GROUND MOTIONS OF THE SUMATRA EARTHQUAKES OF 2004 AND 2005

Paul G. Somerville, Hong Kie Thio and Gene Ichinose

URS Corporation
566 El Dorado Street, Pasadena, CA 91101

Abstract

The Sumatra earthquakes of December 26, 2004 (Mw 9.15) and March 28, 2005 (Mw 8.7) are the largest subduction earthquakes that have ever been recorded on modern digital instruments. Both earthquakes were caused by the subduction of the India–Australia plate beneath the Eurasian Plate. Although these earthquakes were not recorded on scale at close distances, they were recorded at regional distances. These regional recordings shown strong spatial variations in amplitude and duration that are consistent with rupture directivity effects. The duration of ground motion of the December event to the north in Thailand was about 600 seconds, while the duration in other directions, including Sumatra, was about 1,000 seconds.

Earthquake Rupture Models

The December 26, 2004 and March 28, 2005 Sumatra earthquakes occurred on the interface between the India – Australia Plate and the Eurasian Plate. The December earthquake was the largest earthquake to occur anywhere in the world since the Mw 9.2 Alaska earthquake of 1964, and only one of four earthquakes of magnitude Mw 9.0 or larger in the past 100 years. The shallow part of the plate interface on which the earthquakes occurred lies offshore of northwestern Sumatra, and dips at an angle of about 11 degrees from the horizontal, down to the east.

Slip models that we derived using complete seismograms of the two earthquakes are shown in Figure 1 (Thio et al., 2005). The part of the interface that was ruptured by the earthquakes is about 200 km wide, and lies in the depth range of about 5 to 40 km. The rupture length of the December earthquake was about 1,200 km, extending from the epicenter, located about 250 km south of Banda Aceh, to the northern end of the Andaman Islands. The March earthquake had an epicenter located near that of the December earthquake, but it ruptured in the opposite direction for about 400 km to the southeast. The rupture dimensions of the two earthquakes are consistent with the scaling relations for subduction earthquakes developed by Somerville et al. (2002).

Analysis of teleseismic short period body waves of the December event by Ammon et al. (2005) showed that the source duration of the event was about 500 seconds, consistent with rupture propagation at 2.5 km/sec over a 1,200 km rupture length. The earthquake was followed by an aftershock sequence that spanned a zone that roughly coincides with the rupture zone shown in Figure 1, extending northward from the epicenter to the northern end of the Andaman Islands.

The slip involved sudden sliding of the India-Australia plate beneath the Eurasian plate. Before the earthquake, the interface between the two plates was locked, causing the India-Australia plate to drag the Eurasian plate downwards. The sudden rebound of

the Eurasian plate during the earthquake caused its western edge to spring upward. On the ocean floor at the edge of the Eurasian plate, the amount of this uplift was about 3 meters. This sudden uplift of the ocean floor generated a tsunami that propagated in all directions away from the source region of the earthquake. There was little geometrical spreading (reduction in wave amplitude) to the east and west of the source area, because the source was in effect a line source rather than a point source. The tsunami took about 20 minutes to reach the coast of northwestern Sumatra, and about 2 hours to reach the coasts of Thailand and Sri Lanka.

Ground Motions

The earthquakes were not recorded on scale at close distances; the largest earthquake for which nearby strong motions have been recorded is still the Mw 8.4 Peru earthquake of 2001 (Somerville et al., 2003). The closest part of the earthquake rupture surface lies about 50 km off northwest Sumatra at a depth of about 40 km, so the closest distance from the earthquake source to the coast is about 65 km. Given the existence of damage to buildings in Aceh Province at the northwest end of Sumatra, it seems likely that the level of the ground shaking along the west coast of Aceh Province was about 25%g.

The recordings of the two earthquakes at station PSI in northern Sumatra, whose location is shown at the top of Figure 2, are clipped, but they give some idea of the duration of strong ground motion if not its peak amplitude. The time axes of all the ground motion velocity figures in this paper are demarcated at 100 second intervals. The recorded ground motions of the December event are shown at the top of Figure 3, and those of the March event are shown at the bottom of Figure 3. The December event had a duration of about 200 seconds above its clipping level of 1 cm/sec, and peak velocities remained close to 1 cm/sec for about 700 seconds, while the March event had a duration of about 150 seconds above this level, and then dropped well below that level. However, the peak velocities of the March event were evidently stronger than those of the December event, judging by the relative degree of clipping, consistent with the greater proximity of the PSI site to the rupture plane of the March event, as shown at the top of Figure 2.

Although the earthquakes were not recorded on scale at close distances, they were recorded at regional distances at the stations shown at the top of Figure 2. There are five recordings within about one source dimension of the earthquake, which by some definitions would make them “near source,” but that source dimension is very large, about 1,200 km. The recordings, shown at the bottom of Figure 2, have strong spatial variations in amplitude and duration that are consistent with directivity effects observed in the near source region of crustal earthquakes, but on a much larger time scale. Station CHTO in the forward rupture directivity direction to the north in Thailand has much larger ground motion amplitudes and shorter duration, about 600 seconds, than the other stations, which are located to the west in Sri Lanka (PALK), to the southeast in Java (UGM), and to the south on Cocos Island (COCO). Backward rupture directivity at these other stations caused the ground motion durations to be much longer, on the order of 1,000 seconds. We plan to use these recordings to model seismic wave propagation in the region, providing a basis for extrapolating the recorded seismic wave field to closer

distances, and estimating the strength of the ground motions throughout the region that experienced shaking damage.

The broadband peak ground velocities in Figures 2 and 3 contain very long period motions. Highpass filtering these velocity recordings at 5 seconds period results in the filtered ground velocities shown in Figure 4. The filtered peak velocities are reduced to about 0.4 cm/sec at station PSI (which is still influenced by clipping), and attenuate much more rapidly than the broadband peak velocities in Figure 3 at the more distant stations.

A preliminary intensity map of the December 26 Sumatra earthquake from the Amateur Seismology Centre in India is shown in Figure 5. Cassidy and others (2005) have updated this map using data from David Wald from the USGS website "did you feel it?" to give intensity values as high as MMI VIII in northwestern Aceh Province, consistent with damage to buildings in Banda Aceh and towns on the northwest coast of Sumatra.

Acknowledgment

Our work on the Sumatra earthquakes was supported in part by Pacific Gas & Electric Company.

References

Ammon, C.J., J. Chen, H.K. Thio, D. Robinson, S. Ni, V. Hjorleifsdottir, H. Kanamori, T. Lay, S. Das, D. Helmberger, G. Ichinose, J. Polet, D. Wald (2005). Rupture process of the great 2004 Sumatra-Andaman earthquake. Submitted to Science.

Cassidy, J.F., G.C. Rogers, H. Dragert, and K. Wang (2005). The 26 December 2004, M 9.0 Sumatra earthquake: implications for Cascadia. Seismological Research Letters 76, 220.

Petersen, M.D, J. Dewey, S. Hartzell, C. Mueller, S. Harmsen, A. Frankel and K. Rukstales (2004). Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula. Tectonophysics 390, 141-158.

Somerville, P.G., H.K. Thio, G, Ichinose, N. Collins, A. Pitarka, and R.Graves (2003). Earthquake source and ground motion characteristics of the June 23, 2001 M_w 8.4 Arequipa, Peru, earthquake. SRL 74, 223.

Somerville, P.G., T. Sato, T. Ishii, N.F. Collins, K. Dan and H. Fujiwara (2002). Characterizing heterogeneous slip models for large subduction earthquakes for strong ground motion prediction. Proceedings of the Architectural Institute of Japan.

Thio, H.K., G. Ichinose, P. Somerville and J. Polet (2005). Source process and tsunami generation of the 2004 Sumatra-Andaman earthquake. Proceedings of the Second Annual Meeting of the Asia-Oceania Geosciences Society, Singapore, June 20-24.

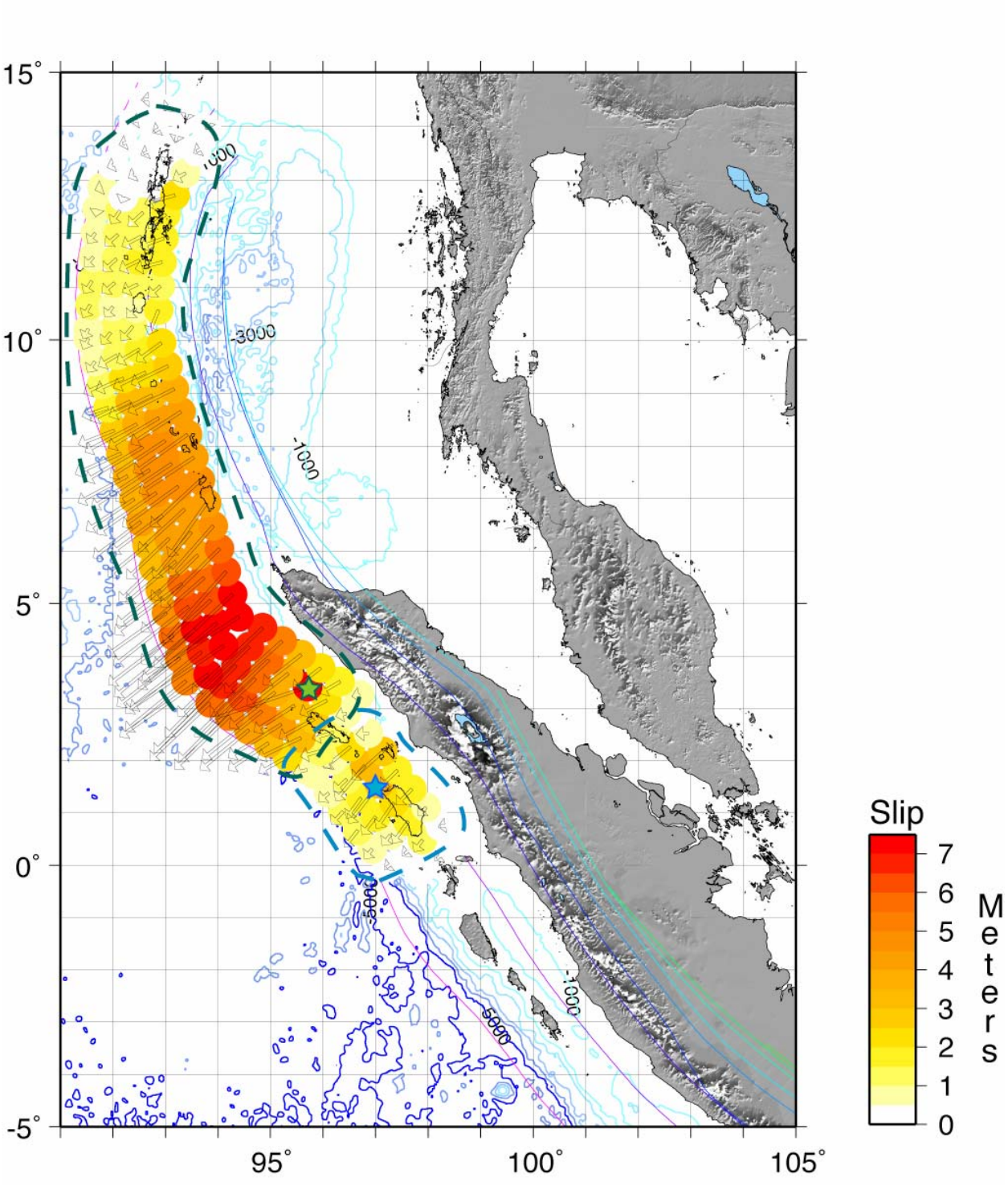

Figure 1. Slip maps of the December 26, 2004 and March 28, 2005 Sumatra earthquakes, with epicenters shown by stars.

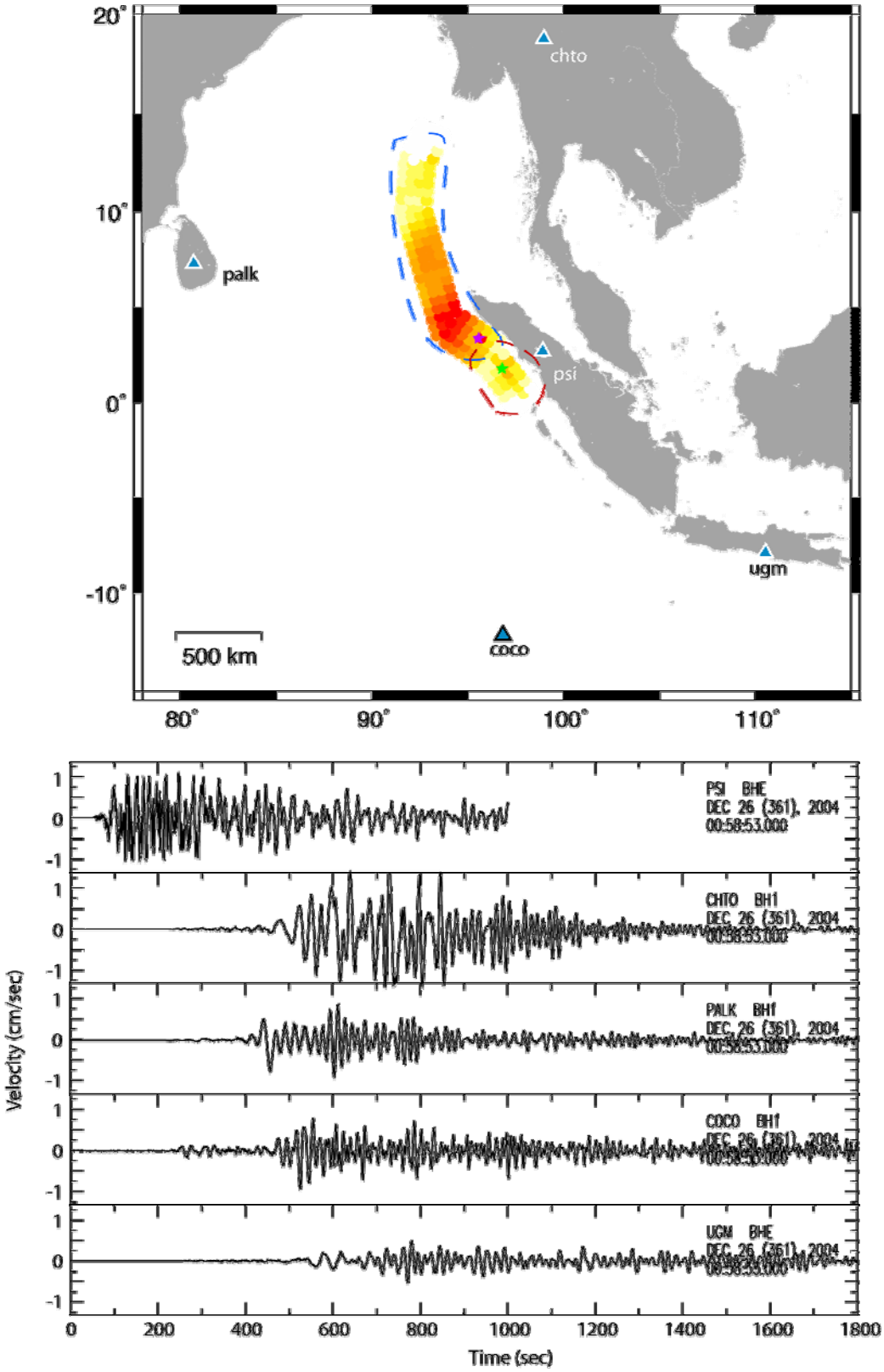

Figure 2. Top: Map of the region around Sumatra showing the slip maps of the December and March earthquakes (epicenters shown as stars), and regional seismic stations. Bottom: Broadband velocity seismograms of the December 26, 2004 earthquake recorded at the regional stations.

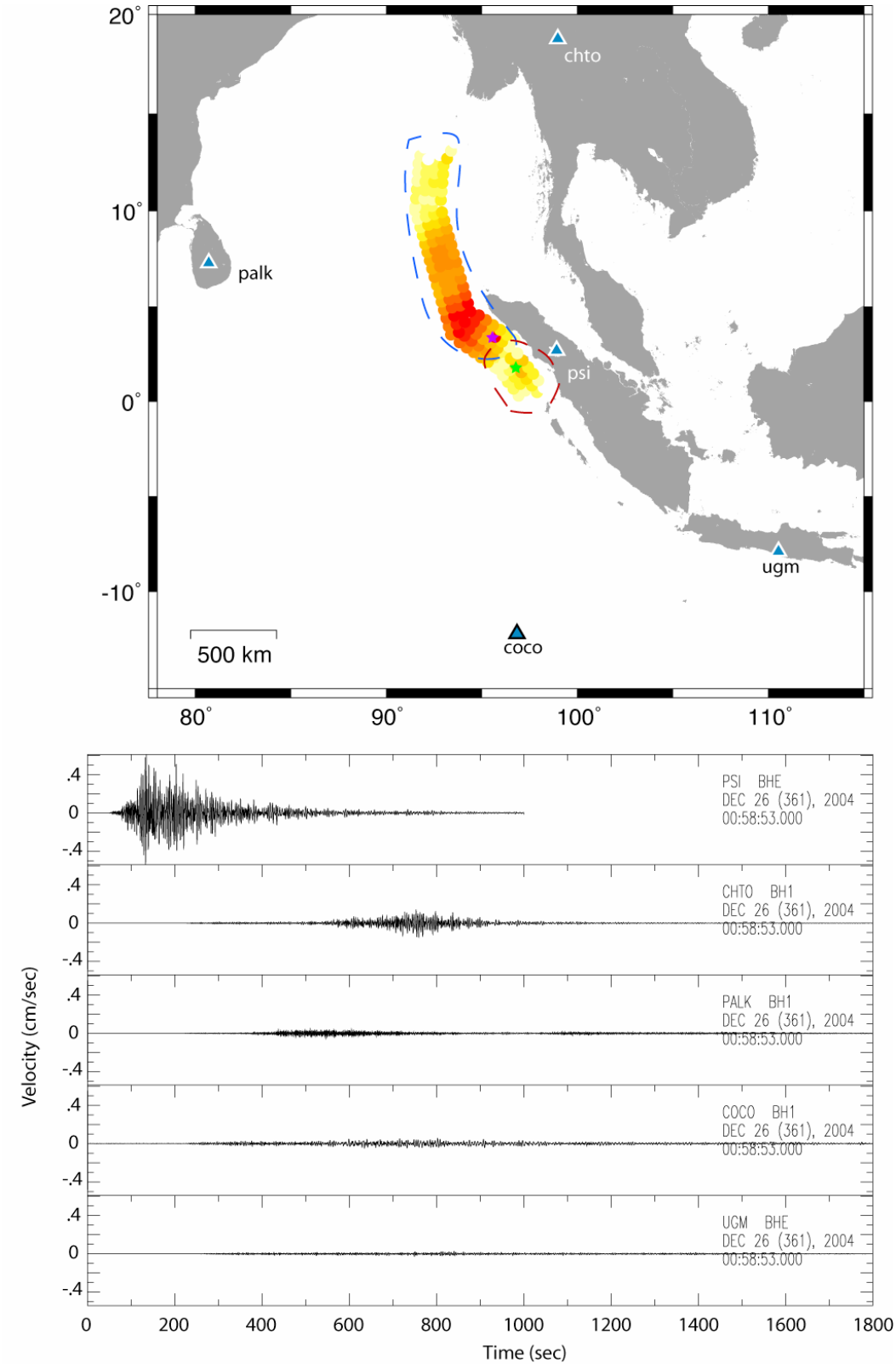

Figure 3. Top: Map of the region around Sumatra showing the slip maps of the December and March earthquakes (epicenters shown as stars), and regional seismic stations. Bottom: Velocity seismograms of the December 26, 2004 earthquake recorded at the regional stations high-pass filtered at 5 seconds.

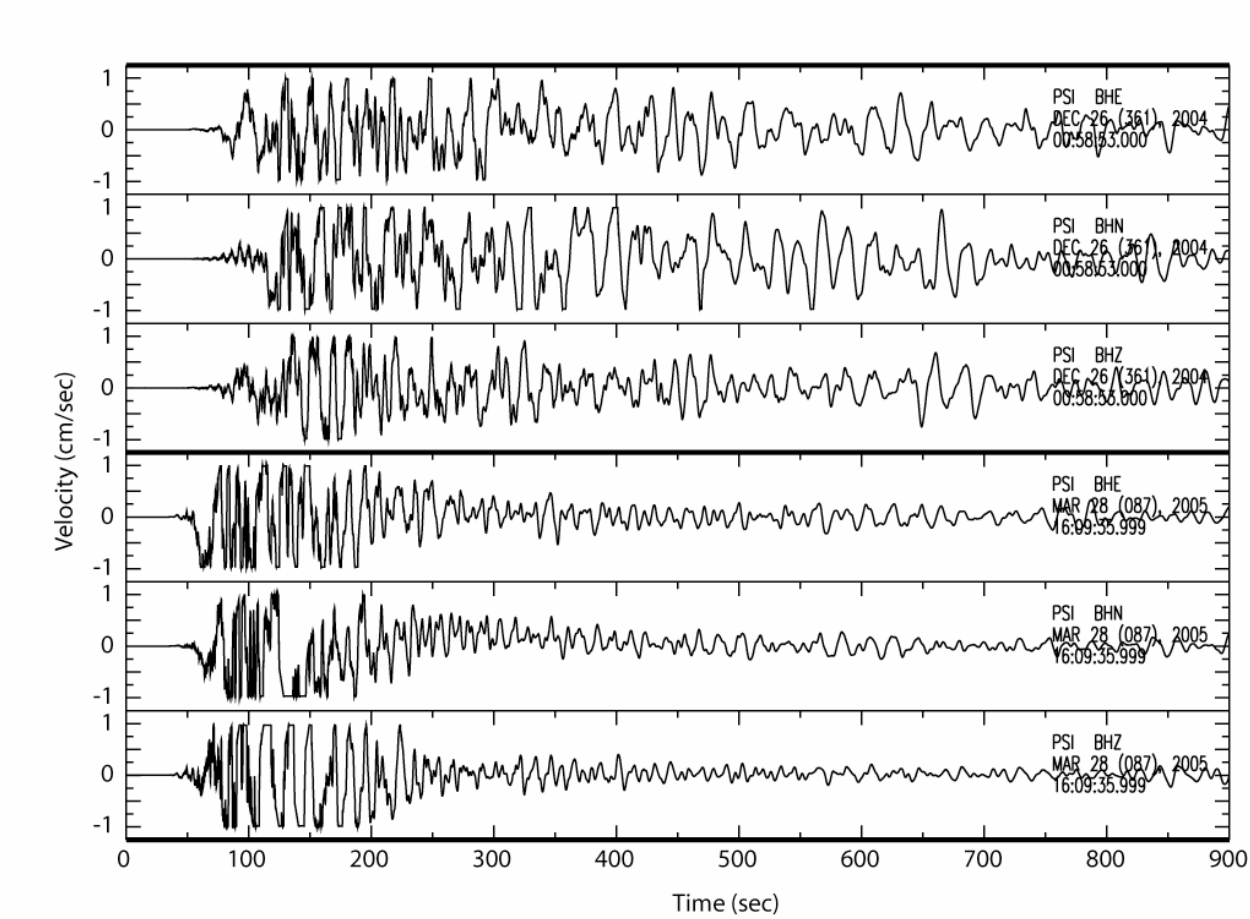

Figure 4. Recordings of the December 26, 2004 (top) and March 28, 2005 (bottom) Sumatra earthquakes at station PSI in northern Sumatra, approximately 350 and 250 km away, respectively.

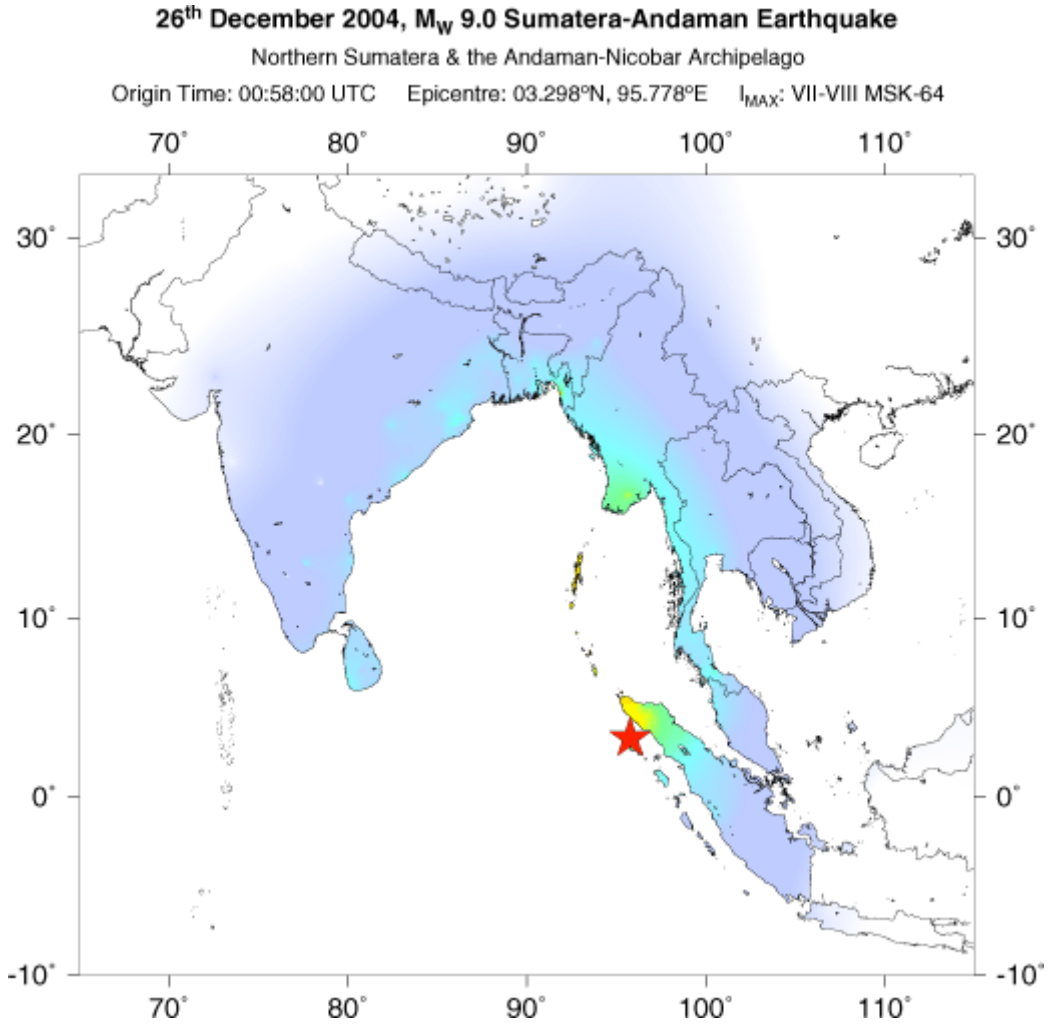

Figure 5. Intensity map of the December 26, 2004 Sumatra earthquake.

Source: Amateur Seismology Center of India, http://asc-india.org/INT/20041226.htm