EXCITATION AND ATTENUATION OF REGIONAL WAVES FROM RECENT SEISMIC EVENTS IN CHINA

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ABSTRACT

In the past few months I have further improved the method for simultaneous inversion for source spectral parameters and path Q using regional wave spectra. I have implemented a new computerized, non-linear algorithm that can be used for spectral inversion using data from multiple events that are nearly co-located. For example, spectra from swarms or mainshock/aftershock sequences from multiple stations can now be used simultaneously to derive event-variable source seismic moments, comer frequencies and path-variable Q values. This new algorithm can further suppress effects of random and modeling errors in regional wave spectral inversion, and can be jointly used with the previous, single event based algorithms (Xie, 1993; 1998).

I tested the new algorithm by applying it to synthetic, as well as real Pn spectra from several last Lop Nor explosions, originally analyzed by Xie and Patton (1999) using an ad hoc algorithm that lacks generality. In all tests I was able to recover the known source and path spectral parameters in the inversions using the new algorithm. I am currently applying this algorithm to analyze the regional wave spectra from the 1997, Jiashi earthquake swarm ($M_W \sim 6$) in Xinjiang, and the 1998, Zhangbei earthquake ($M_W \sim 6$) and its aftershocks in the Hebei province of northern China. Interesting aspects of these events include (1) the magnitude estimated for these events by the USGS and China Seismological Bureau (CSB) differ systematically, with the CSB estimates significantly larger; (2) the Jiashi swarms have mixed focal mechanisms, including strike-slip faulting and normal faulting that is rare in the tectonic environment; (3) some Jiashi events were recorded by strong-motion instruments; data from these recording are now available to the U.S. scientists through the effort of the P.I. and seismologists at University of Nevada.

Estimates of source seismic moments, comer frequencies and path-variable Q using Pn, Lg waves from these events will be presented.

Key Words: Seismic Sources, Q, Seismic Wave Propagation, China

OBJECTIVE

There are two ultimate objectives of this research: (1) We wish to quantify path attenuation of regional waves in continental areas, such as Eurasia, by developing digital, tomographic Q maps. (2) We wish to quantify the difference in the excitations of various regional waves, so that we may achieve better, quantitative understanding and criterion of the P/Lg spectral ratio discriminant of explosions. There proposed research is composed of several tasks. The first is to further improve the inverse method for simultaneous determination of source seismic moment (M_0), corner frequency (f_c) and path-variable Q_0 and η (Q at 1 hz and its power-law frequency dependence, respectively) using regional wave spectra. The second task is to apply the improved inverse method to Lg, Pn, Pg and Sg spectra from many earthquakes and explosions in Eurasia to estimate source M_0, f_c and path Q_0, η. The third task is input the measured Q values to a computerized tomographic algorithm, to obtain laterally varying Q maps for Lg and other regional waves. The fourth task is analyze source spectral scaling and other source spectral characteristics of seismic events, such as the amount of spectral overshoot of explosions, to explore when, how and why the P/Lg spectral ratios can be used to discriminate explosions from earthquakes.

This research provides important input to the implementation of a Comprehensive Test Ban Treaty. The tomographic Q maps can be used for the calculation of source spectral characteristics of any future seismic event to infer the nature and size of the event. These Q maps can also be used for estimating the detection threshold of the existing seismic stations located within the area studied. The source spectral behavior inferred from this study will help to understand if, when and how the P/Lg amplitude ratio can be used to discriminate explosions from earthquakes.

RESEARCH ACCOMPLISHED

Further development of algorithm to study regional wave spectra

In the past several months I have implemented a new version of the non-linear inverse algorithm for estimating source spectral parameters and path-variable Q using regional waves. This is the latest effort in improving the inverse algorithm. Unlike the previous, single-event based algorithm developed and modified by the PI in a series of papers (*e.g.*, Xie, 1993; Xie, 1998; Xie and Patton, 1999), the new version of the algorithm takes regional wave spectra from *multiple* events as the input, and simultaneously estimates the event-variable source M_0, f_c and path-variable Q_0, η values.

The new algorithm is developed for a situation when regional wave spectra from a number of nearly co-located events are available. In this situation the epicentral distance and path Q_0, η values from all events to the same station can be assumed as being constant. Using a stochastic modeling, we may express A_{ijk}, the regional wave spectra observed for the ith station, jth event and kth frequency, as

$$A_{ijk} = S_{jk} G(\Delta_i) \exp\left(- \frac{\pi f_k^{1-\eta_i} \Delta_i}{V_g Q_{0i}} \right) r_{ijk} \quad , \tag{1}$$

where f_k is the kth discrete frequency, Δ_i, V_g are the epicentral distance and group velocity. Q_{0i} and η_i are apparent Q at 1 Hz and its power-law frequency dependence. r_{ijk} is the effect of randomness. S_{jk} is the isotropic component of the source spectrum, which is given by

$$S_{jk} = \begin{cases} \dfrac{M_{0j}}{4\pi(\rho_s v_s \rho_c v_c^5)^{1/2}} \dfrac{1}{1 + f_k^2 / f_{cj}^2} & \text{for } \textit{earthquakes} \\ \dfrac{M_{0j}}{4\pi(\rho_s v_s \rho_c v_c^5)^{1/2}} \dfrac{1}{\left[1 + (1-2\beta) f_k^2 / f_{cj}^2 + \beta^2 f_k^4 / f_{cj}^4\right]^{1/2}} & \text{for } \textit{explosions} \end{cases} , \quad (2)$$

where ρ and v are density and wave velocity, with subscript c and s indicating crustal average and source zone values, respectively. The explosion source model in equation (2) is the modified Mueller-Murphy (M.M.M.) model by Sereno *et al.* (1988), with β being the overshoot parameter ($\beta = 0.75$ for a Poisson medium). $G(\Delta_i)$ in equation (1) is the geometrical spreading factor and takes the form

$$G(\Delta_i) = \Delta_0^{-1}(\Delta_0/\Delta_i)^m \quad , \quad (3)$$

where Δ_0 is a reference distance, and m is the decay rate of A_{ijk} at distances of $\Delta > \Delta_0$. Values of Δ_0 and m can be estimated for 1D velocity models for the study area, using synthetics (*e.g.* Xie, 1996; Xie and Patton, 1999).

If there are I stations, J events and N_d spectral observations, we may define a one dimensional unknown model vector, $\boldsymbol{m}$, as

$$\boldsymbol{m}^T = \left(M_{01}, f_{c1}, M_{02}, f_{c2}, \ldots, M_{0J}, f_{cJ}, Q_{01}, \eta_{01}, \ldots, Q_{0I}, \eta_{0I}\right)^T \quad , \quad (4)$$

where the superscript T denotes transpose. $\boldsymbol{m}$ has a dimension of $N_M = 2 \times J + 2 \times I$ and contains all of the unknown source spectral and path Q parameters to be solved for. We may also map the subscript combination "ijk" into a single subscript, "n", such that n increase from 1 to N_d and has a one-to-one correspondence to the ijk combinations. We may then take the logarithm of equation (1) and write the result into a general form of

$$d_n = \log(A_n) = F_n(\boldsymbol{m}) + \varepsilon_n \qquad (n = 1, 2, \ldots, N_d) \quad , \quad (5)$$

where $F_n(\boldsymbol{m})$ is a non-linear function of $\boldsymbol{m}$, and ε_n is a small, random quantity. Defining a data vector, $\boldsymbol{d}$ and a vector function, $\boldsymbol{F}$, the above equation takes a form of

$$\boldsymbol{d} = \boldsymbol{F}(\boldsymbol{m}) + \boldsymbol{\varepsilon} \quad , \quad (6)$$

where $\boldsymbol{\varepsilon}$ is a small residual vector. Equation (6) is a standard forward relationship between the data and model vectors, $\boldsymbol{d}$ and $\boldsymbol{m}$. It can be used to form a standard non-linear inverse problem in which given a data vector $\boldsymbol{d}$, the unknown vector $\boldsymbol{m}$ can be solved. We use a simple linearization-iteration (Newton-like) method to solve for $\boldsymbol{m}$, which starts with an initial model, $\boldsymbol{m}^0$, and proceeds in a loop (*e.g.*, Aki and Richards, 1980, § 12.3.7). At the $(q+1)$th step of the loop, the estimated model vector $\boldsymbol{m}^q$ is upgraded into $\boldsymbol{m}^{q+1}$ using

$$\boldsymbol{m}^{q+1} = \boldsymbol{m}^q + (\boldsymbol{G}^{q^T} \boldsymbol{G}^q)^{-1} \boldsymbol{G}^{q^T} \boldsymbol{d} \quad , \quad (7)$$

where $\boldsymbol{G}^q$ is the Frechet kernel matrix defined as

$$G^q_{nl} = \partial F_n(m)/\partial m_l|_{m=m^q} \quad . \tag{8}$$

The loop stops when the calculated residual

$$Res^q = \sqrt{(d - F(m^q))^T(d - F(m^q))/(N_d - N_M)} \tag{9}$$

stops to decrease with increasing q.

The motivation of developing and implementing such an algorithm comes from general, as well as specific considerations. In general, inverting spectra from multiple event increases the number $(N_d - N_M)$, thus making the inverse problem more overdetermined. Specifically, spectral inversion problems suffers significantly from modeling errors, as pointed out by Xie (1998) and Xie and Patton (1999). The modeling errors include those caused by ignoring the site response or non-isotropic source radiation pattern, and by the use of imprecise models describing the source spectra (equation (2)) and path geometrical spreading (equation (3)). If individual source spectra deviate from the idealized source spectral models randomly, the effects of these deviations tend to cancel out when spectra from multiple, co-located events are inverted simultaneously. For example, Xie and Patton (1999) studied Pn spectra from five similar Lop Nor explosions. By inverting the Pn spectra from individual explosions separately, they obtained drastically varying source and path spectral parameters, indicating that the event-based algorithm, when used without sufficient a priori knowledge on source and path spectral parameters, is unstable for Pn spectral inversion. They therefore used an ad hoc method to tackle the instability problem. First they used the event-averaged spectra at all stations to derive the event-averaged M_0 and f_c values together with the estimated standard errors. These were then used as a priori knowledge for event-based inversion, in which M_0, f_c values for each individual events are allowed to vary from the event-averaged values within the estimated standard error. The ad hoc method works satisfactorily only when the source spectra from different events are very similar, thus lacking a generality.

Application to Recent Events in China

The multiple-event based algorithm has been applied to regional wave spectra from some recent events in China. The first application is to Pn spectra from three of the five similar Lop Nor explosions studied by Xie and Patton (1999), as mentioned in the last section. Table 1 compares the source spectral parameters obtained using the new algorithm with those obtained by Xie and Patton. The two sets of the estimated parameters are very similar.

We have also applied the new algorithm to Lg spectra from several recent earthquake sequences in northwest and north China. These include (a) a swarm of moderate and small earthquakes in Jiashi County of the Xinjiang Autonomous Region (Li and Kerr, 1997), (b) the mainshock-aftershock sequence of the Zhangbei earthquake north of Beijing (Lin *et al.*, 1999), and (c) an M_b=5.5 event and its largest aftershock in inner Mongolia in May, 1996 (event 05/03/96 in Table 2). Figure 1 shows the location of these events. Table 2 lists the source parameters of the larger ($M_b \geq 5.4$) events studied, including the M_0 and f_c values estimated using Lg, and the M_0 values from the USGS and Harvard CMT solutions. Figure 3 shows an example of the fit of station-averaged, path-corrected Lg spectra to the synthetic source spectra constructed using the M_0, f_c parameters estimated during the spectral inversion.

Table 1 Estimated Pn M_0 and f_c Values for Three Lop Nor Explosions

Event Date	Origin Time (UT)	M_b	Pn M_0 (10^{16} N m)	Pn f_c (Hz)
10/05/93	01:59:56.6	5.9	1.1†, 1.0‡	2.2†, 2.5‡
10/07/94	03:25:58.1	5.9	10†, 8.7‡	2.6†, 2.8‡
05/15/95	04:05:57.8	5.7	1.1†, 1.1‡	2.5†, 2.6‡

†Estimated by Xie and Patton (1999).
‡Estimated by this study using the multiple-event based algorithm.

Table 2 Moderate Earthquakes With Lg M_0, f_c Estimates

Event Date	Origin Time (UT) (USGS)	M_b (USGS)	M_W (USGS, Harvard)	Location by USGS (°N, °E)	Fixed Half Duration by Harvard (s)	M_0 from USGS, Harvard (10^{17} N m)	Lg M_0 (10^{17} N m)	Lg f_c (Hz)
10/02/93	08:42:32.7	6.2	6.0, 6.1	38.190 88.663	2.7	13,15	4.8	0.21
05/02/95	11:48:11.8	5.5	-, 5.6	43.776, 84.660	1.3	-,2.8	0.7	0.6
05/03/96	03:32:48.0	5.5	5.9, 6.0	40.772, 109.672	2.5	8.3, 12	4.5	0.28
04/11/97	05:34:44.1	5.8	6.1, 6.1	39.504, 76.974	2.6	14, 16	3.9	0.28
04/15/97	18:19:11.5	5.4	5.7, 5.9	39.602, 76.934	2.2	3.8, 8.3	1.8	0.33
01/10/98	03:50:41.5	5.8	5.8, 5.8	41.083, 114.500	1.9	5.5, 6.1	3.2	0.27

The Lg M_0 and f_c values are obtained by Cong *et al.* (1996) for event 10/02/93, and by this study for all other events.

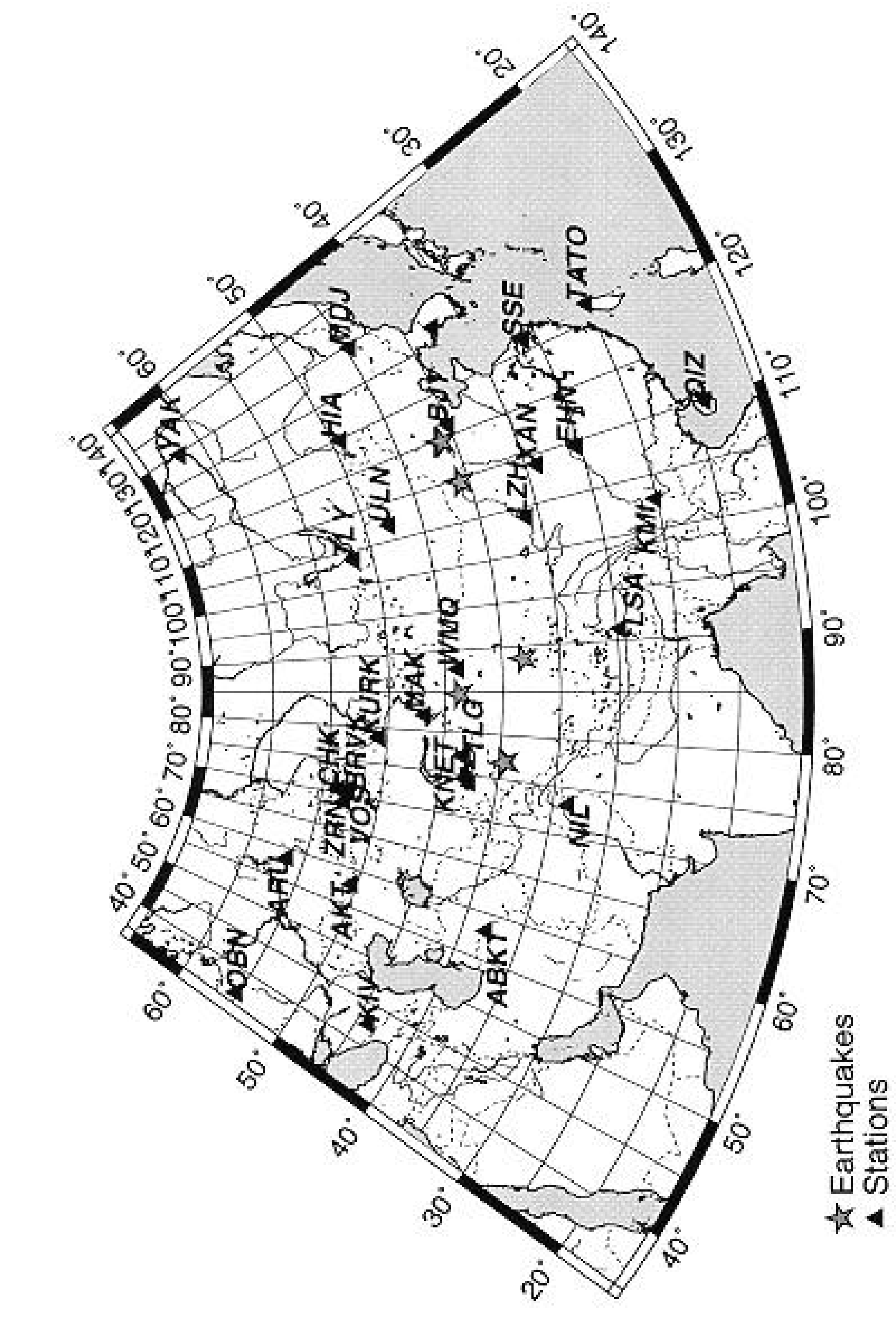

Figure 1. Map showing locations of earthquakes and seismic stations used in this study.

Figure 2. An example of the empirical Green's function deconvolution. Left and middle traces are the Lg waveforms from the 01/10/98 Zhangbei mainshock and an aftershock, observed at station XAN (Δ = 956 km). Deconvolving the left trace by the middle results in the estimated source time function shown on the right, with a rise time reading of about 3.5 s.

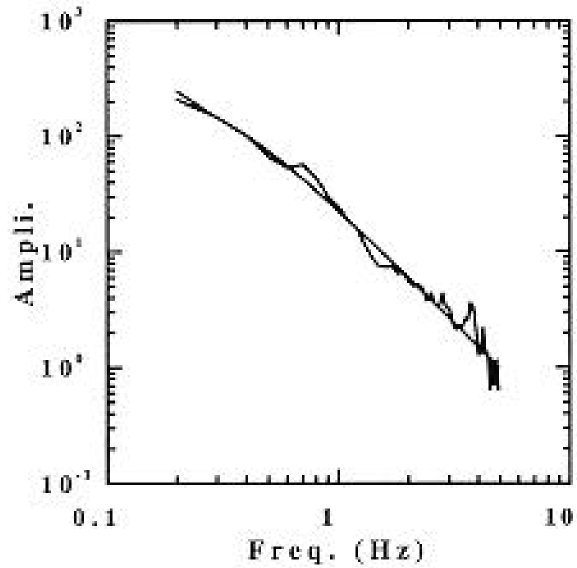

Figure 3 Path-corrected Lg spectra for the 01/10/98 Zhangbei earthquake, averaged over 12 broad-band stations, versus synthetic Lg source spectra constructed using the best-fit source model of ($M_0 = 3.2 \times 10^{17}$ N m, f_c = 0.27 Hz). The average Q_0 and η for the 12 stations are estimated to be 443 and 0.4, respectively.

As an independent check of the reliability of our f_c estimates, we estimated the source rise times (which is roughly the inverse of f_c) of the moderate earthquakes using the empirical Green's function (EGF) analysis, whenever co-located small events with similar focal mechanisms are available. Figure 2 shows an example of the EGF analysis. We found that for all larger events that permit the EGF analysis, the estimated Lg source rise times are very similar to the inverse of the Lg f_c values estimated in the spectral inversion.

It is interesting to note that the Lg M_0 values in Table 2 are systematically smaller, by factors of 2 to 4, than the values from the USGS and Harvard CMT solutions, obtained by modeling long-period, teleseismic waveforms. The measured source sizes for Chinese earthquakes by seismologists at different institutions typically differ. For example, it is well known that the magnitude estimates of Chinese earthquakes by the USGS tend to be 0.5 scale lower than those estimated by the China Seismological Bureau (CSB, *e.g.*, Li and Kerr, 1997), and that the estimates of M_0 by the Harvard GMT solution for central Asian earthquakes tend to be lower than those obtained by modeling regional surface waves (Patton, 1998). It is possible that the Lg M_0 values in Table 1 underestimate the real seismic moment because I have used an improper geometrical spreading with the reference distance Δ_0 set at 100 km. Assuming that the Δ_0 values can be as large as 200 km (Kvamme *et al.*, 1995), the Lg M_0 values can be raised by a factor of 1.4, resulting in Lg M_0 values that are lower than the USGS and Harvard estimates by factors of about 1.5 to 3.0. Patton (1998) suggested that for central Asian earthquakes, the Harvard M_0 estimates may be biased low by an average log-unit of 0.27, owing to the unusually thick crust (~ 50 km) unaccounted by the CMT solution. That suggestion appears to be consistent with Table 2, in which the Lg M_0 and the USGS/Havard CMT M_0 values differ more for earthquakes in northwest China (central Asia), where typical crustal thickness is about 50 km, much greater than the typical thickness of 35 to 40 km in north China (*e.g.*, Mooney *et al.*, 1998).

CONCLUSIONS AND RECOMMENDATIONS

We have implemented a multiple-event based, non-linear inverse algorithm for simultaneous determination of event-variable M_0, f_c values, and path-variable Q_0, η values using regional wave spectra. This marks a further improvement of our capability of reliably retrieving source and path spectral parameters using spectra that are subject to various random and modeling errors (Xie, 1998). Applications of the new algorithm to regional wave spectra from various co-located events, including clustered underground nuclear explosions, earthquake swarms and mainshock-aftershock sequences in China have yielded source spectral parameters and path Q for northwest and north China.

A long-standing problem for estimating sizes of seismic events in China has been that the estimates made by various seismological institutions tend to differ significantly. These include systematic differences in magnitude estimates of about 0.5 scale, and systematic differences in moment estimates of more than a factor of two. This poses a fundamental problem for comparative studies of seismic events in China and other regions of the world. In research so far, we have obtained Lg M_0 estimates for several recent, moderate seismic events in China. These estimates are systematically lower than the respective values estimated by the USGS and

Havard CMT solutions. Various causes could have contributed to this discrepancy, including the mis-calibration of the Lg geometric spreading terms in northwest and north China. Revision of this term involves synthetic calculations using more realistic velocity structures. However, it is unlikely that the discrepancy in M_0 estimates comes solely from bias in estimates using Lg. I suspect that the systematic bias in Lg M_0 estimates, if exists, may account for no more than a factor of about 1.4 of the discrepancy. To reconcile the M_0 estimates, efforts will be needed on examining M_0 estimates obtained by modeling long-period, teleseismic surface/body waves, as done by Patton (1998).

It is thus recommend that a special effort be make to select a number of recent, moderate Chinese earthquakes for a joint study, in which seismologists from different institutes in and outside China re-calculate the source parameters using the same broad-band data set, and compare the result. The cause of the discrepancy may be resolved in such a comparison by examining the data processing and source inversion procedures, as well as the velocity/Q structures used in the inversions.

In the next phase of this research, analysis of regional wave spectra from many more events will be conducted. The work will be optimized for achieving the two ultimate goals of this research: (1) development of new tomographic, regional wave Q maps, and (2) quantification of spectral characteristics of excitation of various regional waves, so that better understanding and criterion of the P/Lg ratio discriminants will be obtained.

References

Aki, K. and P.G. Richards P.G., 1980. *Quantitative Seismology: Theory and Methods* W.H. Freeman, San Francisco, Calif., 1980.

Cong, L., J. Xie & B.J. Mitchell, 1996. Excitation and propagation of Lg from earthquakes in Central Asia with implications on explosion/earthquake discrimination, *J. Geophys. Res.*, **101**, 27779-27810.

Kvamme, L.B., R.A. Hansen & Bungum, 1995. Seismic-source and wave-propagation effects of Lg waves in Scandinavia, *Geophys. J. Int.*, **120**, 525-536.

Li, H. and R.A. Kerr, 1997. Warnings precede Chinese temblors, *Science*, **276**, 526.

Lin, A., G. Zhao, G. Zhao and X. Xu, 1999. Inferred seismic fault associated with the 1998 M = 6.2 Zhangbei-Shanyi earthquake, Hebei Province, China. *Bull. Seism. Soc. Am.*, **89**, 550-554.

Mooney, W., G. Laske and T.G. Masters, 1990. CRUST 5.1: A global crustal model at 5°×5°, *J. Geophys. Res.*, **103**, 727-747.

Sereno, T.J., S.R. Bratt and T.C. Bache, 1988. Simultaneous inversion of regional wave spectra for attenuation and seismic moment in Scandinavia, *J. Geophys. Res.*, **93**, 2019-2036.

Xie, J. 1993. Simultaneous inversion of source spectra and path Q using Lg with applications to three Semipalatinsk explosions, *Bull. Seism. Soc. Am.*, **83**, 1547-1562.

Xie, J., 1996, Excitation and propagation of Pn in central Asia, in *Proc. 18h Seis. Res. Symposium on Monitoring a Comprehensive Test Ban Treaty*, edited by J.F. Lewkowicz, J.M. McPhetres, and D.T. Reiter, Air Force Phillips Laboratory, PL-TR-96-2153, pp. 419-428

Xie, J., 1998. Spectral inversion using Lg from earthquakes: Improvement of the method with applications to the 1995, western Texas earthquake sequence, *Bull. Seism. Soc. Am.*, **88**, 1525-1537.

Xie, J., L. Cong & B.J. Mitchell, 1996. Spectral characteristics of the excitation and propagation of Lg from underground nuclear explosions in Central Asia, *J. Geophys. Res.*, **101**, 5813-5822.

Xie, J. & H. Patton, 1999. Regional Phase Excitation and Propagation in the Lop Nor Region of Central Asia and Implications for the Physical Basis of P/Lg Discriminants, *J. Geophys. Res.*, **104**, 941-954.