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Seismic Observations of the Sonic Boom Produced by the Chebarkul Meteorite

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Synopsis

The Chebarkul meteorite produced a strong sonic boom throughout Chelyabinsk Oblast at 03:20 on February 15, 2013 (UTC). Also at that time a large seismic signal was observed on seismic stations of the IRIS network in the region. We performed a waveform inversion using broadband seismic data from 5 sites to obtain the source-time function of the Chebarkul meteorite signal. Assuming a single force for the source mechanism, the waveform can be explained well with a point source model. We performed a grid search in space to find the location of the source. The best-fit source location was determined on the meteor track and 40 km away from Lake Chebarkul, where the possible meteorite impact was found. We use the modified Friedlander equation to estimate a deconvolved form of the source time function, and the amplitude of the estimated single force is 2.0×10^{11}N with the onset of the pulse at 03:21:58 (UTC), February 15, 2013. Since the location of the estimated source is separated from the impact point, we conclude that the single force generating the seismic waves was produced by the blast wave due to the severe fragmentation of the bolide, not the impact of the meteorite on the ground.

Keywords : Chebarkul meteorite, Sonic boom, Seismic waveform, Waveform inversion

1. Introduction

The Chebarkul meteorite entered the Earth's atmosphere over Russia at 03:20 February 15, 2013 (UTC) producing a strong sonic boom throughout Chelyabinsk Oblast. The dazzling light of the meteor was widely observed around Russia's Ural Mountains, and the strong pressure wave damaged many buildings, especially window glass. More than 1500 people were injured mostly by the broken glass, but there were no fatalities. Although near-source regions were severely damaged, there are few direct observations of the shock wave from the meteorite entry (Brown et al., 2013; Pichon et al., 2013; Seleznev et al., 2013).

In this study, we used ground shaking data recorded by broadband seismometers operated by the Incorporated Research Institutions for Seismology (IRIS). The Chebarkul meteorite is seismologically unique since seismic signals produced by the sonic boom were observed as far as 4000 km from the source (Tauzin et al., 2013; Heimann et al., 2013) and the trajectory of the meteorite was well determined by many visual recordings (Yeomans and Chodas, 2013; Borovička et al., 2013; Zuluaga et al., 2013).

In general, seismic signals from a meteorite directly record the sonic boom, which is a shock wave associated with a large sound produced by an object traveling faster than the speed of sound through the atmosphere. It travels through the air at the speed of sound, however the waveforms observed in the seismic data travel at the much faster speed of S-waves or surface waves, which indicates that the signals travels through the ground, not in the air. The signal is observed as far as 2000 km from Chelyabinsk city (see Figure 1). The parti-

cle motion recorded at the closest station (ARU) shows the Rayleigh wave is dominant in the signal. We performed a waveform inversion using broadband seismic records to find the location of the source. We reconstructed the timing, location, and force history of the seismic source due to the Chebarkul meteorite. This seismological finding of the Chebarkul meteorite helps to understand the cause of damage and mechanism of acoustic coupling.

2. Data and Methods

We used 5 near-source seismic stations operated by IRIS (see Figure 1). The closest station is about 200 km from the impact site and others are about 600-1600 km away. All stations have 3 component broadband seismometers with a sampling frequency of 20 Hz. Components with poor S/N ratio were not used for the analysis.

We processed the broadband records according to the following procedure. First, we removed the mean from the time series and corrected for the instrumental response in all waveforms. The records were then integrated once, and a noncausal fourth order Butterworth filter with corner frequency of 0.01-0.1 Hz was applied to extract signals from microseismic noise. We then decimated the data by a factor of 20, reducing the sampling frequency to 1 Hz. We performed a waveform inversion using these filtered displacement records.

Following the method of Nakano et al. (2008), we performed a waveform inversion in the frequency domain to determine the source process of the seismic signal. We calculated Green's functions at grid points of in a rectangle (from 60.6°E to 61.4°E in longitude and from 54.4°N to 55.0°N in latitude) with 0.1° interval, using the discrete wavenumber method (Bouchon, 1979) and the AK135 one-dimensional velocity model (Kennett et al., 1995). Assuming a single-force mechanism for the source, we estimated the least-squares solution in the frequency domain for each grid point. We performed an inverse Fourier transform on the solution to determine source time functions for three single-force components at each source node (Nakano et al., 2008). We compared the residuals of this process for each point of the grid to determine the best fitting location. The normalized residuals for this grid are shown in Figure 1.

3. Results

Figure 2 shows the source time functions for three single force components at the most probable location (54.8°N, 60.9°E) and the waveform fits between observed and synthetic data. The best-fit source location occurred on the meteor track (Zuluaga et al., 2013) and 40 km away from Lake Chebarkul, where a large hole was found in the ice covered lake. The normalised residual of the waveform fit is 0.35 and the fit of the waveforms are reasonably good. Although we are using the global AK135 one dimensional velocity model, the results shows the velocity structure in that region can be approximated by the simple model. The vector sum of the maximum force is 1.0×10^{11}N for a source occurring at 03:21:58 February 15, 2013 (UTC) at the determined location. The vertical component shows a simple pulse with duration of about 100 s. The horizontal components are substantially smaller than the vertical component, which suggests that the source is stronger in the vertical direction.

Since we applied a bandpass filter to observed waveforms, the source-time functions obtained from the waveform inversion have limited information outside of the filter window. In order to estimate the actual source time function over a wider bandwidth, we need to correct for the frequencies which were filtered out of the data. Therefore, we used the approach of Nakano et al. (2008) which assumes an analytic function for the source-time function. We use the modified Friedlander equation to estimate the form of the source time function, which is widely used to model a blast wave caused by explosions (Baker, 1973; Martins et al., 2001).

$$P(t) = \begin{cases} 0 & (t < t_0) \\ P_s \exp(-\beta \frac{t-t_0}{t^*})(1 - \frac{t-t_0}{t^*}) & (t \geq t_0) \end{cases} \quad (1)$$

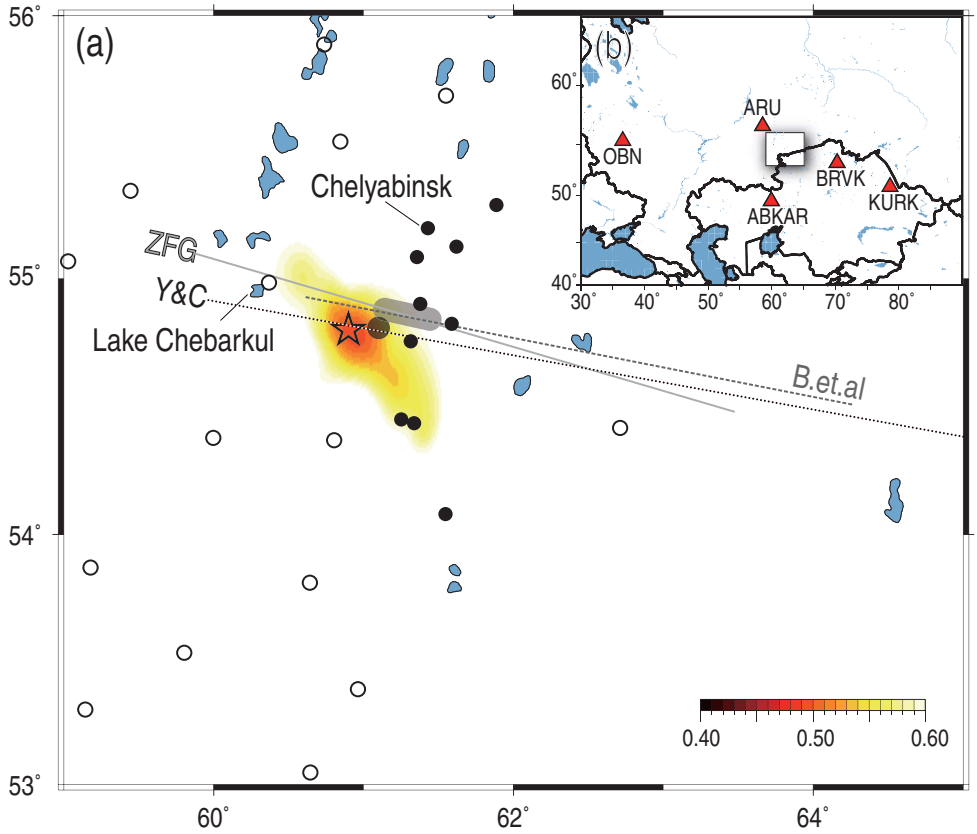

Fig. 1 (a) The normalized residuals of the waveform inversion assuming the source location at each grid point. The star shows the minimum residual. The results of the damage survey are shown with open circles (no damage) and solid circles (severe damage). The meteor tracks computed by Yeomans and Chodas (2013)(Y&C), Borovička et al. (2013)(B.et.al), and Zuluaga et al. (2013)(ZFG) are also shown. The shaded area shows the location of maximum brightness in each model. (b) Distribution of seismic stations used for the analysis. The box shows the region in Figure 1(a)

where P_s is the peak overpressure, t_0 is the onset time of the pressure, t^* is the positive phase duration, which is the time for reaching the reference pressure. β is a parameter to customize the pressure profile curves. We assume that the actual single force is represented by the modified Friedlander equation with a negative sign, and search for the 4 unknown parameters (Ps, t_0, t^*, β) in the function by minimizing the normalized residual between the observed source-time function and the analytic function. For fitting the function, we use the same bandpass filter that was applied to the observed data. The source-time function derived from this procedure and fits between the observed and predicted source-time functions are shown in Figure 3. The obtained parameters in the modified Friedlander equation are: $P_s = 2.0 \times 10^{11}$, $t_0 = 117$, $t^* = 13$, and $\beta = 0.6$. The amplitude of the estimated single force is 2.0×10^{11}N, assuming a point source at the most probable location. The onset of the pulse is estimated to have occurred at 03:21:58. These numbers are consistent with the result of other analysis with seismic waveforms (Heimann et al., 2013; Tauzin et al., 2013).

4. Discussion

The track of the meteor was recorded by many cameras across the region (e.g. https://www.youtube.com/v/bXifSi2K278). The trajectory of the bolide in the atmosphere was reconstructed from the visual observation, including amateur videos, vehicle cameras, and public surveillance cameras. Figure 1 shows the trajecto-

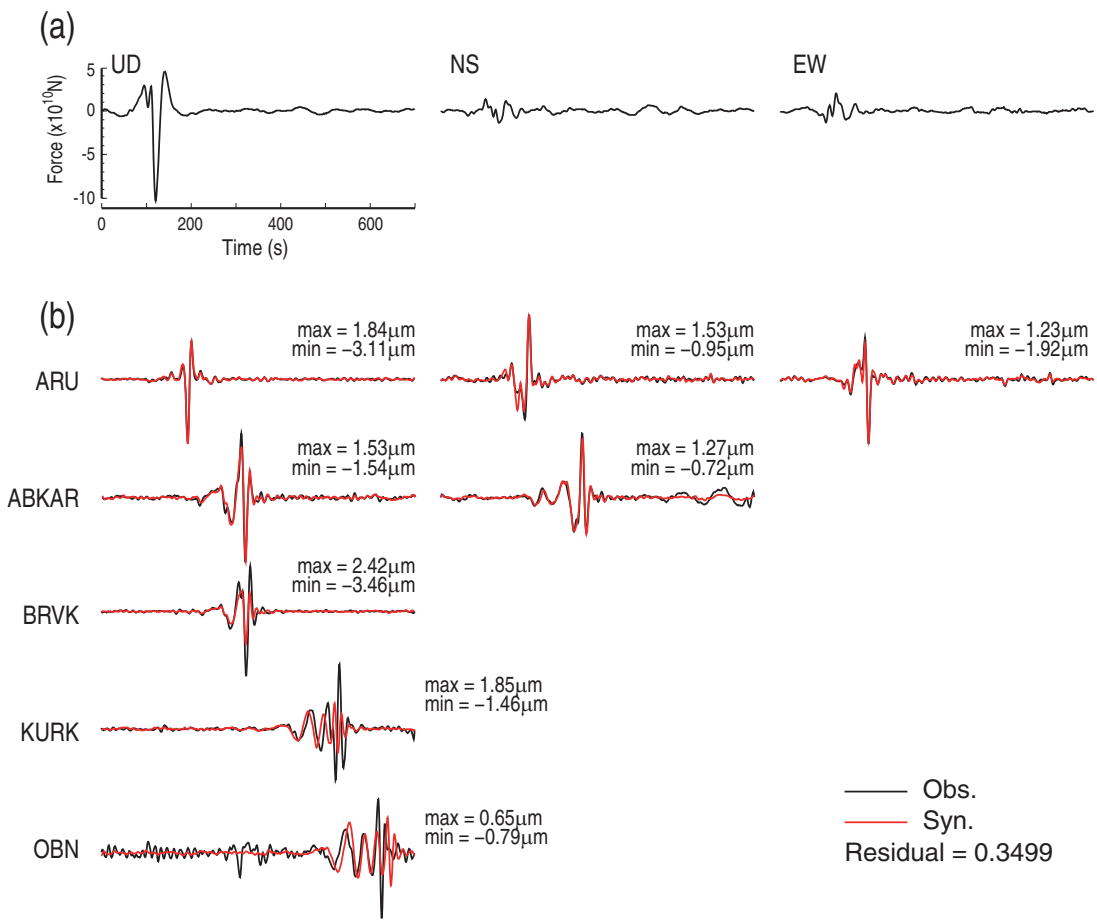

Fig. 2 Seismic waveforms of the Chebarkul meteorite. (a) Estimated single-force source time functions for the EW, NS, and UD components. The horizontal axis indicates the time after 3:20 February 15, 2013 (UTC). (b) Displacement waveform fits between observed (black) and synthetic (red) data obtained from the source inversion. The letters on the left show the station code, and the numbers in the top right show the maximum and minimum amplitudes.

ries reconstructed by Yeomans and Chodas (2013), Borovička et al. (2013), and Zuluaga et al. (2013). All of the estimates of the path are quite similar, with only 10-20 km difference. Therefore, the reconstructed trajectory should be reasonably accurate. Borovička et al. (2013) and Yeomans and Chodas (2013) computed the location of maximum brightness, which may have generated the blast wave. The location is also shown in Figure 1 as a shaded area. The altitude and timing of the maximum brightness is 25-30 km at 3:20:27-28 in Borovička et al. (2013) and 23.3 km at 3:20:33 in Yeomans and Chodas (2013).

This information provides an important clue for identifying the source of the seismic wave. The source time function is dominant in the vertical direction, which suggests the signal arrived from the sky. The location of the most probable source time function is very close to the location of maximum brightness and separated from the impact point of the meteorite by about 40 km. Therefore, we conclude that the single force generating the seismic waves was produced by a blast wave due to the severe fragmentation of the bolide, and not caused by the impact of the meteorite hitting the ground. The location for the fragmentation is consistent with a field survey of damaged structures (Popova et al., 2013). Figure 1 shows the districts with and without glass damage in Chelyabinsk Oblast. The severely damaged region is distributed near the source region in a north-south direction which is perpendicular to the meteor track. According to

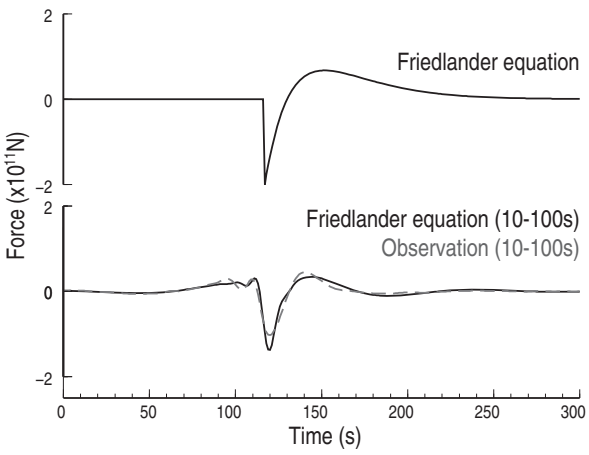

Fig. 3 Comparison of the observed and estimated source-time functions. Top: modified Friedlander equation with the most probable coefficients, bottom: band-passed modified Friedlander equation and observed source-time function.

the trajectory report (Yeomans and Chodas, 2013; Borovička et al., 2013) and result of this analysis, the height of the fragmentation is about 25 km, and the travel time of the blast wave is estimated as 85-90 seconds. The velocity of the blast wave (0.28-0.29 km/s) is consistent with the speed of sound. We suggest that when the meteorite entered the Earth's atmosphere, a severe fragmentation of the meteorite at a height of about 25 km generated a sonic boom associated with the blast wave. The sonic boom caused acoustic coupling between the atmosphere and the solid earth, producing the observed seismic waves. It is possible that the fragmentation occurred over some spatial extent, as evidenced by a strong flare at the time of the explosion which continued for a couple of seconds. However, the residual surface of the waveform inversion has a sharp peak, which suggests that the source is quite localized and it is reasonable to approximate it with a point source. If we assume that the dimension of the source on the ground is a circle with radius of 10 km, the average pressure will be 650Pa. This value is consistent with the pressure to break glass, according to Japan Society for Safety Engineering (1983), however, the values are very dependent on the glass quality and surface area.

5. Conclusions

We performed a waveform inversion using broadband seismic records from 5 sites to obtain the source-time function of the Chebarkul meteorite signal. Assuming a single force for the source mechanism, the waveforms can be explained well with a point source model. We performed a grid search in space to find the location of the source. The best-fit source location occurred on the meteor track (Zuluaga et al., 2013) and 40 km away from the impact site at Lake Chebarkul. We use the modified Friedlander equation to estimate a source time function over a wider frequency bandwidth. The amplitude of the estimated single force is 2.0×10^{11}N and the onset of the pulse is at 03:21:58 (UTC), February 15, 2013. Since the location of the estimated source is separated from the impact point, we conclude that the single force generating the seismic waves was produced by the blast wave associated with the severe fragmentation of the bolide, not due to the ground impact of the meteorite.

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