Variations in Regional Phase Propagation in the Area around Japan

by T. Furumura and B. L. N. Kennett

Abstract The high level of seismicity and dense network of short-period stations in Japan allows a detailed characterization of regional phase propagation. There are substantial differences depending on the location of the source and stations. Despite the structural complexity, Lg is clearly seen in many parts of Japan. Lg is particularly well developed in the western part of the main island, Honshu, and will propagates through some volcanic zones with loss of high-frequency components. There are also zones of Lg blockage in northeastern Honshu and for subduction zone events with significant oceanic paths for which the mantle phases Pn and Sn are particularly clear. The oceanic region in the Sea of Japan blocks Lg propagation paths for events in mainland Asia at many stations, but there are clear Lg propagation corridors through Korea to stations in the west (Kyushu, western Honshu) and in the north into Hokkaido.

The Lg phase carries substantial energy for large events, and the differences in efficiency of propagation influences the intensity of ground shaking. Thus the 1995 Hyogo-ken Nanbu (Kobe) earthquake shows intensity contours extended to the west in the region of efficient Lg-wave propagation. The Rg phase and the fundamental mode of Love waves are very significant for the shallow 2000 Tottori-ken Seibu event, and the effect of the combination of Lg with these slightly lower frequency surface waves would help to explain the discrepancy between the Japan Meteorological Agency magnitude from regional stations ($M_{\rm j}$ 7.3) and the moment magnitude from distant observations ($M_{\rm w}$ 6.6).

Introduction

The Lg phase is usually a prominent feature in the seismic wavefield at regional distances and represents the superposition of multiple *S*-wave reflections propagating within the crustal wave guide. When the crustal structure is homogeneous, *S*-wave radiation from a source can be efficiently trapped within the crustal waveguide to propagate as Lg waves for long distances because of perfect reflection at both the surface and the crust-mantle boundary for *S* waves with low phase velocities.

The Lg wave can be viewed as either a superposition of multiple S reflections within the crust or of higher modes of surface waves. The nature of Lg as an interference phenomenon means that the character of the wave train can be modified significantly by changes in the relative timing of the different contributions. Thus the amplitude of the Lg phase is sensitive to variations in the crustal structure along the propagation path and in some circumstances can be almost completely blocked. The variation in the behavior of Lg on different paths has been used to map structural variations in the Tibetan Plateau (e.g., Ruzaikan *et al.*, 1977; Ni and Barazangi, 1983), central Asia (e.g., Kadinsky-Cade *et al.*, 1981), China (Rapine *et al.*, 1997), the western Alps (Campillo *et al.*, 1993) and the North Sea basin (Kennett *et al.*,

1985). Such studies have endeavoured to localize crustal heterogeneity in the region by mapping the paths with poor Lg propagation. The amplitude of Lg is also well known to be very sensitive to the influence of a continental-oceanic transition zone, where as little as 100 km of oceanic path is sufficient to block the transmission of the Lg wave (Press and Ewing 1952).

In some cases, as across the eastern Pyrenees (Chazalon *et al.*, 1993), Lg waves are observed to propagate despite significant topography on the Moho. For the western Pyrenees, Lg is almost completely blocked and the transition in the nature of Lg can be followed by examining the relative importance of the mantle *Sn* phase and the crustal Lg phase.

The structure in the Japanese archipelago is quite complex, but in some regions, Lg propagates quite well. The high density of seismographic stations and shallow sources means that it is possible to provide an exceptional level of coverage of the Japanese islands and to map out the propagation characteristics of Lg using the relative amplitudes of Sn and Lg.

The Character of the Regional Seismic Wavefield

Despite the intensive study of seismograms in Japan, comparatively little attention has been given to the character of regional arrivals. The main emphasis has been on accurate source location using the onsets of P and S rather than on the later phases such as Lg. A number of standard models are used for different parts of Japan.

Utsu (1956) was the first to recognize the Lg phase in regional records in Japan and later (Utsu, 1958) examined records from a number of events in Asia recorded in Japan that showed clear low-frequency Lg on many paths, as described by Press and Ewing (1952), but showed Lg blockage across the oceanic region of the Sea of Japan with water depth in excess of 2 km.

Shima (1962) examined the records at Matsushiro Observatory (MAJ), in central Honshu, for the Lg phase from events within Japan and noted a systematic variation in the group velocity of Lg between events whose paths crossed southwestern and northeastern Japan. The group velocity for Lg is lower in the southwest (3.44 km/sec), with relatively clear arrivals on Galitzin and Benioff Long Period (LP) seismometers, whereas the group velocity in the northeast is higher (3.57 km/sec), but the Lg arrivals are less distinct.

Over the last few years a very dense array of highquality seismometers has been deployed in Japan (see Fig. 1), and cooperation between a consortium of Japanese Universities means that the records from all the stations in this JARRAY (see, e.g., Yomogida, 1996) are collated and made available for study. The relatively high level of shallow seismicity means that a very large body of information on regional phase propagation can be collected in a short time.

The configuration of the JARRAY is illustrated in Figure 1. Each seismographic station has a three-component shortperiod velocimeter recorded at 20 samples/sec. The majority of stations have seismometers with a natural frequency of 1 Hz and provide a good uniform coverage. A few stations have a natural frequency of 0.5 Hz, and so common filtering was applied to all stations before analysis.

The epicenters of shallow events with magnitude greater than 5 in the period from November 1996 to June 1999 are shown in Figure 1. Over this time span the combination of events and stations provides a good coverage of the Japanese islands for regional ranges.

The varying character of the regional phases within Japan is well illustrated by examples from two events in Honshu (Fig. 2), one in the central region and the other in northern Tohoku. Both events are relatively shallow (10 km deep) and well recorded across a wide range of stations. We extract JARRAY data for nearly linear profiles of stations so that we are able to produce record sections displaying the evolution of the regional phases with range. For the event in central Honshu in Figure 3, we construct record sections for propagation (a) to the southwest, and (b) to the northeast. Similarly in Figure 4, we form record sections from seismograms from the northern event extending to the (c) SSW, and (d) NNE. The profiles (b) and (c) are nearly reciprocal. The travel times for regional phases, including multiple Moho reflections, predicted from the *ak135* model of Ken-

nett *et al.* (1995) are displayed in each section to provide a common reference.

The four profiles show considerable variation in the character of the regional seismic wave field. Profile (a) in southwestern Japan shows a very well developed Lg wave train extending to nearly 800 km; some high frequencies are lost as Lg crosses into the volcanic region of Kyushu beyond 650 km range (see Fig. 2). The mantle phases *Pn* and *Sn* are also quite clear along the whole profile. Except at the shorter distances, Pg is rather weak. In contrast, on profile (b) from central Honshu to the northeast, Pg is quite strong and Sn is not very distinct. Unlike profile (a), Lg is never the dominant phase on the seismograms and is almost eliminated beyond the 500-km range, which corresponds to entry into the main volcanic belt of northern Honshu (see Fig. 2). The propagation characteristics from the northern event differ again. On profile (c) toward the SSW, Lg is initially large and fast, but beyond the 400-km range, it loses its high frequencies, and the maximum amplitude tends to move to lower group velocities. The high group velocities of Lg in the eastern part of northern Honshu are consistent with the observations of Shima (1962) at the Matsushiro Observatory in north-central Japan. The loss of high frequencies again appears to be associated with propagation through a volcanic zone, in this case the central volcanic region in Honshu. Profile (d), from northern Honshu into Hokkaido, crosses a region with considerable water depth and crustal thinning associated with the kink in the subduction of the pacific Plate (see Fig. 1). The mantle phases *Pn*, and *Sn* are well represented with a complex coda, and for the stations in Hokkaido beyond a 300-km range, there is little evidence for distinct crustally guided waves (Pg, Lg). Although the region between Honshu and Hokkaido is not fully oceanic, the propagation pattern for the regional phases is quite similar to that expected for an oceanic zone.

Given the complexity of structure in Japan it is perhaps surprising that there are any zones where a guided phase such as Lg can propagate well. The complex interferences between multiply reflected S are quite sensitive to heterogeneity, but the influence is greatest when paths traverse nearly orthogonal to the trend of the structure (Bostock and Kennett, 1990). In southwestern Japan the paths of profile (a) lie along the main trends in the geology, whereas to the northeast (profiles b–d) the paths are oblique to the general north–south trend imposed by the subduction of the Pacific plate (Fig. 2).

Regional Variations in Lg Propagation, JAPAN

The record sections in Figures 3 and 4 provide a useful insight into the nature of the regional wave field within Japan, but it is not possible to use this approach to cover the full range of available data. We see, however, that Lg has considerable variation in visibility, and we can use this property as a guide to the character of the wave field. Accordingly we have developed summary measures for the efficiency of



Figure 1. Stations in the JARRAY in Japan and epicenters used from November 1996–June 1999.

propagation of Lg for the propagation along each path in terms of the amplitude ratio between Lg and Sn. We use an amplitude measure derived from the three-component records in two group velocity windows: 4.6–4.2 km/sec for Sn and 3.5–2.8 km/sec for Lg. Following Kennett (1993), we use the total vector amplitude for each phase

$$t = (Z^2 + E^2 + N^2)$$

averaged over 2-sec intervals. The measure t has the advantages of being very stable and does not depend on the orientation of the horizontal components (so can also be used directly with rotated records). We are therefore using upper mantle *S* propagation as our reference, and we need to recognize that *Sn* corresponds to a relatively narrow angle of takeoff angles at the source, whereas Lg is built up from a broader range of takeoff angles into the crust and is less sensitive to source mechanism. There is therefore the possibility of the influence of the radiation pattern of a particular source. Fortunately with the extensive range of sources recorded by the JARRAY (Fig. 1), we have a wide range of crossing paths across Japan, and so such effects can be minimized. A further merit of the Lgto *Sn* comparison is that it can readily be automated and therefore make full use of the dense data from the JARRAY. Because the geometrical spreading for Lg is somewhat smaller than that expected for *Sn*, a drop in the Lg/Sn ratio



Figure 2. Locations of the profiles of regional wave propagation from two events in Honshu shown in Figures 3 and 4; *VF* indicates the volcanic front.

with increasing distance indicates severe attenuation in Lg. We illustrate the behavior of Lg propagation by considering four events that span the main Japanese islands (Fig. 5). The events are ordered from south to north in Figure 5; event (b) in Central Honshu and event (c) in northern Honshu are those for which we have shown the record sections in Figures 3 and 4.

For event (a), in the subduction zone off the coast of Kyushu, Lg propagation to stations in northern Kyushu is generally good, but there is some slight influence from the Kyushu volcanic belt (mainly in a loss of high frequencies). Propagation of Lg to western and central Honshu is quite good, but paths that cross into the Japan sea are rapidly attenuated. There is a sharp front between efficient propagation and weak Lg for stations around Tokyo. Those paths that cross oceanic region crust show strong Sn but very weak

Lg (Kennett and Furumura, 2001); whereas those paths that stay within the continental margin still have significant Lg. For event (b), in central Honshu, there is clear Lg to the land stations to the west and for shorter distances toward the northeast, as illustrated in Figure 3. However, Lg is strongly attenuated on most paths to Hokkaido and northern Tohoku that cross the volcanic front. Also paths to the Ryuku islands with an oceanic path have, as expected, Lg almost eliminated.

For event (c) in northern Tohoku there is relatively good propagation of Lg for land paths toward the southwest, as illustrated in Figure 4. The apparent efficiency of Lg to the north is due in large part to relatively low amplitudes in *Sn* rather than a well developed Lg train (cf. Fig. 4d). The suppression of Lg by more than 100 km of oceanic path is very evident along the Sea of Japan side and also on paths into



Figure 3. Vertical-component seismograms for regional wave propagation from central Honshu: (a) to the SW, (b) to the NE. Travel-time curves are shown for the *ak135* reference model (Kennett *et al.*, 1995) for the main regional phases, including multiple reflections at the Moho.

southern Kyushu and the Ryuku Islands. Event (d) in the subduction zone off northern Hokkaido shows some of the strongest contrasts in the character of propagation. Short-range Lg propagation into the island of Hokkaido is quite clear, and there may be some focusing associated with variations in crustal structure. Moderate quality Lg propagation occurs for paths to the southwest even where some part of the path crosses the edge of the Sea of Japan. However, there is very strong attenuation of Lg for eastern paths that either have an oceanic component or cross the volcanic front in northern Honshu.

The 50 events shown in Figure 1 have been chosen in

time periods where the seismic background is low, and thus automated estimation of the Lg to Sn ratio is reliable. In all, we have well over 8000 paths providing a dense sampling of the Japanese Islands and their surroundings. This extensive data set allows us to try to estimate the efficiency of Lgpropagation in some detail. The approach we have adopted for constructing a blockage map for regional wave propagation follows the work of Kennett *et al.* (1985) for the North Sea but has the advantage of much denser data coverage. We work with a simple tomographic inversion, based on back projection with subsequent iterative improvement (10 iterations), to convert the path information into local



Figure 4. Vertical-component seismograms for regional wave propagation from northern Honshu: (c) to the SSW, (d) to the NNE. The same set of travel times are used as in Figure 3 to aid comparison.

properties of the wave transmission using a representation in terms of 0.2-deg cells. The path information used is the four entry code for Lg as displayed in Figure 5, and we attempt to reconcile the various observations with a transmissivity model on a scale of 0 to 1 (Fig. 6).

The result of the inversion for the efficiency of Lg propagation is shown in Figure 6. When interpreting the figure, we need to remember that we have used Sn as a reference phase and that the results could be misleading in circumstances where both Lg and Sn are strongly attenuated, as in volcanic zones. We have assessed the resolution attainable from the inversion by looking at the reconstruction of single-cell anomalies at different points in the model in a point-

spreading test. There is a strong concentration of paths along the Japanese islands and far fewer transverse to the grain of the structure. As a result, there is a tendency for a NE–SW smearing in northern and western Honshu so that the recovered anomalies have a significant amplitude in a zone two cells wide (EW) but four cells long (NS) (0.4×0.8 deg), but in central Honshu and Hokkaido the reconstruction is more concentrated and has significant amplitude in a $0.4 \times$ 0.6 deg zone. The point function for Kyushu is slightly larger but still concentrated. Although we have direct evidence for variations in structure in a SW–NE direction (see, e.g., Fig. 4), it is possible that some degree of elongation in this direction affects the image in Figure 6.



Figure 5. Variations in Lg/Sn ratio along paths from a number of different events.

It is difficult to convey all the information about the behavior in a summary diagram such as Figure 6 since the propagation characteristics of Lg depend on the direction of the propagation path, with the greatest effect when paths are nearly orthogonal to the trend of structural heterogeneity. This leads to some degree of anisotropy in transmittivity in addition to smearing. The very large number of crossing paths minimizes the influence of the direction of propagation.

Nevertheless, Figure 6 provides a useful summary of

the propagation characteristics of Lg and reveals a number of zones of efficient propagation. We have illustrated the efficiency of propagation in the western part of Japan in Fig. 3(a), and this is the main zone where ducted crustal energy can be expected to propagate to some distance from the source. The other patches are more localized. Inefficient Lgpropagation occurs for nearly all propagation across regions of ocean crust; we have indicated the approximate continental crustal margin by the 1000-m contour in Fig. 6. Subduc-



Figure 6. Summary map of the variations in Lg/Sn ratio for propagation paths through different parts of Japan.

tion events close to the continental edge, as in eastern Japan, can often give reasonably well-developed Lg.

Propagation of Regional Phases into Japanese Stations

The dense station network provided by the JARRAY also allows us to examine propagation of Lg into Japan from events outside. We summarize, in Figure 7, observations of three events (Table 1), using a simplified version of the coding employed in Figure 5. Paths for which Lg is clear are shown in solid lines, and those where blockage of Lg has occurred have dashed lines. Paths for which all *S* phases are highly attenuated are indicated by gray lines; most of these are from events in Taiwan and have a large oceanic component.

There is a clear corridor of efficient high-frequency Lg

propagation through Korea and the southern part of the Sea of Japan, but blockage occurs for almost all paths crossing the truly oceanic zone where water depth exceeds 1000 m. A second corridor of more efficient propagation in the north of the Sea of Japan also exists where continental material links across to Sakhalin. This is not well illustrated in Figure 7 because, unfortunately, a suitable event in Sakhalin occurred at a time of high seismic activity in Japan, and the JARRAY records cannot then be used for the automated analysis.

We illustrate the variation in the character of regional phase propagation with vertical-component velocity seismograms for a set of JARRAY stations, with good signal-tonoise ratio, for the event in northeastern China on 29 November 1999. The stations are marked in Figure 7 and are displayed in the record section from south to north (Kyushu to Hokkaido). In the upper panel (Fig. 8a) we show the short-



Figure 7. Efficiency of propagation of Lg waves from events outside Japan into the stations of the JARRAY. Stations used in the record section in Figure 8 are marked by triangles.

 Table 1

 Epicentral Information for the Events Used from Outside

 Japan in Figure 7

Date	Time (JST)	Lat. (N°)	Lon. (E°)	Depth (km)	Mag.	Event Region
10 Jan. 1998	12:50 37.8	41.1	144.4	6	<i>M</i> _w 5.8	Northeastern China
02 Nov. 1999	02:53 04.2	23.2	121.4	33	$M_{\rm w} 6.3$	Taiwan region
29 Nov. 1999	13:10 40.8	40.4	122.8	10	<i>M</i> _b 4.9	Northeastern China

period records from the JARRAY stations. These seismograms show clearly the strong contrasts in Lg amplitude between efficient propagation into Kyushu (stations FUK, JTY) and the suppression of Lg energy crossing the Sea of Japan, particularly to KMJ, HKB, SSKM, and HOJ in Honshu. There is a hint of Lg energy at stations ASBT and ESSI in Hokkaido.

The characteristics of Lg tend to change with frequency as the wavelength varies relative to the scale of heterogeneity. The propagation of longer-period Lg waves would be expected to be less sensitive to the localized variation in the crustal structure such as small bumps in Moho or thick sediment below the surface because of the longer wavelength.



Figure 8. Vertical-component seismograms for regional wave propagation from events outside Japan into the stations of the JARRAY. (a) Short-period JARRAY record and (b) longer-period waveform derived by filtering out the frequencies above 0.33 Hz; note the enhancement of the *S* arrivals.

The differences associated with the frequency band are illustrated in Figure 8b, where we have applied a low-pass filter to the short-period JARRAY data with a cutoff frequency of 0.33 Hz (and thus corresponds to the original definition of Lg from Press and Ewing [1952]). The lower frequency band sees an enhancement of S waves relative to Pwaves, and more noticeable, Lg at the stations SAIJ, AIDA, and KASA. Lg is extinguished for paths through the center of the Sea of Japan to stations KMJ, HKB, and SSKM, but the longer-period Lg is apparent for the northern Hokkaido stations ASBT and ESSI. The oceanic region in the Sea of Japan acts as expected to block Lg. The differences in propagation characteristics reflected in Figure 8 fit well with earlier observations of longer period Lg over paths from the Asian mainland. Utsu (1958) tabulates propagation characteristics for 3–5 sec Lg into a number of Japanese stations. Utsu's results are replotted in Figure 9 using a similar convention to that employed in Figure 7.

The southern and northern corridors for Lg propagation into Japan are clearly displayed in Figure 9. Propagation through Korea and across the shallow continental Yellow Sea is clear into western Japan but blocked further east. Paths crossing the oceanic portion of the Sea of Japan lose most of their low-frequency Lg energy. However a variety



Figure 9. Propagation of longer period Lg waves into Japanese stations based on the observations of Utsu (1958).

of paths show relatively efficient Lg propagation from the west and north into stations in Hokkaido, as we have noted in the discussion of Figure 8b.

It is clearly desirable to undertake a detailed study of the frequency dependence of regional phase propagation in and around Japan to improve knowledge of crustal heterogeneity. The increasing density of high-quality broadband stations in Japan will make such a study feasible in the next few years.

Our results for Lg propagation are consistent with the failure of Rapine *et al.* (1997) to find Lg from subduction zone events in Japan at station MDJ in northern China. However, given the extensive set of observations within Japan and the additional data in Figures 7 and 9, we would place the region of Lg blockage beneath the oceanic part of the Sea of Japan rather than overlapping the island of Honshu as in Figure 14 of Rapine *et al.* (1997).

The Influence of Regional Phases on Patterns of Ground Motion

The summary diagrams such as Figures 6, 7, and 9 provide a useful description of the general behavior of Lg, but these characteristics are modulated by the behavior of specific events. As we have seen above magnitude 5, events are normally well recorded across Japan, and it is possible to use the patterns of behavior of previous events as a template for the future. In particular, smaller events can provide insight into the likely behavior for larger, more destructive events.

Where Lg propagates efficiently, it is generally the dominant phase on the seismogram and therefore acts as the main means of carrying energy away from the source to distances of a few hundred km. The differing character of regional wave propagation has therefore a significant impact on the patterns of ground motions and intensity observed for larger earthquakes. The influence of directionally dependent propagation is evident for two recent destructive events: the 1995 Hyogo-ken Nanbu (Kobe) earthquake (M_w 6.9) and the 2000 Tottori-ken Seibu event (M_w 6.6).

The complex pattern of destruction within Kobe in 1995 reflects the interaction of the fault rupture with complex 3D structure beneath the city (see, e.g., Furumura and Koketsu, 1998, 2000). The pattern of reported intensities across the western part of Japan (Fig. 10) from the 1995 Kobe event shows considerable asymmetry, with contours of comparable intensity extending much further to the west. This western zone is the region where we have identified the most efficient propagation of Lg within Japan. To the east Lg still propagates but with reduced amplitude. The differences can be illustrated by considering the records from two strong

ground motion instruments operated by the Japan Meteorological Agency (JMA) at similar distances from the Kobe event. We have extracted velocity records from the accelerograms at Fukuoka (FKK) and Tokyo (TOK) at ranges close to 445 km from the source. Station FKK lies in a zone of JMA intensity 2 (on a seven point scale), whereas TOK has only intensity 1 even though it is situated on top of the lowvelocity sediments of the Kanto basin, which can give substantial amplification. Three-component records at each station are displayed in Figure 10, and each record is normalized to the maximum total energy so that the relative sizes of the three components are preserved. Lg is both more prominent at FKK, particularly on the transverse component and at higher frequency. At TOK there is a distinct lower frequency Lg component followed by larger amplitude surface waves trapped in the Kanto basin.



Figure 10. Distribution of seismic intensity (JMA seven-point scale) for the 1995 Hyogo-ken Nanbu (Kobe) earthquake (M_w 6.9) and an illustration of the differences in the regional phase patterns to the west and east of the event using three-component velocity records at similar range, derived from JMA accelerometers. The traces for each station have a common normalization. The amplitude scale is shown in the left.

Similar directional differences are seen for the Tottoriken Seibu event of 6 October 2000, which was well recorded by a new network of digital accelerometers (KIKNET and KNET). Figure 11 shows the contours of peak ground velocity derived from the KIKNET records, together with the locations of the stations in western Japan. The strike-slip event had a focal depth of 11 km, and estimates of the slip distribution (Yagi and Kikuchi, private comm.) suggest that a substantial component of the slip was quite shallow. The ground-velocity pattern is influenced by the presence of substantial sedimentary basins in the Osaka and Nagoya areas, which extend the 2 cm/sec contour to the east, with a local enclave near Nagoya. However, the overall pattern shows larger ground velocity extending substantial distances to the west. The origin of this effect can be seen in Figure 12, where we have extracted record sections of vertical and tangential component velocity records from the KIKNET stations, marked with solid triangles, which have a similar disposition relative to the focal mechanism.

The record sections in Figure 12 indicate the importance of the *SH*-wave contribution to the regional wavefield. The

approximately east–west propagation in the sections is dominated by Lg and later surface waves. To the west there is little P contribution to the tangential component, but in the east some off-great-circle propagation occurs, particularly on the edges of the sedimentary basins (200–300 km), which also produce longer Lg coda. For the stations to the west of the source, in addition to prominent Lg which explains the extension of the peak ground velocity contours to the west, we also see a clear contribution from the fundamental modes of Rayleigh waves (Rg) and Love waves (LQ). These waves with periods around 8 sec become even more prominent in the ground displacement. The strong shallow slip is likely to be the cause of the level of excitation of the fundamental mode surface waves.

A notable feature of the Tottori-ken Seibu earthquake is the large discrepancy between the magnitude estimate by the JMA (M_j 7.3) and the moment magnitude M_w 6.6 estimated for teleseismic records by various agencies (U.S. Geological Survey, Earthquake Research Institute) and also from Japanese broadband records in the FREESIA network (NIED). We believe that this problem is caused in large part by the



Figure 11. Contoured peak ground velocity in cm/sec for the Tottori-ken Seibu earthquake (6 October 2000), with the location of KIKNET stations (triangles). Stations used in the record section in Figure 12 are indicated by larger triangles.



Figure 12. Record section of seismic velocities from the 2000 Tottori-ken Seibu earthquake derived from KIKNET accelerograms. Vertical (Z) and tangential (T) components are displayed; traces for the same station have a common normalization.

distance correction term employed in the standard magnitude formula for Japanese events (Tsuboi, 1954): in terms of the maximum amplitude of the north and east components in microns and the epicentral distance, Δ , in km, the magnitude for events shallower than 50 km is estimated as

$$M_{\rm j} = 0.5 \log (A_{\rm N}^2 + A_{\rm E}^2) + 1.73 \log \Delta - 0.83.$$
 (1)

This expression was derived mainly from a study of subduction zone earthquakes around Japan, and the geometric spreading term would be appropriate to an attenuated body wave. When applied to the KIKNET and the KNET data for the Tottori-ken Seibu event there is a rapid increase in the apparent magnitude of the event with distance away from the source (Fig. 13a,b). For stations in the immediate neighborhood the magnitude is about 6.5 and rapidly climbs to over 7.5 for stations beyond 400 km. A similar pattern of increasing magnitude for distant stations is also found using the acceleration records of the JMA network for the 1995 Kobe event.

The distance dependence of the magnitude can be largely suppressed by changing the distance correction term to reflect the dominant role played by the crustally guided waves for this event in western Japan, which is enhanced by working with displacement. The peak displacements for the Tottori-ken Seibu earthquake recorded at 200 KIKNET and 279 KNET stations are plotted in Figure 13 and decay more slowly with distance than predicted by the Tsuboi formula. A regression analysis of this data set yields an attenuation factor of $\Delta^{-0.92}$ as indicated in Figure 13a. An improved representation for the magnitude for the Tottori-ken Seibu event is

$$MI = 0.5 \log (A_{\rm N}^2 + A_{\rm E}^2) + 0.92 \log \Delta + 0.49, \quad (2)$$

which removes most of the distance dependence and yields



Figure 13. (a) Attenuation of peak horizontal displacement during the 2000 Tottoriken Seibu earthquake as a function of distance from the epicenter for KIKNET (solid triangle) and KNET (open circle) data. The two lines indicate different distance attenuation factors. The steeper line with a slope of -1.73 corresponds to the formula of Tsuboi (1954) used for the estimation of JMA magnitude. The second line with a slope of -0.92 was derived by a regression analysis using the data for this event. (b) Apparent magnitude of the event as a function of position estimated from Tsuboi's (1954) formula, and (c) recalculated apparent magnitude using equation (2) derived from regression analysis of the observed displacements. In both (b) and (c) the contours indicate the magnitude 6.6 assigned from waveform studies.

a magnitude in agreement with the moment magnitude estimates (6.6). The application of (2) still leaves a slight positive anomaly along the line of the western profile in Figure 13c where the fundamental modes were so prominent (Fig. 12). The distance dependence implied by (2) is similar to the $\Delta^{-0.833}$ correction used by Nuttli (1973) for *Lg* waves in eastern North America, which is based on a theoretical model for an Airy phases trapped in a crustal wave guide with a strong contrast at the Moho. With an allowance for greater intrinsic attenuation in western Japan, we have a close correspondence. For the region in western Japan where Lg propagates well, the Ml magnitude, based on the assumption that crustally ducted energy dominates, should be useful for shallow events away from the subduction zone.

Acknowledgments

B.L.N.K. would like to thank the Japan Society for the Promotion of Science for an Invitational Fellowship to the Earthquake Research Institute, University of Tokyo, during which much of this work was carried out. The various groups contributing to the JARRAY coordinated by the Earthquake Research Institute, University of Tokyo, are acknowledged for the cooperation that has made such a dense data set readily available for a wide variety of studies. KIKNET and KNET data are made available by the Japanese National Institute for Earth Sciences and Disaster Research in Tsukuba. Constructive comments from the critical reading of the manuscript by Dr. M. Hoshiba and an anonymous reviewer have been very helpful for the revision of the article.

References

- Bostock M. G., and Kennett, B. L. N. (1990). The effect of three-dimensional structure on Lg propagation patterns, Geophys. J. Int. 101, 355– 365.
- Campillo, M., B. Feignier, M. Bouchon, and N. Bethoux (1993). Attenuation of crustal waves across the alpine range, J. Geophys. Res. 98, 1987–1996.
- Chazalon, A., M. Campillo, R. Gibson, and E. Garnero (1993). Crustal wave propagation anomaly across the Pyrenean range comparison between observations and numerical simulations, *Geophys. J. Int.* 115, 829–838.
- Furumura, T., and K. Koketsu (1998). Specific distribution of ground motion during the 1995 Kobe earthquake and its generation mechanism, *Geophys. Res. Lett.* 25, 785–788.
- Furumura, T., and K. Koketsu (2000). Parallel 3-D simulation of ground motion for the 1995 Kobe earthquake: the component decomposition approach, *Pure Appl. Geophys.* 157, 2047–2062.
- Kadinsky-Cade, K., M. Barazangi, J. Oliver, and B. Isacks (1981). Lateral variations of high-frequency seismic wave propagation at regional distances across the Turkish and Iranian Plateaus, J. Geophys. Res. 86, 9377–9396.
- Kennett, B. L. N., (1993). Distance dependence of regional phase discriminants, Bull. Seism. Soc. Am. 83, 1155–1166.
- Kennett, B. L. N., and T. Furumura (2001). Regional phases in continental and oceanic environments, *Geophys. J. Int.* 146 (in press).

Kennett, B. L. N., E. R. Engdahl, and R. Buland (1995). Constraints on

seismic velocities in the Earth from travel times, *Geophys. J. Int.* **122**, 108–124.

- Kennett, B. L. N., S. Gregersen, S. Mykkeltveit, R. Newmark (1985). Mapping of crustal heterogeneity in the North Sea basin via the propagation of Lg waves, Geophys. J. R. Astr. Soc. 83, 299–306.
- Ni, J., and M. Barazangi (1983). High frequency seismic wave propagation beneath the Indian shield, Himalayan Arc, Tibetan Plateau, and surrounding regions: high uppermost mantle velocities and efficient *Sn* propagation beneath Tibet, *Geophys. J. R. Astr. Soc.* **72**, 655–689.
- Nuttli, O. W. (1973). Seismic wave attenuation and magnitude relations for eastern North America, J. Geophys. Res. 78, 876–855.
- Rapine, R. R., Ni, J., and T. M. Hearn (1997). Regional wave propagation in China and its surrounding region, *Bull. Seism. Soc. Am.* 87, 1522– 1636.
- Press, F., and M. Ewing (1952). Two slow surface waves across North America, Bull. Seism. Soc. Am. 42, 219–228.
- Ruzaikan, A. I., I. L. Nersesov, V. I. Khalturin, and P. Molnar (1977). Propagation of Lg and lateral variation in crustal structure in Asia, *Geophys. J. R. Astr. Soc.* 82, 307–316.
- Shima, H. (1962). On the velocity of *Lg* waves in Japan, *Quarterly Journal* of Seismology **27**, 1–6 (in Japanese).
- Tsuboi, C. (1954). Determination of the Gutenberg-Richter's magnitude of earthquakes occurring in and near Japan, *Zisin* **7**, 185–193.
- Utsu, T. (1956). On some remarkable phases on seismograms of near earthquakes (part 2), *Quarterly Journal of Seismology* **21**, 107–111 (in Japanese).
- Utsu, T., (1958). On the Lg phase of seismic waves observed in Japan, Quarterly Journal of Seismology 23, 61–76 (in Japanese).
- Yomogida, K., (1996). J-array: deep structure of the Earth, J. Phys. Earth 44, 655–656.

Earthquake Research Institute

University of Tokyo, 1-1-1 Yayoi

Bunkyo-ku, Tokyo 113-0032, Japan (T.F.)

Research School of Earth Sciences Australian National University Canberra ACT 0200, Australia (B.L.N.K.)

Manuscript received 31 October 2000.