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7.6 Transverse components of explosion-induced Lg waves and upper crustal anisotropy

Introduction

Vertical components of Lg waves have been successfully modelled by many authors (e.g., Bouchon, 1982; Herrmann & Kijko, 1983), but specific problems occur when one attempts to model also their horizontal components. Synthesis of Lg waves produced by explosions and propagating in an isotropic vertically layered crust predicts displacement on the vertical and radial components only. Lg waves produced by explosions, however, commonly show transverse components as large or even larger than the vertical and radial ones both in Eurasia (Mykkeltveit & Husebye, 1981) and in the United States (Blandford, 1981). Examples of Lg recordings at NORSAR 3-component short period station 01A are given in Fig. 7.6.1 for 3 explosions fired at sea during the CANOBE and FENNOLORA refraction experiments (Cassell *et al*, 1983; Ansorge, 1981). The data have been band-pass filtered between 0.5 and 2 Hz. Note in particular that the Lg waves arrive on the transverse components as early as on the vertical or radial ones and cannot therefore be considered only as coda waves. These recordings are representative of a larger collection of NORSAR explosion recordings where Lg wave transverse components are systematically present and large. In the present case, the explosions were fired close to the sea-bed, 73 km from the coast for the CANOBE example, and close to the coast for the FENNOLORA recordings. The near-source structure certainly generates SV waves, but less likely large SH waves. Propagation in a complex structure is required to produce these transverse components.

The heterogeneous nature of the crust is more commonly invoked than anisotropy in order to explain complex polarization of short period waves, though anisotropy has been observed in various regions of the world, and its effect on polarization of body waves and surface waves is well-documented (see Crampin, 1977, for a review). We plan here to contribute to a better understanding of Lg wave propagation by presenting synthetic seismograms of explosion-induced 3-component Lg waves propagating in models with apparent upper crustal anisotropy.

Anisotropy in the upper crust

Shear-wave splitting, the most typical signature of anisotropy, is observed in an increasing number of regional and local studies. Of special interest to us is the analysis of Brooks *et al* (1987) who show evidence of crustal anisotropy in Scandinavia. Anderson *et al* (1974) and Hudson (1981) showed how a uniform distribution of aligned cracks in an otherwise isotropic matrix can be viewed in the long wavelength approximation as a homogeneous anisotropic material. Crampin *et al* (1984) proposed that widespread crustal anisotropy coherent over large areas proceeds from opening of microcracks in preferred directions related to the regional stress field. The polarization directions of observed split S-waves always support this hypothesis, which has become the most commonly accepted one to explain upper crustal anisotropy.

The nature and depth of the anisotropy are very seldom and poorly constrained by S-wave splitting data. Anisotropy confined to the first 10 km of the crust is the best model for Japan after Kaneshima *et al* (1988), and anisotropy to at least 6 km depth has been found in the crystalline basement of the Urals by Koshubin *et al* (1984). When the depth is not directly constrained, an anisotropy in the first few kilometers of the crust is usually consistent with the observations. Observed shear wave delays are often around 0.2 s (Kaneshima *et al*, 1988: Zollo & Bernard, 1989: Brooks *et al*, 1987) and suggest an open crack density of 0.1 over 5 km depth (or any combination giving the same delay such as 0.05 crack density over 10 km). More directly constrained velocities support a crack density averaging 0.05 (Babuska & Pros, 1984; Koshubin *et al*, 1984).

Model and modelling method

In accordance with the foregoing, we assume that the upper crust in Scandinavia has an apparent anisotropy due to a uniform distribution of circular vertical cracks with small aspect ratio and preferred orientation related to the regional stress field, as indicated schematically in Fig. 7.6.1. The formula for calculating the effective elastic coefficients of a medium containing dry og liquid-filled cracks are given in Crampin (1984) after Hudson (1981). We retain only the purely elastic perturbation due to the cracks, and neglect the anelastic part since one can estimate from Crampin (1984) that metric cracks with a 0.1 crack density lead to an attenuation factor Q^{-1} of the order 10^{-11} for the 1 Hz Lg wave. The attenuation depends on the crack radius in the power of 3 and is therefore even smaller for microcracks.

Our basic model for the Scandinavian crust is taken from Cassell *et al* (1983) who interpreted P-wave arrival times and amplitudes from the CANOBE refraction experiment along a profile which exactly fits the propagation path of the Lg wave from CANOBE shot H2 to NORSAR (Fig. 7.6.1). We have replaced the upper 5 km of their model, unconstrained by their data, by a layer having P-wave velocities increasing from 6 to 6.25 km/s. This is similar to what was found by Gundem (1984) in southern Norway, and accounts better for the group velocity and short duration of the observed Lg wavetrains in this area. We derive the S-wave velocity model from the P-wave velocity model assuming a Poisson ratio equal to 0.25. Quality factors are introduced in the model with frequency dependence of $\sqrt{f}$ after Campillo *et al* (1985). The model is displayed in Fig. 7.6.2.

The Lg modes in the frequency band 0.5 to 2 Hz are calculated in the anisotropic models at first order in deviation from isotropy using the quasi-degenerate perturbation method (Luh, 1973; Maupin, 1989). This method is capable of accounting for the full 3-D polarization of the Lg wave generalized modes, though retaining the advantages of treating anisotropy as a small perturbation of an isotropic model. The source for the explosions is taken as a unit pressure dirac at a depth of 150 m, chosen to mimic the refraction shots of the CANOBE profile, though very imperfectly since we cannot account for the water layer in which the explosions were fired or the sedimentary layer underneath. No absolute amplitude is tied to the source, and amplitudes of the synthetic seismograms are reported relative to the maximum amplitude of the synthetic seismogram in the isotropic reference structure. The ground displacement is convolved with the NORSAR short-period instrument response.

Explosion Lg waves and upper crustal anisotropy

Synthetic Lg waves calculated in models having various crack densities at various depths are presented in Fig. 7.6.3. These cases all correspond to a wave propagation direction at 15° from the crack normal preferred orientation, similar to the angle which can be inferred from Brooks *et al* (1987) between crack orientation in Scandinavia and propagation path to NORSAR of the Lg wave from the CANOBE shot H2 and FENNOLORA shot E2 (Fig. 7.6.1). The source-station distance is 450 km. The reference synthetic Lg wave calculated in the isotropic structure has of course no transverse component (Fig. 7.6.3a). For liquid-filled cracks between 0 and 10 km depth and a crack density of 0.02, a small transverse component appears (Fig. 7.6.3b). Increasing the crack density to 0.05 (Fig. 7.6.3c), the transverse component grows larger than the radial one. Note that this anisotropy, the amplitude and depth extension of which are compatible with observations of split shear wave delays (Brooks *et al*, 1987), yields relative amplitudes of the three Lg components that closely resemble the observations (Fig. 7.6.1). In Fig. 7.6.3d is shown the synthetic Lg wave when the cracks are confined to the upper 5 km of the crust with 0.1 crack density. The Lg wavetrain is lengthened on the three components. This lengthening appears also for other propagation directions. The last example (Fig. 7.6.3e) is for a uniform distribution of dry cracks in the upper 10 km of the crust with 0.05 crack density. The transverse components are not strongly developed in that case.

Synthetic Lg waves for wave propagation at other angles from the crack normal direction have also been calculated. For propagation in the crack orientation symmetry planes at 0 and 90°, no transverse component of course appears. For angles ranging from 0 to 45°, the Lg waves are like those for a 15° angle and displayed in Fig. 7.6.3. For angles approaching 90°, the amplitude of the transverse component decreases gradually and its maximum is shifted towards later arrival times. However, the onset time of the Lg wave or group velocity of its first wave packet does not depend on azimuth. The effect of upper crustal anisotropy on the Lg wave is basically a polarization effect and not a velocity effect.

Assuming a uniform anisotropy along the whole propagation path, we have calculated Lg synthetic seismograms for different epicentral distances. Besides fluctuations due to variations in modal interferences, which occur also in isotropic structures, it appears that the ratio between different components is stable with epicentral distance. For an epicentral distance of 150 km, at which the Lg wavetrain becomes an "individualized" wavetrain, the ratio between the transverse and vertical components in our synthetic data is already the ratio which is measured at 750 km, whether large or small. This is in agreement with observations made by Blandford (1981).

The extensive dilatancy anisotropy hypothesis of Crampin *et al* (1984) on which we have based our models, and the widespread character of transverse component observations, rather suggest a regional crustal anisotropy than a local one. We can, however, test the minimum lateral extension of an anisotropic zone necessary to explain the data. As for body waves, if anisotropy along only part of the wavepath introduces polarization anomalies, they are propagated to the station even if the remainder of the propagation path is isotropic. The analysis of Lg wave character as a function of epicentral distance implies that anisotropy over 150 km is sufficient to produce the observed polarization anomalies.

Conclusion

We have shown that an upper crust with a uniform distribution of microcracks aligned in the regional stress field can account for transverse components of Lg waves induced by explosions. Our preferred model to explain with upper crustal anisotropy the observations in Scandinavia is a distribution of liquid-filled cracks in the upper 10 km of the crust with a crack density larger than 0.02 and most favorably around 0.05. This model is consistent with observations of shear wave splitting by Brooks *et al* (1987) in northern Scandinavia.

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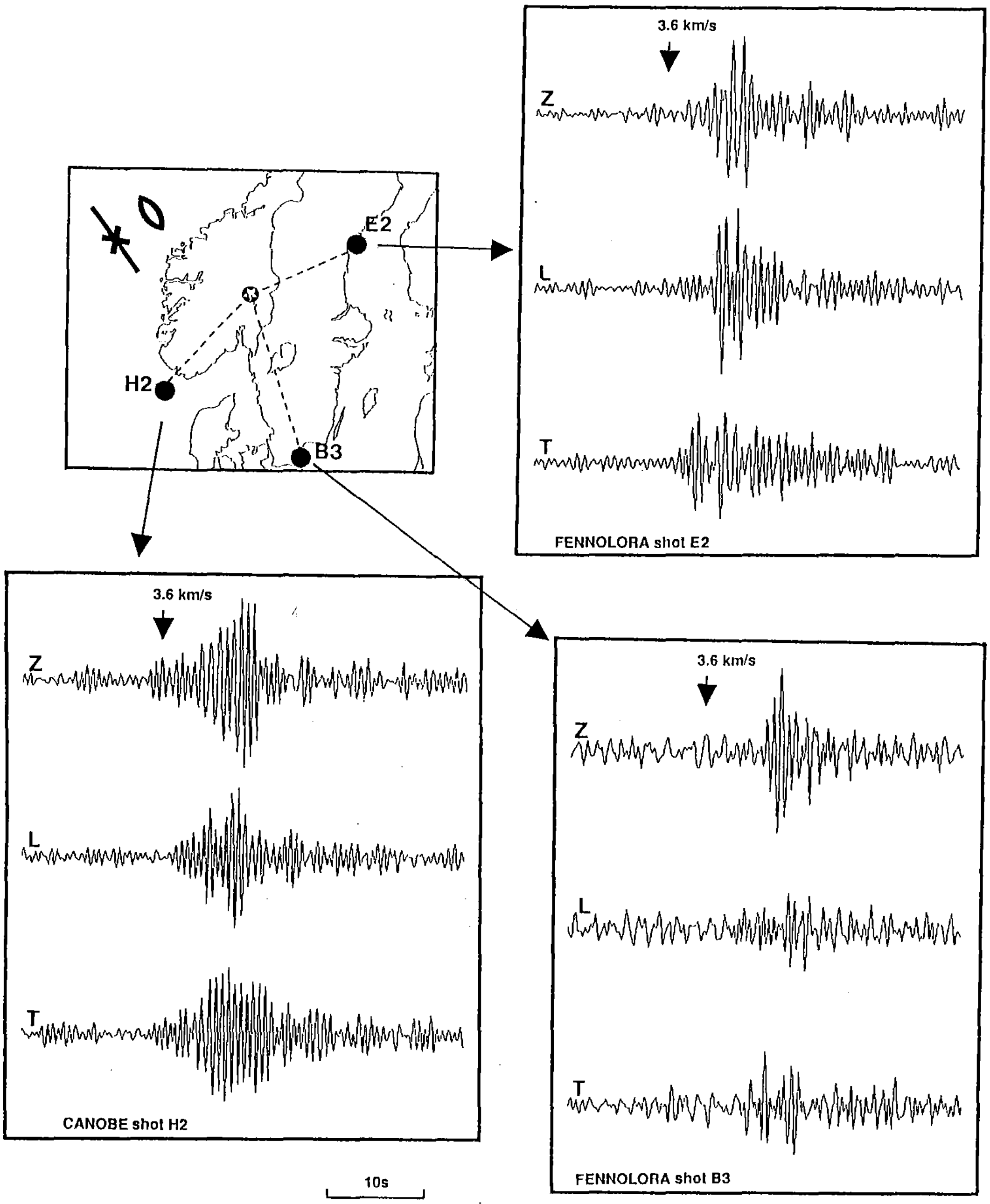


Fig. 7.6.1 3-component Lg recordings at NORSAR short-period station 01A of CANOBE shot H2 and FENNOLORA shots B3 and E2, band-pass filtered between 0.5 and 2 Hz. The arrival time of the wave with group velocity 3.6 km/s is indicated. The amplitude scale is identical on the three components for each recording. The direction of regional maximum horizontal compression and a schematic vertical crack opened by the regional stress field are indicated in the upper left corner of the map of southern Scandinavia.

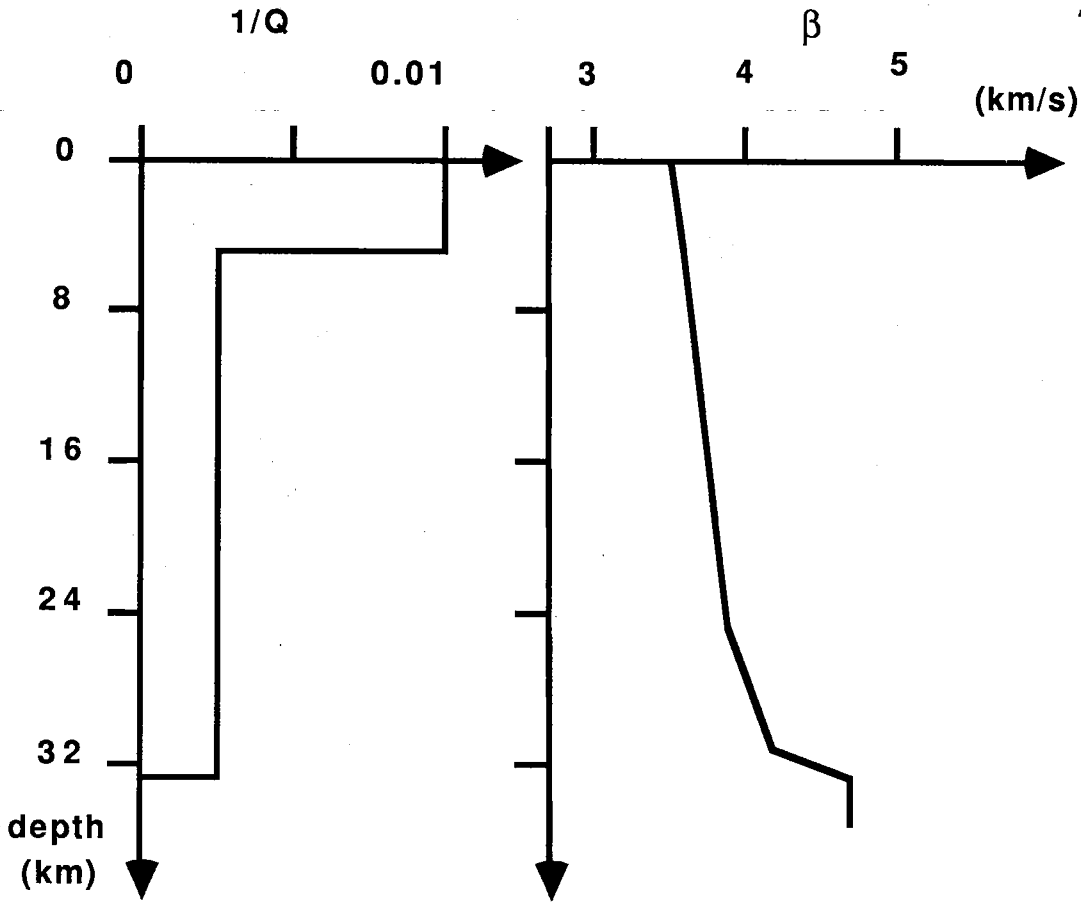


Fig. 7.6.2 Models of inverse quality factor at 1 Hz and shear wave velocity with depth used in the synthesis of the Lg waves.

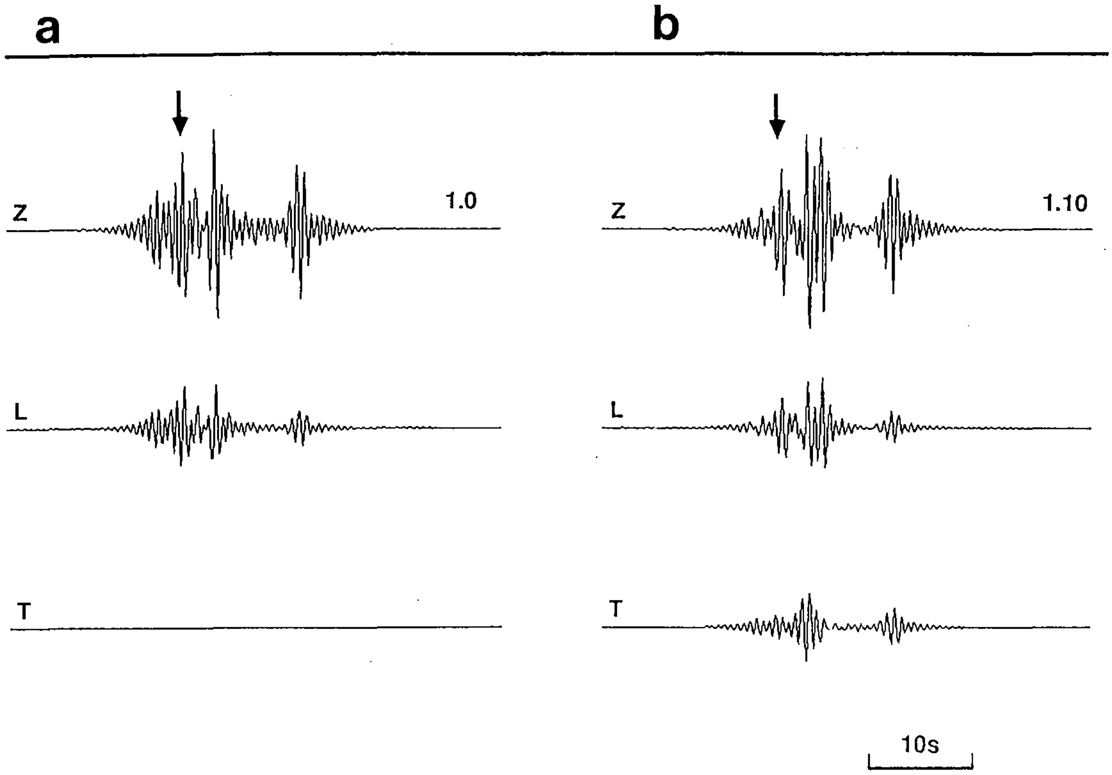
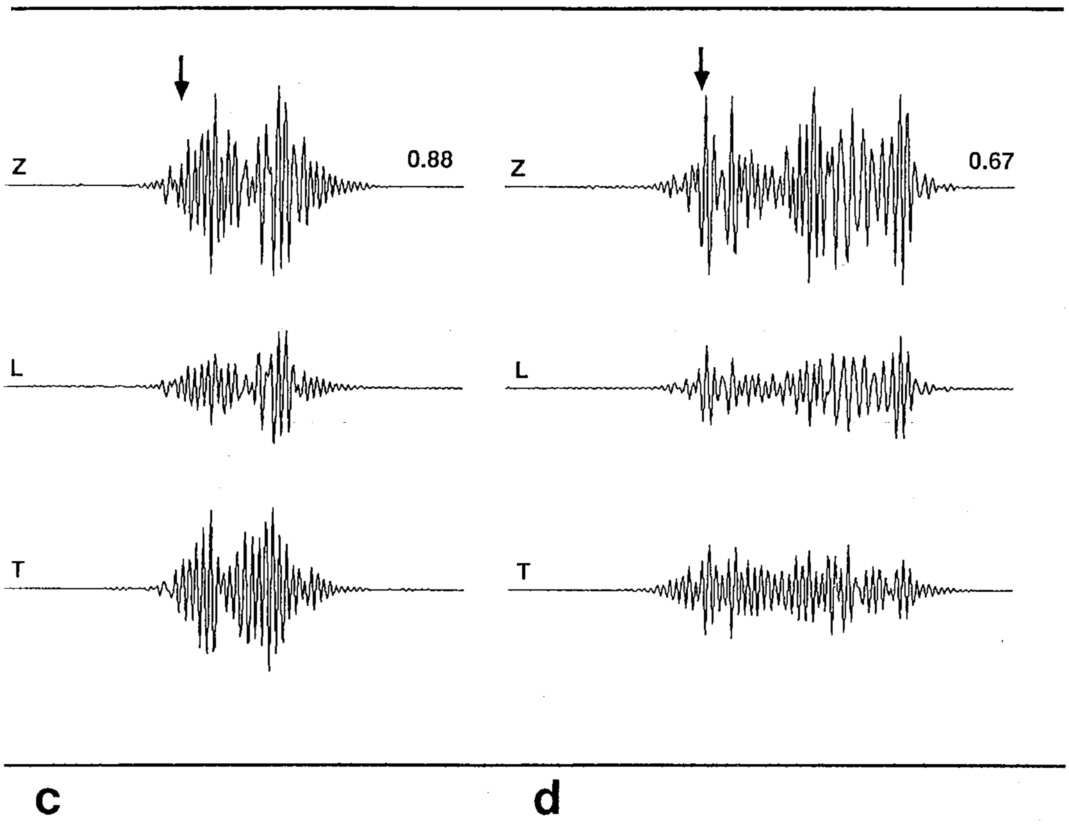


Fig. 7.6.3 3-component synthetic Lg waves produced by an explosion at 150 m depth and 450 km epicentral distance in different models of southern Scandinavia. (**a**) Isotropic model; (**b**) model with liquid-filled circular vertical cracks between 0 and 10 km depth, 0.02 crack density and orientation of the crack normal at 15° from the wave propagation direction; (**c**) the same as for case (b) for 0.05 crack density; (**d**) the same as for case (b) for 0.1 crack density and cracks between 0 and 5 km depth; (**e**) the same as case (c) for dry cracks. The arrow on the vertical traces indicates the arrival time of the 3.6 km/s group velocity wave. The three components of each plot have the same amplitude scale. The ratio between the maximum amplitude of the largest component and the maximum amplitude of the vertical component in the isotropic case is indicated in each 3-component plot at the end of the vertical trace.



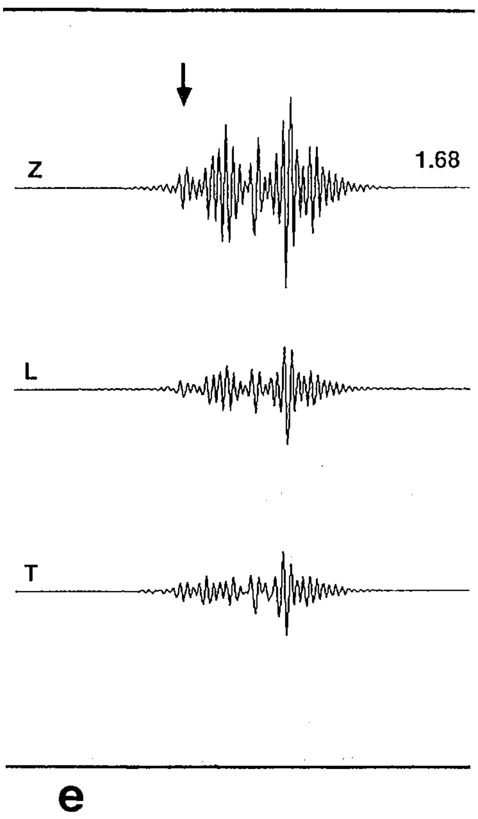


Fig. 7.6.3 (cont.)