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Discrimination between Earthquakes and Chemical Explosions in Eastern Russia Using Amplitude Ratios Obtained From Analog Records

L. Linkimer (*), K. Mackey, K. Fujita, and P. Hidalgo

Michigan State University, Department of Geological Sciences, East Lansing, MI 48824-1115 United States

(*) Now at University of Arizona, E-mail: linkimer@email.arizona.edu

MICHIGAN STATE UNIVERSITY

1. Abstract

Amplitude data from 237 earthquakes ($1.5<mb<4.9$, $10<\Delta<916$ km) and 247 chemical explosions ($1.4<mb<3.9$, $6<\Delta<752$ km), recorded by short period analog seismometers in Eastern Russia, was used to calculate 1164 amplitude phase ratios of five different types: Pg(h)/Sg(h), Pg(z)/Sg(z), Pg(h)/Sg(z), Pg(z)/Sg(h), and full vector, where h is the horizontal component and z is the vertical component. These amplitude ratios were analyzed in two regions of the Yakutia and Magadan regions of Eastern Russia as earthquake-explosion discriminants in four different ways: the raw phase ratio, the distance- corrected phase (DCP) ratio, the network-averaged phase (NAP) ratio, and the network-averaged distance-corrected phase (NADCP) ratio. Chemical explosions tended to show higher values than earthquakes for all types of amplitude ratios studied. The best earthquake-explosion discriminants found for both regions were Pg(h)/Sg(h), Pg(z)/Sg(h), and full vector NAP and NADCP ratios. These discriminants allowed for the classification of 86-92% of the ratios as being either earthquakes or explosions.

2. The Contamination Problem of the Seismic Catalog

Both earthquakes and chemical explosions occur in all regions of Eastern Russia. Earthquakes are concentrated in broad (~ 400-600 km wide) areas associated to the boundaries between tectonic plates in the region, e. g., the Eurasian, North American, Okhotsk, and Amur plates (Figs. 1, 2). On the other hand, chemical explosions are related to mining and the construction of roads, railroads, and dams, many of which occur in the same general area as the natural earthquakes (Figs. 2). The majority of these explosions are conducted under a technique called ripple fire. Both earthquakes and chemical explosions are sources of elastic waves; therefore, both are recorded by seismic networks.

The Magadan and Yakutia seismic networks have been recording and locating seismic activity for over 40 years. Although locations of both earthquakes and explosions are contained in published and unpublished Russian regional network bulletins such as those produced by the Yakutia and Magadan regional networks, very few explosions are explicitly marked in the bulletins. Previous studies based on temporal and geographical distribution of earthquakes and explosions have shown that there is considerable contamination by chemical explosions in the earthquake catalogs for these regions (Godzikovskaya, 1995; Odinets, 1996; Mackey and Fujita; 1999; Mackey et al., 2003). As mine blasting occurs mostly during daytime hours, calculating the fraction of day vs. night events in discrete cells has allowed for the identification of geographic regions where the catalog is likely to be contaminated (Fig. 3). However, it is impossible to discriminate individual events using this method. If explosions are not removed from the seismic catalogs of these regions, there is an "explosion contamination" problem that can result in a misinterpretation of the regional tectonics, and an erroneous assessment of the natural seismic hazard.

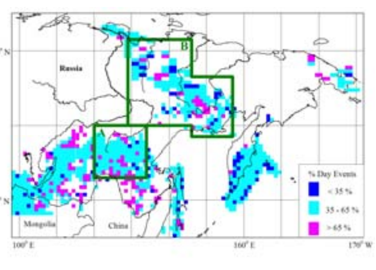

Figure 3. Percentage of seismicity occurring during local daytime in Northeast Russia (Modified from Mackey and Fujita, 2005). Labeled regions are the Southern Yakutia region (A) and the Magadan and Northern Yakutia regions (B).

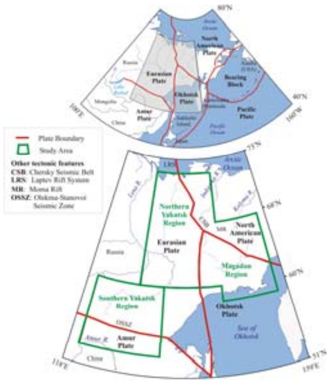

Figure 1. (Top) Regional plate tectonic map of northeast Russia and location of the study area. (Bottom) Enlargement of the shaded area. The total size of the two regions under analysis is about half the size of the United States.

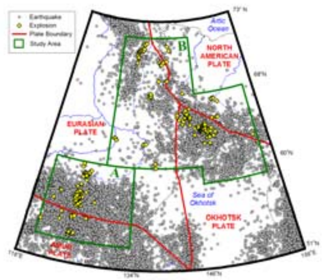

Figure 2. Seismicity map of the study area from 1970 to 2005 and location of 285 know chemical explosions collected for this study. Labeled regions are the Southern Yakutia region (A) and the Magadan and Northern Yakutia regions (B).

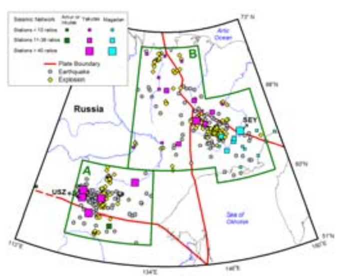

Figure 4. Location map of seismic stations and the 237 earthquakes and 247 know chemical explosions used for creating Pg/Sg amplitude ratios in this study. Labeled regions are the Southern Yakutia region (A) and the Magadan and Northern Yakutia regions (B).

3. Phase Ratio Processing

Amplitude information, arrival times, and location parameters of 237 earthquakes and 247 known chemical explosions, recorded between 1985 and 2000, were acquired from unpublished bulletins and analog seismograms made available from the Yakutia and Magadan regional networks (Fig. 4, Table 1). The earthquake group includes only nighttime events and the explosion group comprises only daytime events clearly identified in the bulletins as "explosions". This separation was done because previous studies has shown that night time seismicity better reflects tectonic trends as most explosions are excluded (Mackey and Fujita, 2001; Mackey et al., 2003).

The amplitude collected from the bulletins consists of peak-to-peak maximum amplitudes for both Pg and Sg phases recorded on each of the three components Z, N-S, and E-W. Amplitudes were also determined from analog seismograms in Russia by measuring the maximum peak of both Pg and Sg phases in millimeters (Fig. 5). The seismic stations that recorded these amplitudes utilized SM-3, SKM, or VEGIK short period seismometers, which record periods between 0.18-1.3 s (0.76-5.5 Hz). This is considered the frequency range in which the phase ratios calculated in this study are valid.

Table 1. Characteristics of collected events and phase ratios

	Southern Yakutia		Magadan and Northern Yakutia	
	Earthquakes	**Explosions**	**Earthquakes**	**Explosions**
UTC time window	11:00-22:59	23:00-10:59	9:00-20:59	21:00-8:59
Number of events	147	117	90	130
Number of Pg(z)/Sg(h)	323	251	370	220
Number of ratios (other four types)	259	206	255	138
Epicentral distance range	10-900 km	6-423 km	16-916 km	9-752 km
K Class range	5.2-12.6	4.8-10.6	6.1-12.8	4.8-10.2
m_b range (1)	1.5-4.8	1.4-3.9	1.9-4.9	1.4-3.7

(1) Magnitude (mb) was calculated using the regional regression of $m_b = 5.4+0.44\ (K-14)$.

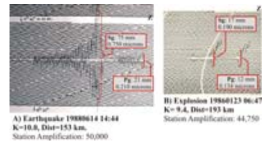

Figure 5. Examples of amplitude measurements made on the vertical component of a seismogram of A) An earthquake recorded at SEY and B) an explosion recorded at USZ. The amplitude calculation is shown for both Pg and Sg phases. Note that these seismograms read from right to left. The location of stations SEY and USZ is shown in figure 4.

4. Types of Phase Ratios

From the amplitude information, the following five types of phase ratios were created:

$$1)\ \frac{Pg(h)}{Sg(h)} = \frac{\sqrt{(Pg_{NS})^2 + (Pg_{EW})^2}}{\sqrt{(Sg_{NS})^2 + (Sg_{EW})^2}}$$

$$2)\ \frac{Pg(z)}{Sg(z)} = \frac{Pg_Z}{Sg_Z}$$

$$3)\ \frac{Pg(h)}{Sg(z)} = \frac{\sqrt{(Pg_{NS})^2 + (Pg_{EW})^2}}{(Sg_Z)}$$

$$4)\ \frac{Pg(z)}{Sg(h)} = \frac{Pg_Z}{\sqrt{(Sg_{NS})^2 + (Sg_{EW})^2}}$$

$$5)\ Full\ Vector = \frac{\sqrt{(Pg_Z)^2 + (Pg_{NS})^2 + (Pg_{EW})^2}}{\sqrt{(Sg_Z)^2 + (Sg_{NS})^2 + (Sg_{EW})^2}}$$

These five types of amplitude phase ratios are shown in four different ways: the raw phase ratio (Fig. 6b), the distance-corrected phase ratio (DCP, Fig. 6c), the network-averaged phase ratio (NAP, Fig. 6d), and the network-averaged distance-corrected phase ratio (NADCP, Fig 6e).

The distance-corrected phase ratio (Fig. 6c) was calculated using a linear regression for the earthquake data in an amplitude-phase-ratio vs. epicentral-distance graph (Fig. 6a). The difference between this regression line and each phase ratio was added to the original phase ratio (Fig. 6b). A network-averaged phase (NAP) ratio was calculated when three or more phase ratios were available for the same event. This average was calculated for both the raw phase ratio (Fig. 6d) and the distance-corrected phase ratio (Fig 6e) and were plotted against the network-averaged K class.

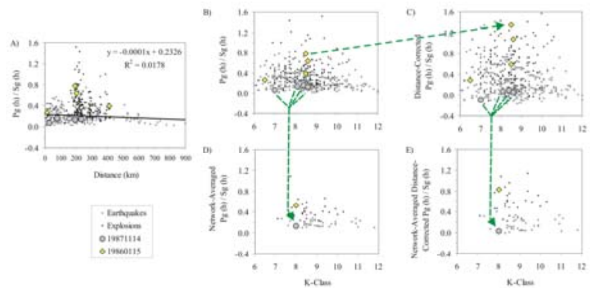

Figure 6. An example of a distance correction and network-average calculation for the Pg(h)/Sg(h) phase ratio of one earthquake and one explosion in the Southern Yakutia region. A) Pg(h)/Sg(h) phase ratio vs. epicentral distance and linear regression for the earthquake data. B) Pg(h)/Sg(h) phase ratio vs. K class. C) Pg(h)/Sg(h) phase ratio vs. K class after the application of the distance correction. D) Network-average Pg(h)/Sg(h) phase ratio vs. averaged K class. E) Network-averaged distance-corrected Pg(h)/Sg(h) phase ratio vs. averaged K class.

5. Critical Values and Best Discriminants

The critical value (CV) of a phase ratio is the value of the ratio that best separates the populations of earthquakes and explosions. Since it is intuitively expected that explosions should have higher values of Pg/Sg phase ratios than earthquakes, the critical values were calculated taking possible values of amplitude phase ratios and counting the number of ratios from earthquakes below that value and the number of ratios from explosions equal or above it. The sum of the number of earthquakes below each value and the explosions equal or above it for one specific value define the number of ratios correctly classified by that value. The maximum number of correctly classified events determines the critical value for the phase ratio analyzed (Tables 2 and 3). Some of the best earthquake-explosion discriminants found are shown in figure 7.

Table 2. Critical values and maximum percentage of correctly classified events for the Southern Yakutia region.

Discrimant	Raw Phase Ratio	Distance-Corrected Phase Ratio	Network-Averaged Phase Ratio	Network-Averaged Distance-Corrected Phase Ratio
Pg(h)/Sg(h)	0.25 (71.3%)	0.29 (71.0%)	0.31 (89.1%)	0.43 (89.1%)
Pg(z)/Sg(z)	0.31 (65.4%)	0.32 (66.6%)	0.44 (78.5%)	0.44 (80.1%)
Pg(h)/Sg(z)	0.41 (69.4%)	0.36 (69.4%)	0.45 (81.3%)	0.55 (80.6%)
Pg(z)/Sg(h)	0.20 (68.0%)	0.23 (68.6%)	0.24 (86.8%)	0.31 (86.8%)
Full Vector	0.31 (71.2%)	0.38 (71.6%)	0.35 (87.9%)	0.48 (89.1%)

Table 3. Critical values and maximum percentage of correctly classified events for the Magadan and Northern Yakutia regions.

Discrimant	Raw Phase Ratio	Distance-Corrected Phase Ratio	Network-Averaged Phase Ratio	Network-Averaged Distance-Corrected Phase Ratio
Pg(h)/Sg(h)	0.23 (70.7%)	0.33 (70.0%)	0.31 (91.0%)	0.35 (91.7%)
Pg(z)/Sg(z)	0.33 (63.8%)	0.27 (63.8%)	0.56 (78.1%)	0.78 (79.1%)
Pg(h)/Sg(z)	0.48 (62.8%)	0.45 (63.3%)	0.62 (80.2%)	0.98 (80.2%)
Pg(z)/Sg(h)	0.18 (67.0%)	0.15 (66.0%)	0.23 (86.4%)	0.29 (86.1%)
Full Vector	0.27 (70.9%)	0.25 (70.8%)	0.33 (91.7%)	0.38 (91.7%)

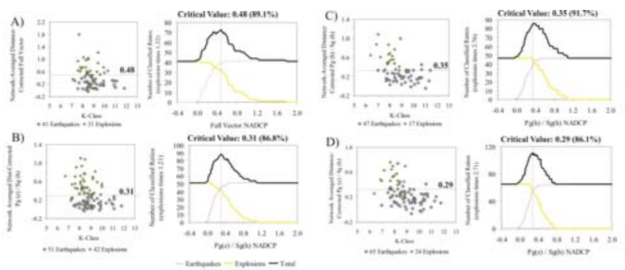

Figure 7. Phase ratio vs. K-Class, critical values, and number of correctly classified events for some of the best discriminants found in this study. A) Full vector NADCP ratio for the Southern Yakutia Region. B) Pg(z)/Sg(h) NADCP ratio for the Southern Yakutia Region. C) Pg(h)/Sg(h) NADCP ratio for the Magadan and Northern Yakutia regions. D) Pg(z)/Sg(h) NADCP ratio for the Magadan and Northern Yakutia regions.

6. Conclusions

- Chemical explosions tended to have higher values than earthquakes for all types of amplitude ratios explored in the Yakutsk and Magadan regions.
- The best earthquake-explosion discriminants found were:
  - The Pg(h)/Sg(h), Pg(z)/Sg(h), and the full vector Network-Averaged Phase ratios
  - The Pg(h)/Sg(h), Pg(z)/Sg(h), and the full vector Network-Averaged Distance-Corrected Phase ratios
- These discriminants allowed for the classification of 86-92% of the ratios as being either earthquakes or explosions.
- There were no important differences in the performance and averages of amplitude phase ratios calculated between the two studied regions.
- For earthquake-explosion discrimination purposes in the two studied regions, an amplitude phase ratio that is lower than the critical value is likely to be considered an earthquake while an amplitude phase ratio that is higher than the critical value is likely to be considered an explosion.
- This study confirms that it is possible to conduct earthquake-explosion discrimination studies using historic Russian regional data. In order to verify the results and increase the reliability of the estimates, the use of the amplitude phase ratios with other alternative discriminants is recommended.

7. Acknowledgements

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