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**CRUSTAL AND UPPER MANTLE VELOCITY GRADIENTS
IN THE VICINITY OF THE EAST KAZAKH TEST SITE;
RAY SYNTHESIS OF L_g IN THREE DIMENSIONAL
CRUSTAL MODELS**

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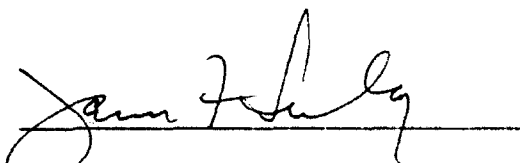
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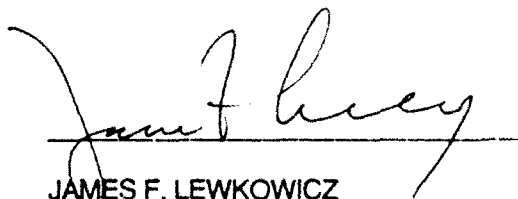


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This technical report has been reviewed and is approved for publication.



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13. ABSTRACT (Maximum 200 words) Using a simple homogeneous crust and a first order Moho discontinuity, Lg waveforms are synthesized in canonical models as well as models chosen for selected Eurasian paths. Lg blockage by basins and Moho transitions is a strong function of the slope of the Moho surface and is only a weak function of the angle of source-receiver path relative to the strike of the structure. Synthetic waveforms are often in good qualitative agreement with observed waveforms, including details in the shape of the Lg coda. Poorer agreement is seen in cases in which either (a) the inferred Moho from surface topography disagrees with that determined from deep seismic sounding observations or (b) sedimentary basin structure is not included in the synthetic modeling. Synthetics that allow single scattering incorporated by the Born approximation show that scattering by heterogeneity within the crustal waveguide can fill up the Lg coda between multiple SmS arrivals and lengthen the Lg coda. The trajectories and geometric spreading of rays contributing to Lg suggest that the most important effects of scattering will be concentrated in the Moho transition and in the upper several kilometers of the crust.				
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INTRODUCTION

In this report we summarize the results of experiments in which Lg waveforms are synthesized either by dynamic raytracing and or superposition of Gaussian beams (Červený, 1985) in three-dimensionally varying crustal waveguides. In both approaches, Lg is represented as a sum of multiply critically reflected SmS waves (Figure 1). Topography of the Moho is correlated with given, or known surface topography under the assumption of Airy isostasy. The starting assumptions are essentially the same as those used by Kennett (1986) in identifying gross effects of crustal thickness on Lg by plotting the bounce points of critically reflected S waves in the crust. Here, however, waveforms are calculated and the effects of geometric spreading are included. Details of the modeling approach, including source functions assumed, are described in (Cormier and Kalnabach, 1991).

RESULTS

Propagation Perpendicular to a Mountain Range

Lg is modeled by summing dynamically traced rays in a laterally varying crustal waveguide simulating a hypothetical mountain range. Crustal thickness contours are shown in map view in Figure 1a. Certain characteristics, such as the square corners of the contour lines, are concessions made for modeling simplicity and are not expected to greatly influence the results. Background crustal thickness is taken as 35 km, which represents continental crust slightly elevated above sea level. The thickness of the mountain root is 50 km, which is consistent with gravity surveys in various high mountainous regions (e.g. Press and Siever, 1982, p. 437). A physical analogy to this model may be found in the South American Andes, which is similarly a narrow range with abrupt fronts on both sides.

Tested propagation paths are shown in Figure 1a and ray synthetic seismograms in Figure 1b for a vertical point force. The first trace shows Lg at the same offset as receiver R_1 through an undisturbed waveguide. Traces 2 through 4 are recordings from receiver locations R_1 through R_4 . Visual comparison of the traces gives a measure of attenuation and the extensive numerical data from the program runs explain the primary cause (mantle transmission and/or defocusing). The seismogram from location R_1 shows that early Lg arrivals have high amplitude but later arrivals are considerably weaker. The effects of crustal thinning are not evident at this location and the weaker signal is explained entirely by propagation across the transition to thicker crust. The method of attenuation is defocusing. The slower ray paths reaching location R_1 are reflected in areas of Moho curvature and as a result, average geometric spreading is increased by a factor of 2. Since Moho curvature is found to cause attenuation in this and other program runs, it is useful to consider an alternative transition model; a planar dipping Moho. The planar surface will not cause the increase in geometric spreading noted above, but will result in attenuation through other means. Specifically, much of the defocused energy that reaches the receiver through curved transitions is reflected by planar transitions in directions that do not reach the receiver. This is easily visualized by considering rays tubes and the area between rays, which is the wavefront. Defocusing leads to larger wavefronts which have a better chance of reaching the receiver than do the smaller wavefronts

reflected by planar surfaces. The present study has compared the methods and found comparable levels of attenuation, although the seismograms are somewhat different in appearance.

A very slight increase in attenuation is evident at receiver location R_2 , primarily because all rays reaching this point are defocused to some extent. Attenuation at location R_3 is quite a bit stronger than at R_1 and R_2 . Here the propagation path crosses the transition to thinner crust, which diverts much of the energy that would otherwise reach the receiver. Diversion occurs in three ways. First, rays travelling at post-critical angles relative to the horizontal Moho become pre-critical at the upward dipping transition, and energy is lost to mantle transmission. Secondly, a large portion of the remaining reflected energy travels at pre-critical angles, leading to mantle transmission beyond the transition. The third method of diversion is back-reflected rays.

Propagation Parallel to a Mountain Range

Figure 2 illustrates the results of tests of Lg propagation parallel to the strike of a mountain range for a vertical point force. Sources and receivers are assumed to lie within a mountain range having a deep crustal root. Seismogram trace 1 shown again for reference propagation in a crust having planar free surface and Moho. Traces 2-4 correspond to receiver locations R_1 , R_2 and R_3 . Transition zones trending parallel to the propagation path form a secondary waveguide and the modeling predicts that rays will be trapped within. These raypaths are weak, however, as Moho curvature causes significant attenuation by geometric spreading. The seismogram at location R_1 , which is not subject to transitions perpendicular to propagation, shows energy roughly equal to undisturbed Lg. Although a large number of raypaths with lateral reflections were traced, the increased geometric spreading leads to weak arrivals. The traces at locations R_2 and R_3 are seen to be strongly attenuated by the crustal thinning transition.

Rays trapped by the lateral waveguide undergo conversion between SV and SH, but conversions of this type are not noticeable in the synthetic seismograms. It is possible that because these rays tend to be weak, the conversions are not noticeable. Another possibility is that SH to SV conversion is generally canceled by SV to SH conversion under the particular conditions of this model. In the real crust, the primary method of SV to SH conversion is scattering by small scale heterogeneities, which can not be considered under the constraints of ray theory.

Propagation Oblique to a Mountain Range

Figure 3 illustrates the attenuation of Lg for paths oblique to the strike of a mountain range for a vertical point force. Sources and receivers are located such that propagation paths are at 90, 70, 45 and 20 degrees relative to the waveguide perturbations. Receiver distance is 2000 km in all cases. Strong attenuation is evident over each propagation path, but the individual waveforms vary considerably. For paths terminating at receivers R_1 and R_2 , rays encounter steep thickness transitions and many rays are entirely transmitted to the mantle. Along the more oblique paths leading to R_3 and R_4 , the Moho dips less steeply and as a result, the number of two-point ray paths increases. It appears that Lg propagates slightly more efficiently at 45 degrees than at the other angles tested, but the difference is insignificant compared to the level of attenuation.

Width of Crustal Transition

In crustal models shown in figure 1a, 4a and 4b, the width of the transition region between thick and thin crust is varied. The source-receiver paths are 2000 km in length and perpendicular to the strike of the transition regions. Synthetic traces 2 and 3 in Figure 4c, which compare a 200 km width of thickened crust with a 500 km width, both show weak Lg. The similarity between traces suggests that the width of a mountainous region has very little effect on overall attenuation. Trace 4 shows Lg after propagation through transition regions 200 km wide (compared to 100 km wide in trace 2) and the difference is readily apparent. The widened transition width results in Lg amplitude analogous to that in the undisturbed waveguide, which implies that the width of crustal transition regions and the corresponding change in overall Moho dip angle impose the primary control over Lg attenuation.

Propagation Across the Tibet Plateau

The map shown in Figure 5a gives source and receiver locations used in the Lg analysis of Razaikin et al. (1977). Shading corresponds to regions of high mountains. Central Asia was chosen to test the methods of the present study because Lg is known to be highly attenuated here and good specific examples are given in published seismograms. A study of focal mechanisms in the Tibetan Plateau (Molnar and Chen, 1983) found these earthquakes to occur at depths of 5 to 10 km with combined strike-slip and normal faulting and T axis primarily east-west. No earthquakes were located below 10 to 15 km, suggesting the crust is essentially aseismic below these depths. The fault solutions indicate the Tibetan Plateau is undergoing east-west extension, much like the Basin and Range province of the Western United States.

Crustal thickness has been hand digitized and the results, in the form of a Moho depth plot, are shown in Figure 5b. Samples are taken at a .5 degree (50 km) sampling of latitude and longitude. (Topography and Moho depth at 10 km sampling are now available in unclassified databases established by Fielding et al., 1992.) The method of determining crustal thickness is a combination of published survey results and inference. Choudary, 1975 estimates crustal thickness of 70-72 km in the Central Himalayas from Bouger gravity anomalies. Bird and Toksoz, 1975 study the velocity of 20-80 second Rayleigh waves and conclude that the crust is 75 km thick within the Tibetan Plateau. Published data on crustal thickness within the Tarim Basin and Tien Shan Mountains were not found, so thickness has been estimated from average elevation. Elevation varies from 500 to 1000 meters within the Tarim Basin and crustal thickness is estimated at 35 km. Average Tien Shan elevation is on the order of 3000 meters, leading to a thickness estimate of 50 km. Estimation of crustal thickness combined with the large digital sampling intervals lead to a very rough model of the crust, but the transitions, which seem to most strongly effect Lg propagation, are represented as closely as the model will allow.

Figure 5a shows propagation paths from the two earthquakes chosen for modeling by the ray method. Double couple radiation patterns have been included. Both paths are subject to crustal thinning at the Tarim Basin then crustal thickening at the Tien Shan mountains before the waves are recorded at Soviet station Talgar (TLG). Since the paths are similar, transition steepness will be approximately the same. The main difference between paths is that the the more westerly path

from the earthquake near 87°E longitude travels about half as far within the Tibetan Plateau as the path from the earthquake near 93° longitude. Figures 6a,b compare the observed and synthetic seismogram for the earthquake ($m_b=5.1$) having the more westerly path. Lg appears to be strongly transmitted, having a high amplitude relative to Pn. The synthetic agrees well with details of the observed Lg coda. Figures 7a,b compare seismograms recorded from earthquake ($m_b=6.1$) having the more easterly path. Lg appears to be very weak in these recordings, having a low amplitude relative to Pn. The synthetic seismogram has high amplitude pulses not seen in the observed seismogram.

Certain additions to the crustal model could significantly improve the match between the synthetics and the recordings. First, inclusion of the low Q believed to exist in the deep crust of the Tibetan Plateau (Bird and Toksoz, 1975) would improve the agreement between observed and predicted Lg transmission. Each ray incident at the Moho beneath the Tibetan Plateau would be subject to high intrinsic attenuation, establishing a direct relationship between travel distance within the plateau and attenuation suggested by the observations. Scattering attenuation by the 3-D heterogeneities associated with the uplifted region would tend to reinforce this relationship. Details of the shallow structure of the Tarim Basin have been omitted from the crustal model. The weak path, for which poor agreement exists between observed and predicted Lg transmission, crosses the Tarim Basin. Baumgardt (1991) found that sedimentary basin structure is at least as important, if not more important, than Moho topography in controlling Lg propagation. Low seismic velocity within the sediments can form a waveguide trapping a significant portion of the rays that would otherwise contribute to Lg, the slopes of the basin on exiting side rays acting to defocus subsequent SmS rays (Figure 8). Rays reverberating within the sedimentary basin would also suffer high levels of scattering attenuation within the sediments. A third possibility for the discrepancy between the observed and predicted Lg waveforms in the weak path example is suggested by comparing the topographically inferred Moho with that determined by the Soviet Deep Seismic Sounding Project (DSS). In the region of the Tibet Plateau, the transition zone between normal and thickened crust is quite different in form in DSS sections than that which would be predicted by simple isostasy (Fielding, personal communication). One or more of these modifications of the crustal model may lead to synthetics that more closely match the attenuation levels seen in the recorded seismograms.

Scattering Within the Crustal Waveguide

The modeling described in the previous subsections does a remarkably good job in predicting the blocking of Lg by major crustal transitions and is often successful in accounting for the most significant details of the Lg coda. It is clear, however, that observed Lg codas will be always contain greater complexity than synthetic codas generated in models having a homogeneous crust. We have conducted several experiments to include the effects of fine scale three-dimensional heterogeneities within a crustal waveguide of variable thickness. To achieve this goal, we added dynamically traced rays to point scatterers within a crustal waveguide of variable thickness (Figure 9). A standard Born approximation (e.g., Wu and Aki, 1985) is used to calculate the radiation pattern of the point scatterers. The results shown in Figure 9 were calculated for a single point heterogeneity having positive 5 per cent contrasts in P velocity, S velocity, and density from the background medium.

It is clear that the existence of even a single point heterogeneity quickly acts to fill up the coda between multiply reflected S waves.

The standard Born approximation used in this demonstration does not conserve energy and does a poor job in recreating scattered codas predicted by finite difference solutions of the elastic equation of motion in heterogeneous media (Coates and Charrette, 1992). Improved agreement with finite difference simulations can be obtained by using the generalized Born approximation (Coates and Chapman, 1991). The generalized Born approximation, in which scattering occurs by a process of frequency dependent reflection by regions of high gradient, is applicable to models in which velocities and density are parameterized by continuous functions of space. Such a parameterization also greatly simplifies the description of the rays contributing regional seismograms.

Importance of Scattering in Different Depth Regions of the Crust

Lg rays have been dynamically traced in models of the crust in which the Moho has been represented by a high gradient transition (Figure 10). The SmS rays contributing to the Lg coda are turning rays in the high gradient region. Geometric spreading factors have been tracked along each ray, demonstrating that the spreading factors of individual rays vanish at the turning points within the Moho transition. It is well known that such a high gradient zone will form a caustic surface within the high gradient zone, to which multiple turning rays will be tangent. A reversed travel time branch and triplication will also be observed for rays traced at a sequence of increasing take-off angles. Scattering of Lg rays near the caustic surface, where amplitudes will be high due to the vanishing of the geometric spreading factor, will be greatly enhanced. This situation is very analogous to the enhanced amplitude of scattered PKIKP precursors due to heterogeneity at the core mantle boundary (e.g., Bataille and Flotte, 1988). For PKIKP precursors, the presence of a caustic surface in the outer core is sufficient to make even a very slight heterogeneity near the core-mantle boundary account for the observed amplitudes of the scattered waves. Likewise, a caustic surface within a Moho transition zone will be capable of amplifying the effects of very slight heterogeneity within the Moho transition.

In predicting regions in which enhanced scattering may occur it is also useful to consider the intersections of SmS rays traced from the receiver with SmS rays that originate at the source. In two-dimensional scattering, the existence of a heterogeneity at such crossing points will make it possible for SmS to SmS scattering to occur, filling up the coda between the individual SmS arrivals making up the Lg coda. The greatest density of such crossing points occurs near the Moho transition and near the free surface. An important source of the late Lg coda will be three-dimensional SmS to SmS scattering occurring out of the vertical plane containing the source and receiver.

CONCLUSIONS AND RECOMMENDATIONS

Modeling Results

(1) Moho Topography and Sedimentary Basins are the two most important elements structures responsible for Lg blockage.

(2) Slopes of major crustal discontinuities and transitions (Moho and basin-sediment interface) are the principal features controlling the propagation efficiency of Lg.

(3) There is only a weak dependence on the azimuth of the propagation path with respect to the strike of blocking features.

(4) Distributed heterogeneities and small scale topography of crustal discontinuities in the crust can act to fill up and lengthen the Lg coda. Heterogeneities within the crust primarily along the source-receiver azimuth fill up the early coda between individual S waves trapped in the crustal waveguide. Off azimuth heterogeneities within the crust are a significant component of the late Lg coda following the last arriving Moho reflected S wave.

Lessons from Ray Based Approaches to Regional Seismogram Synthesis

(1) Utility of a Continuous Model Parameterization: The complexity of ray code descriptions in models described by first order discontinuities argues for models parameterized by functions continuous in space.

(2) Treatment of Reflections and Conversions in Regions of Strong Gradient: A generalized Born approximation can be used to calculate the frequency dependent scattering by regions having strong gradient, including the Moho transition zone resulting from the parameterization described above.

(3) The Most Important Regions of Scattering for the Lg Phase and Why:

(a) Moho transition because a caustic surface is included in this region for many of the S waves composing the Lg phase. In addition there is a high density of S ray intersections in this region permitting scattering from one type of multiply reflected S wave composing the Lg phase to another type.

(b) The free surface region because there is a high density of S ray intersections in this region permitting scattering from a source ray consisting of multiple Moho reflected S waves to a receiver ray consisting of multiply reflected S waves. In addition, this region should be important based on array data suggesting a higher magnitude of velocity and density fluctuations in the upper 2 km of the crust.

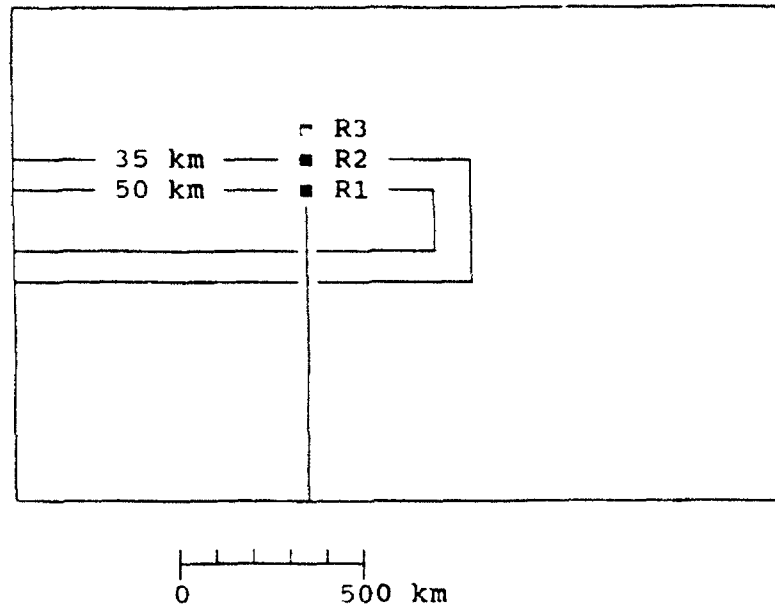
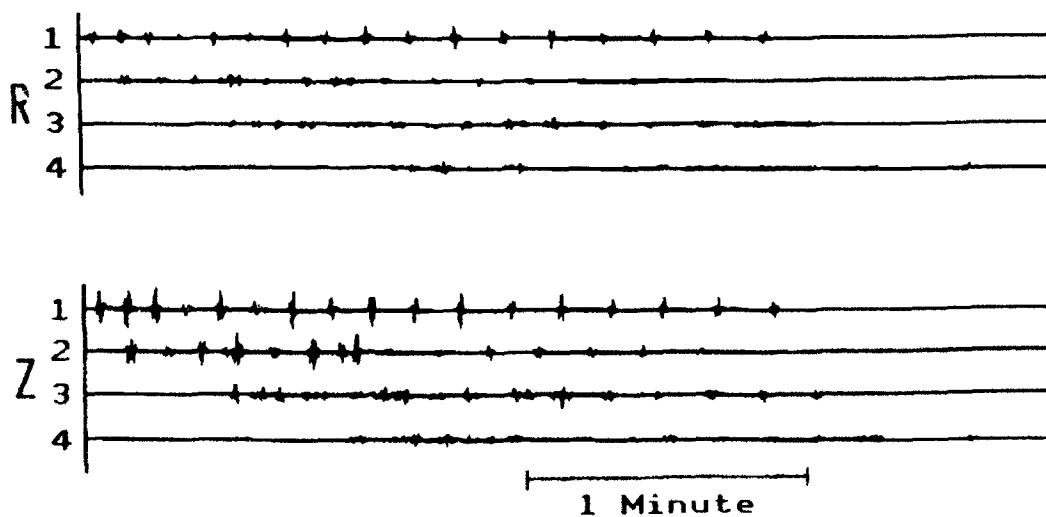


Figure 1 (a) Above: propagation paths normal to strike of mountain range. This map view shows the crustal thickness contours of a narrow hypothetical mountain belt, along with the Lg propagation path and receiver locations. R_1 through R_3 offsets are 2200, 2300, and 2400 km respectively. an unperturbed waveguide. (b) Below: ray synthetic seismograms for paths to receivers R_1 through R_3 . Trace 1 is Lg modeled at the R_1 offset in an unperturbed waveguide. Transverse ground motion is not shown because SV to SH conversion does not occur when the propagation path is perpendicular to waveguide variations.



Trace 1 = Non-attenuated Lg
 Trace 2 = Receiver R_1
 Trace 3 = Receiver R_2
 Trace 4 = Receiver R_3

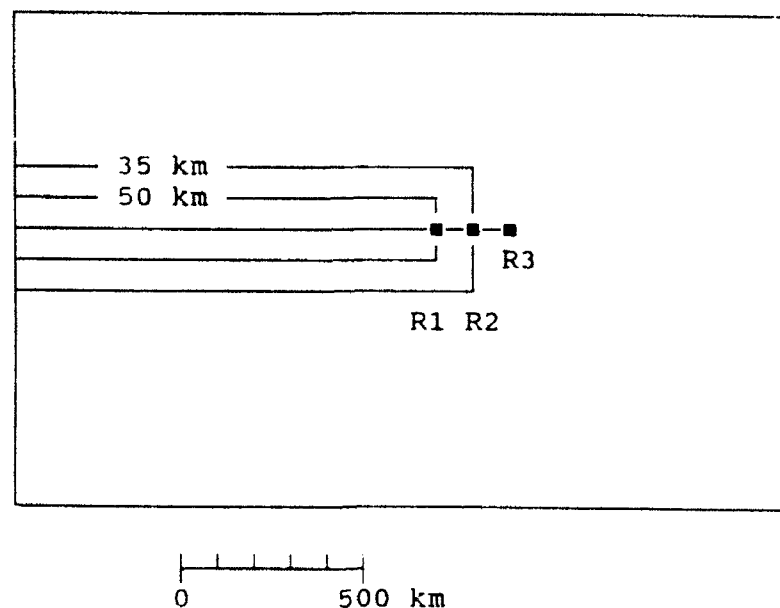
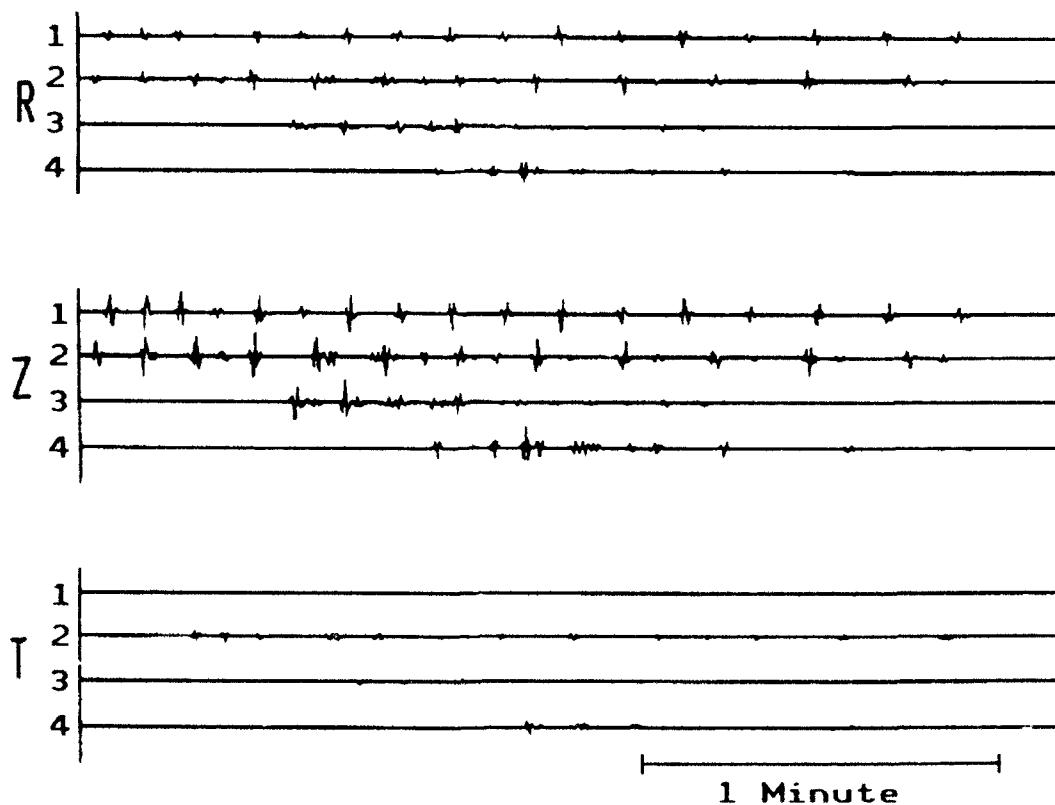


Figure 2 (a) Above: propagation paths parallel to the strike of the mountain range. Offsets are 2200, 2300, and 2400 km. to receivers within the mountain range. (b) Below: ray synthetic seismograms. An increased number of ray paths reach receiver R_1 relative to receivers R_2 and R_3 resulting from lateral reflections within the mountain belt. Coda duration is sharply limited at the R_2 and R_3 . Very weak motion can be seen on the transverse traces.



Trace 1 = Non-attenuated Lg
 Trace 2 = Receiver R_1
 Trace 3 = Receiver R_2
 Trace 4 = Receiver R_3

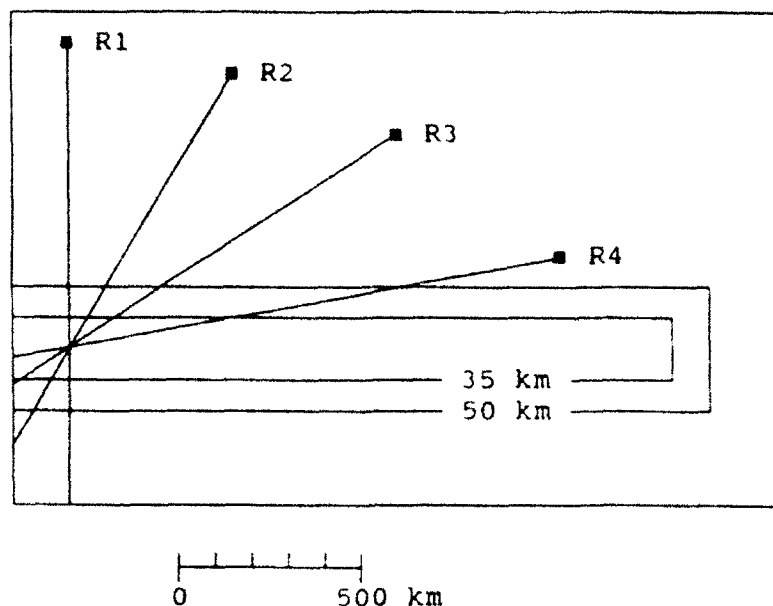
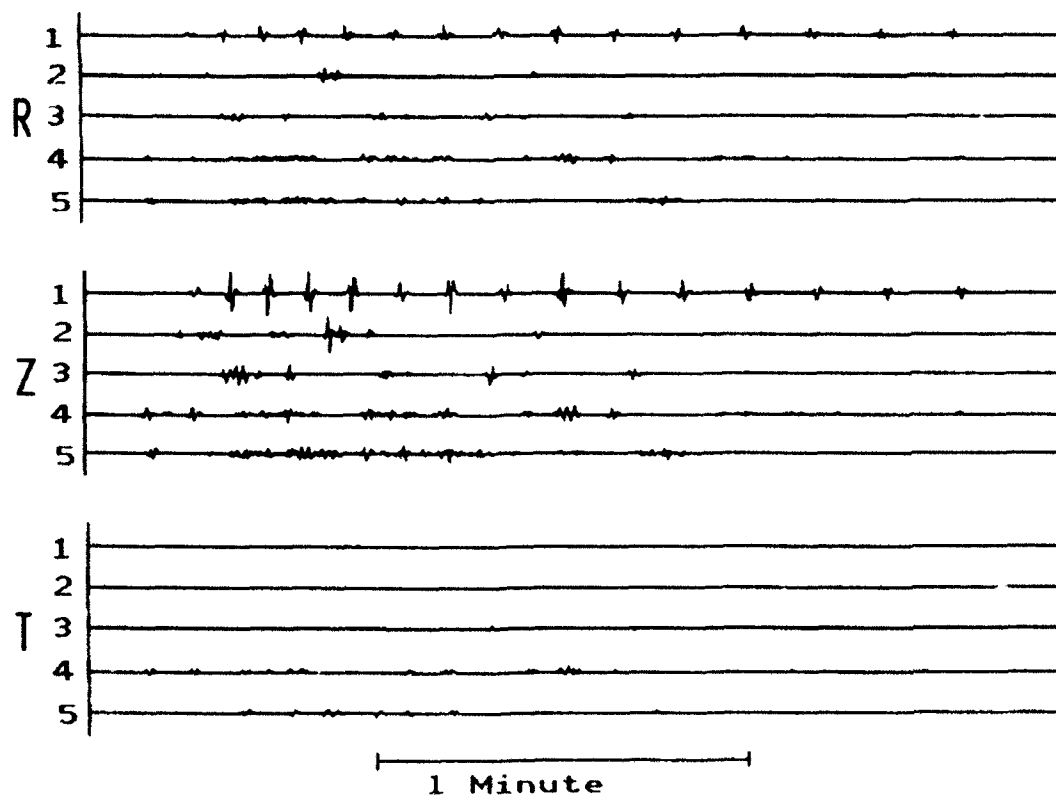


Figure 3 Lg propagation at paths making oblique angles to the strike of the mountain range. Above: (a) path to R_1 is at 90° , path to R_2 is at 70° , path to R_3 is at 45° , and path to R_4 is at 20° . Receiver offset is 2000 km over all paths. Below: (b) ray synthetic seismograms. Although waveforms 2-5 vary considerably, all have been considerably attenuated relative to the reference trace in an unperturbed waveguide and total energy is roughly the same for each of these paths.



Trace 1 = Non-attenuated Lg
 Trace 2 = Receiver R_1 (90 degrees)
 Trace 3 = Receiver R_2 (70 degrees)
 Trace 4 = Receiver R_3 (45 degrees)
 Trace 5 = Receiver R_4 (20 degrees)

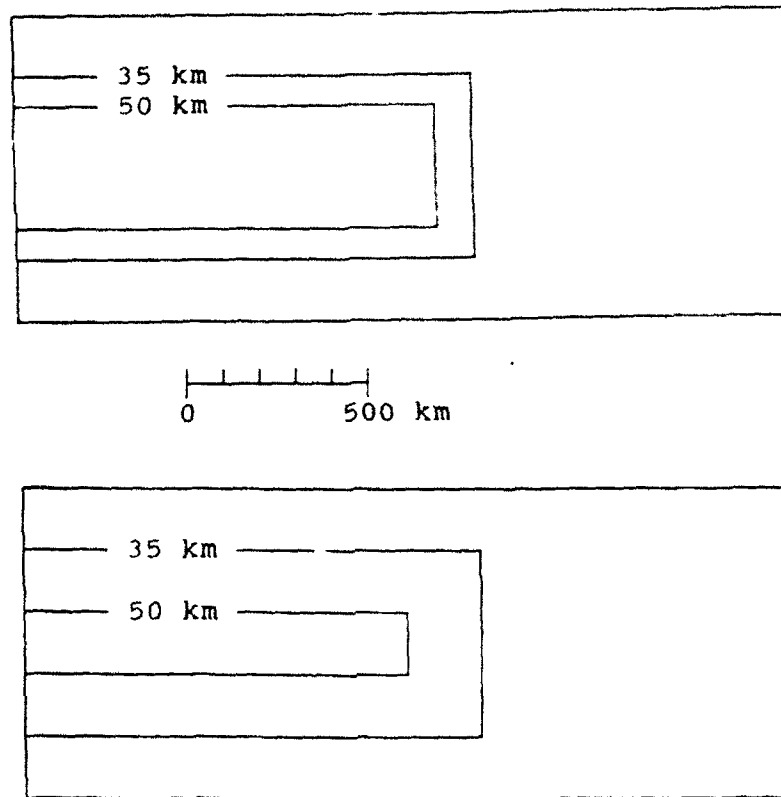
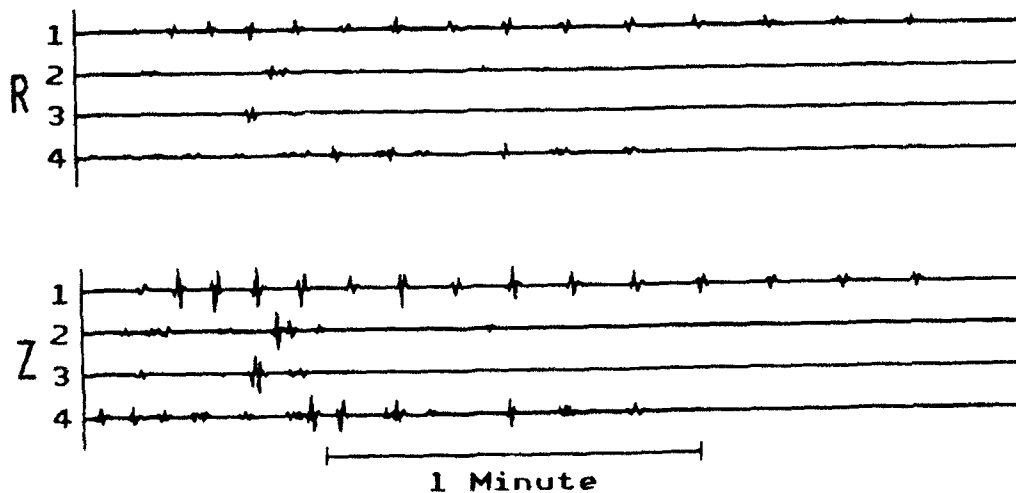


Figure 4 Effect of the width of crustal thickening and thinning. The crust increases and decreases in thickness over transition regions 100 km (above) and 200 km (middle). Ray synthetic Lg wavetrains are shown below for an offset of 2000 km and propagation perpendicular to the strike of the mountain range. Weak Lg in traces 2 and 3 compared to strong Lg in trace 4 indicates that the width of the transition region affects Lg efficiency more than the overall width of the mountain root.



- Trace 1 = Non-attenuated Lg
- Trace 2 = Receiver R_1 Crust Model 1a
- Trace 3 = Receiver R_2 Crust Model 4a
- Trace 4 = Receiver R_3 Crust Model 4b

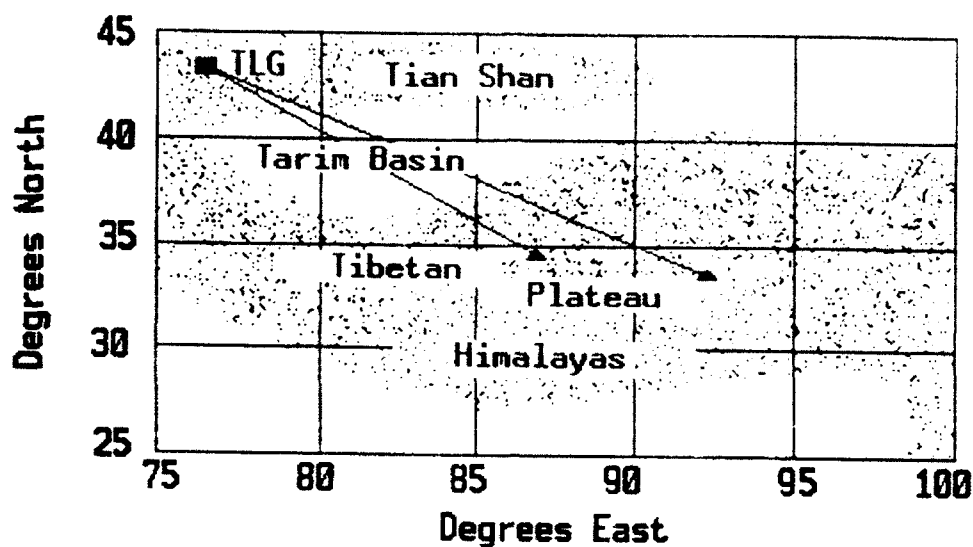
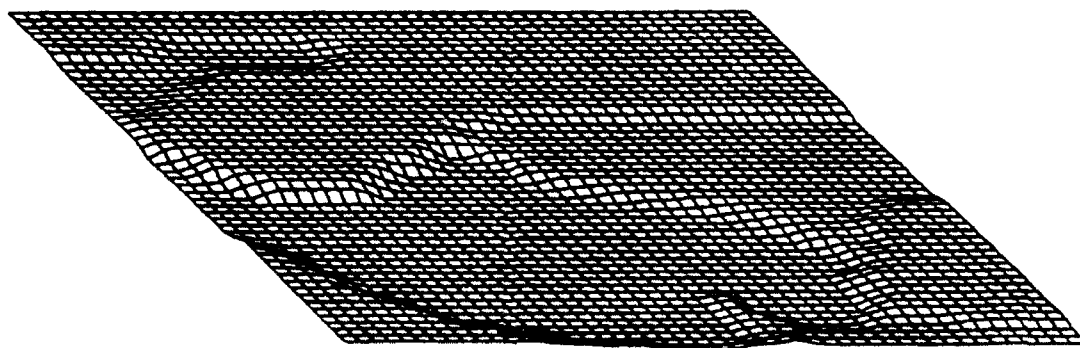


Figure 5 Above: (a) map of Central Asia showing the propagation paths of two earthquakes modeled by ray methods. Shading highlights high mountainous regions of thickened crust. The left path gives a detectable Lg signal and is referred to as the strong path. Lg from the right earthquake is very weak. Below: (b) Central Asian Moho depth plot obtained by digitization of crustal thickness values. Not to scale.



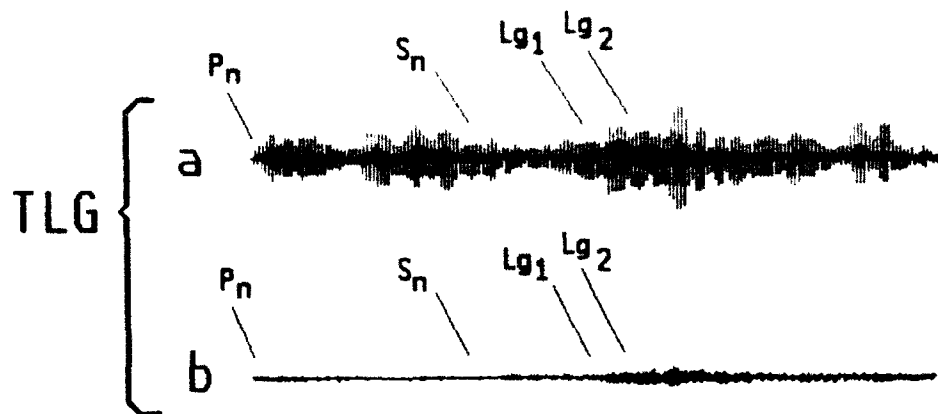
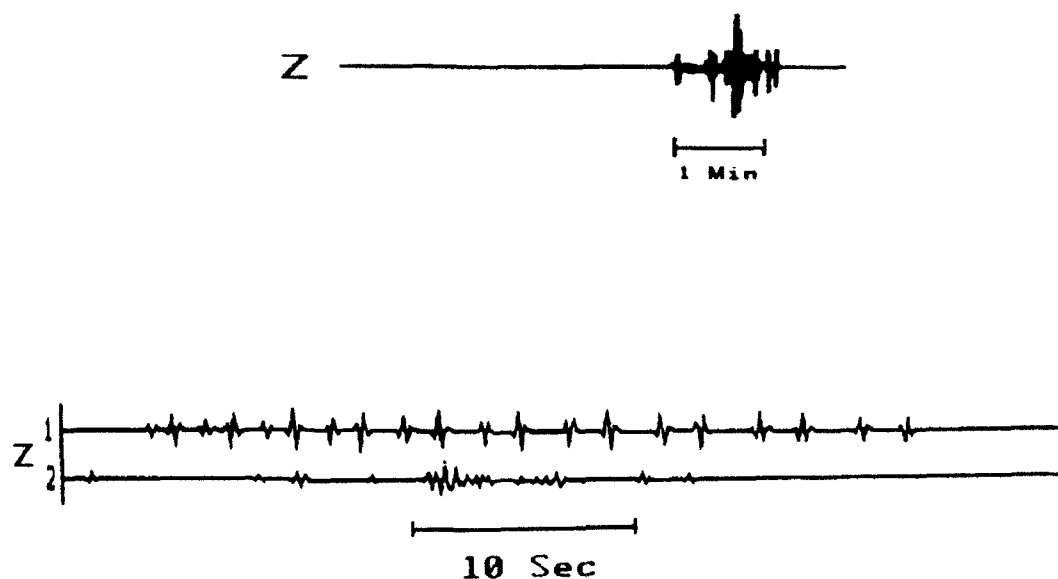


Figure 6 Above: (a) Central Asia strong path seismograms. The seismograms recorded from the left earthquake of figure 5a show clear Lg energy in both the top trace (instrument response peaked between 0.5 to 1 Hz.) and bottom trace (instrument response peaked between 0.2 to 0.5 Hz.). Middle: (b) scaled strong path synthetic. The synthetic seismogram is scaled to the dimensions of the actual seismogram and shows good recreation of Lg. Below (c): detailed strong path synthetic. These synthetic seismograms are not scaled to the recordings and allow determination of the level of attenuation. Ray modeling through a homogeneous crust predicts significant attenuation over this path.



Trace 1 = Non-attenuated Lg
Trace 2 = Strong path synthetic

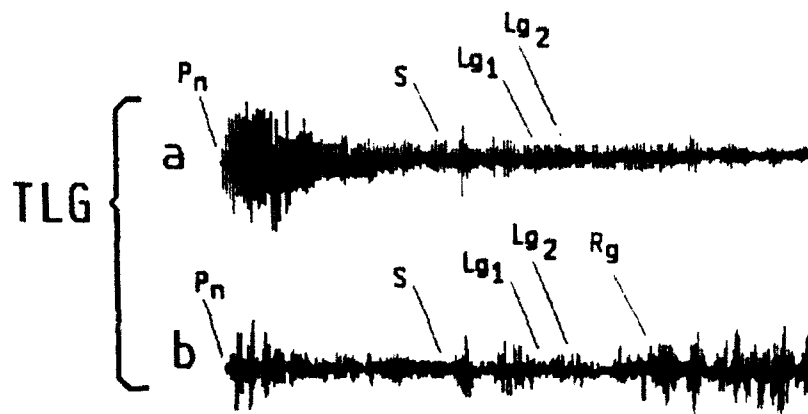
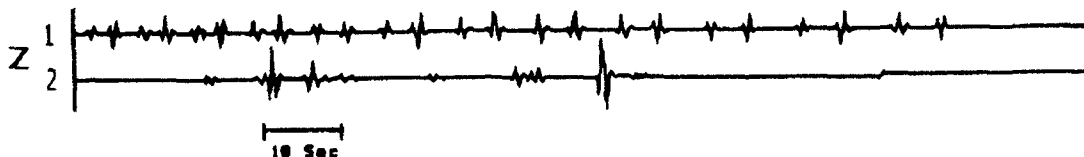
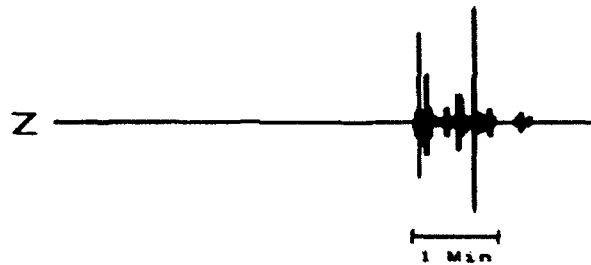


Figure 7 Above: (a) Central Asia weak path seismograms. The seismograms recorded from the right earthquake of figure 5a show very weak Lg, as can be seen by comparing Lg amplitude to Pn. Middle: (b) scaled weak path synthetic. The synthetic seismogram of the weak path predicts energetic pulses that are not present in the actual recordings. Below: (c) detailed weak path synthetic. Lg is clearly attenuated over this path but, as seen in figure 9b, the predicted level of attenuation is insufficient to explain the observations.



Trace 1 = Non-attenuated Lg
Trace 2 = Weak path synthetic

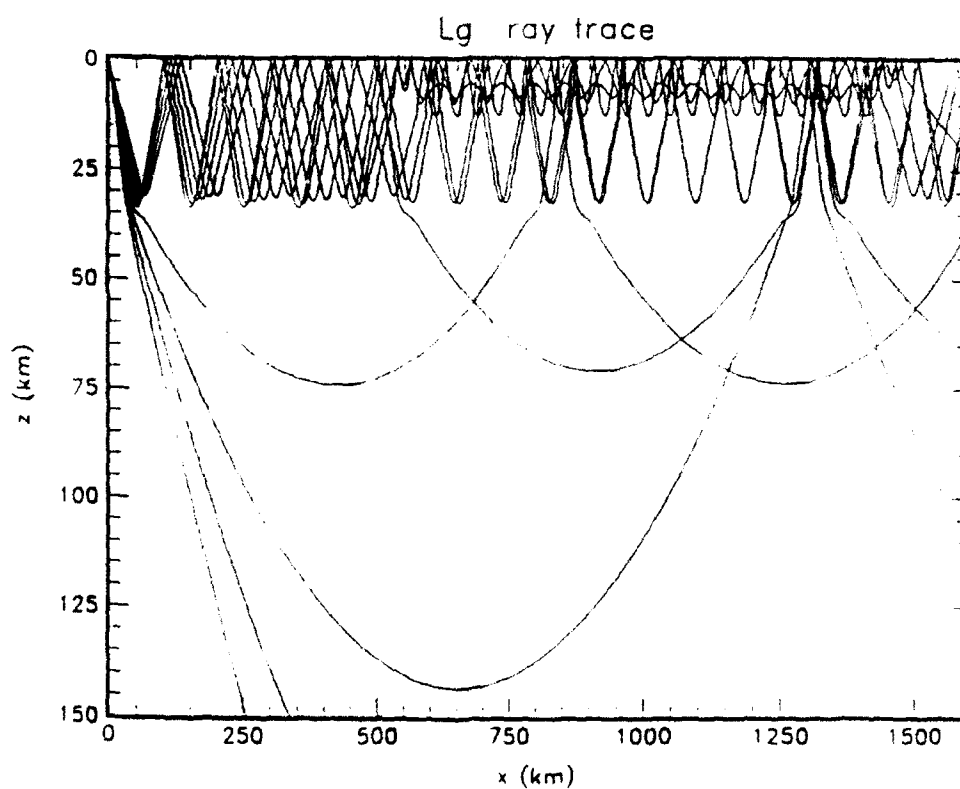
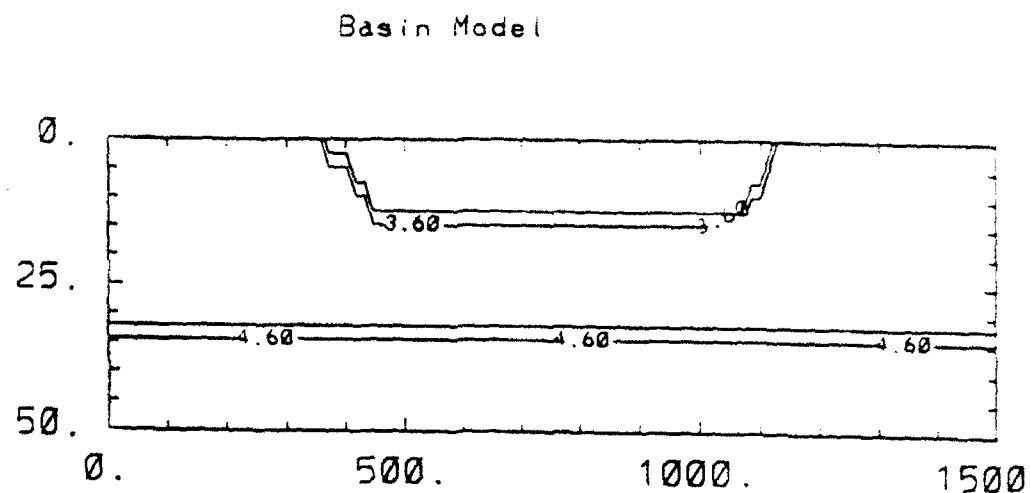


Figure 8. Top: Iso-S velocity contours defining a deep sedimentary basin (Z and X-coordinates are in kilometers.) Bottom: ray trace of S waves trapped in the crustal waveguide (Lg). Note that the effect of the basin will be to attenuate Lg at stations 1400 km and greater range.

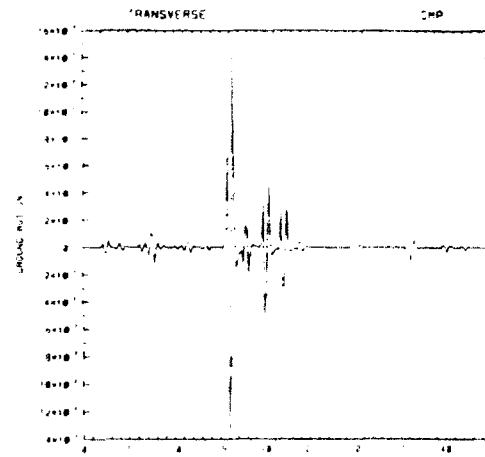
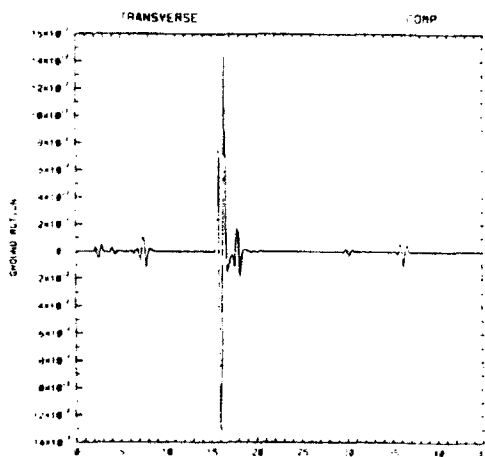
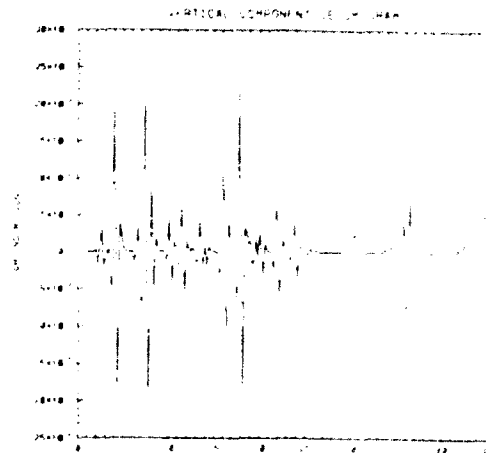
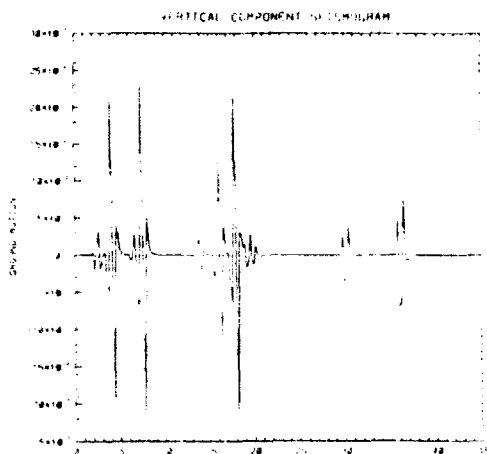
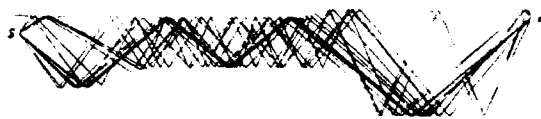


Figure 9. Effect of scattering within a crustal waveguide of variable thickness. Left column: no scattering within the crustal waveguide. Right column: scattering by a single scatterer within the crustal waveguide. (In the synthetics shown in the right column, all of the ray paths shown at top left are included plus the scattering paths shown at top right.)

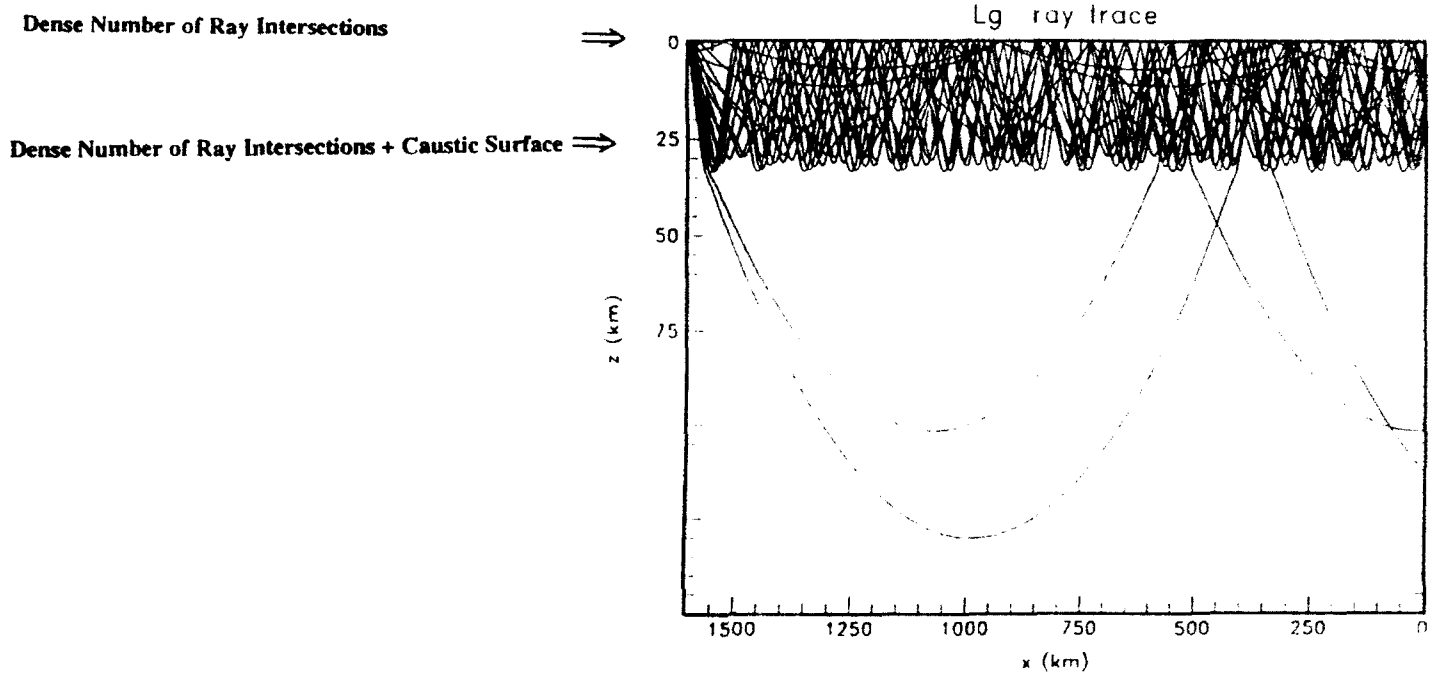


Figure 10. Intersections of rays traced from the receiver with rays traced from the source are densest near the surface and near the SmS turning points. Scatterers at these locations will contribute to the complexity of Lg coda. Scattering near the Moho transition will be particularly important because the presence of a caustic in this region will greatly amplify the effects of small perturbations in elastic moduli and density.

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