# DISCRIMINATION OF EARTHQUAKES, EXPLOSIONS, AND MINING TREMORS USING THE EMPIRICAL GREEN'S FUNCTION METHOD

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## ABSTRACT

Using the empirical Green's function (EGF) method, we have estimated source time functions for earthquakes, industrial blasts, nuclear explosions, and mining tremors covering the magnitude range 0.9 – 6.6. The results show that, for events with magnitudes less than 2.5 or greater than 4.5, the time duration of the source time function can discriminate earthquakes from explosions. For large magnitude events source duration is longer for earthquakes than explosions, but at small magnitudes explosions have longer duration. For the remaining magnitude range (2.5 to 4.5) the earthquake, explosion and mining tremor populations overlap in the source duration vs. magnitude plane. However, the source time functions themselves display features that are indicative of event type, such as source directivity, spall phases, and multiple pulses in industrial blasts and mining tremors. Therefore, we conclude that source time functions inferred by the EGF method are potentially useful for regional event discrimination under a CTBT, and we recommend that further work be done to develop effective EGF-based discriminants for events in the magnitude range 2.5 to 4.5.

## OBJECTIVE

The objective of this work is to develop discriminants for small events based on the empirical Green's function (EGF) method. The EGF method yields an estimate of the source time function (STF) of an event relative to that of a smaller, reference event (the "EGF event"). The result is referred to as the *relative* source time function (RSTF) of the larger event and can be interpreted as a scaled version of its STF when the EGF event has similar location and focal mechanism. The advantage of the EGF approach is that, by using the waveforms of the smaller event as approximate Green's functions, it does not require detailed 3D earth models and computation of propagation effects between source and receiver.

The focus of the research reported here is events having magnitudes less than 5 and detectable at regional distances. The characterization and discrimination of such events is crucial to achieving the goals of the Comprehensive Test Ban Treaty.

## RESEARCH ACCOMPLISHED

In previously reported work (Toksöz et al., 1993; Li et al., 1994, 1995) we applied the empirical Green's function method to teleseismic and regional waveform data from moderate to large ($m_b > 5$) earthquakes and explosions in central Asia to test whether the EGF method was a useful technique for characterizing seismic sources. The results showed that, when suitable event pairs are available, the EGF method reliably determines the RSTF of $m_b > 5$ events and reveals important details about their energy release processes. For example, the RSTF of some of the explosions studied displayed clear indication of a spall phase following the main energy pulse. It was also seen that a very simple property of the RSTF—its time duration—discriminated earthquakes and explosions of similar magnitude. Since the rupture process of moderate and large earthquakes is generally more complex than the energy release from a nuclear explosion, the RSTF time durations of the central Asian earthquakes analyzed were about a factor of 10 longer than those of the nuclear explosions (Figure 1).

We turn our attention now to events having magnitudes below 5. To apply the EGF method to such events it is necessary to use regional or local waveform data. In the first example, we apply the EGF method to small quarry blasts at Kaiser Quarry in northern California recorded at station CCYM. Both blasts (891028-1830 and 891031-1915) were assigned a body-wave magnitude of 0.9. We used a nearby smaller event (891031-1946) with magnitude 0.6 as the EGF event for each. The blasts occurred about 25 km south of station CCYM, and the spatial separation among the three is about 50 m. Figure 2 shows the RSTFs of the two M0.9 blasts. We see that they have different source time functions. The RSTF of the top event can be approximated as a simple pulse with source duration less than 0.1 s. The bottom event, in contrast, is interpreted as a multiply detonated blast with three distinct pulses. The total source duration of the bottom blast is 0.3 s, at least three times longer than the simple blast.

Figure 3 shows further examples of multiply detonated blasts. The events in this case are two construction blasts (labeled 920409-0956 and 920702-0405) located near Deer

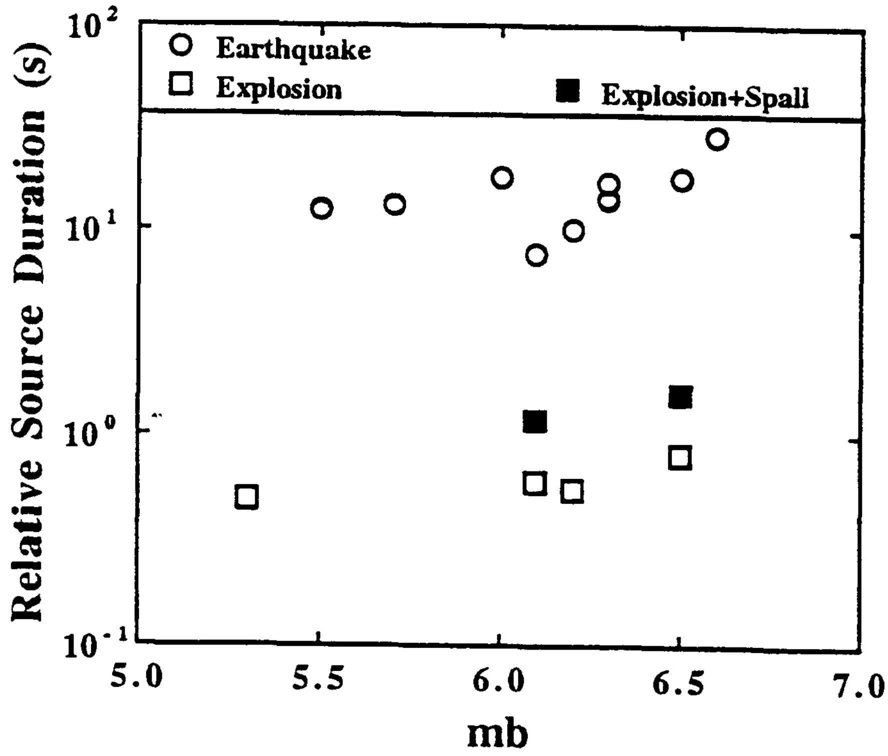


Figure 1: Comparison of source durations of earthquakes and nuclear explosions in central Asia. Source duration of each event was measured from its relative source time function, retrieved using the EGF method. (From Li et al., 1995.)

Island, Boston. The two events have magnitudes of 2.6 and 2.4, respectively. Taking a smaller, nearby blast with M=2.1 as the EGF event, we determined the RSTFs of the two larger blasts using waveform data recorded at station WFM of the M.I.T. seismic network, about 50 km from the epicenters. In Figure 3 we see that the top event has two distinct pulses with total duration of about 0.25 s, while the bottom event consists of four continuous pulses with a total duration of 0.75 s.

These examples (Figures 2 and 3) show that the source duration of industrial blasts is often controlled by shooting practices, such as multiple detonation and ripple firing. This may explain why blasts differing by about 1.5 magnitude units (Deer Island vs. Kaiser Quarry examples) do not differ greatly in source duration. The differences seen between the two locations are comparable to the variation within each location (about a factor of 3). Further, the time durations of the blasts in each example are longer than those of typical earthquakes of comparable magnitude. A typical M=3 earthquake in New England, for example, has a source duration of only about 0.1 to 0.2 s.

In the next example (Figure 4) we look at three nuclear explosions at the Nevada Test Site: JUNCTION (M5.4), MINERAL QUARRY (M4.7) and DISKO ELM (M4.2). We determined their RSTFs using smaller explosions as the respective EGF events, as labeled on the figure. The RSTFs were obtained from regional data from Southern California

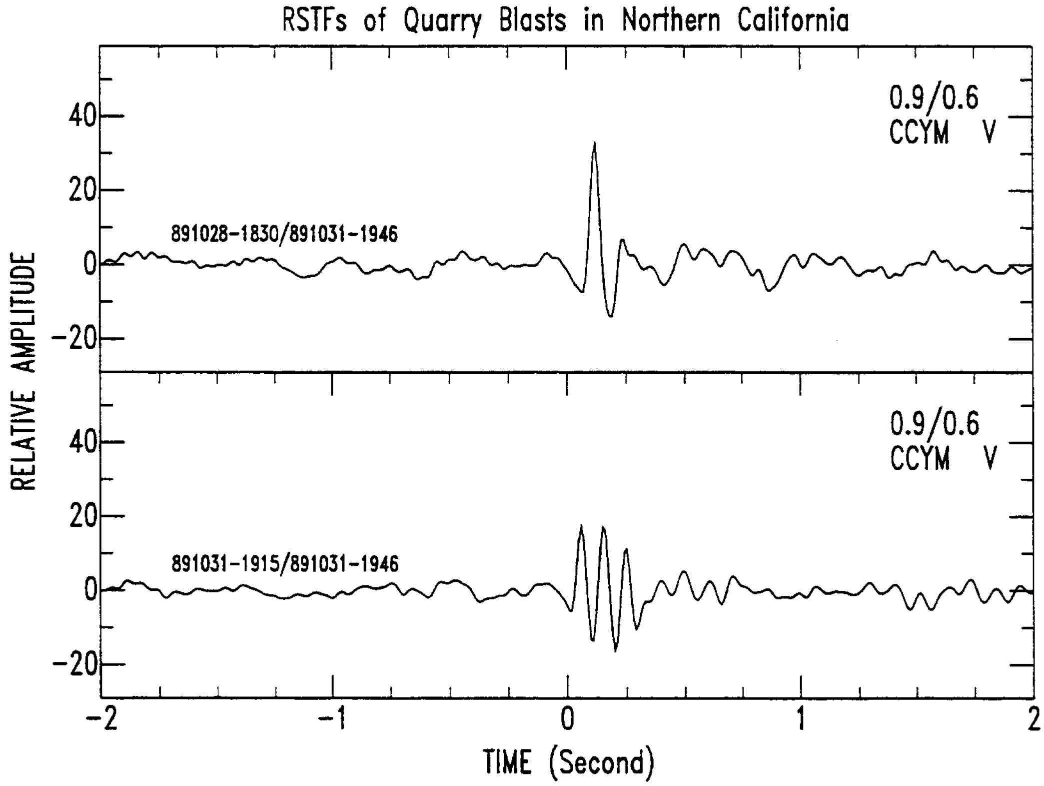


Figure 2: Estimated relative source time functions (RSTFs) of two small blasts (M=0.9) in Kaiser Quarry, California. Both RSTFs were determined relative to the same EGF event. The date and time of each blast and the EGF event are labeled on the left part of each frame. The numbers on the right are the magnitudes of the event and EGF event.

Earthquake Center stations PTQ and BRG, located between 450 and 500 km from NTS. The RSTF of explosion MINERAL QUARRY (middle of Figure 4) is a relatively simple pulse with a source duration of 0.4 s. The RSTF for JUNCTION has a complex structure comprising two pulses. The width of the first pulse is about 0.35 s and the total duration of the event is about 0.65 s. The RSTF of DISKO ELM also has two pulses with a total duration of 0.35 s. Thus, including secondary pulses, the source durations of these explosions increase with magnitude and are significantly shorter than those determined by Li et al. (1995) for larger nuclear explosions in central Asia. As in the case of the central Asia explosions, we interpret the secondary pulses of the NTS explosions (Figure 4) as spall phases.

Next, we examine the source time function of an earthquake with magnitude somewhat smaller than the NTS explosions just considered. The earthquake is a M3.7 event that occurred in central Massachusetts on 2 October 1994. Using a M3.3 aftershock as the EGF event, we determined an RSTF at each of 17 stations varying in epicentral distance from about 60 to 450 km. Figure 5 shows the RSTF from each station, ordered by azimuth from the epicenter. The bottom trace is a stacked RSTF obtained by sum-

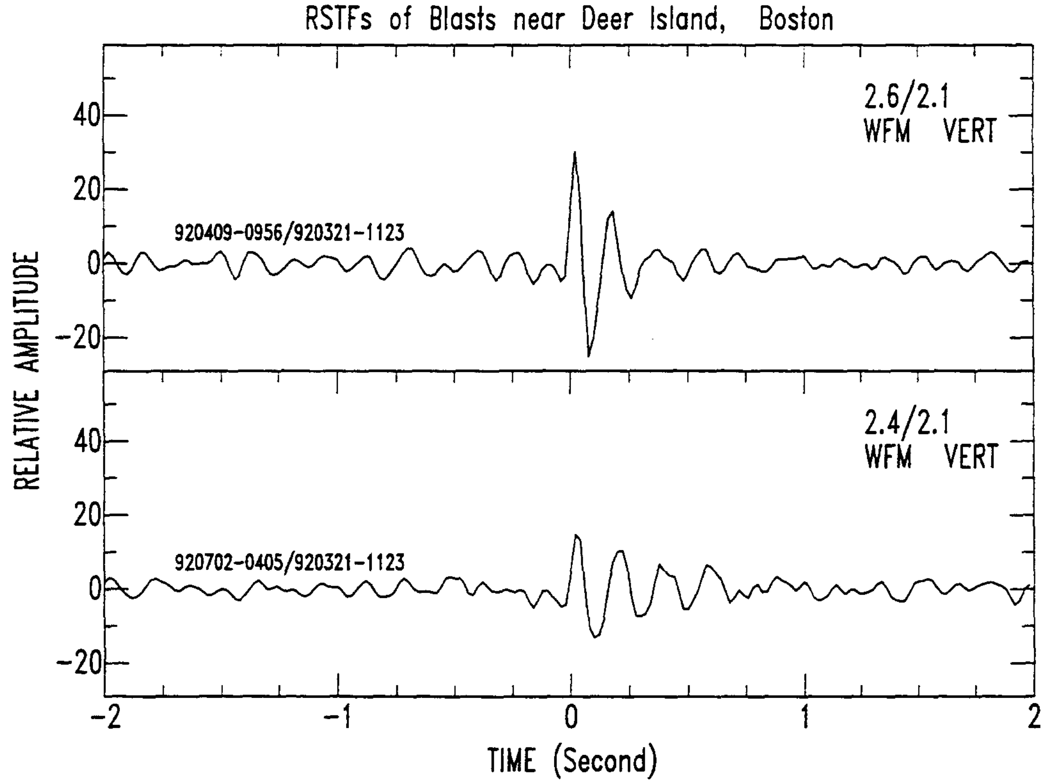


Figure 3: RSTFs of two construction blasts near Deer Island, Boston. The events have magnitudes 2.6 and 2.4, respectively. Note the multiple detonations of the events.

ming the individual station estimates. The stacked RSTF comprises a single pulse with a width of approximately 0.15 s. The individual station RSTFs show evidence of source directivity, i.e. the time duration and amplitude vary systematically with azimuth. From this variation we infer that the rupture propagated toward the southwest.

Our final example, shown in Figure 6, studies six mining tremors in the Lubin copper mining district of Poland. The events were recorded at station KSP, about 80 km away, operated by the Polish Academy of Sciences. The magnitudes of the tremors range from 2.8 to 4.1. For three of the events (second, fifth and sixth) the RSTF is a simple pulse with duration of less than 0.2 s. The other three events (first, third and fourth) are more complex with source durations varying from about 0.4 to 0.55 s. The double pulse RSTFs may be a result of multiple collapses of pillars.

Figure 7 displays source time duration, as inferred by the EGF method, as a function of event magnitude for all the events we have studied to date. Different event types are plotted with different symbols: open circles for natural earthquakes, open squares for explosions (nuclear and chemical), and filled triangles for mining tremors. The events included on this plot include the examples from Figures 2–6, the large events studied by Li et al. (1995), and additional events of each type that we have analyzed but not discussed here. The data for magnitude less than 2.5 include several earthquakes and

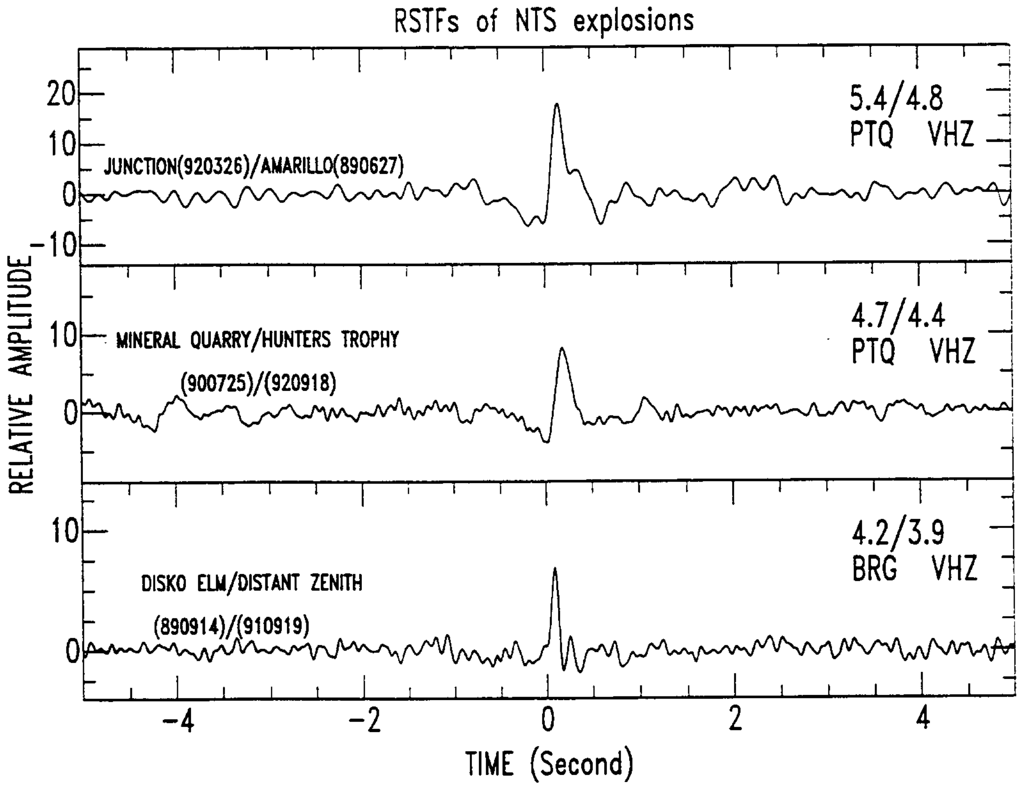


Figure 4: RSTFs of three nuclear explosions at the Nevada Test Site, determined from regional waveform data. The source durations of the explosions range from 0.35 to 0.65 s. The two bottom events are tunnel shots. Note the 'spall phase' of the explosions JUNCTION and DISKO ELM.

industrial explosions from a variety of areas with differing tectonic settings. In addition, some earthquake data from Mori and Frankel (1990) are included in the plot.

From Figure 7 we see that source duration vs. magnitude works as a discriminant between explosions and earthquakes for both the largest (M>4.5) and smallest (M<2.5) events. The earthquake population appears to obey some scaling relation, determined by the dependence of source duration and magnitude on the spatial dimension of the source. If such a relation exists for explosions, it implies a weaker variation of duration with magnitude and perhaps separate relations for nuclear and industrial explosions. For the small (M<2.5) events we analyzed, the discriminant works because the source duration of quarry and construction blasts is significantly longer than that of earthquakes with similar magnitudes. This is consistent with results of Herrin et al. (1994), who found that spectra of small magnitude earthquakes have relatively higher peak frequencies compared to explosions with similar magnitudes. However, as noted earlier, the time duration of industrial explosions may depend on factors, like firing pattern, that are not determined by any underlying physical process.

For magnitudes between 2.5 and 4.5, the earthquake, explosion and mining tremor

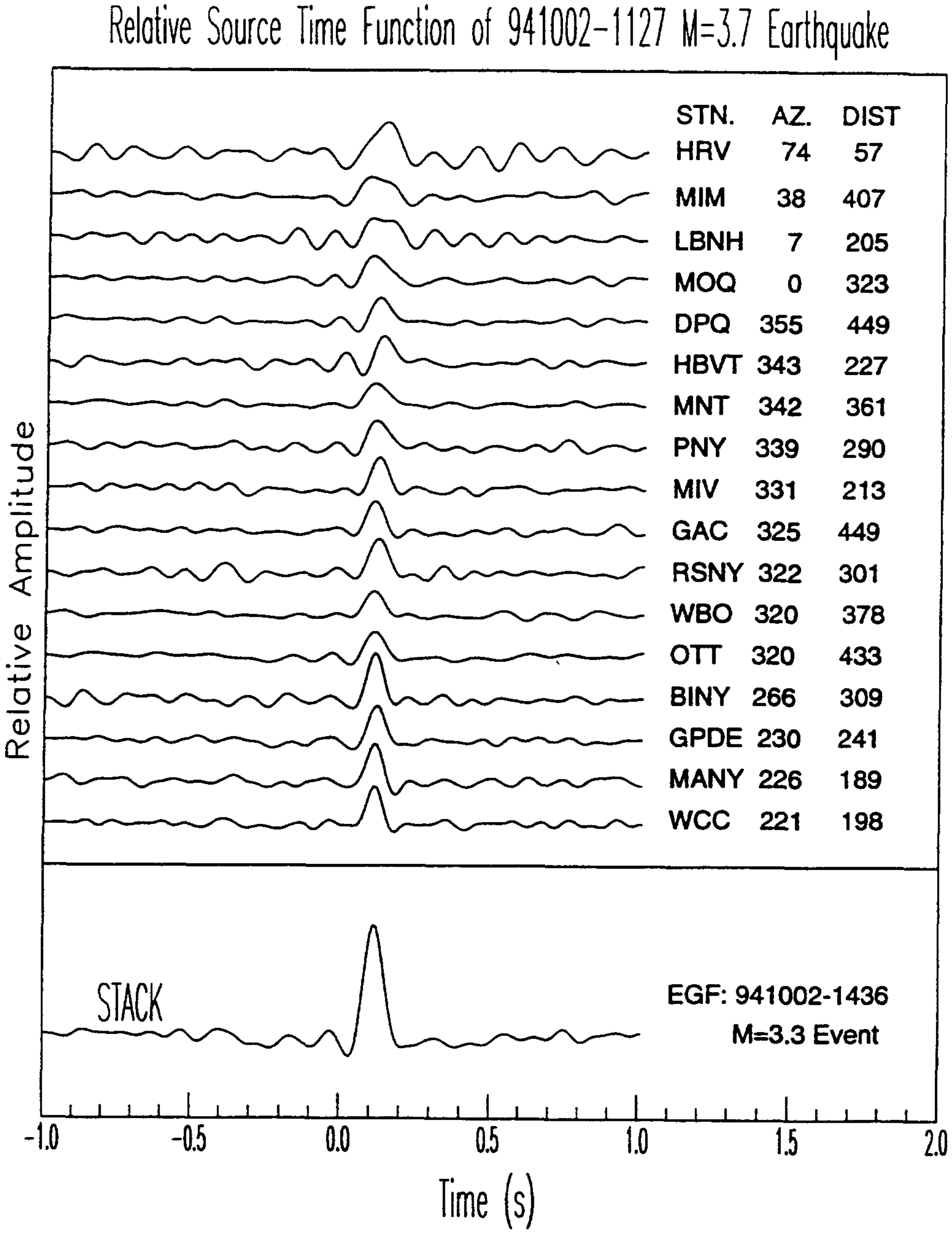


Figure 5: Estimated RSTFs of the 941002-1127 M=3.7 earthquake in central Massachusetts. Shown is the RSTF obtained at each of 17 stations together with the stack of the individual station estimates. The average source duration is about 0.15 s. The columns at the right show the code, azimuth and epicentral distance of each station. The variation of the source pulse width and amplitude with azimuth suggests that the rupture propagates to the southwest.

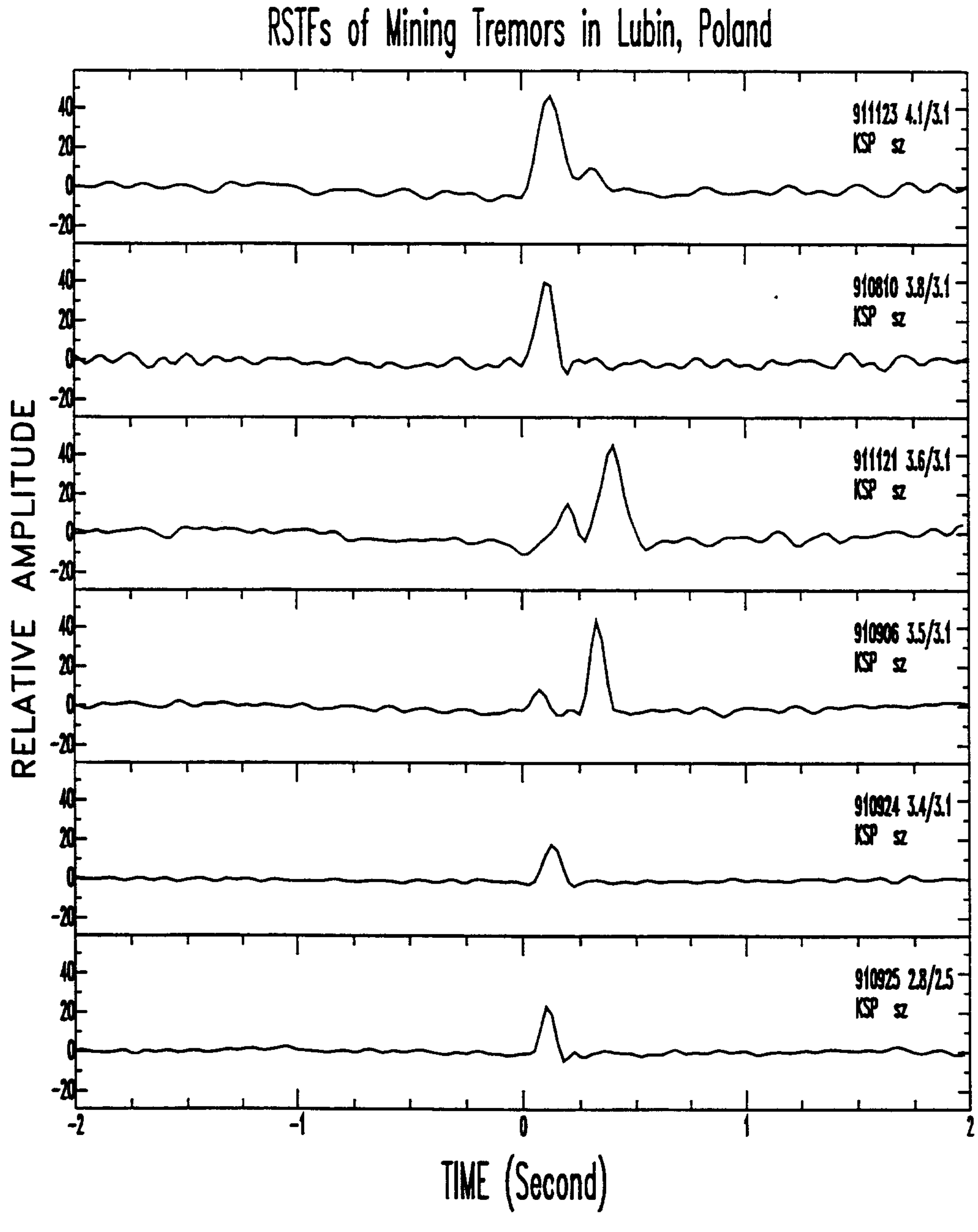


Figure 6: RSTFs of six mining tremors in Lubin, Poland. The magnitudes of the events range from 2.8 to 4.1. The source durations inferred from the RSTFS range from 0.15 to 0.6 s.

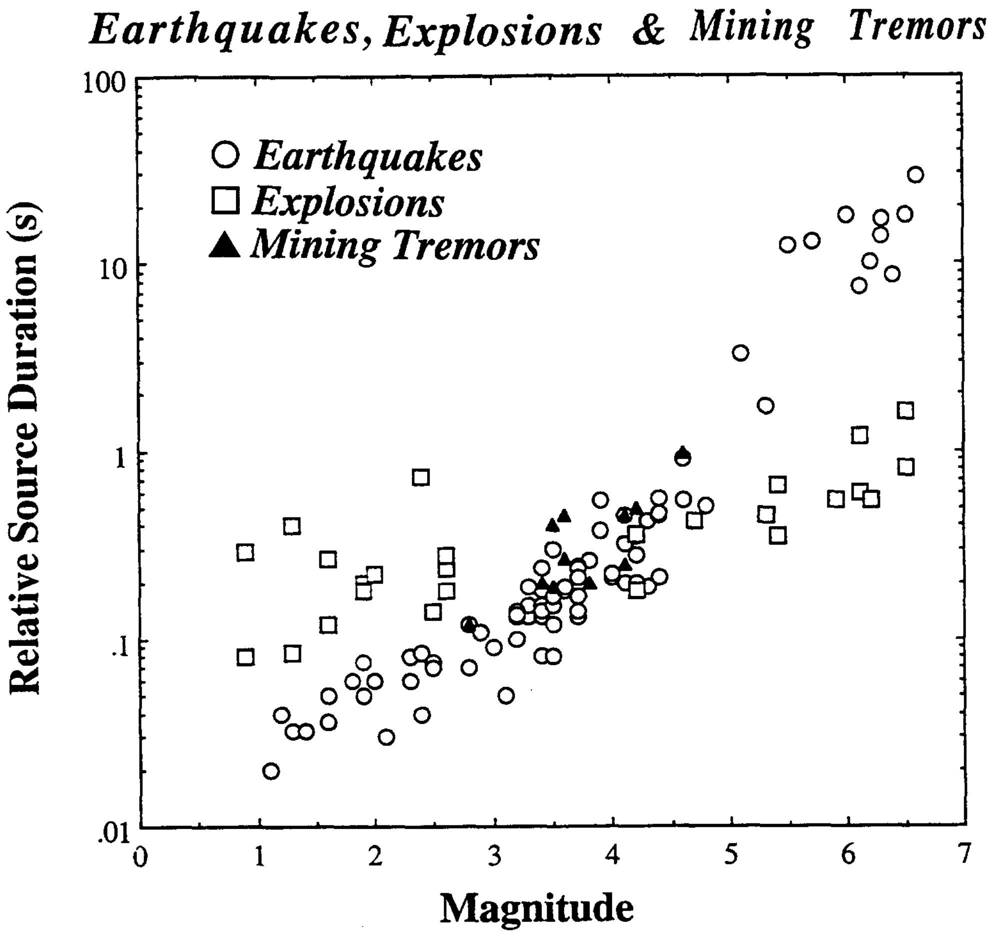


Figure 7: Source duration vs. magnitude for natural earthquakes (circles), explosions (squares), and mining tremors (filled triangles), determined by EGF analysis. For events having magnitude less than 2.5 or greater than 4.5, the source duration is a good discriminator between earthquakes and explosions. In the remaining magnitude range (2.5 to 4.5) the earthquake, explosion and mining tremor populations overlap.

populations overlap, as shown in Figure 7, indicating that simple source duration is not a good discriminant in this magnitude range. However, while source time duration may not be a good discriminant for magnitude 2.5–4.5 events, the examples shown above suggest that other properties of the RSTF may be useful for discrimination. In Figures 2 and 3, for example, the RSTFs show evidence of multiple detonation, characteristic of industrial blasting practices. The RSTFs of two of the nuclear explosions analyzed (Figure 4) show evidence of the spall phase, while the earthquake example (Figure 5) shows clear directivity effects in the RSTF as a function of azimuth. Finally, for three of the mining tremors analyzed (Figure 6), the RSTF shows multiple pulses that are different from both the secondary spall phase of a nuclear explosion and the multiple pulses of multiply detonated blasts.

# CONCLUSIONS AND RECOMMENDATIONS

Our results demonstrate that source time functions retrieved with the EGF method provide valuable information about the energy release process of seismic events of all magnitudes. Source duration vs. magnitude, however, is only capable of distinguishing large (M>4.5) or very small (M<2.5) earthquakes from explosions. Nonetheless, many of the source time functions examined in this study display features that are indicative of event type, such as source directivity, spall phases, and multiple pulses in industrial blasts and mining tremors. Therefore, we conclude that the source time functions inferred by the empirical Green's function method make a useful contribution to the difficult problem of regional event discrimination. We recommend that further work be done to find better EGF-based discriminants for events in the magnitude range 2.5 to 4.5. The effort should include both empirical studies, such as presented here, and theoretical modeling of relevant source types.

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