Two seismic gaps on the Sagaing Fault, Myanmar, derived from relocation of historical earthquakes since 1918

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[1] Relocation of six M (magnitude) ≥ 7.0 earthquakes near the Sagaing Fault in Myanmar since 1918 allows us to image earthquake history along the Sagaing Fault. All the earthquakes were relocated on the Sagaing Fault by using the modified joint hypocenter determination method. Combining the relocated epicenters with information on foreshocks, aftershocks, seismic intensities, and coseismic displacement, we estimated the location of the fault plane that ruptured during each earthquake. This analysis revealed two seismic gaps: one between 19.2°N and 21.5°N in central Myanmar, and another south of 16.6°N in the Andaman Sea. Considering the length of the first seismic gap (~260 km), a future earthquake of up to M ~7.9 is expected to occur in central Myanmar. Because Nay Pyi Taw, the recently established capital of Myanmar, is located on the expected fault, its large population is exposed to a significant earthquake hazard. **Citation:** Hurukawa, N., and P. Maung Maung (2011), Two seismic gaps on the Sagaing Fault, Myanmar, derived from relocation of historical earthquakes since 1918, *Geophys. Res. Lett.*, *38*, L01310, doi:10.1029/2010GL046099.

1. Introduction

[2] The northeastern margin of the Indian Plate is subducting beneath the Burma Plate, forming the Burma Arc (Figure 1), and shallow and intermediate-depth earthquakes occur along the Burma subduction zone [e.g., *Frohlich*, 2006; *Kayal*, 2008]. Many strong, shallow earthquakes occur near the Sagaing Fault, and many such events have caused severe damage in Myanmar. The Sagaing Fault is an active right-lateral strike-slip fault that strikes north–south through Myanmar and into the Andaman Sea, and is a transform fault between the Burma and Sunda plates [e.g., *Le Dain et al.*, 1984; *Guzman-Speziale and Ni*, 1996]. The displacement rate on the fault is 18 mm/yr obtained by GPS observation, indicating a short recurrence interval for large earthquakes [*Socquet et al.*, 2006].

[3] Six M ≥ 7.0 earthquakes occurred near the Sagaing Fault during the years 1930 and 1956 (Figure 2a), resulting in severe damage in Myanmar, including 610 deaths, the generation of landslides, and liquefaction [*Chhibber*, 1934; *Satyabala*, 2002; *Utsu*, 1992]. Although no M ≥ 7.0 earthquakes have occurred since 1957, these inland earthquakes are a hazard in Myanmar, as are giant tsunamigenic earthquakes in the northern Bay of Bengal [*Cummins*, 2007]. To enable an assessment of earthquake hazards in the region, it is necessary to determine the precise locations of past large earthquakes and to predict the locations of future earthquakes. Therefore, to identify the fault planes that ruptured during large earthquakes of the past, it is important to identify seismic gaps because such gaps indicate future earthquakes. However, the precise locations of epicenters and faults related to large earthquakes remain unknown. Although, the International Seismological Summary (ISS) reported hypocenter locations and phase data for earthquakes in the world since 1918, the location data may contain large uncertainties because of the limited number of available seismic stations and because of inaccurate readings of some seismic phases. Therefore, in the present study, we relocated the six M ≥ 7.0 earthquakes with the aim of improving the accuracy of their estimated locations.

2. Data and Method

2.1. Method

[4] We used the modified joint hypocenter determination (MJHD) method [*Hurukawa and Imoto*, 1992; *Hurukawa*, 1995] to relocate earthquakes precisely. Locating a group of earthquakes simultaneously, the MJHD method yields a marked improvement in the accuracy of hypocenter locations by removing the effects of lateral heterogeneity within the Earth, using a station-correction term. Although the arrival times of historical earthquakes include large reading errors, the MJHD method can clearly discriminate reading errors from station corrections. Because data are only available from a small number of stations, especially nearby stations that record historical earthquakes, we fixed the focal depths of all earthquakes to 15 km in this study.

2.2. Data

[5] In the present study, we relocated the six M ≥ 7.0 earthquakes. Combining data for recent M ≥ 6.0 earthquakes recorded by a relatively large number of stations, we relocated all the earthquakes simultaneously using the MJHD method. We selected earthquakes with focal depths shallower than 60 km that occurred between 1918 and 2006 (Figure 2a). We prepared two datasets. The first dataset included all the M ≥ 7.0 earthquakes during 1918–1963, for which phase data are available from ISS (Table 1). Note that we used the surface-wave magnitude M_S for M ≥ 7.0 earthquakes, except the first event in 1946, for which M_S information is unavailable; for this event, we used the body-wave magnitude m_B [*Abe*, 1981]. We also analyzed the two immediate foreshocks of the December 1930 earthquake and one immediate aftershock of the January 1931 earthquake. The second dataset included nine M ≥ 6.0 earthquakes that occurred during 1964–2006, as reported by the International

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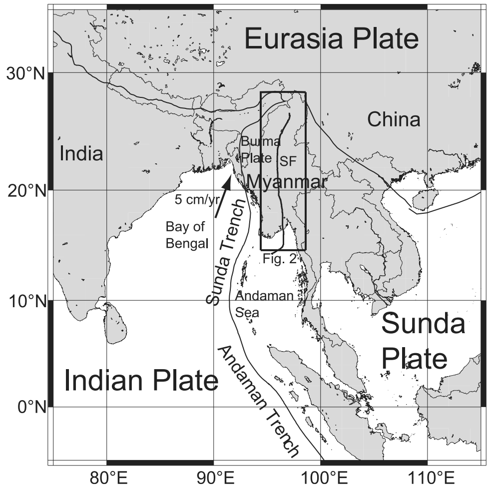

Figure 1. Regional map showing the tectonic setting of Myanmar and surrounding areas. SF represents the Sagaing Fault [*Nielsen et al.*, 2004]. A thick arrow indicates the direction of relative motion between the Indian and Eurasian Plates near Myanmar [*DeMets et al.*, 1994]. The rectangle indicates the area shown in Figure 2.

Seismological Centre (ISC) (Table 1). Note that we used the surface-wave magnitude *Ms* and the body-wave magnitude *Mb* for $M \geq 6.0$ earthquakes reported by the ISC, except the January 1991 earthquake (M_S 7.2, M_W 6.9), for which we used the moment magnitude M_W by the global CMT solution (*Dziewonski et al*. [1981] and later updates).

[6] The relocations were based solely on *P*-arrival times, because the reading accuracy of *P* phases is much higher than that of *S* phases. In using the MJHD method, the accuracy of the solutions is higher when *S* phases are ignored [*Hurukawa et al.*, 2008]. The criteria employed for station and event selection were as follows: each event must be recorded by at least five stations, and each station must record at least five events. Using these criteria, we selected 364 stations worldwide. Using only *P*-wave arrival times with travel-time residuals less than 10 seconds, we accurately relocated the hypocenters of all 18 earthquakes using the MJHD method (Table 1).

2.3. Minute Correction

[7] It is well known that the operators who picked phases during the early days of seismology sometimes misread the minute marks [*Hurukawa et al.*, 2008]; consequently, although the arrival times measured in seconds were correct, some of arrival times measured in minutes were wrong. To increase the number of available phase arrivals, we carefully examined the readings and corrected any artificial errors regarding the arrival times in minutes. For example, two immediate foreshocks of the December 1930 earthquake were reported in the focal area [*Chhibber*, 1934], whereas the ISS epicenter of the first event is located ~300 km south of the towns where the event was felt. Comparing the differences in travel time between the mainshock and foreshocks at common stations, we found that differences were concentrated at multiples of ±60 s, indicating the misreading of minute marks, which we then corrected. The corrected data indicates that the first foreshock was located ~130 km north of the mainshock and is consistent with the felt areas reported.

3. Results

[8] The $M \geq 7.0$ earthquakes were relocated to areas very close to the Sagaing Fault (Figure 2b); consequently, we concluded that all the earthquakes had occurred along this fault. To estimate the location of the fault plane for each earthquake, we combined the relocated precise epicenters and information on foreshocks, aftershocks, the distribution of seismic intensities, and coseismic displacement. This enabled us to estimate the faults ruptured by the five earthquakes listed below.

[9] The 5 May 1930 earthquake (*M* 7.4), known as the Pegu or Bago earthquake, was relocated ~60 km NNE of the ISS location. Coseismic displacements caused by this earthquake were observed between 16.6°N and 17.3°N [*Tsutsumi and Sato*, 2009], in good agreement with the area

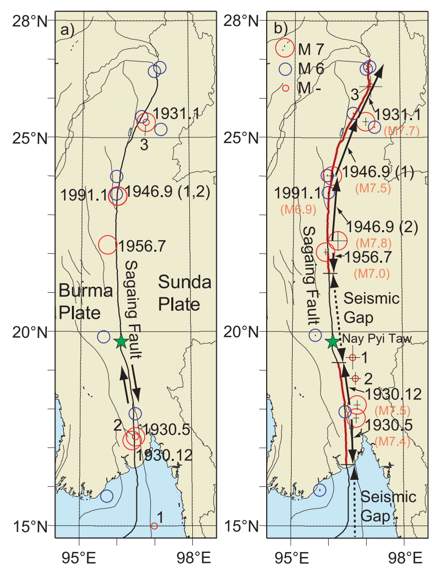

Figure 2. Epicentral distribution of 18 earthquakes analyzed in this study. (a) Epicenter locations according to ISS (International Seismological Summary) and ISC (International Seismological Centre) data. (b) Locations of epicenters relocated by the MJHD (Modified Joint Hypocenter Determination) method in this study. Red and blue circles indicate earthquakes before and after 1964. The numbers assigned to each earthquake indicate the year and month of $M \geq 7.0$ earthquakes and of the January 1991 earthquake. Numbers 1 and 2 (not in parentheses) indicate foreshocks of the December 1930 earthquake; number 3 indicates an aftershock of the January 1931 earthquake. Because two earthquakes occurred in September 1946, their sequence is indicated by numbers in parentheses. Large, intermediate, and small open circles indicate earthquakes with $M \geq 7.0$, $M \geq 6.0$, and unknown magnitude, respectively. Red lines in Figure 2b show the fault planes of the $M \geq 7.0$ earthquakes analyzed in this study. Solid arrows indicate the rupture directions of the $M \geq 7.0$ earthquakes. The paired arrows in Figure 2a indicate the sense of movement along the Sagaing Fault. Dotted arrows in Figure 2b indicate seismic gaps. The green star denotes Nay Pyi Taw, a new capital of Myanmar.

Table 1. List of Relocated Hypocenters of Earthquakes[a]

Date (y/m/d)	Time	Origin	Time (s)	Longitude (°N)	Latitude (°E)	Z	M	Type Name
1930/05/05	13:46	2.64 ± 0.64	96.73 ± 0.08	17.78 ± 0.13	15	7.4	M_S[b]	Pegu (Bago)
1930/12/03	15:42	22.83 ± 2.01	96.65 ± 0.20	19.34 ± 0.32	15	–		
1930/12/03	16:36	25.69 ± 1.31	96.72 ± 0.15	18.80 ± 0.17	15	–		
1930/12/03	18:51	45.49 ± 0.72	96.76 ± 0.10	18.12 ± 0.13	15	7.5	M_S[b]	Pyu
1931/01/27	20:09	16.80 ± 0.59	97.02 ± 0.09	25.41 ± 0.11	15	7.7	M_S[b]	Kamaing
1931/01/30	3:32	30.06 ± 1.87	97.17 ± 0.33	26.31 ± 0.28	15	–		
1946/09/12	15:17	21.01 ± 0.76	96.09 ± 0.12	24.02 ± 0.12	15	7.5	m_B[c]	
1946/09/12	15:20	20.97 ± 1.39	96.24 ± 0.26	22.35 ± 0.25	15	7.8	M_S[b]	
1956/07/16	1:57	6.95 ± 0.45	95.90 ± 0.06	22.06 ± 0.08	15	7.0	M_S[b]	Sagaing
1976/08/12	23:26	46.54 ± 0.17	97.05 ± 0.03	26.77 ± 0.03	15	6.2	Mb[d]	
1991/01/05	14:57	13.42 ± 0.13	95.97 ± 0.02	23.59 ± 0.03	15	6.9	M_W[e]	Tagaung
1991/04/01	3:53	7.40 ± 0.19	95.77 ± 0.03	15.93 ± 0.04	15	6.3	Ms[f]	
1992/06/15	2485	7.89 ± 0.13	95.94 ± 0.02	24.03 ± 0.03	15	6.3	Ms[f]	
1994/01/11	0:51	59.29 ± 0.11	97.27 ± 0.02	25.27 ± 0.02	15	6.0	Ms[f]	
1994/11/21	8:16	36.83 ± 0.11	96.67 ± 0.02	25.63 ± 0.02	15	6.0	Ms[f]	
1995/05/16	21:48	9.02 ± 0.14	96.44 ± 0.02	17.94 ± 0.03	15	6.1	Ms[f]	
2000/06/07	21:46	55.43 ± 0.10	97.15 ± 0.01	26.83 ± 0.02	15	6.5	Ms[f]	
2003/09/21	18:16	16.29 ± 0.11	95.63 ± 0.02	19.91 ± 0.02	15	6.8	Ms[f]	Taungdwingyi

[a]Z = depth in km (fixed), M = magnitude, Type = magnitude type.
[b]M_S [*Abe*, 1981].
[c]m_B [*Abe*, 1981].
[d]Mb (International Seismological Centre).
[e]M_W (*Dziwonski et al.* [1981] and later updates).
[f]Ms (International Seismological Centre).

in which high intensities were reported. In terms of the modified Rossi–Forel Intensity scale used in Burma, areas between 16.7°N and 17.3°N recorded an intensity of IX (extremely strong shock: partial or total destruction of most of the masonry buildings of the types constructed in Burma), and areas between 16.6°N and 17.5°N recorded an intensity of VIII (very strong shock: widespread cracking in the walls of buildings; some houses collapse; most pagodas damaged) [*Satyabala*, 2002]. Therefore, the epicenter of the Pegu earthquake was located north of these areas (Figure 2b). This finding indicates that the rupture propagated southward and that the length of the fault was approximately 131 km.

[10] The 3 December 1930 earthquake (M 7.5), known as the Pyu earthquake, was relocated ~40 km north of the Pegu earthquake. Rossi–Forel Intensities IX and VIII were distributed between 18.2°N and 18.7°N and between 17.9°N and 19.4°N, respectively [*Satyabala*, 2002], located north of the epicenter. The two foreshocks that occurred on the same day were relocated ~100 km north of the mainshock (earthquakes No. 1 and 2 in Figure 2), while the ISS located one of them ~250 km south of the mainshock (Figure 2). Furthermore, fissures, sand vents, and water vents developed between 17.9°N and 19.2°N [*Satyabala*, 2002]. Therefore, the rupture associated with this earthquake is estimated to have propagated northward. Based on these observations, the northern end of the fault that ruptured during the Pyu earthquake is considered to be located at ~19.2°N and the length of the fault plane is estimated to be 120 km (Figure 2b).

[11] Two M 7 earthquakes occurred within a 3-minute interval on 12 September 1946. Although the ISS located these events at the same epicenter, we were able to locate their epicenters independently with high accuracy (Figure 2). The differences of arrival times of the two events clearly indicate the difference of their epicenters. The first event (M 7.5) was relocated ~60 km north of the ISS location, while the second event (M 7.8) was relocated 185 km south of the first event. Because the epicenter of the second event is close to that of the January 1956 earthquake, it is natural to consider that the fault plane of the second event is located north of the epicenter. We consider that the rupture propagated as far as the epicenter of the first event and that the fault length of the second event was approximately 185 km (Figures 2 and 3a). We consider that the first event ruptured northward as far as the epicenter of the January 1931 earthquake, along a fault length of 155 km (Figures 2 and 3a).

[12] The 5 January 1991 earthquake (Mw 6.9) was immediately followed by two aftershocks located 30 and 49 km north of the mainshock; the June 1992 earthquake (M 6.3) occurred at the same site as the second aftershock. Accordingly, we conclude that the 1991 earthquake ruptured northward along a fault length of 49 km (Figure 3a).

[13] Based on the fault lengths of the five earthquakes outlined above, we established the following relationship between the magnitude (M) and fault length (L) of large earthquakes along the Sagaing Fault, referring to a previous study [*Utsu*, 1961]: $\log (L) = 0.66\ M - 2.83$ (Figure 3b). This formula was used to estimate the fault lengths of two other earthquakes, as follows.

[14] The 27 January 1931 earthquake (M 7.7) was relocated near the northern edge of the 1946 doublet. The fault length is estimated to have been ~180 km, based on the M–L relation. Therefore, the rupture is estimated to have been located north of the epicenter (Figures 2 and 3a). The aftershock on 30 January (earthquake No. 3 in Figure 2) was relocated at ~100 km north of the epicenter of the mainshock, which is consistent with our interpretation regarding the location of the fault plane of the mainshock.

[15] The 16 July 1956 earthquake (M 7.0) was relocated very close to the second event of the 1946 doublet. Therefore, the fault plane of the 1956 earthquake is estimated to have been located south of the epicenter, and its length is

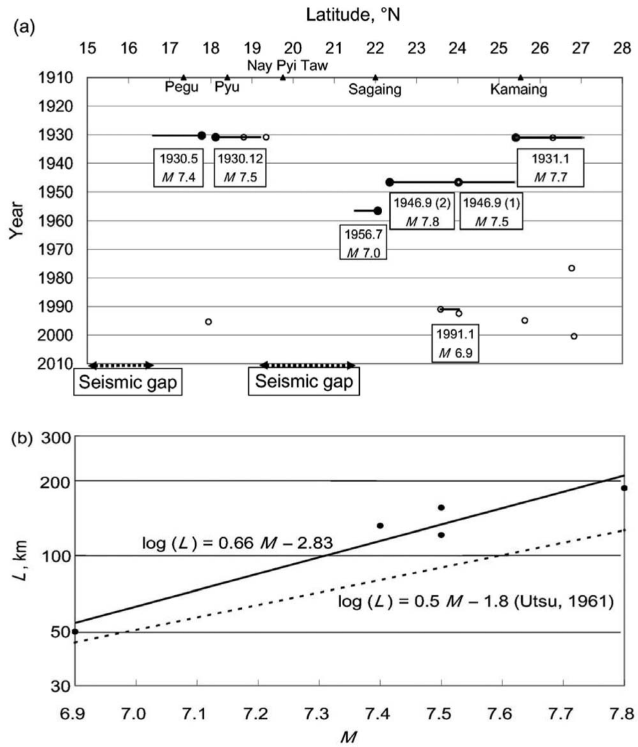

Figure 3. (a) History of earthquakes along the Sagaing Fault. Large solid circles indicate $M \geq 7.0$ earthquakes relocated in this study. Small open circles indicate $M < 7.0$ earthquakes relocated in this study. Horizontal bars represent the extent of the ruptured fault for each earthquake, as estimated from factors such as foreshocks, aftershocks, the distribution of seismic intensities, and displacement. Also shown are seismic gaps (double-headed arrows at the base of the figure) and the locations of towns (triangles at the top of the figure) after which the earthquakes are named, as well as the location of Nay Pyi Taw—the capital of Myanmar. (b) Relationship between magnitude (*M*) and length (*L*) of the fault plane of the earthquake on the Sagaing Fault. The solid line indicates best fit to the data. For reference, the formula calculated for shallow earthquakes in Japan is also shown by the broken line [*Utsu*, 1961].

estimated to have been ~60 km, based on the *M–L* relation (Figures 2b and 3a).

4. Seismic Gaps

[16] We identified two seismic gaps along the Sagaing Fault (Figures 2b and 3a). The first exists between 19.2°N and 21.5°N in central Myanmar, with a length of ~260 km, corresponding to *M* 7.9 according to the *M–L* relation. Although the *M* 7.7 Maymyo (Burma) earthquake occurred at ~21°N on 23 May 1912, it occurred along the Kayukkyan Fault, ~80 km east of the Sagaing Fault [*Chhibber*, 1934; *Satyabala*, 2002]. Previous studies on the magnitudes of large shallow earthquakes from 1897 have reported that no other $M \geq 7.0$ earthquake occurred in central Myanmar between 1897 and 1918 [*Abe*, 1981; *Abe and Noguchi*, 1983a, 1983b]. Therefore, at least 113 years has passed since the last earthquake in this seismic gap. The recurrence interval of May 1930-type earthquakes (*M* 7.4) would be 160 years or longer, based on the horizontal slip rate of the Sagaing Fault and the 3 m of coseismic horizontal slip that occurred during the May 1930 earthquake [*Tsutsumi and Sato*, 2009]. Consequently, it is likely that more than half of the recurrence interval has passed in this seismic gap, meaning that the fault has accumulated elastic strain of ~2.0 m during the past 113 years. Therefore, the next large earthquake is expected to strike the area in the near future. Nay Pyi Taw, the recently established (since 2006) capital of Myanmar, is located near the southern end of the expected fault, meaning that its population is exposed to a significant earthquake hazard. To evaluate the recurrence interval of the Nay Pyi Taw earthquake, paleo-seismological and geomorphological studies of the fault are required, including trenching.

[17] The second seismic gap exists south of 16.6°N, located mainly in the Andaman Sea (Figures 2b and 3a). Given that the length of the seismic gap exceeds ~180 km, a *M* ~7.7 or larger earthquake is expected. Same as the Nay Pyi Taw seismic gap, the fault here has accumulated elastic strain of ~2.0 m during the past 113 years, and the next large earthquake is expected to strike this area, too, in the near future.

[18] The general characteristics of the *M* 7 earthquakes are as follows. First, all of the $M \geq 7.0$ earthquakes show unilateral ruptures, indicating that the rupture of the future Nay Pyi Taw earthquake may be unilateral. Second, six *M* 6 earthquakes have occurred on the Sagaing Fault, with all occurring near the edges of the fault planes of the *M* 7 earthquakes (Figures 2b and 3a). This distribution of events indicates segmentation of the Sagaing Fault; that is, the boundaries of fault segments are highly heterogeneous and cause *M* 6 earthquakes.

5. Conclusion

[19] Relocations of historical earthquakes in Myanmar by the MJHD method yielded a marked improvement in the accuracy of hypocenters and made it possible to estimate their ruptures of the 6 $M \geq 7.0$ earthquakes since 1918 and to construct the history of earthquakes along the Sagaing Fault. Then, we identified the two seismic gaps along the Sagaing Fault.

[20] Because ISS data are available for other regions worldwide from 1918, application of the MJHD relocation method to other regions would contribute to assessments of seismic hazards in these areas.

[21] **Acknowledgment.** We thank F. Klein for his helpful comments during review.

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