

Integral Source Characteristics of the Sumatra Earthquakes of December 26, 2004, and March 28, 2005

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Abstract—The integral characteristics of source geometry, source duration, and rupture propagation for the Sumatra–Andaman earthquake of December 26, 2004 and for the March 28, 2005 earthquake near northern Sumatra have been determined. The source parameters were found by analyzing records of the higher orbits of long-period surface waves. The results are compared with the large-scale average characteristics of tomographic models for the source process based on different data sets that diverge in some details, as well as with the aftershock distribution for the considered earthquakes.

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INTRODUCTION

The December 26, 2004, Sumatra–Andaman earthquake and the March 28, 2005, event that occurred near northern Sumatra three months later were the largest earthquakes for the past 40 years. The aftershocks of these events cover an area that extends for more than 1500 km from southeast to northwest (Fig. 1). The extensive data obtained for these events include broadband seismic records, records of tsunami waves and hydroacoustic signals, and GPS measurements. These data were used to develop various tomographic source models [8, 18, 21, 25, 27, 29] and provide different detailed descriptions of rupture propagation and slip distribution. The aim of this work is to derive average, coarse, and hence more stable, characteristics of the source region and the rupture process. These characteristics can be expressed in terms of the integral moments of the seismic moment tensor density [9, 10], which are usually found from records of teleseismic waves [2, 4, 5–7, 11–17, 19, 22–24]. This paper provides integral estimates of the source shape and the time history of the Sumatra quakes derived from long-period surface waves recorded by the global seismograph network.

The second moment approximation. Space–time characteristics of the earthquake source. The time derivative of the moment tensor density $\dot{\Gamma}$ can be represented in the form

$$\dot{\Gamma} = f(\mathbf{x}, t)\mathbf{m}. \quad (1)$$

Here, $f(\mathbf{x}, t)$ is a nonnegative scalar function, $\mathbf{m}$ is a normalized moment tensor, $\mathbf{x}$ is a point in the source region, and t is time.

Following [9, 10], we define that $f(\mathbf{x}, t)$ is not equal to zero for an earthquake source region and that the source duration is the time during which inelastic

movements occur at various points of the source region; i.e., $f(\mathbf{x}, t)$ is nonzero. In this case the spatial and temporal source characteristics can be expressed in terms of the corresponding integral moments of the $f(\mathbf{x}, t)$ function.

The following relations specify the space–time moments of the $f(\mathbf{x}, t)$ function of total degree (in space and time) 0, 1, and 2 with respect to some point $\mathbf{q}$ and an instant τ :

$$\begin{aligned} f^{(0,0)} &= \int_V dV \int_0^\infty f(\mathbf{x}, t) dt, \\ f_i^{(1,0)}(\mathbf{q}) &= \int_V dV \int_0^\infty f(\mathbf{x}, t)(x_i - q_i) dt, \\ f^{(0,1)}(\tau) &= \int_V dV \int_0^\infty f(\mathbf{x}, t)(t - \tau) dt, \\ f^{(0,2)}(\tau) &= \int_V dV \int_0^\infty f(\mathbf{x}, t)(t - \tau)^2 dt, \\ f_i^{(1,1)}(\mathbf{q}, \tau) &= \int_V dV \int_0^\infty f(\mathbf{x}, t)(x_i - q_i)(t - \tau) dt, \\ f_{ij}^{(2,0)}(\mathbf{q}) &= \int_V dV \int_0^\infty f(\mathbf{x}, t)(x_i - q_i)(x_j - q_j) dt. \end{aligned} \quad (2)$$

Here V is the source region.

These moments are used to find the integral source characteristics.

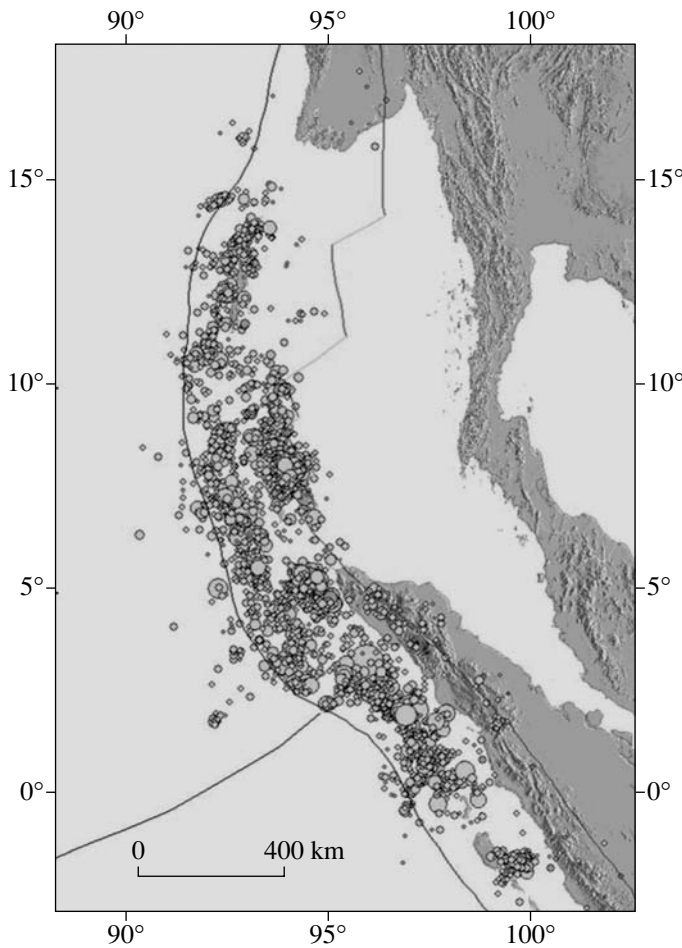


Fig. 1. Aftershocks of the Sumatra earthquakes of December 26, 2004, and March 28, 2005.

The source position in space is estimated using the spatial centroid $\mathbf{q}_c$ of the $f(\mathbf{x}, t)$ function:

$$\mathbf{q}_c = \mathbf{f}^{(1,0)}(\mathbf{0})/M_0, \quad (3)$$

where $M_0 = f^{(0,0)}$ is the seismic moment.

The temporal centroid τ_c is defined by the formula

$$\tau_c = f^{(0,1)}(0)/M_0. \quad (4)$$

The source duration Δt is characterized by the value $2\Delta\tau$ defined by the relationship

$$(\Delta\tau)^2 = f^{(0,2)}(\tau_c)/M_0. \quad (5)$$

The source region geometry is described by the matrix $\mathbf{W}$

$$\mathbf{W} = \mathbf{f}^{(2,0)}(\mathbf{q}_c)/M_0. \quad (6)$$

The average source dimension along the unit vector $\mathbf{r}$ is characterized by the $2l_r$ value determined from the formula

$$l_r^2 = \mathbf{r}^T \mathbf{W} \mathbf{r}, \quad (7)$$

where $\mathbf{r}^T$ is the transpose of $\mathbf{r}$. Knowing $\mathbf{W}$, we can estimate the principal source axes. Their directions are given by the eigenvalues of the matrix $\mathbf{W}$, while the squares of the lengths of the corresponding semiaxes are equal to the matrix eigenvalues. We illustrate the relationship between the integral estimates of source duration and source dimensions and their actual values when $f(\mathbf{x}, t)$ is a Gauss function. The actual spatial dimension and the actual source duration will be taken as the values corresponding to the 99% confidence level. In such a case, it turns out that the actual source duration is 2.5 times as large as its integral estimate, and the actual principal axes in the case of a plain two-dimensional source are three times as large as their integral estimates.

The mean velocity $\mathbf{v}$ of the instantaneous spatial centroid [5] is estimated using the formula

$$\mathbf{v} = \mathbf{w}/(\Delta\tau)^2, \quad (8)$$

where $\mathbf{w} = \mathbf{f}^{(1,1)}(\mathbf{q}_c, \tau_c)/M_0$.

The velocity of the instantaneous centroid demonstrates how the rupture propagates in the source. This velocity is zero in the case of a symmetric propagation relative to the hypocenter and is the mean rupture velocity $\bar{v}$ in the case of a unilateral propagation.

We now locate the origin at the point of a spatial centroid $\mathbf{q}_c$ and count the time from the instant coincident with the time centroid τ_c (i.e., we assume that $\mathbf{q}_c = \mathbf{0}$ and $\tau_c = 0$). In this case the first moments of $f(\mathbf{x}, t)$ with respect to the origin $\mathbf{x} = \mathbf{0}$ and zero time $t = 0$ are equal to zero. Under these conditions, the spectrum of the surface-wave displacements at a rather long period as compared to the source duration can be expressed in terms of the source moment tensor, the centroid depth, and the integral moments of the $f(\mathbf{x}, t)$ function of total power 2 in the following form:

$$\begin{aligned} u_i(\mathbf{x}, \omega) = & \frac{1}{i\omega} M_0 m_{jl} \frac{\partial}{\partial y_l} G_{ij}(\mathbf{x}, \mathbf{0}, \omega) \\ & + \frac{1}{2i\omega} f_{mn}^{(2,0)}(\mathbf{0}) m_{jl} \frac{\partial}{\partial y_m} \frac{\partial}{\partial y_n} \frac{\partial}{\partial y_l} G_{ij}(\mathbf{x}, \mathbf{0}, \omega) \\ & - f_m^{(1,1)}(\mathbf{0}, 0) m_{jl} \frac{\partial}{\partial y_m} \frac{\partial}{\partial y_l} G_{ij}(\mathbf{x}, \mathbf{0}, \omega) \\ & + \frac{i\omega}{2} f^{(0,2)}(0) m_{jl} \frac{\partial}{\partial y_l} G_{ij}(\mathbf{x}, \mathbf{0}, \omega). \end{aligned} \quad (9)$$

Here, $G_{ij}(\mathbf{x}, \mathbf{y}, \omega)$ is the spectrum of the surface-wave Green function, which is computed on the assumption that the Earth is an environment with a weak lateral inhomogeneity [1, 5, 28], and ω is the angular frequency. We also assume that the waves propagate along the great circle arcs. Under these assumptions, the displacement amplitude spectrum $|u_i(\mathbf{x}, \omega)|$ is independent of wave velocity and is little affected by errors in determining earthquake epicenter location [3]. Let the depth of the best point source and the moment tensor be known. In such a case the above relation yields the set of linear equations for the second moments of the $f(\mathbf{x}, t)$ function. However, the displacement phase spectrum defined by (9) depends on surface wave velocities which are insufficiently accurate for the actual Earth. Therefore, the desired moments will be determined using only surface-wave amplitude spectra, in spite of the fact that the relationships connecting these spectra are nonlinear.

Considering only a plain source, we can express all moments of the $f(\mathbf{x}, t)$ function of total power 2 defined by formulas (2)–(8) in terms of the following six parameters: the integral source duration estimate (Δt); the integral estimate of the maximal mean source dimension (length of the major axis, $l_{\max}$); the angle between the direction of the major axis and the strike (φ_l); the integral estimate of the minimal mean source dimension (length of the minor axis $l_{\min}$); the absolute value of the mean velocity v of instantaneous spatial centroid (v); and the angle between v and the strike (φ_v). Using the surface-wave amplitude spectra, we determine precisely these six parameters describing the source geometry and time evolution.

If all the parameters of the environment, the depth of the equivalent instantaneous point source, and the source seismic moment tensor are known (e.g., are determined from an analysis of surface wave spectra at longer periods), and one of the nodal planes has been identified as a fault plane, then formula (9) can be used to compute surface-wave amplitude spectra for any combination of the six parameters and for all registration sites. A comparison of the theoretical and observed values yields the amplitude-spectrum residual $\varepsilon^{(i)}$ for each i observation ($i = 1, \dots, N$). The normalized residual function of the amplitude spectra for each combination of the desired parameters $\varepsilon(\Delta t, l_{\max}, \varphi_l, l_{\min}, v, \varphi_v)$ is calculated using the formula

$$\varepsilon(\Delta t, l_{\max}, l_{\min}, \varphi_l, v, \varphi_v) = \left[\frac{\sum_{i=1}^N \varepsilon^{(i)^2}}{\sum_{i=1}^N |u^{(i)}(\mathbf{r}, \omega)|^2} \right]^{1/2}, \quad (10)$$

where $|u^{(i)}|$ is the i th value of the observed amplitude spectrum.

The optimal parameter values that minimize ε are assumed to be the estimates of these parameters. We search for them by a complete exploration of a grid in 6-dimensional parameter space.

We assess the resolution of a parameter by constructing partial residual functions. We fix the parameter and assign to it the corresponding minimum value of ε for all possible combinations of the other parameters. In such a way, we determine six partial residual functions:

$$\varepsilon_{\Delta t}(\Delta t), \varepsilon_{l_{\max}}(l_{\max}), \varepsilon_{l_{\min}}(l_{\min}), \varepsilon_{\varphi_l}(\varphi_l), \varepsilon_v(v), \varepsilon_{\varphi_v}(\varphi_v).$$

The method is described in detail in [4, 11].

The Sumatra–Andaman earthquake of December 26, 2004. The focal mechanism, depth of focus, source duration, source geometry, and rupture velocity were determined using the spectra of the second and third orbits of the fundamental Love and Rayleigh modes using time periods ranging from 500 to 650 s. Surface waves were isolated on records using the time–frequency analysis programs and floating filtering [5]. We used only signals with high signal/noise ratios and normal polarization for determining the source parameters. The data selection includes 24 Love and 22 Rayleigh waves recorded by the IRIS and GEOSCOPE global networks. The azimuthal coverage for these waves is shown in Fig. 2. The sites of the relevant stations are listed in Table 1.

Surface-wave spectra for describing the crustal structure around the earthquake source and under the seismic stations were computed using the 3SMAC model [26], and the upper mantle structure was specified by the PREM model. The Q-values from the same PREM model were used to compute surface-wave attenuation.

Surface-wave amplitude spectra and first motions were inverted to estimate the moment tensor which describes the source in the instantaneous point-source approximation [20]. The following angles for the focal mechanism were obtained: 330° for strike, 8° for dip, and 105° for slip. The depth of the best point source was 13 km, and the seismic moment was 0.52×10^{23} N m.

To find the integral characteristics of the source process that describe its spatial and temporal extent, we fixed the centroid depth and the focal mechanism listed above. The nodal plane dipping northeastward was taken to be the fault plane.

When the parameters of a double couple are estimated from spectra at periods that are long enough to treat the rupture as an instantaneous point source, we usually fixed seismic moment before determining second moments. However, the longest period that could be identified on wave records (650 s) was not long enough for our purposes; therefore, we revised the seismic moment when determining the second moments

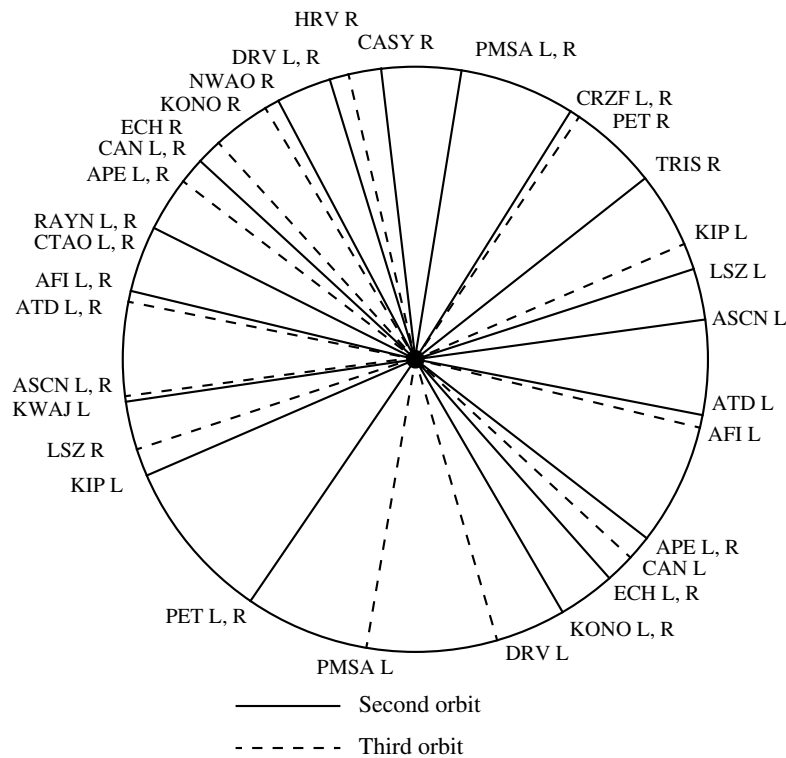


Fig. 2. Azimuthal coverage of the surface-wave paths used to find the parameters of the December 26, 2004 earthquake. The letters L and R appended to station abbreviations denote Love and Rayleigh waves, respectively. For the abbreviations, consult Table 1.

using surface-wave spectra in the same range of time periods (from 500 to 650 s). Finally, we obtained the value 0.84×10^{23} N m for the seismic moment. The corresponding moment magnitude is $M_w = 9.2$. The partial residual functions for the six integral source characteristics are shown in Fig. 3. The estimated integral source duration is 160 s, and the major axis has a length of 350 km.

The minor axis has a poor resolution within 0–200 km. The mean velocity of the instantaneous centroid was about 2 km/s. The angles that characterize the direction of the major axis and the centroid velocity direction are measured on the footwall in the clockwise sense from the strike axis. The value 15° was obtained for both of these angles. Using the above estimates for the Gaussian distribution and multiplying the integral source duration by 2.5, we obtain 400 s for the duration. Multiplying the integral estimate for the major axis length by 3, we obtain 1050 km for the greatest source length. Similarly, the minor axis has a length of 300 km.

We compared our estimate for the source duration with the analogous integral estimate which we calculated for the moment rate function [8]. The resultant value (187 s) was rather close to our integral estimate (160 s).

The rupture propagation may be characterized by the “directivity ratio” d proposed in [24]. The param-

eter is defined as the ratio of the mean velocity of the instantaneous centroid to the “apparent” velocity $l_{\max}/\Delta t$. Unilateral rupture at a constant velocity and with a constant slip in a rectangular region gives the value $d = 1$. When a symmetric bilateral rupture propagates from the source center to both ends at a constant velocity and a constant slip, we obtain $d = 0$. We have $0 \leq d < 0.5$ for a predominantly bilateral rupture and $0.5 \leq d \leq 1$ for a predominantly unilateral rupture. For our model, we have $d = 0.9$, indicating practically unilateral propagation north-northwestward. The fit of the second-moment approximation to the observed surface-wave amplitude spectra is illustrated by Fig. 4. Figure 4 shows the amplitude spectra observed in different directions and converted to the same epicentral distance and the corresponding theoretical values computed in two approximations: the instantaneous point source and the second-moment approximation. It is clear that the difference between theoretical and observed values substantially decreases when the second moments are taken into account.

March 28, 2005, earthquake near Northern Sumatra. We estimated the seismic moment, the focal mechanism, and the depth of the best double couple from the amplitude spectra of the second and third orbits of the fundamental Love and Rayleigh modes in the interval 250 to 500 s. The time–frequency analysis and floating filtering were applied to the records to iso-

Table 1. Coordinates of the seismic stations we used to determine the earthquake parameters

Station	Network	Coordinates	Locality
AFI	IRIS	$-13.91^{\circ}, -171.78^{\circ}$	Afiamalu, Samoa
APE	IRIS	$37.07^{\circ}, 27.53^{\circ}$	Naxos I., Greece
ASCN	IRIS	$-7.93^{\circ}, -14.36^{\circ}$	Ascension I.
ATD	GEOSCOPE	$11.53^{\circ}, 42.85^{\circ}$	Djibouti
CAN	GEOSCOPE	$-35.32^{\circ}, 149.00^{\circ}$	Canberra, Australia
CASY	IRIS	$-66.28^{\circ}, 110.54^{\circ}$	Casey, Antarctica
CRZF	GEOSCOPE	$-46.43^{\circ}, 51.86^{\circ}$	Crozet Is.
CTAO	IRIS	$-20.09^{\circ}, 146.25^{\circ}$	Townsville, Australia
DRV	GEOSCOPE	$-66.67^{\circ}, 140.01^{\circ}$	Terre Adelie, Antarctica
ECH	GEOSCOPE	$48.22^{\circ}, 7.16^{\circ}$	Echery, France
FFC	IRIS	$54.73^{\circ}, -101.98^{\circ}$	Flin Flon, Canada
HRV	IRIS	$42.51^{\circ}, -71.56^{\circ}$	Harvard, USA
KIP	GEOSCOPE	$21.42^{\circ}, -158.01^{\circ}$	Kipapa, Hawaii, USA
KONO	IRIS	$59.65^{\circ}, 9.60^{\circ}$	Kongsberg, Norway
KWAJ	IRIS	$8.80^{\circ}, 167.61^{\circ}$	Marshall Is.
LSZ	IRIS	$-15.58^{\circ}, 28.19^{\circ}$	Lusaka, Zambia
MA2	IRIS	$59.58^{\circ}, 150.77^{\circ}$	Magadan, Russia
NWAO	IRIS	$-32.93^{\circ}, 117.23^{\circ}$	Narrogin, Australia
PET	IRIS	$53.02^{\circ}, 158.65^{\circ}$	Petropavlovsk-Kamchatskii, Russia
PMSA	IRIS	$-64.77^{\circ}, -64.05^{\circ}$	Palmer Station, Antarctica
RAYN	IRIS	$23.52^{\circ}, 45.50^{\circ}$	Ar Rayn, Saudi Arabia
RER	GEOSCOPE	$-21.16^{\circ}, 55.75^{\circ}$	La Reunion, Indian Ocean
TRIS	GEOSCOPE	$-37.07^{\circ}, -12.32^{\circ}$	Tristan da Cunha I.

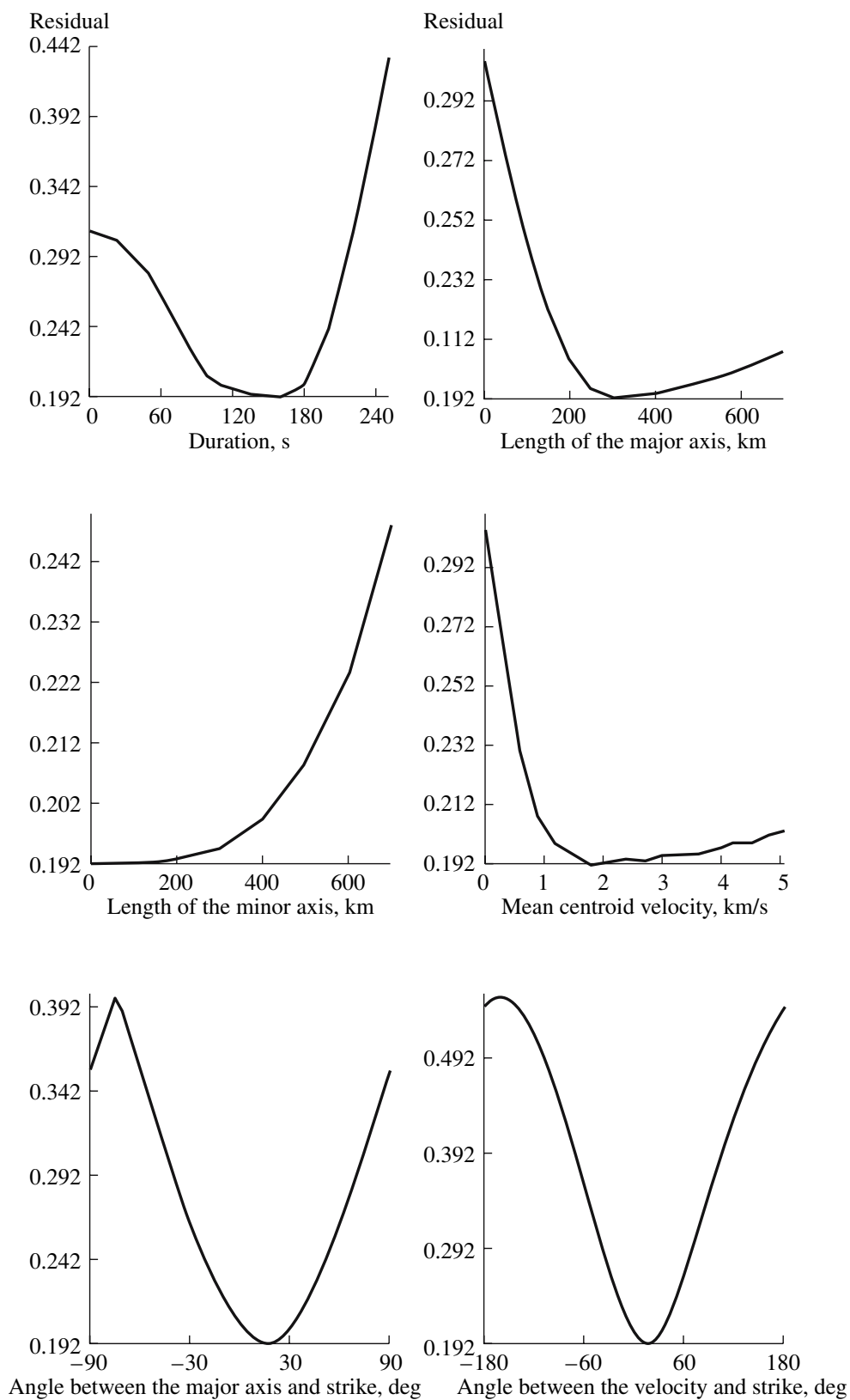


Fig. 3. Partial residual functions characterizing the resolution for the integral characteristics of the Sumatra–Andaman earthquake.

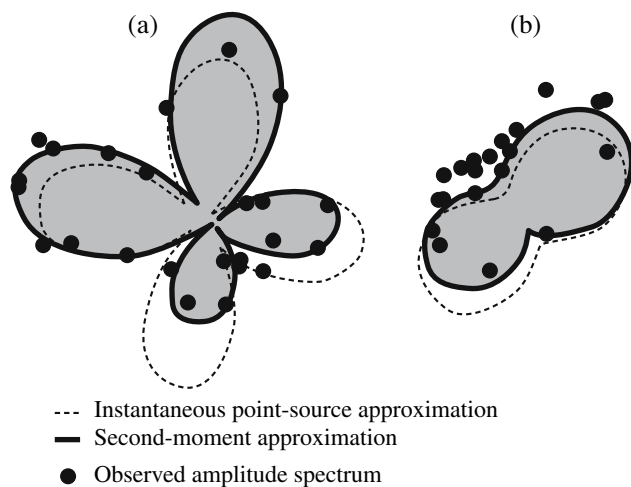


Fig. 4. Radiation diagrams for (a) the fundamental Love and (b) Rayleigh modes and the observed amplitude spectra at a period of $T = 550$ s for the Sumatra–Andaman earthquake.

late 26 Love waves and 29 Rayleigh waves recorded by the IRIS and GEOSCOPE global networks. The azimuthal coverage for these waves is shown in Fig. 5, and the station sites can be found in Table 1. The same earth models were used to calculate the surface wave spectra as for the Sumatra–Andaman earthquake.

The following focal mechanism angles were obtained: 315° for strike, 10° for dip, and 90° for slip. The depth of the best point source was found to be 8–10 km. The seismic moment was 0.85×10^{22} N m, and the corresponding magnitude was $M_w = 8.6$.

To compute the integral source characteristics we fixed the depth at 10 km and used the focal mechanism obtained in the instantaneous point-source approximation. The northeastward-dipping nodal plane was assumed to be the fault plane. The second moments were determined from spectra in the interval 175–300 s using two different data sets: the records of the surface-wave first orbits and of the second and third orbits. The results obtained for these two different data sets were very similar.

The integral characteristics based on the Love and Rayleigh wave records have poor resolution. The analogous estimates based on the Rayleigh wave spectra alone are close to those derived from a joint inversion of the Love and Rayleigh waves, but their resolution is substantially better. The partial residual functions for the integral source characteristics are shown in Fig. 6. The integral estimate of the source duration is 40 s, and such an estimate of the length of the major axis is 150 km. The length of the minor axis has poor resolution within the range 0–50 km. A value of approxi-

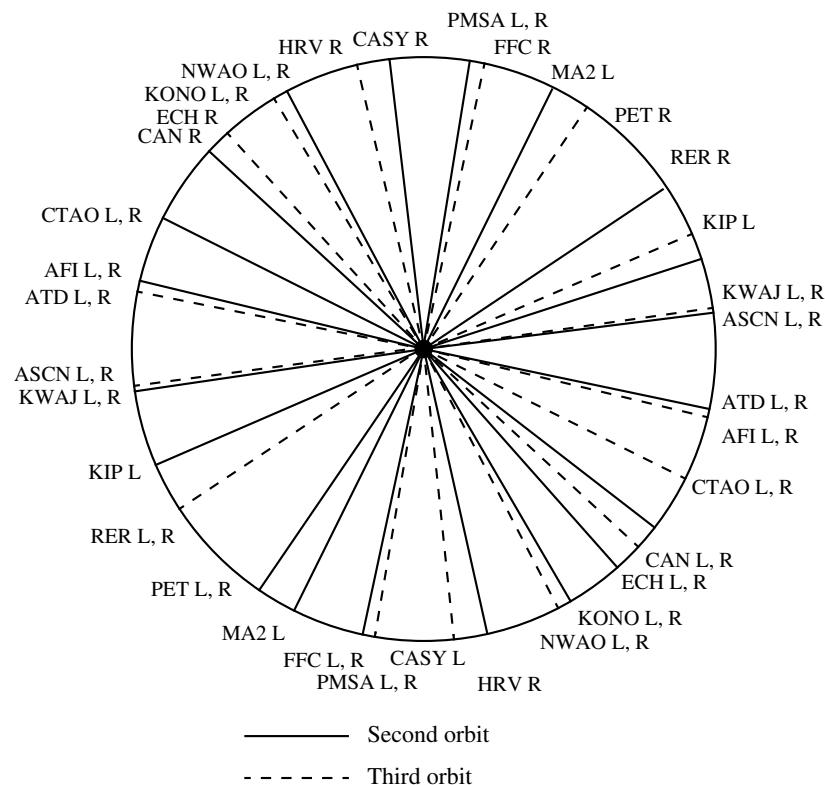


Fig. 5. Azimuthal coverage of the surface-wave paths used to find the parameters of the March 28, 2005, earthquake near northern Sumatra. The notation is as in Fig. 2. For station abbreviations consult Table 1.

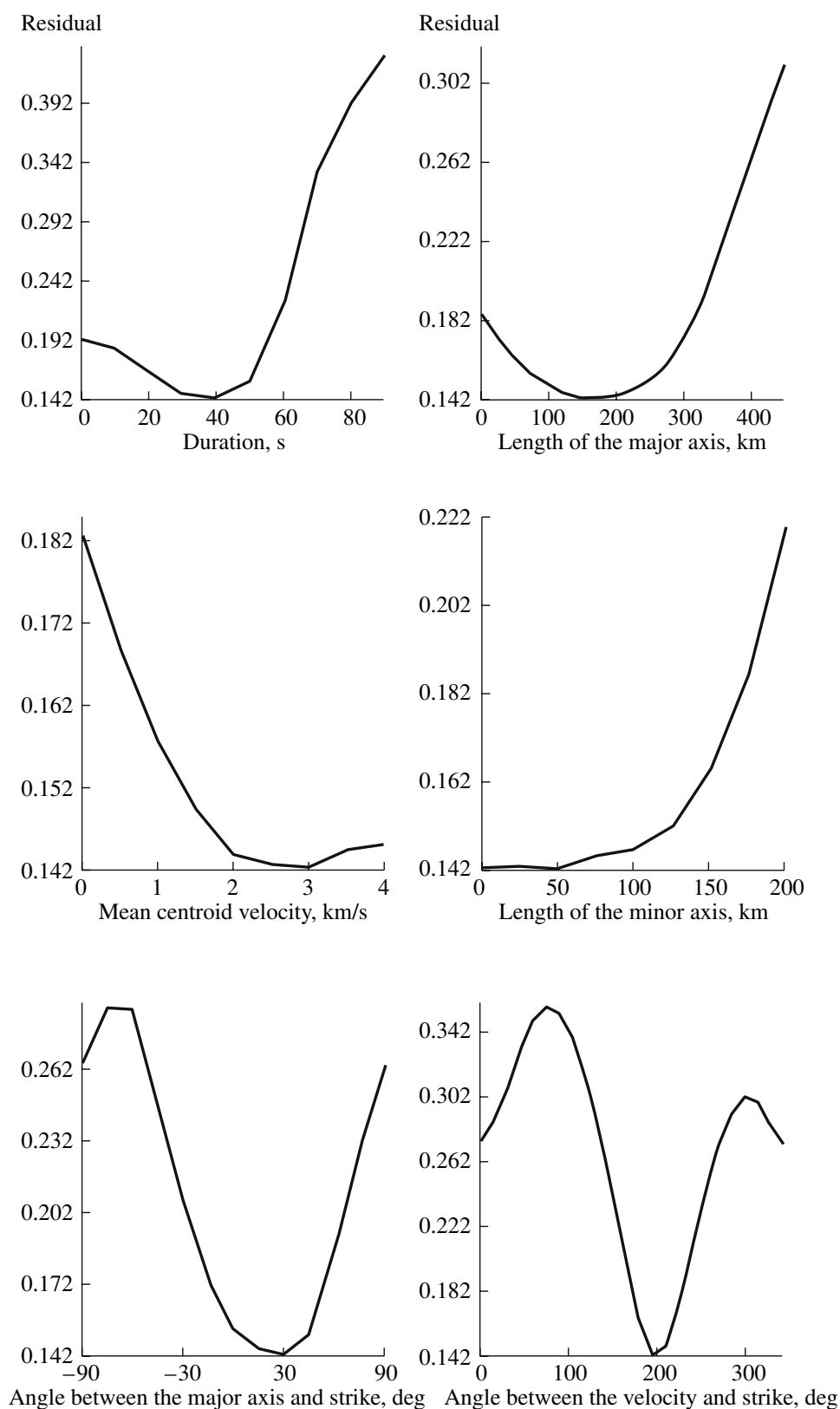


Fig. 6. Partial residual functions which characterize the resolution of the integral characteristics obtained for the March 28, 2005 earthquake.

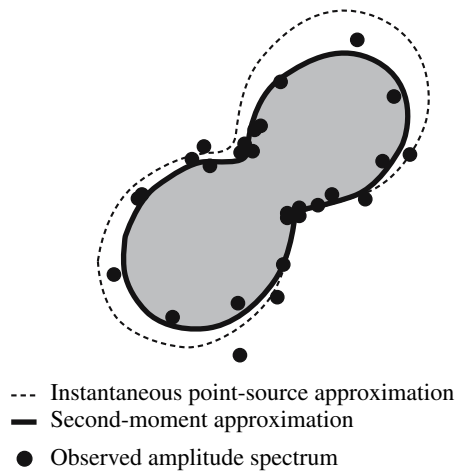


Fig. 7. Radiation patterns for the fundamental Rayleigh modes and observed amplitude spectra at a period of $T = 254$ s for the March 28, 2005 earthquake.

mately 3 km was obtained for the mean velocity of the instantaneous centroid, and values of 30° and 195° were found for the angles that characterize the directions of the major axis and the centroid velocity, respectively. The “directivity ratio” is $d = 0.8$, indicating a predominantly unilateral rupture propagation toward the south-southeast.

Multiplying the integral source duration estimate by 2.5, we obtain 100 s as the source duration. Multiplying the estimated length of the major axis by 3, we obtain 450 km for the greatest source dimension. Similarly, we get 150 km for the length of the minor axis. We compared our source duration estimate (40 s) with the analogous integral estimate that we computed for the moment rate function [29]. The value obtained, (46.5 s), was close to our integral estimate of 40 s.

Figure 7 shows the amplitude spectra of the Rayleigh-wave displacements converted to a single epicentral distance as observed along different directions as

well as the corresponding theoretical values computed in the instantaneous point-source approximation and in the second-moment approximation. Similarly to the preceding case, the difference between the theoretical and observed values substantially decreases when the second moments are taken into account.

RESULTS AND DISCUSSION

The main results obtained from this analysis of surface waves are displayed in Table 2. The seismic-moment estimate for the Sumatra–Andaman earthquake that we derived on the assumption of a finite duration of the source process, both in space and time, is twice as large as the Harvard estimate of 0.395×10^{23} N m obtained in a point-source approximation. Our rupture propagation is unilateral toward north-northeast at a mean velocity of 2 km/s. Our estimate of the source duration is 400 s, and that of the source extension is 1050 km. These results, as well as our estimates for the smaller March 28, 2005 earthquake, agree with averaged large-scale characteristics derived from a variety of tomographic source models [8, 21, 29], which differ in some details from one another.

Figure 8 illustrates the comparison of the estimates that characterize the source geometry with the aftershock distribution. The axes of the ellipse for each of the two earthquakes are the major and minor axes of the respective source regions. The aftershocks were divided into two parts: Figs. 8a and 8b show the aftershocks that occurred before and after the March 28, 2005, earthquake, respectively. Figure 8b indicates that the ellipse characterizing the extension of the March 28, 2005, rupture zone is fairly consistent with the distribution of its aftershocks. At the same time, the ellipse that characterizes the source extension for the Sumatra–Andaman earthquake does not cover the upper segment of the aftershock area in Fig. 8a. In the tomographic models [8, 21] based on an analysis of different seismological data, this region is also slightly deformed. How-

Table 2. Main earthquake parameters

Event date	M_0 , N m	M_w	H , km	Δt , s	L , km	V , km/s
26.12.2004	$0.84 \cdot 10^{23}$	9.2	13	400	1050	2
28.03.2005	$0.85 \cdot 10^{22}$	8.6	10	100	450	3

Note: M_0 is the seismic moment, M_w is the moment magnitude, H is the centroid depth, Δt is the source duration, L is the length of the major axis, and V is the mean velocity of the instantaneous centroid.

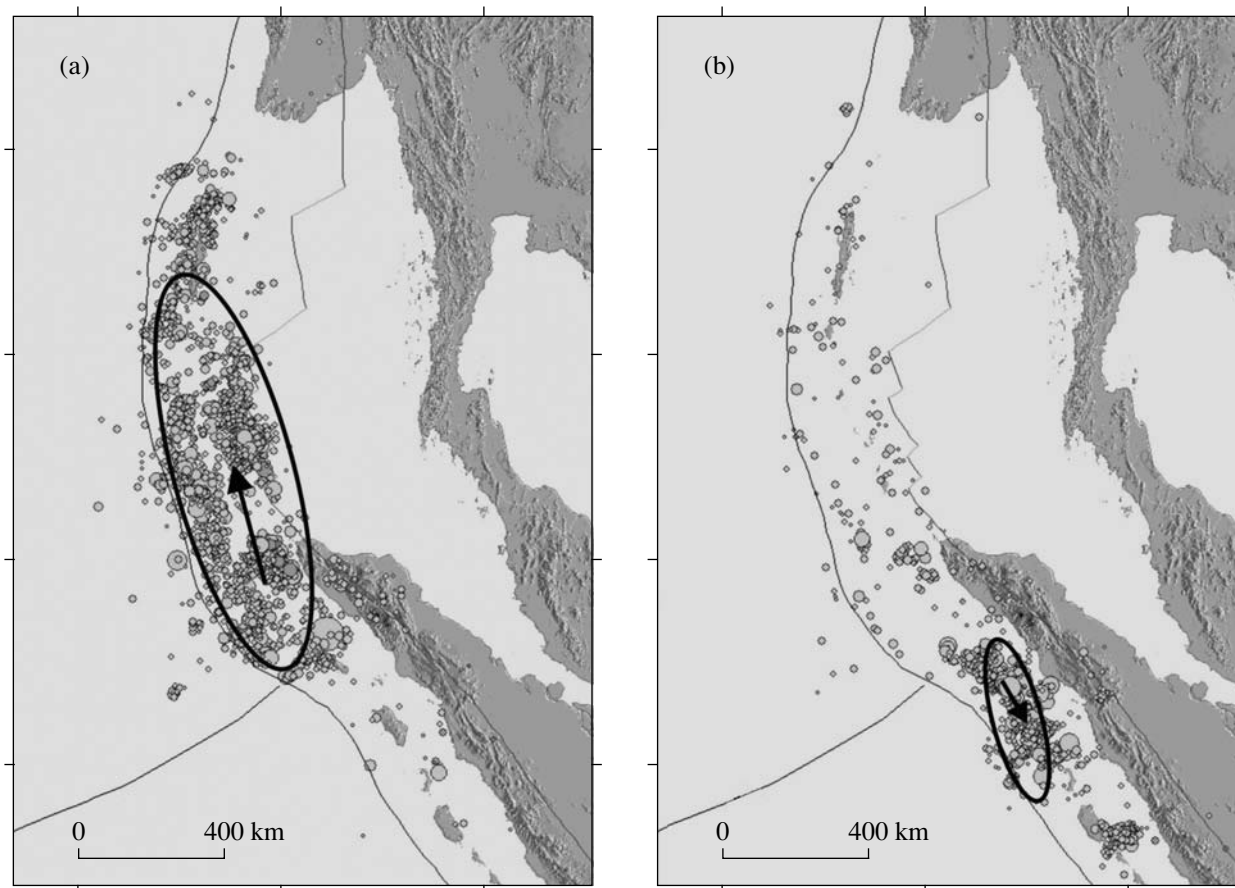


Fig. 8. Ellipses characterizing the extension of the rupture zones against a background of the aftershock for the earthquakes of (a) December 26, 2004 and (b) March 28, 2005. Arrows show rupture propagation directions.

ever, the GPS observations [27] indicate a substantial deformation in this region. This contradiction can possibly be attributed [8, 21] to slow deformations in the northern segment that did not affect the seismological data.

Finally, we note that the integral estimates considered in this paper can be used as linear constraints stabilizing construction of detailed tomographic models of earthquake sources.

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