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COMPLEXITY AND SPECTRAL RATIO OF EARTHQUAKES AND NUCLEAR EXPLOSIONS IN CHINA

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تعقد والنسبة الطيفية للزلازل والتفجيرات النووية فى الصين

الخلاصة: فى إطار معاهدة الحظر الشامل للتجارب النووية يعتبر التمييز بين الزلازل الطبيعية والتفجيرات النووية من الأمور الهامة. هناك طرق عديدة للتمييز بين الزلازل الطبيعية والتفجيرات النووية منها النسب الطيفية للأحداث ومدى تعقيدها. تعتبر الصين من المناطق الأكثر نشاطا على المستوى التكتونى خاصة فى الجزء الغربى وهى أيضا نشطة زلزاليا فى الجزء الشمالى. يهدف هذا البحث إلى التمييز بين الزلازل الطبيعية والتفجيرات النووية لمنطقة الصين باستخدام عدة طرق منها النسب الطيفية للأحداث ومدى تغييرها لعدد سبعة زلازل وسبعة تفجيرات شدتهم تتراوح ما بين ٤,٥ إلى ٦,٥ بمقياس ريختر. وأظهرت النتائج أن مقدار تعقيد الزلازل أكبر بكثير من التفجيرات النووية على المسافات البعيدة، وبالتالى التمييز ما بين الزلازل والتفجيرات النووية تكون أكثر وضوحا. وعلى العكس قد تبين أن النسب الطيفية للتفجيرات النووية أكبر من النسب الطيفية للزلازل، حيث أن موجات التفجيرات النووية لها محتوى ترددى أعلى من الزلازل.

ABSTRACT: *The discrimination between nuclear explosions and earthquakes is an important issue for the verification of compliance with a Comprehensive Test Ban Treaty (CTBT). Several diagnostic techniques are examined for identifying earthquakes as events distinct from possible underground nuclear explosions such as complexity and spectral ratio. China is a tectonically and seismically complicated region, especially in the western part. Seismicity is active in North China. The objective of this paper is discriminating the nuclear explosions from natural earthquakes in China region by using the complexity and spectral ratio tools for a set of seven nuclear explosions and seven earthquakes with $4.5 \le mb \le 6.5$. It was found that, the complexity of natural events (earthquakes) is higher than of artificial events (explosions), therefore, natural earthquakes are more complex than nuclear explosions at teleseismic distances and separation is clear between both of them. On the other hand, the spectral ratio is larger for explosions than for earthquakes due to the seismogram of explosions have higher frequency content than that for earthquakes.*

1. 1. INTRODUCTION

China is tectonically and seismically complicated region, especially in its western part. Large earthquakes occur frequently along the line of the Yinshan, Yanshan and Taihang mountain ranges, and along the Tan-Lu fault. The seismic velocity structure findings from earthquake data and methods were widely employed in investigations of this tectonic motion. Many findings show that the velocity structure analyses are available for studies on tectonic motion and evolution as well as of the collision, subducted trench, trough and converge zones (ZHAO et. al., 2009).

Source complexity method has been used as a tool for discrimination between natural earthquakes and nuclear explosions. Natural earthquakes are more complex than nuclear explosions at teleseismic distances and separation is clear between both of them as shown in Figure 1.

For explosions, Energy is released suddenly and maximum amplitudes are observed in the beginning of the record in the time. The maximum energy spreads through large frequencies in the frequency domain while in earthquake records; S-wave amplitudes are larger than P-wave amplitudes. Maximum amplitudes are observed in the S-wave train arriving later than P-wave train in the time domain. The maximum energy spreads through lower frequency than those of P-wave in the frequency domain. Therefore, the concept of complexity was developed in an attempt to quantify this difference in signal duration hence; the complexity is the comparison of amplitudes of the initial part of the short period signal with those of the succeeding coda.

The need for a suitable tool for measuring strength of any seismic event, as well as for discrimination between natural and artificial ones, is very important issue. Our study has been put forward to apply both the complexity and spectral ratio tools for the verification of a nuclear explosion at China and the seven natural earthquakes. These tools can help in resolving possible biases in the identification of an explosion.

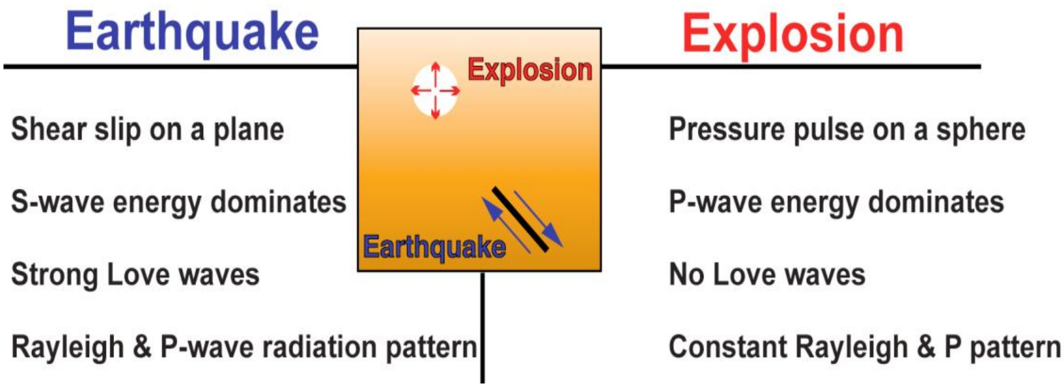

Figure 1: An overview of the theoretical differences between a pure explosion and a pure earthquake leading to expected observational differences (after William, et. al., 2007).

Table 1: Parameters of the studied events.

Event	Date [Y M D]	Origin Time [h m s]	Lat. N [deg.]	Long. E [deg.]	H (Km)	m_b
Earthquake (1)	2011 06 08	01:54:38	43.01	88.38	35.00	5.0
Earthquake (2)	2014 04 30	06:20:55	43.02	94.26	10.00	5.3
Earthquake (3)	2003 02 13	17:32:00	43.83	85.80	11.50	4.9
Earthquake (4)	2013 08 30	05:27:29	43.84	87.47	16.40	5.1
Earthquake (5)	1995 05 02	11:48:11	43.76	84.66	33.00	5.5
Earthquake (6)	2010 02 08	07:57:21	43.87	86.21	27.30	5.0
Earthquake (7)	2015 02 22	06:42:54	44.13	85.56	11.92	5.1
Explosion (1)	1992 05 21	05:00:00	41.52	88.80	00.00	6.5
Explosion (2)	1992 09 25	08:00:01	41.70	88.31	00.00	5.0
Explosion (3)	1993 10 05	01:59:59	41.63	88.68	00.00	5.9
Explosion (4)	1994 10 07	03:26:00	41.57	88.76	00.00	6.0
Explosion (5)	1995 05 15	04:06:00	41.58	88.81	00.00	6.1
Explosion (6)	1995 08 17	01:00:00	41.56	88.79	00.00	6.0
Explosion (7)	1996 06 08	02:56:00	41.60	88.66	00.00	5.9

Discrimination between earthquakes and underground nuclear explosions is a difficult task. Seismic methods provide the principal means for verification of nuclear test ban (Basham and Dahlman 1988). An underground nuclear explosion has a small point source compared to an earthquake. An earthquake occurs along a rupture because of sliding rupture sides. Due to this frictional sliding, an earthquake emits more shear waves and surface waves than a nuclear explosion. The need for a suitable tool for measuring strength of any seismic event, as well as for discrimination between natural and artificial ones, is very important issue. In this study, we used two methods (complexity and spectral ratio); these tools can help in resolving possible biases in the identification of an explosion.

2. DATA AVAILABLE

In this study, we collected the data of earthquakes and nuclear explosions from different websites IRIS (Incorporated Research Institute for Seismology), IMS (International Monitoring System), ISC (International Seismological Center) and the data set consists of seven (7) nuclear explosions and seven (7) natural earthquakes in China and the selection is based upon event size (magnitude), focal depth and location proximity. The search for the available natural earthquakes with relatively comparable magnitudes to that of the explosion and very close to the test site has been done. Table 1 shows the parameters of the 14 tested events. Figure 2 displays the location of the earthquakes and explosions used in the study and also illustrates the seismic stations which used in picking the studied events. As shown in Figure 3 at a number of major nuclear test sites and earthquakes, these observations did not show clear separation between event types.

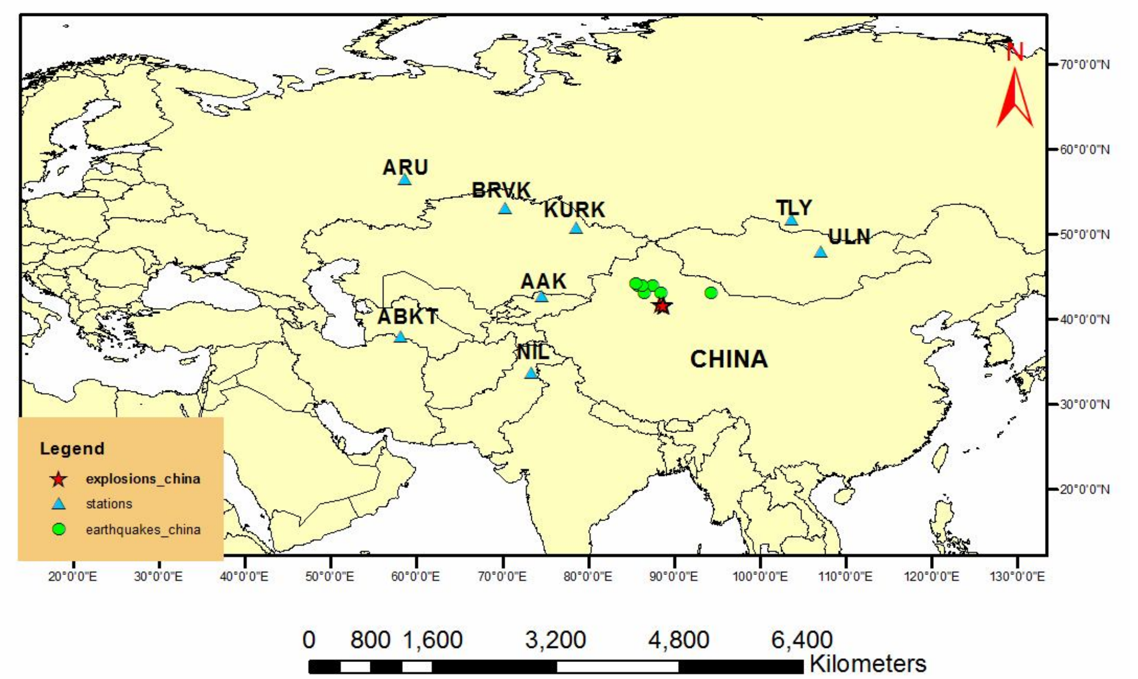

Figure 2: Seismic stations used for discrimination between studied earthquakes and nuclear explosions.

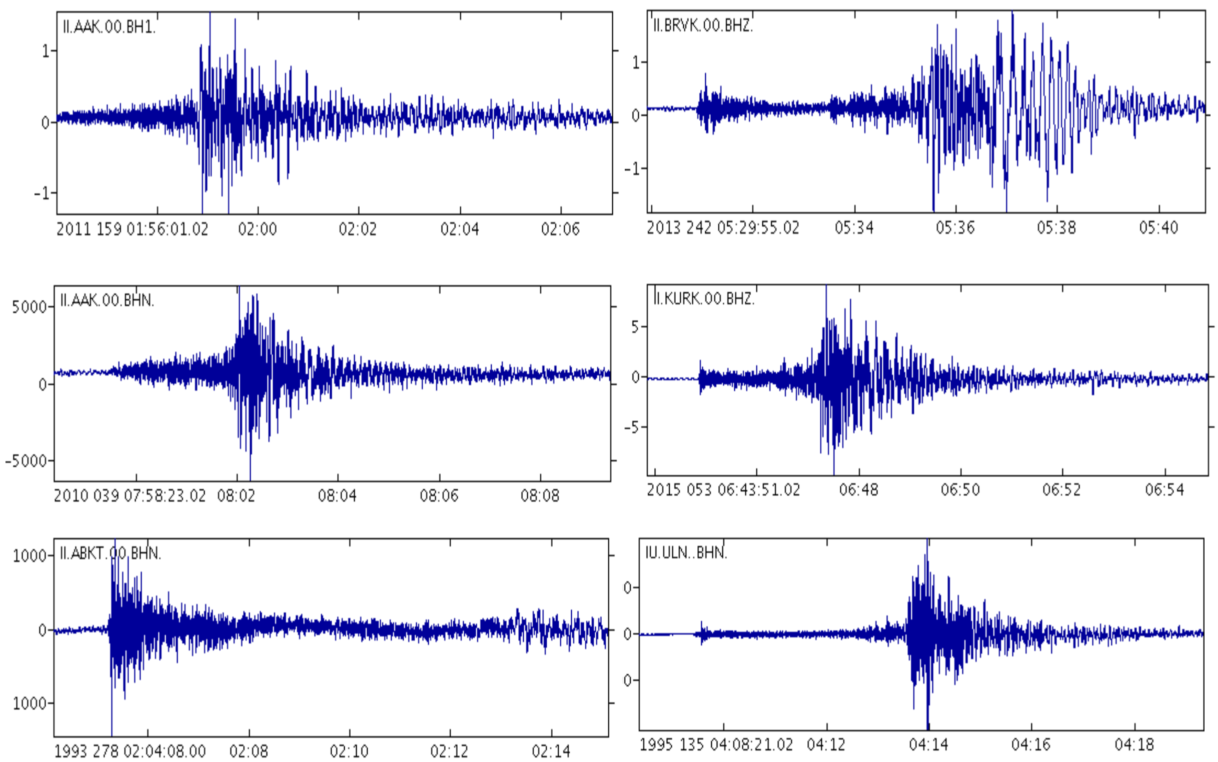

Figure 3: The waveforms of earthquakes (at Northern Xinjiang) (2011 06 08) at origin time 01:56:01 of (AAK) station (upper left), earthquake (2013 08 30) at origin time 05:29:55 of (BRVK) station (upper right), earthquake (2010 02 08) at origin time 07:58:23 of (AAK) station (middle left), earthquake (2015 02 22) at origin time 06:43:51 of (KURK) station (middle right), nuclear explosion (at Southern Xinjiang) (1993 10 05) at origin time 02:04:08 of (ABKT) station (lower left), and nuclear explosion (1995 05 15) at origin time 04:08:21 of (ULN) station (lower right).

Table 2: Complexity and spectral ratio parameters for explosions and earthquakes used in the study.

Events	Stations	Distance [km]	Distance [degree]	l_1-l_2 [Hz]	h_1-h_2 [Hz]	Sr	C	T_1 [sec]	T_2 [sec]
Explosion 07/10/1994 03:26:00 M_b 6.0	TLY	1400	< 25°	0.7-2.5	2.5-4.5	0.10	17.47	168.59	801.22
	BRVK	1700				0.27	02.96	179.98	1023.22
	ARU	2400				0.74	02.80	293.29	1193.57
Earthquake 30/08/2013 05:27:29 M_b 5.1	TLY	1300				0.11	26.37	58.52	651.61
	BRVK	1500				0.19	06.83	305.94	1869.26
	ARU	2200				0.36	15.33	253.75	1029.33
Explosion 25/9/1992 08:00:01 M_b 5.0	AAK	1000	< 20°	0.5-2.0	2.0-5.0	0.67	4.48	109.95	593.92
	TLY	1400				0.49	3.26	151.62	647.38
Earthquake 30/04/2014 06:20:55 M_b 5.3	AAK	1400				0.24	13.46	186.42	1059.33
	TLY	1100				0.11	28.48	130.85	587.07
Explosion 05/10/1993 01:59:59 M_b 5.9	AAK	1100	< 25°	0.5-2.0	2.0-4.0	0.46	2.58	108.13	658.25
	TLY	1400				0.1	40.35	156.01	852.51
	ARU	2400				0.44	1.86	364.07	1136.61
	ABKT	2400				0.22	1.6	265.5	952.88
Earthquake 13/02/2003 17:32:00 M_b 4.9	AAK	800				0.16	8.96	116.88	615.69
	TLY	1400				0.03	31.52	127.39	899.93
	ARU	2100				0.22	45.5	212.41	987.99
	ABKT	2200				0.27	12.69	249.74	1064.86
Explosion 15/5/1995 04:06:00 M_b 6.1	AAK	1100	< 25°	0.2-1.0	1.0-3.0	1.09	2.99	103.2	923.31
	ABKT	2400				1.28	1.64	348.8	1179.14
	ARU	2400				1.14	2.32	301.2	1189.34
	BRVK	1700				0.85	4.16	180.2	1037.29
	NIL	1500				2.00	3.57	123.7	576.92
	ULN	1400				0.57	5.77	168.7	900.97
Earthquake 02/05/1995 11:48:11 M_b 5.5	AAK	800				0.44	32.6	85.06	837.44
	ABKT	2100				0.27	16.06	229.95	1183.83
	ARU	2100				0.16	31.75	228.16	1043.65
	BRVK	1300				0.29	184.49	131.57	974.06
	NIL	1300				0.39	12.81	294.67	1718.84
	ULN	1600				0.13	14.09	171.02	1056.09
Explosion 21/5/1992 05:00:00 M_b 6.5	AAK	1100	< 15°	0.25-1.0	1.0-2.5	0.7	6.9	103.55	1142.6
Earthquake 08/06/2011 01:54:38 M_b 5.0	AAK	1000				0.45	18.87	110.39	919.42
Explosion 17/08/1995 01:00:00 M_b 6.0	AAK	1100	< 20°	0.5-2.5	2.5-5.0	0.42	6.53	98.19	937.06
	TLY	1400				0.09	4.1	218.12	886.11
	BRVK	1700				0.24	7.96	100.78	1055.04
Earthquake 08/02/2010 07:57:21 M_b 5.0	AAK	900				0.21	6.5	119.1	785.18
	TLY	1400				0.18	6.14	106.65	721.03
	BRVK	1400				0.13	8.17	140.8	694.35
Explosion 08/06/1996 02:56:00 M_b 5.9	AAK	1100	< 25°	0.7-2.5	2.5-4.5	0.38	3.43	107.8	791.37
	KURK	1100				0.32	7.59	122.96	658.24
	NIL	1500				0.45	0.55	232.88	616.1
	BRVK	1700				0.27	2.21	180.76	782.97
	ARU	2400				0.41	1.01	366.29	1117.53
Earthquake 22/02/2015 06:42:54 M_b 5.1	AAK	800				0.04	23.47	223.54	1142.07
	KURK	800				0.11	52.5	184.28	1066.31
	NIL	1400				0.16	5.82	288.52	1809.26
	BRVK	1300				0.15	5.28	376.17	2006.4
	ARU	2100				0.18	4.34	290.66	978.04

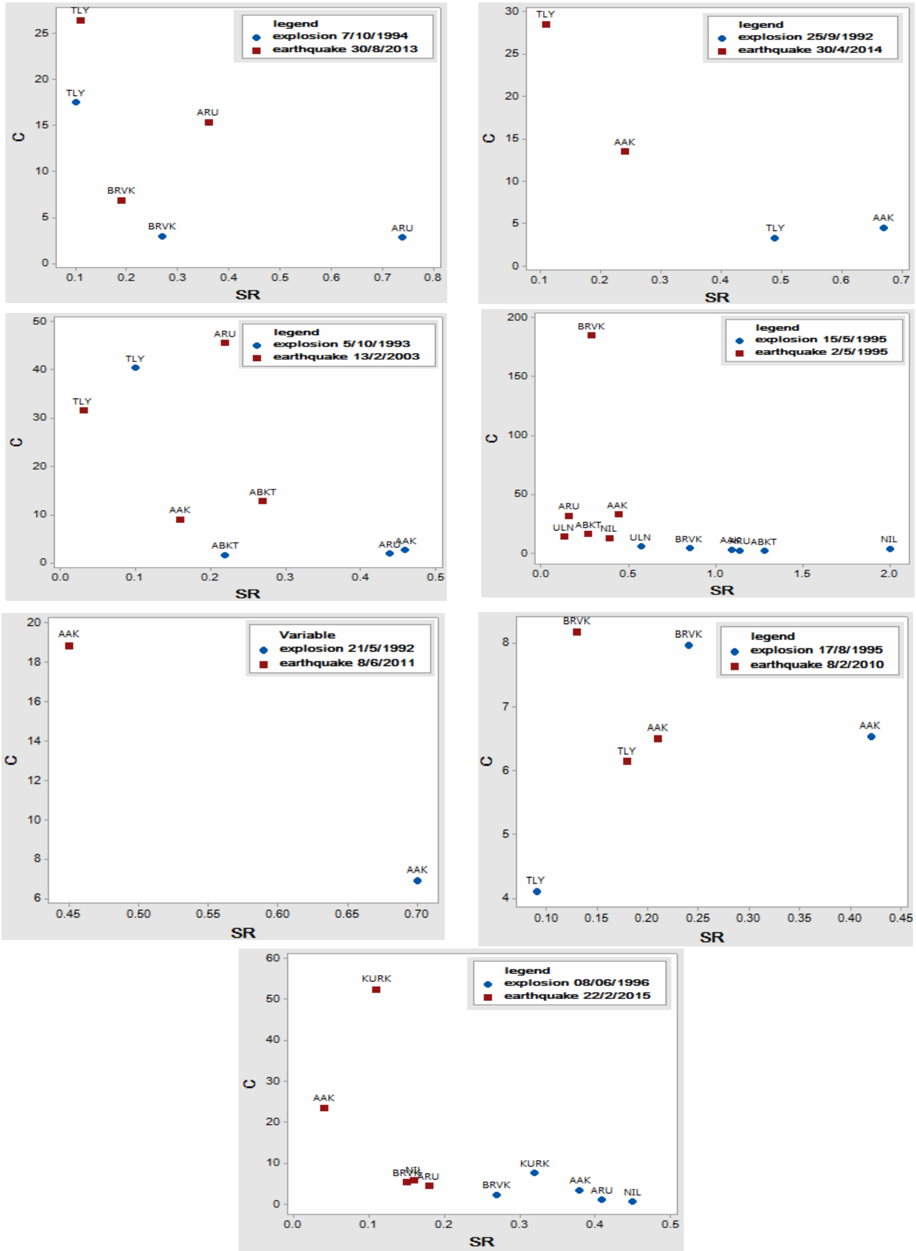

Figure 4: Plot of complexity versus spectral ratio of each earthquake and explosion recorded by the different seismic stations

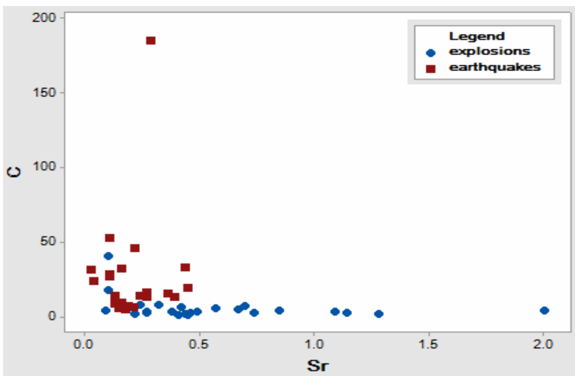

Figure 5: Plot of complexity versus spectral ratio for all explosions and earthquakes used in the study

3. COMPLEXITY

Source complexity method has been used as a tool for discrimination between natural earthquakes and nuclear explosions. The seismic events could be classified through their degree of spectral complexity and richness of different types of waves and amplitudes. This phenomena can be studied by comparing the energy content of the first five seconds of the seismogram for natural or artificial events. The following equation was used to calculate the (C) parameter which resamples complexity in time domain (Ari and Yosida, 2004).

$$C = \int_{t1}^{t2} s^2(t)dt / \int_{t0}^{t1} s^2(t)dt \qquad (1)$$

Where: s(t) refers to the signal amplitude as a function of time (t) and (C) is defined as the ratio of integrated power of the vertical component of the velocity seismogram $s^2(t)$ in the selected time windows length (t_0, t_1 and t_2) which t_0 is the onset time of P-wave but t_1, t_2 is the first and second time window.

4. SPECTRAL RATIO

The spectral ratio is the most discriminated method for classification of underground explosions from natural earthquakes. The (Sr) parameter is defined as the ratio of integrated spectral amplitudes a(f) of the seismogram in the selected frequency bands (high frequency band h_1, h_2 and low frequency bands l_1, l_2) which is visually selected from the spectrum of the earthquake and explosion for the same station and the Sr equation can be written as follow (Gitterman and Shapira, 1993).

$$Sr = \int_{h1}^{h2} a(f)df / \int_{l1}^{l2} a(f)df \qquad (2)$$

The limits of the integrals of (Sr) were selected by comparing the low and high-energy part of the event.

5. RESULTS

The focal depths of the selected earthquake events are ranged between 10 and 35 km, while for explosion events are not deeper than 0.0 km that may give a reliable indication for the preliminary discrimination analysis (Table 1). Table 2 shows the magnitude-frequency distribution of the explosions and earthquakes and the magnitude of the earthquakes are ranged between 4.9 and 5.5 but for the explosions are ranged between 5.0 and 6.5. The minimum number of stations used in the analysis was one station (only one case) but the maximum number of stations used was six stations which are in epicentral distance ranged between less 15^o (less than about 1500 km) and 25^o (less than about 2500 km).

In this study, discrimination methods for seven earthquakes and seven explosions are applied to the identification of earthquakes and explosions are well recorded by IRIS, IMS, and ISC seismic network with stations that is the nearest to area in the region of the study area. Table 2 summarizes the values of the filters (l_1-l_2) and (h_1-h_2) used in the different analysis steps through this study for the different events.

Complexity and spectral amplitude values for the selected seismograms were calculated by using special code on MATLAB program.

The discriminant criterion was obtained from the plot of complexity (C) versus the spectral ratio of the seismogram (Sr) for the selected probable events and earthquakes in the study region. The equation (1) was used to complexity (Ari and Yosida, 2004).

As in earlier studies, frequencies and amplitudes of the seismic waves resulting from earthquakes and explosions are different. Particularly, using low and high time-frequency intervals, it is easier to identify how the energy is distributed and allows to estimate the fraction of the total signal energy at the time and frequency domain. Such cross-spectral measures may be attractive for the best discriminant performance. Therefore, different frequency bands were tested in order to find differences in spectral shapes between explosions and earthquakes in the study.

Spectral ratio is probably the most promising discrimination method for classification of underground explosions from shallow earthquakes. The Sr parameter is calculated using the ratio of integrated spectral amplitudes a(f) of the seismogram in the selected frequency bands for explosions and earthquakes. The spectral ratio (Sr) between the high-frequency (h_1, h_2) and the low-frequency bands (l_1, l_2) can be represented as (Gitterman and Shapira, 1993) in equation (2).

Figure 4 shows the complexity (C) versus the spectral ratio (Sr) for each pair of earthquake and explosion recorded by the different seismic stations in the studied region. Figure 5 shows the complexity (C) versus the spectral ratio (Sr) for all explosions and earthquakes used in the study.

The complexity of earthquakes of each station is higher than of explosions of the same station due to the S-wave amplitude of the earthquake waveform is greater than the P-wave amplitude while in case of explosions; the P-wave amplitude on the seismogram is larger than the S-wave amplitude. Finally, we concluded that the spectral ratio is larger for explosions than for earthquakes due to the seismogram of explosions have higher frequency content than for earthquakes. However, we conclude that frequency domain analyses provided more reliable separation than amplitude discrimination in the study region.

6. CONCLUSION

We investigated the correlation between the complexity (C) and spectral ratio (Sr) of both explosions and earthquakes in China region where we were able to show that the time-frequency discriminant separated 95% of a certain type of explosions from the earthquake population.

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