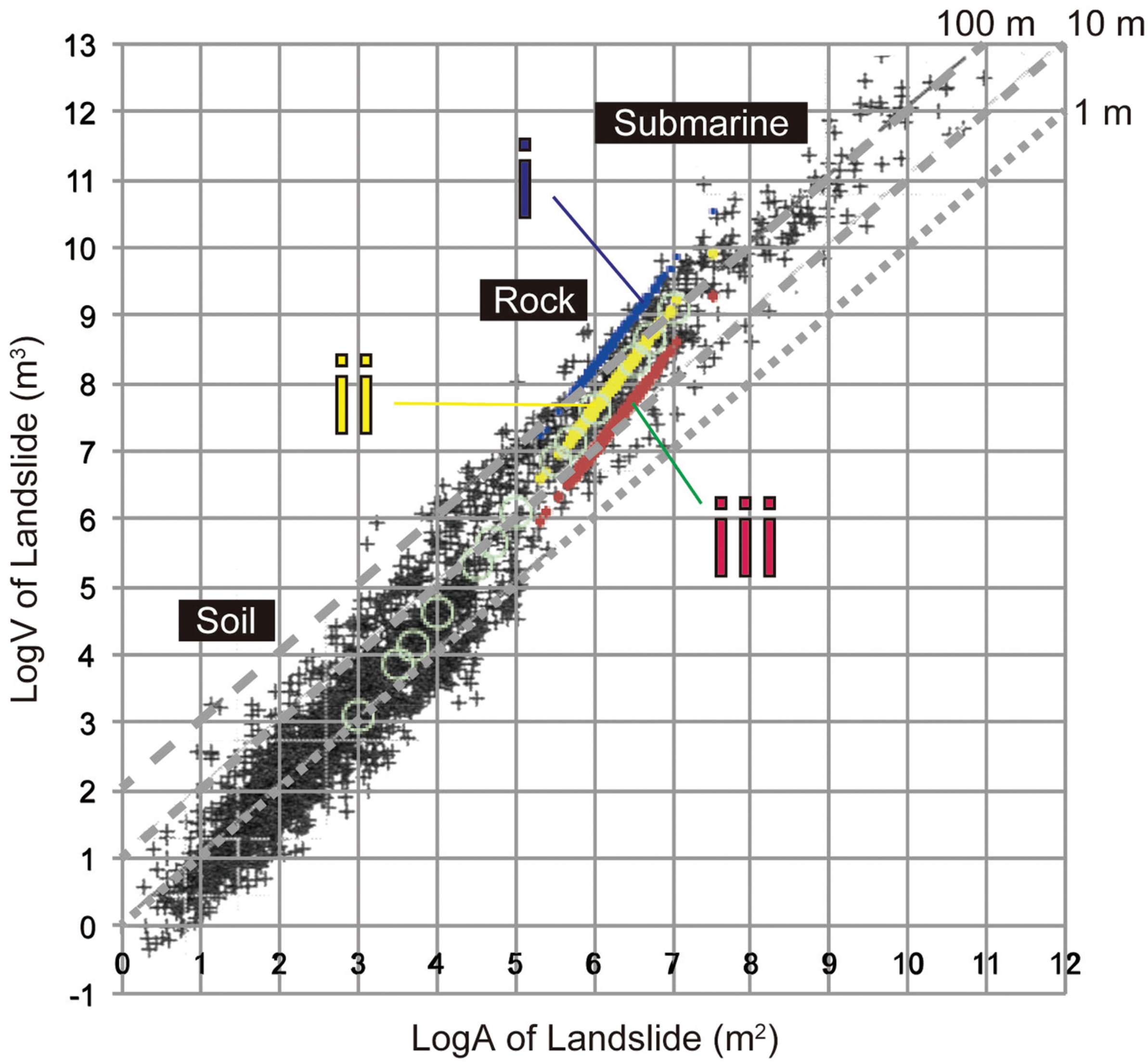

Figure 8. Relationship between log*A* and log*V* for about 4200 globally observed soil, bedrock, and submarine landslides [35, 36]. The two dashed lines and dotted lines shown in the figure indicate the average thicknesses of 100 m, 10 m, and 1 m, respectively. The colored data points were obtained by using relationships i, ii, and iii to estimate the areas of the 332 large-scale collapses of dataset 2. The 13 large circles show the relationship for events with areas of 10^3–10^7 m^2 (calculated by applying thickness-area relationship ii).

Korup [35], following Larsen et al. [36], performed volume-area scaling of about 4200 soil, bedrock, and submarine landslides (**Figure 8**). Here, the term "landslide" encompasses a wide variety of mass-movement types. Korup [35] reported that "more than half of ca. 4200 landslides with field-verified volume and area data have an average thickness of 1 m, a value largely controlled by local soil depth," and Larsen et al. [36] noted that large bedrock landslides produce much thicker deposits (10–100 m) than smaller ones. In the current author's experience, too, an increase in the areal magnitude of an event is associated with an increase in the average thickness of the collapsed landmass: the thickness of smaller mass movements is <10 m, whereas the thickness of the largest ones can be more than 100 m. Therefore, in this study, the average thickness of each of 332 events described in reference [26] was estimated as described below to produce a volume-based dataset that could be merged with mega-collapse dataset 1. Three possible thickness-area relationships were tested:

i. Average thickness is equivalent to the square root of the depositional area divided by 100.

ii. Average thickness is equivalent to the square root of the depositional area divided by 25.

iii. Average thickness is equivalent to the square root of the depositional area divided by 6.

Equivalent volumes of 332 events were calculated using each of the three relationships (i, ii, iii), and relationship ii was selected as the most appropriate because the resulting data points aligned in the central part of the larger global dataset (*N* = ca. 4200) (**Figure 8**). Therefore, the volumes of the 332 events of dataset 2 were calculated by multiplying the square root of the depositional area divided by 25. The calculated volumes ranged from 10^7 to 10^9 m^3, which agree well with the range of suggested volumes noted in reference [26].

Thus, the large-scale collapse and mega-collapse datasets were combined after converting the areal magnitudes to volume magnitudes as described above. Twelve events were included in both datasets, including Ura-Bandai, Bandai volcano (No. 22 in **Figure 1**, **Table 2**); Otsukigawa, Yatsugatake volcano (No. 44); and Mayuyama, Unzen volcano (No. 58). For these 12 events, the volume data reported in **Table 2** (dataset 1) were used in the analysis because they were based on geological and topographical evidence. Therefore, a total of 423 events, 103 from dataset 1 and 320 events from dataset 2, were analyzed to determine the magnitude (volume)-frequency distribution of collapses with volumes of 10^7–10^9 m^3 or larger.

The resulting distribution (**Figure 9**) was interpreted as exponential. The fitted values of *a* and *b* (Eq. (1)) were 8.67 and 0.80, respectively, and the correlation was extremely strong (R = -0.995), when the four smallest bins were excluded from the regression analysis (**Figure 10**). This exponential distribution thus represents the combined large-scale and mega-scale collapse dataset, which includes collapses with volumes of 10^7–10^9 m^3 or more in Japan.

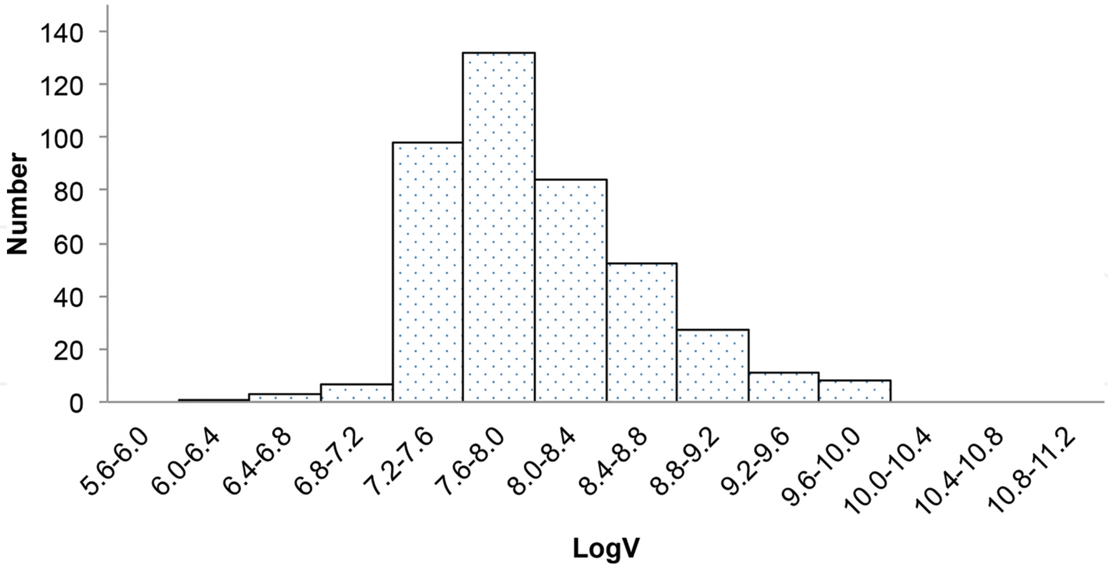

Figure 9. Magnitude (log*V*)-frequency histogram for 423 collapses with volumes greater than 10^7 m^3 (datasets 1 and 2 combined). The bin size is 0.4.

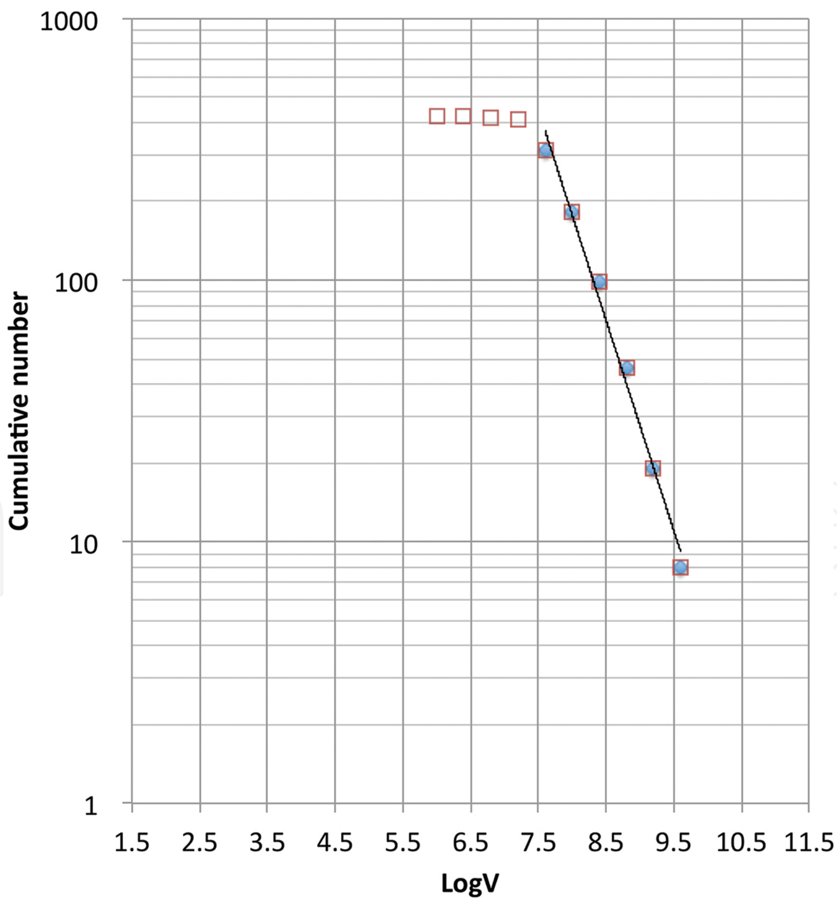

Figure 10. Regression analysis result for the 423 large-volume collapses in Japan, obtained by fitting Eq. (1) to the filled data points.

In Japan, most of slope failures with a volume of more than 10^9 m^3 occur on volcanic edifices, and the largest one known is the Middle Pleistocene sector collapse of Yatsugatake volcano, central Japan. This collapse produced the Nirasaki debris avalanche, whose volume has been estimated to be about 9×10^9 m^3 [37]. Drilling surveys in the Kofu depositional basin [38] have suggested that the actual volume was probably even larger, perhaps more than 10×10^9 m^3. On the other hand, by using the magnitude-frequency distribution determined above for collapses with volumes of $10^{7–9}$ m^3 or more in Japan, the maximum volume can be estimated as $10^{10.8}$ m^3 (=6.3×10^{10} m^3) (**Figure 10**). Thus, this volume estimate is of the same order of magnitude as well as with those of the largest known sector collapse volumes in other parts of the world, such as Shasta volcano, the United States (estimated volume, 4.6×10^{10} m^3); Avachinsky volcano, Kamchatka, Russia ($1.6–2.0 \times 10^{10}$ m^3); and Popocatépetl volcano, Mexico (2.8×10^{10} m^3) [11, 39].

In Japan, future mega-collapses with a comparable magnitude are most likely to occur on large stratovolcanoes with steep slopes. A prime candidate is Fuji volcano, the highest mountain in Japan (summit altitude ~3800 m, central Japan) (**Figures 1** and **11B**). The following discussion examines the likely magnitude of a mega-collapse on Fuji volcano by considering its geometry and comparing it with that of Bandai volcano, still another candidate volcano for a future mega-collapse event even though multiple slope failures occurred there previously.

Bandai volcano (**Figure 11A**) was the site of the Ura-Bandai event in AD 1888 (No. 22), which attracted attention globally [40]. The largest sector collapse in the history of Bandai volcano occurred in the Late Pleistocene, ca. 40 ka, and affected 30% of the volcano by area; this collapse created a horseshoe-shaped caldera on the southwestern side of the summit and produced the Okinajima debris avalanche deposits, which are distributed on the slope below the caldera [29]. If a similar proportion of Fuji volcano were to collapse, the maximum volume of the resulting mega-collapse would exceed 5×10^{10} m^3; this estimate is consistent with the maximum collapse volume of 6.3×10^{10} m^3 computed above from the magnitude-frequency distribution determined in this study. For a more realistic estimate, however, the difference in magma type between the Bandai and Fuji volcanoes should be taken into account. Bandai volcano is andesitic, and as a result the slopes of the volcanic edifice are relatively steep. By contrast, Fuji volcano, somewhat rare for Quaternary Japan, mainly produces basaltic lavas. As a result, the slopes, especially the lower slopes, of the Fuji volcanic edifice are gentler than those of Bandai volcano. Fundamentally, volcanic mega-collapses are triggered by gravitational instability in connection with the growth of the volcanic edifice [15]. Therefore, because the slopes of Fuji volcano are less steep, the area of the volcanic edifice that is susceptible to topographical instability should be smaller than the susceptible area of Bandai volcano. Note that in **Figure 11**, Bandai and Fuji volcanoes are shown at different map scales (the scale of the Bandai map is three times that of the Fuji map). The white circles on the maps are centered on the present summit of each volcano, and the area of Fuji volcano that is encircled is nine times the encircled area of Bandai volcano. In addition, the contour interval is 100 m on the Bandai map and 300 m on the Fuji map. Thus, the relative steepness of the two volcanic edifices can be visually compared. The source area of a possible mega-collapse of Fuji volcano may be roughly within the area defined by the white circle, which was determined by the reference to the case

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of Bandai volcano. If 30% of the area enclosed by the circle collapsed, the estimated volume of the Fuji volcanic edifice that would be involved in the collapse is 2×10^{10} m^3; this volume is equivalent to the second or third largest event in the magnitude-frequency distribution.

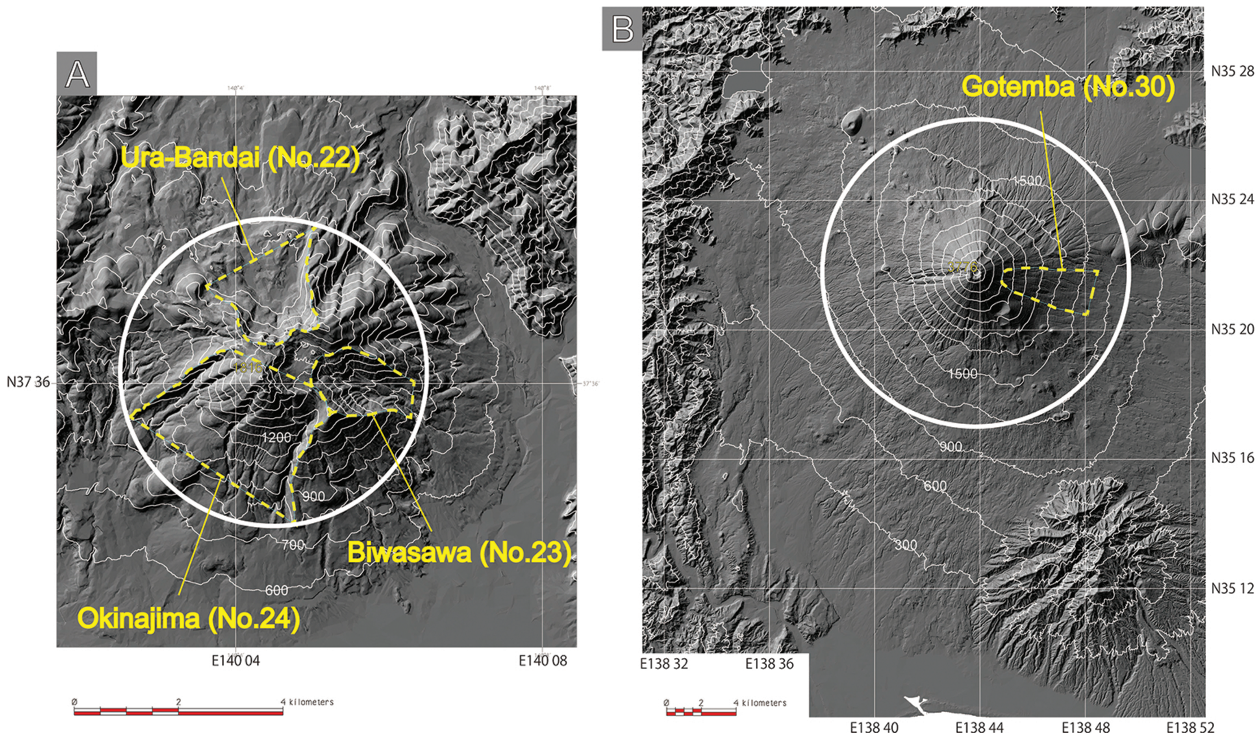

Figure 11. Topography of Bandai (A) and Fuji (B) volcanoes, both on Honshu Island. The dashed yellow lines outline collapse calderas. The white circle on Bandai volcano is drawn to enclose the three collapse scars (A). A white circle of the same relative size is centered on the summit of Fuji volcano (B).

6. Examination of smaller-scale rapid mass movements

The volume range ($10^{7–9}$ m^3) of the very large events discussed so far is equivalent to a depositional area of more than $10^{5.5–6}$ m^2. The question arises of whether the relationship between magnitude and frequency of these very large collapses, including catastrophic volcano sector collapses, is similar to the relationship for much smaller, more frequently observed events. To answer this question, rapid mass movements recorded in Japan during 1975–1983 [10] (dataset 3) were examined. These slope failure events have an areal range from 10^3 to 10^7 m^2; thus, their magnitudes in terms of area are smaller than those of the larger collapses examined in the previous sections of this chapter.

In this analysis, rapid mass-movement data for rocky mudflows and steep slope collapses [10], a total of 2083 events, were considered (see Section 2). Although a few of these events might not fit the criterion of this study for a rapid mass movement, the number would be sufficiently small that they would not significantly affect the results of the following statistical analysis.

First, the depositional areas were converted into equivalent volumes. Each event was identified on 1:25,000 or 1:50,000 topographic maps, and the depositional area was measured in hectares. Then, Ohmori and Hirano [10] divided their log*A* values from 3.0 to 7.0 into 13 bins. Here, these areas were converted to volumes (by multiplying the depositional area by the twenty-fifth part of its square root), and the resulting log*V* values ranged from 3.12 to 9.10 (13 plotted circles in **Figure 8**).

These equivalent volume data show an exponential relationship between magnitude and cumulative frequency, and Eq. (1) can be fitted to the entire dataset (R = -0.975). Nonetheless, it is also possible to fit two regression lines to the magnitude-frequency data (**Figure 12**), using as a cutoff value log*V* around 5.0–5.5. Therefore, the five smallest (log*V* <5.5; **Figure 12A**), or the four smallest bins (log*V* <5.0; **Figure 12B**), were analyzed separately from the larger bins. In the former case, the correlation coefficients are -0.990 and -0.985 (**Figure 12A**), and in the latter case, they are -0.980 and -0.986 (**Figure 12B**), for the smaller and larger bins, respectively. Thus, the correlation coefficients for the larger events are almost the same between the two cutoff values, whereas those for the smaller events are somewhat different. Here, the regression function for events with log*V* greater than ~5.5 is considered to effectively represent the trend of the combined rocky mudflow and steep slope collapse data. When Eq. (1) was fitted to the events with log*V* >5.5, the fitted values of *a* and *b* were 6.90 and 0.77, respectively.

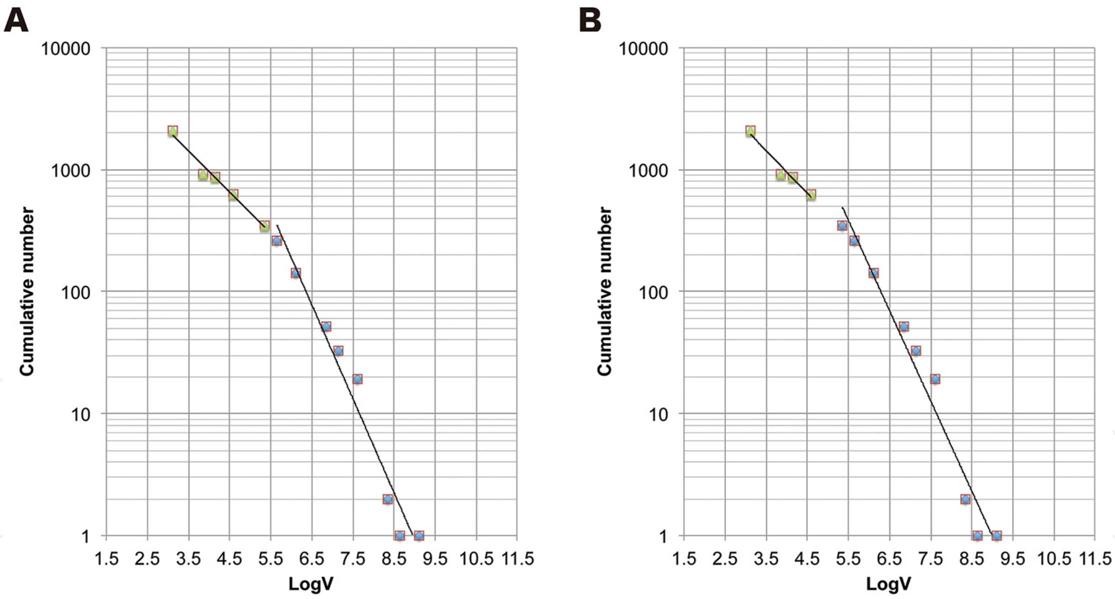

Figure 12. Results of regression analyses of 2083 smaller events in Japan, obtained by fitting Eq. (1) separately to the green and blue data points with a cutoff value of log*V* = 5.5 (A) or 5.0 (B).

The value of *b*, 0.77, is surprisingly close to the value (0.80) obtained for the combined dataset of very large (>10^7 m^3) collapses, as described in Section 5, although they were obtained from two completely independent datasets. Basically, *b* is the slope coefficient, and when *b* is positive, it shows the rate of decrease in the cumulative number of events as the magnitude increases. Thus, its value can potentially vary over a wide range. Nevertheless, these data for

Japan show that for slope failure events with volumes of more than $10^{5.5}$ m^3, b is uniformly in the range of 0.7–0.8. The value of b may depend on the geological or geomorphological setting, and various b values have been recognized for different local study areas [7, 10]. However, the present result suggests that in an analysis targeting all of Japan, it is unnecessary to take into account the local setting and that a single regression formula with a constant b value can be unambiguously derived.

7. How frequently do mega-collapses of volcanic edifices occur in Japan?

By using the results of the regression analysis of very large collapses ($V > 10^7$ m^3) in Japan, based on the combined dataset of large-scale and mega-collapses, and taking into account the results obtained in Section 6 for events with $V > 10^{5.5}$ m^3, some statistical values respecting slope failures with volumes of more than $10^{5.5}$ m^3 can be calculated. The magnitude-frequency relationship of slope failures of this magnitude can be expressed as follows:

$$\log N(x) = 8.67 - 0.80x \tag{3}$$

By using Eq. (3) with a minimum value of x of 5.6, the cumulative number of events can be calculated to be 14,941. Because all of the analyzed events occurred after the Middle Pleistocene, the empirical relationship expressed by Eq. (3) reflects the situation during the last 800,000 years in Japan. Thus, the recurrence interval of events of a certain magnitude (more than $10^{5.5}$ m^3) can be calculated as follows [7, 10]. First, Eq. (1) is rewritten as

$$F(x) = N(x) = 10^{a}\,10^{-bx}. \tag{4}$$

Then, the probability (p(x)) that an event with a magnitude equal to or greater than a certain magnitude (x) has a cumulative frequency $F(x)$ which is calculated as

$$p(x) = F(x) / F(x_0) = 10^{-b(x-x_0)}, \tag{5}$$

where x_0 is the recorded minimum magnitude (5.6 in this study). Further, if the total number of recorded events occurred during a certain time span, then the recurrence interval (y) between events with a magnitude greater than or equal to a certain value x is calculated as

$$r(x) = 1 / p(x) / n \tag{6}$$

where n is the total number of events. Thus, probabilities and recurrence intervals were calculated using Eqs. (5) and (6) for various values of x and three time spans by way of experiment (**Table 4**). For example, if a time span of 0.8 My is assumed, then the calculated recurrence interval of events with a magnitude (log$V$) of 8.0 is ~4500 years. However, a large number of mega-collapses (i.e., volume ≥10^8 m^3) may have occurred in the last 100,000 years (**Figure 13**) [25], which suggest that the recurrence interval of 4500 years might be too long. Further, although the occurrence date of some events in dataset 2 is not clear [25], most of them probably occurred since the Late Pleistocene. This assumption is reasonable because many landforms in Japan older than the Late Pleistocene are no longer identifiable, owing to rapid crustal movements and the humid climatic conditions, which cause topographical changes to be extremely rapid [4, 5]. More specifically, although a few of the oldest (and largest) events occurred around a million years ago, it is probably impossible to recognize every event that occurred during the last million years.

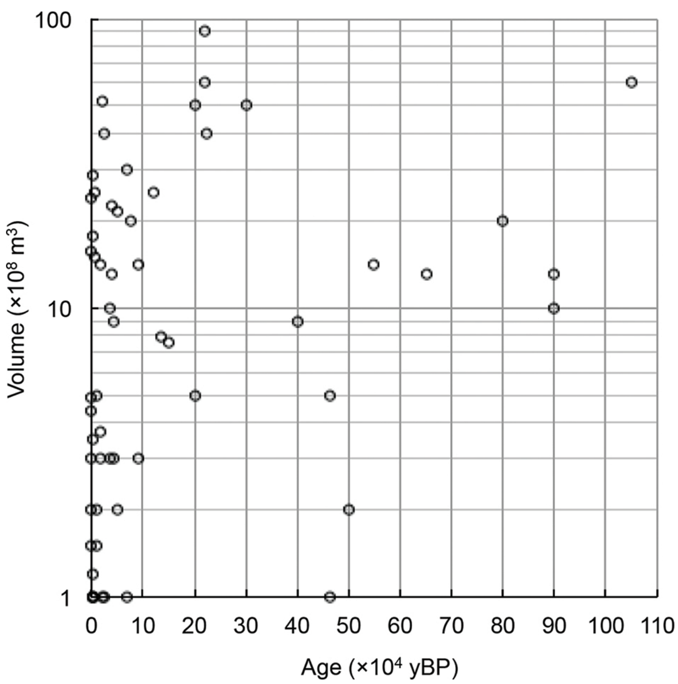

Figure 13. Occurrence ages of mega-collapses with volume ≥10^8 m^3 in Japan.

Therefore, it is necessary to select a realistic and suitable time span to which the magnitude-frequency relationship obtained in this study can be applied. Thus, the recurrence interval of events with a volume of 10^8 m^3 for time spans of 40,000 or 20,000 years, for an experiment, was computed to be about 230 and 110 years, respectively (**Table 4**). These computed values were then compared with such events occurring in the last thousand years (**Table 2**). During the past millennium, nine events with volumes of more than 10^8 m^3 occurred (**Table 5**), for a recurrence interval of 110 years. This corresponds well with the recurrence interval computed for a time span of 20,000 years. Among the nine events, the volume of the two largest, the Shikabe lobe of the Kurumizaka debris avalanche, Oshima Komagatake volcano, and the Nishiyama debris avalanche of Oshima-Oshima, both in Hokkaido (see **Figure 1**), each exceeds 10^9 m^3. More strictly, their volumes are $10^{9.2–9.3}$ m^3 (one has a volume of $10^{9.2}$ and the other a volume of $10^{9.3}$ m^3). For time spans of 20,000–40,000 years, the computed recurrence interval of events of such magnitude is 1000–2000 years. Among events with magnitude 10^9 m^3, the

Kisakata debris avalanche of Chokai volcano and the Gotemba debris avalanche of Fuji volcano occurred 2600 and 2900 years ago, respectively (**Table 2**, locations shown in **Figure 1**). Thus, in the last 3000 years, four mega-collapses (volume >10^9 m^3) have occurred. This result concords well with the recurrence interval of 700–1400 years computed under the assumption that the magnitude-frequency distribution determined in this study is applicable over a time span of 20,000–40,000 years for events with their volumes of 10^9 m^3.

Log *V*	**Cumulative frequency among 423 events**	**Estimated frequency**	**Probability p(*x*)**	**Recurrence interval (*y*)**		
				0.8 My	**40 ky**	**20 ky**
9.6	8	9	0.0006	87217.1	4360.7	2180.3
9.2	19	19	0.0013	41630.6	2081.4	1040.7
8.8	46	40	0.0027	19871.2	993.5	496.8
8.4	98	84	0.0056	9484.9	474.2	237.1
8.0	182	177	0.0118	4527.4	226.4	113.2
7.6	314	370	0.0248	2161.0	108.0	54.0
7.2	412	776	0.0519	1031.5	51.6	25.8
6.8	419	1625	0.1088	492.4	24.6	12.3
6.4	422	3404	0.2278	235.0	11.8	5.9
6.0	423	7132	0.4773	112.2	5.6	2.8
5.6	-	14941	1.0000	53.5	2.7	1.3

Estimated collapses (N = 14941; log$V$ ≥5.6); a' = 468854337.7, b = 0.802972851

Table 4. Statistical results of estimated frequency, probability of occurrence, and recurrence intervals of the events with volume ≥$10^{5.6}$ m^3 in Japan.

No. (from Table 2)	**Volcano**	**Debris avalanche**	**Date (AD)**	**Volume ×$10^8 m^3$**
49	Hakuba-Oike	Hiedayama	1911	1.5
22	Bandai	Ura-Bandai	1888	4.9
48	Tateyama	O-Tombi	1858	1.3-2.7
58	Unzen	Mayuyama	1792	4.4
42	Asama	Kambara	1783	1.38
6	Oshima-Oshima	Nishiyama	1741	24
5	Komagatake (Oshima)	Kurumizaka (Onuma)	1640	3
4	Komagatake (Oshima)	Kurumizaka (Shikabe)	1640	14.2–17.0
44	Yatsugatake	Otsukigawa	888	3.5

Table 5. Collapse events with volume ≥10^8 m^3 during the past millennium in Japan .

Even when much smaller events are considered, the findings are still reasonable. The smallest events with magnitudes of $10^{5.6–6.0}$ m^3 have recurrence intervals of 1.3–2.7 or 2.8–5.6 years. Because many such relatively small slope failures have obviously occurred in recent years in Japan, these results should be close to reality. For example, the magnitude of a slope failure on Izu-Oshima Island (location shown in **Figure 1**) in 2013 corresponds to an event that should recur every several years (debris flow volume estimated to be >10^6 m^3). Similarly, slope failures (non-volcanic) such as those that occurred in Hiroshima City in 2014 might be expected to recur once every 1–3 years (numerous slope failures with an estimated maximum sediment volume of several tens of thousands of cubic meters occurred approximately simultaneously as a result of heavy rainfall). Thus, when records for the past millennium in Japan are considered, the magnitude-frequency relationship proposed in this study substantially reflects the real situation during the last several tens of thousands of years.

Finally, how often is a given volcano likely to experience an extremely large collapse (volume >10^9 m^3)? Certainly, the answer will differ depending on the volcano. Therefore, the question should be phrased in another way: in all of Japan today, how often can such a huge-scale collapse be expected to occur? This question can be answered by referring to some well-known examples. Some volcanoes in Japan have experienced collapses of this magnitude more than once. Multiple huge-scale collapses have been recorded during the last 0.10–0.15 My for Iwate, Chokai, Shirataka, and Bandai volcanoes (locations shown in **Figure 1**). This information suggests that a similar volcanic body will experience a huge slope failure (>10^9 m^3) about every 50,000 years. If at any given time, 25–50 candidate volcanoes for such a huge collapse exist, then one should occur at least every 1000–2000 years somewhere in Japan. This recurrence interval range is of the same order as that calculated by using Eq. (6) as shown above.

8. Concluding remarks

This study aimed to explore the characteristics of the magnitude-frequency distribution of mega-scale slope failures in Japan, which often occur on the flanks of mature volcanoes. Despite the importance of this topic for possible mitigation of disasters caused by huge and rapid mass movements, few studies have addressed it, mainly because relatively few such gigantic events occur within a short time period, though large amounts of data on much smaller collapses are available for statistical analysis. Such huge events (e.g., with volume >10^8 m^3) have been recognized as not only "usual" in a geological context but also significant in terms of the geomorphic development of volcanic (or mountain) bodies and surrounding areas, as shown by the catastrophic event associated with the eruption of Mt. Saint Helens. However, to date, knowledge of such events has been mainly qualitative. To deepen our understanding of volcanic mega-collapses in Japan, this study used a statistical approach.

Three datasets were used for statistical analysis as follows:

1. Volcanic mega-collapses in Japan, comprising 59 events with a volume of more than 10^8 m^3 and eight with a volume of more than 10^7 m^3.

2. Large-scale slope failures in Japan, comprising 332 events with an estimated volume on the order of $10^{7–9}$ m^3 (from the original data of area with $10^{5–7}$ m^3). More than 74% of these originated on volcanic bodies and in volcanic terrains.

3. Smaller rapid mass movements in Japan (rocky mudflows and steep slope collapses) recorded between 1975 and 1983 by the former Ministry of Construction of Japan. The estimated volume range of these events is $10^{3–9}$ m^3 (from the original data of area with $10^{3–7}$ m^3).

Datasets (1) and (2) were used to show that the magnitude-frequency distribution of slope failures with volumes greater than or equal to 10^7 m^3 can be fitted by an exponential equation. For these events, the slope coefficient (b in Eq. (1)), which represents the rate of decrease in the cumulative frequency with increasing magnitude, was about 0.7 or 0.8; thus, smaller events occur more frequently. In addition, a reanalysis of dataset (3) showed that a comparable constant b value could be obtained for events with volumes greater than or equal to $10^{5–6}$ m^3. These results show that the frequency-magnitude relationship of mega-collapses is similar to that of such smaller events. This finding leads to the conclusion that b may be 0.7–0.8 for all Japanese slope failures with volumes from about 10^5 m^3 (not necessarily volcanic) to 10^{10} m^3 (generally volcanic). Recent records for the past millennium or so in Japan show that the obtained magnitude-frequency relationship substantially reflects the situation during the past several tens of thousands of years. This finding allows the probability and recurrence interval of an event with a certain magnitude to be estimated. For example, mega-collapses with a volume more than 10^9 m^3 should recur at least every 1000–2000 years somewhere in Japan, from a probabilistic viewpoint. This geo-statistical investigation indicates that mega-collapses are not so much “rare” events as “millennial” events in Japan.

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