Propagation of seismic waves away from earthquakes

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Abstract

The seismic records from significant earthquakes are profoundly affected by 3-D variations in crustal structure both in the source zone itself and in propagation to some distance. Even in structurally complex zones such as Japan and Mexico relatively coherent arrivals are found associated with different classes of propagation paths. The presence of strong lateral variations can disrupt the arrivals, and such effects can be modelled using a combination of simple ray concepts and detailed numerical modelling using e.g. the pseudospectral method. Where detailed structural control is available, 3-D computations can capture the character of the observations.

Introduction

Although the seismic source dictates a large part of the character of seismic disturbances, the influence of crustal structure can frequently be significant. Where events occur in complex 3-D structures, the structure in the immediate neighbourhood can have a significant impact on the focussing and defocussing of energy. Such local effects were very important in the Kobe earthquake of 1995. As the seismic waves spread away from the source the different components of the wavefield interact with crustal structure in a variety of ways which can lead to quite complex behaviour in the distance range out to a few hundred kilometers from the source.

The trapping of waves within sedimentary basins is well known and leads to complex, elongated wavetrains. The contrast in seismic properties at the base of the crust is generally large enough to lead to substantial reflection especially for waves at grazing incidence. The waves reflected at the base of the crust (or any intermediate boundary) return to the surface and can often be efficiently reflected back into the structure. Surface reflection without change of wavetype tends to be more efficient when the wavespeeds at the surface are not too high. The result is that a strong train of different classes of multiples of P and S can be established. The waveforms of such phase groups are composed of the interference of many different components and are quite sensitive to the presence of lateral heterogeneity since this will disrupt the superposition of the different multiples. The wave groups which are most commonly observed are Pg and Lg comprising P and S waves trapped within the crustal waveguide. In volcanic areas such as Japan and Mexico, mid-crustal interfaces are quite common and can have a significant role in shaping the ducting of seismic energy to considerable distances.

Energy from the source will also enter the mantle and will be refracted back to emerge at distances of the order of 200 km from the source. In regions where there is a significant velocity gradient at the top of the mantle, a strong interference head wave can be built up from multiple underside reflections at the crust-mantle boundary which enhances the amplitude of the mantle refracted phases such as Pn and Sn. The mantle arrivals avoid the

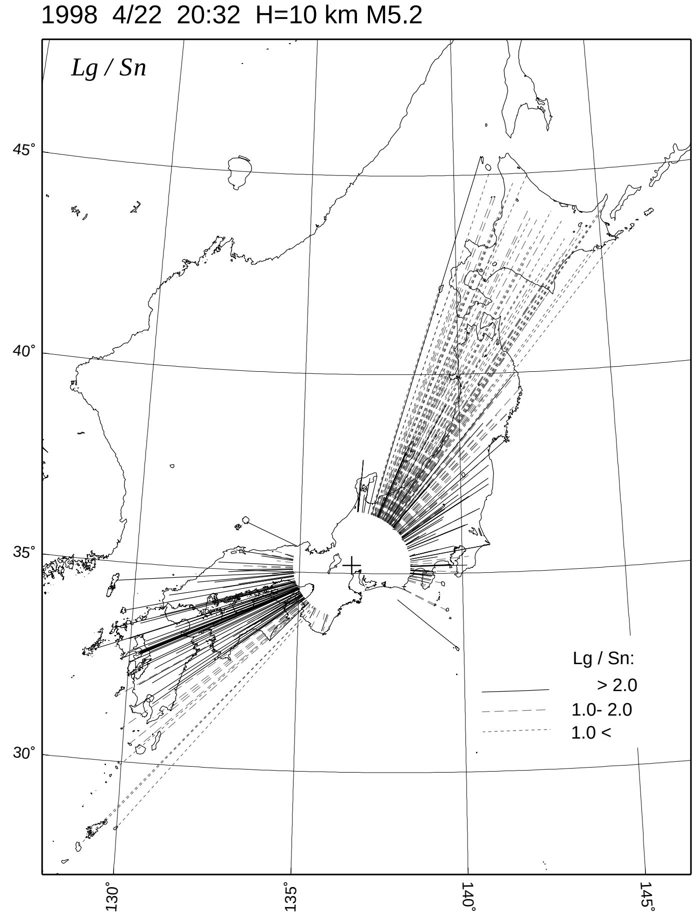

Figure 1: Summary of regional S wave propagation from the central Honshu event in terms of the relative amplitudes of Lg and Sn.

complexity of crustal structure and can provide a convenient comparator for the behaviour of the crustal arrivals.

Examples of regional phases in Japan

The relatively high density of seismic stations in Japan provides an excellent opportunity to map out the variations in regional phases across the country using sources both in the off-shore subduction zones and crustal sources inland (Furumura & Kennett, 2000 [6]) 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. However, much of western Japan shows good propagation as illustrated by the results for an event in central Honshu (figure 1), where the propagation characteristics of Lg are summarized using the amplitude ratio between Lg and the mantle phase Sn, which is relatively insensitive to local site effects. The paths are coded with continuous lines representing more efficient propagation. There is clear Lg to the land stations in the west and for shorter distances to the northeast. However for paths to Hokkaido and northern Tohoku which cross the volcanic front Lg is suppressed, even though this is also known to be a zone of strong attenuation for Sn.

The significance of the Lg phase can be illustrated with seismograms for the 1995 Kobe earthquake (figure 2). These acceleration records show relatively strong Lg which is more dominant for propagation towards the west. The result is that the intensity pattern for the event has contours extended towards the west where crustally guided energy is most significant.

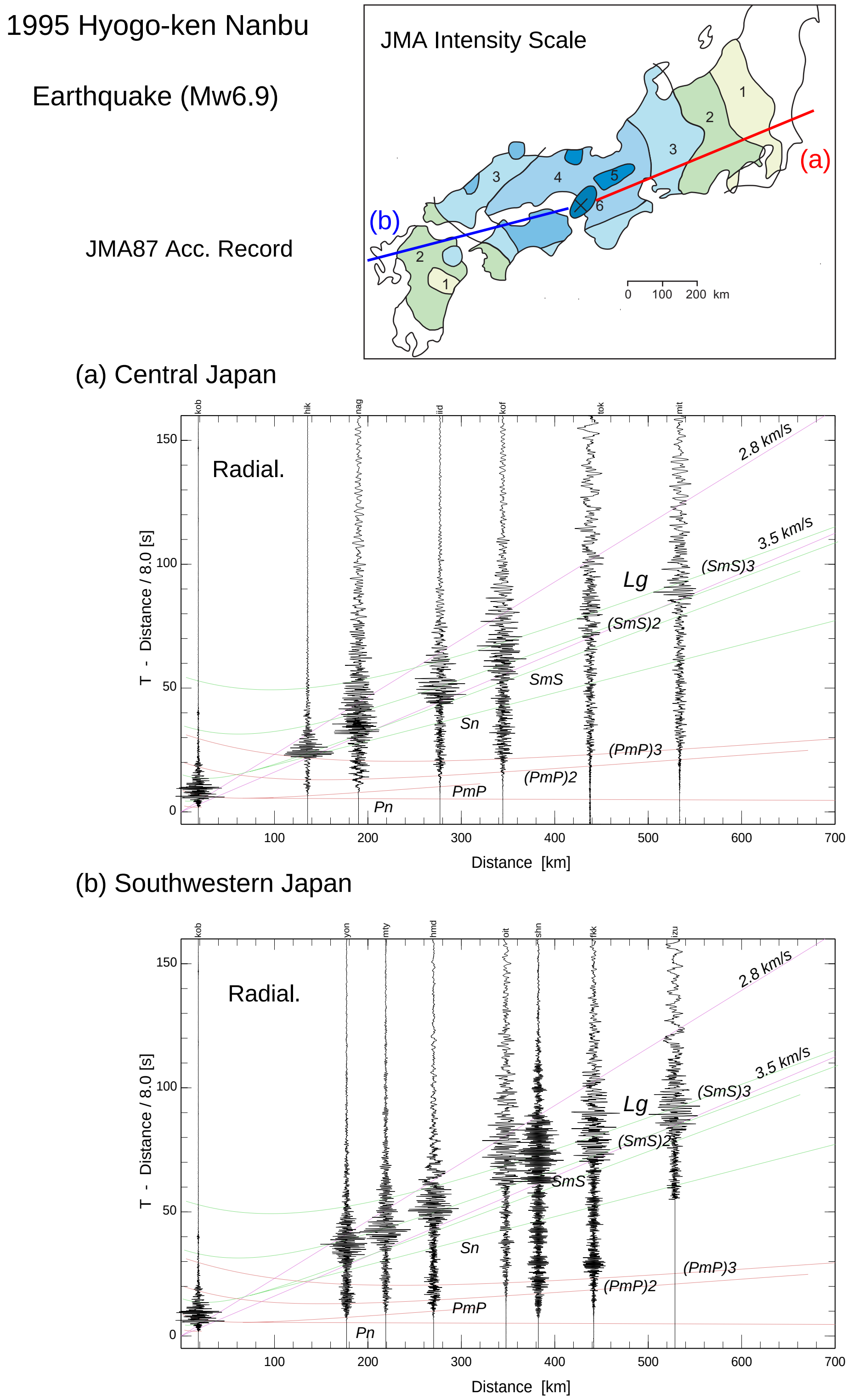

Figure 2: Intensity pattern for the 1995 Kobe event (JMA seven point scale) and records sections of acceleration seismograms (radial component) for the event.

Modelling of regional phases

Because the regional phases such as Pg, Lg involve the interference of multiple crustal arrivals, it is not easy to provide an effective simulation. Nevertheless, useful insight into behaviour can be gained by relatively simple means using ray methods in 2-D (Kennett, 1986 [2]), or 3-D (Bostock and Kennett, 1990 [1]; Kennett, Bostock and Xie, 1990 [3]). These techniques rely on following the patterns of multiple reflections in the crustal waveguide with the dominant effects arising from the topography at the surface and the crust-mantle boundary. This approach, linked to the analysis of seismograms, has provide strong evidence for multipathing e.g. associated with reflection from the continent-ocean transition, and also trapping of waves in narrow structures such as the peninsula of Baja California (Kennett et al, 1990 [3]).

More detailed analysis requires the use of direct numerical procedures, but these need to be applied in circumstances where the propagation range is long compared to seismic wavelengths. It has proved possible to employ pseudospectral techniques which do not require too fine a grid spacing to achieve a suitable balance between the computational requirements and the representation of the model (Furumura and Kennett, 1997,1998 [4],[5]). Relatively detailed models can be used for 2-D structure and this has enabled the study of a variety of structures which might provide potential blockage of Lg. Crustal thinning from above and below is very effective at disrupting the Lg wavetrain. Surficial conditions can also be important. A local zone of reduced velocities can provide significant signal amplification, as in Mexico City from the great 1985 Michoacan earthquake (Furumura and Kennett, 1998 [5]). A longer region of attenuative sediments will tend to leach energy from the S wavefield in the body of the crust into attenuating P and S waves in the sediments with a consequent diminution of Lg amplitude. The presence of a subduction zone close to the source can have a significant effect on the regional wavefield. For a source in or near the subduction zone, the sloping interface through the crust alters the beginning of the reverberation pattern for the P and S waves (Furumura and Kennett, 1998 [5]) and can tend to enhance the crustal trapped waves. For sources which lie inland away from the subduction zone, there is the possibility of multipathing with oblique reflection from the zone.

Figure 3 illustrates a 3-D simulation of the 1995 Kobe event, with snapshots of the horizontal ground motion, together with record sections of the radial component of ground velocity and the distribution of peak ground velocity at the surface obtained in the calculation. A simple point source has been employed in a 3-D model incorporating structure on the mid-crustal discontinuity and the Moho as well as the configuration of the Philippine plate beneath Western Japan. This simulation using a hybrid pseudo-spectral approach in horizontal coordinates and finite differences in depth (Furumura, Koketsu and Takenaka, 2000 [7]) is carried out on a $512\times256\times160$ node grid with horizontal spacing of 1.6 km and vertical spacing of 0.8 km. The 3-D simulation can provide results to frequencies approaching 1 Hz and can reproduce the general character of the regional wave propagation.

The challenge for the future is how to include all the relevant features in a 3-D calculation. The local influence of sedimentary basins is large but needs fine scale representation. The broad scale computation such as in figure 3 needs to be linked to finer resolution calculations for specific targets to allow the inclusion of detail at the level needed to provide a good representation of ground motion. The use of linked calculation schemes at different grid resolution presents some interesting computational issues.

1995 Hyogo-ken Nanbu (Kobe) Earthquake (Mw6.9, H=8km)

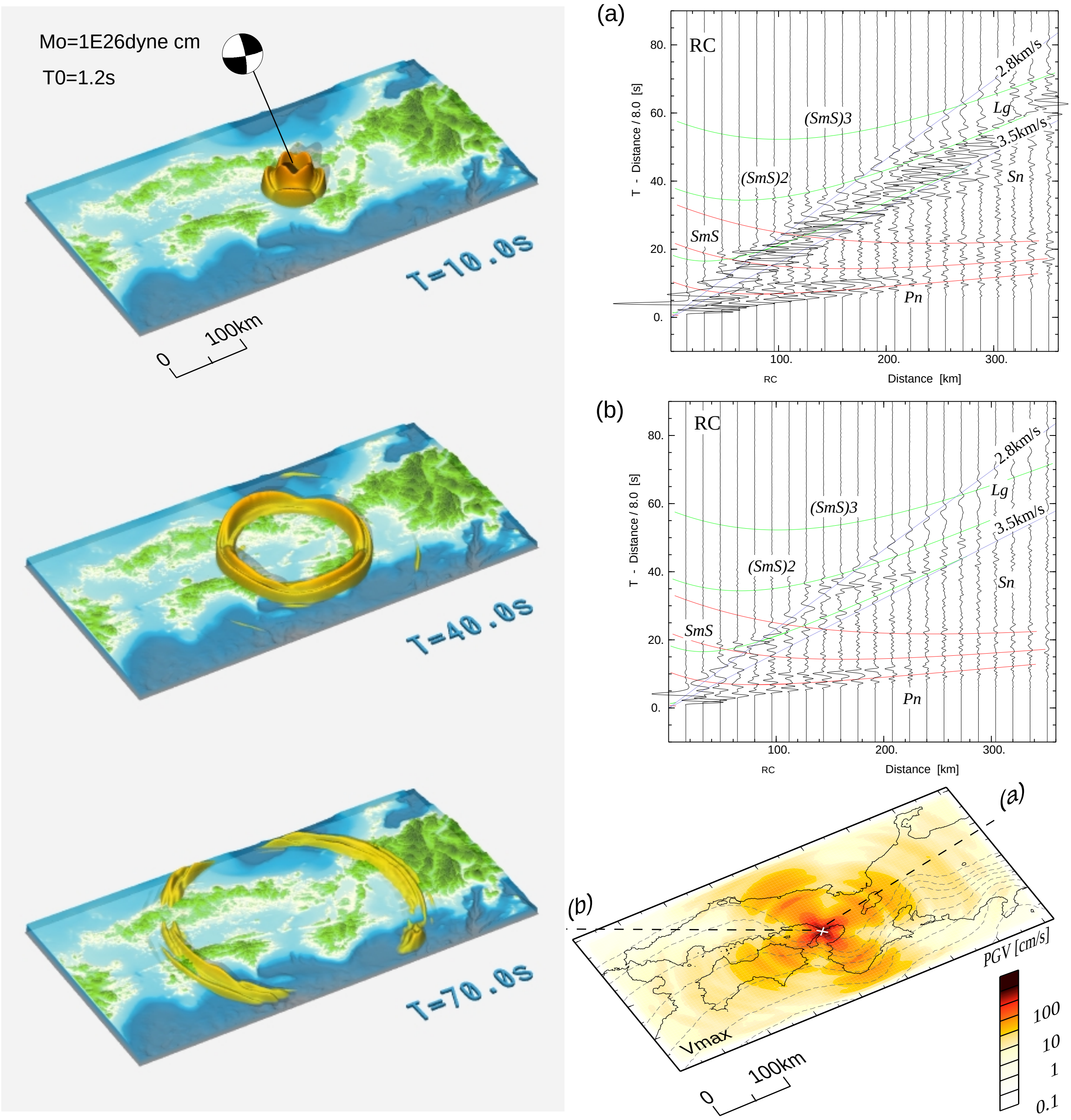

Figure 3: Snapshots of horizontal ground velocity, record sections of radial component velocity and the distribution of Peak ground velocity from a 3-D simulation of the Kobe event.

Acknowledgments

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