Head Waves, Diving Waves and Interface Waves at the Seafloor

Ralph Stephen, WHOI

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MOTIVATION

When seismic energy from earthquakes or acoustic energy from sources in the ocean interacts with the seafloor a broad range of elastic wave phenomena are excited.

Since we are talking about ”interface waves” we must include rigidity, that is “elastic” waves.

The goal of this talk is to review the various wave types that occur in seafloor bottom interaction and to give examples of how they have been applied.

OUTLINE

Wave types are defined in the context of a model (or representation) of the seafloor structure. These include:

1) A homogeneous fluid half-space overlying a homogeneous solid half-space.
2) A homogeneous fluid half-space overlying a solid half-space in which P and S velocities increase with depth.
3) A homogeneous fluid layer (with a free surface) overlying a homogeneous solid half-space.
4) A homogeneous fluid layer (with a free surface) overlying a solid half-space in which P and S velocities increase with depth.
5) Waveguides in the water layer (the SOFAR channel) and/or in the seafloor (the sediment layer)

REFERENCES

Brekhovskikh, L.M. (1960). Waves in layered media. Academic Press, New York.

Cagniard, L. (1962). Reflection and refraction of progressive seismic waves. McGraw-Hill, New York.

Cerveny, V. and R. Ravindra (1971). Theory of seismic head waves. University of Toronto Press, Toronto.

Rauch, D. (1980). Seismic interface waves in coastal waters: a review. SACLANT ASW Research Center, San Bartolomeo (SP), Italy.

Wave Equations

1) The elastic wave equation for isotropic, perfectly elastic, heterogeneous media can be written:

$$\rho\ddot{\mathbf{u}} = (\lambda+\mu)\nabla(\nabla\cdot\mathbf{u}) + \mu\nabla^2\mathbf{u} + \left[\nabla\lambda(\nabla\cdot\mathbf{u}) + \nabla\mu\times(\nabla\times\mathbf{u}) + 2(\nabla\mu\cdot\nabla)\mathbf{u}\right]$$

where **u** is the displacement vector, λ and μ are Lamé's parameters and ρ is density. The terms in square brackets are zero for homogeneous media.

2) If the shear modulus is set to zero in the elastic wave equation we obtain the acoustic wave equation in terms of displacement:

$$\rho\ddot{\mathbf{u}} = \lambda\nabla\left(\nabla\cdot\mathbf{u}\right)+\left[\nabla\lambda\left(\nabla\cdot\mathbf{u}\right)\right]$$
$$= \nabla\left(\lambda\left(\nabla\cdot\mathbf{u}\right)\right)$$

This form of the acoustic wave equation is useful for studying problems with coupled fluids and solids.

3) The acoustic wave equation is more commonly expressed as a scalar wave equation in terms of pressure, :

$$\rho\ddot{P} = \lambda\nabla^2 P + \left[\lambda\rho\nabla(1/\rho)\cdot\nabla P\right] = \lambda\rho\nabla\cdot\left((1/\rho)\nabla P\right)$$

For the acoustic case, with shear modulus μ equal to zero, λ equals k, the coefficient of compressibility of the fluid and $\alpha = (\lambda/\rho)^{1/2}$.

4) If the time history of the source is a single frequency sine wave (CW), then it is convenient to take the Fourier transform in time of the pressure wave equation (3):

$$-\rho\omega^2\hat{P} = \lambda\nabla^2\hat{P} + \left[\lambda\rho\nabla(1/\rho)\cdot\nabla\hat{P}\right]$$

where ω is angular frequency. For homogeneous media, that is without the term in square brackets this is the scalar Helmholtz equation.

5) In the elastic wave equation (1) the assumption of slowly varying or homogeneous media with some symmetry considerations leads to a separation in terms of compressional and shear wave displacement potentials (now both scalars), ϕ and ψ which satisfy:

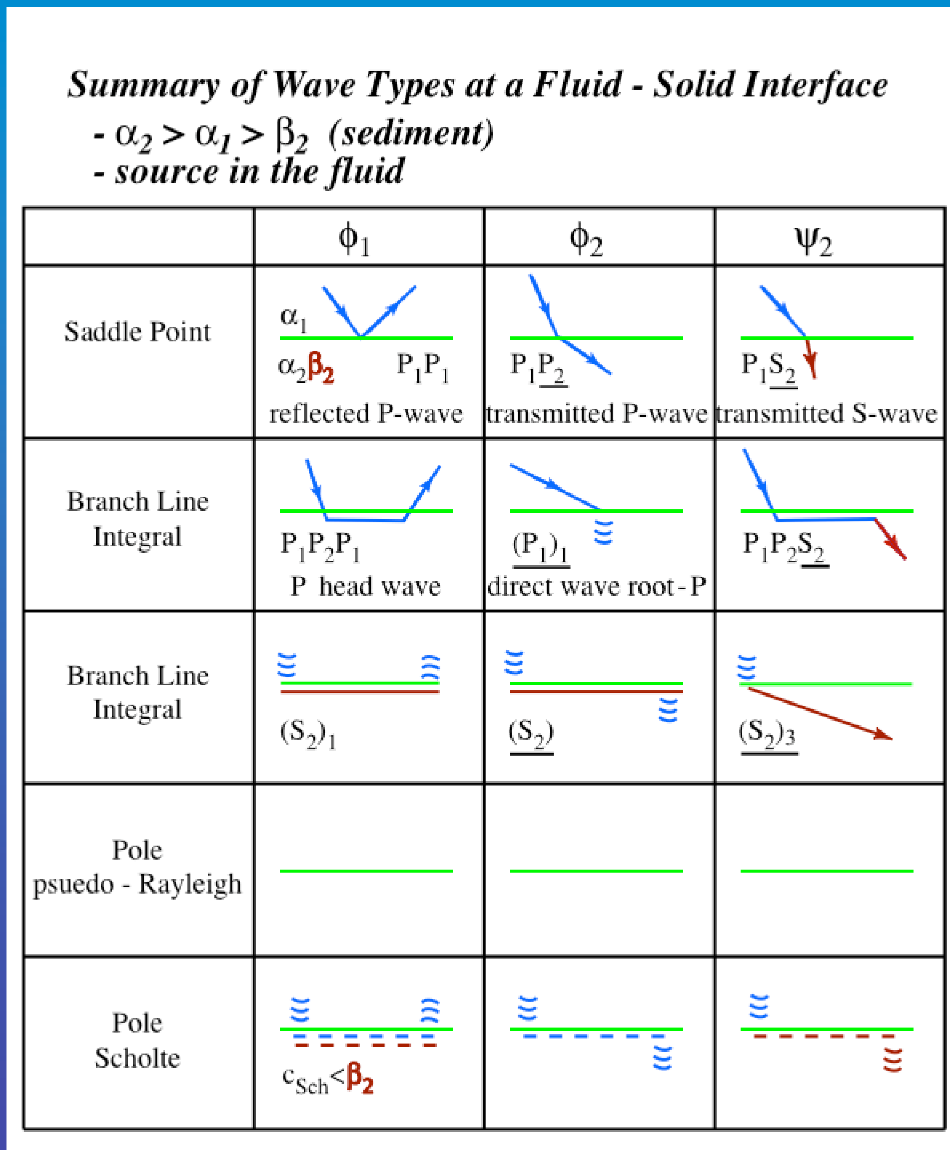
$$\mathbf{u} = \nabla\phi + \nabla\times\psi$$

$$\nabla\cdot\psi = 0$$

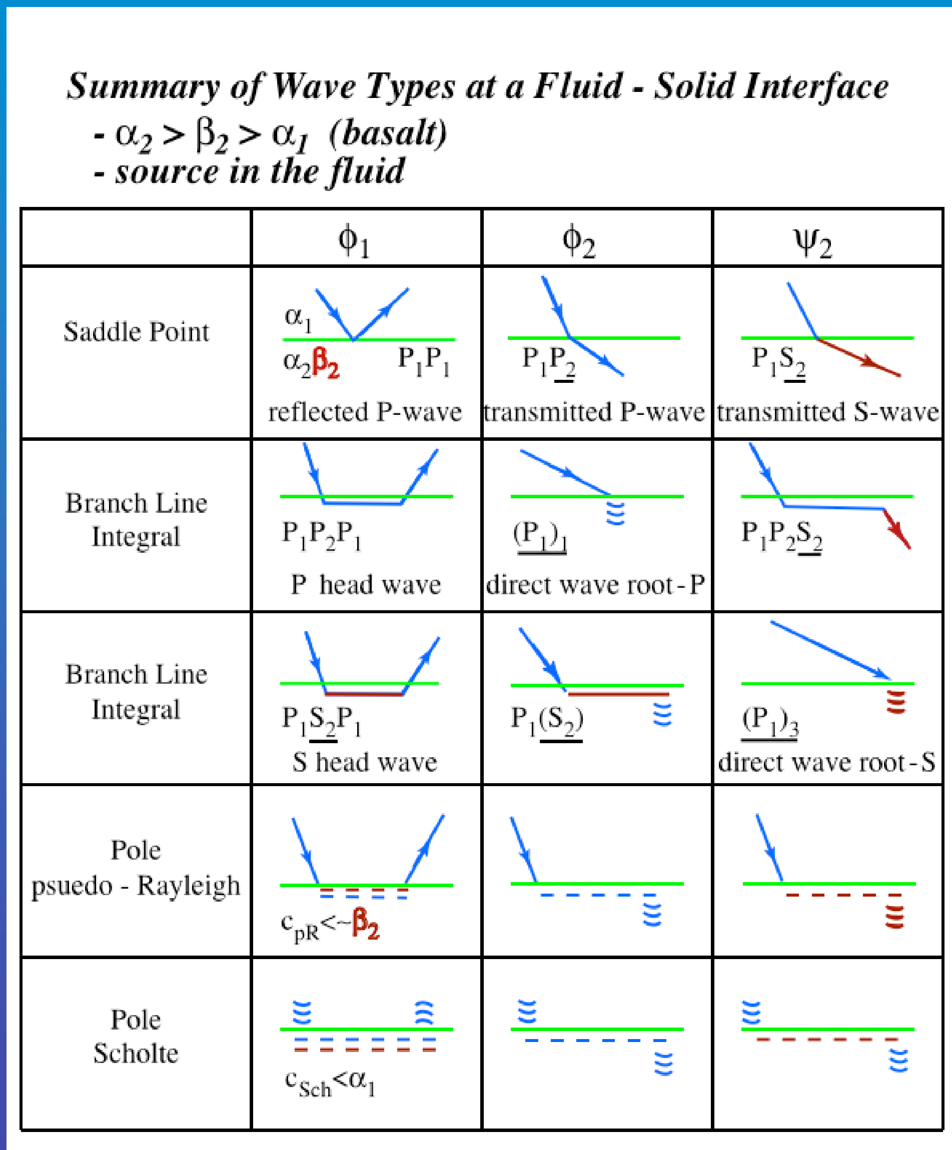
$$\ddot{\phi} = \alpha^2\nabla^2\phi$$

$$\ddot{\psi} = \beta^2\nabla^2\psi$$

In this case the compressional and shear wave speeds are $\alpha = \left(\left(\lambda + 2\mu\right)/\rho\right)^{1/2}$ and $\beta = \left(\mu/\rho\right)^{1/2}$.

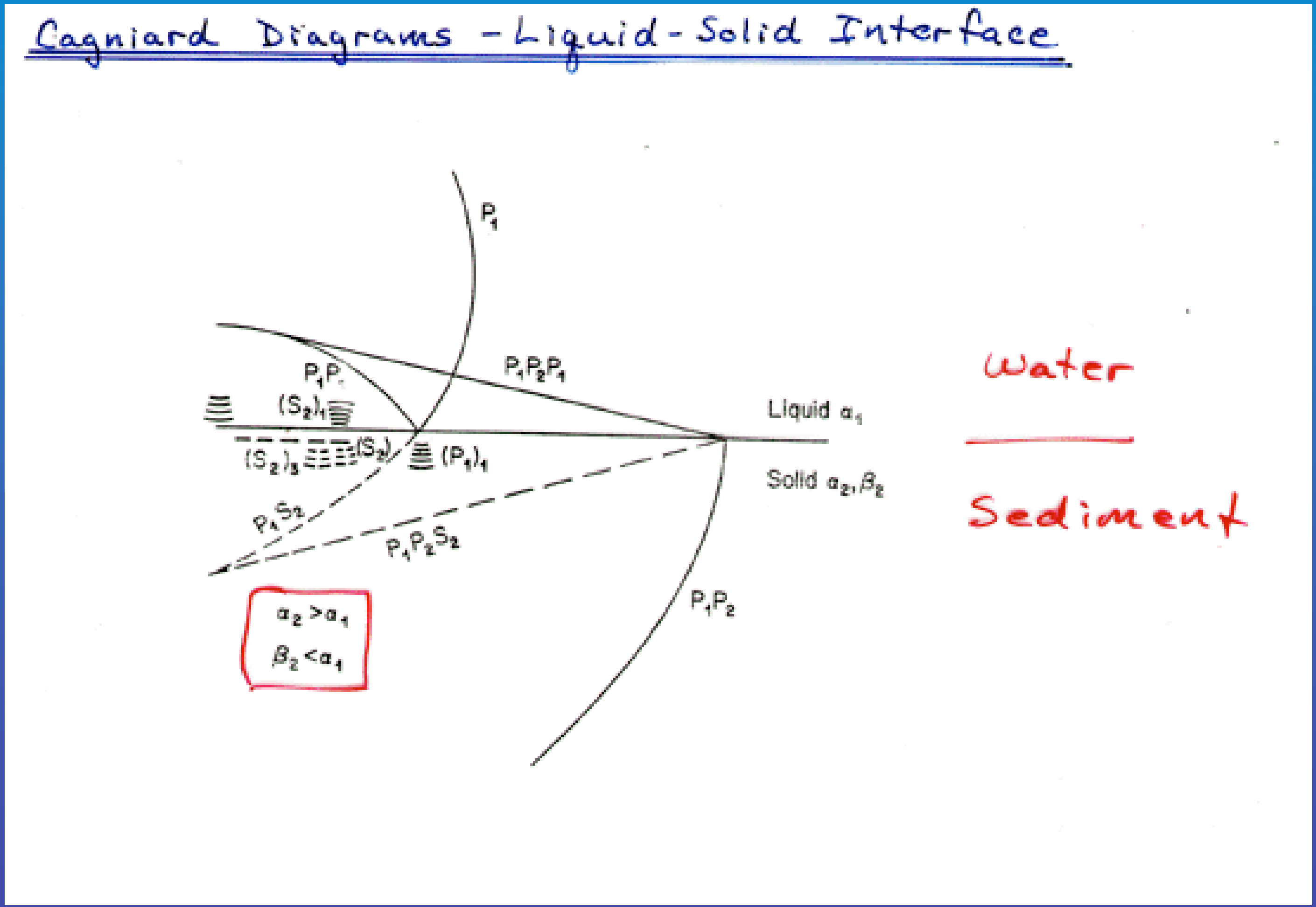


Summary of wave types at the <u>water-sediment</u> interface based on Brekhovskikh (1960). Assumes homogeneous half-spaces.

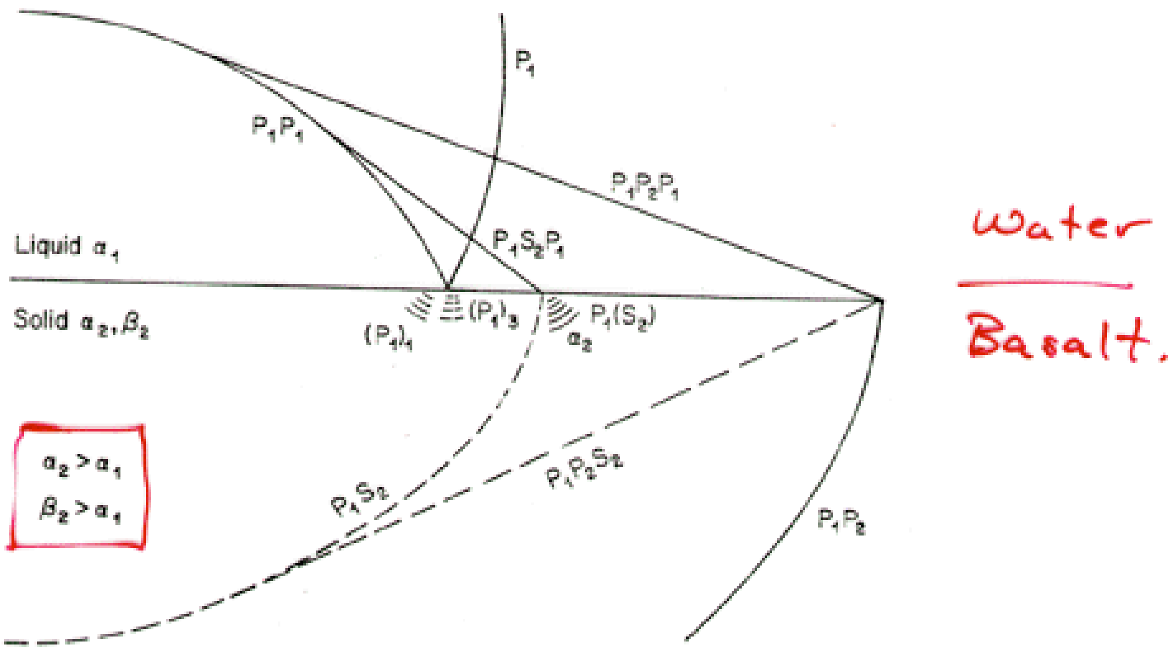


Summary of wave types at the water-basalt interface based on Brekhovskikh (1960). Assumes homogeneous half-spaces.

Wavefront diagrams based on Cagniard (1962) for a water-sediment interface.

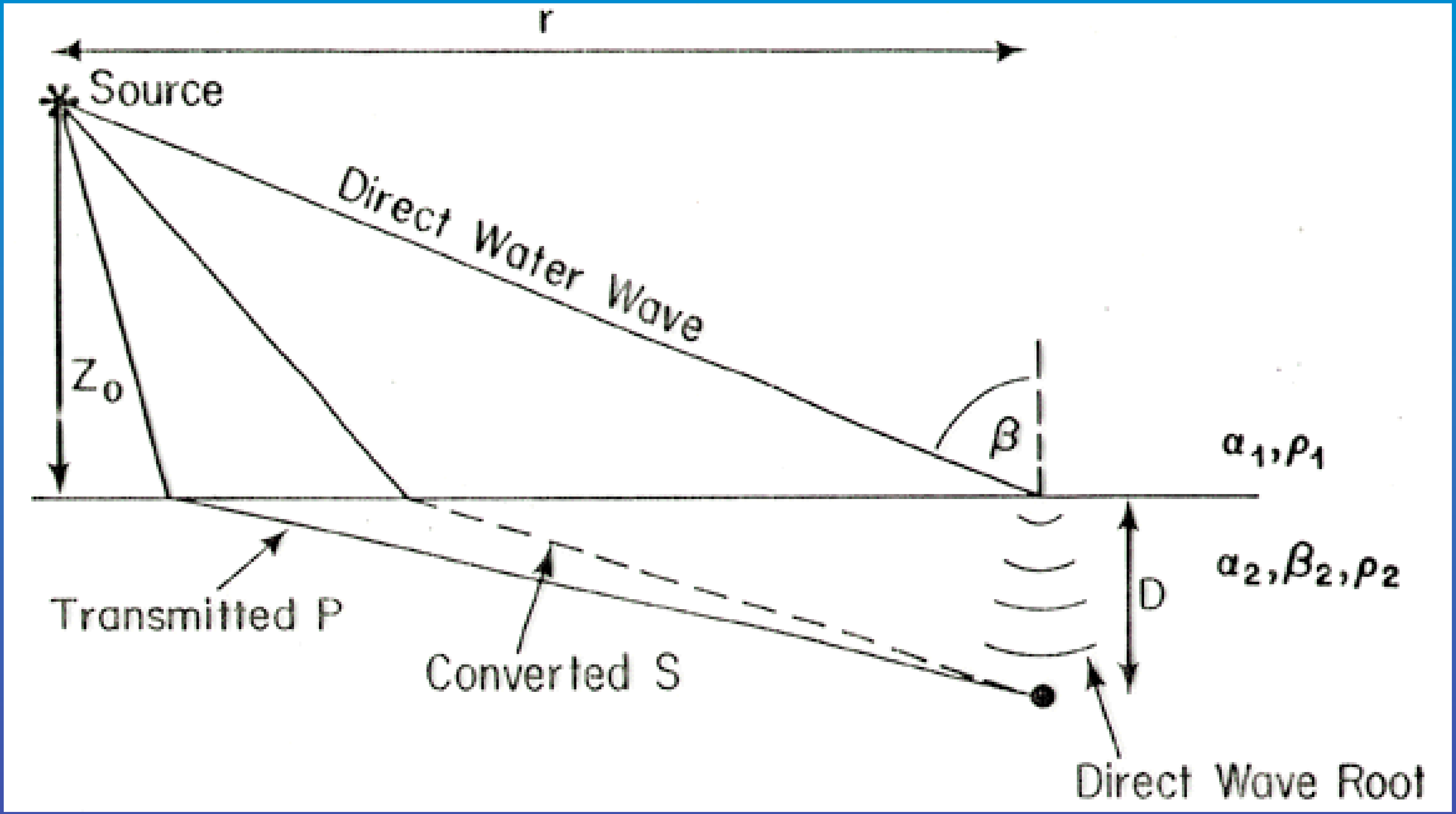


Wavefront diagrams based on Cagniard (1962) for a water–basalt interface.



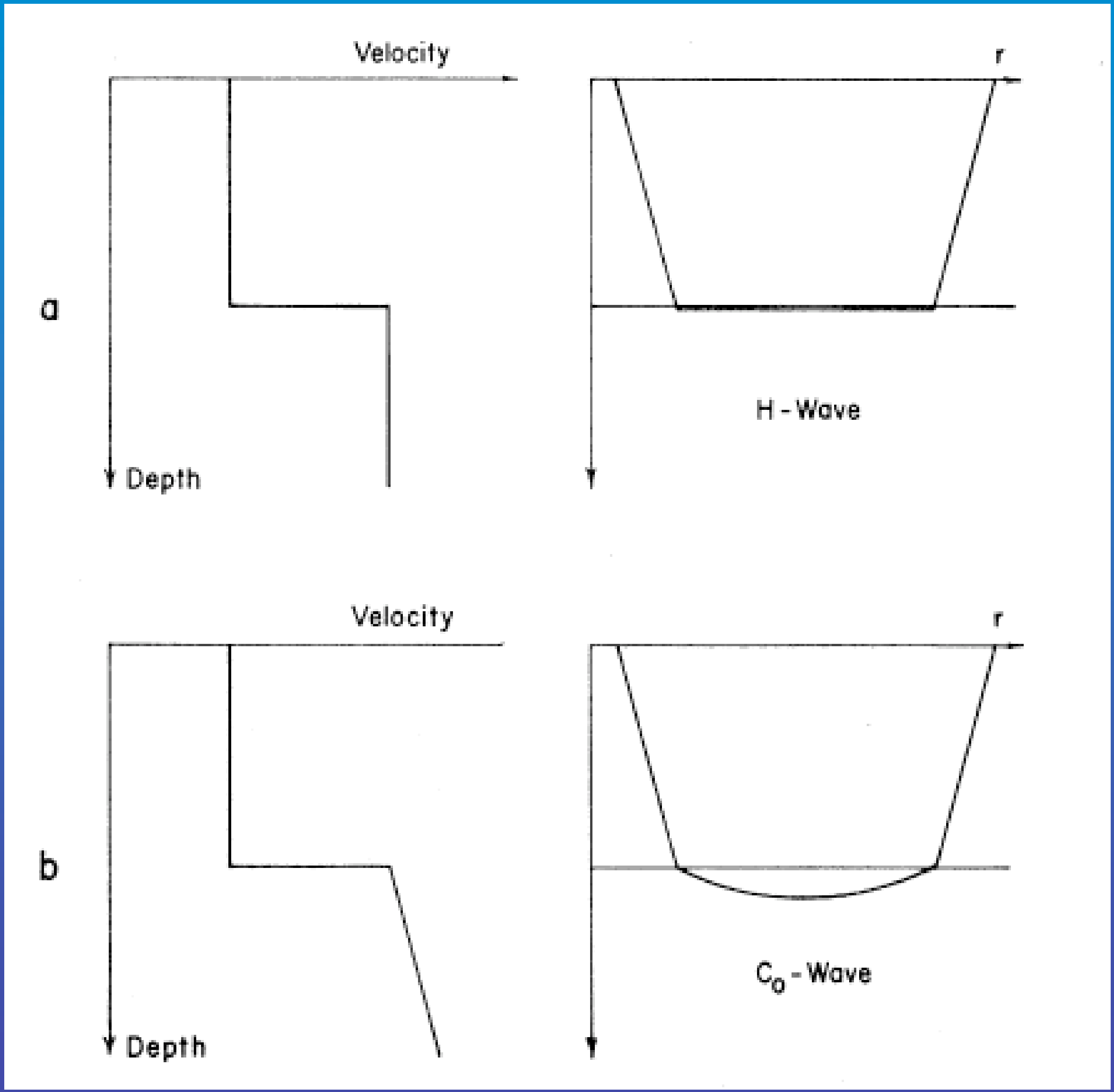
NOTE: Stoneley and pseudo-Rayleigh waves not included.

The Direct Wave Root for Buried or Borehole Receivers



Water–basalt interface

Head Waves and Diving Waves

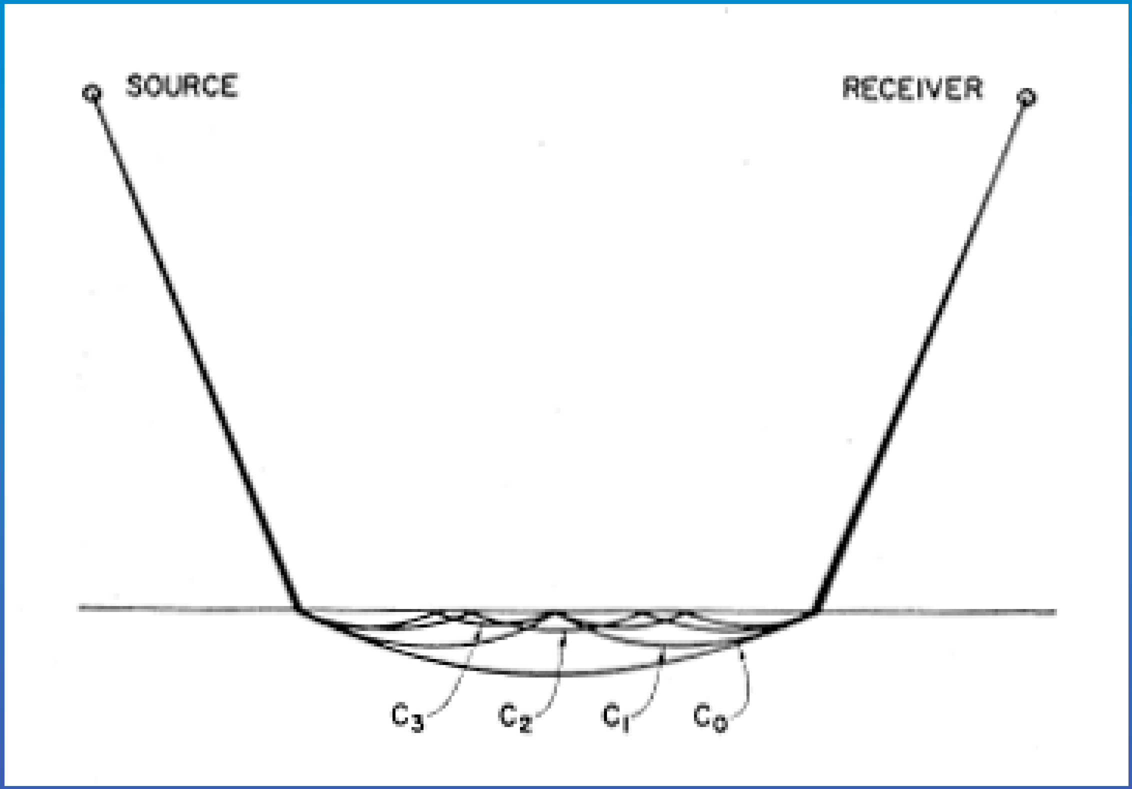


(from Cerveny and Ravindra, 1972)

Head waves exist at the interface between homogeneous media

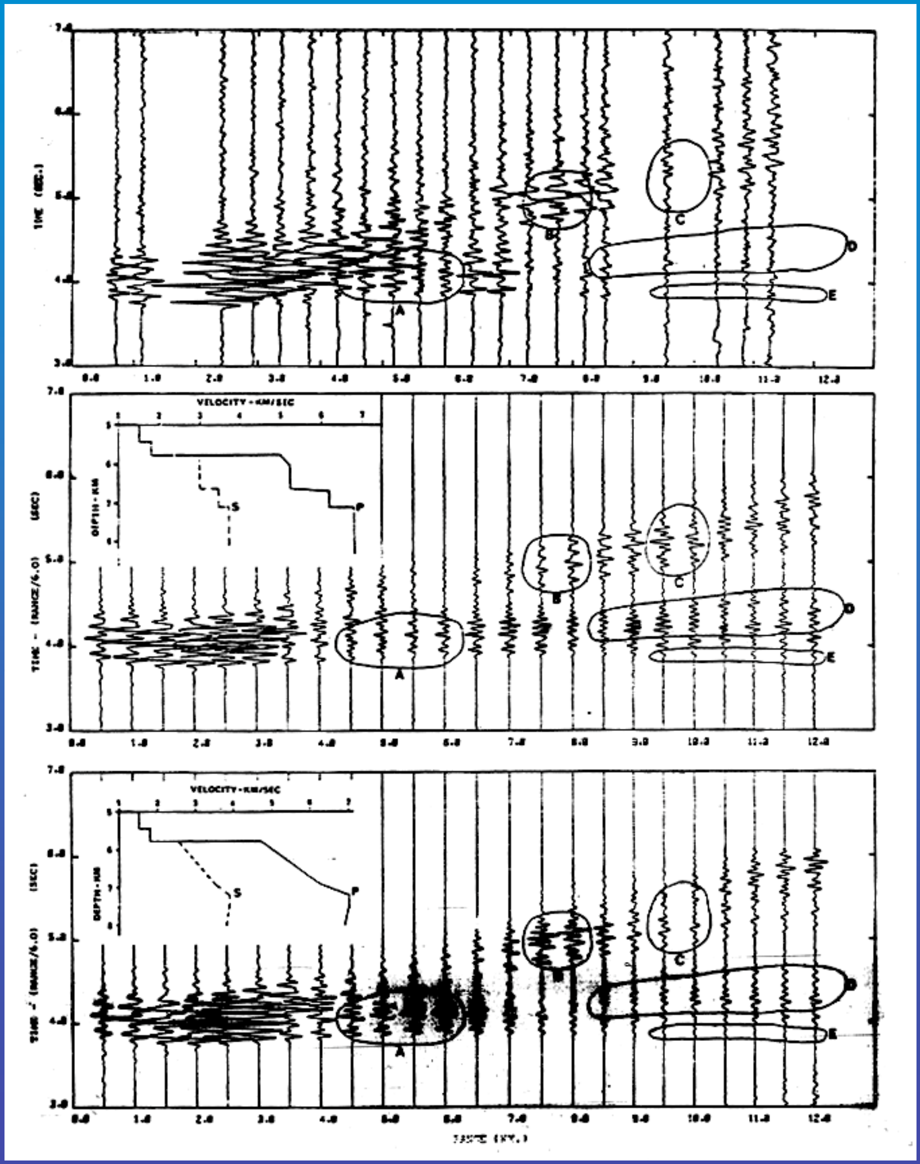
Diving waves exist when there is a vertical velocity gradient in the lower layer.

Interference Head Waves



Interference head waves are excited below an interface when there is a velocity gradient in the lower layer. They are a "ray" representation of a "mode" problem. (from Cerveny and Ravindra, 1972)

Head Waves versus Diving Waves



Observed data – horizontal particle velocity on a borehole receiver in basalt.

Thick layer model of oceanic crust based on <u>head waves.</u>

Gradient layer model of oceanic crust based on <u>diving waves</u>.

Stoneley (Scholte) Waves

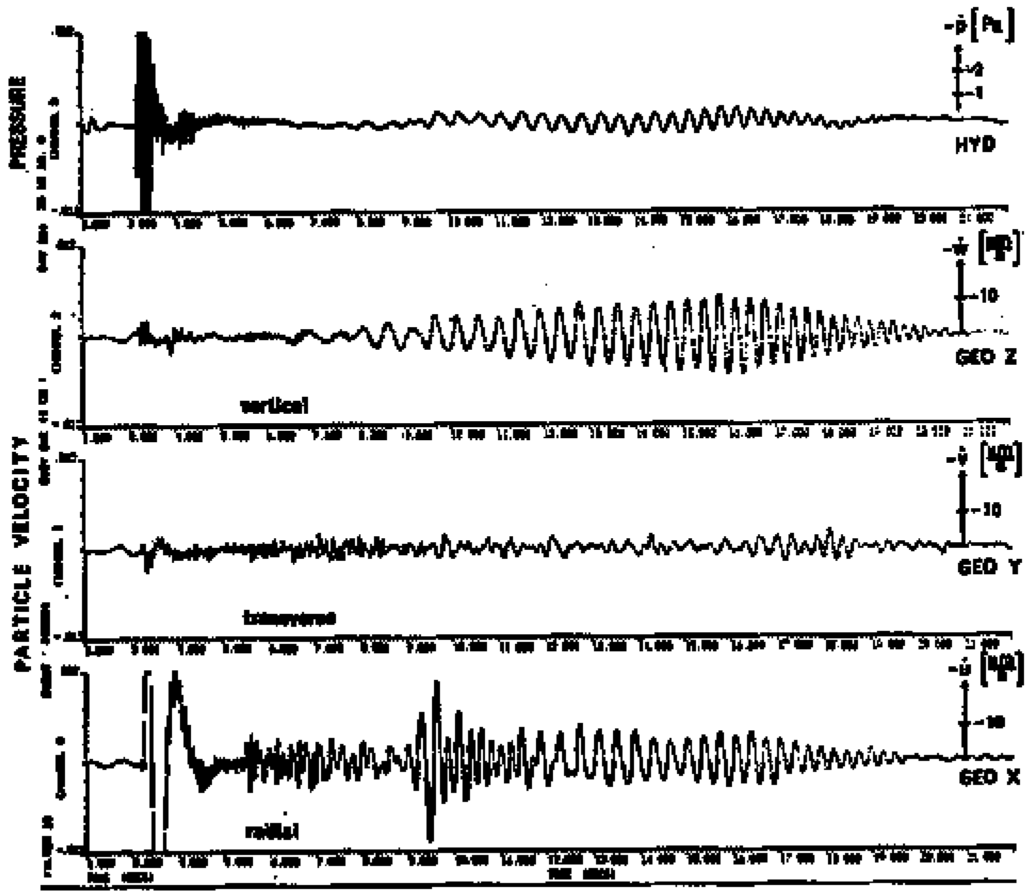


FIG. A4 LINE-PRINTER PLOT OF THE SIGNALS FROM THE FOUR BASIC SENSORS (180 g TNT FIRED AT 1.3 km DISTANCE)

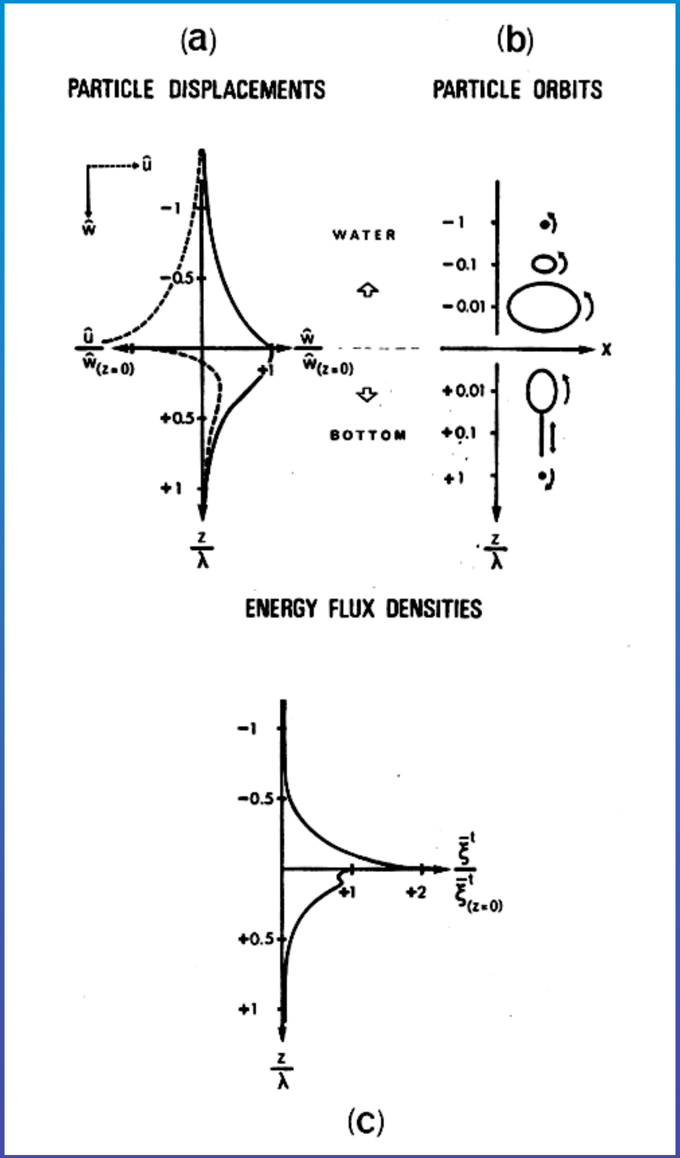
Pressure

Vertical Particle Velocity

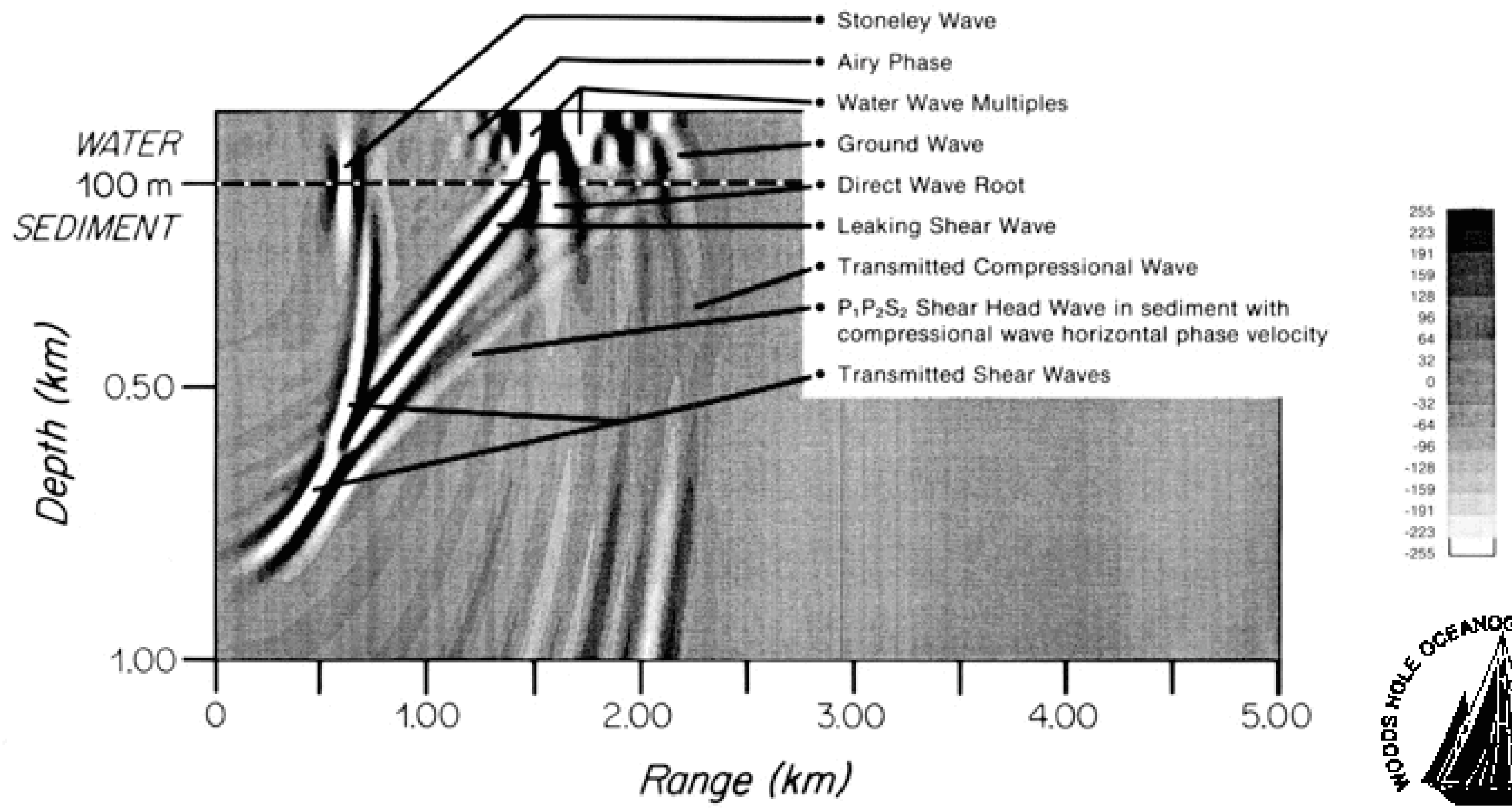
Transverse Particle Velocity

Radial Particle Velocity

Stoneley (Scholte) waves observed on the seafloor over a soft sediment bottom
(from Rauch, 1980).



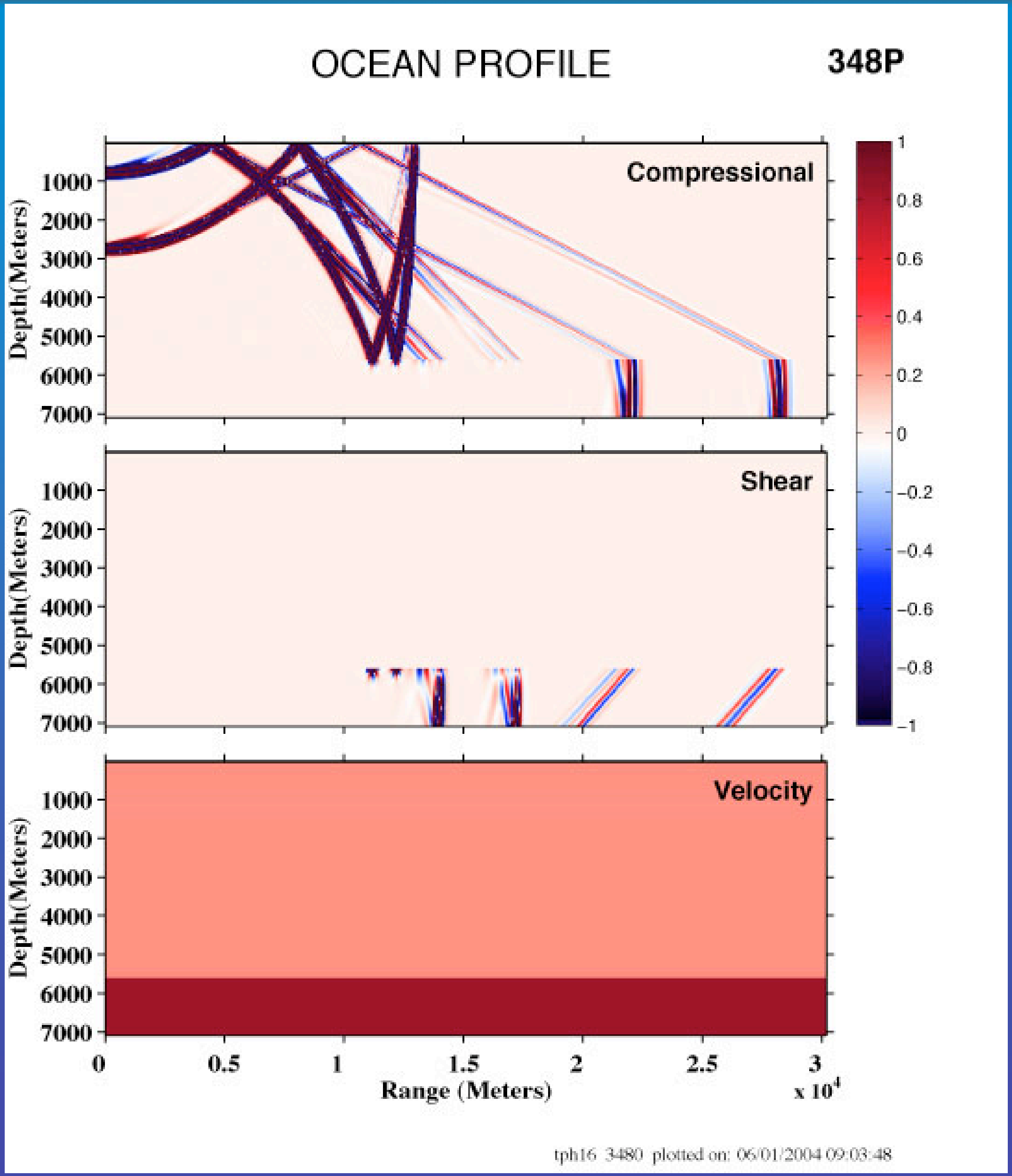
Stoneley (Scholte) wave behavior near the seafloor with a soft sediment bottom
(from Rauch, 1980).



STEPHEN

The family of waves excited by a point source in a thin water layer over a sediment bottom.

Simple Hard Bottom

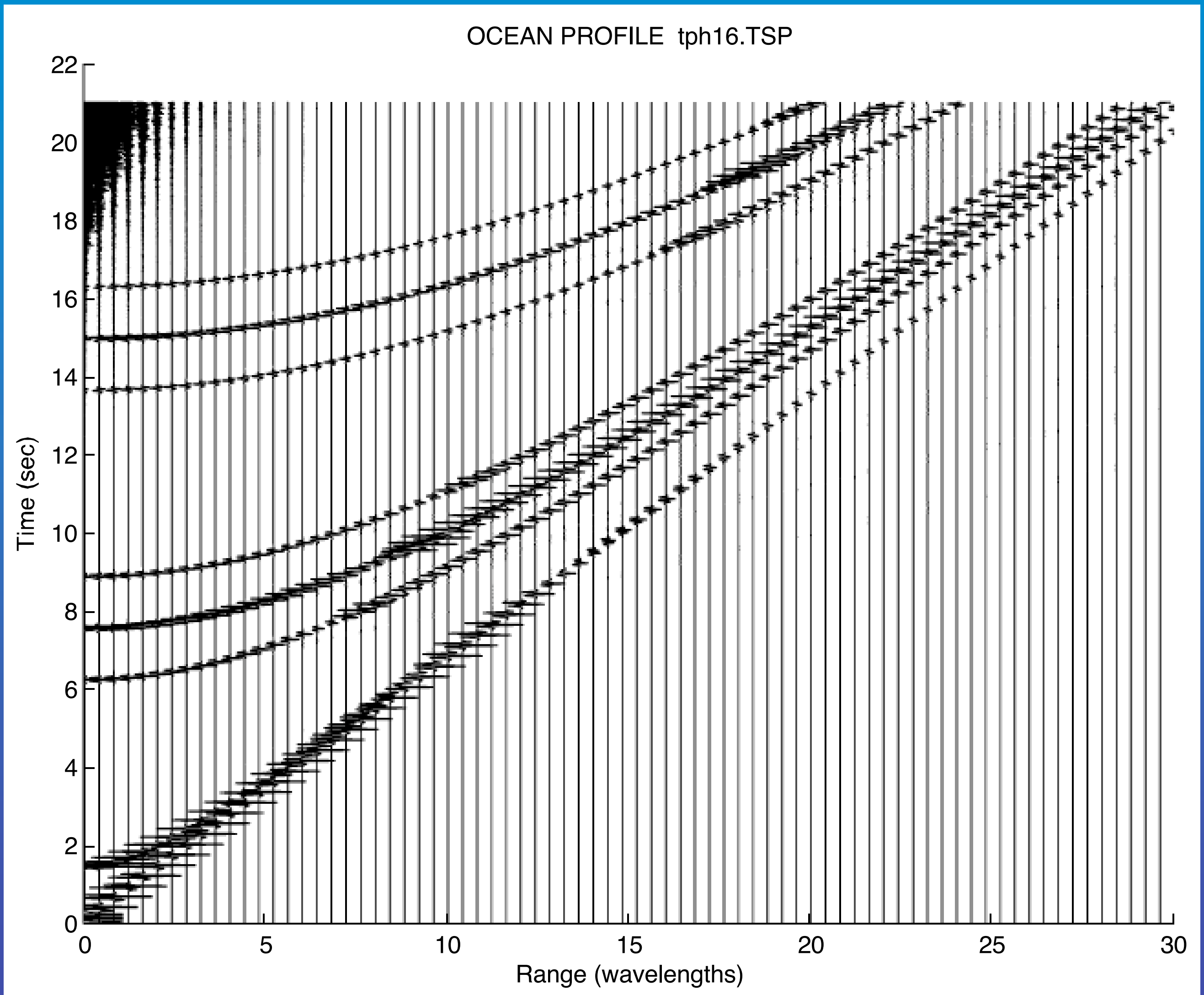


Numerical Schlieren Diagrams

Point source at the sound channel axis in deep water with hard bottom (no sediment) to 30km range at 10Hz.

Principle "ray" arrivals with some evanescent effects.

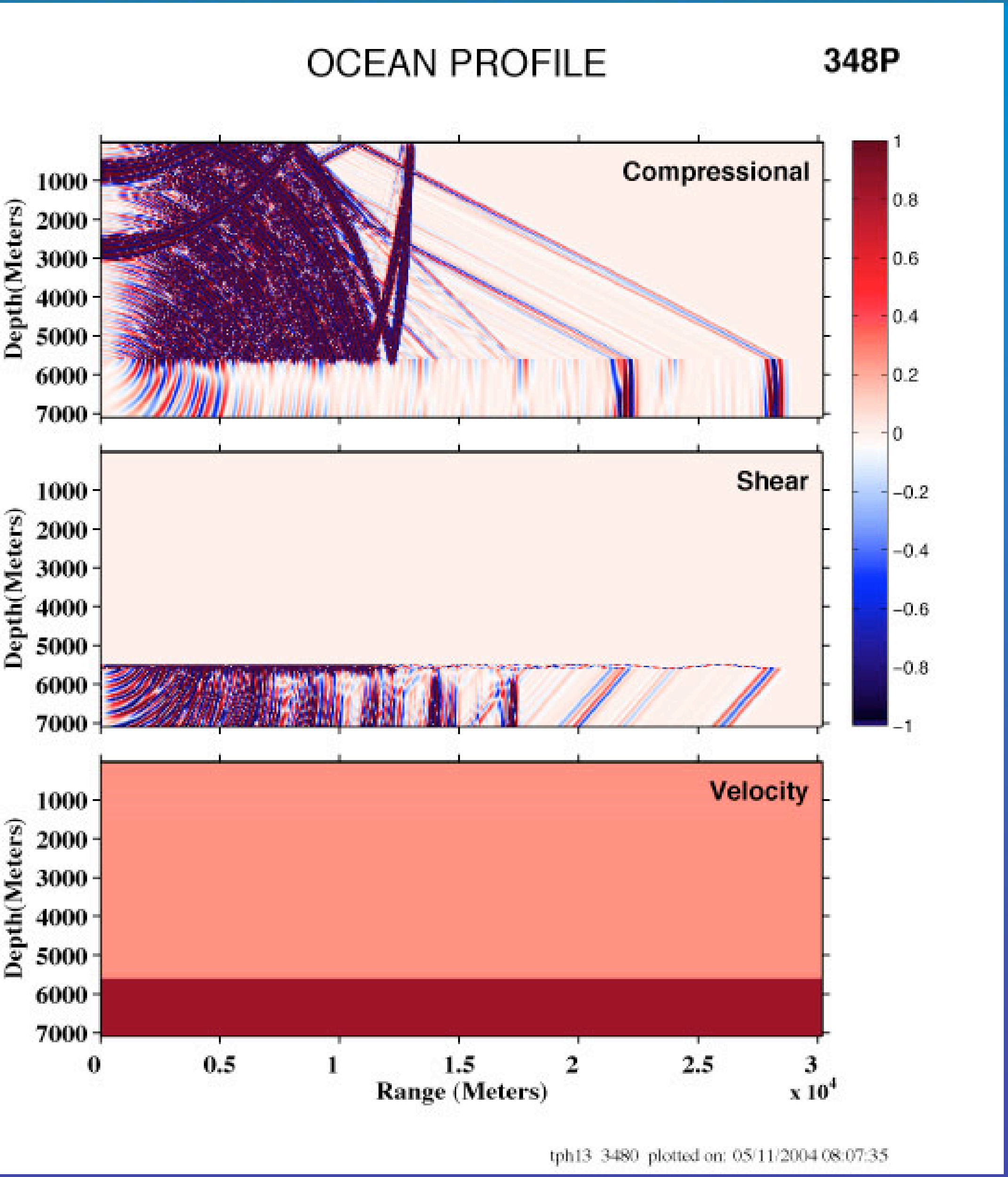
Simple Hard Bottom



Pressure time series at the sound channel axis.

Distinct arrivals

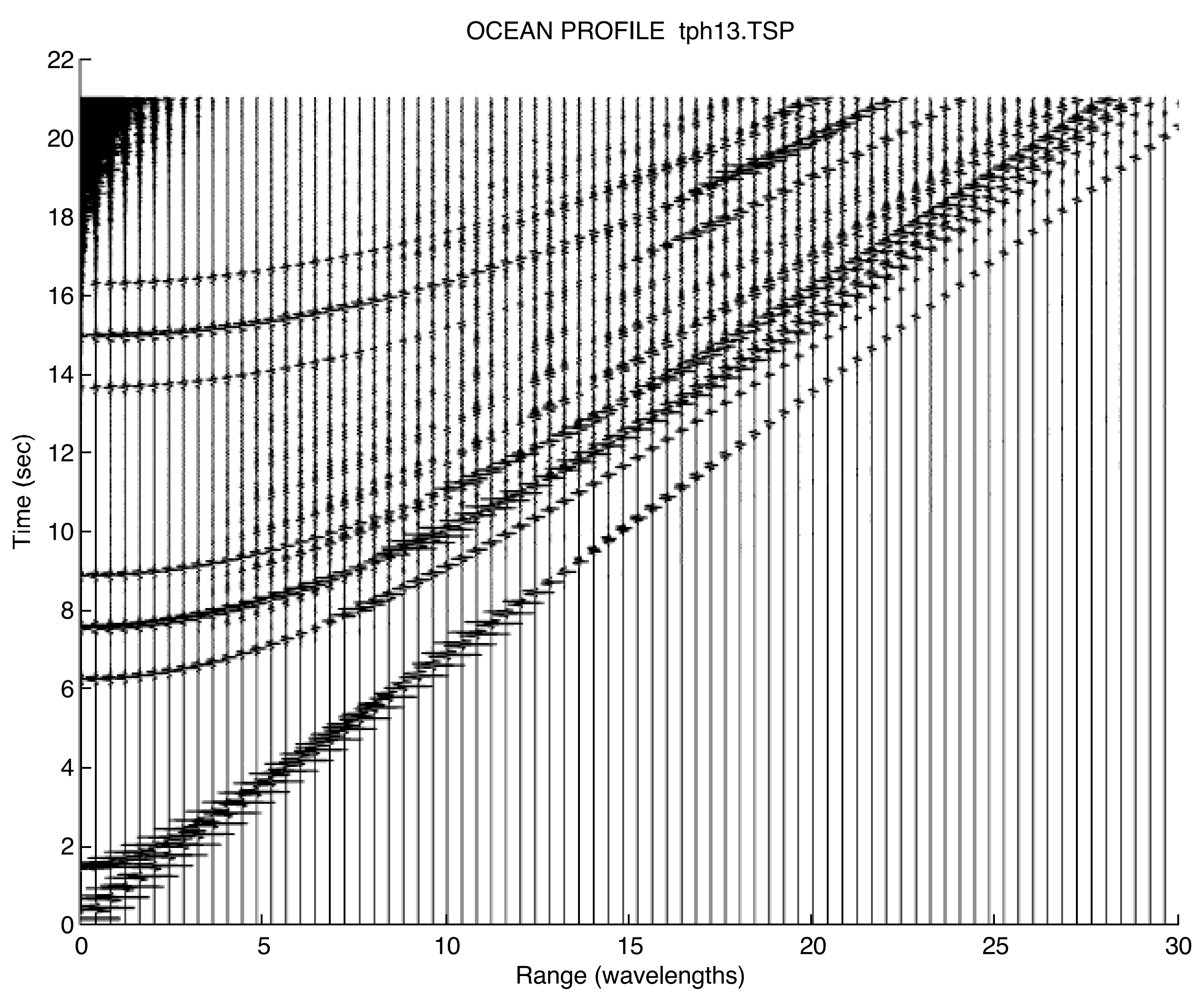
Sedimented Simple Bottom



Point source at the sound channel axis in deep water with a thin sediment layer to 30km range at 10Hz.

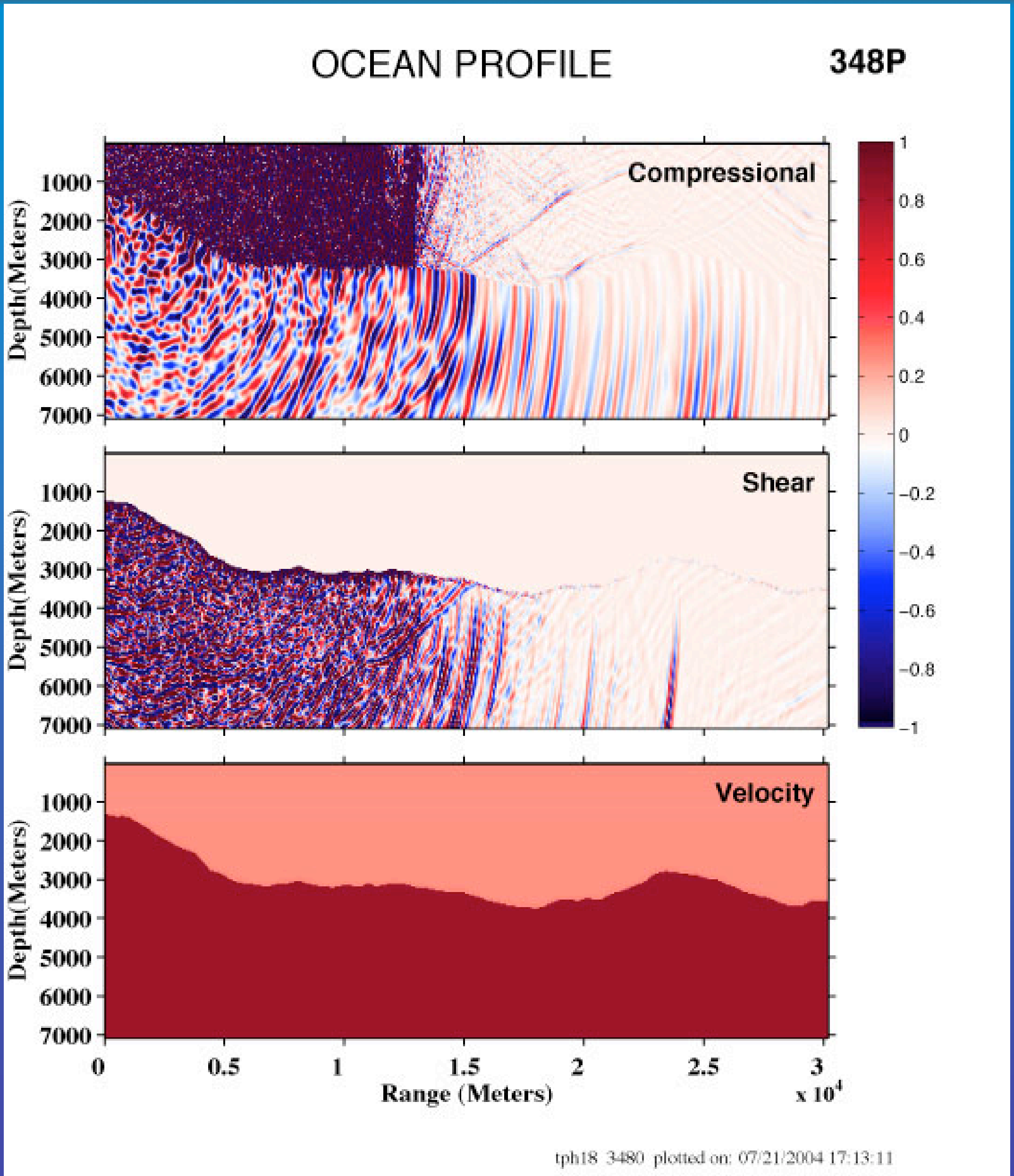
Principle “ray” arrivals plus sediment shear reverberation.

Sedimented Simple Bottom



Sediment shear reverberation fills-in between principle arrivals

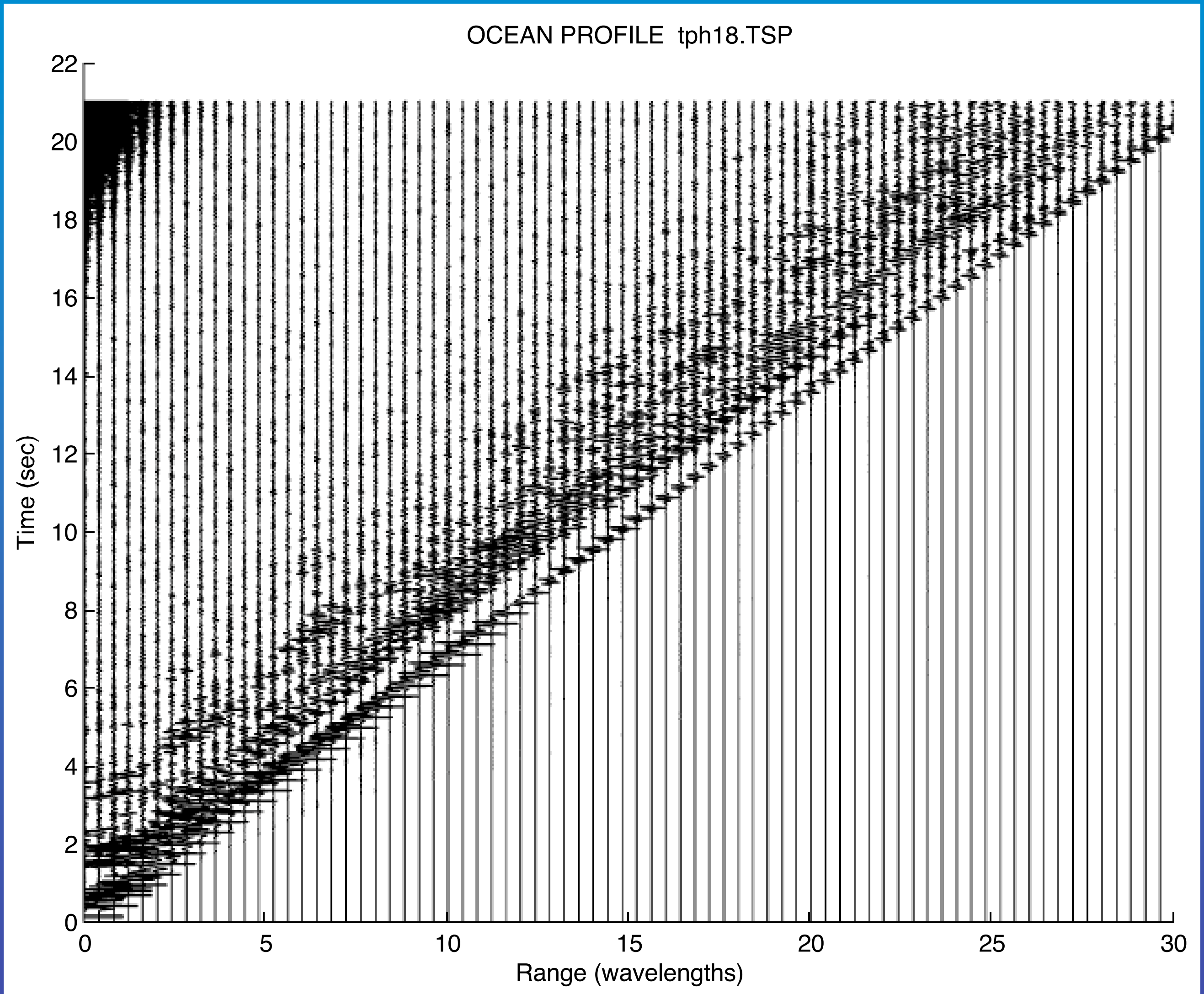
Sedimented Mid-Atlantic Ridge Bathymetry



Point source at the sound channel axis over a typical bathymetry with a thin sediment layer to 30km range at 10Hz.

Scattering and reverberation remove distinct multi-paths and contribute to incoherent, signal-generated “noise”.

Sedimented MAR Bathymetry



Incoherent signal-generated noise looks more like observed sound channel propagation.

What about real life?

The classic nomenclature was based on isotropic, perfectly elastic, homogeneous or slowly-varying media.

Things in real life that complicate matters:

1) Intrinsic Attenuation
2) Scattering from the rough interfaces (water-sediment , water-basement, sediment-basement) and heterogeneities within the seafloor.
3) Anisotropy

Take Home Messages

Ideal “head waves” and “interference head waves” have never been observed at the seafloor. Observations are better explained by “diving waves” in velocity gradients and “modes” in low velocity channels (for example, a sediment layer over a hard basement).

Rigidity is necessary to support interface waves and other shear wave effects that are commonly observed.

Evanescently generated waves (not principle rays) can be the largest observed arrivals.

In some instances branch line integrals contribute more to the asymptotic solution than saddle points and poles.