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Final Report

Fundamental Studies of Seismic Body Wave Attenuation

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This contract was for work that had two principal parts. First, a study of the properties of seismic waves P_n and S_n. Second, a more general study of effects due to scattering, of seismic wave propagation in heterogeneous media.

The completed work resulted in six publications in reviewed journals, plus three publications in non-reviewed journals and books. [illegible]

The Ph.D. theses of two students were supported. One of these students (William Menke) went on to receive a Presidential Young Investigator award as a junior faculty member at Oregon State University.

The first reviewed publication was entitled " Crust-Mantle Whispering Gallery Phases: A Deterministic Model of Teleseismic P_n Wave Propagation" (by William H. Menke and Paul G. Richards, Journal of Geophysical Research, 85, 5416-5422, 1980). Teleseismic P_n waves are modeled as a sum of whispering galley waves, which propagate in a waveguide composed of a simple high velocity mantle lid underlain by a low velocity zone. This model is able to account for those P_n wave propagation properties that are not dominated by scattering that is, their apparent velocity and lack of long period energy. P_n apparent velocity data constrain the P wave velocity gradient in the upper 100 km of mantle to be low; $dv_p/dz < 0.001s$. The whispering gallery rays are shown to have significant amplitude (when compared to the direct P wave) and to have spectra that rapidly fall off at long periods. Yet this model cannot account for certain details of the observed P_n amplitude spectra. Most important among these is the spectral ratio of P_n to P, which the model underestimates by a factor of 10. Nevertheless, the model presents a useful framework for understanding some characteristics of P_n wave propagation and provides an estimate of the distribution of energy with depth in the P_n waves.

The second reviewed publication was entitled "On extending Biot's theory of low-frequency acoustic scatter about a rough fluid-rigid interface to more general acoustic media" (by William Menke and Paul G. Richards, Journal of the Acoustical Society of America, 71, 1101-1105, 1982). We extend Biot's [J. Acoust. Soc. Am. 44, 1616-1622 (1988)] boundary conditions for multiple scatter at low frequencies to a medium consisting of a fluid wholespace containing a layer of spherical fluid inclusions. At low frequencies the layer of inclusions has a scattering effect equivalent to that of a set of linear boundary conditions acting on the center of the layer. These boundary conditions are of order $k\tau$ where k is the wavenumber and τ is a measure of the size of the inclusions. The boundary conditions predict that a normally dispersed acoustic boundary wave can propagate along the plane of inclusions for specific acoustic contrasts between inclusions and wholespace. When the acoustic contrast is small the boundary wave exists only when the compressional velocity of the inclusions is slower than that of the wholespace. When the contrast is large, boundary waves exist on some layers of high-velocity inclusions as well.

The third reviewed publication was entitled "On extending Biot's theory of multiple scattering at low frequencies from acoustic to elastic media" (by William Menke, Geophysical Journal Royal Astronomical Society, 69, 819-830, 1982). We derive a linear, inhomogeneous boundary condition that approximately describes long-wavelength multiple scatter about a plane of spherical inclusions embedded in an elastic wholespace. This boundary condition relates the discontinuity in the displacement-stress vector to a description of the material properties of the inclusions and to spatial derivatives up to fourth order of the average displacement field across the plane. The boundary condition is an elastic medium analogue to Biot's boundary condition for scattering in an acoustic medium. While the acoustic theory predicts that a plane of rigid, fixed inclusions can support a boundary wave, our results suggest that in elastic media analogous modes are leaky.

The fourth reviewed publication was entitled "The horizontal propagation of P waves through scattering media: analog model studies relevant to long-range P_n propagation" (by William Menke and Paul G. Richards, Bulletin of the Seismological Society of America, 73, 125-142, 1983). We compare seismograms produced through the use of analog models of scattering and nonscattering Earth structure to access the effect of lateral heterogeneties on the horizontal propagation of P waves. Our results are applicable to propagation out to 16 degrees and to periods as short as 5 s. We find that layers of scatterers within the mantle near the turning points of P waves can cause these phases to have long coda similar in certain respects to the coda observed in long range P_n. The overall appearance of this coda is similar to that produced in laterally homogeneous models that include low velocity crustal material near their surfaces. Scatterers at shallower depths in the mantle of crust have a different effect. Those in the very uppermost mantle seem to suppress the horizontal propagation of P waves while those in the crust have very little overall effect, at least at the period range we studied. We also find that the scatterers have an amplifying effect on the horizontal propagation of the very longest periods (>20 s) an effect that may be related to the scattering controlled boundary waves discovered by Biot (1968).

The fifth reviewed publication was entitled "The apparent attenuation of a scattering medium" (by Paul G. Richards and William Menke, Bulletin of the Seismological Society of America, 73, 1005-1021, 1983). We report the results of some numerical experiments that bring out the low-pass characteristics of a purely elastic medium with a heterogeneous velocity structure. Although the typical fluctuation is spatially confined within less than a wavelength, waves propagating over a sufficiently long path suffer major cumulative effects. We summarize the removal of high frequencies during transmission by a frequency-independent apparent Q, and show that attenuation by intrinsic friction and scattering are approximately additive. We propose some diagnostics that might help to distinguish the presence of velocity fluctuations and resultant scattering from the presence of anelasticity and true dissipation. When scattering dominates over intrinsic friction: (1) the coda of a transmitted wave contains relatively higher frequencies than the initial pulse; (2) the attenuation deduced from the power spectrum of the transmitted wave is greater than that deduced from the phase spectrum; (3) compressional and shear wave apparent Q's are approximately equal; and (4) estimates of apparent Q made from reflected coda vary with frequency, while estimates made from the transmitted waves do not. We also outline several topics in the theory of wave propagation that will be relevant in a satisfactory interpretation of short-period observations, if the amplitude of such signals is affected by scattering.

This publication has since been referenced by many authors, and has triggered a series of papers by Robert Burridge and co-workers.

The sixth reviewed publication was entitled "On wave fronts and interfaces in anelastic media" (by Paul G. Richards, Bulletin of the Seismological Society of America, 74, 2157-2165, 1984). When a wave front is incident upon an interface between two anelastic media, the amplitudes of transmitted and converted waves can grow exponentially with distance from the interface. Such phenomena can be reconciled with radiation conditions. For waves from finite sources within multi-layered anelastic media, and particularly for waves studies by generalized rays, the choice between scattered waves that grow and those that decay can usefully be made with reference to the corresponding elastic problem, rather than relying on radiation conditions.

The first non-reviewed publication was entitled "Seismic wave propagation effects-development of theory and numerical modeling" (by Paul G. Richards, Chapter in DARPA commemorative volume, The VELA Program: A Twenty-Five Year Review of Basic Research, ed. A.U. Kerr, 183-251, 1985). Methods applied to the detailed interpretation of seismograms are discussed, emphasizing what has been learned about Earth structure (rather than the seismic source). The theory and practice of working with synthetic seismograms is described in broad terms. The main idea is to work with the sum (or integral) over wave solutions in separated variables. The sum is taken over horizontal wavenumber (or ray parameter), and frequency. The terminology of normal modes, surface waves, and body waves, supplies three somewhat different perspectives. Some detailed examples are given of the opportunities and problems of seismic wave analysis, where there is influence from structure in the crust, and/or mantle, and/or core. At periods (T) greater than about twenty seconds, there is now, in general terms, a fairly complete understanding of seismograms, apart from certain effects due to lateral variation in Earth structure. For $1<T<20$ seconds, only limited portions of a teleseismic record (e.g., about 15 seconds following a P-arrival, or 30 seconds after SH) may be well understood. At the short-period end of this range there is debate about trade-offs between the seismic source (for a particular event, is it strong or weak?) and attenuation in the Earth (strong, or weak). For methods based on spherically symmetric Earth models, and particularly clean data sets (why are they clean?), excellent agreement between waveform synthetics and data is often possible. But of course this is not enough, particularly in deciding the trade-off between source spectrum and attenuation; and sometimes the agreement is less than excellent. This paper will give a case for interpreting body wave observations in terms of Earth models with quite low intrinsic friction for teleseismic short-period phases, and will criticize certain use of absorption band models in which pulse broadening is linked to properties of pulse amplitude spectra. Scattering, either by thin layering in the mantle or by lateral and vertical heterogeneities, may plan an important role. The success of future analysis may lie in separating the deterministic component of the Earth's profile (i.e., a standard model in which there is smooth variation of velocity with depth, plus a few discontinuities), from a superimposed statistical component. As we face the complications of an Earth which internally may be inhomogeneous on all spatial scales, with evidence too for some anisotropy in the upper mantle, it is clear that our science is now restrained by inadequacy of our data.

The second non-reviewed publication was entitled "Modeling seismic wave propagation in 2-D and 3-D structures" (by Dean Witte and Paul G. Richards, Lamont-Doherty Geological Observatory Yearbook, 64-68, 1987).

The third non-reviewed publication was entitled "The pseudospectral method for simulating wave propagation" (by Dean C. Witte and Paul G. Richards, Proceedings of the Second IMACS Symposium on Computational Acoustics, North-Holland, 1989). We review several aspects of implementing the pseudospectral method for solving the linear equations of propagation of acoustic waves in fluids and elastic waves in solids. Because the intended applications were principally in seismology, particular attention was paid to the effects of heterogeneity in the medium; to methods that address practical problems of 2D and 3D wave propagation in a medium larger than that which may easily be represented by a finite grid; and to methods of quantifying attenuation due to intrinsic friction.

STATEMENT "A" per Randy Jacobson
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