1.3 Short Review: Preliminary results and observations of the December 2004 Great Sumatra Earthquake

Kenji Hirata

We give a brief review about observations and preliminary results regarding the 2004 great Sumatra earthquake based on information as of up to early February 2005.

1.3.1 Hypocentral parameters

A great earthquake occurred northwest of Sumatra in December 26, 2004. The hypocentral parameters by USGS/NEIC (United States Geological Survey/National Earthquake Information Center) are; origin time = 00:58:53 UTC, longitude and latitude = 95.799 E and 3.251 N in degree, depth = 30 km (fixed; this should be confirmed), M=9.0. Centroid moment-tensor (CMT) solution by Harvard University are; origin time of centroid = 01:01:9.0 UTC, longitude and latitude of centroid = 94.26 E and 3.09 N in degree, centroid depth = 28.6 km, Mw=9.0 and scalar seismic moment = 4.0 x 10^{22} Nm. NEIC/USGS hypocenter was determined mainly from teleseismic, short-period (~ 1 to 10 sec) seismic waves, while Harvard CMT solution was obtained analyzing long-period (longer than 300 sec for this earthquake) mantle surface waves. Therefore, NEIC/USGS hypocenter and HAVARD CMT represent the hypocenter (focal point, or initial break point) and a centroid of seismic moment release, respectively.

1.3.2 Aftershock area and rupture zone

Assuming that the one-day aftershock distribution is representative of the earthquake rupture zone, the total length is approximately 1400 km along the northern Sunda Trench (Fig.1.3.1). However, it is still under debate whether or not aftershock area represents the entire co-seismic rupture zone [e.g., Satake, 2005].

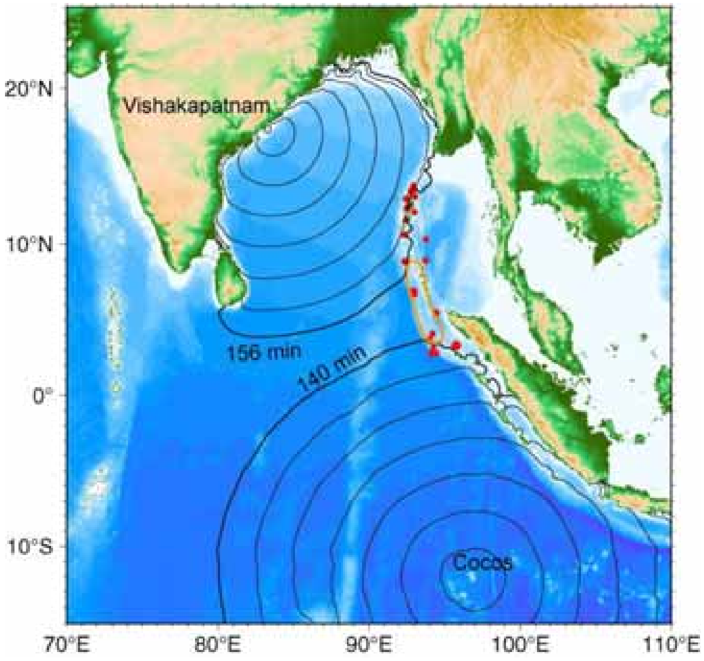

Figure 1-3-1 One-day aftershock area. Red circles indicate aftershocks occurring within 24 hours after the mainshock. Imaginary back-going (inversely propagating) tsunami wave fronts from two tide gauge stations are plotted by solid curves (after Satake [2005]).

1.3.3 Other basic seismic information

Considerable strong shakings seem to be reported in the northernmost Sumatra and Nicobar Islands via mass-media, in contrast with no or less strong shaking in other regions. Its exact data, however, still remain unknown so far. Seismic intensity pattern along the coast of the Indian Ocean has not been collected yet.

1.3.4 Seismic body wave analyses

Seismic body wave analyses resolved the rupture process in the southern segment of the aftershock zone in a region approximately 600 km or 900 km long [Ji, 2005; Yagi, 2005; Yamanaka, 2005; Tuncay et al., 2005]. All of the seismic body wave analyses suggested a common feature that relatively small amount of slips occurred near the hypocenter. They also suggested that a large slip area existed west or southwest of the northern Sumatra, but its location seems to differ slightly; A large slipped area estimated by Yamanaka[2005] and Ji [2005] is located approximately 150 km to the northwest of the epicenter (Figure 1-3-2a), whereas those by Yagi [2005] and Tuncay et al. [2005] are between 200 and 250 km to the northwest of the epicenter (Figures 1-3-2b and 1-3-2c). Another large slip area was marked between 500 km and 700 km to the north, near the Nicobar Islands, of the epicenter by Yagi [2005] and Yamanaka [2005]. Some of seismic body wave analyses claim a constraint on rupture propagation of the great earthquake; Ji [2005] and Yagi [2005] suggested that a normal, high-speed rupture is required at least in the initial few-hundred-second of rupture stage or southern several-hundred-long segment.

It might be worth noting that all body wave analyses could not explain the entire earthquake rupture process because a very long-period seismic wave (~ more than 300 sec) generated from the earthquake prevents seismologists from investigating the entire rupture process [e.g., Yagi, 2005]. In other words, seismic body wave analyses could retrieve only the initial part of the whole rupture process or shorter period images of it.

Analysis of teleseismic, high-frequency seismic energy radiation observed with Japanese HI-Net network suggested that the rupture propagated about 1300 km to the north along the Sumatra-Andaman Trench at a normal high speed rupture velocity of 2.8 km/sec on average [Ishii et al., 2005]. Total duration reaches eight minutes [Ishii et al., 2005]. Their result might also be nothing but short-period image of the rupture process.

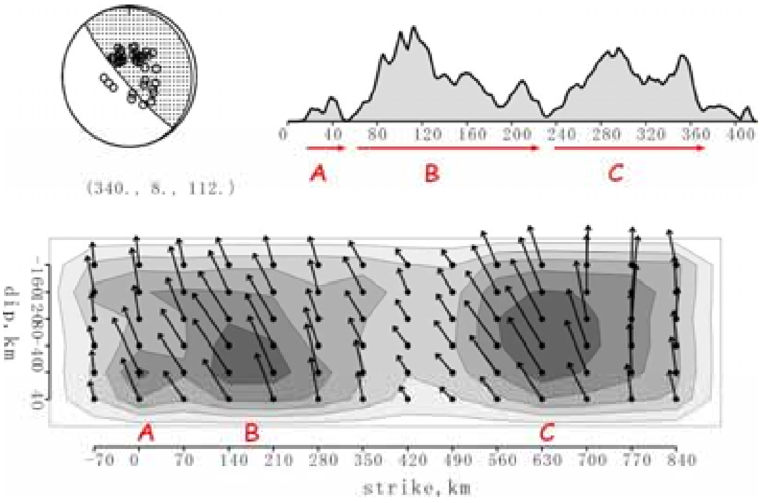

Figure 1-3-2a Co-seismic slip distribution estimated by Yamanaka [2005]. Upper left shows body wave focal mechanism solution that she assumed. Upper right represents the estimated far-field moment-rate function. Lower panel shows estimated co-seismic slip distribution (after Yamanaka [2005]).

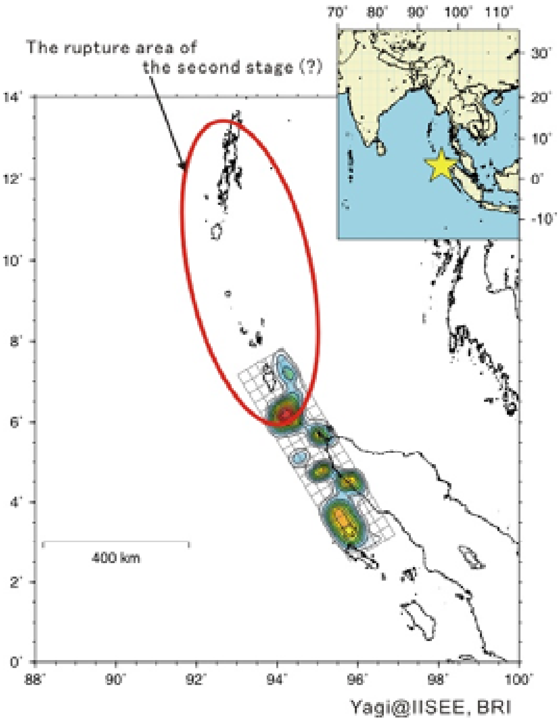

Figure 1-3-2b Co-seismic slip distribution estimated by Yagi [2005]. Yellow star indicates the mainshock epicenter. Red ellipse indicates a possible, slow rupture zone (after Yagi [2005]).

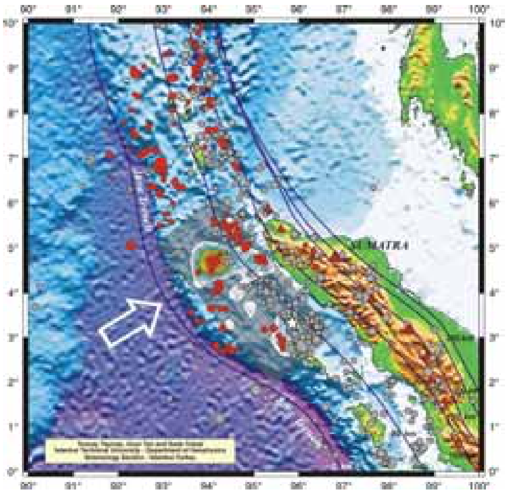

Figure 1-3-2c Co-seismic slip distribution estimated by Tuncay et al. [2005] with aftershocks (red circles). Back ground seismicity (between 1973 and 2004, M>5, USGS/NEIC) are also plotted by gray circles. Blue lines are every 50 km depth contours of the upper boundary of the subducting oceanic plate (after Tuncay et al. [2005]).

1.3.5 Normal-mode study

Analysis of the longest period normal modes yielded a seismic moment of 1.3 x 10^{23} Nm and 9.45 x 10^{23} Nm for normal mode multiplets ${}_0S_2$ and ${}_0S_3$, respectively (Figure 1-3-3), and revised the moment-magnitude Mw 9.3[Stein and Okal, 2005]. This moment estimate is approximately 3 times larger than that from long-period surface wave studiers. The normal mode study, however, does not constrain the location of the ultra-long period source or slow slip region as mentioned by themselves.

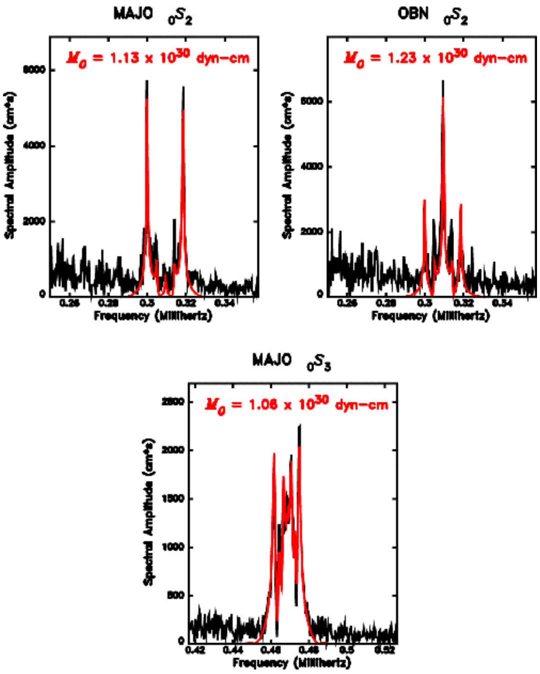

Figure 1-3-3 Normal mode multiplets observed at some seismic stations. Observed and calculated spectrum is depicted by black and red lines, respectively (after Stein and Okal [2005]).

1.3.6 Observation of crustal deformation and GPS study

Crustal deformation was observed at some places near the aftershock area. Subsidence of 1-3 meters along west coast of northern Sumatra was recognized as coastal line degradation imaged with Satellite [Tobita, 2005]. Northern and southern coasts in the Simeulue Island were found uplift of 1.2-1.5 meters and 1 meter subsidence, respectively [D.H. Natawidjaja, personal comm. via Dr.Safri]. In Port Blair in the Andaman Islands, subsidence of approximately 1 meter was observed [Satake, 2005, personal comm.].

Horizontal crustal displacements were also measured with GPS networks. Hashimoto [2005] reported that a GPS station SAMP east coast of the Sumatra moved approximately 13 cm nearly to the East (Figure 1-3-4) and that NTUS in Singapore moved approximately 3 cm to the East with a relatively large estimation error.

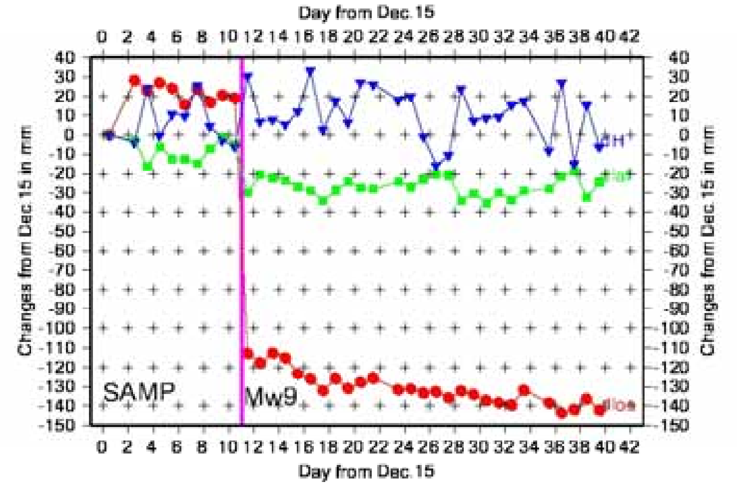

Figure 1-3-4 Three components of crustal deformation observed with a GPS station SAMP, nearest to the epicenter, east coast of the Sumatra, Red, green, and blue lines represent east(+)-west(-), north(+)-south(-), and up(+)-down(-) displacements, respectively (after Hashimoto [2005]).

1.3.7 Tsunami

The earthquake generated a devastating tsunami throughout the Indian Ocean. Almost all victims of more than a hundred and sixty thousands (as of 25th January 2005) are likely responsible to the Indian Ocean tsunami generated by the great Sumatra earthquake.

Tsunami field surveys have been done soon after disasters of the Indian Ocean tsunami. The highest tsunami run-up of about 35 meters was observed at west coast of Banda Aceh [Japanese Tsunami Survey Team, 2005]. Averaged tsunami run-up height of 20-25 meters along the west coast of the northern Sumatra should be responsible for total destruction in this region. On the west coasts of the Phuket, Thailand, tsunami run-up height were observed to range between 5 and 10 meters [Phuket Tsunami Survey Team, 2005]. More than 10 meters of tsunami run-up was recognized several tens kilometers to the north of Phuket along west coast of the Malay Peninsula [Phuket Tsunami Survey Team, 2005]. Along southwest coast of the Sri Lanka, tsunami run-up heights were averaged approximately 5 meters with a maximum of 10 meters [Tsunami Survey Team at Sri Lanka, 2005]. West coast of India seemed to be attacked by a large tsunami with its maximum run-up heights falling in between 5 and 10 meters [Government of India, 2004].

Tsunami travel times observed at tide gauge stations suggested an approximately 900-km-long tsunami source area (Figure 1-3-1) if one does not assume a finite rupture propagation speed. Figure 1-3-5 shows tide gauge records over the Indian Ocean. Record from tide gauge stations east of the aftershock zone such as Belewan (east coast of Sumatra) and Sibolga (west coast of Sumatra) show that the first motion of tsunami was down (low tide) in east, similar to eyewitness observation at Phuket, Thailand. In contrast with this, records west of the aftershock zone such as Colombo (India) and Male (Maldives) show that first tsunami motion was up (high tide) in west. These observations suggest a fundamental seafloor deformation pattern with vertically up trenchward and down landward, strongly indicating that the Indian Ocean tsunami was basically generated from the plate interface thrust. Tsunami magnitude was assigned 9.1 by Abe [2005] using maximum amplitudes of tsunamis on tide gauge records.

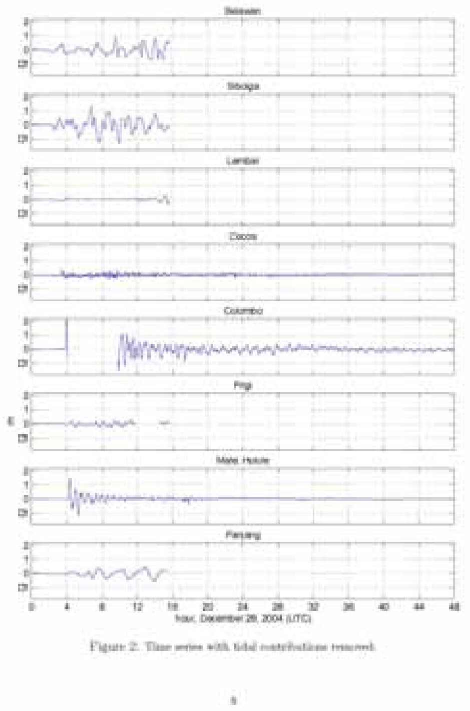

Figure 1-3-5 Tide gauge records showing the Indian Ocean tsunami in December 26, 2004. Vertical axis is amplitude in meters (after Merrifield et al. [2005]).

Two hours after the occurrence of the great earthquake, two NASA/French Space Agency’s joint mission satellites “Jason-1” and “TOPEX/Poseidon” passed across the Indian Ocean from southwest to northeast at a speed of approximately 7 km/sec and for the first-time captured sea surface height (SSH) disturbed by the Indian Ocean tsunami from the great Sumatra earthquake [Gower, 2005; JPL/NASA, 2005]. By using forward modeling Titov [2005] first modeled the observed satellite SSH data successfully except for a region between 0° N and 15°N in from the Jason-1 observations. Hirata et al.[2005] inverted the SSH data to estimate co-seismic slip distribution and suggested that the mainshock rupture propagated approximately 1300 km to the north along the Sumatra-Andaman Trench at an extremely slow speed of =0.7 km/sec. If their estimate is correct, the Sumatra earthquake may be a so-called “tsunami earthquake” , which was first defined by Kanamori[1972] to represent an earthquake accompanied by tsunami larger than expected from seismic waves. Seafloor vertical deformation calculated from the earthquake rupture model of Hirata et al. [2005] is shown in Figure 1-3-6.

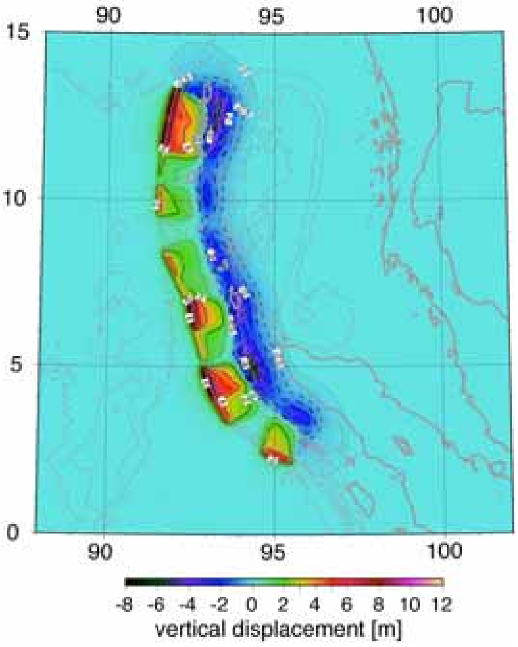

Figure 1-3-6 Vertical displacement of seafloor along the northern Sunda Trench calculated from an earthquake rupture model that was estimated by Hirata et al. [2005] from satellite altimetry data.

1.3.8 Summary

Seismic body wave analyses [Ji, 2005; Tuncay, 2005; Yagi, 2005; Yamanaka, 2005] and tsunami inversion [Hirata et al., 2005] together suggested that the largest co-seismic slipped area was located west of the northernmost Sumatra, in which on-board surveys have been extensively done during Leg.1 of NT0502. The average dislocation around the epicenter at the southern end of the entire aftershock zone was relatively small, comparing with the largest amount of slip, but was still of an order of M8-8.5 class earthquake. As Stein and Okal [2005] have noted, segments to the south from the aftershock zone, in which two M~9 class earthquakes occurred in 19th century [Newcomb and McCann, 1987], should be carefully assessed for future tsunami and earthquake potential.

References

Abe, K., http://www.eri.u-tokyo.ac.jp/topics/SUMATRA2004/abe.html, 2005.

Ishii, M., P. Shearer, H.Houston, and J.Vidake, http://mahi.ucsd.edu/shearer/ SUMATRA/ ishii.html, 2005.

Ji,C., http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ff.html, 2005.

Government of India, Ministry of Home Affairs, http://www.ndmindia.nic.in/Tsunami2004/

sitrept4.htm, 2004.

Gower, J., EOS, transactions, AGU, 86, 4, 37-38, 2005.

Hashimoto, M., http://www.rcep.dpri.kyoto-u.ac.jp/~hasimoto/Manabu/sumatraEQ.htm, 2005.

Hirata, K., et al, submitted to science, 2005.

Japanese tsunami survey team leaded by Dr.Y.Tsuji, http://www.eri.u-tokyo.ac.jp/ namegaya/ sumatera/surveylog/eindex.htm, 2005.

JPL/NASA, http://sealevel.jpl.nasa.gov/mission/jason-1.html & http://sealevel.jpl.nasa.gov/ mission/topex.html, 2005.

Kanamori, H., Phys. Earth Planet Inter., 6, 246-259, 1972.

Merrifiled, M.A., et al., written commucation, 2005.

Newcomb, K.R., and W.R.McCann, J.Geophys.Res., 92, 421-439, 1987.

Phuket Tsunami Survey Team, http://www.drs.dpri.kyoto-u.ac.jp/sumatra/phuket_survey.html/, 2005.

Satake, K., http://staff.aist.go.jp/kenji. satake/Sumatra.html, 2005.

Stein, S., and E. Okal, Extended abstract, http://www.iris.iris.edu/sumatra/.

Titov,V., http://www.noaanews.noaa.gov/stories2005/s2365.htm, 2005.

Tobita, M, http://www.yomiuri.co.jp/science/news/20050128i105.htm, 2005.

Tsunami Survey Team at Sri Lanka, http://www.drs.dpri.kyoto-u.ac.jp/sumatra/srilanka/ galle_survey_e.html, 2005.

Tuncay Taymaz, Onur Tan and Seda Yolsal, http://www.geop.itu.edu.tr/~taymaz/ sumatra/, 2005.

Yagi,Y., http://iisee.kenken.go.jp/staff/yagi/eq/Sumatra2004/Sumatra2004.html, 2005.

Yamanaka,Y.,http://www.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/2004/EIC161ea.html., 2005.