Estimation of active fault during the 2004-2005 earthquake events

Introduction

The magnitude ~9.2 earthquake on December 26, 2004, followed by a large tsunami, initiated at a depth of ~50 km offshore Aceh, occurred along a portion of the subduction zone from Sumatra to the Andaman Islands. Three months later, March 2005, another earthquake occurred south of 2004's epicenter, with a magnitude ~8.7. There was no large tsunami on the latter earthquake event. After the 2004 earthquake, there was an unprecedented effort from multinational research institutions of data collection in this region. Various studies have been conducted as well as many hypotheses in explanation of tsunami height and precise location of epicenter.
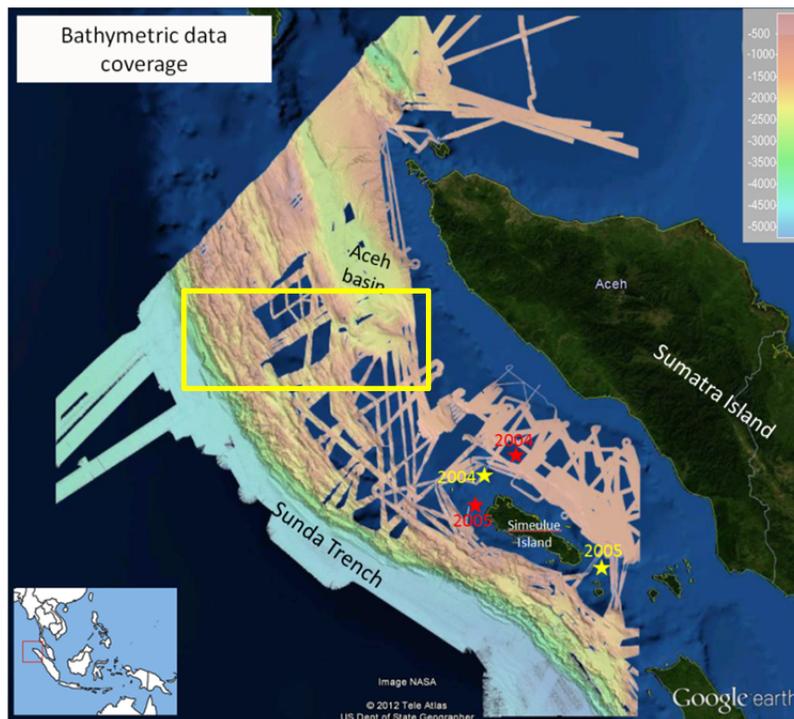

Figure 1. Bathymetric data covering the 2004 and 2005 earthquake events (red stars-USGS, yellow stars-relocated as published by Engdhal, 2007) offshore of Aceh Province, Indonesia. The color bar display depths in meter. Inset figure show the study area with respect to Southeast Asia region.

Figure 1 shows the coverage of bathymetric data available. The area of coverage is 1°-7°N and 93°-98°E. The red stars denote the epicenters of 2004 (Mw 9.2) and 2005 (Mw 8.7) earthquakes as reported by USGS. The yellow stars are reported by Engdhal, et al (2007) from recalculation based on teleseismically well-recorded earthquakes. The position accuracy of an earthquake depends on the distribution of seismometers and/or GPS around earthquake event. Region to the west of Aceh is Indian Ocean with limited seismometers installed.

The study area is a subduction zone with subduction rate of 5-6 cm/year and at an oblique angle. Figure 1 also shows that the accretionary prism offshore of Aceh is quite wide (~190 km on the northern section) and highly deformed with areas of high and low topography. The scale bar displays depths on meter. The Sunda trench is ~4,600 m and the shallowest part of the wedge is < 1,000 m. Each fold is

caused by thrust faults. The aim for this project is to investigate whether earthquake epicenters may be used to estimate the location of fault plane(s) that are active or reactivated during the respective earthquake events using earthquake epicenter locations published by USGS and the various tools available in ArcGIS. Since there is no bathymetric data near the epicenters of either 2004 or 2005 earthquakes, it was decided to use the foreshock (up to 15 days before) and aftershock (up to 2 months after) epicenters and focused on earthquakes located within the yellow rectangle in figure 1 because any earthquake at any depth may occur within a fault plane (Figure 2).

Magnitude	Fault Dimensions (Length x Depth, in km)
4.0	1.2 x 1.2
5.0	3.3 x 3.3
6.0	10 x 10
6.5	16 x 16, 25 x 10
7.0	40 x 20, 50 x 15
7.5	140 x 15, 100 x 20, 72 x 30, 50 x 40, 45 x 45
8.0	300 x 20, 200 x 30, 150 x 40, 125 x 50
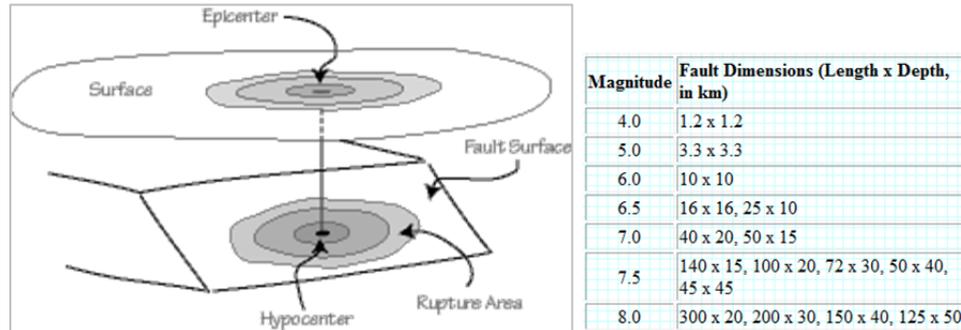
Figure 2. Description of rupture area within a fault surface. Area of rupture increase with magnitude
(Ref. http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/faults.html)

Data resources and collection
1. Bathymetric data from five research cruises conducted from January 2005-March 2009 were cleaned and merged is processed prior to this GIS project. The spatial resolution of this data is 50 meter. Figure 1 shows the bathymetric data coverage. The color bar shows depth in units of meter. The bathymetric data is in grid/ascii format as a result from GMT software. ArcGIS can't open this file format so the data is converted to csv format using Matlab software. The preprocessing of this data is discussed in the preprocessing section.

2. The coordinate of earthquakes is downloaded from the internet, the NEIC-USGS earthquake epicenters: http://earthquake.usgs.gov/earthquakes/eqarchives/epic/

Figure 3. NEIC earthquake search template.

Figure 3 shows the website to search earthquake events for the period of 2004-2005 with magnitudes between 3 and 10. The global earthquake information is available from 1973 until now. The format of search result can be chosen from various types. Figure 4 shows the first few earthquake events resulting of this search displayed in the spreadsheet format (comma delimited) output type.

Figure 4. Result of search from the NEIC-USGS catalog.

The result of search is in spreadsheet format, comma delimited, which is easily opened by MS Excel, then the file is saved as in xls format which can be read by ArcGIS using the 'add xy data': File -> Add data -> add xy data.

3. ASTER DEM data

Aster DEM data were downloaded from ERSDAC website (http://www.jspacesystems.or.jp/ersdac/ GDEM/E/index.html). After login, search for DEM tiles is as shown in figure 5. For the northern part of Sumatra Island, there are 17 tiles to download. These files are compressed and after uncompressed, can be opened in ArcMap, this is shown in Figure 6. All 17 tiles are shown before conducting mosaic into one raster file.

Figure 5. Window to search DEM tiles to download and general information of ASTER-DEM tile.
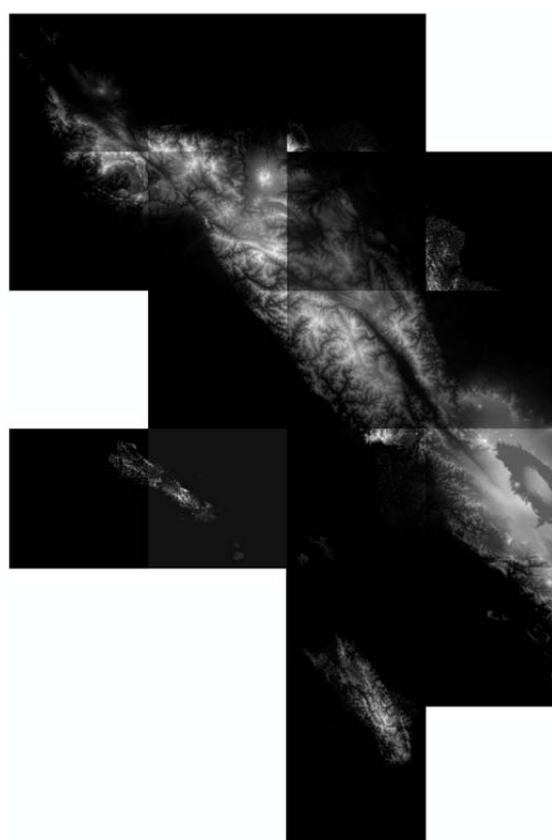

Figure 6. Seventeen tiles of ASTER DEM that overlap with the study area.
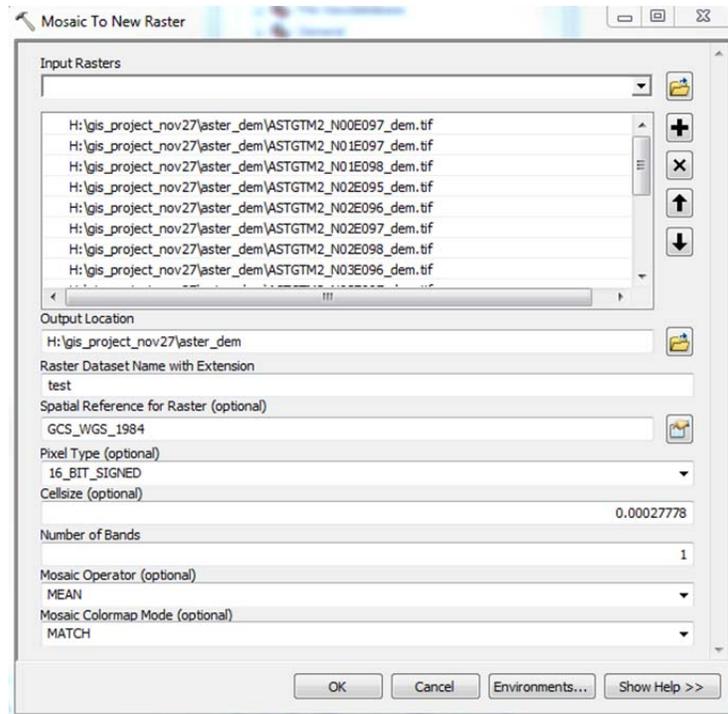
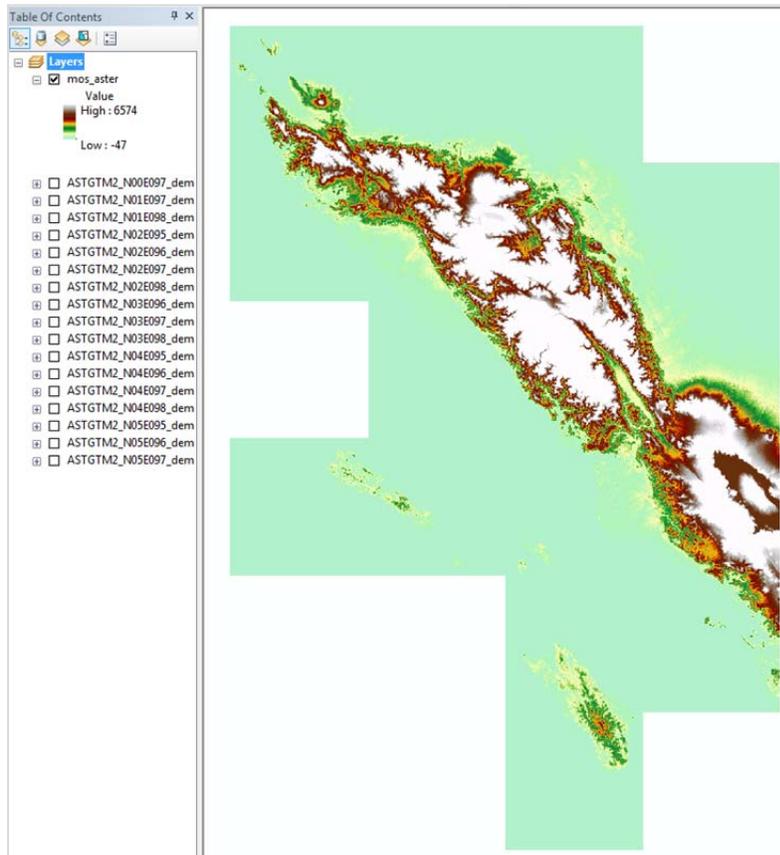Figure 7. Window on step to raster mosaic

Figure 8. Mosaicked DEM

Figure 7 displays the step of mosaicking the 17 tiles DEM data. After processing, the mosaicked data result is shown in Figure 8 with a color symbol 'Elevation # 1' to highlight the elevation change in the Island of Simeulue (the small on the west in the figure 8). To display this DEM with the bathymetric data without blocking one another, the pixel values of ASTER DEM that is on sea level and below is converted to NoData. The step to do this conversion is using raster reclassification. This step is shown in Figure 9a and 9b.
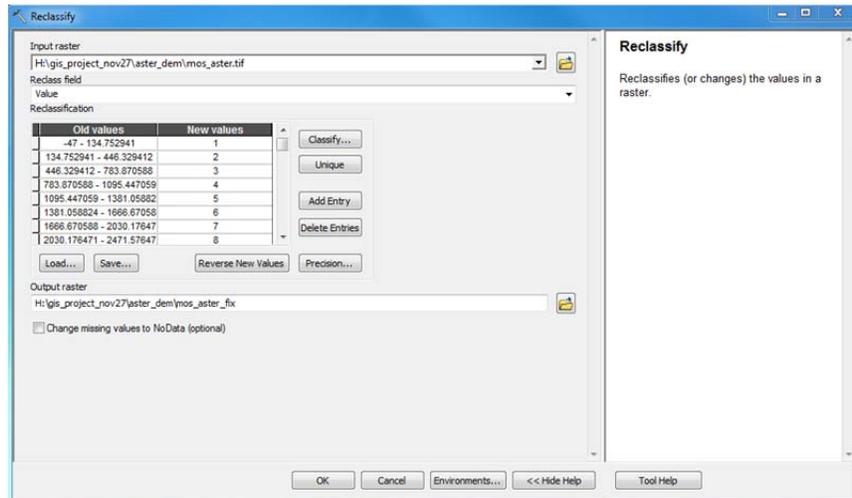

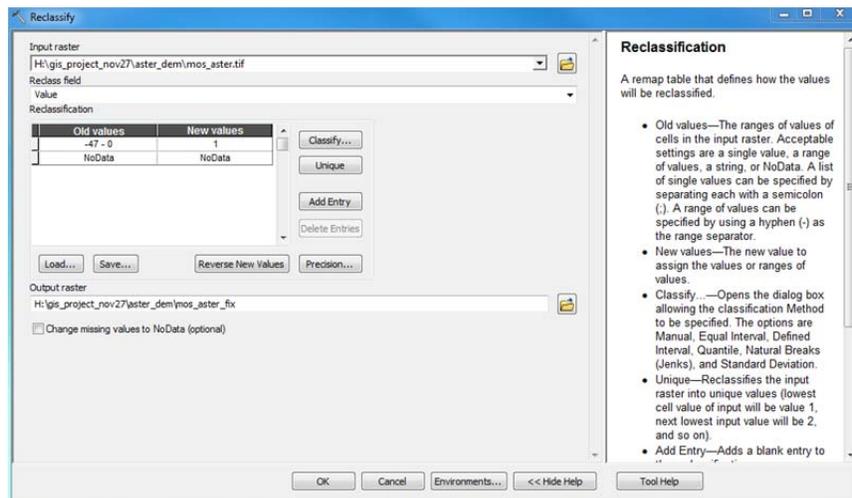Figure 9a. Original raster values.

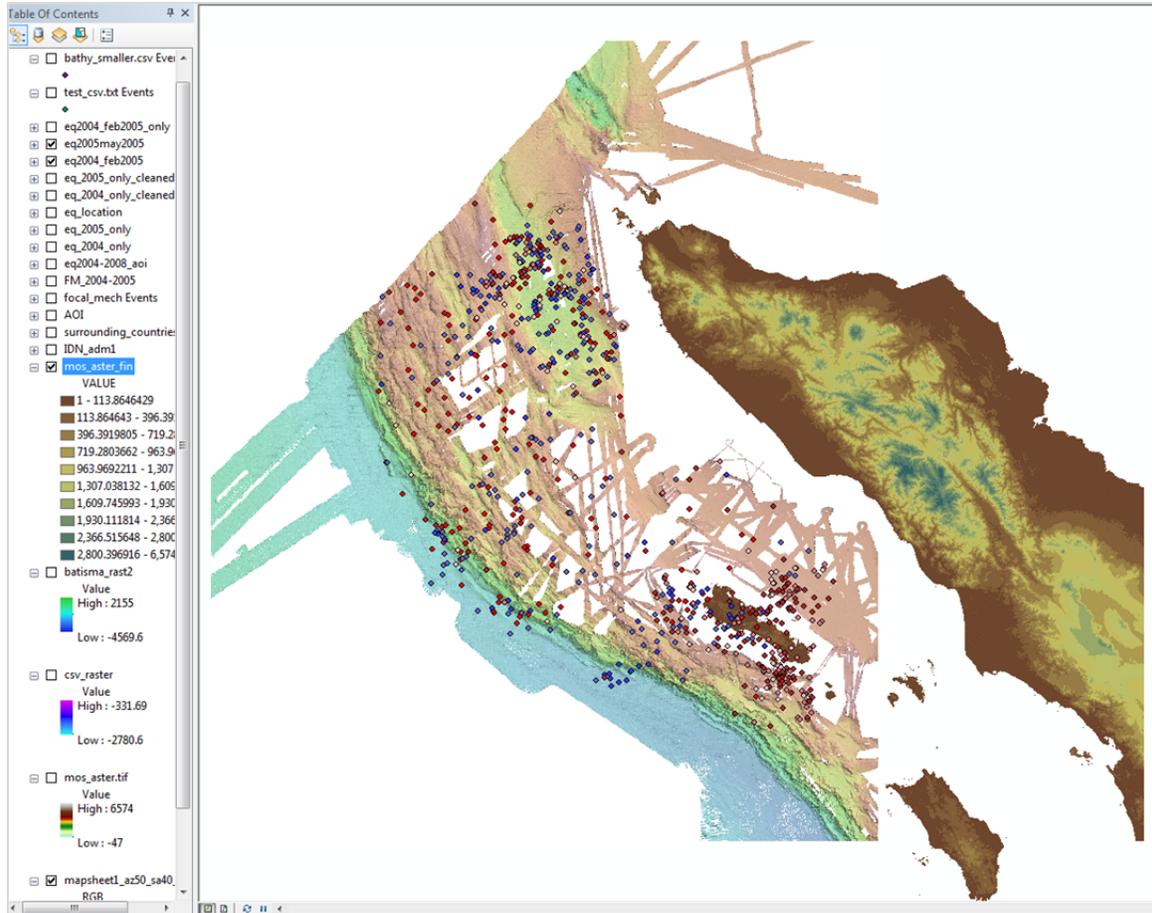Figure 9b. Change pixel values of zero and below to NoData.

Figure 9c. Result of changing data of Mosaic Aster

Figure 9c displays the result of reclassifying the ASTER DEM data and now it is able to show all data without overlapping. The ASTER DEM data is shown using 10 classes with manual classification method. In figure 9c, it is shown that there are numerous aftershock data occurring on Simeulue Island. It Is unfortunate that there are no more detailed DEM data for that area.

Data preprocessing
All of the data used in this project is in geographic projection and WGS84 datum.

Earthquake locations
There are more than 1,600 earthquakes between 2004 and 2005 with magnitudes ranging from 3 to 9.5. This study will limit earthquakes that occurred around the big events and that are on marine area and not on land (Sumatra Island). From the original number of earthquakes, these are reduced to earthquakes that occur 15 days (foreshock) and 2 months after (aftershock) the big earthquake event. For the 2004, the main earthquake occurred in 26 December, the number of earthquakes between 11 December 2004 and 26 February 2005 is 471. The second big earthquake occurred in 28 March 2005, the number of earthquakes between 13 March and 28 May is 294. Figure 10 shows the before reduction of number of earthquakes based on date of occurrence. Figure 10 on the right shows the result of the reduction process. In general, one can group the earthquake clusters into 3 big clusters: on the northeast, on the southwest, and on the southeast. It is decided to investigate the clusters on northeast and southwest only considering the bathymetric data coverage on these two clusters.
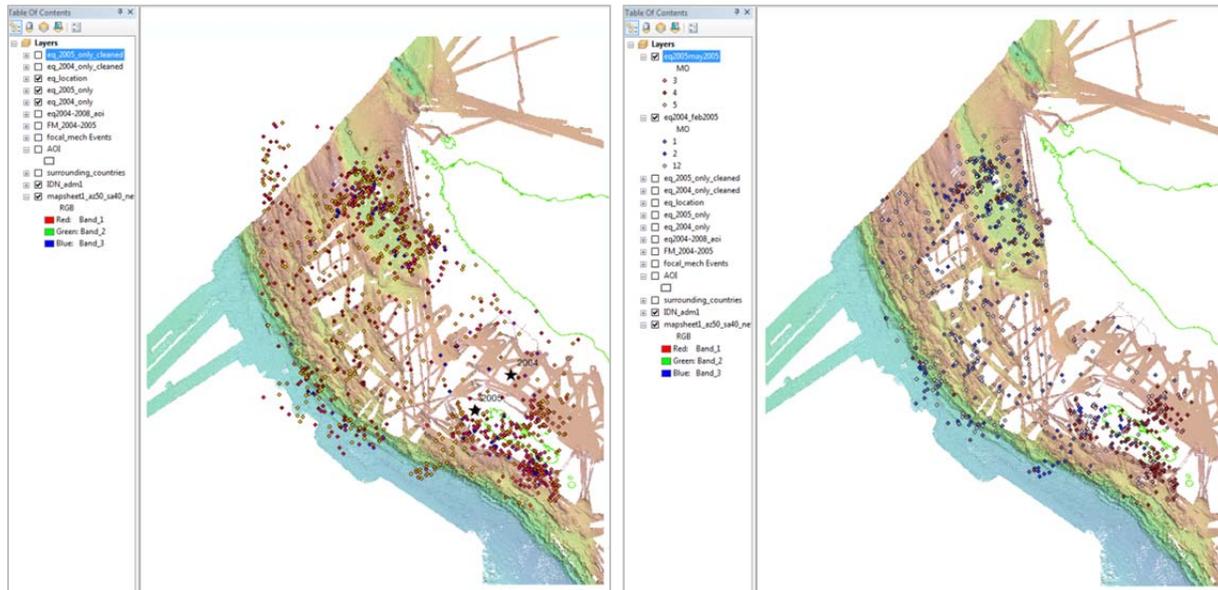
Figure 10. (Left) Distribution of 2004-2005 earthquakes events. (Right) Cleaned earthquake distribution within the study area according to 2004 period (shades of blue) and 2005 period (shades of red).

Bathymetric data

The bathymetric data is in grid/ascii format as a result from GMT software. ArcGIS can't open this file so the file has to be converted in Matlab and exported in csv format. Because of the large data points and ArcGIS can't handle the large data size (~427 MB), the bathymetric data used for this project is cropped to the boundary of 93.212-95.093° E and 2.500-4.620 N. Data reduction or resizing is conducted using Matlab, which then exported in csv format that can be read by ArcGIS. After this resizing, it is again too large to be uploaded into ArcGIS, so the bathymetric file is further reduced to the boundary of boundary of 93.212-95.093° E and 3.806-4.620 N. Figure 11 shows the window in Matlab for the data content (upper left window) and export command to csv format (lower left window). After resizing, then using notepad insert the header for the 3 columns: Long, Lat, Depth. This is shown in figure 11 (right figure). The step to input the data into ArcGIS is using the 'add xy data': File -> Add data -> add xy data. This step is shown in Figure 12 (left). The imported bathymetric data is shown as black dots that make up the black rectangular shape in figure 12 on the right.

Figure 11. (Left) Matlab display for exporting to csv format. (Right) insert of header to csv file.
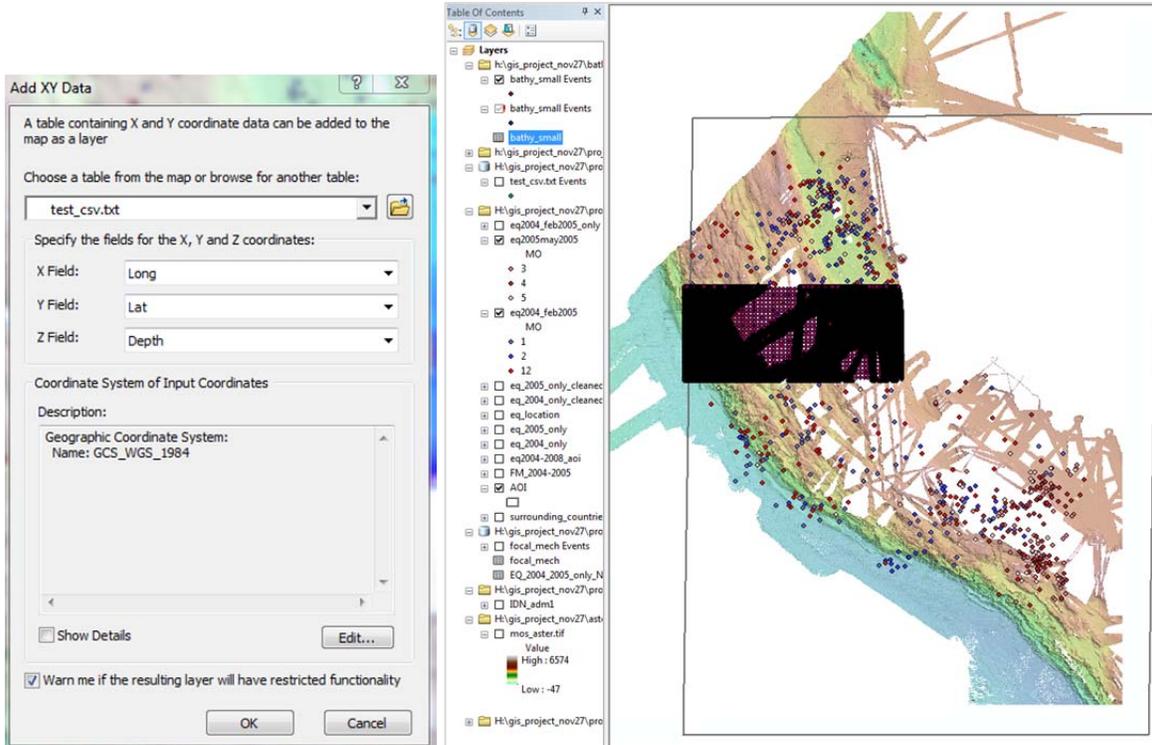
Figure 12. (Left) Import of bathymetric data in csv format. (Right) display of bathymetric data points.

After importing, then the point data is then converted to raster. This step is shown in figure 13 on the left. And on the right shows the cropped bathymetric data using Green to Blue symbology.
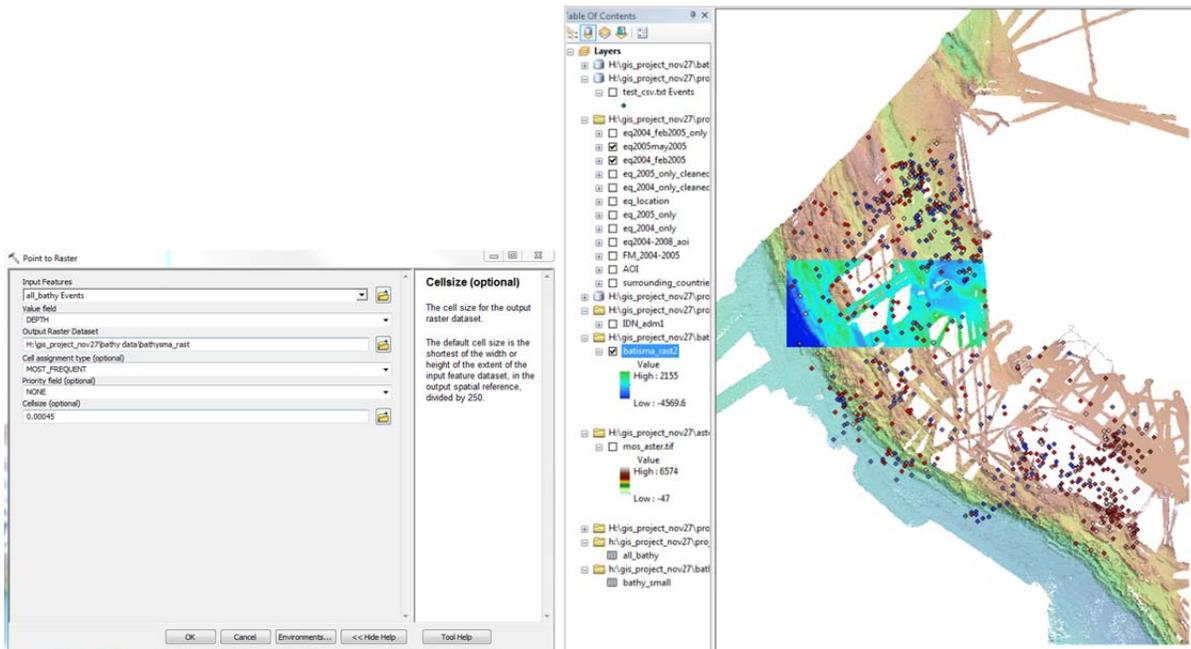
Figure 13. (Left) Step to convert point to raster. (Right) display of raster bathymetric data.

ArcGIS processing
Figure 14 displays the displacement area as observed on land surface with respect to the location of hypocenter and epicenter during an earthquake. As can be seen, the observed displacement is not at the same location of the epicenter but at a distance away. So estimating the fault activated during an earthquake require interpolation among the hypocenters to find the fault plane and then extrapolate that plane to meet the seafloor topography.
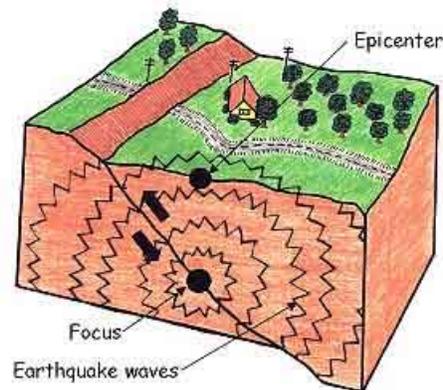
Figure 14. Location relationship among hypocenter (focus), epicenter, and fault plane.
(ref. http://www.kids-fun-science.com/earthquake-epicenter.html)

Analysis using ArcScene
Earthquake hypocenter, bathymetric data, and ASTER DEM are loaded into ArcScene. The plan is to produce fault plane from the earthquake points and then extrapolate the fault plane onto the bathymetry surface to estimate the displaced area on seafloor.
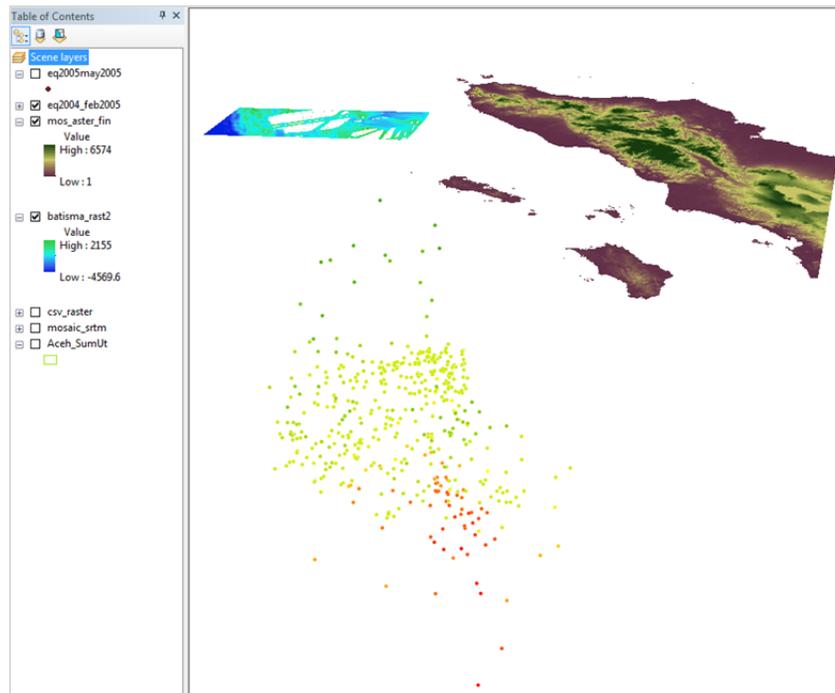
Figure 15. Depth distribution of earthquakes during the 11 Dec 2004 – 26 February 2005 period.
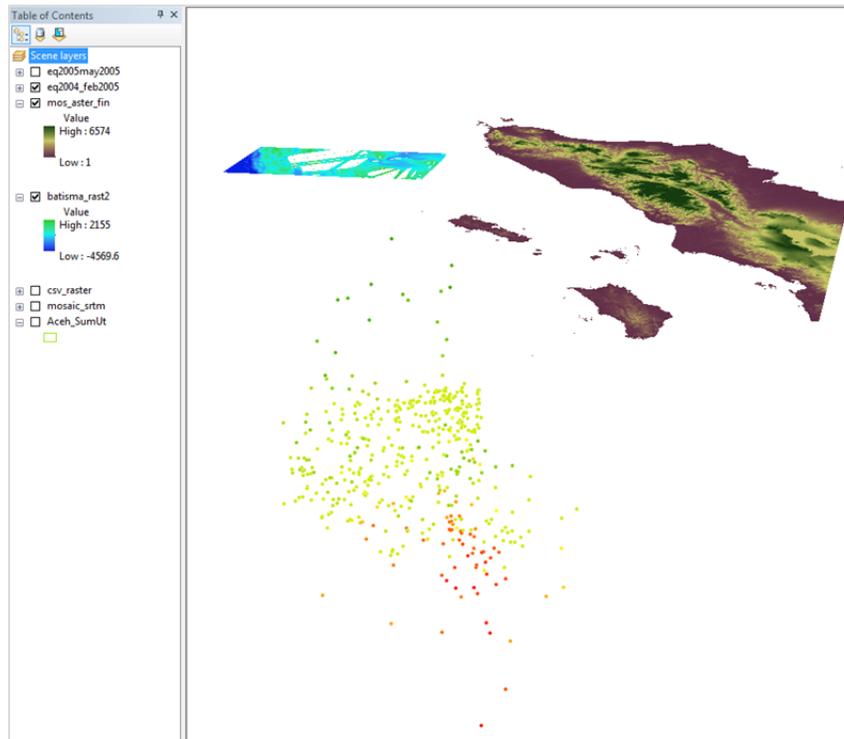
Figure 16. Depth distribution of earthquakes during the 13 March - 28 May 2005 period.

Figure 15 and 16 shows the distribution of earthquake in depth. The shades of darker green occurred between 0 – 25 km, shades of lighter green to orange occurred between 25 – 35 km, and shades of red occurred between 35 – 60 km. Both of these figures show that the earthquakes occurred in depths considered as shallow depths. Earthquakes that occur shallower than 70 km is the most destructive and the two earthquakes were quite destructive.

From the point distribution of hypocenters, calculation of interpolation between these points to create a 'surface' that may represent the fault plane is using the natural neighbor (spatial analyst) tool. Figure 17 shows the window to calculate the interpolation. Figure 18 show the result where dark blue is deepest and yellow is shallowest.
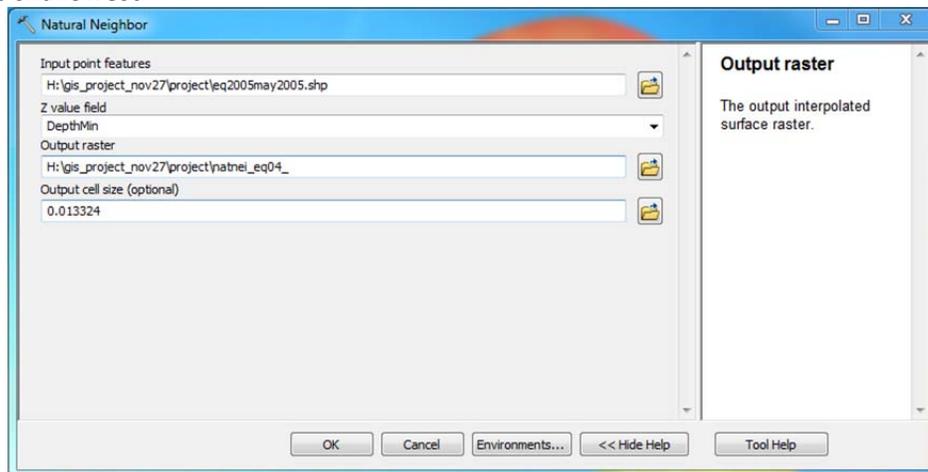
Figure 17. Step for raster interpolate from points for earthquake during the 13 March - 28 May 2005.
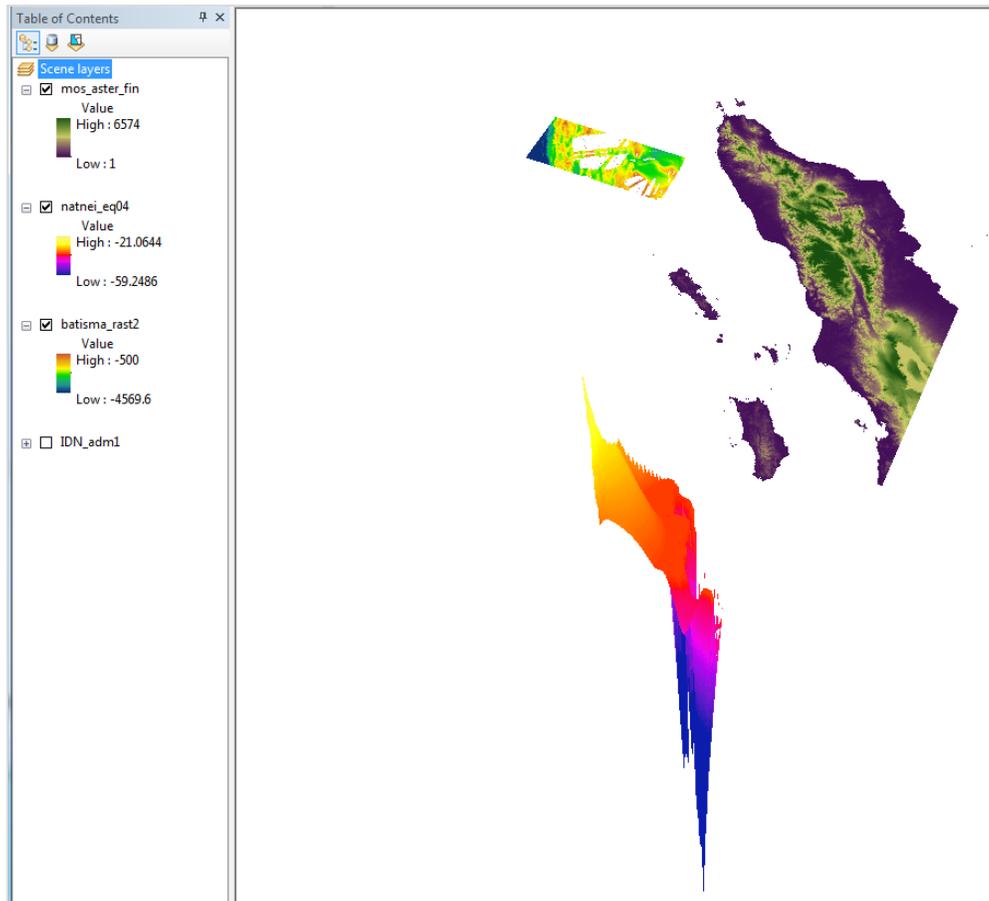
Figure 18. Plane of fault using the natural neighbor.

By looking at figure 18, it can be estimated that if an extrapolation is conducted toward the seafloor, then the meeting line between the bathymetric data and the extrapolation plane will be around the trench (blue region on the bathymetric data). The extrapolation process was not successful.

Analysis using ArcGIS
Another way to estimate the fault activated during an earthquake is by using buffer of the epicenters and investigate with the bathymetric data of the buffered area.

The first step is to find the steepest slope on the bathymetric data. The maximum slope is created using the tool: slope (spatial analyst) that can calculate the rate of maximum change in z-value. Figure 20 display the window on slope calculation. Figure 21 displays the result of slope calculation where the slope values are displayed in stretched symbology (color green). Figure 22 shows the result of the slope processing in 9 class classification symbology, where the light green area represent high rate change of slope. By comparing between figure 21 and 22, the areas with largest slope change is well represented.
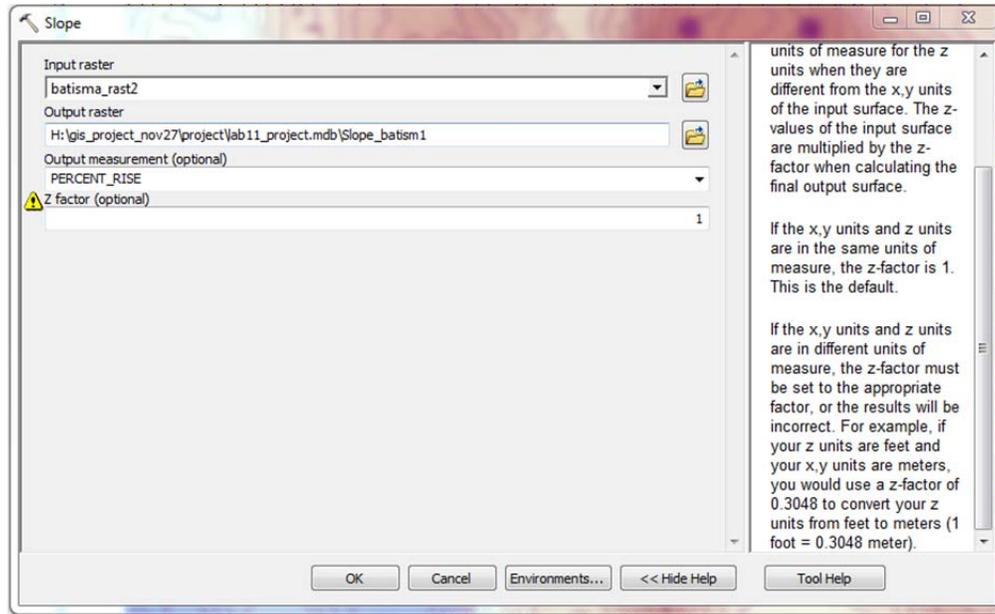
Figure 20. Slope calculation of bathymetric data.
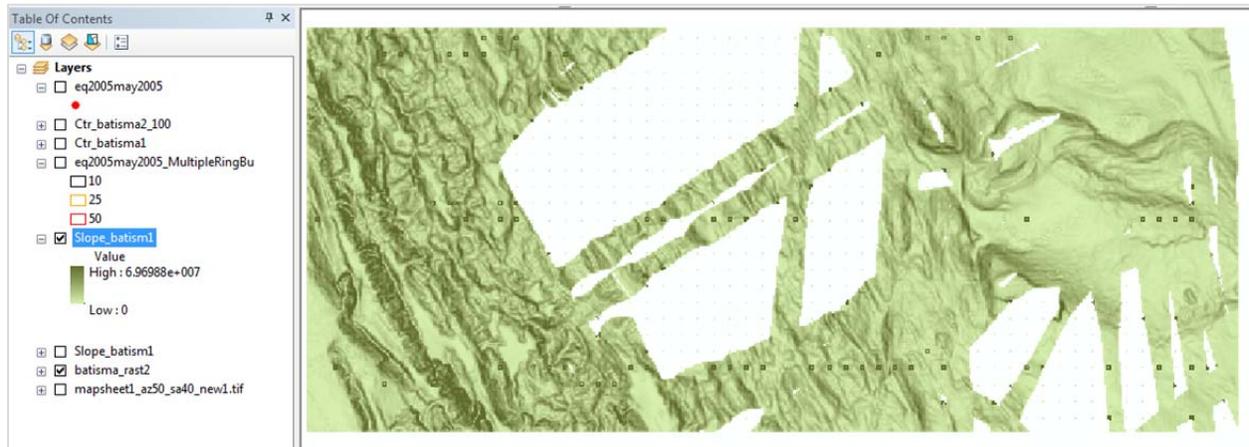
Figure 21. The result of slope measurement.
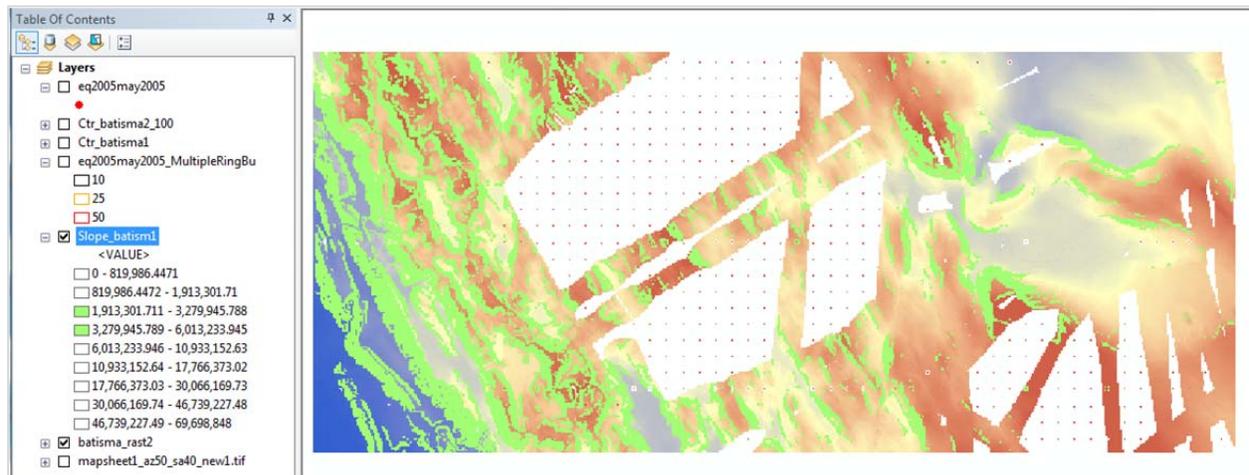
Figure 22. The result of slope measurement with light green shows the maximum slope rate of change.

The next step is to create a region around the epicenters that may represent a possible part of fault plane on the seafloor that is the extension of the fault plane near the hypocenter in deeper subsurface. This is done by using the buffer tool: Multiple ring buffers (analysis). Figure 23 display the window to create multiple buffer rings. In this step, three rings are created that represent diameters of 10, 25, 50 km. Figure 24 shows the buffer rings where 10 km buffer ring is colored black (not visible), 25 km buffer ring is orange, and 50 km buffer ring is red. The negative numbers are depth for each epicenter (red dots).
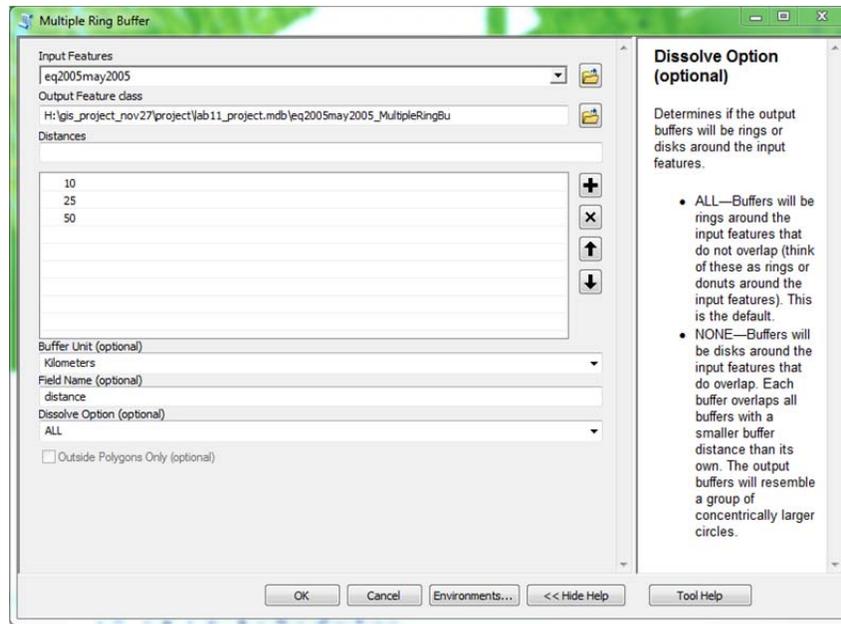
Figure 23. Window to calculate multiple buffer rings.
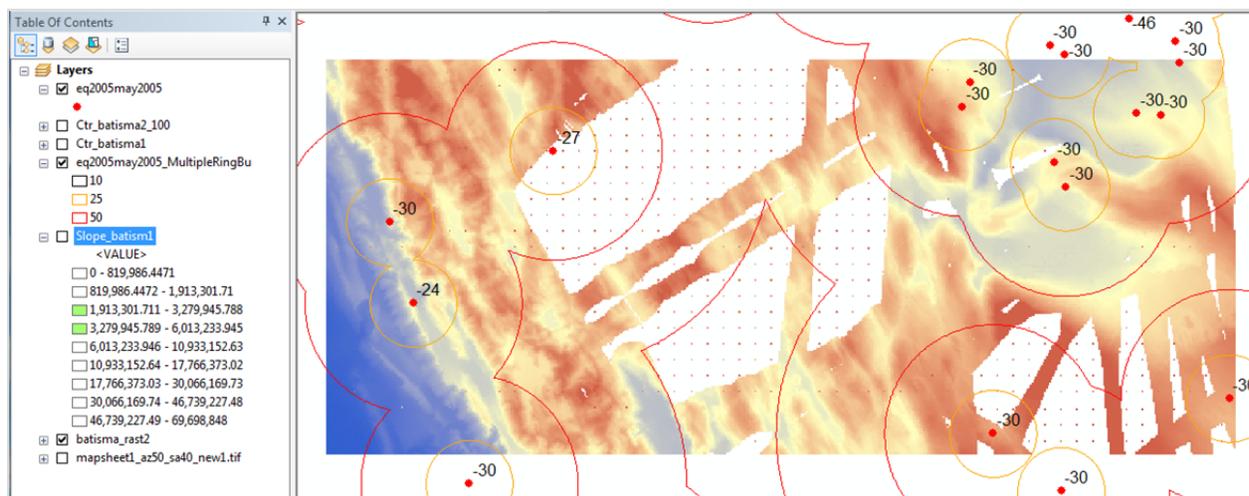
Figure 24. Result of multiple ring buffer overlay with bathymetric data.

Discussion

Figure 25 shows the overlay of the collected data for this project. The bathymetric coverage displayed in the background is a tiff file. The elevation data is from ASTER DEM showing the Aceh province and the island of Simeulue. Looking at Figure 25, earthquake locations are displayed according to the month it occurred. The red dots occurred in December 2004, light green dots in January 2005, and blue occurred in February 2005. The large light blue dot is the main earthquake, magnitude 9.2, on 26 December 2004. Considering the distribution of earthquakes, about the same locations occurred during foreshock and aftershock events. Furthermore, there seems to be clustering of earthquakes on the Aceh Basin, close to the deformation front on the southwest area, and around the Simeulue Island.

Figure 26 shows the distribution of earthquakes before and after the 28 March 2005 event. These locations are for the 13 March - 28 May 2005 period. The big light blue dot designate the 28 March (8.7 Mw) event. The pink dots occurred in March, yellow dots are in April and light green dots are in May 2005. From this distribution, there are basically two clusters of earthquakes, one on the north (on the Aceh Basin) and one around the Simeulue Island. Further analysis is conducted only around the December 26, 2004 earthquake since the cropped bathymetric data is located in this area with more earthquake locations.

The final step on estimating the faults that are active during big earthquakes is to overlay the epicenters and its buffer rings, with the bathymetric data. This is shown in figure 27. A simplistic interpretation for estimating the activated fault is to 'see' the overlap area between the zone of maximum rate of change of slope and buffer ring area. Looking at figure 27, for epicenters located on the northeast, the buffer with diameters of 25 and 50 km are shown to reach the nearest maximum slope (light green area). For the epicenter on the southeast, only 50 km buffer reach the nearest maximum slope zone. For epicenters on the west, all buffer rings reach some part of the maximum slope zone. Considering the 2004 earthquake produced a big tsunami, where large water displacement occurred. It may be concluded that the fault zone that was active extended toward the trench where it is located on deeper water. This is consistent with existing theories of the tsunami height.

Figure 25. Bathymetric data, ASTER DEM, and earthquake locations during 11 Dec 2004 – 26 February 2005 period. The light blue dot is the mega thrust (Mw 9.2) earthquake on 26 December 2004.
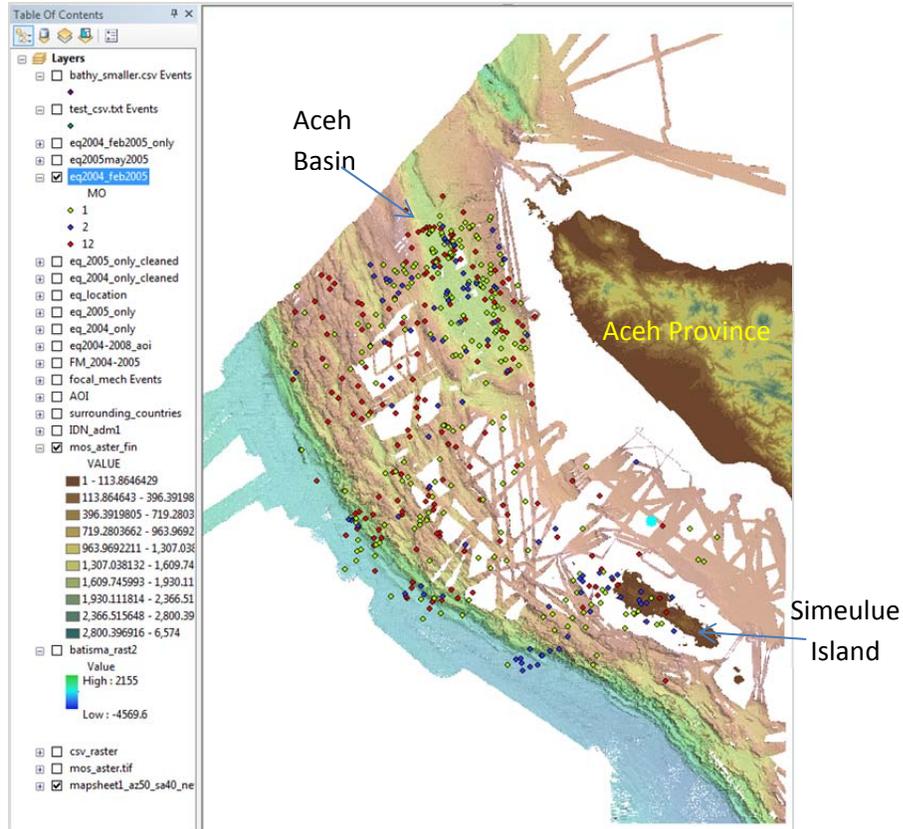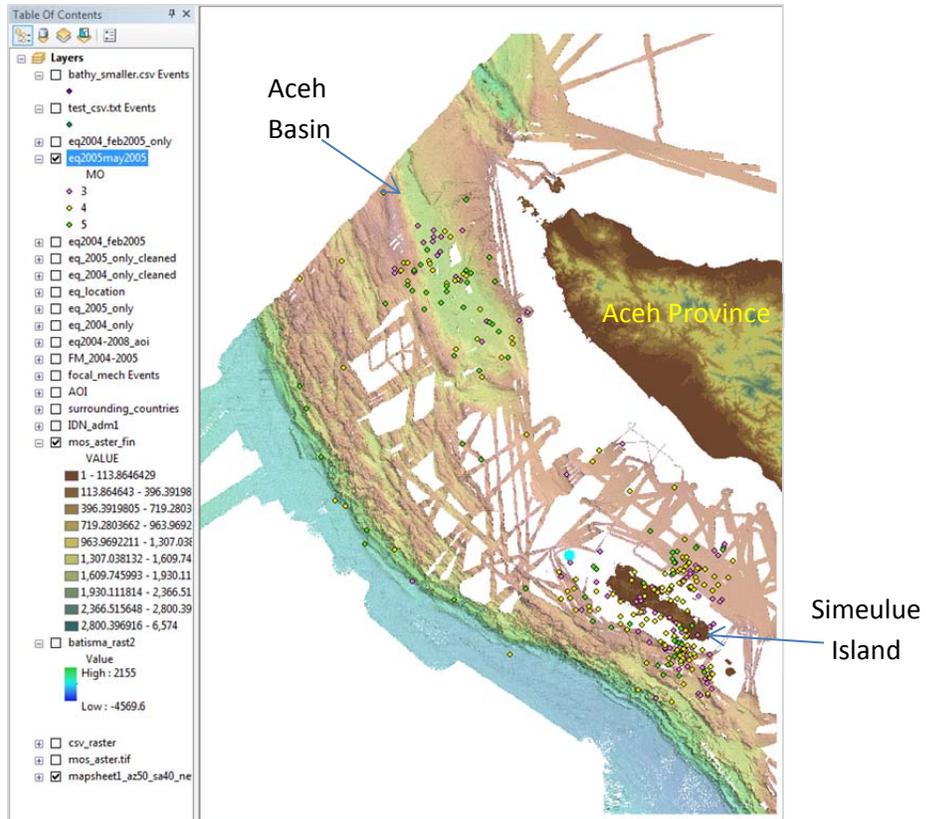
Figure 26. Bathymetric data, ASTER DEM, and earthquake locations during 13 March - 28 May 2005 period. The light blue dot is the Mw 8.7 earthquake on 28 March 2005.
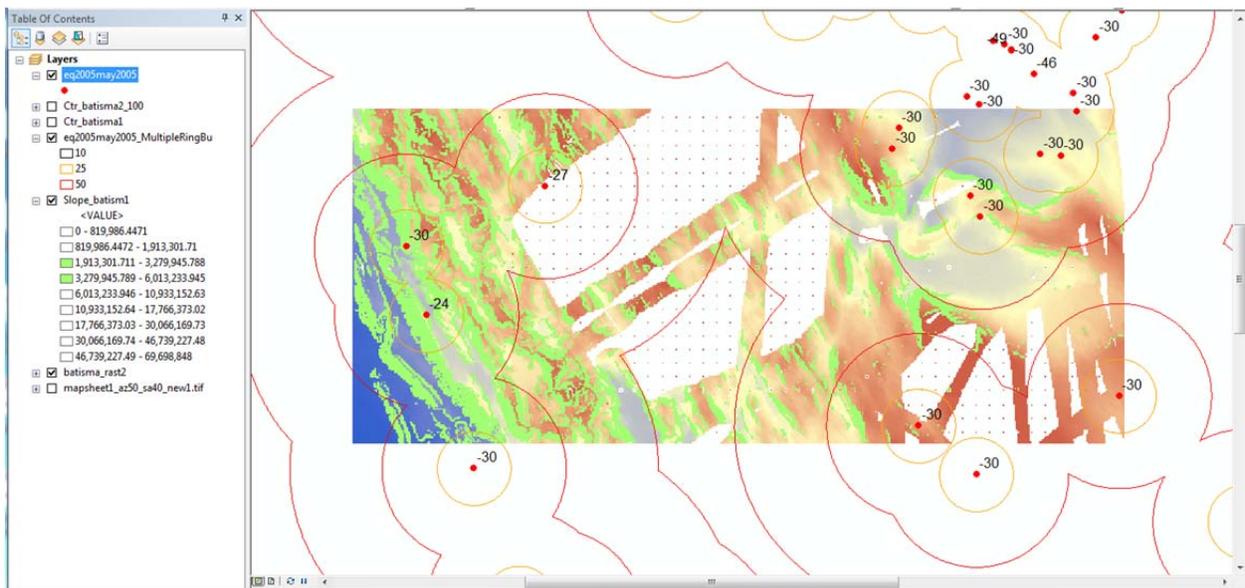

Figure 27. Overlay of buffer rings, maximum slope change rate (light green colored), and bathymetric data

Conclusion

This project aimed to investigate the possibility to estimate or map fault plane(s) activated during a period of foreshock and aftershock around a big earthquake. It is proven to be a challenging task, for example with file size limitation for import data. But there are various tools in ArcGIS that are very useful for this project also the ArcGIS discussion is beneficial. As shown in Figure 1, there are differences in epicenter locations from USGS and Engdhal, et al (2007). One reason for this discrepancy is the distribution of seismometers in this area. There are several seismometers installed in the Sumatra Island and the Simeulue Island but there are no seismometers in the Pacific Ocean which is to west side near these islands. So the epicenters are not well constrained. This project used the epicenters from USGS which is not well constrained. Considering the epicenters may not be located correctly, more confidence can be placed on the bathymetric data. This project shows that it may be possible to locate the fault plane but may require more hypocenter data, i.e., longer period than 3 months. While using the multiple buffer rings method may be easier, it does not give good certainty.

References

E. Robert Engdahl, Antonio Villaseñor, Heather R. DeShon, Clifford H. Thurber (2007), Teleseismic Relocation and Assessment of Seismicity (1918–2005) in the Region of the 2004 M_w 9.0 Sumatra–Andaman and 2005 M_w 8.6 Nias Island Great Earthquakes, Bulletin of the Seismological Society of America, Vol. 97 no. 1A, pp. S43-S61, doi: 10.1785/0120050614.
Earthquake epicenter (http://www.kids-fun-science.com/earthquake-epicenter.html)
Finding fault plane (http://www.data.scec.org/Module/s1act05.html)
ArcGIS discussion forum (http://forums.esri.com/Forums.asp?c=93)