Report on Loan No. 860

Assessment of the earthquake and tsunami hazard in western Sumatra following the 09/07 Mentawai Islands earthquake sequence.

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1 Background

The September 2007 Bengkulu earthquake sequence of on the Sunda Megathrust west of Sumatra (figure 1) continues the rupture of an entire plate boundary and it is now the case that from the Andaman Islands to Engganno Island, a distance of more than 2500km, less than 300km of the great Sunda megathrust remains un-ruptured in the last 5 years (see for Konca etal 2008 for example). The September 2007 earthquakes presented a first opportunity to test the predictions of earlier NERC funded work which suggests that the height of tsunamis in the near-field of megathrust earthquakes is predictable in the short term by measuring the vertical coseismic displacement on the coast. In November and December 2007 we travelled to Sumatra and used NERC GEF GPS equipment to make unprecedentedly detailed measurements of the run up of the tsunami from the 2007 earthquake. Here we report on this deployment.

2 Theoretical relationships

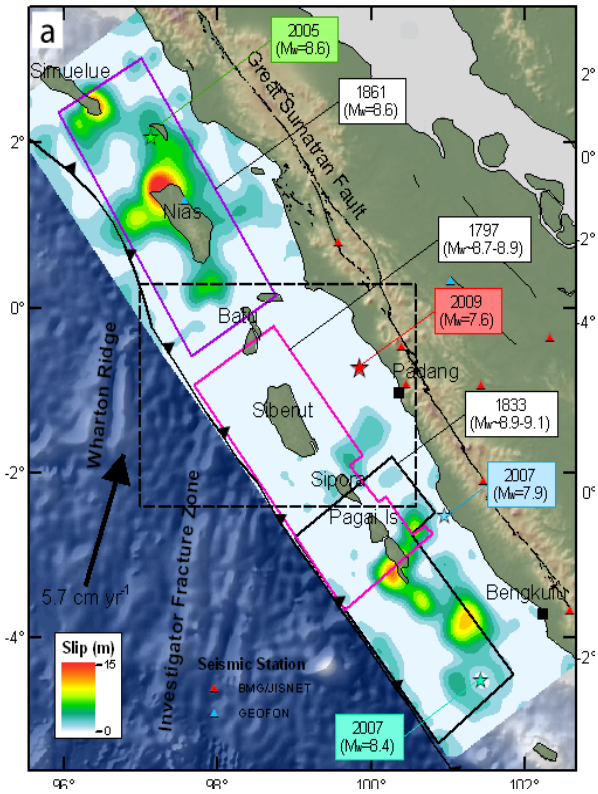

Figure 1. Distribution of slip during recent earthquakes. Red – blue colours from about 3°N to the equator indicate the amount of slip on the megathrust during the 2005 earthquake and from about 1.5 to 5 °S the amount of slip on the megathrust during the 2007 sequence.

Recent work (McCloskey et al. 2007; McCloskey 2008) attempted to constrain the distribution of probability of runup heights from the threatened M>8.5 earthquake whih hs been forecast for the Mentawai Islands, offshore Padang. A customised, finite-element model of the Sumatran forearc to predict the vertical co-seismic surface displacements which would result from more than 100 complex fractal slip distributions chosen for consistency with historical Mentawai Islands earthquakes. These surface displacements were used as initial conditions for tsunami propagation simulations over high resolution bathymetric models of the region. This work suggested that, despite the complexity of the slip distributions employed, the large scale geometry of the problem dominates tsunamigenesis and propagation in the near field and that 1) the travel time of the highest wave observed in the near field was independent of the slip distribution and even of the magnitude and 2) the height of the tsunami observed at any near-field location was proportional to the vertical coseismic displacement observed there Figure 2. The implications of these results both for our understanding of the physics of tsunamis generated from subduction zone earthquakes and for preparedness planning for western Sumatran cities are significant.

3 The September 2007 Sequence

On 12 and 13 September 2007 a series of earthquakes ruptured a large area of the megathrust between the islands of Enganno and Sipura. The first earthquake (Mw8.4; Event 1; figure 1) occurred at 11:10:26 UTC 2007/09/12 generating a tsunami which propagated throughout the Indian ocean. Given the rapid plate convergence and the well constrained slip on the great 1833 earthquake which last ruptured this segment of the sunda megathrust, the 2007 sequence was not unexpected (eg Nalbant et al. 2005) and ruptures of this area were included in the tsunami simulation work described above. At 23:49:04 UTC on 2007/09/12 the megathrust failed again in a M7.9 earthquake (Event 2) to the north of the first event and at 03:35:28 UTC on 2007/09/13 a M7.1 event ruptured the fault under Sipura Island (Event 3).

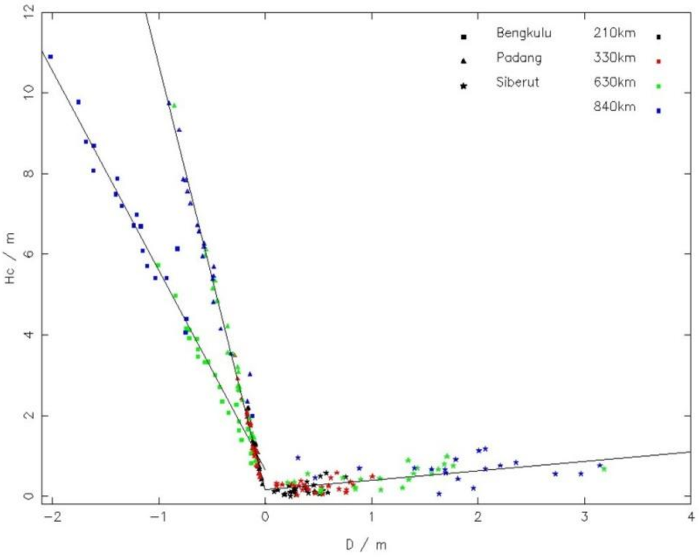

Figure 2. Relationship between vertical coseismic displacement of the Sumatran coast and on the off shore islands, D, and the maximum amplitude of the tsunami generated. Note that the slope of the characteristic lines is different for each location.

While the nucleation of the main shock of this sequence was farther south than expected, the nature of the rupture was similar to the the slip models in the earlier modelling study. Clearly this event should gnerate coseismic displacements and tsunami runups in line with the 2007 predictions. Rapid estimates of tsunami runup were done within a few days of the earthquake and suggested that the runup was locally up to 4m high. Such local estimates were made at only one point, however, and since the modelling study had a simulation grid spacing of 500m, more detailed measurements would be required if the theoretical relationship could be check by observation. On 17 November 2007 a team comprising scientists from Universiies of Ulster and Newcastle, the Instituto Nazionale di Geofisica e Vulcanologia, Rome and ITB Bandung, Indonesia arrived in Bengkulu to carry out a high resolution survey.

4 Aims

The aim of the project was to test the tsunami height - vertical displacement relationship for the M8.4 Mentawai earthquake. In particular to:

1) Estimate the tsunami height at an appropriate spatial resolution at about ten locations from about 50km north of Bengkulu to 100km south.
2) Estimate the coseismic displacement at each location using the best available slip distribution for the event.
3) Predicting the tsunami runup for each location by interpolating the characteristic relationship between coseismic displacement and runup for computed for that location.
4) Comparing predicted and observed wave heights.

5 Estimating tsunami height

We used stop-go kinematic carrier phase GPS to survey the heights of various tsunami markers at twelve separate locations along an 80 km stretch of coastline (Figure 3), between 18th – 29th

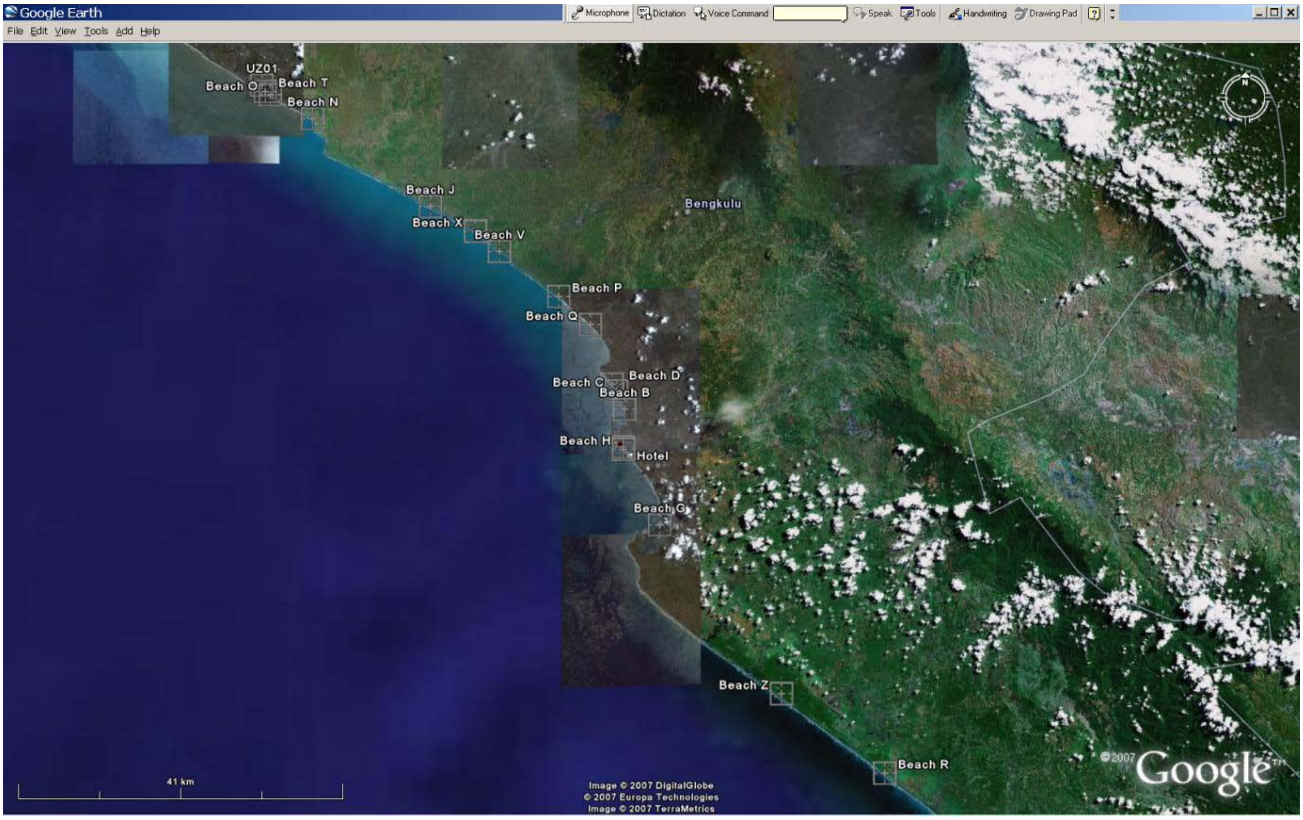

Figure 3. Locations of survey sites

November 2007. Features included recent debris deposits and wave-cut notches in soft sediment clearly above the normal tidal range, watermarks on vegetation or buildings, and upper limits of saltwater-killed vegetation; wherever possible these features were associated with the tsunami by local inhabitants' verbal evidence. Where no physical evidence of the maximum tsunami height was available, we surveyed features known to have been inundated or to have remained dry, as extreme lower or upper bounds respectively. We attempted as complete coverage as possible within each zone, in order to obtain a representative mean without undue emphasis on very local extreme values.

Long	Lat	Beach ID
102.262	-3.762	B
102.248	-3.734	D
102.301	-3.891	G
102.260	-3.804	H
102.043	-3.535	J
101.858	-3.406	T
101.911	-3.437	N
102.187	-3.636	P
102.223	-3.667	Q
102.554	-4.168	R
102.121	-3.585	V
102.094	-3.563	X
102.437	-4.079	Z

Table 1. Coordinates of survey sites

Each beach was observed relative to a temporary local GPS base station occupied for 4 –6 hours on the day of the survey, which in turn was tied to the ITRF2005 global reference frame using data from permanent sites COCO (distance ~1100 km; data not available every day), SAMP (distances 600 – 1000 km), MKMK and MLKN (typical distances 130 – 330 km) which were operating contemporaneously. We used the Bernese GPS software version 5.0, with IGS Final precise satellite orbits, to compute daily static solutions leading to adjusted campaign coordinates for each temporary base station. These coordinates were then fixed during local stop-go kinematic GPS processing using the Leica GeoOffice software. Heights of tsunami markers were obtained relative to the GRS80 ellipsoid with an estimated precision of 25 – 30 mm, based on the daily repeatability of MKMK and MLKN and on formal error estimates from Leica GeoOffice.

In order to compare these observed heights with predictions, they must be expressed as heights above the sea surface as it was immediately before the 12th September tsunami, which occurred at when the sea surface was 42 cm above mean sea level (MSL) according to the FES2004 numerical ocean tide model, close to high tide on that day. Predicted variations in tidal height and dynamic sea surface topography (including the inverse barometer effect due to atmospheric pressure) are less than 5 cm along the surveyed section. However, because of the steep geoid gradient in the region (approaching 0.1 m/km, Figure 4) and paucity of local gravity data with which to refine a geoid model, it is not possible to reliably convert ellipsoidal heights into heights above MSL using the geoid-ellipsoid separation combined with a model of sea surface topography. Instead, we observed markers at each location representing high water at the latest spring tide (HWS) before or during the survey; this datum lies 77 cm above MSL according to FES2004. By fitting a running Gaussian mean of full width 5 km through these points, we established the HWS datum (35 cm above the pre-tsunami sea surface) throughout the survey area. The root mean square misfit to this running mean is 17 cm, which we judge to be commensurate with the overall error of height taking into account the identification of markers and of the measurement location on each features. As a check, where it was possible to do so in sheltered inlets free of wave action we observed heights of instantaneous sea level during the survey. Once corrected for tidal state, these have a mean of 85±16 cm below HWS, which confirms the accuracy of the tidal model and of our datum definition. Figure 5 shows the variability of observed tsunami height along the entire profile.

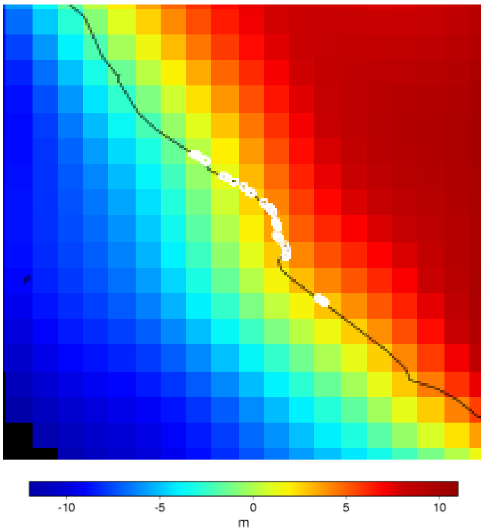

Figure 4. GRACE EIGEN-gl04c geoid model. White dots indicate locations of

The survey techniques involved measuring a wide range of different evidence on the beaches. These not only included estimates of the tsunami run-up but also included marks, such as previous high tide marks or current sea-level which were clearly not estimates of the run-up. The run-up relevant heights were isolated and averaged for each beach giving a measured run-up and uncertainty for each beach.

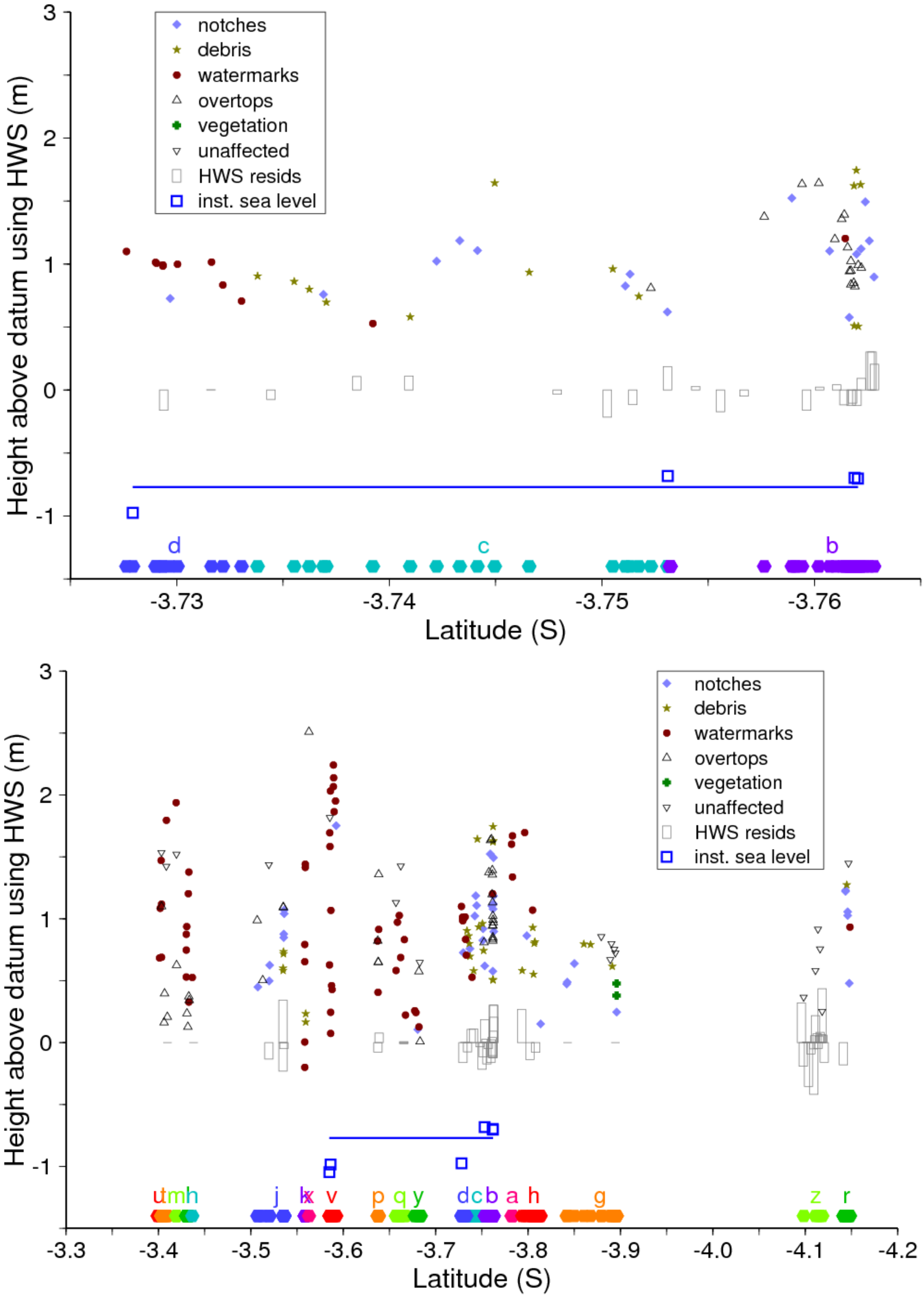

Figure 5. Measured data A) on contiguous beaches b, c and d and B) along the entire surveyed coast. along entire survey. Key indicates features surveyed.

6 Predicting tsunami height

As noted in Section 2 above, the characteristic relationship between coseismic displacement of the coast and the tsunami run-up (refered to here as the DH characteristic) is unique for each location on the coast. To forecast run-up it is therefore necessary to compute this characteristic locally. A series of 22 slip distributions (eg Figure 6a) for the Bengkulu segment of the megathrust were calculated and used to compute the coseismic displacement, D(L), for each synthetic slip model at each coastal locality and for the entire seafloor. The seafloor displacement is used to compute the tsunami mareogram (eg Figure 6b) for each event at each field locality and the maximum run-up, H(L), is estimated. The best fitting linear model for the characteristic and its uncertainties are estimated (eg Figure 6c). The vertical coseismic displacement at each location is calculated for each location using the best joint inversion of both geodetic and seismic data for the M_w8.4 event of the Bengkulu sequence (see http://www.tectonics.caltech.edu/slip_history/2007_s_sumatra/ssumatra-update.html) and the DH characteristic models are interpolated to provide a prediction for the run-up for the tsunami at that location. Standard techniques allowed an estaimte in the uncertaintly for each interpolation based on the standard error in the estimates in the a and b parameters of the linear model. Since the grid spacing of the tsunami calculations are on the same order as the length of a typical beach, only one characteristic and run-up prediction is calculated for each locality.

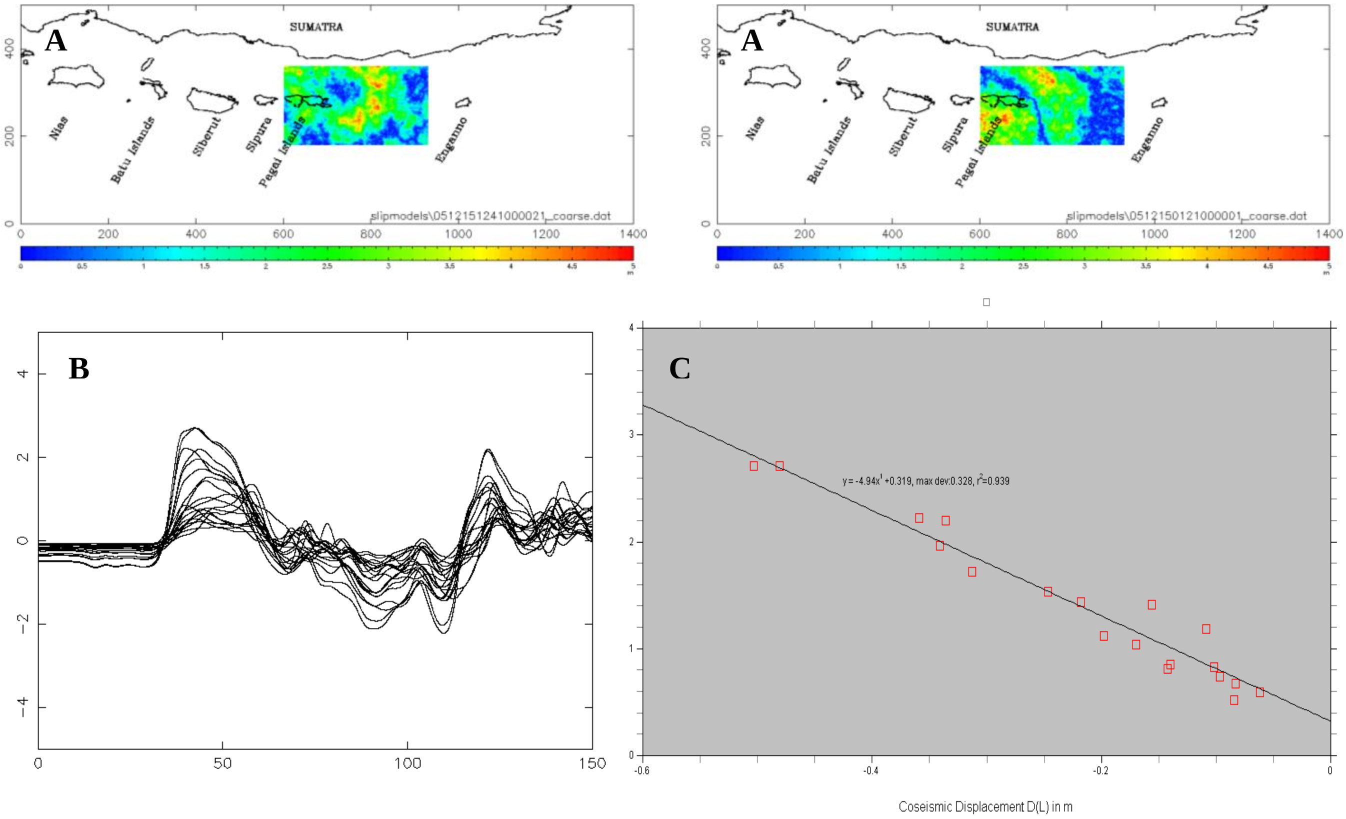

Figure 6. Predicting tsunami run-up. A) typical slip distributions used in calculating DH characteristics. B) 22 tsunami mareograms for beach P. C) DH characteristic for beach P. The first point and maximum wave height on each curve in B are the coseismic displacement and maximum run-up respectively in C

7 Results

Figure 7 shows the plot of the tsunami run-up predicted by McCloskey et al. 2007 for each beach against the measured tsunami heights.

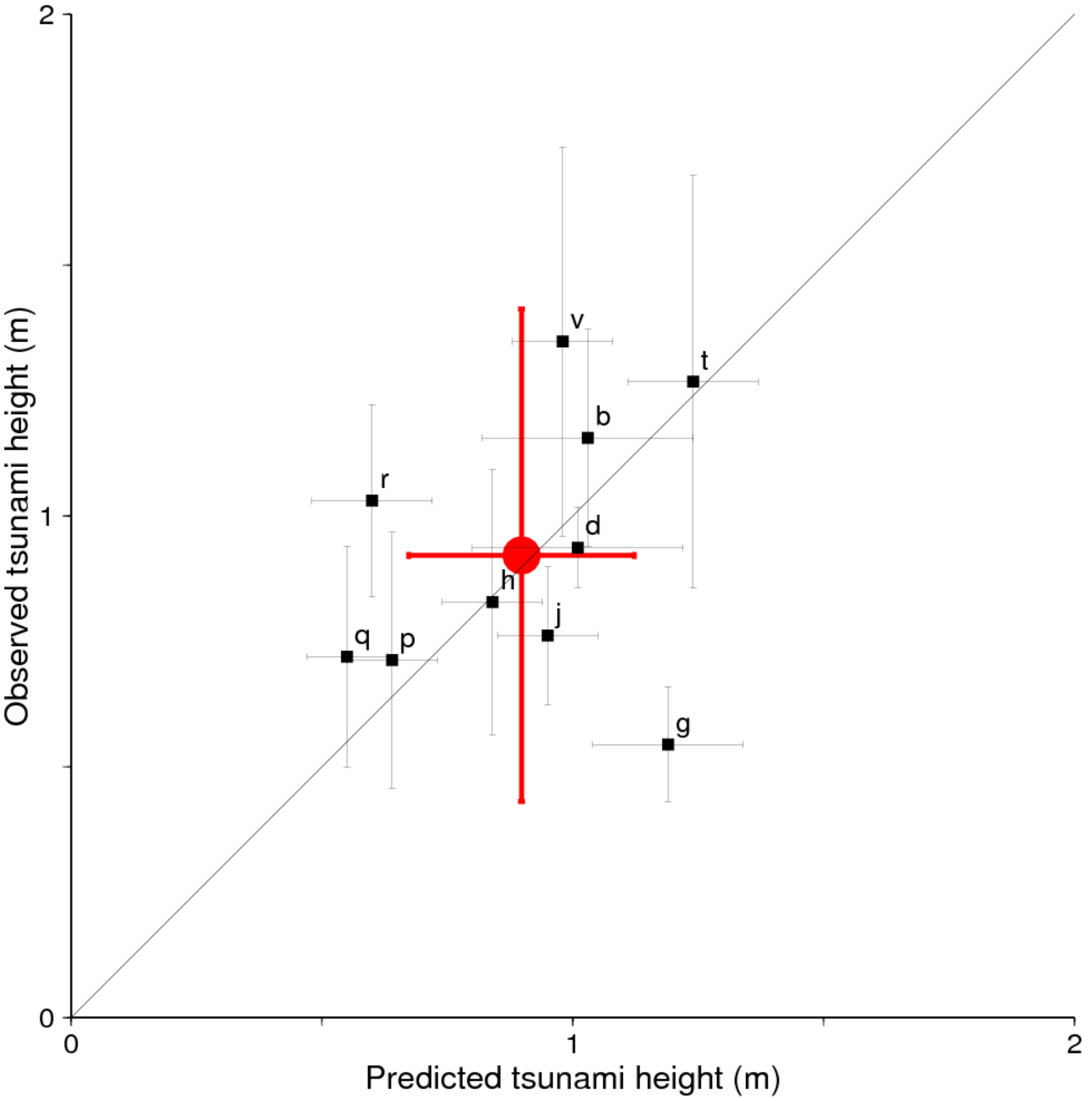

Figure 7. Predicted versus observed tsunami heights. Black symbols with error bars are the means and uncertainties for each beach, indicated by the associated letter. Red circle and error bars are the result for the entire survey

8 Discussion

The most striking feature of the results here is the strong variability of the inundation over relatively small distances along the shore which has a higher amplitude than the uncertainties in its measurement and is therefore real. A clue to its origin might come from the south of beach B (Figure 5a) where the measured run-up varied by more than its mean. This site was located at the mouth of a small river and had strongly varying local topography. Which extended seaward where several bars could be seen breaking the surface and disturbing the flow. Clearly such micro-bathymetric features are not included in any bathymetric model for the area and the variability of the inundations could therefore never be predicted by numerical simulations. Given the very long wavelength of the tsunami waves heterogeneous run-up is not due to wave processes but is probably the results of hydrodynamic interaction with the shallow bathymetry and local topography. It is probable that such interactions will be very important in controlling the precise run-up in larger tsunamis and this study would support the use of detailed bathymetric and topographic models for assessing likely run-up from threatened tsunamis. In this instance the correct run-up for beach b for comparison with numerical simulations is the mean of the measurements, about 1.2±0.25m not the maximum run-up along this stretch of coast, about 1.7m, which is often recorded in tsunami surveys.

Figure 7 shows predicted versus observed tsunami run-up for the project. Firstly, the average result for the entire survey is entirely consistent with theory. The theoretical relationship would have predicted an average inundation for this coast of about 0.9±0.3m, the observed heights were about 0.9±0.5m. The detail, however, is more complex and this mean is the result of long-wavelength smoothing of significant variability.

A clear finding of this work is the importance of using appropriate scale variability and the use of full hydrodynamic models in the forecasting of tsunami inundation. We note that such work is currently being carried out for the city of Padang in western Sumatra.

9 Publications

McCloskey et al. (2007), Lessons from the 2007 Mentawai Islands earthquakes, *Eos Trans. AGU, 88* (52), Fall Meet. Suppl., Abstract U53A-03

A paper is in preparation for Nature Geoscience.

10 References

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