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Tracking unilateral earthquake rupture by $P$-wave polarization analysis

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SUMMARY
Rapid estimation of earthquake rupture propagation is essential to declare an early warning for tsunami-generating earthquakes. An increasing number of seismological methods have been developed to determine rupture parameters, such as length, velocity and propagation direction, especially since the occurrence of the Sumatra–Andaman earthquake that resulted in a devastating tsunami in the Indian Ocean region. Here, we present a new method to follow the rupture process in near real time by a polarization analysis of local and regional $P$ phases that permits a faster determination of rupture properties than using teleseismic records. The new technique has the capability to provide detailed information in less than 10 min. Originally, the method stems from a single-station earthquake location method and is expanded here to monitor $P$-phase polarization variations through time. As the earthquake source moves away from the hypocentre, the backazimuth of an incoming $P$ phase is expected to change accordingly. With polarization analysis we may be able to monitor the temporal change in $P$-wave backazimuth to follow the rupture process in near real time. Three component $P$ phases are scanned to determine the azimuthal variation as a function of time. The backazimuth of a moving rupture front is determined by the first eigenvector of the covariance matrix. The linearity of the particle motion is used as a measure of the quality of the data. Seismic stations at local and regional distances ($>30^\circ$) are used. We tested the new method with a theoretical simulation and observed seismograms of the Sumatra–Andaman earthquake (2004 December 26, $M_w = 9.3$), and we were able to follow the rupture for the first 200 s. For larger ruptures, stations at more than 30° epicentral distances would be required. The method is also successfully applied to the Wenchuan earthquake (2008 May 12, $M_w = 8.0$).

Key words: Time-series analysis; Earthquake source observations; Early warning.

1 INTRODUCTION
Recently, efforts to issue an early warning for tsunami-generating earthquakes have been steadily increased, especially since the Sumatra–Andaman earthquake (see Shearer & Burgmann 2010, for a recent review), which generated a huge devastating tsunami in the Indian Ocean region. These methods are based upon different kinds of geoscientific knowledge to determine the rupture characteristics, such as rupture time, length, direction, magnitude and seismic moment. Focusing on more seismological aspects, one promising method involves the seismological array technique (Ishii et al. 2005; Krueger & Ohrnberger 2005; Xu et al. 2009), in which teleseismic $P$ waves are used to reconstruct the rupture propagation process. In the case of the Sumatra–Andaman earthquake, the method has the capability of providing detailed rupture information starting about 12 min after the origin time (Krueger & Ohrnberger 2005). Local strong-motion $S$ phases, which have the potential for obtaining results faster, have been used for rupture tracking by Ghatteri & Cocco (1996) and Zollo et al. (1999). Another method uses the directivity effect to get rough information on rupture direction (e.g. Ammon et al. 2005). The high-frequency energy content (1–2 Hz) of seismic waves may also be used to estimate the total rupture duration (Houston & Kanamori 1986; Lomax 2005; Ni et al. 2005). Here, we present a new method to track the moving source along a unilateral rupture by analysing the polarization of local and regional $P$ phases. The method originates from a single-station earthquake location method (Frohlich & Pulliam 1999). For big earthquakes with sufficient rupture length, one can expect to observe $P$-phase polarization variations through time, allowing the tracking of the rupture process. Assembling the polarization variations for several local and regional stations may help to determine

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useful rupture propagation characteristics in time and space within about 10–15 min after the initiation of the event.

To test the idea of rupture tracking by polarization analysis, we calculated synthetic seismograms for a simulated unilateral rupture using the algorithm of Wang (1999) that calculates Green's functions for a multilayered half-space. The program enables modelling an extended source with a number of subevents. We modelled the unilateral rupture process of the Sumatra–Andaman earthquake with 30 single-point sources evenly distributed along the entire rupture. The rupture propagated approximately from south to north and terminated at about 1200 km distance from the epicentre (e.g. Krueger & Ohrnberger 2005). The source mechanism (strike 329°; rake 110°; dip 8°) was taken from the National Earthquake Information Center (NEIC) and the rupture speed of 2.6 km s\(^{-1}\) from Krueger & Ohrnberger (2005). Seismological stations at local and regional distances surrounding the extended rupture area are used to observe the temporal polarization variation caused by unilateral rupture propagation (Fig. 1). One would expect, for example, for station STA5 a decreasing backazimuth with time, whereas for stations located east of the rupture (STA1–STA3), an increasing of the backazimuth (denoted by green arrows). At the beginning of the rupture, the paths are assumed to point to the epicentre (blue lines). The grey paths in Fig. 1 represent the reconstructed backazimuths at each station pointing to the propagating rupture.

2 SINGLE-STATION POLARIZATION ANALYSIS

Theoretical seismograms for a regional station STA5 are shown in Fig. 2. STA5 is 25.7° away from the epicentre. The upper trace represents the vertical ground motion, whereas the lower traces display the horizontal components. Three seismic phases observable at regional distances, namely \(P, P_{cP}\) and \(S\) for the IASP91 model (Kennett & Engdahl 1991) are marked with dashed lines. Note that the \(PP\) phase is not generated at the modelled distance. The red curve (Fig. 2, middle panel) represents the calculated polarization (backazimuth) derived from the waveforms. Note the decreasing values from 66° to 55° between the \(P\)- and \(S\)-wave arrivals as the station is located west of the rupture. A sliding time window of 60 s for each time sample was chosen for calculation of the covariance matrix and the resulting polarization parameters. The linearity, shown as the blue curve in the bottom panel (Fig. 2), keeps a constant value of approximately 1 between the \(P\)- and \(S\)-wave arrivals. The arrival of the \(S\) waves disturbs the polarization and the linearity of the \(P\) waves (steep jump of the backazimuth at about 250 s).

An earthquake generates different types of seismic waves. A useful method to distinguish them is to look at their polarization or the particle motion. Body waves and Love waves are characterized by a linear polarization, although in different directions, whereas the Rayleigh wave has an elliptical particle motion. With three component seismic records, the polarization or the deduced direction, and angle of incidence can be determined. The single-station earthquake location method analyses \(P\)-phase polarization to find the earthquake backazimuth and incidence angle (Frohlich & Pulliam 1999).

In general, the orientation of elliptical polarization can be determined by the three so-called Euler angles, which describe the rotation of the polarization ellipse through the three coordinate axes. In the literature, these angles and the linearity are often referred to as polarization parameters. Kanasevich (1981), Vidale (1986), Plesinger et al. (1986), Lomax & Michelini (1988) and Jurkevics

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**Figure 1.** Map of the simulated Sumatra–Andaman earthquake and hypothetical seismic stations at regional distances (red triangles). Orange dots denote subevents simulating the unilateral rupture process of the Sumatra–Andaman earthquake. Grey lines are great circle paths representing the moving backazimuths at each station, derived from synthetics and reconstructed by the polarization analysis. The green arrows denote the rupture direction.
Figure 2. Synthetic seismograms for the Sumatra–Andaman earthquake calculated for a hypothetical station STA5 at 25.7° distance (see also Fig 1 for source-station geometry). The extended source was modelled by 30 single-point sources forming a unilateral rupture process. In the top panel, the traces represent the vertical and horizontal ground motions. The theoretical arrivals of P, PcP and S are marked with dashed lines. In the middle panel, the backazimuth variation, as a function of time, is shown by the red curve. The decreasing trend between the P- and S-wave arrivals is clearly visible. The bottom panel represents the linearity (blue curve). The steep step at about 250 s is caused by the arrival of the S wave.

(1988) have described methods to determine the polarization parameters. In this study, the analysis of the polarization behaviour over time based on the calculation of the covariance matrix was adapted from Jurkevics (1988) to three component data. In general, the wavefield over a distinct time window was considered. The auto- and cross-variances of a three component data set $u_x$, $u_y$ and $u_z$ containing $N$ time samples can be obtained from,

$$C_{ij} = \frac{1}{N} \sum_{s=1}^{N} u_i(s) u_j(s),$$

where $i$ and $j$ are component indices, and $x$, $y$, $z$ and $s$ is the index variable for a time sample. The real and symmetrical $3 \times 3$ covariance matrix can then be written as,

$$C = \begin{pmatrix}
C_{xx} & C_{xy} & C_{xz} \\
C_{xy} & C_{yy} & C_{yz} \\
C_{xz} & C_{yz} & C_{zz}
\end{pmatrix}.$$ 

The covariance matrix $C$ represents the above-mentioned polarization ellipsoid with the best fit to the real data. The eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$ and eigenvectors $\hat{p}_1$, $\hat{p}_2$, $\hat{p}_3$ of the covariance matrix $C$ are related to the principal axes of this ellipsoid and fulfill the equation $(C - \lambda I) \hat{p} = 0$ where $I$ is the identity matrix. With the knowledge of the eigenvalues, the three parameters (1) azimuth/polarization $\theta$, (2) linearity $L$ and (3) incidence angle (dip) $\phi$ can be obtained. To be more precise and to describe the relevant parameter included in the newly developed method, the azimuth is specified as, $\theta = \arctan\left(\frac{p_1(x)}{p_1(y)}\right)$ and is defined counter-clockwise from the positive $x$-axis. The second parameter $L$ is linked to the linearity and relates all three eigenvalues by, $L = 1 - \left(\frac{\lambda_2 + \lambda_3}{\lambda_1}\right)$. Obviously, the values fall into the range between one and zero. The value is one for a perfectly linearly polarized wave as the largest eigenvalue $\lambda_1$ is much larger than the other two and decreases to zero the more elliptical the wave is. Note that the azimuth interpretation is supposed to be done only in combination with the linearity as its knowledge allows qualifying the measurement. For the sake of completeness, but not further discussed within this study, the mathematical relation for the incidence angle (dip) can be given as,

$$\phi = \arctan\left(\frac{p_1(z)}{\sqrt{p_1(x)^2 + p_1(y)^2}}\right).$$

It is zero for horizontal polarization and is defined to be positive in the positive $z$ direction. Both angles, $\theta$ and $\phi$ describe the orientation of the largest eigenvector.

To study the polarization over time, time windows (optional with overlap) are shifted over the entire time-series. The choice of the window length is a trade-off between resolution and stability, with optimum values being provided by a window approximately equal to the dominant period of the recorded signal. The longer the time window is, the smoother the curve appears. This means that with a longer time window, the high-frequency content of the signal disappears.

3 Tracking the Rupture Process with a Number of Regional Stations

If we consider only one single station, the source is located somewhere along the backazimuth direction. In the case of two stations,
the source will be located at the intersection of the two lines pointing in the direction of the backazimuths of the stations. Considering three stations, we obtain three intersections, which are not necessarily identical. We need to define some procedure to determine the source location from many intersection points, as we have to consider a number of stations to get an unambiguous solution. We define a function $E(x, y, t)$ of the geophysical coordinates, $x$ and $y$, and the time $t$ after the $P$ onset as a summation of the deviations of a particular point from the backazimuth direction determined at each station.

$$E(x, y, t) = \sum_{i=1}^{\text{station}} (d_i^2 (x, y, t) \ast l_i^2 (t)),$$

where $d_i(x, y, t)$ is the distance of $(x, y)$ to the backazimuth direction determined at each station at time of $t$. The linearity, $l_i(t)$, is used as a weighting factor. By a grid search scheme, a minimum of the $E$ function is searched at each time over the $x$–$y$ plane. The minimum of the function $E(x, y, t)$ moves with time over the $x$–$y$ space and indicates the propagating rupture (see Supporting Information for more details).

4 DISCUSSION

4.1 Proximity and geometrical aspects

Proximity of stations to the earthquake is useful for a fast determination of the rupture process as the opening angle to the earthquake rupture $\alpha$ is greater for shorter epicentral distances (see Fig. 3). For an extended rupture with a length of 500 km and a seismic station at epicentral distance $d$ of 25° (marked by dashed lines in Fig. 3), the observable polarization variance $\alpha$ is about 11°. However, for a small rupture length of about 100 km $\alpha$ is $>2^\circ$, which may be too small to stand out above the uncertainty of the polarization determination (about 2–3°). On the other hand, when a station is located far away from a source (at teleseismic distances), the angle $\alpha$ may also be too small for a reliable observation. However, for stations at short epicentral distances, $S$ waves may reach the stations before the rupture terminates, prohibiting to track the entire rupture process for a large earthquake. One limit is, therefore, set by the onset of the $S$ waves (thick grey line in Fig. 3). Assuming again a seismic station with epicentral distance $d$ of 25°, a maximum rupture length of about 730 km may be observed before the first $S$ waves approach the station. In the case of the Sumatra–Andaman earthquake with a rupture length of about 1200 km, the opening angle $\alpha$ may be more than 10° for teleseismic distances and may be observable in the polarization analysis. In Fig. 4, we show the expected polarization variations for different epicentral distances $d$ and for different station azimuths around an extended rupture. The curves show the opening angle $\alpha$, or in other words, the maximum observable polarization variance for different rupture length ranges between 100 and 1000 km. Obviously, the best geometrical constellation, which means a location for which the variation of the polarization angle is significant, is for a station sited perpendicular to the rupture front ($\gamma = 90^\circ$). No variation, which is equivalent to a constant backazimuth over time, can be observed for stations located in the direction of the rupture front ($\gamma = 0^\circ$ or $180^\circ$). In general, an increase in the rupture length results in an increase in the opening angle. For more local distances (say 10°, upper left-hand panel in Fig. 4) even a 100 km rupture length results in a 4°-polarization variance. On the other hand, for 40° distance, the same rupture length causes a variation $>2^\circ$ (see lower right-hand panel). This value lies within the error bar for a reliable determination of the polarization.

4.2 Discussion of influence of noise

To test the influence of noise, we added white noise at different levels to the theoretical ground motion calculated for station DGAR. A time window of 30 s that slides over the synthetic seismograms was chosen to estimate the polarization variation (Fig. 5a). The blue crosses are the theoretical $P$-wave onsets for a number of subevents located at different backazimuths simulating the extended rupture. They are best fitted when no noise disturbs the synthetics (blue curve). An increase of noise level causes a greater error of the polarization analysis. However, the trend is preserved even for recordings with a very poor signal-to-noise ratio. The test indicates the validity of the analysis in the case of strong earthquakes with high signal-to-noise ratio.

4.3 Discussion of influence of length of sliding time window

As mentioned in a previous subsection, the choice of the analysis window sliding over the entire time-series is crucial. There is a
tracking unilateral earthquake

Figure 4. Polarization variance expressed as opening angle $\alpha$ versus station azimuth $\gamma$ for several distances (10–40°) and for rupture length varying between 100 and 1000 km. Spherical trigonometry was applied to calculate the curves. The geometry between the station and the extended rupture is shown in the inset in the centre.

Figure 5. Influence of (a) noise and (b) length of sliding time window on the polarization. (a) White noise with different levels was added to the synthetics before the determination of the polarization values. The higher the added noise (small SNR value), the higher the disturbance, but the trend is preserved even for recordings with a poor SNR (e.g. black or green curves). (b) Different lengths for the sliding time window were used for the calculations. The longer the time window, the smoother the polarization curve (e.g. red curve). Even for short-time windows (e.g. blue curve), the trend is preserved.

trade-off between stability and accuracy. To demonstrate this fact, we determined the polarization and corresponding linearity for different time window lengths. Before this, we added white noise with a signal-to-noise ratio of 8 to the synthetics. The experiment is shown in Fig. 5(b). A long time window may smooth the polarization curve (red curve for a window length of 60 s) and match well the theoretical values (denoted as blue crosses). However, a small mismatch remains between the theoretical and determined values. Another important observation is the preservation of the trend also for a small time window (the blue line for the 10 s window length).
4.4 Discussion of the method

In the following, we discuss several points, which could influence the obtained results.

4.4.1 Influence of inhomogeneous earth structure

Our starting point is the determination of the epicentre published within minutes by several data centres (e.g. GEOFON, NEIC). Therefore, we can subtract from each polarization angle the backazimuth of the known epicentre, which makes the error of the backazimuth at the epicentre equal to 0. However, the error may grow with increasing time and distance from the epicentre. Comparison with teleseismic array techniques (Krueger & Ohrnberger 2005), however, shows that both techniques agree reasonably well with similar scatter in the case of the Sumatra–Andaman event (Fig. 6) and less scatter in our technique in the case of the Wenchuan earthquake (Fig. 7). This means that the heterogeneities in the different regions sampled by the two techniques due to different ray turning points and different incidence angles have little influence on the results.

4.4.2 Geometrical effects due to the changing epicentral distance to each station during rupture

The first backazimuth at a station is determined from the waveforms within a time window of 60 s starting at the $P$ onset. The next backazimuth is determined again within a time window of the same length but shifted at each station by one time sample. Because, however, the epicentral distance to each station changes during rupture, the $P$ onset arrives at each station at a different time within the used window. It might also arrive outside the window for large changes in epicentral distance. The stations perpendicular to the rupture direction are the sensitive ones to changes in backazimuth and they are also the ones with the least changes in epicentral distance. The opposite is true for stations in the rupture direction or in the direction opposite to rupture. For example, the station MBWA in Australia has an epicentral distance of about 30$^\circ$ to the epicentre of the Sumatra–Andaman event. The slowness at this distance is about 9 s deg$^{-1}$ and the increase in epicentral distance after 190 s is about 5$^\circ$ (see Fig. 8 and Supporting Information). The resulting 45 s additional delay still keeps the $P$ onset within the used time window. The station MBWA is the extreme case, and changes in epicentral distance at all other stations are significantly smaller.

4.4.3 Influence of bilateral rupture

Our study was so far limited to unilateral rupture, which seems to be the case for the two earthquakes used as examples. Bilateral rupture is certainly a problem for the general usage of the method. We are planning tests in the near future for this case using theoretical seismograms.

5 Polarization Analysis with Field Data

5.1 Sumatra–Andaman earthquake

Until now, we discussed the polarization and linearity and its time dependence for synthetics. In the top panel of Fig. 9, real data from
Figure 7. Map of Wenchuan earthquake region with a moving source derived by the regional polarization analysis (blue line with crosses). Blue arrow denotes the retrieved track of the rupture propagation. At about 75 s, the rupture direction turns back. An estimated average velocity of about 2.9 km s\(^{-1}\) can be derived. Orange dots are aftershocks in the vicinity of the fault zones (black lines). Green crosses denote the rupture process determined by a teleseismic array method. Also in this technique, the rupture is moving continuously from southwest to northeast, however with much scatter. An animated figure of the moving source is provided in the Supporting Information.

the Sumatra–Andaman earthquake recorded at the station DGAR are presented. We calculated the polarization and linearity with a sliding time window of 60 s for each time sample in the frequency band of 0.02–0.2 Hz. A trend can clearly be seen in backazimuth and linearity. The linearity of the real seismograms is smaller than 1 attributed to a locally heterogeneous crustal structure that deforms the homogeneous wavefield.

This is also supported by the comparison between the theoretical backazimuth based on the IASP91-model (green star) and the estimated polarization. The observable discrepancy, in the case of DGAR of the backazimuth, amounts to 5°. A station correction for local heterogeneity is, therefore, necessary. Here, we define the difference between theoretical and observed values for the polarization at the arrival time of the P phase as the estimated station correction. A better estimate of the station correction can be obtained by analysing the polarization for smaller earthquakes from a series of different backazimuths. Further examples of real ground-motion data generated by the Sumatra–Andaman earthquake are shown in Figs 10 and 11, for stations QIZ and KMI, respectively. Both stations are located east of the rupture front and an increasing polarization angle is, therefore, expected. The temporal behaviour of the polarization, obtained from the Sumatra–Andaman earthquake, is summarized in Fig. 8 by great circle paths corresponding to the polarization values for a time window of 60 s for the four stations DGAR, KMI, QIZ and MBWA. Detailed polarization information for station MBWA is provided in the Supporting Information. The blue rays mark the first polarization values, which are corrected for the station structure. They point directly to the epicentre after subtracting the station correction. All later polarization values were corrected by the same station correction.

5.2 Wenchuan earthquake

Another devastating earthquake was investigated regarding its polarization and linearity behaviour, namely the Wenchuan earthquake of 2008 May 12 with a magnitude of 8.0. According to a back projection of teleseismic P energy from several seismic arrays (Xu et al. 2009), the rupture turned out to be unilateral with three main shocks. A total length of about 300 km and a rupture duration of 110 s were derived. The rupture propagated in the NNE direction, which agrees with the aftershocks taken from NEIC (http://neic.usgs.gov/neis/eq Depot/2004/eq_0412261). Some selected seismograms and the corresponding backazimuths and linearity as a function of time, are shown in Fig. 12. We observe an increase in the values for stations located east of the rupture (stations CHTO, TATO and SSE) and a decrease in the backazimuth for stations to the west of the rupture (stations TLY and ULN). Station MDJ is not useful, because it is located in the rupture...
Figure 8. Seismic stations used for the polarization analysis of the Sumatra–Andaman earthquake. Blue lines represent great circle paths for the first time point of the polarization analysis at each station, and are corrected to point to the epicentre of the earthquake. Grey paths correspond to later time points averaged over a 20 s moving window. The blue–green dots represent the numerous aftershocks.

Figure 9. Seismograms of the Sumatra–Andaman earthquake recorded at station DGAR (epicentral distance is 25.7°) are shown in the top panel. The middle panel represents the polarization behaviour over time. The red curve derived from 0.02 to 0.2 Hz bandpass-filtered data clearly shows the decreasing trend, as already verified by synthetics. In the bottom panel, the corresponding linearity is shown.
Figure 10. Same as Fig. 9, but for station QIZ. Epicentral distance is 20.8°.

Figure 11. Same as Fig. 9, but for station KMI. Epicentral distance is 22.7°.
Figure 12. Selected seismograms and the results of the polarization analysis for the Wenchuan earthquake. Red curves in the middle panels are the corresponding backazimuth variance, while blue lines in the bottom panels represent the linearity. A sliding time window of 60 s was used. Green stars denote the theoretical backazimuth. The interpretation of the polarization parameters is restricted to about 100 s after the first arrival of the P waves (marked with vertical dotted lines). Black arrows at about 75 s denote reversal points.
5.3 Tracking the rupture process

We applied a new polarization technique to the data sets previously introduced for the Sumatra–Andaman and Wenchuan earthquakes. For data sets, some selected grids as well as animated figures of the rupture movements are provided in the Supporting Information.

In Fig. 6, a moving source of about 190 s for the Sumatra–Andaman earthquake is derived by applying the technique (track with blue crosses). As input values the backazimuths and linearity of the four stations DGAR, QIZ, KMI and MBWA (see Figs 9–11 and the Supporting Information) were used. At about 190 s, we terminated the calculation as the minimum values of $E(x, y, t)$ began to scatter significantly due to the approach of the first $S$ waves. The technique could perhaps be expanded by dropping now the closer station and adding another one at a larger distance. The polarization track (blue crosses) aligns perfectly with the plate boundary (black line) and fall into the aftershock region (orange circles, Fig. 6). The rupture track obtained by the teleseismic array technique (green crosses; Matthias Ohrnberger, personal communication, 2009) is also in good agreement. For the first 190 s, we obtained a rupture length of about 440 km.

In Fig. 7, a moving source of about 100 s for the Wenchuan earthquake can be derived by applying the new technique. The propagating source is illustrated with blue crosses and they form the rupture track, for which we obtained a length of about 180 km for the first 75 s. The end of the rupture is not clear as the rupture direction turns back at about 75 s, before the first $S$ waves approach the station. As one can see from the data in Fig. 12, the trend of the backazimuth changes abruptly at about 75 s for every station involved (denoted with black arrows), which is caused by the reversal. However, we terminated the procedure as the linearity falls below a threshold of about 0.75 (marked with dotted lines in Fig. 12). The obtained rupture track falls within the fault zones (thin black lines) and the aftershock area (orange circles). Our polarization track is furthermore in good agreement with the rupture-propagating track obtained by the teleseismic array technique (green crosses in Fig. 7; Matthias Ohrnberger, personal communication, 2009).

6 CONCLUSIONS

The backazimuth of an incoming $P$ wave is expected to change with the propagation of the earthquake rupture. On the basis of this, we developed a new technique to follow the rupture propagation in near real time by polarization analyses of local and regional $P$ signals. The new technique permits faster determination of rupture properties than using teleseismic records. So far we have only determined propagation features for two large earthquakes. The technique was
successfully applied to recordings of the Sumatra–Andaman and Wenchuan earthquakes. We stopped the polarization analysis at the arrival time of the S wave of the closest station used. However, it should be straightforward to extend the method to also determine the end of larger ruptures by using stations at larger distances. Stations up to 40° epicentral distance would be required to measure rupture lengths of about 1000 km (Fig. 3). Another necessary extension is the tracking of bilateral rupture. Our results are very promising for the determination of the rupture properties of large earthquakes within a few minutes after the origin time. This is important information to estimate the destructive potential of an earthquake.

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REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Seismograms of the Sumatra–Andaman earthquake recorded at Australian station MBWA (epicentral distance is about 30°) are shown in the top panel. The middle panel represents the polarization behaviour over time. The red curve derived from 0.02 to 0.2 Hz bandpass-filtered data, clearly shows a nearly constant backazimuth. This is due to the station that is located in direction of the propagating rupture and, thus, only a small variance of backazimuthal change can be observed. In the bottom panel, the corresponding linearity is shown.

Figure S2. Here, we illustrated the idea with synthetics of the Great Andaman earthquake. The top panel (a) shows a map of the Indonesia region with the Great Andaman earthquake denoted as red line in the centre. The small dots covering the area are the gridpoints spaced in that special case with 1° in latitude and longitude. At time 0 s, concurring with the earthquakes origin, the first rays (blue coloured) with the direction obtained by the stations backazimuth point to the epicentre, comparable with an intersection point of all rays. The green dot represents for instance a gridpoint far away from each (blue coloured) backazimuth ray. From that gridpoint, the projections (or orthogonal distances) denoted as green lines to each polarization(back)-azimuth ray were being calculated. The orange dot with the correspondent lines (vertical to the blue rays) represents a gridpoint that is close to the epicentre and, therefore, close to each backazimuth ray.

In panel (b), the weighted-distance grid at time 0 s for station STA2 with coordinate axes denoting gridpoint indices is shown. The elongated area coloured in blue tones represents the close area around the backazimuth ray. It means that gridpoints within the elongated area have small orthogonal distances to the ray. The final step resulting in the weighted-distance grid is a summation over all station grids for the same time followed by a search after the smallest value. This is shown in panel (c) for time 0 s, where the white dot marks the smallest value within the weighted-distance grid. All grids of the station shown in panel (a) with red triangles were included.

Figure S3. Grid search results for rupture process of the Andaman earthquake at different time slices between 0 and 200 s. Minimum weighted-distance values at a time interval of 30 s are shown as white dots. Map of Sumatra–Andaman earthquake region with a moving source derived by the regional polarization analysis (blue line with crosses). Some crosses are labelled with the corresponding time. The resulting track lies within the aftershock area and is in good agreement with the solution of the teleseismic array technique (green crosses, Krueger & Ohrnberger 2005). An estimated average velocity of about 2.9 km s⁻¹ can be derived (see also Movie S1).

Movie S1. An animated figure of the moving source of Andaman earthquake. Input data are the grids and its minimum
already being introduced and being part of the Supporting Information.

**Figure S4.** Grid search results for rupture process of the Wenchuan earthquake at different time slices between 0 and 100 s. Minimum weighted-distance values taken every 5 s are shown as white dots. Map of Sumatra–Andaman earthquake region with a moving source derived by the regional polarization analysis (blue line with crosses). Some crosses are labelled with the corresponding time.

**Movie S2.** An animated figure of the moving source of Wenchuan earthquake. Input data are the grids and its minimum already being introduced and being part of the Supporting Information.

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