Imaging the rupture of the $M_w$ 6.3 April 6, 2009 L’Aquila, Italy earthquake using back-projection of teleseismic P-waves

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[1] We present rupture details of the $M_w$ 6.3 April 6, 2009 L’Aquila earthquake derived by back-projecting teleseismic P waves. This technique has previously been applied to large magnitude earthquakes, but this is the first application to a moderate size event. We processed vertical-component seismograms for 60 broadband stations obtained from the Incorporated Research Institutions for Seismology (IRIS) data center. The traces were aligned and normalized using a multi-channel cross-correlation algorithm and 4th root stacking was used to image the rupture. We found that the L’Aquila earthquake ruptured towards the south and that a second discrete pulse of energy occurred 20–25 km east of the epicenter about 17–18 s after the nominal origin time. The spatial extent of the rupture image correlates well with a post-seismic survey of damage in the region. Because the technique is potentially very fast (images can be produced within 20–30 minutes of the origin time), it may be useful to governmental agencies tasked with emergency response and rescue. Citation: D’Amico, S., K. D. Koper, R. B. Herrmann, A. Akinci, and L. Malagnini (2010), Imaging the rupture of the $M_w$ 6.3 April 6, 2009 L’Aquila, Italy earthquake using back-projection of teleseismic P-waves, Geophys. Res. Lett., 37, L03301, doi:10.1029/2009GL042156.

1. Introduction

[2] On April 6, 2009 (3:33 AM local time) a moderate magnitude earthquake ($M_w = 6.3$) struck central Italy near the city of L’Aquila, about 100 km east of Rome. It was felt throughout Italy and about 300 persons were killed and about 65,000 were left homeless. It was the deadliest Italian earthquake since the 1980 Irpinia earthquake, with initial estimates placing the total economic loss at several billion Euros [Akinci and Malagnini, 2009]. The mainshock was followed by thousands of aftershocks, the smallest of which were detected and located by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) using a portable network of seismometers installed a few hours after the earthquake. Within the first three weeks INGV had located over 4,000 seismometers installed a few hours after the earthquake.

[3] In this study, we apply a relatively new method of rupture imaging to the L’Aquila earthquake that is based on the back-projection of teleseismically recorded P waves [Ishii et al., 2005; Kruger and Ohrnberger, 2005; Walker and Shearer, 2009; Xu et al., 2009]. The approach has previously been used successfully in studies of large earthquakes ($M > 7.5$) with rupture dimensions of hundreds of kilometers. In the present study we show that it is also capable of resolving important rupture properties for a moderate sized earthquake having fault dimensions of tens of kilometers. This method can be applied quickly (within 20–30 minutes of origin time) because it does not require knowledge of the fault plane; it only requires a radial earth model and a hypocentral estimate.

2. Tectonic Background

[4] At present day the study area is under extension and characterized by the presence of numerous 15–30 km long, NW–SE trending normal faults that are considered responsible for past earthquakes [Vezzani and Ghisetti, 1998; Galadini and Galli, 2000; Barchi et al., 2000; Roberts and Michetti, 2004]. Based on the historical record the town has suffered intensity IX or higher at least three times in the past (in 1349 A.D., 1461 A.D. and 1703 A.D.) [Boschi et al., 2000] and is known to be an area of high seismic hazard [Akinci et al., 2009]. The current extensional stress field is oriented in the NE direction as inferred from focal mechanism analysis of local earthquakes [Montone et al., 2004]. This is consistent with the results obtained from borehole break-outs [Martucci et al., 1999] and geological mapping [e.g., Lavecchia et al., 1994]. The current NE–SW extension is around 2–3 mm/yr [Hunstad et al., 2003] and the uplift rate is around 0.2–0.5 mm/yr.

3. Data and Methods

[5] We collected teleseismic data for the L’Aquila earthquake using the Incorporated Research Institutions for Seismology (IRIS) data center (www.iris.edu/data). We chose stations located at distances of 30–95 degrees from the epicenter (Figure 2) to avoid waveform complexities created by propagation in the upper mantle and core. We downloaded about 780 broadband vertical component seismograms in the proper distance range, inspected all the waveforms, and removed the few traces that were null or had significant glitches.

[6] Using all of the acceptable data (with equal weights) would result in a biased rupture image because of the uneven geographical distribution of seismometers. To counteract this we desampled the stations to a more uniform geometry, retaining only one seismogram for each ~1000 km $\times$ 1000 km patch of the Earth’s surface. The retained seismograms each had the highest average correlation coefficient in a geographical patch as determined from a multi-channel cross-
correlation (MCCC) [VanDecar and Crosson, 1990] analysis of all the data. Next, we re-ran the MCCC algorithm using only these 67 traces, and then discarded seven traces with average correlation coefficients below 0.6. Ultimately, this left 60 traces that were aligned one final time with MCCC and then normalized using the first 10 s of P wave energy. As shown in Figure 2, this geometry produces an array response function (ARF) [Xu et al., 2009] with a small mainlobe and mild sidelobes at frequencies near 1 Hz.

For imaging the rupture of the L’Aquila earthquake we used the approach described by Xu et al. [2009]. The source region was gridded with increments of 0.01 degrees in latitude and longitude, and increments of 0.2 s in time. Since the technique relies on teleseismic P-waves, there is no depth resolution and the results are obtained at the nominal hypocentral depth; in this case 8.8 km. All the grid points are assumed to be possible source locations and the theoretical travel times are calculated (using AK135) for each grid point and seismometer in the array. A short time segment is extracted from the data around the corresponding arrival time and a stacking procedure is performed on the segmented data. The corresponding measurement of the beam power is mapped back to the grid point. Regions of space and time that show high relative amplitude indicate constructive interference and can be considered potential rupture locations.

4. Results and Discussion

Figure 3 (left) shows the L’Aquila rupture at different time steps imaged with fourth root stacking. The analysis was performed using a frequency band of 0.33–1.67 Hz and a 4-s long sliding window. The beam pattern is sharper and more symmetric than the ARF (Figure 2) because of the non-linear stacking. The rupture appears to move slightly south and east over the first 15 s; a continuous animation of this is available as Animation S1 of the auxiliary material. The energy appearing 20–25 km east of the epicenter, about 17–18 s after the origin time, seems distinct from the main event. It can be considered to be an early aftershock, or some sort of triggered slip, and is not necessarily part of the primary rupture.

We carried out several tests to check on the robustness of the results shown in Figure 3 (left). These are described in detail in the auxiliary material and include varying the array geometry (e.g., removing traces in which PcP might interfere), the frequency band, the length of the sliding time window, and the method of stacking the individual traces into a beam. The relative timing and amplitude of beam power peaks varied somewhat in these tests. For instance the later, eastward patch is more visible when the data are bandpassed at short periods as opposed to unfiltered; however, in all cases there is a trend of later energy appearing to the south and east of the epicenter.

We further tested our results by backprojecting synthetic seismograms created using the technique of Herrmann [2002], which accounts for the complete near source wavefield including interference of depth phases, mode conversions, and reverberations. We generated synthetics using an appropriate moment tensor (shown in Figure 1, and

1Auxiliary materials are available in the HTML. doi:10.1029/2009GL042156.
described in detail in the auxiliary material) and the same station geometry used with the observed seismograms. The synthetics incorporated a single discrete pulse (5 s long triangle) as the source function, so major differences between the synthetics and the data can be ascribed to source complexities of the L’Aquila earthquake. As shown in Figure 3 (right), the synthetic images lack the complexity, and especially the southern and eastern energy, observed in the data. An animation of the synthetic backprojection is available as Animation S2 of the auxiliary material.

[11] Figure 4 presents a time-integrated version of the rupture image. It is in rough agreement with the finite fault results obtained using satellite data [Atzori et al., 2009; Salvi et al., 2009] and is consistent with the INGV earthquake survey of ground shaking (Figure 4). The latter showed that the heaviest damage was located at the epicenter and in locations to the east. Salvi et al. [2009] and Atzori et al. [2009] obtained initial results on co-seismic surface displacement using a DInSAR analysis of 17 interferograms from the COSMO-SkyMed constellation and two interferograms from the Envisat satellite. The results using the different interferograms are consistent and in good agreement with those obtained by INGV geodesists (http://portale.ingv.it/primo-piano/archivio-primo-piano/notizie-2009/terremoto-6-aprile/dati-gps). In addition, we note that the aftershock distribution trends toward the east relative to the epicenter.

[12] Our results are also roughly consistent with the finite fault model presented by Cirella et al. [2009, hereafter C09], however some differences are present. For instance, we image energy nearly due south of the epicenter, while as given by C09 the large patch of slip is to the southeast. The differences may be due to several factors. In the finite...
fault technique, it is necessary to impose certain constraints in order to regularize the inversion and reduce the number of degrees of freedom. Commonly the fault geometry is assumed, as well as a rupture velocity, and slip is prohibited to occur behind a healing front. Even so, there remains a significant degree of non-uniqueness in finite-fault models. On the other hand, the back-projection method gives variable results depending on array geometry, frequency band, and other tuning parameters. Ideally, both approaches would be combined to give the most robust model of earthquake rupture (T. Lay et al., Effects of kinematic constraints on teleseismic finite-source rupture inversions: Great Peruvian earthquakes of 23 June 2001 and 15 August 2007, submitted to Bulletin of the Seismological Society of America, 2009). Nevertheless, the backprojection method, although cruder than finite fault inversion of waveforms, is capable of giving quicker insight into the rupture directivity and extent of damaging earthquakes.

5. Conclusions

We back-projected teleseismic P-waves from 60 broadband seismometers to resolve important rupture details of the L’Aquila earthquake. This is the first application of this technique to a moderate magnitude earthquake. We found that the rupture moved first towards the south and later up-dip toward the east with respect to the epicenter. We observed 2–3 spikes in beam power, the latest of which occurred about 10–12 s after the primary peak. It occurred about 20–25 km east of the epicenter and may represent an early aftershock.

The back-projection image shows a strong correlation with post-seismic surveys of damage in the region. In fact, it is a better predictor of damage than the early aftershock distribution. Because the back projection technique can be applied quickly, it may therefore be useful for emergency response efforts as a complement to traditional approaches such as ShakeMap®. In the particular case of the L’Aquila earthquake, Faenza et al. [2009] have emphasized the importance of determining a quick rupture model because the original ShakeMap® products were insufficient to replicate the observed ground motions.

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