Contrasts in regional seismic wave propagation to station WMQ in central Asia

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SUMMARY
The varying character of regional seismic phase propagation in central Asia is well illustrated by the character of the seismograms at the Urumqi station (WMQ) in Xinjiang, China. Three different classes of behaviour are seen for propagation across the relatively stable platforms to the north, along the Tien Shan chain and across the Tarim basin from Tibet. These paths demonstrate the influences of the variation in crustal structure on the regional phases particularly the Tibetan plateau and its north and south boundaries, but also the influence of the Pamirs on propagation along the Tien Shan. As an interference phase, $L_g$ is sensitive to changes in crustal structure and can be used to study crustal heterogeneity. $L_g$ can propagate along the Tien Shan chain trapped by the gradients in structure on either side, but with a progressive loss in amplitude and frequency. However, once the northern boundary of Tibet is crossed the high frequencies in the $L_g$ train are lost and there is little recognizable arrival. The amplitude ratios of the different crustal phases $P_n$, $S_n$ and $L_g$ can be used to characterize the behaviour and the different classes of propagation can be further separated when account is made of the frequency content in the $L_g$ window. The influence of the transitions in crustal structure at the northern edge of the Tibetan plateau on propagation to WMQ is investigated using numerical modelling with the pseudospectral method for models of crustal variations, this demonstrates how the crustal pinch at the northern boundary operates to modify the fairly efficient propagation inside Tibet with substantial transfer of energy into the mantle.

Key words: Lg blockage, numerical modelling, pseudospectral method, regional seismic phases, Tibet, Tien Shan.

1 INTRODUCTION
The Urumqi station (WMQ), located in the XinJiang province of northwestern China, central Asia, is one of the stations in the China Digital Seismic Network (CDSN). It lies in an area with complex and heterogeneous crustal structure and with rapid changes in topography over the regional distance range (Fig. 1). To the south of the station, the relatively stable block of the Tarim Basin lies between Tibet in the south and the Tien Shan. The Tibetan plateau is the largest region of elevated topography and thickened crust on earth with an average elevation of 5000 m accompanied by a near doubling of the normal crustal thickness to around 70 km. The Tien Shan range is a major tectonic mountain system, extending in a northeast trending arc about 200 km long across Kyrgyzstan and Xinjiang. The almost quadrilateral Pamir Plateau lies to the southwest of the Tien Shan and marks the southern boundary of Central Asia. In contrast the area to the north of the station has a relatively simple tectonic setting. Here lies the Junggar basin with the Altai Mountains along its northern border.

Crustal thickness varies dramatically in Central Asia; based on analysis of gravity data it has been estimated that the crustal thickness decreases to about 45 km in the middle of the Tarim basin, increasing to about 52 km in the Tien Shan and 70 km in the Tibetan Plateau. In addition, most of central Asia is a region of high seismicity and tectonic activity whereas the Tarim Basin is unusually aseismic. The complex structure around the Urumqi station WMQ provides a good opportunity to look at the way in which the properties of regional seismic phases are modified by different classes of structure.

Regional seismic phases carry a wealth of information about structural variations in the crust and the upper-mantle (see, e.g. Kennett 2002). Differences in travel times, amplitudes and frequency content of regional phases have proven to be very useful in characterizing such variations (Molnar & Oliver 1969; Ruzaikan et al. 1977; Ni & Barazangi 1983). Among the regional seismic phases, $P_n$ is the first arrival and represents energy returned from the uppermost mantle with a phase velocity about 7.9 km s$^{-1}$. Like $P_n$, $S_n$ also

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The crustally trapped phase $Lg$ is the most prominent in the regional wavefield, and is characterized by a group velocity close to 3.5 km s$^{-1}$. $Lg$ can be regarded either as a superposition of higher-mode surface waves (Oliver & Ewing 1957; Mitchell 1995) or as interference between multiply reflected $S$ waves from the free surface, crust-mantle boundary and any internal boundaries (Gutenberg 1955; Kennett 1985). The nature of $Lg$ as an interference phenomenon indicates that the character of the wave train can be modified significantly by changes in relative timing of the different contributions (Furumura & Kennett 2001). $Lg$ is sensitive to variations in crustal thickness and crustal wave speed structures. There are many observations that the amplitudes of $Lg$ are weakened by the influence of structural boundaries (e.g. Kennett 1986) or attenuation (e.g. Ruzaikan et al. 1977) along the propagation path and $Lg$ can be even completely blocked in some circumstances, such as a continent-oceanic transition zone, where as little as 100 km of oceanic path is sufficient to block the transmission of the $Lg$ wave (Press & Ewing 1952; Zhang & Lay 1995). $Lg$ typically has a similar amplitude on both the vertical and tangential components, whereas $Pn$ is clearer on the vertical component and $Sn$ is clearer on the transverse component.

The strong variations in the nature of regional phase propagation across central Asia have been the focus of a number of studies of the influence of crustal structure and tectonic environment on the nature of the seismic wavefield. In particular, attention has been focussed on the behaviour of $Lg$ and $Sn$ in order to map structural variations and heterogeneities in central Asia, especially in Tibet. Previous results (Ruzaikan et al. 1977; Ni & Barazangi 1983) have illustrated that $Lg$ often propagates inefficiently for paths crossing the Tien Shan range. $Lg$ is generally weak or absent for paths crossing the edges of the Tibetan plateau. Using a ray simulation method (Kennett 1986), Bostock & Kennett (1990) have studied the effect of 3-D structure on $Lg$ propagation patterns in central Asia. Their results based on the constructive interference of multiple reflections in a heterogeneous crustal model give a visual measure of the interaction of guided wave trains with variations in crustal structure. The behaviour of the $Lg$ phase predicted from the model compares well with many of the observations. It has been observed (Ni & Barazangi 1983) and confirmed (McNamara et al. 1995) that $Sn$ is severely attenuated for paths that cross the north central portion of Tibet Plateau and is strongly dependent on frequency. In analysis of data recorded by seismometers on the Tibet Plateau from events located both within the Tibet and outside Tibet, McNamara et al. (1996) noted that $Lg$ can propagate within Tibet with strong attenuation, but is dramatically cut-off by the north and south boundaries of Tibet.

In this study, we illustrate the behaviour of regional seismic wave propagation, covering the distance range from 500 to 2000 km, by events with three different classes of propagation path to WMQ. The groups of events contrast propagation in the stable continental platform (class A) with waves propagating along the Tien Shan range (class B) and propagation across a continent-oceanic transition zone, where as little as 100 km of transverse component.

Figure 1. Map of the major features of central Asia showing the locations of the events and the position of the WMQ station. The 73 events in the three classes are indicated together with the relative strength of the arrivals in the $Lg$ and $Sn$ windows. Events for which $Lg$ is strong are indicated with an open circle, when $Lg$ is weaker than $Sn$ an open diamond is used, and when $Lg$ is absent a solid triangle is plotted.
mountain range (class B) and events from the south which cross the Tarim basin and include events within the Tibetan plateau (class C). For each class of path we present record sections of seismograms recorded at WMQ, and examine the attenuation behaviour through the amplitude ratios \( Lg/Pn \), \( Lg/Sn \) and \( Sn/Pn \) and the frequency content of the regional phases using the adaptive scheme of Tong (1995). The combination of amplitude and frequency information helps to provide a clear distinction between the propagation characteristics of the three different classes of events. The blockage of \( Lg \) at the northern boundary of Tibet is not abrupt. With the profile of events recorded at WMQ we are able to see the evolution of the regional waves and compare these with numerical modelling of propagation through a 2-D model of the structure across the Tarim Basin and Tibetan Plateau.

2 DATA

The Urumqi station, WMQ, is a three-component, broad-band station with a sampling ratio of 40 samples per second. Events with a reported focal depth less than 35 km and good signal-to-noise ratio for regional phases have been extracted from the IRIS Data Management Center in Seattle for the period 1988–2000. All of the 73 events have \( m_r \) greater than 4.5 and lie in the epicentral range from 500–2000 km from WMQ.

The data have been divided into three groups. Class A comprises 27 events distributed across the tectonically stable region to the north of the WMQ station. The second class (Class B) comprises 25 events along the south branch of the Tien Shan mountain range so that propagation occurs along the range; beyond about 14\(^\circ\), the seismic waves also travel through the Pamir Plateau. Class C includes 24 events with azimuth of about 160\(^\circ\) extending across Tibet through the Tarim basin, and the Kun Lun range approximately orthogonal to the main changes in crustal thickness.

The seismic waves in the three classes propagate through very different tectonic environments, thus class A travel through simple structure from the north to WMQ, class B along the strike of Tien Shan mountain to WMQ and class C across the Tibetan plateau to WMQ. In Fig. 2 we show three representative sets of seismograms for each of this classes of paths at a similar epicentral distance. On each of the rotated three-component sets we have marked the time windows associated with the main regional phases: \( Pn, Sn \) and \( Lg \) derived from the \textit{ak135} reference model (Kennett \textit{et al.} 1995). Fig. 2 illustrates the variations in the frequency content and amplitude of the \( Lg \) wave train, as well as the variations in \( Sn \) with the nature of the propagation path. Characteristic high-frequency \( Lg \) is clearly seen on the path from the north, and a somewhat lower frequency arrival \( Lg \) for the class B event propagating along the Tien Shan. However the energy from the event in the Tibetan plateau (C) is dominated by fundamental surface waves with almost no indication of a coherent \( Lg \) arrival.

3 THE CONTRASTS IN REGIONAL SEISMIC WAVE PROPAGATION

The vertical-component record sections in Figs 3, 4 and 5 provide a useful insight into the nature of the regional wave for the three classes of propagation paths. The epicentral distance of the events lies between 5 and 18\(^\circ\).

Fig. 3 show seismograms from Class A events propagating along the simplest paths across the area to the north of WMQ. The regional wave trains are rich in high frequencies and \( Lg \) is the most prominent phase which sustains considerable amplitude out to 17\(^\circ\) epicentral distance. The dominance of \( Lg \) reflects the typical propagation pattern of regional phases across stable continental regions. For epicentral distance in the range 10–14\(^\circ\), the mantle arrivals \( Pn \)

![Figure 2](https://example.com/figure2.png)

Figure 2. Representative seismograms (ground velocity) recorded at WMQ from paths from the three event clusters A, B, C at a similar distance. Each set of 3-component traces is normalized to the total energy content on the seismograms and no filtering is applied.
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Figure 3. Vertical component seismograms (unfiltered ground velocity) for regional wave propagation to WMQ generated by events in class A to the north of the station.

and $Sn$ are relatively weak compared with $Lg$. However, the amplitude of the $P$ and $S$ arrivals increases noticeably with the returns from the upper-mantle transition zone which arrive beyond 14°, on the last 4 traces. The weakness of $Sn$ for paths across the Mongolian plateau has been noted by Rapine et al. (1997).

The events in class B displayed in Fig. 4 propagate along the strike of the Tien Shan range where the axial crustal thickness of 52 km is significantly thicker than either the northern area or the surroundings of the range. For these class B events the mantle phases $Pn$ and $Sn$ are clearly visible over most of the profile and again increase in amplitude once the influence of the upper-mantle transition zone is felt on the furthest traces. For distances to WMQ less than 14°, the $Lg$ phase is well developed with large amplitudes but at a lower frequency and more elongated wave train than in class A (Fig. 4a). As the distance increases, both the frequency and the amplitude drop somewhat; the $Lg$ wave is trapped within the mountain range by the strong gradients in crustal properties at each side but there is some leakage from the wave duct. Once the distance increases beyond 10°, there is an indication of the development of fundamental Rayleigh waves.

However, from 14–16° there is a distinct change in the $S$ arrivals. Two pulses with strong amplitude and somewhat lower frequency arrive with a group velocity around 3.3 km s$^{-1}$, and are even more prominent on the tangential component. Fig. 4(b) shows the 3-component seismograms for these distances which are dominated by the strong pulses. This feature of the $S$ wave train appears to be associated with the influence of the Pamir plateau; since the events displaying these pulses lie on the further side of the Pamir from WMQ. Thus the waves have to traverse the Pamir first and then travel along the Tien Shan range in their passage to the WMQ station. The Pamir plateau appears to work as a kind of coupling regulator producing a distinctive sets of arrivals injected into the waveguide along the Tien Shan. Only for the furthest events beyond 16° do we see a more complex set of arrivals.

Fig. 5 displays record sections for the events in class C which form a profile crossing the Tarim Basin and the Tibetan plateau. When the epicentral distances is less than 6°, and so the events lie at the southern edge of the basin, we can see that the propagation of $Lg$ is generally good, as the seismic waves just cross the stable Tarim region. As the sources gradually move back into the Tibetan plateau the propagation efficiency of $Lg$ begins to diminish. $Lg$ can still be seen for events at the northern edge of the Kun Lun Mountains ($8.5°$), and then $Sn$ is also clearly visible. For the more distant events lying further into the Tibetan Plateau there is very little amplitude in the expected group velocity range for $Lg$ and the higher frequency content is quickly lost; as compared with Figs 3, 4(a) at the same distances the change is pronounced.

The results of the numerical simulations shown in Section 6 suggest that the transition from thick to a suddenly thinner crust at the northern margin of Tibet has a major effect on the regional phases. Only part of the potential $Lg$ energy can couple into the thinner waveguide and cross the Tarim Basin to WMQ. Part of the remainder is transformed to fundamental mode surface waves and the rest is lost into the upper mantle. Thus for more distant sources $Lg$ is basically blocked, and converted Rayleigh waves progressively becomes the most prominent phase.
Figure 4. Seismograms (unfiltered ground velocity) for regional wave propagation to WMQ generated by events in group B with propagation along the Tien Shan range: (a) vertical component, (b) 3-component records for events at larger distances.
Figure 5. Seismograms (unfiltered ground velocity) for regional wave propagation to WMQ generated by events in class C in a profile crossing the Tarim Basin into the Tibetan Plateau: (a) vertical component, (b) tangential component.

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On this profile the mantle phase \( Pn \) is quite clear but the observations of \( Sn \) are rather patchy. For epicentral distances beyond 14°, the events are located on the far side of Tibet, and so crustal waves need to travel though both boundaries, across the whole Tibet Plateau and then through the Tarim Basin before finally coming to WMQ. The \( Pn \) and \( PP \) phases, which avoid the very complicated crust, are prominent with high frequency and large amplitude; similarly \( Sn \) emerges strongly from the coda of \( P \). However, there is no significant energy in the expected group velocity window for \( Lg \), which is completely blocked.

The Class C events in a narrow azimuth band present three distinct kinds of seismic wave propagation patterns as the distance from WMQ increases due to the dramatic crustal thickness variation along the travel path. The first pattern is generated from events located at the southern edge of the Tarim Basin which show the typical continental pattern where \( Lg \) is the dominant phase with high frequency and great amplitude, and \( Sn \) can be seen clearly. The second pattern is associated from events located in the Tibet Plateau where most of the amplitude of \( Lg \) is lost, \( Sn \) is weak and Rayleigh waves are the dominant arrivals. The last pattern arises from events on the further side of Tibet from WMQ where mantle arrivals are the strongest phases and there is no indication of \( Lg \).

## 4 The Regional Variations in \( Lg \) and \( Sn \)

### 4.1 Amplitude ratio

As we have seen the pattern of propagation of regional seismic phases varies considerably along different propagation paths and the relative visibility of the phases can be used as a guide to the character of the wavefield. Amplitude ratios are often used to look at blockage of phases, and we here look at the way in which an automatic analysis might handle these different propagation paths into a single station. We have therefore examined the use of different amplitude measures applied to the group velocity windows where the different regional phases are expected. As all the observations are made at a common station in the same frequency band, there is no need to correct for instrument response. A common filter was applied to all the ground velocity data with a 4-pole Butterworth filter, with 3 dB points at 0.5 and 5.0 Hz. For \( Pn \) we used a group velocity window spanning the range from 8.1–7.7 km s\(^{-1}\) for most of seismograms in Class C, based on the work of McNamara et al. (1995) whose results show that the velocity of \( Pn \) is higher under Tibet. For the other two classes we used a 8.0–7.4 km s\(^{-1}\) group velocity window. In all cases we used a group velocity window from 4.5–4.0 km s\(^{-1}\) to pick \( Sn \) and from 3.5–3.0 km s\(^{-1}\) to pick \( Lg \).

We designate the measured amplitudes in the \( Lg \) window by \( Lg \), with a similar notation for the other phases, and look at the behaviors of the ratios: \( Lg/\!Sn \), \( Lg/\!Pn \), and \( Sn/\!Pn \) between the major regional phases.

We have tested three different measures of amplitude behaviour. First, we have employed the maximum amplitudes measured for the \( Lg \) and \( Pn \) windows on the vertical component, and for the \( Sn \) window from the tangential component. Secondly, we have used the mean value of the total vector amplitude \( t \) over each phase window; \( t \) is defined as (Kennett 1993):

\[
t = (Z^2 + R^2 + T^2)^{1/2},
\]

where \( Z \), \( R \) and \( T \) are the vertical, radial and tangential components of motion after rotation to the great circle between source and receiver. The third measure is the mean value of total envelope amplitude \( env[t] \), which is defined as:

\[
env[t] = \left( Z^2 + (HZ)^2 + R^2 + (HR)^2 + T^2 + (HT)^2 \right)^{1/2}
\]

where \( H \) represents the Hilbert transform.

We have examined the amplitude ratios for the various regional phase windows in the Tibet data set (class C) as a function of distance from WMQ in some detail. Although similar results are obtained with all three methods, the amplitude ratios calculated using the total vector amplitude are more stable (with less variance) than those using the maximum amplitude and total envelope amplitude. Therefore, we display the ratios using the total vector amplitude measure in the subsequent analysis.

The amplitude ratios carry with them the influence of the differing source radiation effects from the diverse events recorded at the single station WMQ. The radiation characteristics are quite different for \( Pn \), \( Sn \), \( Lg \) but nevertheless we see a clear trend in the amplitude behaviour with only modest variations between nearby events. Fig. 6 shows a comparison of the logarithmic of the ratios \( Lg/\!Sn \), \( Lg/\!Pn \), \( Sn/\!Pn \) as a function of distance for these three data sets. There is not a noticeable difference in \( Sn/\!Pn \) among the three paths; the logarithmic ratio gradually decreases with increasing distance and can be adequately approximated by a straight line, so there is no indication of partial blockage of \( Sn \). For the \( Lg/\!Sn \) ratio, there are no distinct differences between the three propagation...
classes when the distance from WMQ is less than 900 km. This arises in part because of limited sampling in class C (Tibet). Beyond 900 km, there is a clear separation in the amplitude ratios for the three classes; the lowest values are associated with paths from Tibet, slightly higher values occur for the Tien Shan (class B), and the northern paths (Class A) have the largest amplitude ratios with a tendency for the \(Lg/Sn\) ratio to increase slightly with distance.

The \(Lg/Pn\) ratio declines with distance for all three event classes but in general the largest ratio is associated with northern paths. Beyond 900 km the ratios from events in Tibet are consistently below but in general the largest ratio is associated with northern paths.

Although the amplitude measurements take place over the expected window for \(Lg\) arrivals, we have seen in Figs 3–5 that the character of the wave train varies significantly with the class of events. There is a major change in the frequency content in the \(Lg\), so that if we can combine both amplitude and frequency measures we can provide an effective means of recognizing the differences in propagation characteristics for the three event classes.

### 4.2 Frequency content index for \(Lg\)

Tong (1995) described an automatic analysis system for seismic traces based on the use of pattern recognition techniques. The segmentation of the trace in this procedure provides a good estimate of the local dominant frequency without the need for time varying Fourier analysis. We use the average of the local frequency values for the three components to provide a robust estimate of the local frequency as a function of time along the seismogram. Fig. 7(a) shows the variation of the apparent frequency of \(Lg\) with distance for the three classes of events. We can see that from 500–900 km, the apparent frequency decreases rapidly, dropping from 6 Hz to 2 Hz very quickly for profiles B and C. The local frequency is generally higher for the northern events (class A). From 900 to 1600 km, frequencies of the Tibetan events (class C) are usually lower (between 1–2 Hz); for the northern paths with the simplest propagation the local frequency is the highest (greater than 2 Hz). The behaviour fits in well with the variation of amplitudes. The local frequency fits well with the visual inspection of Figs 3–5. \(Lg\) loses high frequency content quickly for events located in interior of the Tibet Plateau and propagation along the Tien Shan (class B) leads to a lesser but significant loss of high frequency content compared with events in class A.

We have experimented with a number of ways of combining both the amplitude and frequency information for the regional phases, so that we can include the influence of complex structure and attenuation. A suitable composite measure of the influences on \(Lg\), is obtained by multiplying the logarithmic amplitude ratios for the raw ground velocity records by the local frequency estimate \(\omega_L\) for the window in which \(Lg\) would be expected. Thus we calculate \(\omega_L \log_{10}(Lg/Pn)\), and \(\omega_L \log_{10}(Lg/Sn)\) using amplitude measures calculated from unfiltered data and plot as a function of distance in Figs 7(b) and (c). The composite index provides an improved separation between the three different classes of propagation paths as compared with the logarithmic amplitude ratios for filtered data used in Figs 6(b) and (c).

![Figure 7](image)

**Figure 7.** (a) The variation of the local frequency \(\omega_L\) in the \(Lg\) window as a function of distance. (b) Distance dependence of the composite index \(\omega_L \log_{10}(Lg/Pn)\) for the three data classes derived from unfiltered data, (c) Distance dependence of the composite index \(\omega_L \log_{10}(Lg/Sn)\) for the three data classes derived from unfiltered data.

### 5 NUMERICAL SIMULATION OF SOURCES IN THE TIBET AND PROPAGATION TO WMQ ALONG PROFILE C

A number of authors have noted that the apparent blockage of \(Lg\) on paths leaving Tibet towards the north occurs within the Tibetan Plateau (see, e.g. Ruzaikan et al. 1977); this results is confirmed by our observations of the seismograms at WMQ. Kennett (1986) provides an heuristic explanation of this process in terms of the coupling of sources within the plateau into the thinner crustal waveguide across the Tarim Basin. However, the rather simple model employed in that study only allows for the shape of the waveguide and not internal structural variations. In recent years increasing detail has been revealed for the seismic structure in Tibet, and the plateau has been and is the subject of major international experiments (see, e.g. Kind et al. 2002; Vergne et al. 2002). As a result there is a significant increase in the knowledge of the structure, although no current
profile is available along the line of the record section from the WMQ station.

We have employed the pseudospectral method (Furumura et al. 1998) to model P-SF propagation at regional distances across models of the Tibetan plateau and Tarim Basin, which include a substantial change in crustal thickness. We have therefore looked at the influence of two different classes of 2-D seismic wave speed model on the profile of the events in class C from the Tarim Basin into the Tibetan Plateau, which lies nearly orthogonal to the northern boundary of the Tibetan Plateau. The first model (I) based on information from Chinese sources has a rather smooth increase in crustal thickness from 56 km at the northern edge of the plateau to 72 km maximum thickness, as shown in Fig. 8(a). The second model (II), illustrated in Fig. 8(b), has instead a rapid jump in crustal thickness of the style inferred by Vergne et al. (2002). In each case, the structure includes a sediment layer 13.5 km thick, extending from WMQ to the Kun Lun on the northern margin of Tibet with surface elevation rising from 1.5 to about 4 km. The total crustal thickness for Tarim basin zone is 45 km, and the lower crustal layer has somewhat higher Q than for the sediments.

With the aid of these contrasting models we are able to look at the propagation processes from sources in Tibet and examine the character and evolution of the regional phases. These results help us to understand the nature of the arrivals observed for events in class C.

In Figs 9, 10 we compare the character and evolution of the regional phases and the nature of the propagation processes for the models I, II in Fig. 8. In each case we take a source at 10 km depth at an epicentral distance of 1000 km from WMQ, on the farther side of the crustal transition and well within the Tibetan Plateau. A double couple source with just $M_{xx}$, $M_{xz}$ components is used with a dominant frequency of 2 Hz. For each model, we display record sections of vertical component seismograms and snapshots of the wavefields. The record sections are split at the source location with the left-hand panel representing propagation towards WMQ, and the right-hand panel propagation further into the Tibetan plateau.

The extreme left hand seismograms correspond to the receiver point closest to the position of WMQ. For both models it is clear that the wavefield establishes a very different character for propagation towards WMQ compared with towards the south, deeper into Tibet, where the crust is thicker. Although there are differences in detail between the results for the two models in Figs 9 and 10, the general character of the seismograms and snapshots is similar despite the differences in the profile of the crust-mantle boundary.

The source lies above a region of thickened crust and so the time delays for crustal multiples are larger than for typical continental crust. The effect is to separate the $SmS$ multiples which normally interfere to generate the $Lg$ phase. For model I with a smooth increase in crustal thickness (Fig. 8a), the influence of the crustal thickness can clearly be seen in the snapshot at 54 s for the crustal $P$ and $S$ phases travelling towards the thinner crust to the left, and the thicker crust to the right. There is a tighter pattern of multiple $S$ reflections within the crust for propagation towards WMQ at 0 km. The influence of the sediments of the Tarim and the thinner crust begin to be felt after about 200 km from the source in propagation to the left. In the snapshot at 108 s, we see some reflection of the $Lg$ energy from the crustal pinch zone, which then propagates back into Tibet. As the multiple crustal reflections interact with the zone of thinning crust (e.g. at 162 s), significant energy is shed into the mantle with each interaction with the crust–mantle boundary. The angle of incidence at the inclined boundary is no longer beyond critical, and so transmission can occur from the formerly trapped waves into the upper-mantle, at angles such that they are lost from the regional phase system. This leakage into the mantle extracts significant $S$ energy from the crustal waveguide and so a relatively weak $Lg$ arrival reaches the WMQ receiver. Although up-dip propagation leads to precritical reflection and loss in transmission, down-dip propagation deeper into Tibet retains post-critical reflections and keeps the $S$ energy in the crustal waveguide. However the relatively low $Q$ in Tibet leads to significant attenuation.

The differences in the propagation characteristics are reflected in the synthetic seismograms for the vertical component displayed.
in the upper panel of Fig. 9 with a linear gain with range from the source. For propagation towards WMQ there are distinct packets of S wave energy in the normal Lg wave window (group velocity between 3.5 km s\(^{-1}\) and 2.8 km s\(^{-1}\)) followed by a distinct fundamental mode Rayleigh wave (Rg). The changes in the near surface structure with the increase in sediment thickness beyond 200 km from the source lead to a complicated coda in the Lg window. Initially we see individual pulse like arrivals and then from 500 km out the wave train acquires the typical behaviour of Lg but at slightly lower frequency than normal continental crust. However, this wave train is not sustained and the amplitude relative to P diminishes significantly for the position closest to WMQ. The simplified numerical model does not show strong indication of the converted Rayleigh waves seen in the records at WMQ, but such effects are enhanced for shallower sources or for lower frequency excitation.

For propagation into Tibet, we see initial pulses followed by a lower frequency arrival corresponding to the overlap of crustal multiples. The amplitude decays significantly with passage across the plateau due to the effect of the relatively low Q used for the lower crust in the numerical model. The appearance of the records in the Lg window is very different from that for propagation to WMQ and reflects the greater reverberation times for the thicker Tibetan crust.

The comparable results for model II (Fig. 8b) with a sharp change in the Moho depth are shown in Fig. 10. Although there are differences in detail, the general character of the regional wavefield is quite similar to that for the smooth variation in crustal thickness shown in Fig. 9. The distribution of the energy within the Lg window is somewhat different reflecting the differences in the way the S crustal multiples are established in the thinner crust. There is no longer the progressive leakage of crustal energy into the mantle but rather a concentrated loss in the zone of the crustal pinch.

Fig. 11 displays the results of reciprocal calculations undertaken with the pseudospectral method in which the excitation from many sources is recorded at a single receiver. We have taken the receiver to lie at WMQ, i.e. at 0 km in the numerical model, and have again used a double couple source with just a \(M_{xx}, M_{zx}\) combination at a depth of 10 km and the same frequency content as in Figs 9 and 10 (dominant frequency of 2 Hz). The vertical component seismograms for models I, II are displayed in Fig. 11.

In each model, for sources out to 800 km, lying within the Tarim basin, there are well developed high frequency Lg arrivals, but there is a notable drop in both amplitude and high frequency content once the sources penetrate into the Tibetan plateau itself (beyond 800 km). This behaviour fits well with abrupt change in frequency content seen in the observations, but we have not succeeded in matching the strong surface wave arrivals with the simplified models. The Sn arrival is well excited by the source but decays relative to Pn. We note the emergence of later mantle arrivals in the Sn window.
Figure 10. Pseudospectral calculations of the seismic wavefield for model II with a sharp jump in Moho thickness at the northern boundary of the Tibetan Plateau for a crustal source at 20 km depth at a distance of 1000 km from WMQ, with a 2 Hz dominant frequency for the source pulse: (a) Snapshots of the seismic wavefield; (b) Vertical component seismograms.

shed from the crustal wave complex. The complexity of the $P$ wave arrivals out to 600 km is in quite good accord with the observations (cf. Fig. 5). The amplitudes of the mantle phases are rather larger than seen in the observations and suggest the presence of rather low $Q$ in the upper-mantle, as suggested by Rodgers & Schwarz (1998).

The loss of high frequency $S$ arrivals for sources within the Tibetan Plateau is only weakly dependent on the model employed for the transition from thick crust to the thinner crust beneath the Tarim basin. The major role played by the crust–mantle boundary is to allow energy to leak into the mantle; this may be progressive as in the smooth model (model I—Fig. 8a) or in a concentrated burst for the Moho step (model II—Fig. 8b). The elimination of the Tarim sediments against the northern boundary of Tibet plays a major role in the suppression of the high frequency $S$ crustal arrivals.

6 DISCUSSION

The observations and amplitude ratios for the regional phases $Pn$, $Sn$, $Lg$ give a very clear indication of the noticeable differences in the character of the regional wavefield in the central Asian area. The differences arise from the way in which the different wave types interact with the complex crustal structure. Both structural variation along the propagation path and localized heterogeneity can significantly influence the propagation pattern, especially for $Lg$.

The presence of significant structure is not by itself a barrier to regional phases, since we have seen that $Lg$ waves can be ducted along the Tien Shan chain. There is a progressive loss of amplitude and frequency because the trapping of the waves by the bounding gradients is not complete, but nevertheless $Lg$ persists to $14^\circ$ away from the WMQ station. An interesting and unusual feature of far-regional propagation occurs for events beyond the Pamirs; distinct pulses with a group velocity around 3.3 km s$^{-1}$ arrive at WMQ, indicating selection of modes with a rather narrow group of group velocities in passage through the Pamir Plateau.

We have also noted the way in which major tectonic boundaries act on the crustally trapped waves. The funnelling of the waves from the thick waveguide under Tibet into the much thinner crystalline crust of the Tarim basin is accompanied by loss of energy into the mantle, and transfer from steeper propagation into fundamental mode surface waves. The process is gradual and so the blockage of $Lg$ is not fully developed until the source location lies some way inside the Tibetan Plateau. When events lie beyond the southern boundary of Tibet, two crustal structure transitions have to be negotiated and complete blockage of $Lg$ occurs. As expected from ray simulations, e.g. Bostock & Kennett (1990) the influence of crustal changes tends to be stronger when propagation is nearly orthogonal to the trend of
the structure, although ducted waves can occur along the trend in suitable circumstances (as for the Tien Shan).

The mantle arrival $Sn$ can be seen clearly against the background of the $P$ coda for the Tien Shan events and across the Tarim basin. For certain events within the area to the north of WMQ, $Sn$ is weak. From events in Tibet $Sn$ is highly attenuated; there is no clear onset of $Sn$ and it is not even visible on the tangential component. This suggests that there is high attenuation, which could be associated with partial melt, in the uppermost mantle beneath Tibet (Rodgers & Schwarz 1998) and possibly also in the neighbourhood of the Altai range.

The numerical modelling of the propagation of waves from sources in Tibet provides some useful insight into the nature of the influence of crustal thickness on the crustal waveguide. For the thick crust under Tibet, a ducted system of $S$ waves is indeed established in the crust but the time separation between successive multiples from the crust–mantle boundary is such that the records in the group velocity window from 3.6–3.0 km s$^{-1}$ consist of distinct pulses followed by a relatively low frequency composite pulse built from the interference of the latter part of the multiple train. The appearance is therefore rather different from the normal $Lg$ arrival for thinner crust (35–40 km) where the multiple reflections from the crust and crust–mantle boundary overlap to give a complex interference wave train with an amplitude maximum close to a group velocity of 3.5 km s$^{-1}$ linked to the critical point of the current dominant $SmS$ reflection, followed by a complex coda of the other reflection branches. For thinned crust, the various reflections tend to coalesce in time and so a simple burst of energy appears, rather than the elongated $Lg$ wave train. In the case of an oceanic environment, there is strong loss into the mantle and so the closely packed multiple reflections rapidly lose energy and the $Lg$ arrival cannot be sustained beyond 100 km or so of oceanic structure (cf. Kennett & Furumura 2001).

**REFERENCES**


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**Figure 11.** Reciprocal seismogram calculations for a receiver at WMQ at the left hand edge of the numerical model. The vertical component seismograms show the evolution of the regional wavefield as a double couple source at a constant depth of 20 km is moved away from the receiver into the Tibetan structure. The seismograms are normalized by the maximum energy in the vertical plane. (a) Model I with a smooth increase in crustal thickness under the Tibetan Plateau, (b) Model II with a sharp jump in Moho thickness at the northern boundary of the Tibetan Plateau. Note the loss of high frequency $Lg$ for sources beyond 800 km from WMQ in each case.


