Rupture process of the 2004 Sumatra-Andaman Earthquake from Tsunami Waveform Inversion

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Abstract

The aim of this work is to infer the slip distribution and rupture velocity along the rupture zone of the 26 December 2004 Sumatra-Andaman earthquake from available tide-gauge records of the tsunami. We selected waveforms from 14 stations, distributed along the coast of the Indian Ocean. Then we subdivided the fault plane into 16 subfaults (both along strike and down dip) following the geometry and mechanism proposed by Banerjee (2005) and computed the corresponding Green's functions by numerical solution of the shallow water equations through a finite difference method. The slip distribution and rupture velocity were
determined simultaneously by means of a simulated annealing technique. We compared the recorded and synthetic waveforms in the time domain, using a cost function that is a trade-off between the L1 and L2 norms. Preliminary tests on a synthetic dataset, together with a posteriori statistical analysis of the model ensemble enabled us to assess the effectiveness of the method and to quantify the model uncertainty. The main finding is that the best source model features a non-uniform distribution of coseismic slip, with high slip values concentrated into three main patches: the first is located in the southern part of the fault, off the coast of the Aceh Province, the second between 6.5°N and 11°N, and the third at depth, between 11°N and 14°. Furthermore, we estimated that the rupture propagated at an average speed of 2.0 km/s.

Introduction

On December 26, 2004, an earthquake of Mw=9.3 (Stein and Okal, 2005) struck the Sumatra-Andaman region and generated a huge tsunami. This was the most devastating and deadly event of this type that has occurred during the last centuries, causing more than 250,000 fatalities and spreading destruction along the coasts of the whole Indian Ocean.

Initially, the exceptional rupture extent and duration of the earthquake made it difficult to retrieve the details of the whole source mechanism using classical inversion methods. Actually, the problem of determining the rupture properties of this earthquake is still unresolved: several proposed source models, using different geophysical datasets (seismological, geodetic, hydroacoustic, etc.), differ in length, width, slip and rupture velocity (e.g. Ammon et al., 2005; Banerjee et al., 2005; Bilham, 2005; de Groot-Hedlin, 2005; Fine et al., 2005; Guilbert et al., 2005; Ishii et al, 2005; Krüger and Ohrnberger, 2005; Lay et al., 2005; Park et al., 2005; Stein and Okal, 2005; Tsai et al., 2005; Vigny et al., 2005).
Tsunami data can help resolve some of these source parameters. In fact, it has been shown that tide-gauge records and run-up heights are useful to constrain some earthquake source parameters. In particular, they have good resolving power of the spatial extent and slip distribution for a tsunamigenic earthquake (e.g. Satake, 1987; Johnson et al., 1996; Piatanesi et al., 1996; Geist, 1999; Ortiz and Bilham, 2003). It has been also shown that near-field tsunami data may be used to retrieve information on the size and rheologic properties of a tsunamigenic slump or landslide (Heinrich et al., 2001). This work deals with the problem of inferring the coseismic slip distribution for the 2004 Sumatra-Andaman earthquake using the available tide-gauge records of the tsunami. Furthermore, since the rupture duration of the Sumatra earthquake is exceptionally long, of the order of 10 minutes (e.g. Guilbert et al., 2005; Ishii et al., 2005; Krüger and Ohrnberger, 2005; Ni et al., 2005; Park et al., 2005; Stein and Okal, 2005; Tsai et al., 2005), we will use the tsunami data also to infer the speed of rupture propagation. We first describe the method and the data selection and processing and then we discuss a synthetic test used to check the effectiveness of our technique. Finally we show the results obtained for the Sumatra earthquake and tsunami.

Forward modelling and Green's functions

Tsunamis are considered long shallow-water gravity waves, since their wavelength is usually much larger than the sea depth. In this study we use the nonlinear shallow water equations written as follow:

\[
\begin{align*}
\frac{\partial (z + h)}{\partial t} + \nabla \cdot [v(z + h)] &= 0 \\
\frac{\partial v}{\partial t} + (v \cdot \nabla)v &= -g \nabla z + C + F
\end{align*}
\] (1)
In eqs. (1), $z$ represents the water elevation above sea level, $h$ the water depth in a still ocean, $v$ the depth-averaged horizontal velocity vector, $g$ the gravity acceleration, and $C$ and $F$ represent the Coriolis and bottom friction forces respectively. The boundary conditions are pure wave reflection at the solid boundary (coastlines) and full wave transmission at the open boundary (open sea). The equations are solved numerically by means of a finite difference method on a staggered grid. The initial seawater elevation is assumed to be equal to the coseismic vertical displacement of the sea bottom, computed through the Okada’s analytical formulas (Okada, 1992), while the initial velocity field is assumed to be identically zero. Numerical modelling of the tsunami is carried out in the domain depicted in Fig. 1 with 1 arc-minute of spatial resolution, using the ETOPO2 bathymetric dataset (Smith and Sandwell, 1997). This dataset is supposed to be inaccurate in very shallow waters and it may constitute an additional source of error. A good practice is that followed by Fujii and Satake (2006) and by Geist et al. (2006) which merged different bathymetric datasets.

The usual way to deal with the problem of retrieving the slip distribution on the fault from tsunami data is to first subdivide the fault plane into a number of subfaults and compute the Green’s function (i.e. the tsunami waveform at a station produced by a subfault) by solving the linear form of eqs. (1). The tsunami waveforms produced by the whole source are then calculated as a linear combination of the Green’s functions corresponding to each subfault, multiplied by a coefficient that is the actual slip amount. It is evident that this method holds if the linear equations are valid for propagation of the entire wavefield. For tsunami propagation in very shallow water and when the wave amplitude is large, the linear approximation is no longer valid. We find that this is what happens in some regions (for instance along the coast of Thailand), characterized by a very large and very shallow continental shelf and when the incoming tsunami wave exceeds a few meters of amplitude. Using the nonlinear eqs. (1), we compute two waveforms corresponding to a subfault with 1
and 10 m of slip respectively and find that the two waveforms do not scale by a simple factor 10, as expected if propagation was linear. Without abandoning the idea that the whole source may be viewed as a combination of elementary sources, we follow a non-conventional approach to compute the Green’s functions for our problem: instead of solving the linear equations and assuming unitary slip amplitude on a subfault, we use the nonlinear shallow-water equations and 10 m of slip amplitude for each elementary subfault. We use 10 m of slip for the elementary source, since this is the mean slip along the whole fault compatible with seismic moment estimations (Stein and Okal, 2005). It is reasonable to assume that the slip value for each subfault of heterogeneous source will be centred on this mean value. From this point of view, our approach to compute the Green’s functions may be seen as a way to linearize the problem around the mean slip value.

**Waveform selection and processing**

The 26 December 2004 Sumatra-Andaman tsunami propagated worldwide and was recorded by several tide-gauges in the Indian Ocean, and by stations in both the Pacific and Atlantic Oceans (Merrifield et al., 2005; Nagarajan et al., 2006; Tanioka et al., 2006; Tsuji et al. 2006).

After a careful inspection of the available records, we select 14 stations that are azimuthally distributed along the coast of the Indian Ocean (see Fig.1). Some of these records have been manually digitized at a sampling interval of 5 minutes while others were recorded by digital instruments, with sampling interval ranging from 2 to 10 minutes (see Table 1 for a summary). We choose a time window that includes only the first oscillations in the waveforms, since errors in the bathymetric dataset and the coarse grid does not allow modelling of local effects (e.g. resonance of the bays) that may contribute to later arrivals (coda) on the recorded waveforms.
Global search inverse technique

The observed and synthetic waveforms are compared in the time domain. A key issue in inverse problems is choosing a suitable cost function to represent the goodness of fit for a given model. A widely used approach is to minimize the $L_2$ norm, since this leads to easy computations taking the form of a least squares problem. The main drawback is that the least squares solutions are not robust. In fact, they are very sensitive to a small number of large errors in the data set (Tarantola, 1987). Here we use an objective function that is a hybrid representation between $L_1$ and $L_2$ norm (Sen and Stoffa, 1991) that can be written as:

\[
E(m) = \sum_{k=1}^{N} \frac{2 \sum_{t=t_i}^{t_f} (u_O(t)u_S(t))}{\sum_{t=t_i}^{t_f} u_O^2(t) + \sum_{t=t_i}^{t_f} u_S^2(t)} \]  

(2)

In eq. (2) $u_O$ and $u_S$ are the observed and synthetic waveforms respectively, $t_i$ and $t_f$ are the lower and upper bounds of the time window and $N$ is the number of records used in the inversion. This cost function takes information from both the shape and the amplitude of a waveform and is more robust than the standard least squares technique.

The general forward problem may be written as:

\[
d = G(m) \]

(3)

Here $d$ represents the theoretical data values (tsunami waveforms), $m$ are the parameters describing the model (slip amplitude and rupture velocity) and $G$ is a function linking the
observables to the model. The problem of inverting tsunami waveforms to determine slip distribution on the fault was originally formulated by Satake (1987) as a linear inverse problem. In this case $G$, the Green’s functions, do not depend on $m$ and the problem may be solved using a generalized inverse of $G$. The Green’s functions used to assemble the matrix $G$ should depend on the rupture velocity as they have to account for the appropriate time delay of the unit sources. In Satake’s (1987) work the unit sources turn on at the same time, thus implicitly assuming an infinite rupture velocity along the whole fault. In this work we invert for both the slip distribution and the rupture velocity simultaneously. In this case, $G$ will depend on the rupture velocity, which is one of the parameters to be inverted, thus leading to a nonlinear inverse problem.

To deal with this problem, we use a global optimization method that is a particular implementation of the simulated annealing technique, called the “heat bath algorithm” (Rothman, 1986). This technique, already used in non-linear finite fault inversion (e.g. Ji et al., 2002; Liu and Archuleta, 2004), performs a large sampling of the model space and concentrates the search on regions characterized by low values of the cost function, i.e. where the optimal models are likely to be found.

**Synthetic test**

To check the effectiveness of our method in inverting for both the slip distribution and the rupture velocity, we perform a synthetic checkerboard test. We subdivide the fault plane into 16 subfaults, following the geometry and mechanism proposed by Banerjee et al. (2005) from analysis of far-field static displacements recorded by GPS. The parameters characterizing each subfault are listed in Table 2. Then we build a test rupture model that consists of a slip distribution having a checkerboard pattern, with slip values alternating
between 5 and 15 meters. The velocity of the rupture front is taken at 2 km/s. The synthetic waveforms are then resampled at the same intervals as the observed data (see Table 1) and corrupted by adding a gaussian random noise with a variance that is 10% of the clean waveform amplitude variance (Ji et al., 2002). The artificial noise level we introduce is at least three times larger than the background noise of the tide-gauge records before the first tsunami arrival. We assign a relative weight to each station in order to take into account non-uniformity in both the sampling rate of the records and azimuthal distribution of the stations (see Table 1). We introduce a priori information on the model solution by imposing lower and upper bounds to the range of possible source parameters, namely 0-30 meters for the slip amplitude and 0.25-5.0 km/s for the rupture velocity.

The best inverted model is very similar to the target one: the checkerboard shape of the slip distribution is well reproduced and the rupture velocity is estimated exactly (see Fig.2). The test and inverted models are not strictly identical in terms of slip for some subfaults, especially for those located in the northern part of the rupture zone. Nevertheless, because the cost function of the inverted model is very low and the comparison of the observed and synthetic waveforms is good (Fig.4), it is likely that the problem is ill conditioned and the solution is not unique.

**Simple appraisal of the ensemble**

During the search stage of the simulated annealing method, a large number of models are tested (about 1 million) and the corresponding cost function computed. All of these models represent a sample of the model space that may be viewed as a statistical *ensemble*. An important step of a nonlinear inverse method is the appraisal stage, where some information of the model solution is inferred from the whole ensemble (e.g. Mosegaard and Tarantola, 1995; Sambridge and Mosegaard, 2002). Other interesting properties may be
extracted from the ensemble, such as the mean and the variance. Fig.2 shows the marginal distribution corresponding to each parameter, together with the values of the best model. To emphasize the properties of those models that are most suitable (i.e. with small value of the cost function $E$), we calculate a weighted mean and standard deviation of each parameter, using as weighting function $w = 1/E$ (Shibutani et al., 1996). The standard deviation may be interpreted as the uncertainty in the estimation of the corresponding parameter. Smaller values of the standard deviation indicate that the corresponding parameters are better resolved than those characterized by larger deviations. In general, the distributions are strongly peaked around the mean and both the best and the target models are always found within 1 standard deviation of the mean (see Fig.3). Nevertheless, the standard deviations increase from south to north: this can be interpreted as a decrease in the resolution for parameters in the northernmost subfaults. To a smaller extent, it appears that the shallow subfaults are better resolved than the deep ones. Surprisingly, one of the best resolved parameter is the mean rupture velocity, for which the corresponding marginal distribution features a well defined peak, centred on the value of the target model. We furthermore examine the sensitivity of the tsunami waveforms to variation in rupture velocity. We perform synthetic tests with different target rupture velocities, ranging from 0.5 km/s to 3.0 km/s at 0.5 km/s intervals. Figure 3c clearly shows that the best model in all cases exactly estimates the mean rupture velocity. Moreover, the standard deviation tends to slightly increase with the velocity value of the target model. At least for this exceptionally long earthquake the tide-gauge records are able to constrain the mean rupture speed.

**Application to the 2004 Sumatra earthquake**
The results of the synthetic test are encouraging: they show that the nonlinear inversion method and the station distribution are able to resolve the rupture process, thus allowing us to apply this procedure to the 2004 Sumatra tide gauge data.

The results of the inversion are summarized in Fig. 5, where we show the slip distribution corresponding to the best model found during the whole search of the parameter space. The slip distribution is strongly heterogeneous, with high slip concentrated in three main patches. The first is located in the southern part of the fault and extends from the hypocenter to about 5°N: the mean slip exceeds 10 m with a high concentration of 30 m on the deep subfault just off the Aceh Province. This region of high slip is consistent with the severe inundation and run-up observed along the coast of the Aceh Province and in Banda Aceh, reaching 30 meters in some places. The second main region of slip is located between 6.5°N and 11°N, with a mean slip of about 10 meters, mainly distributed on the shallow part of the fault. A third concentration of slip appears in the northernmost deep part of the fault with a mean slip of about 20 m. The mean speed of the rupture is estimated to be 2.0 km/s.

We performed a posteriori analysis on the model ensemble to assess the uncertainty and the resolution of the model solution, in the same way as described above for the synthetic test. In Fig. 5, we show the marginal distribution corresponding to each parameter, together with the values of the best model. The marginal distributions relative to most subfaults feature a distinct peak, thus indicating a fairly good resolution of the corresponding parameter. As expected from what we learned with the synthetic test, there is a loss of resolution from south to north and, in general, the shallow segments are better resolved than the deeper ones. In particular the high slip value we find in the northernmost part of the fault at depth is poorly resolved and probably overestimated, as revealed by the results of the synthetic checkerboard test. Furthermore, differently from what found in the synthetic test, the values corresponding to the best model do not always lie within 1 standard deviation from the mean: this reveals
that the real records are affected by other sources of error than the noise injected into the synthetics. In general, when the marginal are large the output should be interpreted with great care (Mosegaard and Sambridge, 2002): in such cases the best model should be regarded as an outlier (see Fig.6). The comparison of the recorded and synthetic waveforms generally shows a good agreement (Fig.7). Nevertheless, some tide-gauges do not show some of the high frequency content in the synthetic waveforms. This may be due to the sampling interval of the records and most probably to a poor instrumental response of the tide-gauges, which are generally designed to measure ocean tides at periods much longer than tsunami waves.

**Conclusions**

Our method makes use of tsunami waveforms, recorded by several tide-gauges in the Indian Ocean to infer the finite-fault rupture process of the 2004 Sumatra earthquake. To our knowledge, this is the first time that a nonlinear inversion method (simulated annealing technique) is applied to tsunami data to retrieve simultaneously the slip distribution and the rupture velocity. We find a heterogeneous distribution of the slip, characterized by three distinct patches: the first is located in the southern part of the fault, off the coast of the Aceh Province, the second between 6.5°N and 11°N, and the third at depth, between 11°N and 14°N. This is in fairly good agreement with the model proposed by Subarya et al. (2006), derived from inverting near-field GPS surveys in Northern Sumatra and observations of the vertical motion of coral reefs: they found three main patches, with the highest slip offshore of Banda Aceh and a significant amount of slip at depth in the northernmost end. We also find reasonable agreement in both slip amplitude and distribution with model C of Ammon et al. (2005), derived from teleseismic body waves (5-200 s), intermediate-period regional seismograms (50-500 s) and long-period teleseismic seismograms (250-2000 s). These
authors found a large slip release between 3°N and 6°N and, to a smaller extent, up to 10°N. As they noted, larger amounts of slip are needed north of 8°N to explain GPS displacements in the Nicobar and Andaman Islands: the second patch of our model (see Fig.5) extends from 6.5°N to 11°N and has 10 meters of mean slip, slightly larger than Ammon’s et al. (2005) model, and could be consistent with geodetic observations.

Though we are using a different parametrization of the source, we find a partial agreement with other authors that invert tsunami data to reconstruct the source process. In particular our results are roughly consistent with those obtained by Tanioka et al. (2006) from tide-gauge records and coseismic vertical deformation observed along the coast: they find large slip off Banda Aceh and a relevant slip release between 7°N and 11°N. Conversely, their results do not show any relevant slip North of 12°N: to this respect the model obtained from satellite altimetry by Hirata et al. (2006) is more consistent to our findings.

Assuming a rigidity $\mu = 3.0 \times 10^{10}$ N/m$^2$, the seismic moment of our best model is $M_0 = 5.7 \times 10^{22}$ Nm, corresponding to $M_w = 9.1$, whereas that of the mean model is $M_0 = 7.5 \times 10^{22}$ Nm, corresponding to $M_w = 9.2$. These values agree with other estimates based on seismological data. Our nonlinear inverse method enables us to also estimate a mean rupture velocity of about 2.0-2.25 km/s. This is consistent with some seismological results (e.g. Ammon et al., 2005) $v = 2.5$ km/s, Kruger and Ohrnberger (2005) $v = 2.3-2.7$ km/s) and those obtained by inversion of tide-gauge records by Tanioka et al. (2006) ($v = 1.7$ km/s). Conversely, our estimate of the rupture speed differs from those of Ishii (2005) ($v = 2.8$ km/s, from seismological data), Fujii and Satake (2006) ($v = 1.0$ km/s, from joint inversion of tide-gauge and satellite altimetry) and Hirata et al. (2006) ($v = 0.7$ km/s, from satellite altimetry).

Some authors suggested that the slip in the northern section of the rupture zone may have been released very slowly, at a time scale beyond the seismic band (Bilham, 2005). The model parameterization we adopt in this work enables us to estimate only the mean rupture
speed. This aspect of the source process as well as a refinement of the source geometry (e.g. Banerjee et al., 2006; Subarya et al., 2006) may be the subject for future investigations.

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Figure captions

**Figure 1.** Map of the computational domain, location of the tide-gauges and boundaries of the subfaults (surface projection) used in this work.

**Figure 2.** a) Slip distribution of the best model resulting from the checkerboard test: the rectangles represent the projection of the subfaults to the Earth’s surface. b) Marginal distributions of the slip amplitude corresponding to each subfault: shallow subfaults in the left hand column, deep subfaults in the right hand one. c) Marginal distribution for the rupture velocity. In b) and c) vertical dashed lines represent the best model values of each parameter.

**Figure 3.** a) Standard deviation (±σ interval, gray line), average (gray cross), best (black star) and target (black circle) slip amplitude (in meters) for the synthetic checkerboard test: shallow subfaults in the left hand column, deep subfaults in the right hand one. b) same as a) for rupture velocity (in km/s). c) same as a), with target velocities ranging from 0.5 to 3.5 km/s, at 0.5 km/s steps.

**Figure 4.** Comparison between the waveforms corresponding to the target (black solid) and the inverted best model (gray dashed) for the checkerboard test. Amplitudes are in meters and time window in minutes after the earthquake origin time.

**Figure 5.** a) Slip distribution of the best model for the Sumatra earthquake: the rectangles represent the projection of the subfaults to the Earth’s surface. b) Marginal distributions of the slip amplitude corresponding to each subfault: shallow subfaults in the left hand
column, deep subfaults in the right hand one. c) Marginal distribution for the rupture velocity. Vertical dashed lines represent the best model.

**Figure 6.** a) Standard deviation ($\pm \sigma$ interval, grey line), average (grey cross), best (black star) slip amplitude (in meters) corresponding to the inverted model for the Sumatra earthquake: shallow subfaults in the left hand column, deep subfaults in the right hand one. b) same as a) for the rupture velocity (in km/s).

**Figure 7.** Comparison between the tide-gauge records (black solid) and the waveforms computed using the inverted best model (grey dashed). Amplitudes are in meters and time window in minutes after the earthquake origin time.
Table 1
List of tide-gauge stations

<table>
<thead>
<tr>
<th>Station</th>
<th>Lat</th>
<th>Lon</th>
<th>analog/digital</th>
<th>Sampling Interval (min)</th>
<th>Weight for sampling interval</th>
<th>Weight for azimuthal distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Krabi</td>
<td>08.05 N</td>
<td>98.92 E</td>
<td>a</td>
<td>5</td>
<td>0.75</td>
<td>0.67</td>
</tr>
<tr>
<td>Trang</td>
<td>07.40 N</td>
<td>99.52 E</td>
<td>a</td>
<td>5</td>
<td>0.75</td>
<td>0.67</td>
</tr>
<tr>
<td>Ta pao</td>
<td>07.77 N</td>
<td>98.42 E</td>
<td>a</td>
<td>5</td>
<td>0.75</td>
<td>0.67</td>
</tr>
<tr>
<td>Sibolga</td>
<td>01.75 N</td>
<td>98.77 E</td>
<td>d</td>
<td>10</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>Diego garcia</td>
<td>07.28 S</td>
<td>72.40 E</td>
<td>d</td>
<td>6</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Gan</td>
<td>00.68 S</td>
<td>73.15 E</td>
<td>d</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Male</td>
<td>04.18 N</td>
<td>73.52 E</td>
<td>d</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Hanimaadhoo</td>
<td>06.67 N</td>
<td>73.17 E</td>
<td>d</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Visakhapatnam</td>
<td>17.68 N</td>
<td>83.28 E</td>
<td>d</td>
<td>5</td>
<td>0.75</td>
<td>1</td>
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<tr>
<td>Paradip</td>
<td>20.26 N</td>
<td>86.70 E</td>
<td>d</td>
<td>6</td>
<td>0.75</td>
<td>1</td>
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<tr>
<td>Chennai</td>
<td>13.10 N</td>
<td>80.30 E</td>
<td>d</td>
<td>5</td>
<td>0.75</td>
<td>1</td>
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<td>Tuticorin</td>
<td>08.80 N</td>
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<td>d</td>
<td>6</td>
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<td>d</td>
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<td>0.75</td>
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Table 2
Subfault parameters

<table>
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<tr>
<th>Fault segment</th>
<th>LONG.(*) E</th>
<th>LAT.(*) N</th>
<th>W (km)</th>
<th>L (km)</th>
<th>Strike (deg)</th>
<th>Rake (deg)</th>
<th>Dip (deg)</th>
<th>Top (km)</th>
<th>Bottom (km)</th>
<th>Slip (m) best</th>
<th>Slip (m) average</th>
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</thead>
<tbody>
<tr>
<td>1 deep</td>
<td>96.073</td>
<td>3.028</td>
<td>35</td>
<td>175</td>
<td>322</td>
<td>90</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>10</td>
<td>13.4</td>
</tr>
<tr>
<td>1 shallow</td>
<td>95.868</td>
<td>2.870</td>
<td>157</td>
<td>175</td>
<td>322</td>
<td>90</td>
<td>11</td>
<td>0</td>
<td>30</td>
<td>11</td>
<td>12.8</td>
</tr>
<tr>
<td>2 deep</td>
<td>95.103</td>
<td>4.268</td>
<td>35</td>
<td>175</td>
<td>322</td>
<td>90</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>30</td>
<td>21.4</td>
</tr>
<tr>
<td>2 shallow</td>
<td>94.898</td>
<td>4.110</td>
<td>157</td>
<td>175</td>
<td>322</td>
<td>90</td>
<td>11</td>
<td>0</td>
<td>30</td>
<td>10</td>
<td>11.2</td>
</tr>
<tr>
<td>3 deep</td>
<td>94.233</td>
<td>5.352</td>
<td>35</td>
<td>178</td>
<td>343</td>
<td>105</td>
<td>35</td>
<td>30</td>
<td>50</td>
<td>6</td>
<td>12.6</td>
</tr>
<tr>
<td>3 shallow</td>
<td>93.982</td>
<td>5.277</td>
<td>116</td>
<td>178</td>
<td>343</td>
<td>105</td>
<td>15</td>
<td>0</td>
<td>30</td>
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(*) Longitude and latitude refer to the southernmost point on lower edge of each subfault.
Figure 1, MS#2005627, Piatesi, 1,2 columns
Figure 2, MS#2005627, Piatanesi, 1 column
Figure 3, MS#2005627, Piatanesi, 1 column
Figure 4, MS#2005627, Piatanesi, , 2 columns
Figure 5, MS#2005627, Piatanesi, 1 column
Figure 6, MS#2005627, Piatesi, 1 column