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**A STUDY OF EAST KAZAKH EXPLOSIONS AND
PROPAGATION IN CENTRAL ASIA USING
REGIONAL CHINESE SEISMOGRAMS***

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INTRODUCTION

This paper reports the results of a study using Chinese seismic data to analyze signals from eleven Asian events, including seven presumed nuclear explosions at the East Kazakh test site. The pilot study of Harris et al., (1982) brought attention to the excellent recording of mid-period surface waves from East Kazakh explosions at the Urumchi Station in northwestern China, about 950 km southeast of the test site. These excellent recordings are due to a combination of instrumental response well suited for recording surface waves at regional distances and a source-receiver path structure producing well-dispersed wavetrains. In addition, effects of tectonic strain release, which are known to cause signal degradation for many East Kazakh events, are probably minimal at the Urumchi Station because the station lies very close to a minimum in the inferred radiation patterns of tectonic strain release at East Kazakh. As such, these data are of considerable interest to the seismic verification program, particularly for their potential to give additional information about explosion sources at East Kazakh.

In this study, we have restricted our analysis to signals recorded at the Urumchi station in the Sinkiang Province (station coordinates: 43.821N, 87.695E). These data were recorded in analog format and have been distributed on 70 mm microfilm chips by the National Oceanic and Atmospheric Administration (NOAA) through a data exchange program with the State Seismological Bureau of the People's Republic of China. When this study was initiated, data were available for years 1980 and 1981 and have recently become available for the year 1979. Our analyses cover: (1) measurements of group velocity dispersion for paths over basin and fold-belt terrains, (2) single-station location and backazimuth estimates using three-component data,

3) application of a differential phase method to Rayleigh waves from explosions, and (4) seismic moment estimates for seven East Kazakh explosions. In a separate note, these moments have been used to infer yield employing an empirical moment-yield relationship.

DATA

Epicentral data for events in this study are taken from the National Earthquake Information Service (NEIS) and the International Seismological Center (ISC). Table 1 is a listing of these data for seven East Kazakh explosions, an atmospheric explosion at Lop Nor, and three earthquakes. As seen from the map in Fig. 1, the earthquakes are located to the east of Urumchi in southern Mongolia, to the southeast in the Nan Shan fold-belt, and to the southwest in the Tarim Basin. Epicentral distances to the Urumchi Station are about 955 km from the East Kazakh test site, 362 km from Lop Nor test site and 1347 km, 1190 km and 951 km from the three earthquakes, respectively.

Surface-wave signals from these events were manually digitized from paper records made from the 70 mm film chips obtained from NOAA. Time windows were selected to include Love and Rayleigh waves. For the East Kazakh events, it was impossible to digitize the entire wavetrain because of the faint recordings and high frequency content of the L_g portion of the record. The raw digitized data were detrended and resampled to a constant rate of four samples/sec. The data were scaled to a trace amplitude in centimeters and, when necessary, adjusted for clock errors. Playouts of the corrected, digitized data are presented in Fig. 2.

As described in the NOAA circular on the Chinese data, these data were recorded on a three-component SK Kirnos Galvanometric seismograph for which we have only nominal values of the instrumental parameters. Unfortunately, there were no recordings of calibration pulses on any of the dates for which we received data. In lieu of any other calibration data, we made use of the transfer functions calculated from the nominal instrumental parameters as was done in the study of Harris et al. (1982). (See Figs. 2-4 and Table 1 from that study.) After instrument deconvolution, we bandpass-filtered the resulting trace between .05 Hz and 0.3 Hz to remove long-period noise arising from the deconvolution and inaccuracies at high frequencies arising from digitization.

The instrument-corrected, bandpassed data were rotated to apparent backazimuths as determined from particle motion analyses described below. These rotated data are plotted in Fig. 3, where positive deflection on the radial is away from the source and positive on transverse is counter-clockwise. It is notable that all signals from East Kazakh explosions show large amplitude, highly dispersed Rayleigh waves on the vertical component. Rayleigh waves on the radial component are significantly smaller in amplitude and are poorly correlated with the vertical channel at frequencies above 0.2 Hz. It is also apparent that Rayleigh waves on the radial component have been truncated at the beginning of the record due to the restricted digitization window. This is also the case for Love waves, if any were present (L_g waves dominated the record and made it impossible to see Love waves). Records of the Chinese atmospheric explosion show a classic Rayleigh-wave pulse and no Love waves. Records of the Mongolian earthquake show clear Love waves and very weak Rayleigh waves, probably indicating that

the station lies near a node in the Rayleigh-wave radiation pattern. On the other hand, records of the Sinkiang Province earthquake (in the Tarim Basin), although they have poor signal-to-noise ratio, indicate the presence of Rayleigh waves and small amplitude Love waves.

GROUP VELOCITY DISPERSION

Group velocity dispersion curves of Love and Rayleigh waves were measured in order to obtain insight into the extent of lateral heterogeneity in the region of the Urunchi Station. The rotated, instrument-corrected seismograms shown in Fig. 3 were used for this dispersion study. A phase-matched filter technique similar to that of Herrin and Goforth (1977) was used, where group velocity dispersion curves are developed by iterative approximation. In this application, the initial group velocity dispersion was taken from works of Chun and Yoshi (1977) and Harris et al. (1982). A phase-matched filter was constructed from the group velocity dispersion by interpolating the curve and integrating to obtain phase velocities with an assumed phase velocity at a given period in the integration constant. The phase spectrum of the filter was computed using these phase velocities and assuming a source phase of zero. A tapered unit-amplitude spectrum and the computed phase spectrum were transformed to the time domain. We show an example of the initial and final phase-matched filters along with the observed seismogram for the Lop Nor explosion in Fig. 4.

At each iteration, the phase-matched filter was cross-correlated with the observed seismogram. A cross-correlogram is shown in Fig. 5 along with an auto-correlogram of the phase-matched filter for the Lop Nor example. A suite of zero-phase bandpass filters were applied to the cross-correlogram, and the

results were used to determine whether the dispersion model accurately fit the observed waveform (i.e., whether the peak of the filtered cross-correlograms showed small variation from zero lag from one bandpass to another). Passbands of 3-4s, 4-5s, 5-6.67s, 6.67-10s, 10-15s, and 15-20s were chosen with four pole rolloff on each end of the passband (see Fig. 6). The group velocities for the synthetic seismograms were then adjusted in order to peak the cross-correlation function at the same point (near zero) for each of the above passbands.

Errors in estimated group velocities arise primarily due to errors in matching arrival times of wave packets of the phase matched filter with observed arrival times. Timing errors are generally no greater than 10 seconds, and usually less than 3-5 seconds. These timing errors lead to standard errors for the group velocity dispersion of about 0.1 km/s at periods shorter than 15 seconds. At longer periods, errors increase due to degraded signal-to-noise ratio and poor resolution of the arrival time of maximum amplitude of the filtered cross-correlogram. For the shortest path (Lop Nor to Urumchi), uncertainties of less than 3 seconds were achieved in the arrival time estimates leading to errors again of about 0.1 km/s for group velocities.

The assumed phase velocity used in the integration constant for generating the phase-matched filter may introduce bias in the group velocity estimates. Its value was determined by picking a phase velocity slightly higher (0.1 to 0.2 km/s typically) than the apparent group velocity of the main pulse of energy, obtained by dividing its travel time into the distance. The period at which this was done was typically 10 sec, and the resulting bias in group velocities is believed to be much smaller than the errors due to matching arrival times of wave packets.

The final dispersion curves for Rayleigh waves (Fig. 7) show two extremes, high velocities for the earthquake of 4/24/80 in Qinghai Province and low velocities for the earthquake of 3/29/81 and the explosions at East Kazakh. The high velocity path is predominately over the Nan Shan and Tien Shan fold-belts where crystalline basement rocks are close to the surface. The low velocity paths cross one or more sedimentary basins, and apparently the great thicknesses of sediments give rise to these low group velocities. Rayleigh waves from the Chinese atmospheric nuclear test at Lop Nor on 10/16/80 show dispersion which is between the extremes.

Comparison with Rayleigh-wave dispersion curves from other studies (Fig. 8) shows that the group velocities measured in this study are in good agreement with previous measurements in or near this region. Rayleigh wave dispersion for the 4/24/80 Qinghai Province earthquake has the highest group velocities observed and is similar to dispersion for Chun and Yoshi (1977) between 7 and 25 seconds and Chen and Molnar (1975) between 5 and 12 seconds for paths across the Tibetan Plateau which lies just to the south of this region. Dispersion for Rayleigh waves produced by East Kazakh Test Site explosions and crossing the Dzhungarian Basin is similar to dispersion reported by Arkhangel'skaya and Kuznetsova (1969) for periods between about 4 and 13 seconds for paths crossing basins with about 10 km of sediment to stations at Alma-Ata, Przhavl'sk, and Fergana, north of the Pamirs. Dispersion for the path from Lop Nor to Urumchi is roughly similar to Rayleigh-wave dispersion reported by Arkhangel'skaya and Kuznetsova (1969) between 5 and 12 seconds for paths through regions with less than 0.5 km of sediment overlying crystalline basement rocks.

DISTANCE AND BACKAZIMUTH ESTIMATES

In this section we estimate the epicentral distance and backazimuth for events using arrival times and particle motions of regional phases measured on the three-component Urumchi seismograms. Taken together, these estimates can give a preliminary location based on information recorded on a single station (Burr, 1982).

Epicentral distances were estimated from the differential arrival times of P_n and L_g . The epicentral distance, Δ , is related to the differential arrival time, δT , and velocities as follows:

$$\Delta = \frac{V_1 V_2}{V_1 - V_2} \delta T$$

and

$$\delta T = T_2 - T_1$$

where V_1 is the apparent velocity of P_n and V_2 is the velocity of L_g and T_1 and T_2 are arrival times of P_n and L_g , respectively. Here we assumed values of 8.0 km/sec and 3.5 km/sec for V_1 and V_2 , respectively, which are nominal velocities for these phases in stable platforms.

Estimate of the arrival times of P_n and L_g are given in Table 2 along with calculated differential times, epicentral distances, and errors. The P_n phase was visible on the Urumchi records only for the East Kazakh explosions. The arrival times for this phase could be picked to ± 2.0 seconds. Arrival times of L_g were more difficult to pick, and uncertainties are ± 4.0 seconds. Uncertainties in picking the arrival times of these phases represent a net random error (one standard deviation) in the distance calculation of ± 28 km. Errors in the epicentral distances were computed assuming that distances based on locations in Table 1 are true. In general, the estimated distances were shorter than the true distances by, on average,

about 35 km. Most likely, this is a systematic error due to the assumed velocities of P_n and L_g .

Backazimuths were estimated from the particle motion of Rayleigh waves on the horizontal components. We followed the method described in Harris et al., (1982) where cross-correlation functions were calculated between the vertical-component Rayleigh-wave signal and each horizontal signal shifted in phase by 90° to compensate for retrograde elliptical polarization. The backazimuth was then computed from the amplitude and sign of the peaks in the cross-correlation functions. An example is given in Fig. 9 showing the cross-correlation functions and auto-correlation function of the vertical-component signal for the event on 12/14/80. In general, the peaks of cross-correlation functions did not coincide in time nor occur at zero, indicating random time synchronization errors between the components. The probable cause of these errors is due to time registration errors when the data were digitized.

The resulting backazimuth estimates for all events with three-components of digitized data are given in Table 3. As with the distances, errors were computed assuming that azimuths based on locations in Table 1 are true. Errors in azimuths were converted to distance errors by assuming $\delta d = \Delta \delta \theta$, where $\delta \theta$ is the error in backazimuth in radians and Δ is the epicentral distance.

The backazimuth estimates for the East Kazakh explosions show a spread of 17.7° , with an average error of 3.9° and standard deviation of 7.2° . The standard deviation is probably a fair estimate of the random error in measurements of backazimuth using short-period surface-wave data. For a 1000 km path length, a 7.2° error translates into a 250 km long axis of a

location error ellipse. In addition, there can be systematic errors due to propagation effects such as horizontal refraction of Rayleigh waves crossing boundaries with significant phase velocity contrast. Systematic errors are probably the cause of large discrepancies in the backazimuth estimates for events southeast of the Urumchi Station. Paths from these events to the Urumchi Station cross-basins and orogenic belts which display very different group velocity dispersion curves (see Fig. 7). Complex paths and the fact that the path lengths are longer than the East Kazakh paths will favor the occurrence of lateral refraction.

In summary, use of the Chinese analog recordings of regional seismograms without some calibrations offers only limited capability for locating epicenters. The single-station error ellipse for a 1000 km uncalibrated path has a major axis of 250 km length (azimuth uncertainty) and minor axis of 56 km (distance uncertainty). Systematic errors due to structure affecting surface-wave paths and velocities of regional phases can seriously bias single-station estimates of location, especially on complicated paths in central Asia. The use of calibration or master events would help to reduce systematic errors in distance and backazimuth estimates (see Burr, 1982). Also, independent estimates of backazimuth based on particle motions of other phases such P_n and L_g could reduce systematic errors. Significant reductions in both random and systematic errors could be achieved if the data were recorded digitally with wide dynamic range and known instrument parameters.

SPECTRAL PHASE

Here we apply a relative spectral phase technique on Rayleigh waves from the East Kazakh explosions in order to check for phase reversals and for possible frequency dependence in the spectral phase, which may provide clues about source effects. The difference between phase spectra, $\phi(\omega)$, of Rayleigh waves from an unknown event and a reference event (subscript R) is

$$(\phi - \phi_R) + \omega(t - t_R) = (\phi^S - \phi_R^S) + (\phi^I - \phi_R^I) + \frac{\omega}{C} (\Delta - \Delta_R)$$

where ϕ^S and ϕ^I are source and instrumental phases, respectively, which are both functions of frequency, ω ; t is the beginning time of the record relative to origin time in seconds, Δ is the epicentral distance and C is the phase velocity, also a function of frequency. We assumed that instrumental phases are common since all signals are recorded on the same sensor. After equalizing the phases for origin time, we get the relationship for relative source phase to be

$$\delta\phi^S = \delta\phi' + \omega\delta t - \omega \frac{(\Delta - \Delta_R)}{C}$$

where $\delta\phi'$ is the relative equalized phase spectrum and δt is a net timing error due to relative origin time errors and, more importantly, time registration errors of the digitized data. Timing marks were difficult to see on the paper records and clock errors were known to be present. Thus, our analysis must account for significant phase errors due to mis-timing.

The seismograms used in this analysis were the Rayleigh-wave signals recorded on the vertical component shown in Fig. 2, where 10/12/80 was used as the reference event for all of the explosions. Each seismogram was tapered and Fourier transformed, and the phase spectrum was unwrapped using the

algorithm due to Tribolet (1977). Phase differences were computed, and the results were equalized to the origin time to get $\delta\phi'$. Figure 10a shows an example of $\delta\phi'$ for the 12/14/80 event. Next we corrected this phase for differences in epicentral distance using an assumed phase-velocity curve, in this case the Canadian Shield dispersion curve of Brune and Dorman (1963). This corrected phase spectrum is shown in Fig. 10b for 12/14/80. Finally, we removed timing errors by fitting a line through the data (with intercept of zero) as shown for 12/14/80 in Fig. 10b and subtracting the line from the data. The slope of the line is the net apparent timing error, which was about a 2 sec advance in the example. The detrended result is our estimate of the spectral source phase relative to the reference event. This is shown in Fig. 10c for 12/14/80. The phase-jump (discontinuities in the phase) at low frequencies in this example is probably caused by poor signal-to-noise ratio causing instability in the unwrapping algorithm. Adding 2π (a cycle) corrected this problem.

Results of calculating differential source phase spectra for six East Kazakh explosions are shown in Fig. 11. Table 4 gives the timing errors obtained from the linear trends in the corrected spectra along with differences in the epicentral distance, $\delta\Delta$, and in the backazimuth, $\delta\theta$, relative to the reference event on 10/12/80. The spectra of all events indicated that signals are "in phase" with the reference event except possibly at the extremes of the frequency band. At high frequencies ($f > 0.2$ Hz), the phase is non-zero for events with large $\delta\theta$ (e.g., 4/25/80, 9/14/80, 4/22/81), which suggests that the common-path assumption is breaking down, and phase velocities are slower on the reference path than on the path followed by signals from these events. Also note that the phase jump at about 0.14 Hz is

absent for the events with small $\delta\theta$ (e.g., 6/12/80, 3/29/81), another indication of a path effect and that the interference causing this jump is a sensitive function of event location. At low frequencies ($f < 0.1$ Hz), events on 9/14/80 and 4/22/81 show differential phases that become increasingly non-zero below 0.08 Hz and reach values of about $\pi/2$ at 0.05 Hz. The fact that these non-zero phases show up at periods near and longer than the free-period of the seismometer is suggestive that the common instrumental phase assumption is not valid due to changes of the actual instrumental parameters between the time of these events and the reference event. There is no way to check this without calibration pulses near the time these data were recorded. We did carry out sensitivity calculations to determine the size of changes required in free period and damping to produce the effect seen on these spectra. The change in free period would have to be in excess of two seconds. Furthermore, the free period would have to be longer for one event and shorter for the other. Although we cannot rule out instrumental effects, other possibilities seem more likely.

Figure 12 shows low-pass filtered seismograms for the events on 9/14/80, 10/12/80 and 4/22/81. The Rayleigh waves from the reference event display very clear dispersion with good signal-to-noise ratio (S/N) out to about 20 sec. On 4/22/81, the S/N is poorer, and correlation with 10/12/80 degrades noticeably at the longest periods. The signal on 9/14/80 shows what appears to be long period arrivals well above the noise level, but their arrival time is much too late compared to 10/12/80 for the difference in epicentral distance. Rather, it seems more likely that the signal on 9/14/80 has been subjected to interference, either due to multipathing or possibly due to multiple sources. In summary, the character of the differential phase at low

frequencies for events on 4/22/81 and 9/14/80 is probably caused by noise, in one case poor signal to ambient-noise ratio and in the other signal-generated noise.

SPECTRAL AMPLITUDES AND SEISMIC MOMENT ESTIMATES

In this section, we obtain seismic moments for the East Kazakh explosions using models of explosion sources with associated tectonic release. Of particular interest is the fact that the moment estimates in this study will provide information about the source strength for a frequency band bridging the low-frequency teleseismic surface-wave observations and the teleseismic body-wave observations. What will emerge, when various studies are completed, is a picture of the broadband moment spectrum of explosions in the hard rock environment of East Kazakh.

The instrument-corrected signals in Fig. 3 were Fourier transformed, and the resulting amplitude spectra were smoothed using a five-point running mean. The spectra were normalized for geometric spreading to a distance of 500 km. We corrected the vertical component Rayleigh-wave spectra for attenuation using the decay rate for eastern and central United States (Mitchell, 1973). These corrected Rayleigh-wave spectra are plotted in Fig. 13 for frequencies where the S/N is believed to be good. Also plotted in Fig. 13 are synthetic spectra calculated from source models discussed below.

The first source model is the spherically-symmetric explosion buried 1 km deep in the Gutenberg continental earth model. The Gutenberg earth model was chosen because of its hard-rock, thick-crust characteristics. The source-time function of Von Seggern and Blandford (1972) was used in the calculation, where K , which is inversely proportional to the rise time, was set to a value of

5 sec^{-1} and B, the overshoot, was set to a value of 2. Plausible K-values have little effect on the amplitude spectrum in the frequency range of interest in this study (Patton and Vergino, 1981). However, the overshoot parameter is important. Von Seggern and Blandford (1972) found that B-values near 2.0 satisfied the granite observations of Werth and Herbst (1963). Burdick and Helmberger (1979) found that body-wave synthetics with B-values between 2.0 and 7.0 matched observations of explosions at Novaya Zemlya. But recent arguments by Douglas and Hudson (1983) claim that the large B-values obtained by Burdick and Helmberger are in fact not required by their data. In light of the results of these studies, a B value near 2.0 is probably a good assumption.

Synthetic spectra were computed for this source model and were fit to the observed amplitude spectra for the East Kazakh explosions. As the purpose of this experiment was to estimate seismic moments, particular care was taken to fit amplitudes at the lowest frequencies. The moments obtained in this manner are listed in the first column in Table 5, and the synthetic spectra are plotted with the observed in Fig. 13. It is apparent from Fig. 13 that the observed spectra are considerably richer in high frequencies than the synthetic spectra. In the following discussion we consider another source model that may explain the frequency content in the observed spectra.

Explosions at East Kazakh exhibit significant non-isotropic source effects, such as large Love waves and reversed polarity Rayleigh waves, which indicate that the explosions trigger tectonic strain release. A dip-slip thrust mechanism appears to be consistent with many observed effects (Patton, 1980). In Fig. 14, we show the effect of a thrust tectonic-release

mechanism on the amplitude spectra as a function of F-value. Here we use F-value defined by Muller (1973):

$$F = \frac{\alpha^2}{2\beta^2} \frac{M_Q}{M_X}$$

where M_Q and M_X are seismic moments of the thrust event and explosion, respectively, and α and β are p- and s-wave velocities in the source region, respectively. The spectra are calculated based on the earthquake trigger model, where a pure dip-slip thrust earthquake with fault strike of 105° is superimposed on an explosion with a moment of 1×10^{25} (see Patton, 1980, for details of this calculation). The amplitude spectra in Fig. 14a decrease significantly at low frequencies for increasing F-values up to about 2.0 due to destructive interference between waves from the explosion and the thrust fault. The net result are spectra that appear to be richer in high frequencies. The phase spectra in Fig. 14b show that reversals appear at low frequencies for F-values slightly greater than 2.0 and step to higher frequencies as F increase. Before we apply this model to our observations, bounds must be placed on F-value and strike of the fault for explosions in this study.

Sykes and Cifuentes (1983) measured Love to Rayleigh-wave amplitude ratios (LQ/LR) at 20 sec period for many East Kazakh explosions including some in this study. The LQ/LR values for events in this study and inferred F-values are given in Table 6. North and Fitch (1984) determined fault azimuths for nine East Kazakh explosions, none of which were used in this study unfortunately. The average fault strike for their nine events was 127° with a standard deviation of about 20° . Preliminary results for the fault strike associated with the explosion on 9/14/80 based on teleseismic surface waves (Mellman, 1983; Smith et al., 1984) indicate a value near 135° .

In our source model of tectonic release, we will assume that the Urunchi Station (azimuth of 133°) lies on the strike of the fault. To see the effect of this assumption on our moment estimate, we calculated amplitude spectra varying the fault strike, and the results are shown in Fig. 15. The fault strike is changed in steps of 10° counter-clockwise from the station azimuth of 133° to an azimuth of 83° . (The results are the same for clockwise rotation.) For an F-value of 1.0 we could underestimate the explosion moment by a factor of about 1.5 if tectonic release actually occurred on a fault striking 30° (or -30°) from the assumed azimuth. From similar calculations, we find that the potential bias in the moment is much smaller at F-values near 0.5. Another interesting feature about the spectra in Fig. 15 is the change in frequency content with strike, where spectra are richer in high frequencies for station azimuths farther away from the fault strike.

Synthetic spectra were calculated for source models with different F-values and were fit to the observed spectra in the same manner as the previous experiment involving a pure-explosion model. The resulting explosion moments are listed in Table 5 for F-values as large as 2.0. Adopting the F-values inferred by Sykes and Cifuentes (1983), we find that the seismic moment, M_x , increased by 66% for the event on 9/14/80 over the moment obtained assuming a pure explosion. Likewise, moments increased for the explosions with F-values around 0.5, but only by about 20%. If we assume an F-value as large as 2.0 for the remaining events which have no F-value data, there is about a factor of two increase in the explosion moment over that for a pure explosion. Above an F-value of 2.0, the model predicts Rayleigh-wave phase reversals for this station. On the assumption that the reference event on 10/12/80 is a small F-value event, phase reversals are not supported by our observations of differential source phase.

Synthetic spectra for the tectonic release model are plotted along with the observed spectra and the synthetic spectra for a pure explosion in Fig. 13. The observed spectra for events on 10/12/80, 12/14/80 and 4/22/81 are still richer in high frequencies than the tectonic model predicts. Even the large F-value event on 9/14/80 appears to have more high frequencies than the model predicts.

There are a number of source parameters of the tectonic release model that can affect the frequency content of computed spectra. In this regard, fault strike (see Fig. 15) is a very important parameter because the radiation pattern of the tectonic source is at a minimum on the Urumchi azimuth for our choice of fault strike, and even small changes in the strike can dramatically increase the amplitude of the tectonic contaminant. For the small F-values events though, the effect of changing fault strike alone cannot account for the high frequencies.

We considered other model parameters that could significantly affect the frequency content. For example, we relaxed the assumption that the tectonic event occurred simultaneously with the explosion. Observations of time delays in reversed Rayleigh-waves for East Kazakh explosions (Rygg, 1979; Cleary, 1981) suggest the possibility of a few seconds delay in the triggering of the tectonic event. Interestingly, a two second delay will introduce a frequency-dependent phase perturbation such that low frequencies are cancelled, but frequencies above 0.12 Hz are actually enhanced by the tectonic contaminant. Synthetic spectra were computed at an F-value of 0.5 and the results are plotted in Fig. 16. For reference, we plot the spectrum of the simultaneous-release model for an F-value of 0.5 in this figure. The calculated spectra are richer in high frequencies than spectra of the

simultaneous release model. If the fault strike is rotated by 40° to 50° , it is possible to fit the observed frequency content of the low F-value explosions.

In general, our experience is that other source parameters of the tectonic release can enhance the high frequencies if the assumed fault strike is rotated by up to 40° or 50° . This suggests the possibility that tectonic release occurred on more east-west oriented faults for these low F-value explosions. We have looked for evidence in the teleseismic surface-wave data to support this. Results of several studies currently in progress (e.g., Given *et al.*, 1983; Smith *et al.*, 1984) indicate that fault strikes for these events are not much different from the strike of the 9/14/80 explosion, which is estimated to be 135° .

There are other possibilities that could explain the frequency content of the observed spectra. The first two listed below are source-related and the third is path:

- (1) more high frequencies in the explosion source (e.g., B-values greater than 2).
- (2) source medium (e.g. more high frequencies in the Green's functions).
- (3) energy focussing or amplification at the Urumchi Station; also possibly a very high effective Q for the path implying that the attenuation correction using eastern U.S. decay rate is too large.

We believe that energy focussing or amplification at the Urumchi Station is the most plausible explanation considering the large velocity contrast between basins and fold-belt terrains and that the Dzhungarian Basin (see Fig. 1) would act as an effective seismic lens between the East Kazakh test site and the Urumchi station. It is interesting to note that any of the above effects

would cause the seismic moments in Table 5 to be over-estimated. As mentioned earlier, uncertainties in the fault strike assumed in the tectonic-release model would lead to underestimation of the moment. The net result of effects causing high frequencies and of uncertainties in the fault strike should produce less systematic bias in the explosion moments estimated from these single-station recordings at Urumchi.

CONCLUSIONS

We have analyzed Chinese seismograms from eleven Asian events with special emphasis placed on the study of seven East Kazakh nuclear explosions. The data recorded at the Urumchi Station offers a unique opportunity to study the explosion sources at East Kazakh due to its proximity to the test site (about 950 km) and its azimuth being close to a minimum in the surface-wave radiation pattern of the tectonic release. The instrumentation is also well suited for recording surface waves at regional distances, although we cannot understate the full usefulness of this data had it been recorded digitally. We also recognize the limitations on our conclusions since we restricted the analysis to recordings at a single station.

The group velocity dispersion of Rayleigh waves was measured on a number of paths through central Asia and was seen to vary considerably with composition of the path. The slowest velocities are observed on paths through basins with thick sedimentary deposits such as the Dzhungarian Basin between Urumchi and the East Kazakh test site. The highest group velocities are observed on paths over fold belts where crystalline rocks reach the earth's surface. The observed dispersion curves are in excellent agreement with Soviet measurements north of the Pamirs, suggesting that these basin and fold-belt terrains are prominent seismic features of significant lateral extent in central Asia.

Epicentral distance and backazimuth were estimated for events using arrival times and particle motions of regional phases measured off a single-station three-component recording. We estimated that without calibration events the location error ellipse for the analog data recorded at Urumchi for a 1000 km path has a 250 km long major axis (azimuthal

uncertainty) and 56 km long minor axis (distance uncertainty). In addition, systematic errors due to structure affecting surface-wave paths and the velocities of phases can seriously bias location estimates. Significant reductions in both random and systematic errors could be achieved if the data were recorded digitally, thus permitting the use of other regional phases for backazimuth determinations.

We applied a differential phase method to Rayleigh waves from the East Kazakh explosions using the explosion 10/12/80 as the reference event. The method took account of possible phase errors due to mis-timing when the data were digitized. The results indicated that signals of all events are "in phase" with signals from the reference event. Non-zero differential phases at high frequencies (> 0.2 Hz) are probably caused by path effects related to changes in phase velocities (i.e., breakdown of common path assumption). Non-zero differential phases at low frequencies (< 0.1 Hz) are probably caused by ambient noise (i.e. poor S/N) in the case of the event on 4/22/81 and by interference in the case of 9/14/80.

The amplitude spectra of Rayleigh waves from the East Kazakh explosions were computed and seismic moments of the explosions were estimated based on models of the explosion source triggering tectonic release. These models incorporated independent estimates of the overshoot parameter, B , the F -value, and the fault strike. We found that observed spectra were richer in high frequencies than predicted by the model. To explain the frequency content requires more high frequencies in the source medium excitation or a path effect caused by energy focussing and/or amplification. By not accounting for these effects, our present seismic moment estimates will be biased high, whereas uncertainties in the fault strike will lead to under-estimation of the

moment. The net bias on moment estimates should be less than if any one factor were acting alone. In a separate paper, these moment estimates have been used to infer yield employing an empirical moment-yield relationship.

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Table 1: Epicentral data for events in this study.

Date	Origin Time	Latitude	Longitude	m_b	
East Kazakh explosions					
04/25/80	03:56:57.4	49.95°N	78.81°E	5.5	
06/12/80	03:26:57.5	49.94°	79.04°	5.6	
09/14/80	02:42:39.3	49.94°	78.86°	6.2	
10/12/80	03:34:14.0	49.91°	79.05°	5.9	
12/14/80	03:47:06.6	49.93°	79.00°	5.9	
03/29/81	04:03:50.0	50.01°	79.03°	5.6	
04/22/81	01:17:11.4	49.90°	78.90°	5.9	
Other events					
04/24/80	07:59:38.1	37.82°	99.40°	4.7	
04/26/80	03:22:32.3	43.26°	104.38°	4.6	
10/16/80	04:30:28.9	41.04°	89.99°	4.4	(ISC)
03/29/81	19:21:15.0	38.16°	79.19°	4.8	

Table 2: Epicentral distances calculated from differential arrival times of regional phases

Event	Arrival Times(GMT)		δT sec	Δ km	$\delta \Delta$ km
	P_n	L_g			
04/25/80	03:58:31	04:00:59	148	921	38
06/12/80	03:28:27	03:30:55	148	921	26
10/12/80	03:35:49	03:38:14	145	902	42
12/14/80	03:49:22	03:51:52	150	933	15
04/22/81	01:19:19	01:21:44	145	902	49

Table 3: Backazimuths (BAZ) calculated from Rayleigh-wave particle motion.

BAZ in degrees clockwise from North				
Event	Estimated	Actual	δ BAZ	δd , km
04/25/80	325.6	318.3	7.3	121
06/12/80	317.7	319.0	-1.3	22
10/12/80	314.5	318.9	-4.4	73
12/14/80	322.8	318.8	4.0	66
04/22/81	332.2	318.4	13.8	228
04/24/80	140.2	120.1	20.1	417
04/26/80	66.7	86.9	-20.2	475
10/16/80	159.2	147.8	11.4	72

Table 4: Apparent timing errors in seconds and differences in epicentral distance and backazimuth relative to event on 10/12/80

Date	$\delta\tau$ (+ : delay)	$\delta\Delta x$, km	$\delta\theta$, deg.
04/25/80	-1.87	15	-0.7
06/12/80	0.2	2	0
09/14/80	0.97	12	-1.0
12/14/80	-2.03	4	-0.5
03/28/81	-1.8	8	0.1
04/22/81	-1.97	7	-0.9

Table 5: Explosion seismic moments, M_x , (in units of $\times 10^{23}$ dyn-cm) for a pure explosion and for plausible F-values

Date	Pure explosion	F-value			
		0.5	1.0	1.5	2.0
04/25/80	0.15	0.15	0.19	0.23	0.3
06/12/80	0.4	0.5	0.5	0.65	0.8
09/14/80	1.6	1.9	2.2	2.7*	3.2
10/12/80	1.6	1.9*	2.2	2.7	3.2
12/14/80	1.3	1.5*	1.7	2.2	2.8
03/29/81	0.3	0.35	0.4	0.5	0.6
04/22/81	1.6	2.0*	2.2	2.8	3.2

*Preferred values based on F-values deduced from LQ/LR observations.

Table 6: Love-to-Rayleigh wave ratios, LQ/LR, and equivalent F-values* from study of Sykes and Cifuentes (1983)

Date	LQ/LR	F
09/14/80	0.83	1.25
10/12/80	0.22	0.3
12/14/80	0.35	0.4
04/22/81	0.34	0.4

*F-values are inferred from an empirical relationship between measured LQ/LR ratio and F-value obtained from independent studies (e.g., North and Fitch, 1984).

FIGURE CAPTIONS

- Figure 1. Map of central Asia showing locations of test sites (solid squares), events (solid circles) and the Urumchi station, WMQ (triangle). The base map is reproduced from Figure 17 of *Tapponnier and Molnar (1979)*. Bold lines indicate major active faults, and dashed lines are ancient and less certain faults. Thin dashed lines indicate regions of intense late Cenozoic crustal shortening.
- Figure 2. Digitized seismograms for events in this study recorded on the Urumchi seismographic station. Three panels show motions on the vertical (top), north (middle) and east (bottom) components. Amplitudes are in centimeters.
- Figure 3. Rotated and instrument-corrected waveforms for the events in this study. Amplitudes are in centimeters.
- Figure 4. Comparison of initial and final phase-matched filters with observed seismogram for the Lop Nor explosion. The initial filter is calculated using the dispersion curve obtained by *Chun and Yoshi (1977)*.
- Figure 5. Auto-correlogram of the final phase-matched filter and cross-correlogram with the Lop Nor seismogram.

Figure 6. Results of narrow-band filtering the cross-correlogram shown in the previous figure. See text for details of the filter.

Figure 7. Observed group velocity dispersion of Rayleigh waves (a) and Love waves (b). Rayleigh wave dispersion curve from earthquake of 4/24/80 is shown by diamonds, from Lop Nor explosion by squares, from East Kazakh explosions by triangles, and from earthquake of 3/29/81 by circles. Love wave dispersion curve is for earthquake of 4/26/80.

Figure 8. Comparison of observed Rayleigh wave dispersion curves with previously reported curves for the Tibetan Plateau (Chun and Yoshi, 1977, circles; Chen and Molnar, 1975, diamonds) and for Central Asia northeast of the Pamirs (Arkhangel'skaya and Kuznetsova, 1969; mountainous regions, inverted triangles and basins, X's). Observations from this study are shown by pluses, stars, and squares for East Kazakh, Lop Nor, and the earthquake of 4/24/80, respectively.

Figure 9. Cross-correlations for backazimuth estimation. Three panels show auto-correlation of vertical component (top), cross-correlation of vertical with north-south component (middle), and cross-correlation of vertical with east-west component (bottom). This example is for the event on 12/14/80.

Figure 10. (a) Equalized, differential phase spectrum for the explosion on 12/14/80. This phase corresponds to $\delta\phi$ in cycles. (b) Distance-corrected differential phase spectrum. A straight line through the origin is fit to this spectrum and the slope of this line is an estimate of $\delta\tau$, the net differential timing error (see text). In this case, the estimate of $\delta\tau$ was about a 2 sec advance. (c) Detrended differential phase spectrum. A value of zero implies that the source phase of Rayleigh waves from the 12/14/80 explosion is identical to the source phase of Rayleigh waves from the reference explosion. Unity (i.e. 2π) was added to the phase values at low frequencies (see text).

Figure 11. Differential phase spectra for all six explosions.

Figure 12. Low-pass filtered vertical component seismograms for explosions on 9/14/80 (top), on 10/12/80 (middle), and on 4/22/81 (bottom). Corner frequency of the low-pass, 3-pole Butterworth filter (2 passes) is 0.08 Hz.

Figure 13. Amplitude spectra of Rayleigh waves from the seven East Kazakh explosions and synthetic spectra for the models described in the text. Observed spectrum is shown by solid line and synthetic spectra are shown by short-dashed and long-dashed lines for pure-explosion and explosion with associated tectonic release, respectively.

Figure 14. (a) Synthetic amplitude spectra and (b) phase spectra for Rayleigh waves as a function of F-value. The thrust fault has a strike of 105° east of North, and the spectra are calculated for a station azimuth of 133° . The explosion moment is 1×10^{25} dyn-cm. F-values range from 1.0 to 4.0 with a step of 0.5. Notice that reversals of the Rayleigh wave phase occur at higher and higher frequencies as F-value increase and that reversals occur in the frequency band of interests for F-values greater than 2.0.

Figure 15. Synthetic amplitude spectra of Rayleigh waves as a function of fault strike. Here the F-value is fixed at 1.0 and fault strike is stepped in increments of 10° from the station azimuth to 50° off the station azimuth.

Figure 16. Synthetic amplitude spectra of Rayleigh waves for a source model having a 2.0 sec delay between the detonation of the explosion and the release of tectonic strain. Spectra for an F-value of 0.5 at selected fault strikes are shown for comparison with the spectrum of the simultaneous release model for an F-value of 0.5. Spectra labeled B, C, and D are computed for fault strikes of 10° , 30° , and 50° from the station azimuth, respectively.

A STUDY OF EAST KAZAKH EXPLOSIONS AND
PROPAGATION IN CENTRAL ASIA USING
REGIONAL CHINESE SEISMOGRAMS*

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ABSTRACT

We have analyzed seismograms recorded at the Urumchi Station in northwestern China from eleven Asian events including seven presumed East Kazakh nuclear explosions. Group velocity dispersion curves of Rayleigh waves were measured at short periods on paths through basin and fold belt terrains. At 10 sec period, the velocities on paths over sedimentary basins are 25% slower than velocities on paths over fold belts. We interpret these differences in velocities to be due to the great thicknesses of sedimentary deposits in basin terrains. Epicentral locations were estimated using differential travel times between P_n and L_g and particle motions of Rayleigh waves measured on a single three-component record. For a 1000 km path, the location errors (one standard deviation) are about ± 125 km in azimuth and ± 30 km in distance. In addition, systematic errors due to structural effects on surface-wave paths and on velocities of regional phases are shown to seriously bias location estimates of several events. We applied a differential phase method to Rayleigh waves from the East Kazakh explosions and found that signals of all events are "in-phase" with signals from the reference event on 10/12/80. Thus, there is no evidence for phase reversals or shifts at the Urumchi station in the frequency band where signal to noise ratio is good and where assumptions of the method are valid. Seismic moments of explosions were estimated using models of explosion sources with associated tectonic release. *Observed amplitude spectra of Rayleigh waves were richer in high frequencies than predicted by the model. This could be a source effect related to source medium excitation (i.e., Green's functions) or a path effect caused by energy focussing and/or amplifications. We discuss the potential bias in the estimates of moment due to assumptions/limitations.*

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Figure 1

Figure 2

Figure 2
(con't.)

Figure 2
(con't.)

Figure 2
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Figure 2
(con't.)

Figure 3

Figure 3
(con't.)

Figure 3
(con't.)

Figure 3
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Figure 3
(con't.)

Figure 4

Figure 5

Fig.

Figure 7

Comparison with Other Regions

Figure 8

CROSS-CORRELATIONS FOR BACKAZIMUTH ESTIMATION...12-14/80

Figure 9

Figure 10

Figure 11

LOW-PASS FILTERED SIGNALS FOR 9/14/80, 10/12/80 AND 4/22/81

Figure 12

Figure 13

Figure 13
(con't.)

Figure 13
(con't.)

Figure 13
(con't.)

Figure 14

SYNTHETIC RAYLEIGH-WAVE SPECTRA AS A FUNCTION OF FAULT STRIKE

Figure 15

Figure 16