Engineering Seismology and Seismic Hazard – 2019

Lecture 8

Surface Waves

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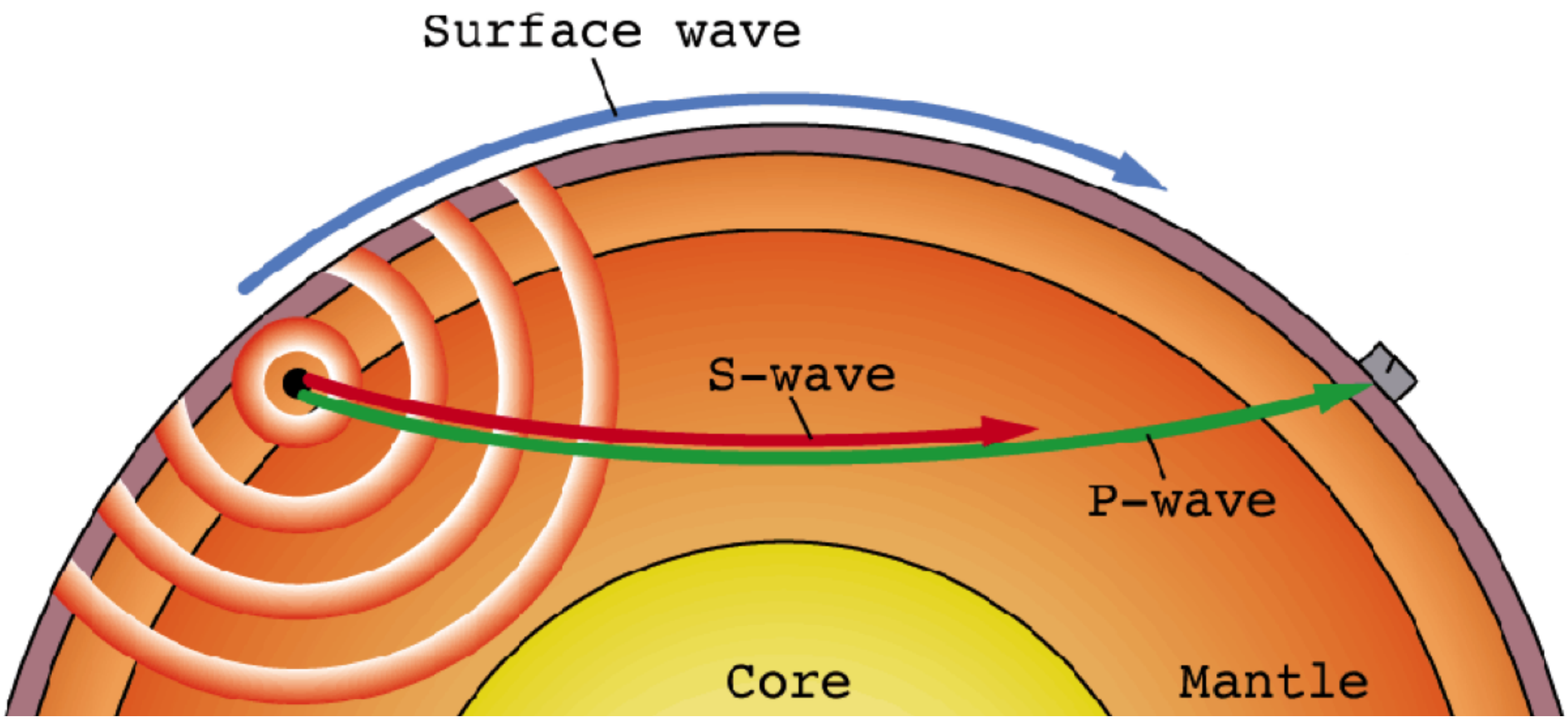
Surface Waves

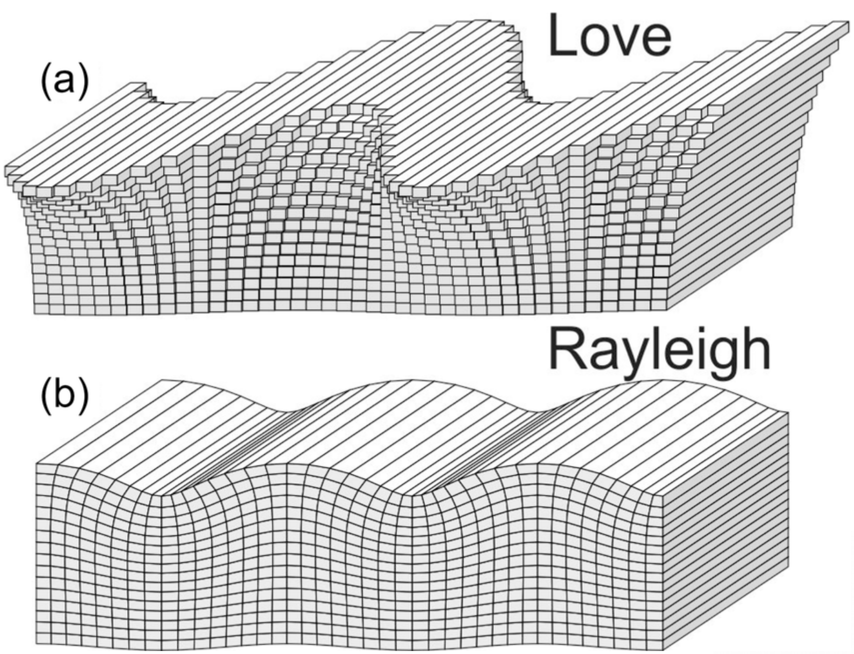
We now consider the interaction of body waves (P and S) with a particular discontinuity of the Earth, the free surface.

At the free surface, both incident and reflected waves coexist. This interaction creates a new type of waves called surface waves, which propagate parallel to the free surface itself.

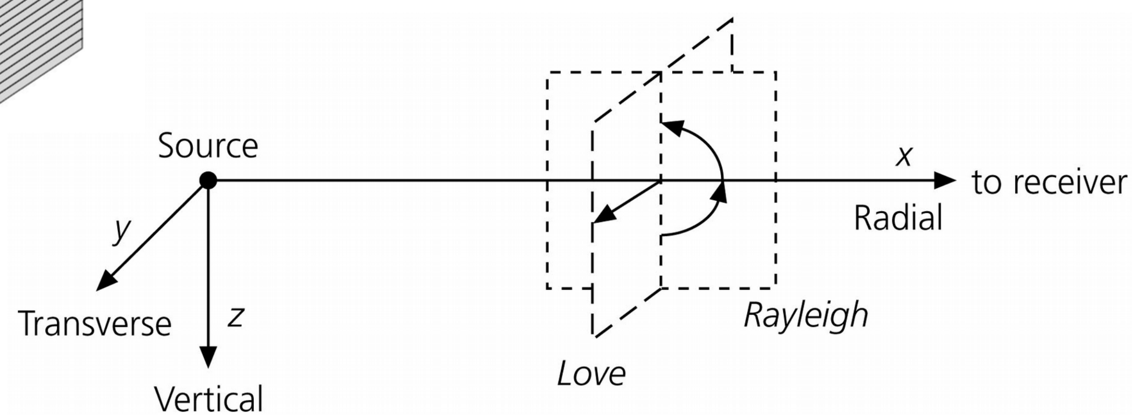


Rayleigh and Love Waves

At the free surface, SH waves do not interact with the P and SV components, giving rise to two different surface wave types: Love and Rayleigh waves.



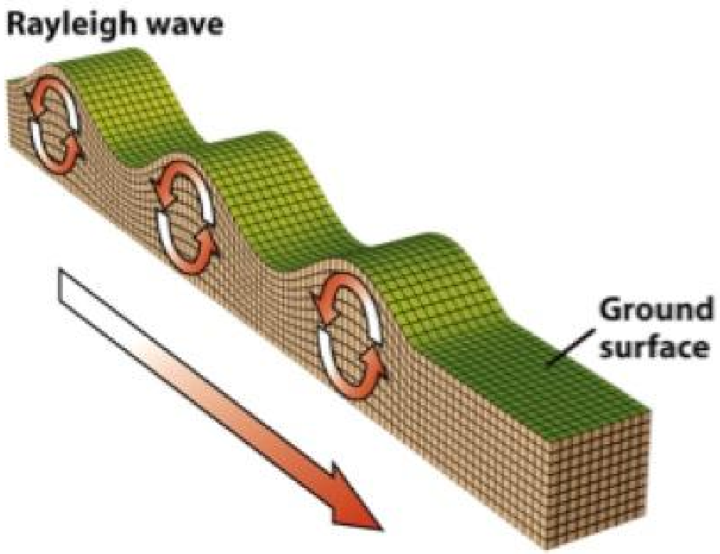
Rayleigh and Love waves have ground displacement with specific polarization with respect to the free surface

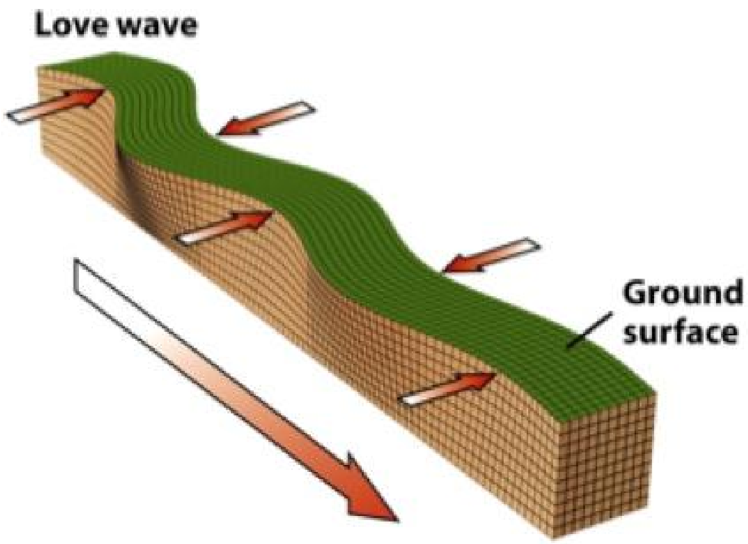


Rayleigh and Love Waves

1) Rayleigh waves are polarized on a vertical plane containing the direction of propagation. Their motion can be described by a two perpendicular components (V+R).

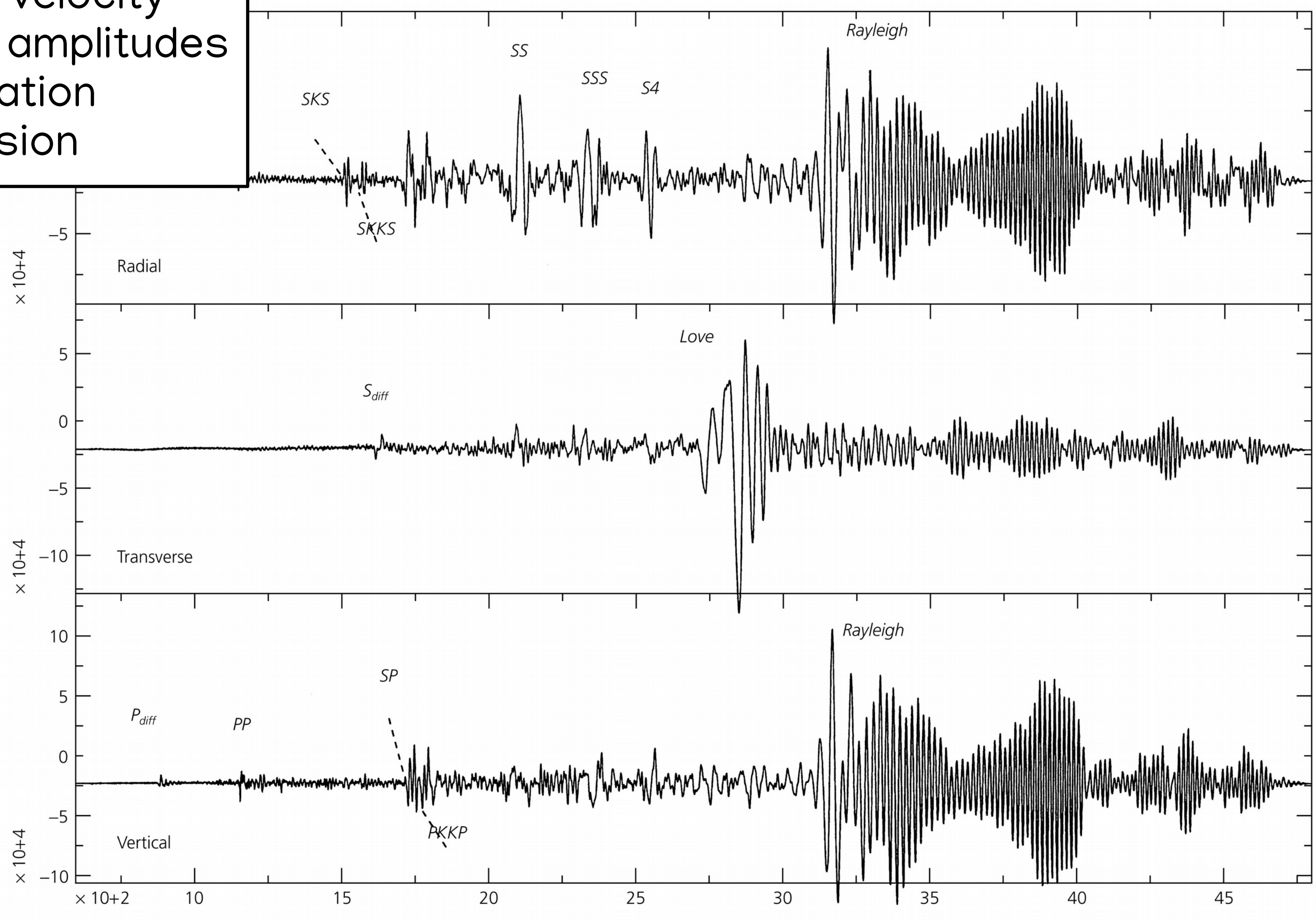
2) Love waves are polarized on a horizontal plane containing the direction of propagation. Their motion can be described by a single component (T).





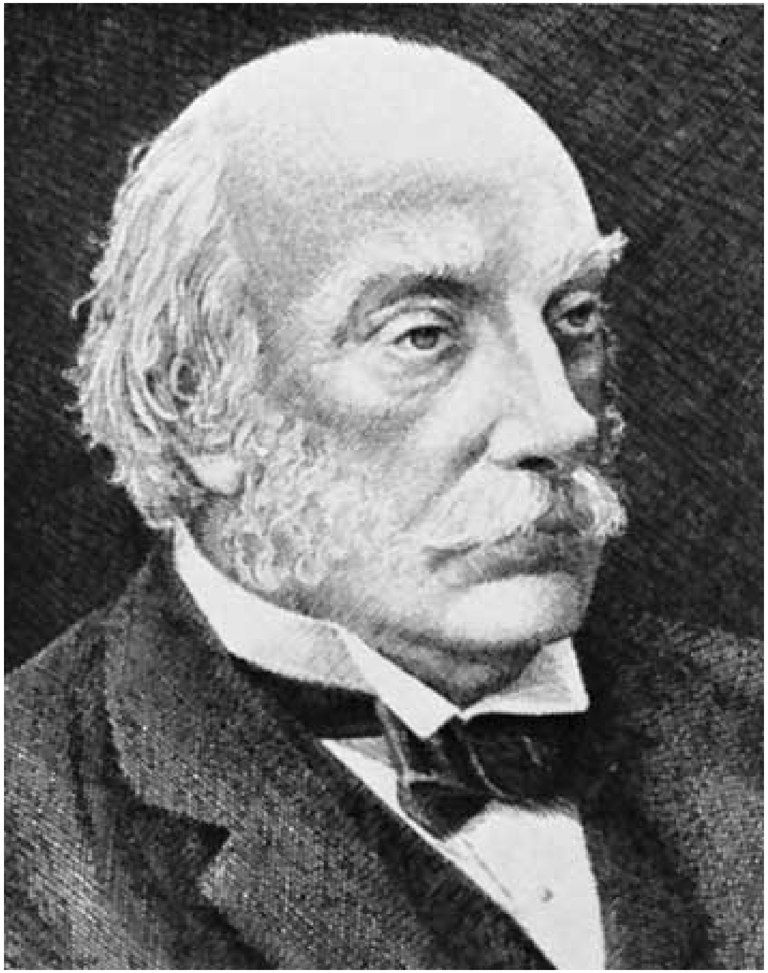
Surface Waves Anatomy

Main properties:
- Slower velocity
- Larger amplitudes
- Polarization
- Dispersion



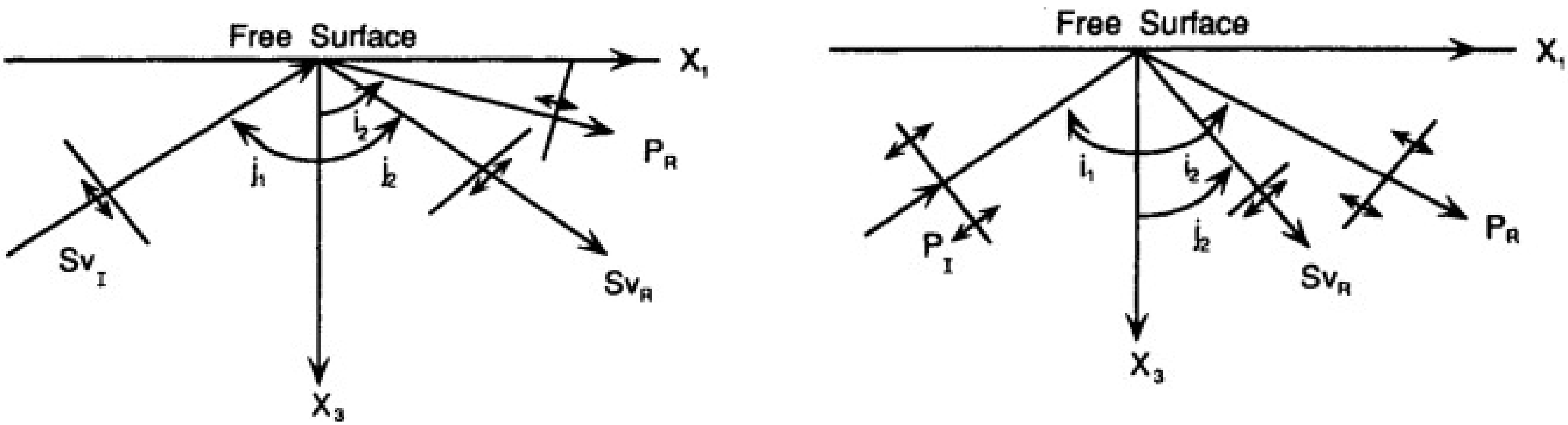
Rayleigh Waves

Rayleigh waves take their name from John William Strutt, 3rd Baron Rayleigh of Terling Place, who predicted mathematically their existence in 1885 (in his famous book "The Theory of Sound"), before any actual seismological observation of the phenomenon.



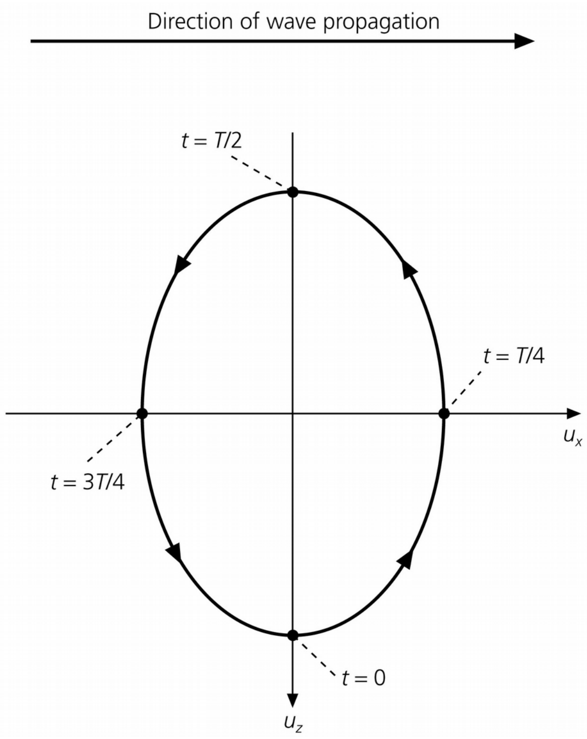
Rayleigh Waves

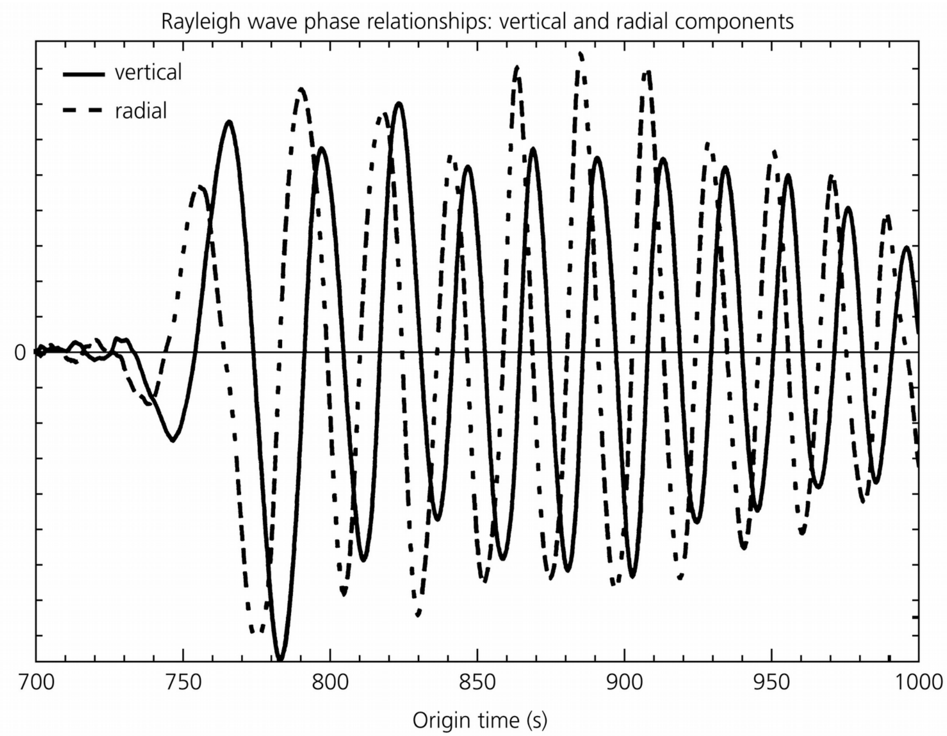
Rayleigh waves are the results of the interaction of P and SV waves with the free surface (and the interfaces below), where they couple.



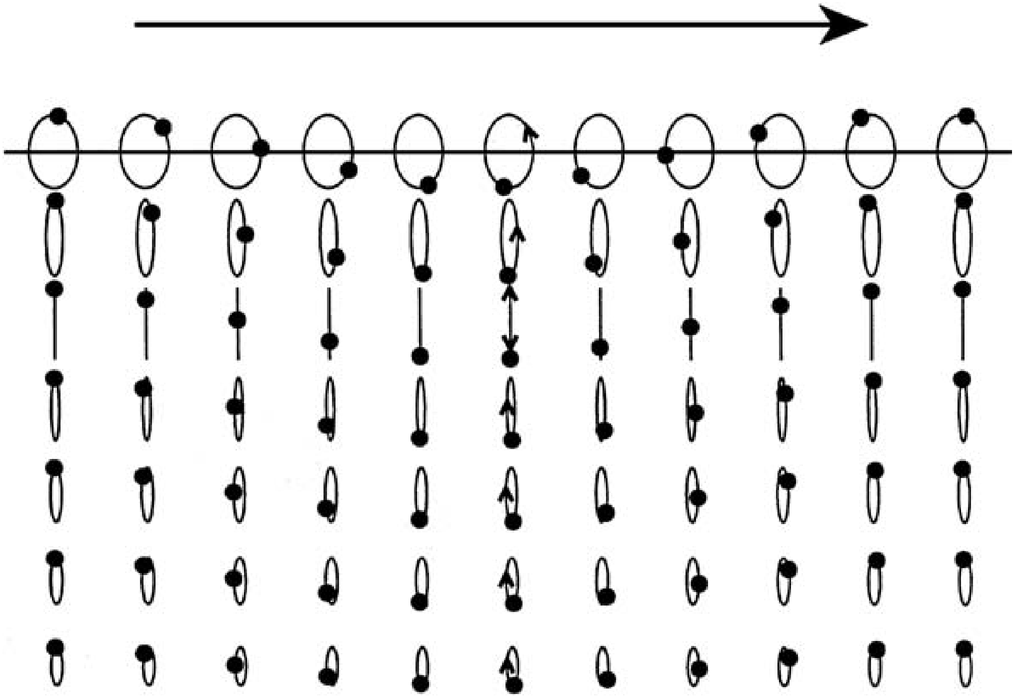
If the SV incidence is post-critical, emerging P waves are evanescent, which means their amplitude decays exponentially with depth.

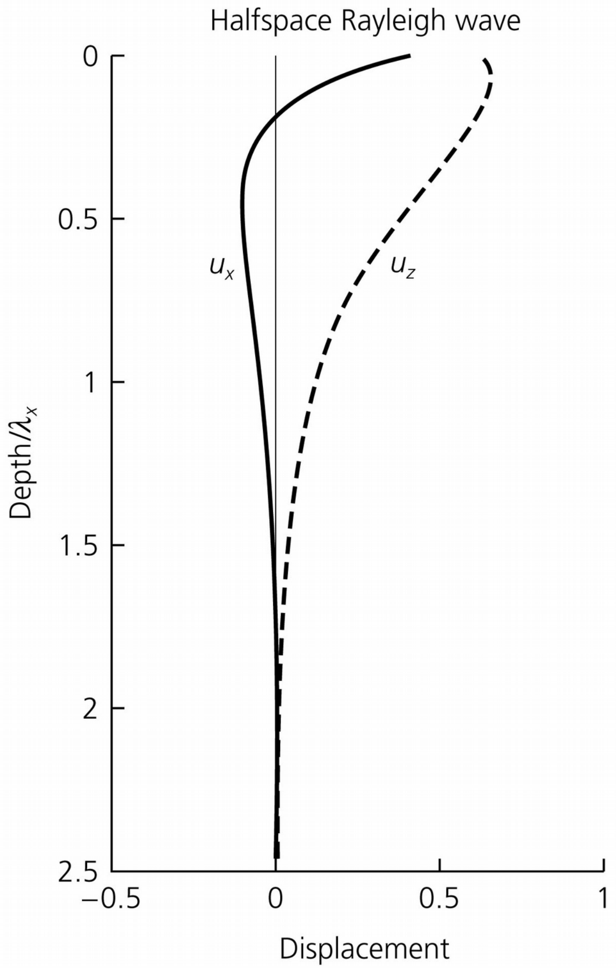
Rayleigh Wave Polarization





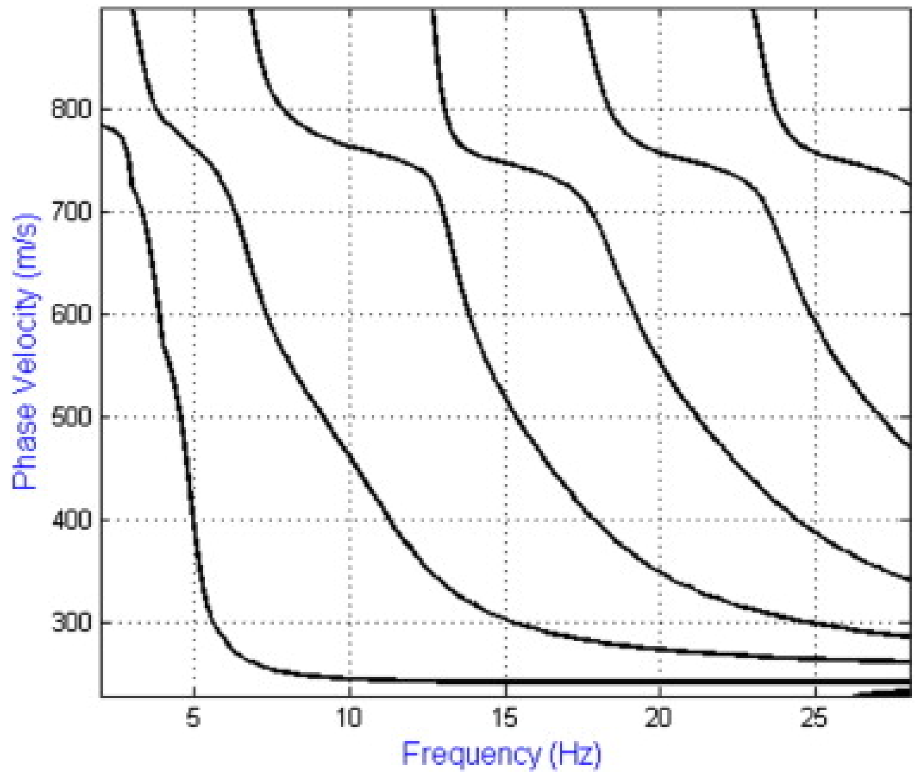
Rayleigh Wave Displacement





Dispersion and Modes

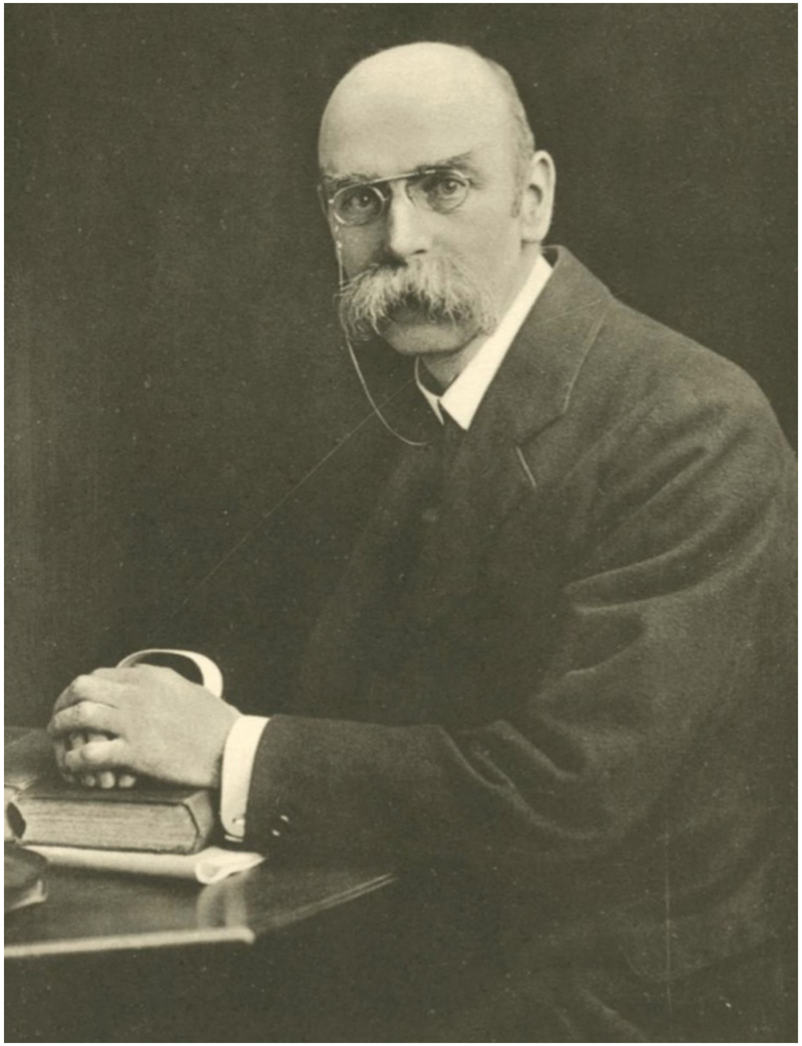
Rayleigh waves propagate in homogenous half-space with constant velocity C_R. In heterogeneous media, however, their velocity becomes frequency dependent. They assume a dispersive behavior.



As for the case of vibrating strings, Rayleigh waves shows multiple modes, each one propagating with its own dispersion pattern.

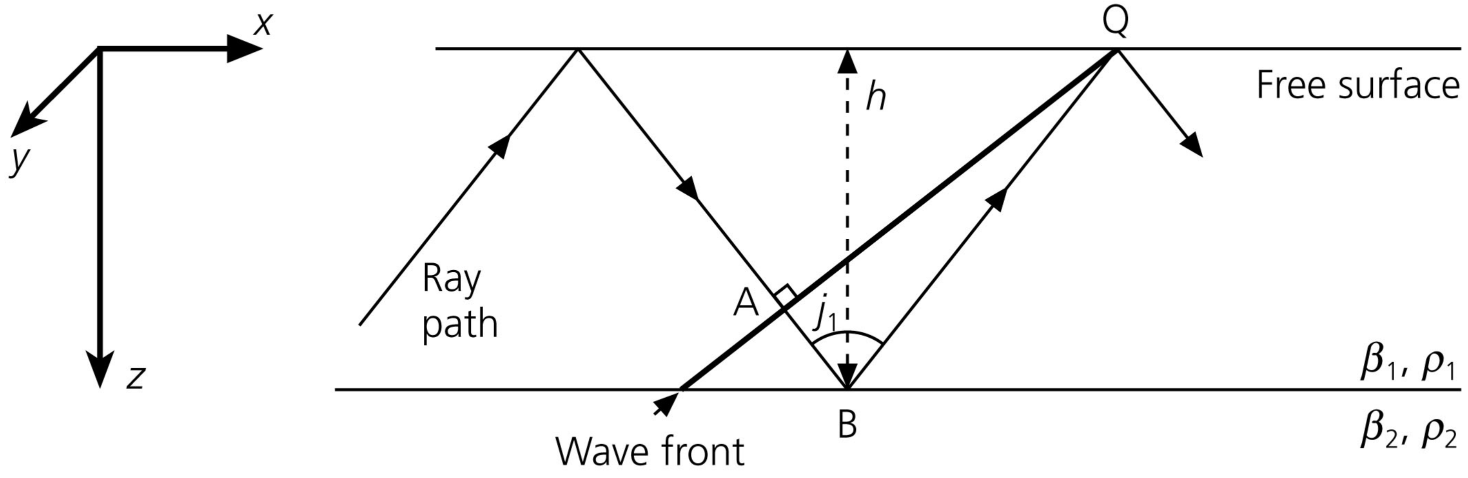
Love Waves

Love Waves take their name from Augustus Edwards Hough Love, who predicted mathematically their existence in 1911 (Chapter 11 from Love's book "Some problems of geodynamics").



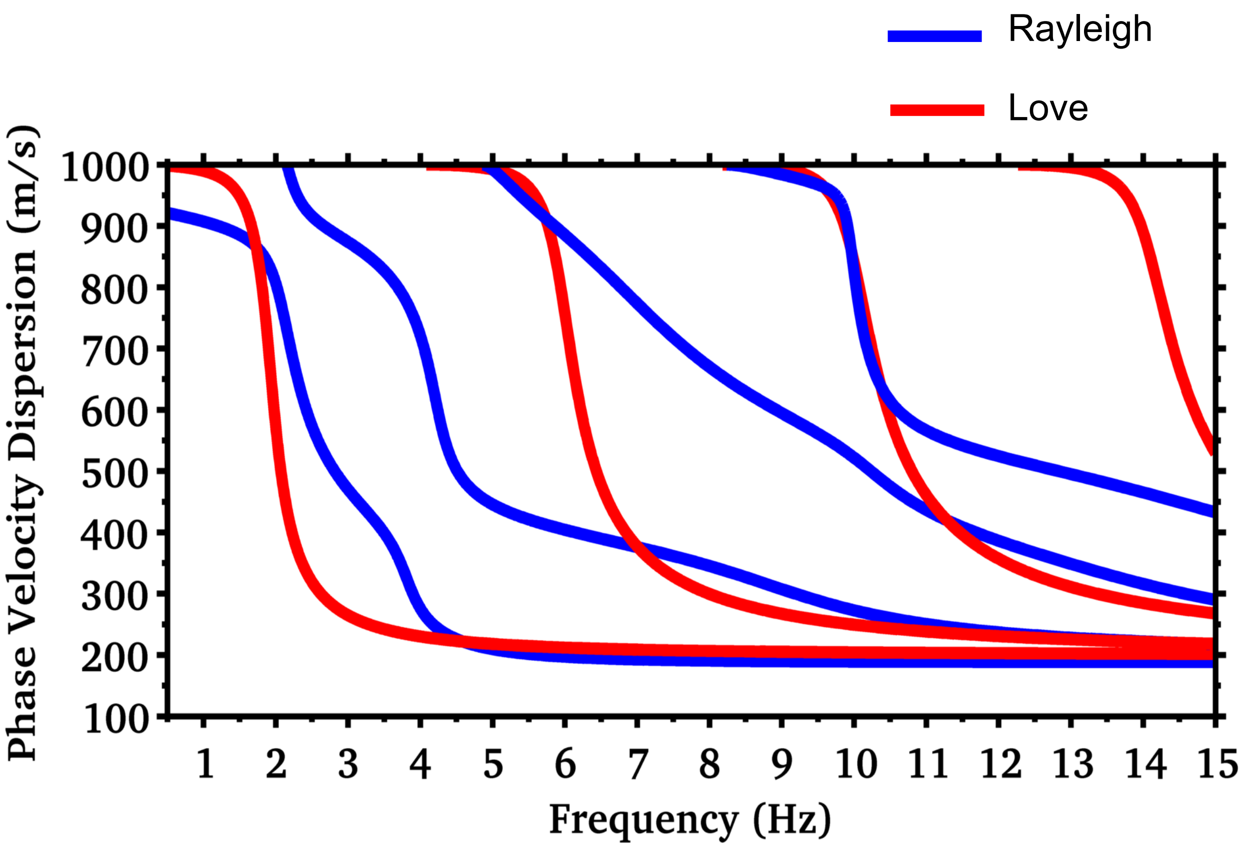
Love Waves Generation

SH waves are totally reflected at the free surface, therefore the interference condition for the creation of surface waves requires the presence of (at least) one low velocity layer where waves are post-critically reflected (wave guide).

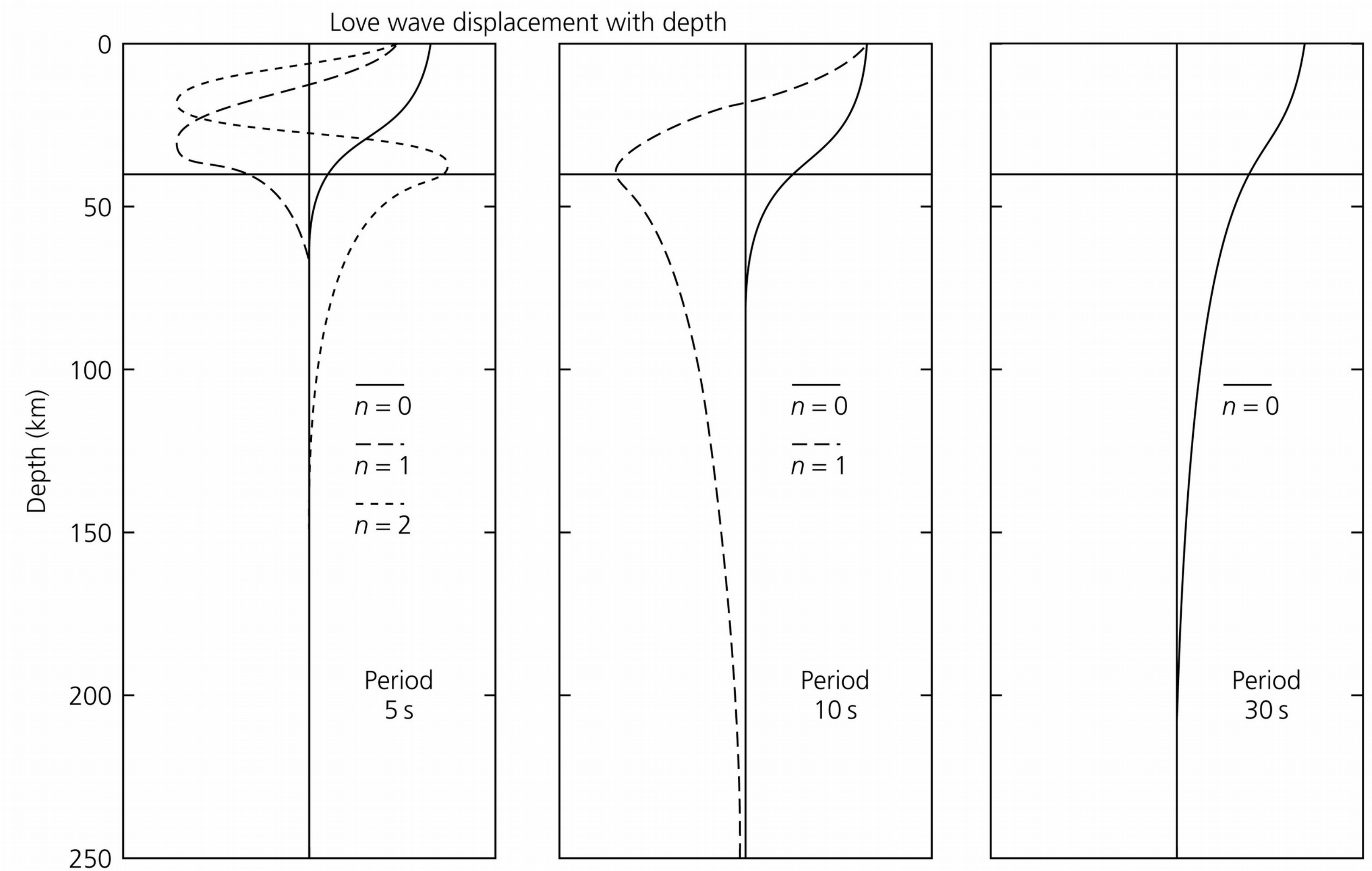


Love Wave Dispersion

Love waves are always dispersive, but <u>cannot propagate in homogenous half-space</u> (as Rayleigh do), as they need "at least" one low-velocity layer over the bedrock.

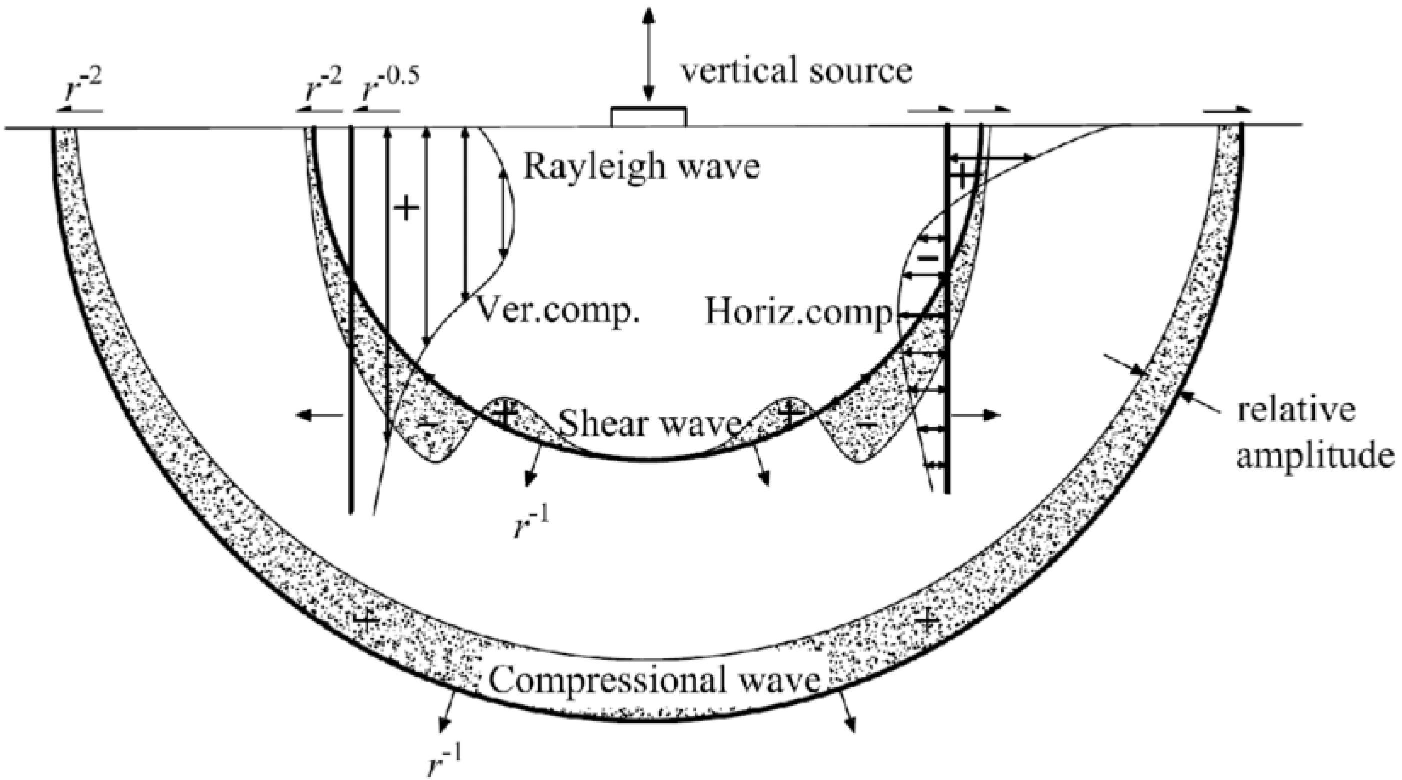


Love Waves Displacement



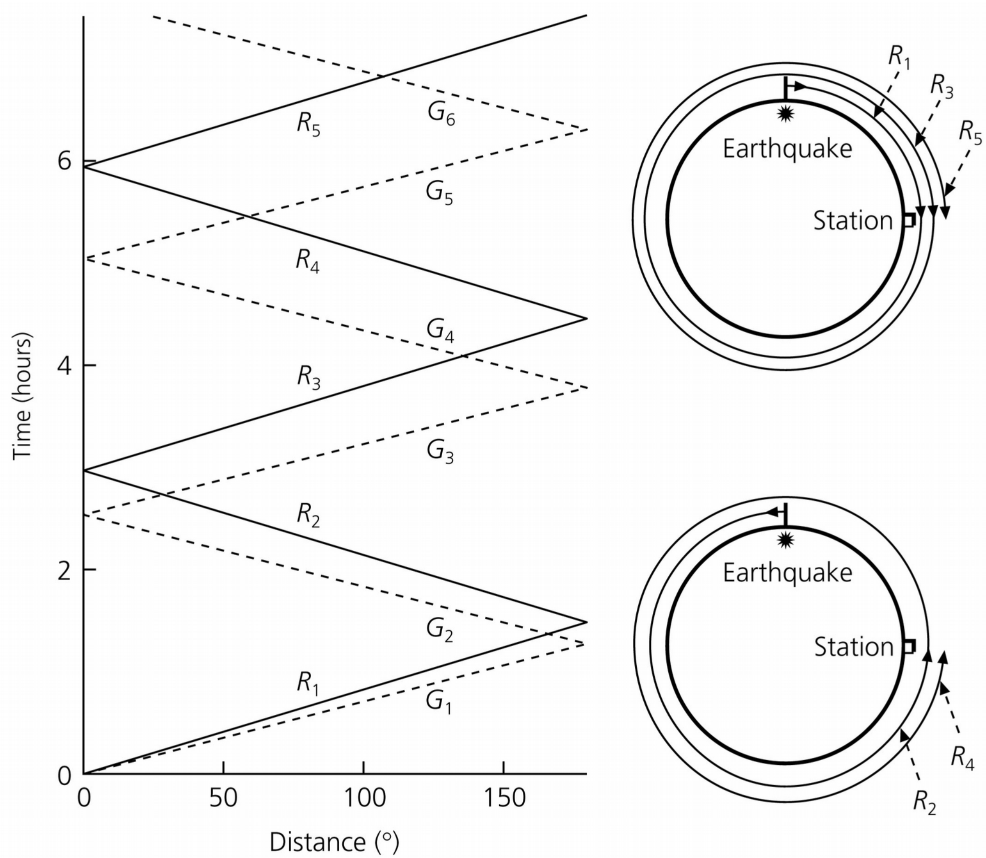
Decay with Distance

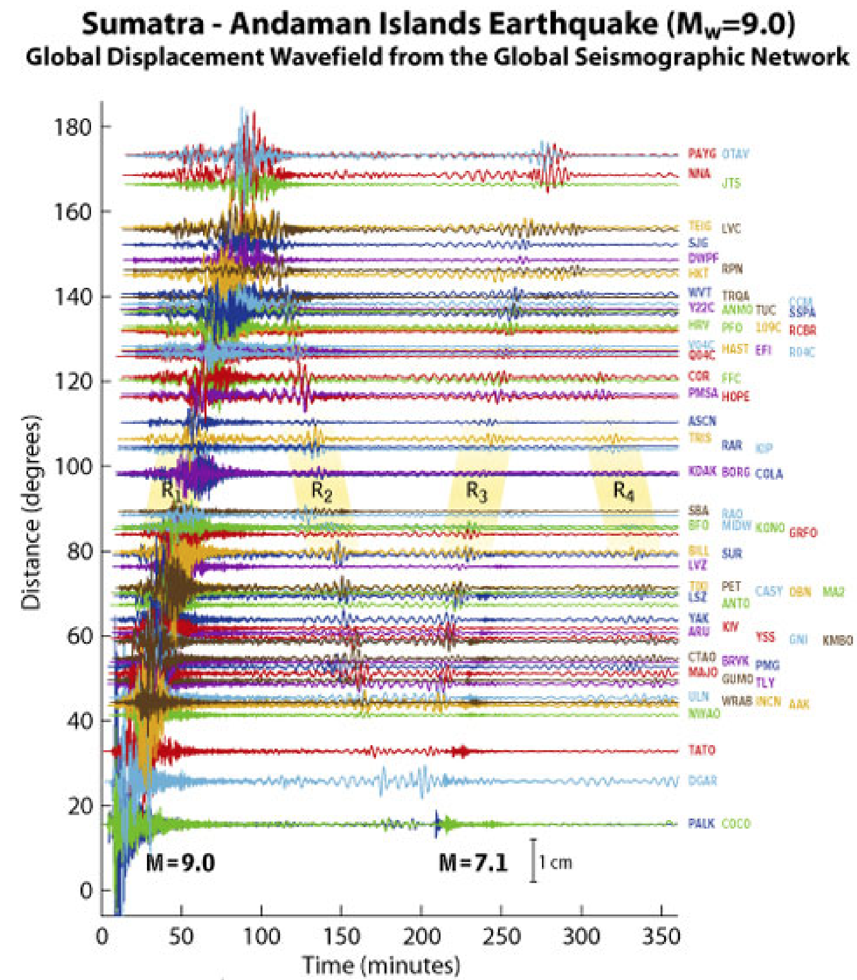
The energy carried by surface waves decays with distance r from the source as 1/r; this is in contrast to $1/r^2$ for body waves, which is why they are usually much less prominent on a Seismogram.



Multiple Surface Waves

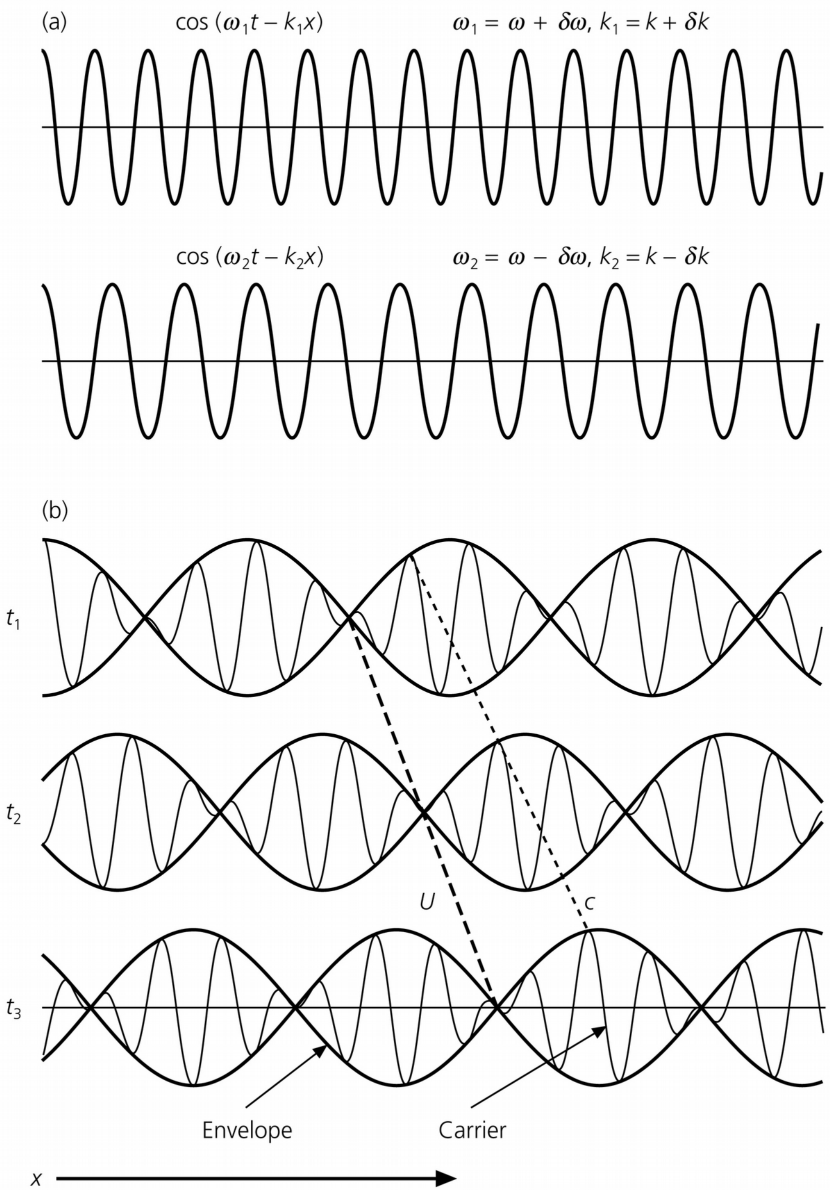
Due to their slower rate of decay, surface waves can circle the globe many times following a large earthquake.





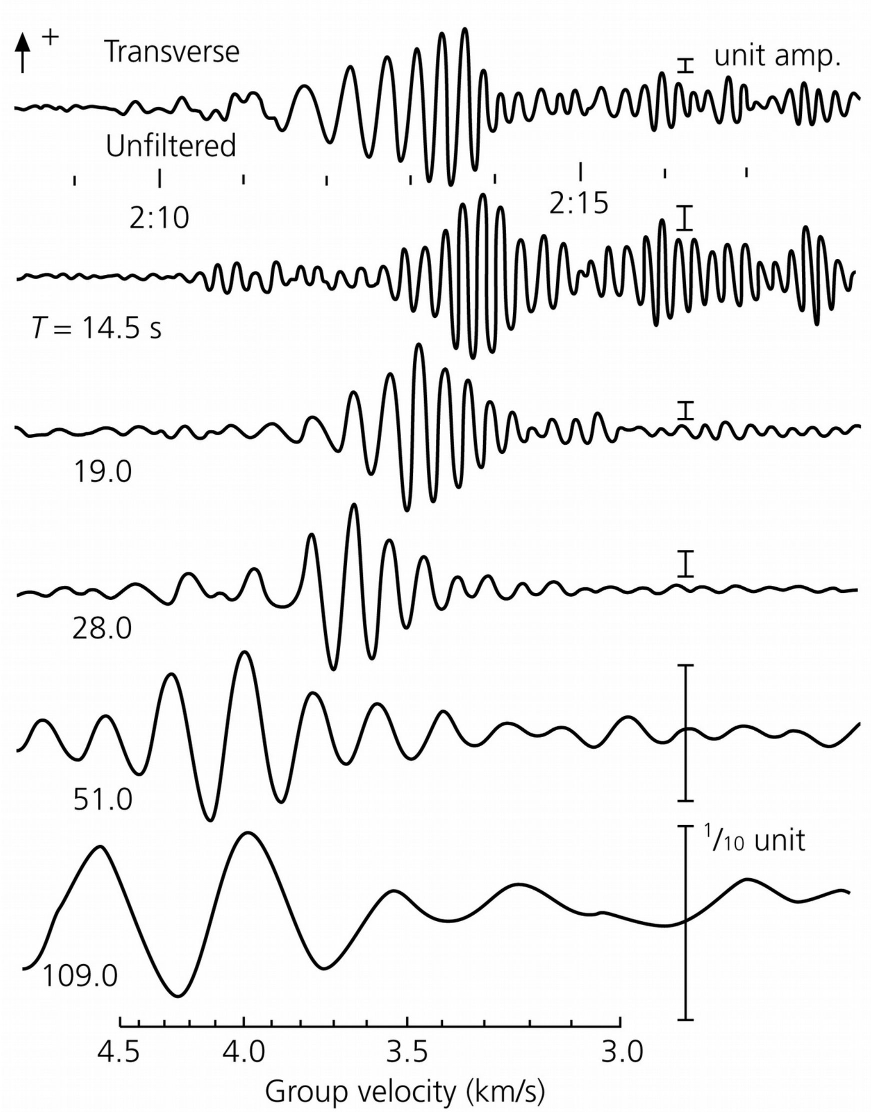
Effect of Dispersion

Due to dispersion, two harmonic waves with slightly different frequency and velocity (**phase velocity**) combine creating an interference pattern (the envelop) that propagates with a generally different velocity (**group velocity**)

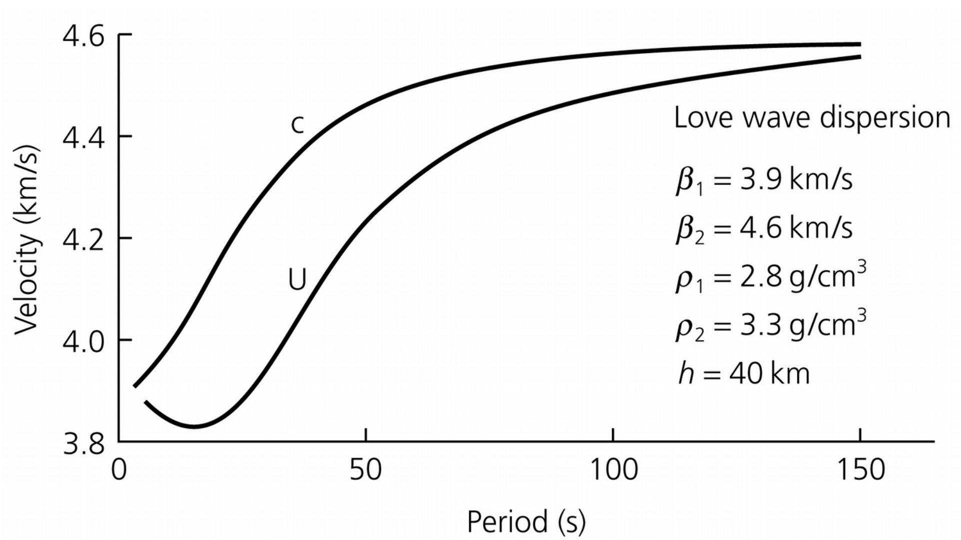


NOTE: amplitude peaks and envelopes propagate with different speed!

Phase and Group Velocity



This is clearly seen by narrowband filtering of the surface waves recordings



Mathematical Formulation

The phase function of a wave is: $\phi = \omega t - k x$

Intuitively, the phase of an harmonic wave does not change with time, it is therefore:

$$\frac{\partial \phi}{\partial t} = 0 \Rightarrow \omega - k \frac{\partial x}{\partial t} = 0 \Rightarrow \boxed{\frac{\partial x}{\partial t} = \frac{\omega}{k} = c}$$

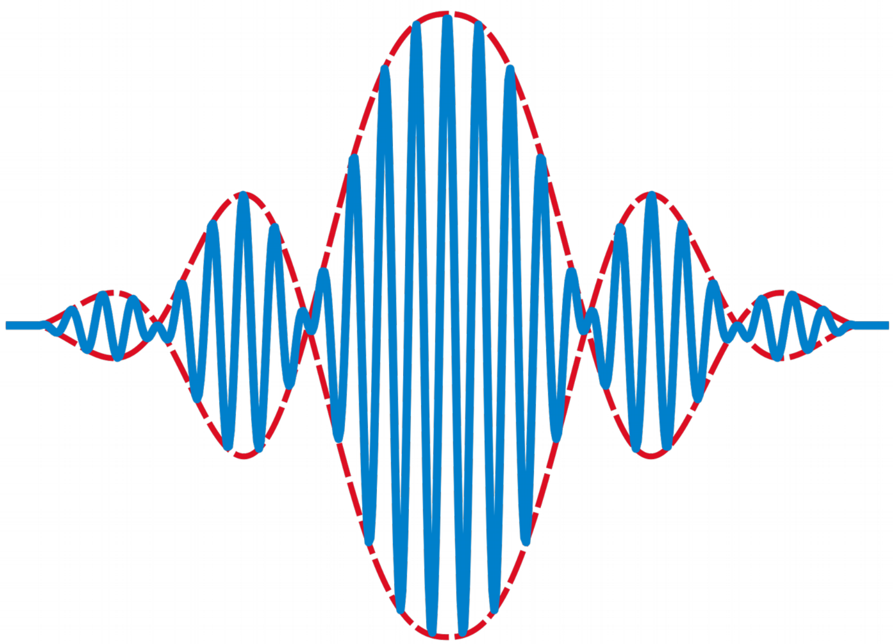
On the contrary, the phase function of wave packet does not change with frequency:

$$\frac{\partial \phi}{\partial \omega} = 0 \Rightarrow t - x \frac{\partial k}{\partial \omega} = 0 \Rightarrow \boxed{\frac{x}{t} = \frac{\partial \omega}{\partial k} = U}$$

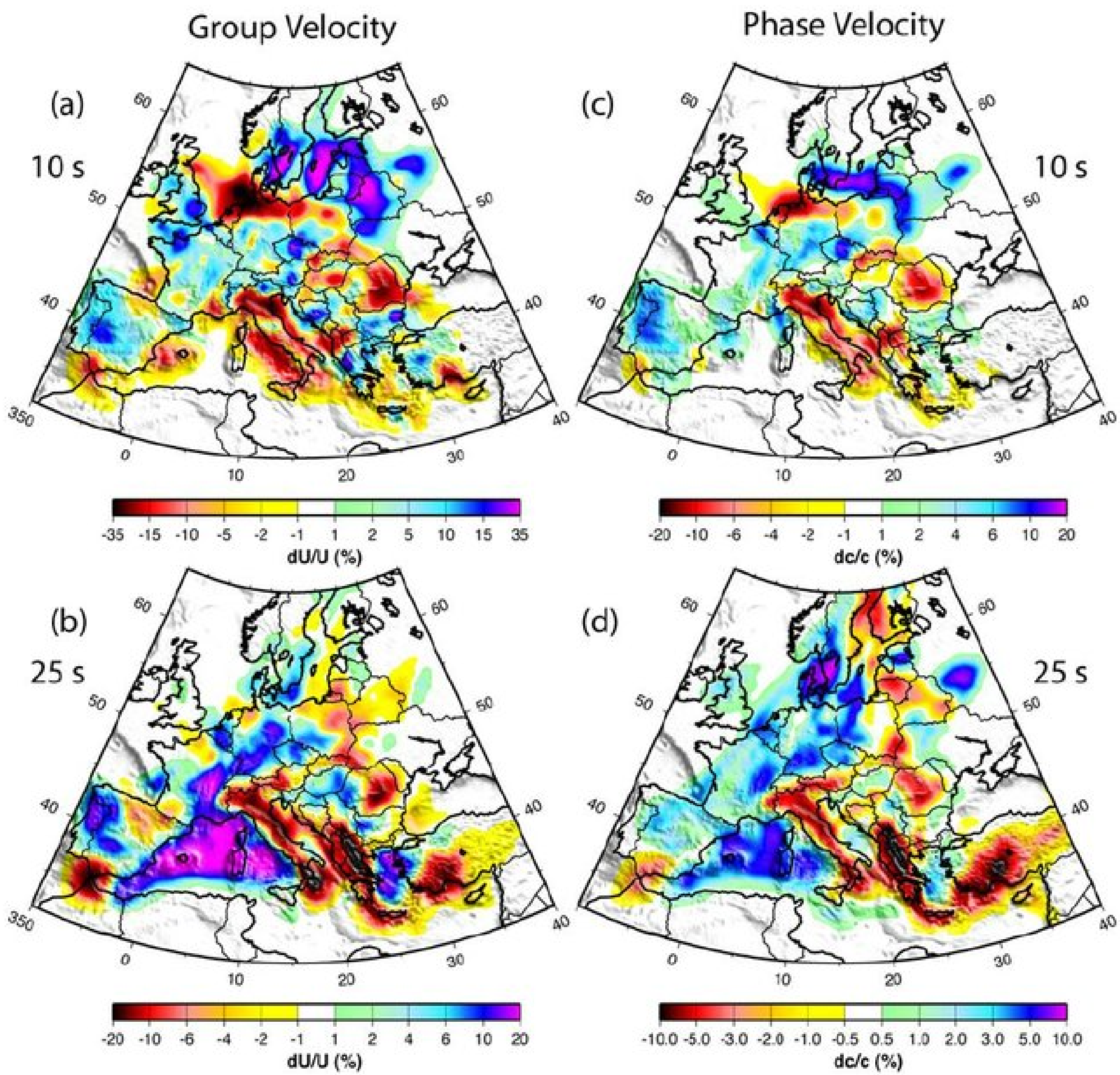
Mathematical Formulation

From that it follows the relation between phase and group velocities:

$$U = \frac{\partial \omega}{\partial k} = \frac{\partial (c\,k)}{\partial k} = c + k\frac{\partial c}{\partial k}$$



Phase and Group Velocity Maps



Surface Wave Inversion

Inversion of surface wave dispersion curves is a highly **non-linear** and **non-unique problem**, which often lead to erroneous solutions in case of insufficient data constraints.