The Effects of Major Structural Features in Western China on Explosion Seismograms

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Abstract

Synthetic explosion seismograms have been calculated on paths from Lop Nor to the NIL station in northern Pakistan, from NIL to Lop Nor, and from Lop Nor to the TLY station in the Baikal Rift. Computational studies were done of the influence on the character of the seismograms of major structural features such as sedimentary basins, topography associated with the Himalayas and the Tibetan Plateau, roughness of the Moho, and the presence of a deep Moho depression under the Tibetan Plateau. The simulations were done with a 1-Hz Kelly wave source and 500-m resolution. Uniform elastic constants and frequency-independent quality factors, $Q_P$ and $Q_S$, were used in each of three materials: basin sediments, crust, and mantle. The deep basins which straddle both paths were found to have the dominant influence due to the generation of large-amplitude Rayleigh waves at the transition from crustal material to basin sediment at the source-ward basin edges. In simulations done with the effects of anelastic attenuation included, the amplitude of the Rayleigh-wave train was reduced to insignificance during passage across the 800-km-wide Tarim Basin on the Lop Nor -> NIL path but not on the 200-km path across the basin that straddles the Lop Nor -> TLY path.

Introduction

In simple geologic settings, seismograms recorded at regional distance from earthquakes and from explosions exhibit significant differences in character. Explosive sources produce strong, early arrivals of compressive-wave energy while earthquake sources produce primarily strong, later-time arrivals of shear-wave energy. For simple settings, the gross features of a recorded seismogram can be used to characterize the source.

In complex geologic settings, seismic waves traversing regional paths from the source to the seismic station are modified by interactions with the free surface and with geologic structures such as low-velocity basins and the crust/mantle interface. Multiple reflections and interconversions of compressive and shear wave energy can change even the gross features of the recorded seismograms and complicate the source characterization process.
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Generally, the best guide to source characterization is a qualitative and/or quantitative comparison between seismograms from a source being analyzed and seismograms recorded with the same instruments for sources of known types that previously occurred at approximately the same location as the uncharacterized source. Necessarily, the seismograms from the uncharacterized source and the known sources will contain similar path effects and, to the extent that the known earthquake and explosion seismograms show differences, judgements about the character of the unknown source can be made.

If suitable comparison seismograms are not available, numerical simulations can be used to (1) identify the structural features along the source-receiver paths that are most likely to produce significant signal modifications, (2) identify similar paths for which suitable comparison spectra are available and/or (3) produce synthetic seismograms for use in the characterization process. Toward these ends, we present the results of a parametric study of the effects of major structural features on seismic waves in Western China.

In a prior study (App, Bos, and Kamm 1996), we discussed variations in waveforms recorded for a 15 May 1995 explosion at Lop Nor and for a 2 May 1995 earthquake that occurred about 400 km northwest of Lop Nor. Generally, there were pronounced variations in the character of the waveforms from station to station and, in the previous study, we were able to reproduce the general character of most of the waveforms with finite-difference, elastic-wave-propagation simulations appropriate to each of the paths.

Of particular interest were the recorded and simulated waveforms for the paths from Lop Nor to the seismic stations at NIL in Pakistan and TLY in the Baikal Rift. These two station are separated by about 180 degrees in azimuth and, in a simple geologic setting would show similar seismograms for any centrally-located source. However, as can be seen in bottom part of Figure 1, the explosion seismograms recorded at the two stations show significant differences. In particular, TLY shows a much reduced ratio of P-wave to S-wave amplitudes.

The geologic structure along each of the paths is shown in the top part of Figure 1 and was extracted from the Cornell Middle East/North Africa Project's on-line Profile Maker (Barazangi et al 1996). In both cases, Lop Nor is 50 km from the left edge. Along the Lop Nor -> NIL path, the major features are the Tarim Basin, an undulating Moho surface at roughly 50-km depth, the Tibetan Plateau, the Himalayas, and, a depression in the Moho beneath the Plateau. Along the Lop Nor -> TLY path, the major features are an undulating Moho and two relatively small basins. Readers should note that
the Lop Nor -> NIL topographic features shown in Figure 1
where not used in simulations reported in the prior study.

In this paper, we examine the effects on simulated waveforms
of the various structural features along the two paths. The
simulations used in this study were performed with the
elastic wave propagation code, AFD (Kamm, Bos, and Jones
1996), which was also used in the prior study. The
simulations were all performed in planar, x-z geometry.
Approximate values of the elastic constants (Warren 1996)
were assigned to each of three homogeneous materials which
were picked to represent (1) basin sediments, (2) the crust,
and (3) the mantle. The chosen densities were 2.8, 2.8, and
3.3 g/cm³, respectively, while the P-wave speeds were 5.6,
6.1, and 8.2 km/s and the S-wave speeds were 2.5, 3.5 and 4.7
km/s. Some of the simulations included the effects of
anelastic attenuation and the chosen values of the frequency-
independent compressive quality factors, Q_p, were 200, 500,
and 1000 for compressive waves in the basin sediment, crust,
and mantle, respectively, while the shear quality factors, Q_s,
were 53, 219, and 439 (Minster 1979). The anelastic
description used in AFD is based on the method of Emmrich and

Each of the calculations was performed on a 1700 km by 150 km
mesh with 500-m cells. In each of the simulations, a 1-Hz,
explosive, Kelly-wave source (Kelly et al 1976) was placed 50
km from the left lateral boundary at a depth of 10 km below
the free surface. Although this burial depth is far greater
than that of any plausible nuclear test, it avoids numerical
problems that can result when there are too few cells between
the source and the surface. Each of the simulations was run
to 600 seconds and vertical-velocity seismograms were
calculated at the free-surface at range intervals from the
left boundary of 150 kilometers. The seismograms presented
below were bandpass filtered between 0.1 and 1.0 Hz. The
low-frequency cutoff eliminates numerical resonances due to
the finite size of the mesh and the high-frequency cutoff
eliminates numerical noise produced by 500m cells.

Readers should note that the simulations were designed
for the study of the relative influences of the various
structural features and do not capture more than the general
character of seismograms recorded for real events. Limiting
assumptions include: (1) use of simplified cross-sections;
(2) source placement at 10 kilometers depth instead of a more
plausible 1 to 2 km; (3) use of Cartesian (x-z) geometry
which ignores the effects of geometric spreading; (4) neglect
of the effects of attenuation in some of the simulations; and
(5) use of 0.5 km cells, which provide only marginally
adequate resolution for a 1-Hz source. In general, these
simplifications were adopted so that simulations could be
carried out to 1700 kilometers in no more than 36 hours of CPU time on an HP workstation.

Single-Feature Simulations

Figure 2 shows synthetic seismograms for a set of simulations which each included one of the major structural features characteristic of the Lop Nor to NIL path. The seismograms were calculated at a range of 1350 km from the left boundary and 1300 km from the source. The following summaries highlight only the dominant features in the synthetic seismograms calculated at 1350-km range. A more detailed discussion of these features is presented in a later section.

The Flat Moho simulation (top) had a 48-km crust overlying a flat Moho and, therefore, was the simplest possible case other than a homogeneous half space. The first arrival at 1350-km range is a compressive head wave (Pn), which travels primarily in the mantle and arrives at about 170 seconds. The next arrival is the direct compressive wave (Pg) traveling in the crust. This is followed by a series of signals produced by reflections at the Moho and at the free surface with attendant P -> S conversions. The last notable arrival is a low-amplitude Rayleigh wave which is produced at the source as a result of interactions with the free-surface (see, for example, App, Jones and Bos 1997). The Rayleigh wave arrives at 1350 km at about 400 seconds.

The Rough Moho simulation (second panel) had a roughened Moho. The left half of the Moho profile was taken from the Lop Nor -> NIL path while the right half of the profile was adapted from the Lop Nor -> TLY path. As can be seen in the synthetic seismogram calculated at 1350-km range, the roughened Moho disrupted the regular pattern of reflections that dominated the Flat Moho seismogram. The roughened Moho also enhanced P -> S conversion and, consequently, produced relatively large S-wave amplitudes at 1350-km range at times between 320 and 430 seconds.

The Moho Depression simulation (third panel) incorporated the full Lop Nor -> NIL Moho profile. The main difference from the Rough Moho case was the large amplitude signal which arrives at 1350-km range just after 280 seconds and, in addition, a train of reverberations which follows. Examination of seismograms calculated at other ranges (not shown) indicated that the depression-related signals occurred intermittently.

The Tarim Basin simulation (fourth panel) showed a very different seismic character, due primarily to P -> S conversions and, as well, the creation of Rayleigh waves at the source-ward edge of the basin. The dominant feature in
the seismogram at 1350-km range was the Rayleigh-wave train which arrived just after 480 seconds. In higher-resolution simulations (not shown) that covered a portion of the path, the Rayleigh waves in the basin had a period of 2 seconds and a wavelength of about 5 km. As was expected from standard analysis of Rayleigh waves (for example, Kolsky 1963), the vertical extent of the Rayleigh waves was about one-quarter wavelength, or about 1.25 km. Surprisingly, the Rayleigh wave amplitudes were not altered significantly by the change in resolution.

The Topography simulation (not shown) was dominated by a Rayleigh wave that was generated by interactions of the source signal with near-source topographic features. Because these features were poorly resolved with 500-m cells, an auxiliary run (also not shown) was made with 200-m cells and the main result was a reduction in the Rayleigh-wave amplitude to a level well below that of the basin-related Rayleigh waves. The results of these simulations led us to conclude that, although topographic signals probably will be present in well-resolved simulations of seismic waves traversing the Lop Nor -> NIL path, they will not be as important as the basin-related signals. A definitive assessment of the role of topography will require simulations run at adequate resolution over the entire path and that is beyond our present capability. In the following models, topography is not included, in part to simplify a comparison of runs made with and without anelastic attenuation.

All-Feature Lop Nor -> NIL Simulation

The top portion of Figure 3 shows synthetic seismograms calculated at 150-km intervals in a simulation which incorporated all of the Lop Nor -> NIL structural features other than topography. The major features in the seismogram at 1650-km range are labeled. These are the compressive mantle head wave (Pn), the compressive crustal wave (Pg), a shear-wave packet (S1 to S2) and the basin-related Rayleigh wave (R). As can be deduced from the successive seismograms, the labeled shear-wave packet originates at the basin edge between ranges 900-km and 1050-km.

The bottom portion of Figure 3 shows synthetic seismograms for a simulation done with the same Lop Nor -> NIL structure but with the effects of anelastic attenuation included. Readers should note that, in order to accommodate the effects of attenuation, the vertical scale used in the plots was changed more frequently in this series of seismograms than in the series shown in the upper panels of the figure. As mentioned previously, the quality factors, Q, were adapted from Minster (1979). The adopted values for compressive waves (Qp) were 200, 500, and 1000 for the basin sediments, the crust, and the mantle, respectively. Corresponding values
for shear waves ($Q_s$) were 53, 219, and 439. The most important effect of attenuation in the Lop Nor -> NIL case was the near-total elimination of the basin-related Rayleigh wave due to the low value of $Q_s$ in the basin. In essence, although the transition from crustal material to basin sediments at the source-ward edge of the basin was effective in producing Rayleigh waves, the long traverse across the basin was equally effective in attenuating them. Note the near equality of the $Pn$, $Pg$, and $S1/S2$ amplitudes at 1650-km range.

**All-Feature NIL -> Lop Nor Simulations**

The upper portion of Figure 4 shows a series of synthetic seismograms calculated along the NIL -> Lop Nor path for a hypothetical explosion at NIL. The simulation included the effects of all of the structures along the path - including topography - but not that of anelastic attenuation. The source was placed 50 km from the right lateral boundary of the mesh. In the left panel of Figure 4, one of the major features is a Rayleigh wave which originates in the small basin shown at 1600-km range in the upper left panel in Figure 1. In the right panel of Figure 4, the feature labeled "S" is at 50-km range is a shear wave - or possibly a Rayleigh wave - which originates at the source-ward edge of the Tarim basin at the 1000-km range. As with the Lop Nor -> NIL simulations, we anticipated that the Rayleigh wave amplitudes would be greatly reduced during passage across the Tarim Basin.

**Lop Nor -> TLY Simulations**

As mentioned previously and as shown in Figure 1, data recorded at the TLY station in the Baikal Rift for the May 1995 Lop Nor explosion was dominated by a very large amplitude S-wave arrival at about 480 seconds. The explosion simulation done by App, Bos, and Kamm (1996) showed similar behavior. The upper portion of Figure 5 shows a series of synthetic seismograms calculated in a Lop Nor simulation that did not include anelastic attenuation. The dominant feature at all ranges is a Rayleigh wave which arrives at 1650-km range at about 500 seconds. The bottom portion of Figure 5 shows the results of a similar simulation that included anelastic attenuation. Here, although the ratio of the Rayleigh wave amplitude to the $Pg$ amplitude is reduced from about 16/1 to about 7/1 at 1650-km range, the Rayleigh wave is still dominant. The main reason for this is the small lateral extent of the main basin, which is deep enough to generate Rayleigh waves but not wide enough to significantly attenuate them.

**Summary and Conclusions**
In numerical simulations of seismic wave propagation along the paths from Lop Nor to the NIL and TLY seismic stations, we find that large amplitude Rayleigh waves are produced as seismic energy passes from crustal materials into the basin sediments. These Rayleigh waves are the dominant features in seismograms calculated without the effects of anelastic attenuation. When anelastic attenuation is included, a wide basin such as the Tarim Basin, which straddles more than 800 km of the Lop Nor -> NIL path, can reduce the Rayleigh wave amplitudes to insignificant levels. A narrower basin, such as the 200-km-wide basin which straddles the Lop Nor -> TLY path, can produce high amplitude Rayleigh waves, but the path length through highly-attenuating material is too short to reduce the Rayleigh wave amplitudes significantly. Clearly, a resolution of 0.5 km is barely adequate for the simulation of 1-Hz Kelly wave sources on these paths and a resolution of 0.1 to 0.2 km would be much more desirable.

One significant result of this study is that the important structural features which control the character of seismograms recorded at regional distances seem to be the near surface features. Because it should be possible to secure data on the distribution of sedimentary basins and to estimate elastic constants and quality factors for those basins, it appears likely that there will be no major impediments to the production of qualitatively accurate, synthetic explosion seismograms for use in the characterization of sources for the CTBT program.

References


Figure 1 - Comparison of data and simulations for May 1995 earthquake and explosion in western China. The top panel shows the assumed structure along the Lop Nor -> NIL path (top left) and the Lop Nor -> TLY path (top right). In each case, Lop Nor is 50 km from the left boundary. The bottom panels show data and synthetic seismograms at NIL (lower left) and TLY (lower right). Adapted from App, Bos, and Kamm (1996).
Figure 2 - Synthetic vertical velocity seismograms for simulations with a single structural feature: a Flat Moho at 48-km depth (top panel), a Rough Moho with an average depth of about 48 km (second panel), the full Lop Nor -> NIL Moho profile including the depression underlying the Tibetan Plateau (third panel), the Tarim Basin (fourth panel), and the full Lop Nor -> NIL topographic profile. All the sources were placed at 10-km depth.
Figure 3 - Synthetic vertical velocity seismograms for simulations including all the Lop Nor -> NIL structural features except topography. The top two frames show results for a run done without anelastic attenuation. The bottom two frames show results from a run done with anelastic attenuation and frequency-independant quality factors discussed in the text. Note the changes in vertical scale between and within the various panels.
Figure 4 - Synthetic seismograms along the NIL -> Lop Nor path for a hypothetical explosion in Pakistan. The structure used in this simulation is the one shown at the upper left in Figure 1. The only difference between this run and the one shown in upper panels of Figure 3 was placement of the source 50 km in from the right boundary.
Figure 5 - Synthetic seismograms for a simulation on the Lop Nor -> TLY path. The top panels show a run made without anelastic attenuation. The dominant signal is a Rayleigh wave which originates at the sourceward edge of the near-source basin. The lower panels show a run made with attenuation.