SEISMOLOGY & EARTH STRUCTURE

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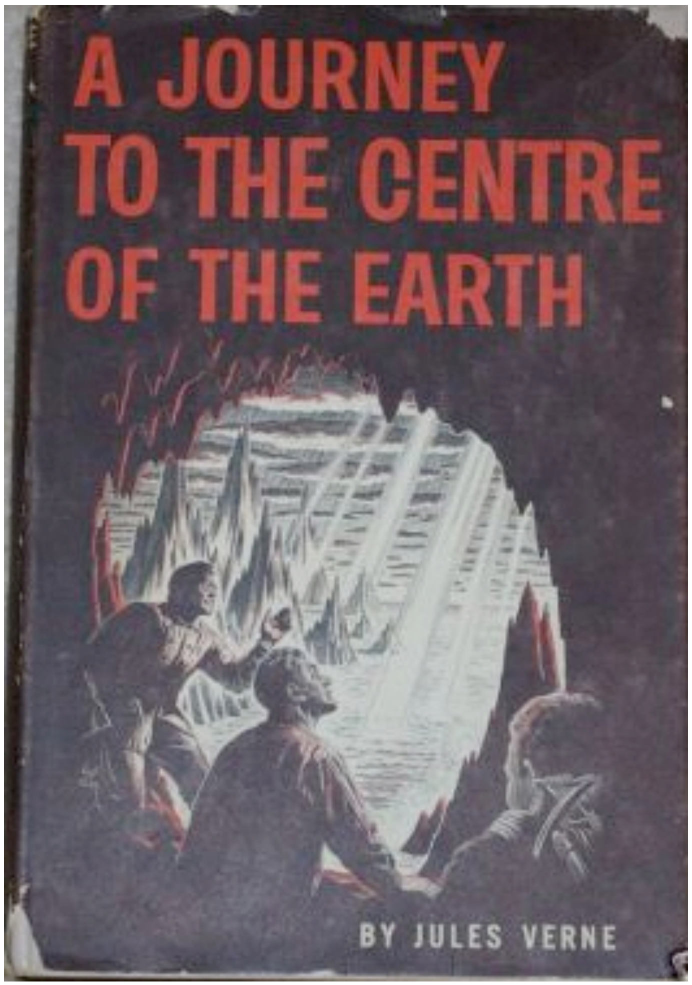
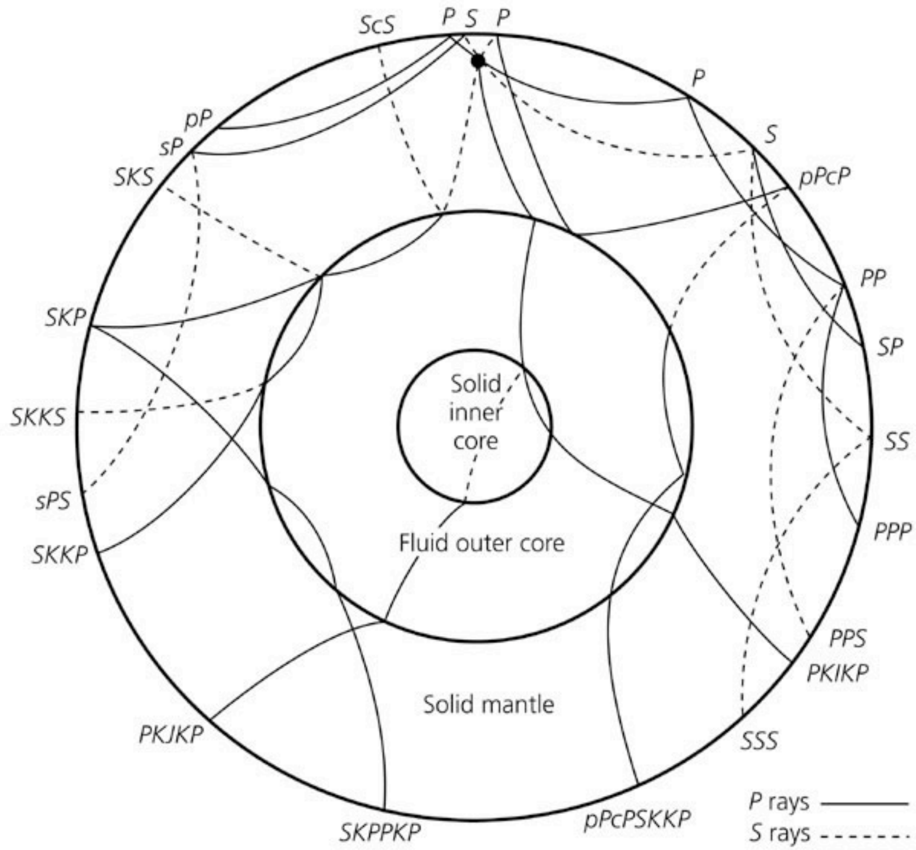
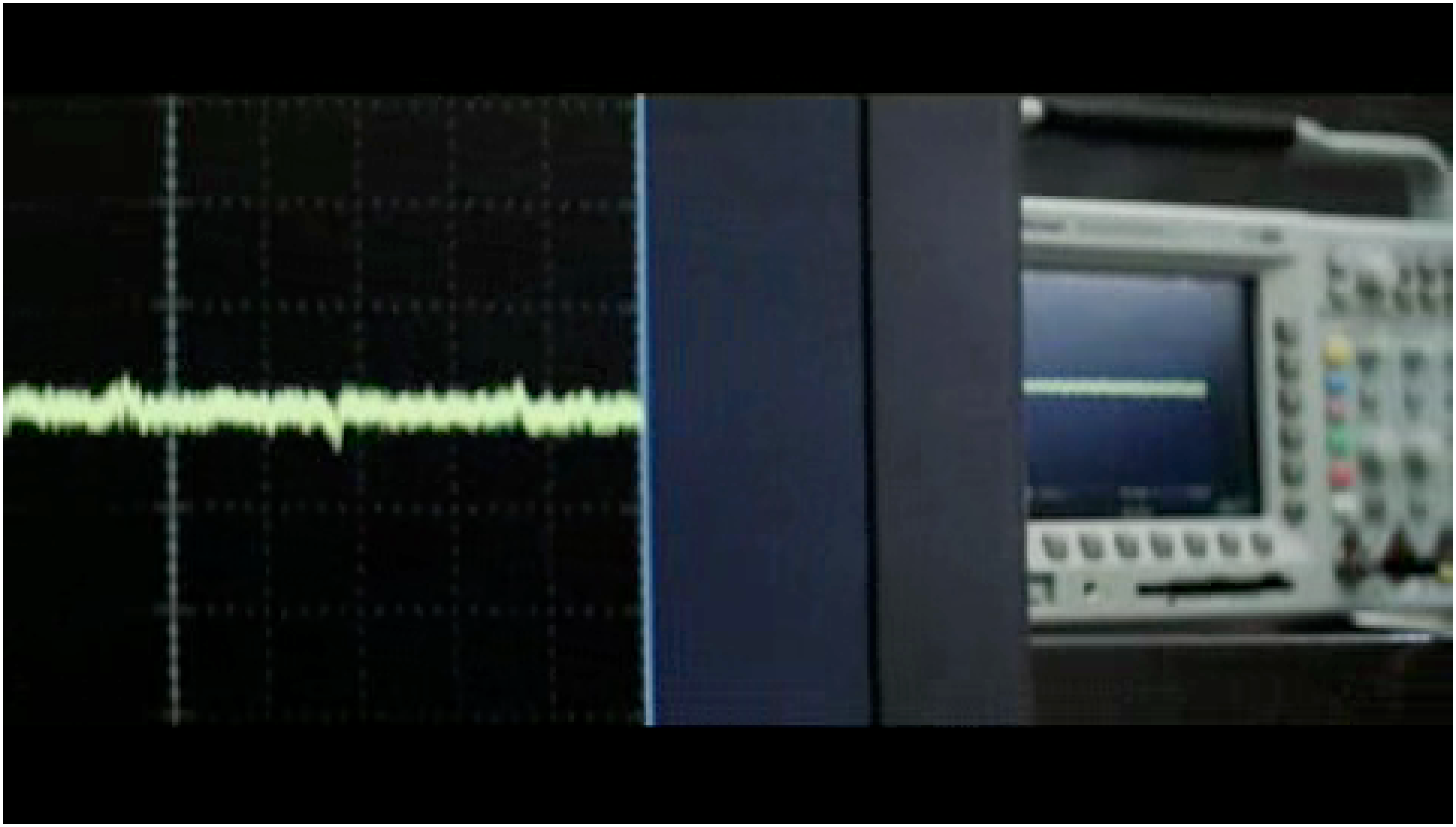
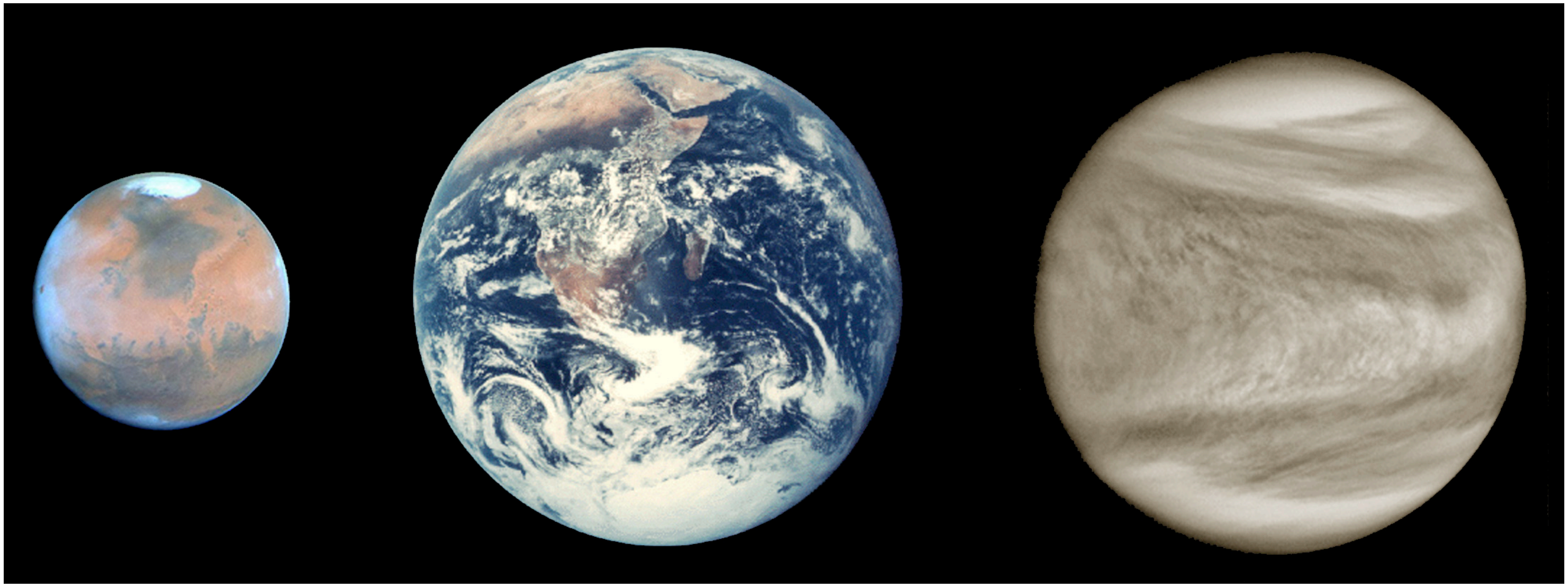


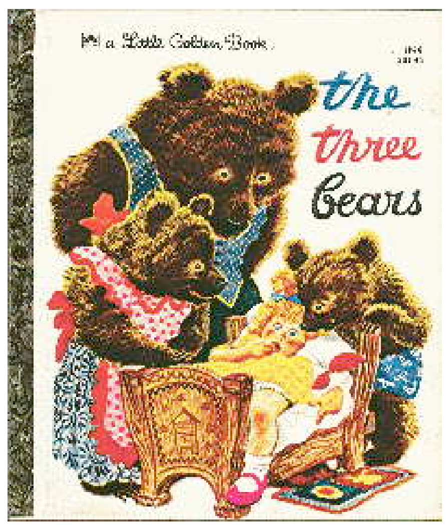
Figure 3.5-5: Illustration of various body wave phases.







Mars is too cold **Earth is just right** **Venus is too hot**



PROBING THE DEEP EARTH

SEISMOLOGY USES TRAVEL TIMES AND AMPLITUDES OF SEISMIC WAVES TO STUDY VARIATIONS IN SEISMIC WAVE VELOCITY & DENSITY

+

GRAVITY STUDIES MEASURE VARIATIONS IN DENSITY

+

MAGNETIC STUDIES GIVE INSIGHT INTO CORE'S MAGNETIC FIELD

+

LABORATORY STUDIES OF ROCK PROPERTIES

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MODELS OF EARTH'S COMPOSITION, TEMPERATURE, & INTERNAL PROCESSES TODAY & OVER TIME

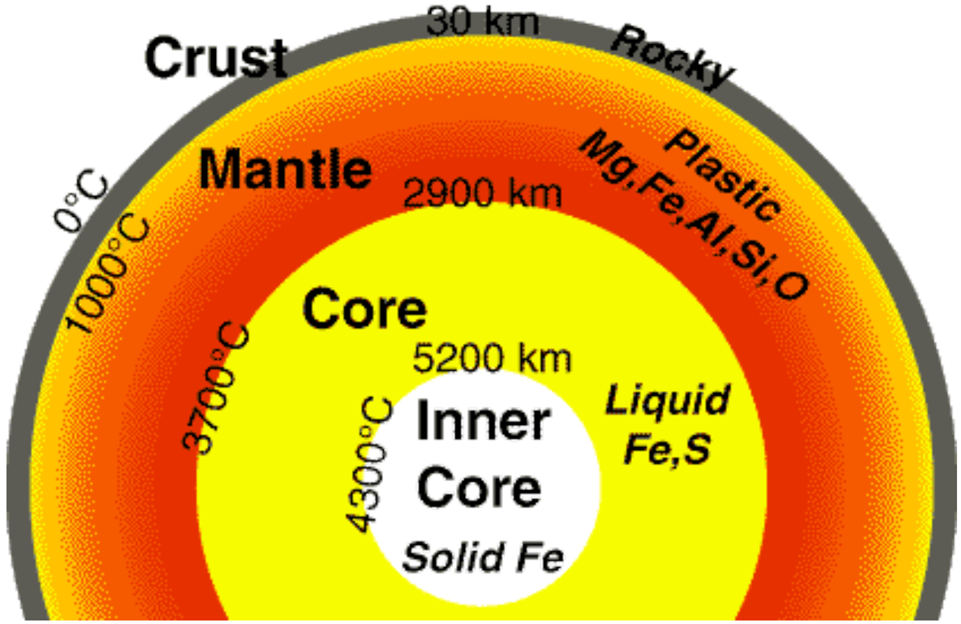
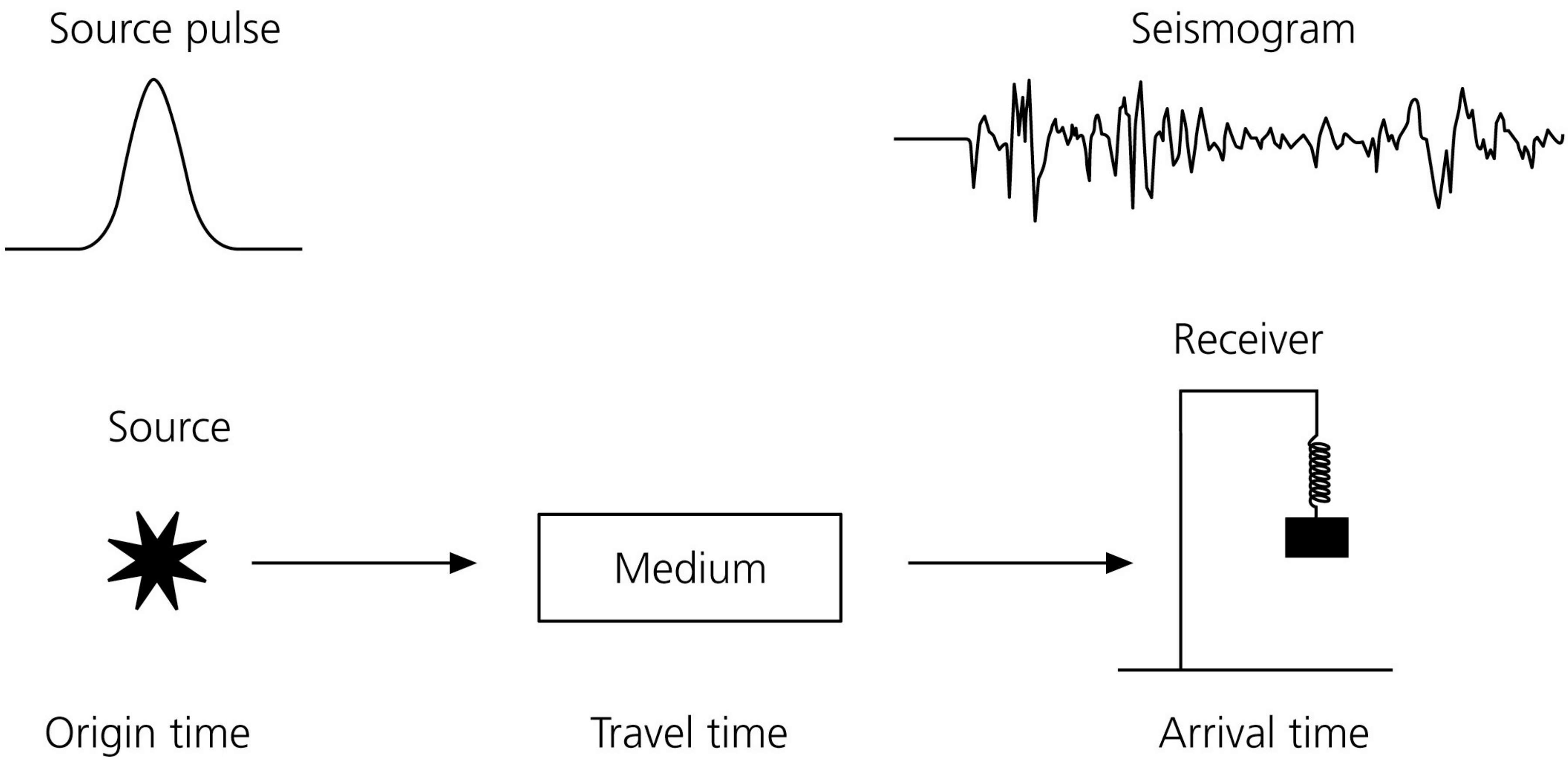


Figure 1.1-1: Schematic geometry of a seismic experiment.



STUDY BOTH SOURCE AND MEDIUM

One seismologist's signal is another's noise

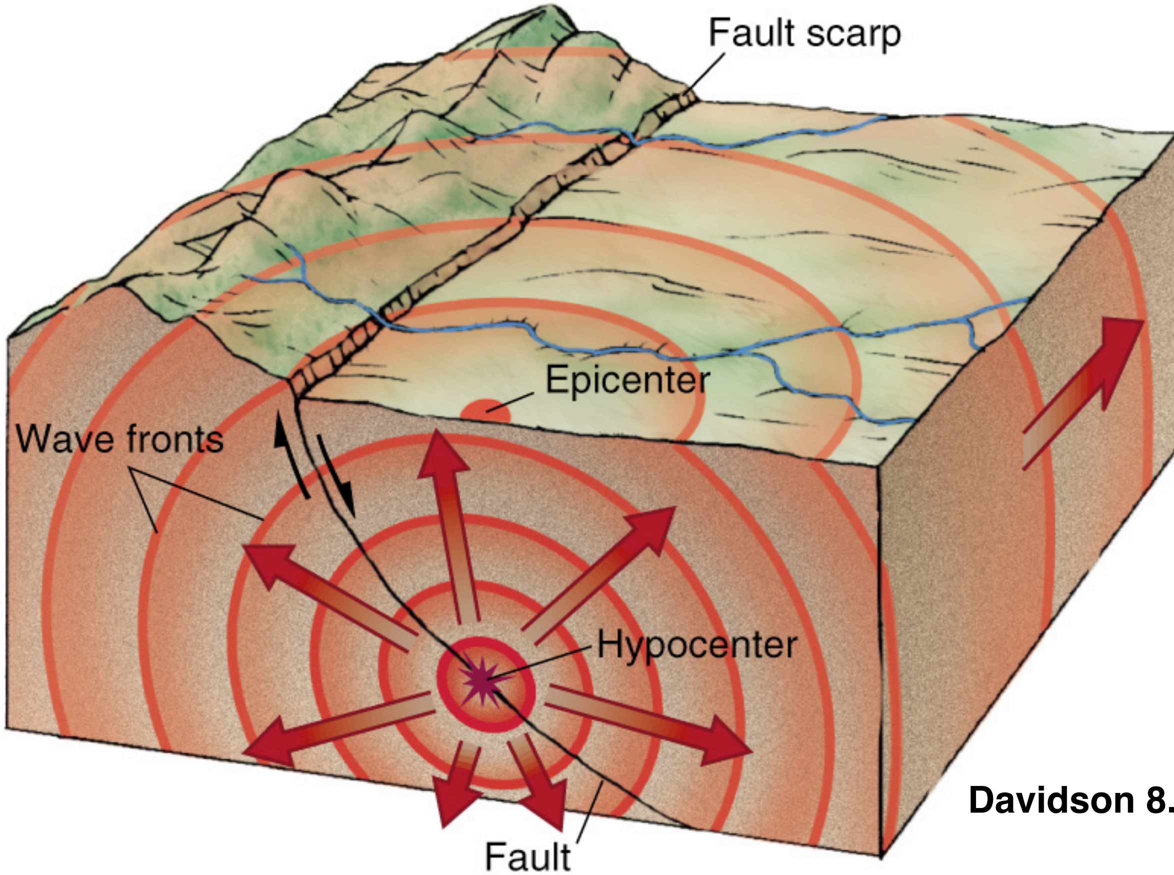
SEISMIC WAVES

DISTURBANCES AS FUNCTION OF SPACE & TIME THAT TRAVEL THROUGH SOLID EARTH

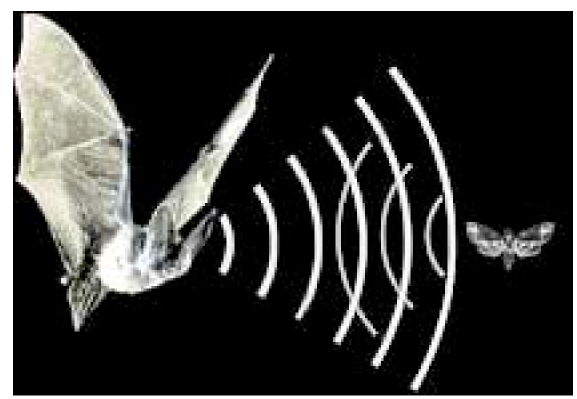
LIKE SOUND WAVES, LIGHT (ELECTROMAGNETIC) WAVES, OR WATER WAVES

USE SEISMIC WAVES TO "SEE" INSIDE EARTH

LIKE LIGHT (VISION, XRAYS) OR SOUND (ULTRASOUND, SONAR, DOLPHINS, BATS)

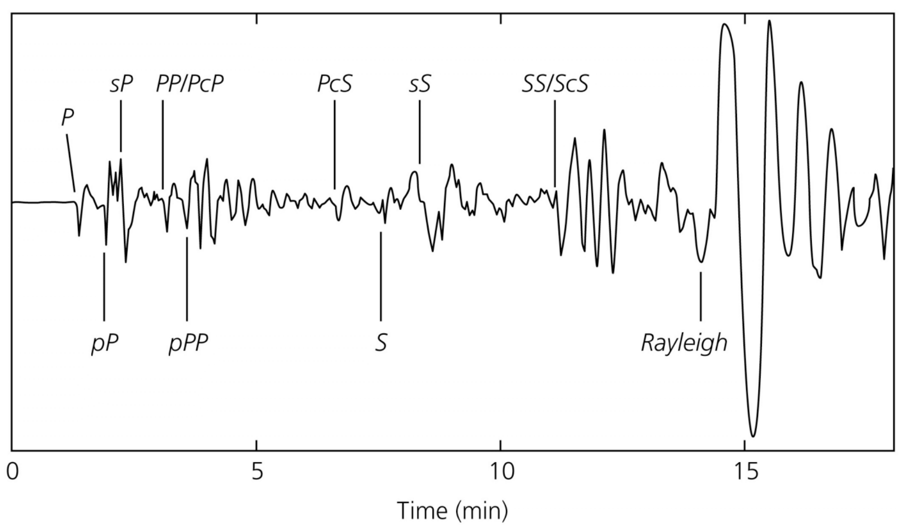


Davidson 8.11



SEISMIC WAVES TRAVEL THROUGH EARTH

Use to study earthquakes & structure of the earth



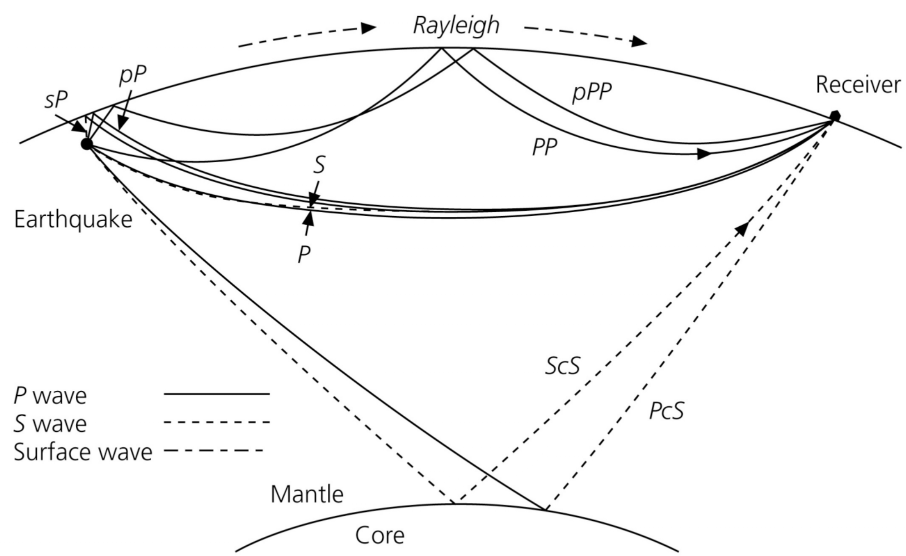
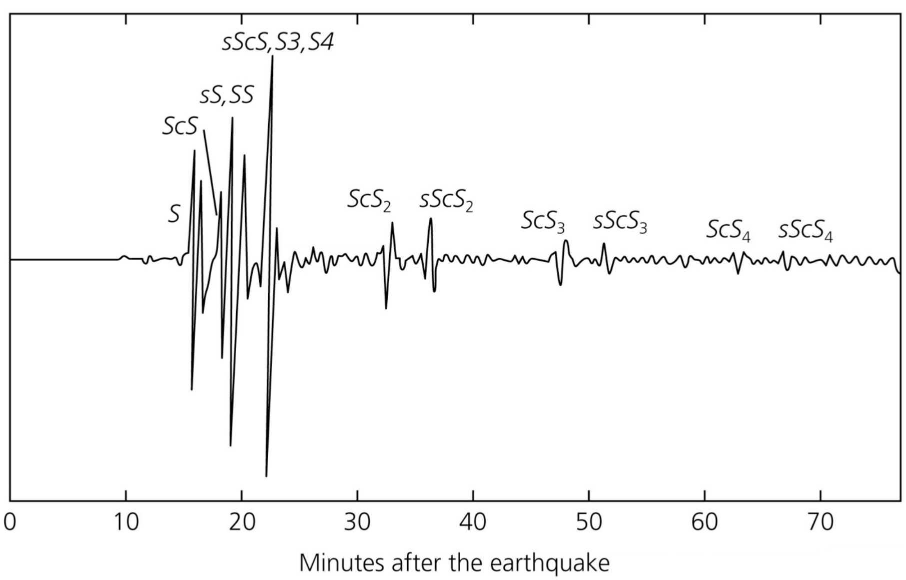
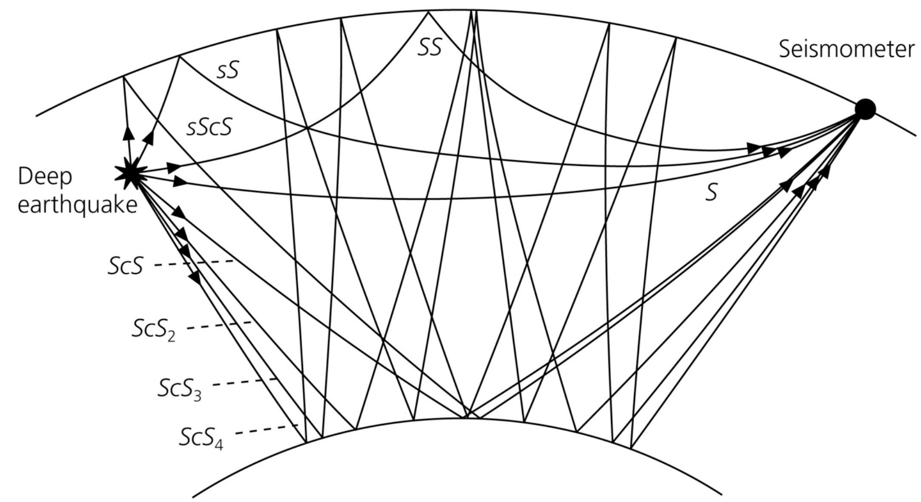
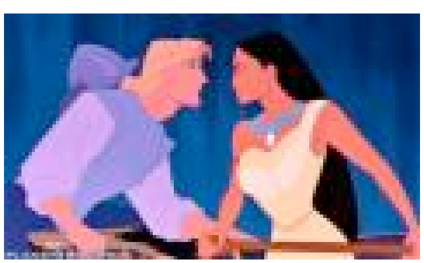


Figure 1.1-4: Seismogram and ray paths for multiple core reflections.

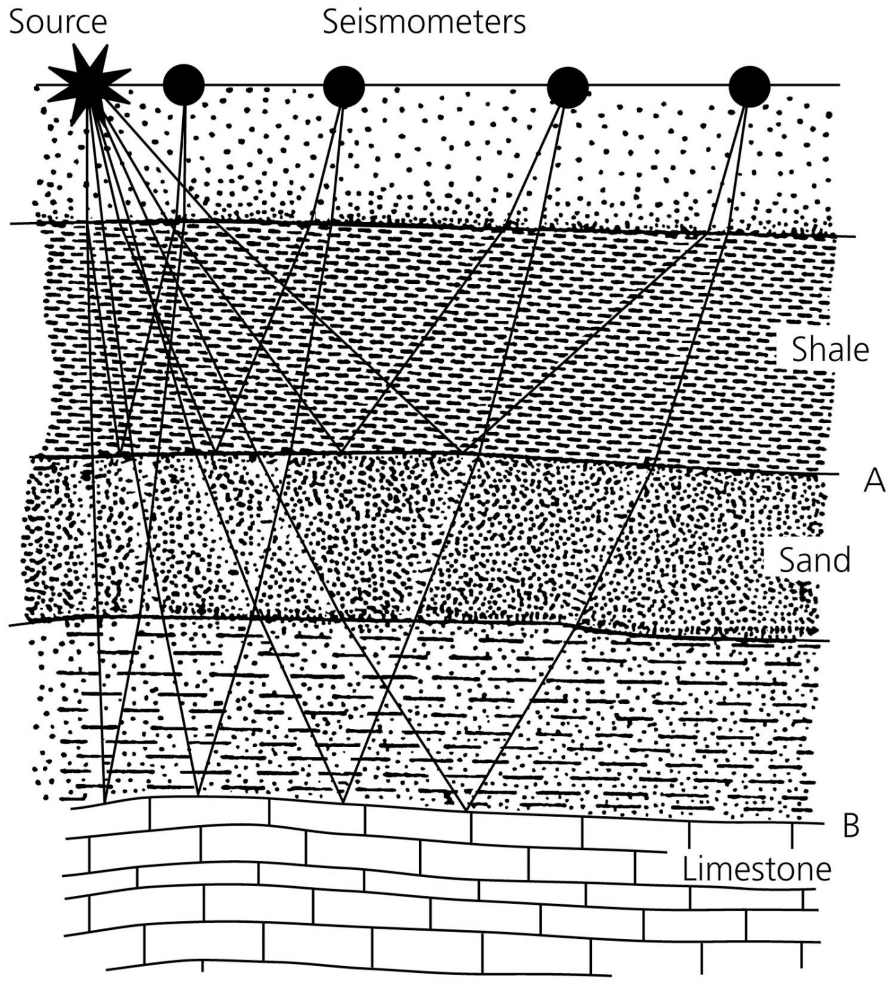






"every rock and tree and creature has a life, has a spirit, has a name…"

Figure 1.1-5: Demonstration of the seismic reflection method.



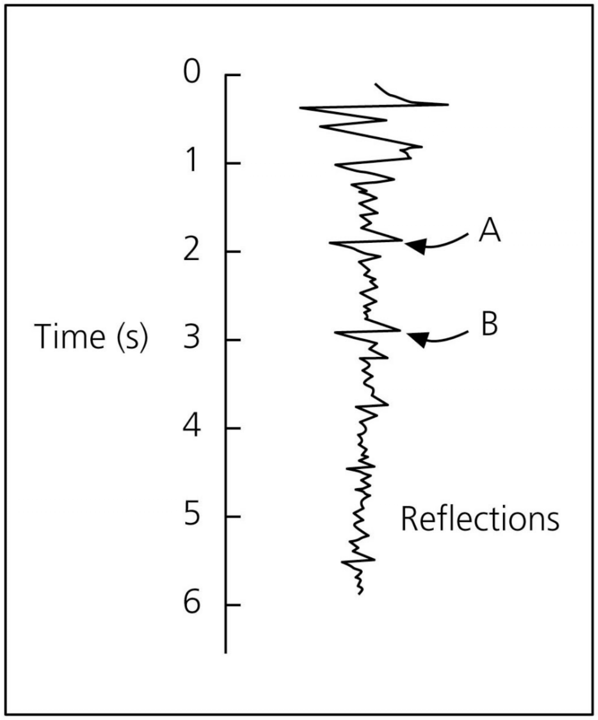
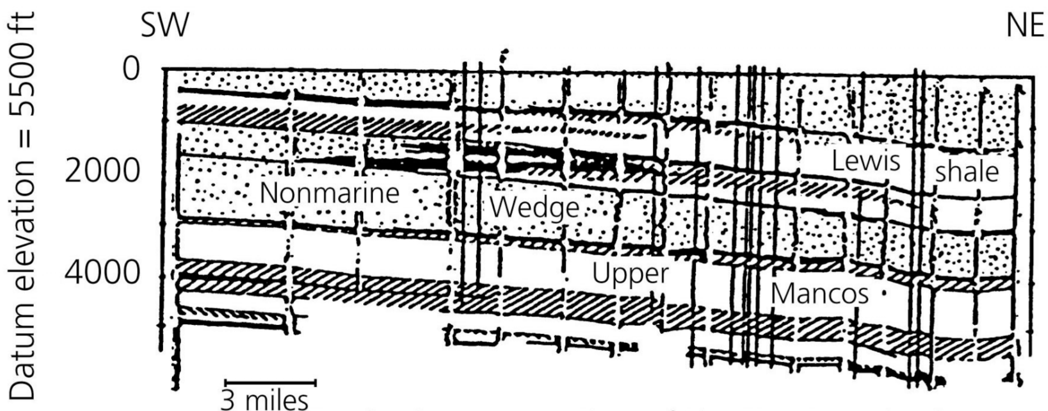
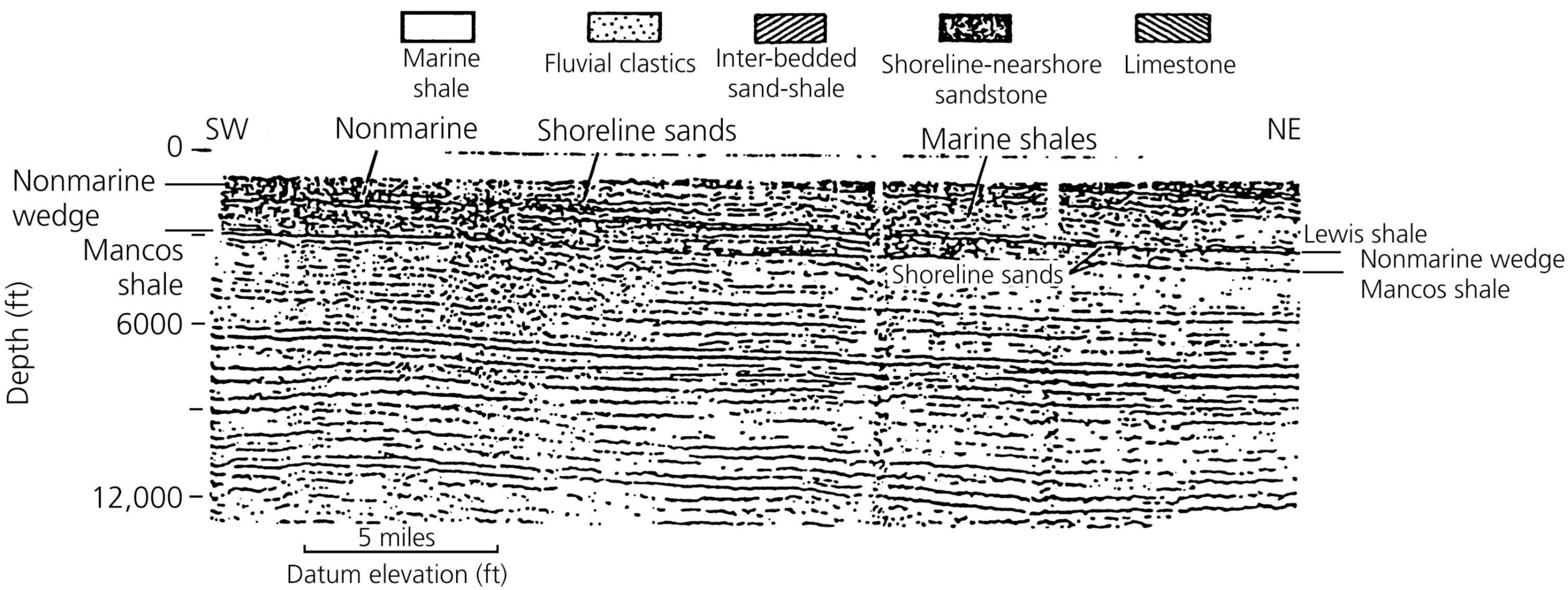


Figure 1.1-6: Example of a seismic reflection survey.



Geologic cross-section of the San Juan basin.



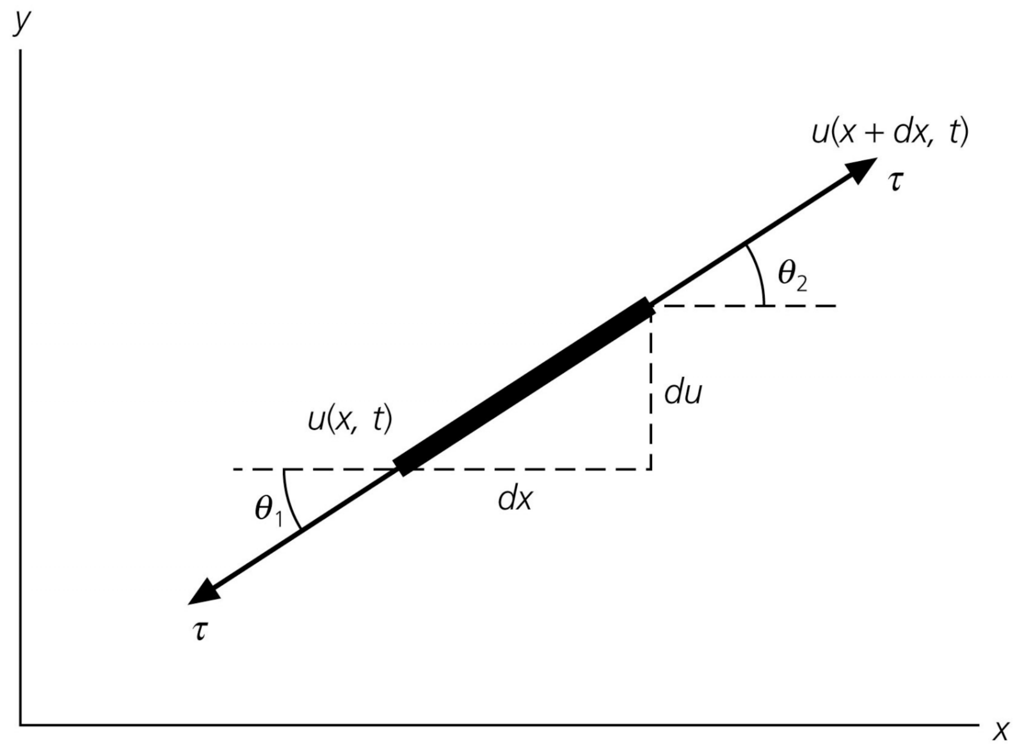
$$\mathbf{F} = m\mathbf{a}$$

$$F(x,t) = \tau \sin\theta_2 - \tau \sin\theta_1 = \rho dx \frac{\partial^2 u(x,t)}{\partial t^2}$$

For θ small, $\sin\theta \approx \theta \approx \tan\theta$:

$$\tau\left(\frac{\partial u(x+dx,t)}{\partial x} - \frac{\partial u(x,t)}{\partial x}\right) = \rho dx \frac{\partial^2 u(x,t)}{\partial t^2}$$

Figure 2.2-1: Tensions on a string segment.



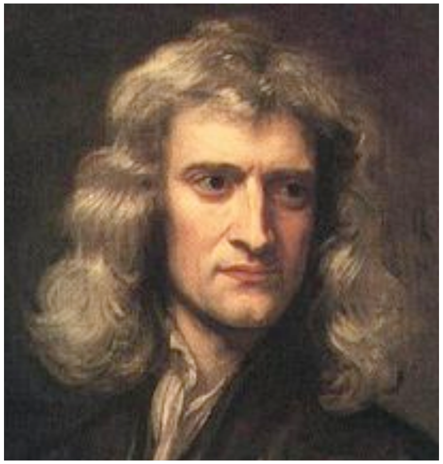
Discarding the higher Taylor series terms:

$$\tau\left(\frac{\partial u(x,t)}{\partial x} + \frac{\partial^2 u(x,t)}{\partial x^2} dx - \frac{\partial u(x,t)}{\partial x}\right) = \tau \frac{\partial^2 u(x,t)}{\partial x^2} dx = \rho dx \frac{\partial^2 u(x,t)}{\partial t^2}$$

Wave equation:

$$\frac{\partial^2 u(x,t)}{\partial x^2} = \frac{1}{\mathrm{v}^2} \frac{\partial^2 u(x,t)}{\partial t^2}$$

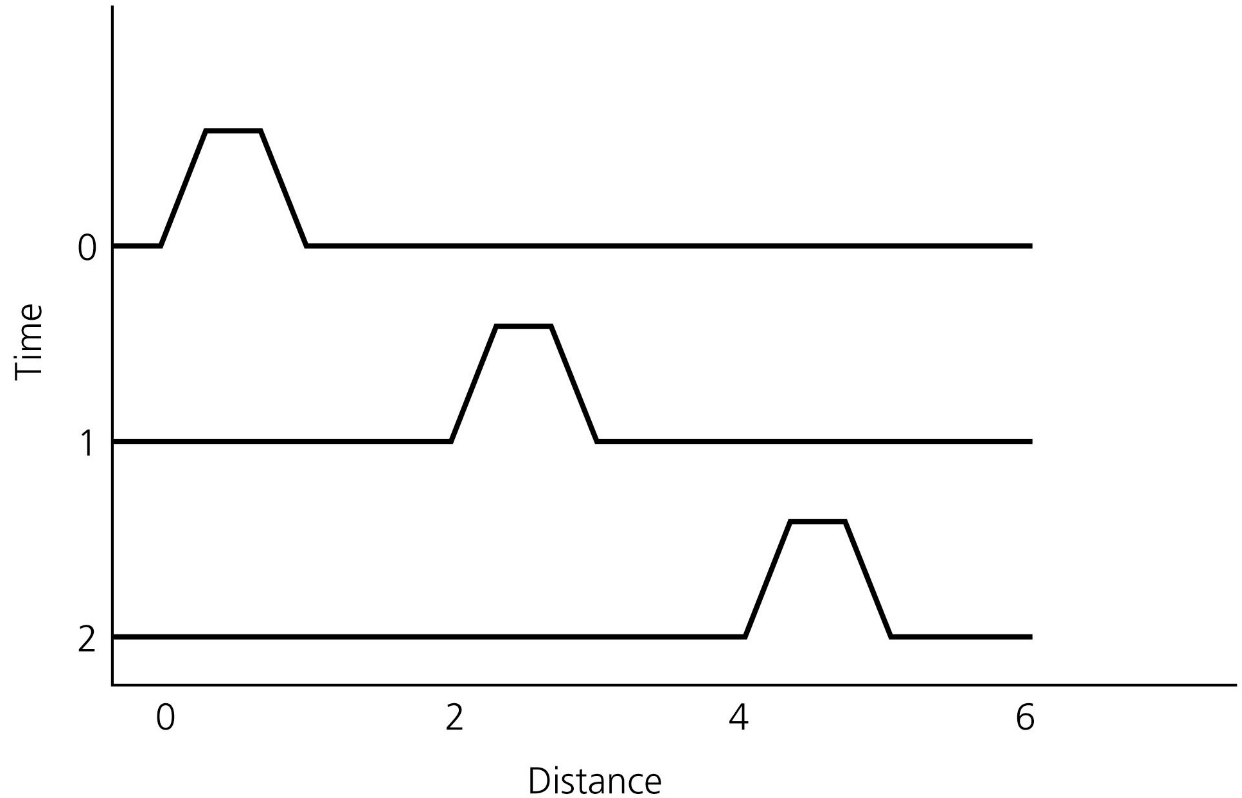
where $\mathrm{v} = (\tau/\rho)^{1/2}$



" If I have seen further it is by standing on the shoulders of giants."   1676

TRAVELING WAVE

Figure 2.2-2: Propagating pulse, *f(x - 2t)*.



$$\frac{\partial^2 u(x, t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 u(x, t)}{\partial t^2}$$

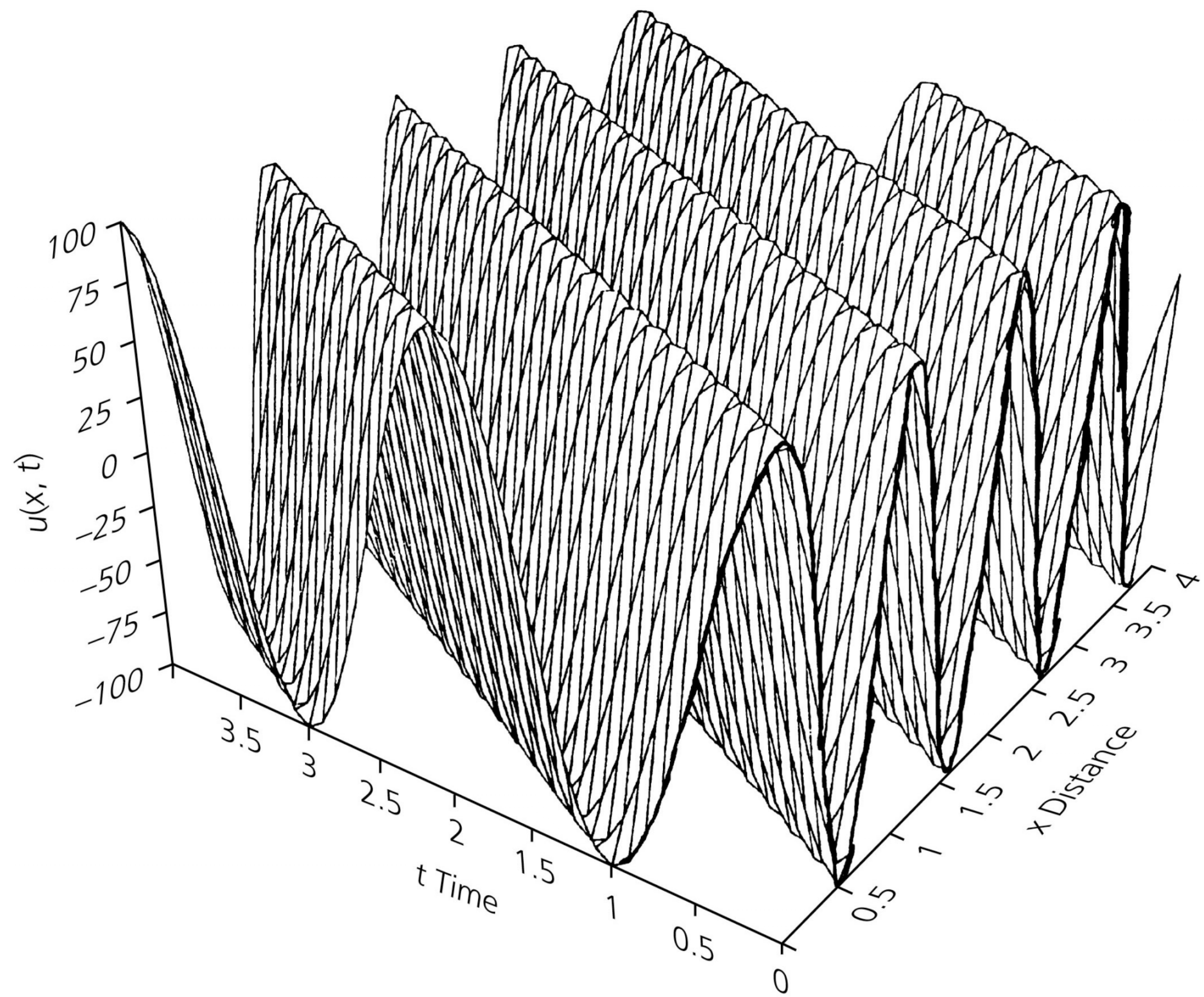
The solution has the form $u(x, t) = f(x \pm vt)$:

$$\frac{\partial^2 u(x, t)}{\partial x^2} = f''(x \pm vt) \quad \text{and} \quad \frac{\partial^2 u(x, t)}{\partial t^2} = v^2 f''(x \pm vt)$$

where f'' is the second derivative of f

WAVE FIELD COUPLES SPACE AND TIME

Figure 2.2-3: Displacement field of *u = A cos (πt - 2πx)*.



Harmonic (sinusoidal) function:

$$u(x, t) = Ae^{i(\omega t \pm kx)} = A\cos(\omega t \pm kx) + Ai\sin(\omega t \pm kx)$$

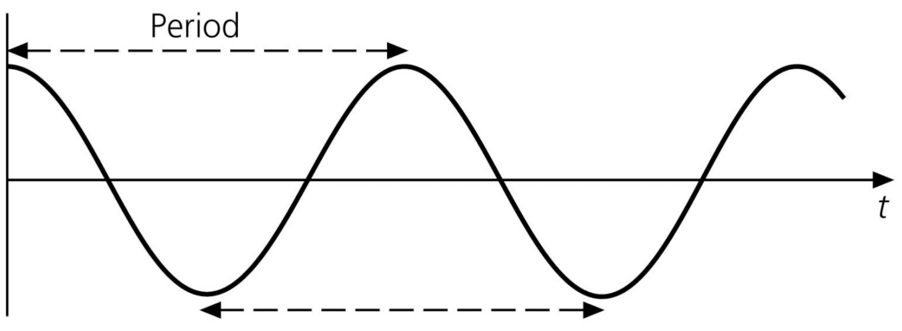
gives $v = \omega/k$

POINT IN SPACE, FUNCTION OF TIME

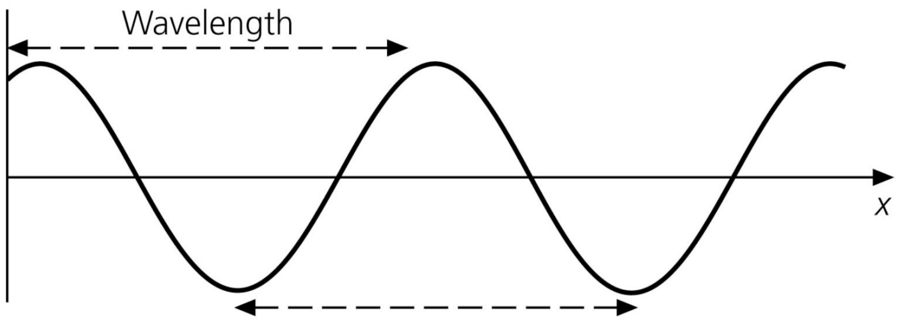
Table 2.2-1 Relationships Between Wave Variables

QUANTITY	UNITS	
Velocity	distance/time	$v = \omega/k = f\lambda = \lambda/T$
Period	time	$T = 2\pi/\omega = 1/f = \lambda/v$
Angular Frequency	time^{-1}	$\omega = 2\pi/T = 2\pi f = kv$
Frequency	time^{-1}	$f = \omega/(2\pi) = 1/T = v/\lambda$
Wavelength	distance	$\lambda = 2\pi/k = v/f = vT$
Wavenumber	distance^{-1}	$k = 2\pi/\lambda = \omega/v = 2\pi f/v$

Figure 2.2-4: Harmonic wave, $u = A\cos(\omega t - kx)$.



POINT IN TIME, FUNCTION OF SPACE



SEISMIC WAVES OCCUR BECAUSE AN APPLIED FORCE MAKES ROCK DEFORM ELASTICALLY & THEN RETURNS TO ORIGINAL SHAPE

COMPRESSION - VOLUME CHANGES

SHEAR- DISTORTION: SHAPE CHANGES

Davidson 5.3

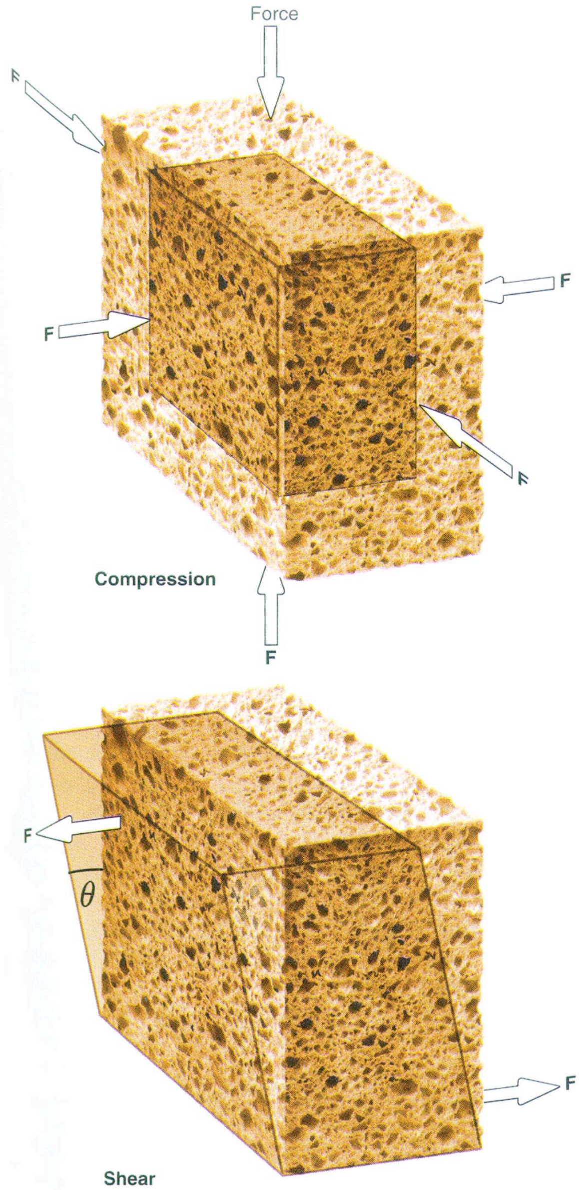
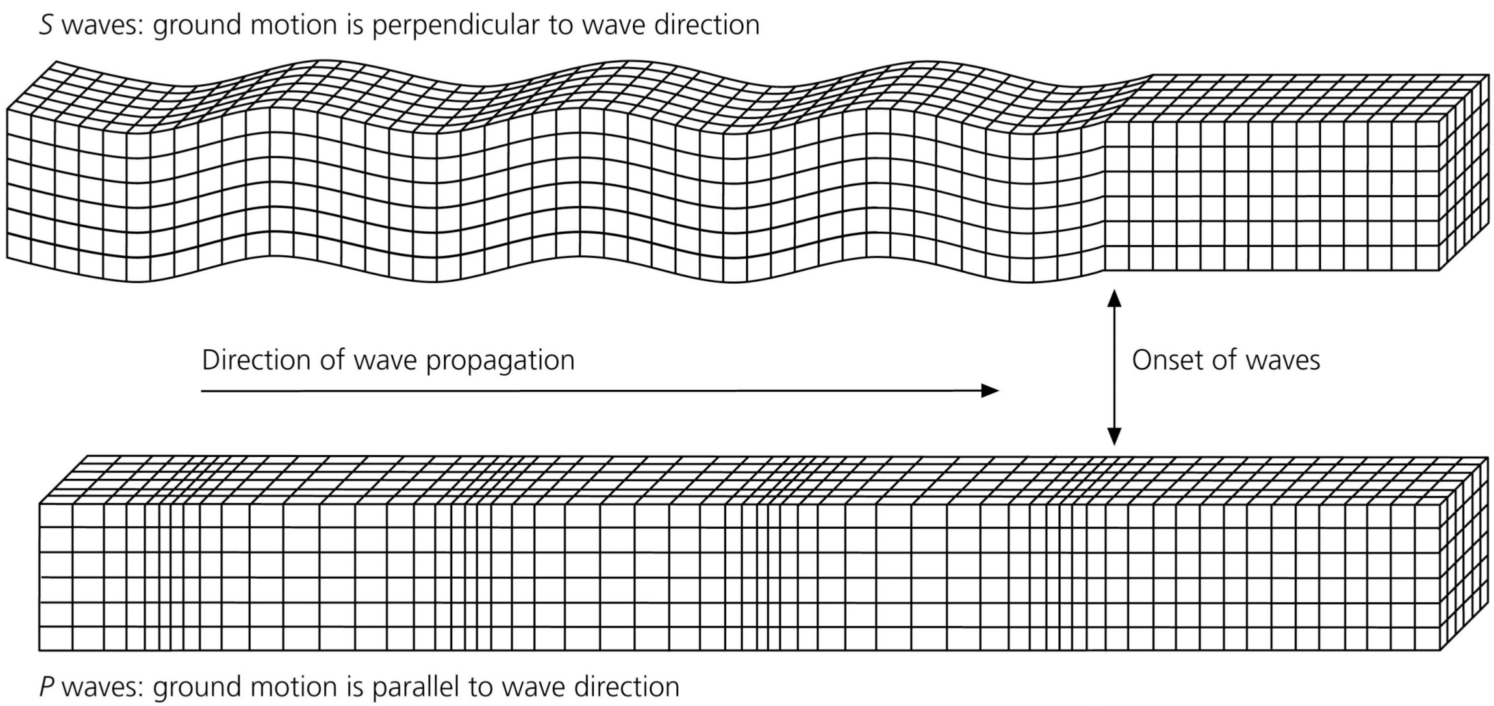


FIGURE 5.3 Two different ways of straining a rock (illustrated with a sponge): compression and shear. F represents the applied force. The shear strain is $\theta/2$, which is half the angle by which right angles change after shearing.

Figure 2.4-3: Displacements for *P* and *S* waves.



P OR *COMPRESSIONAL* WAVES - VOLUME CHANGES MATERIAL COMPRESSED OR EXPANDED IN DIRECTION WAVE PROPAGATES

S OR *SHEAR* WAVES - DISTORTION WITHOUT VOLUME CHANGES - MATERIAL SHEARED IN DIRECTION PERPENDICULAR TO WAVE PROPAGATION

SEISMIC WAVE SPEED (VELOCITY)

DEPENDS ON ELASTIC CONSTANTS (MODULI) & DENSITY OF MATERIAL

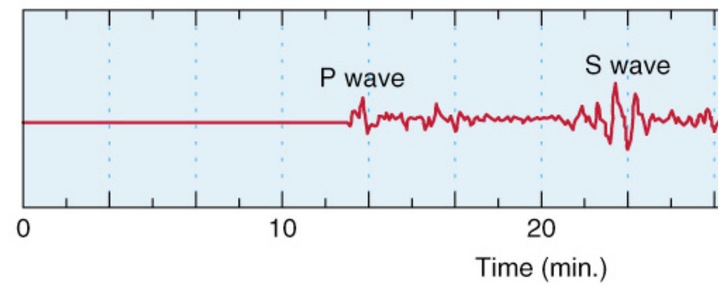
K - BULK MODULUS - LARGER K IS HARDER TO COMPRESS

μ - SHEAR MODULUS - LARGER μ IS HARDER TO SHEAR

ρ- DENSITY

$$V_p = \sqrt{\frac{\left(\frac{4}{3}\mu + k\right)}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$



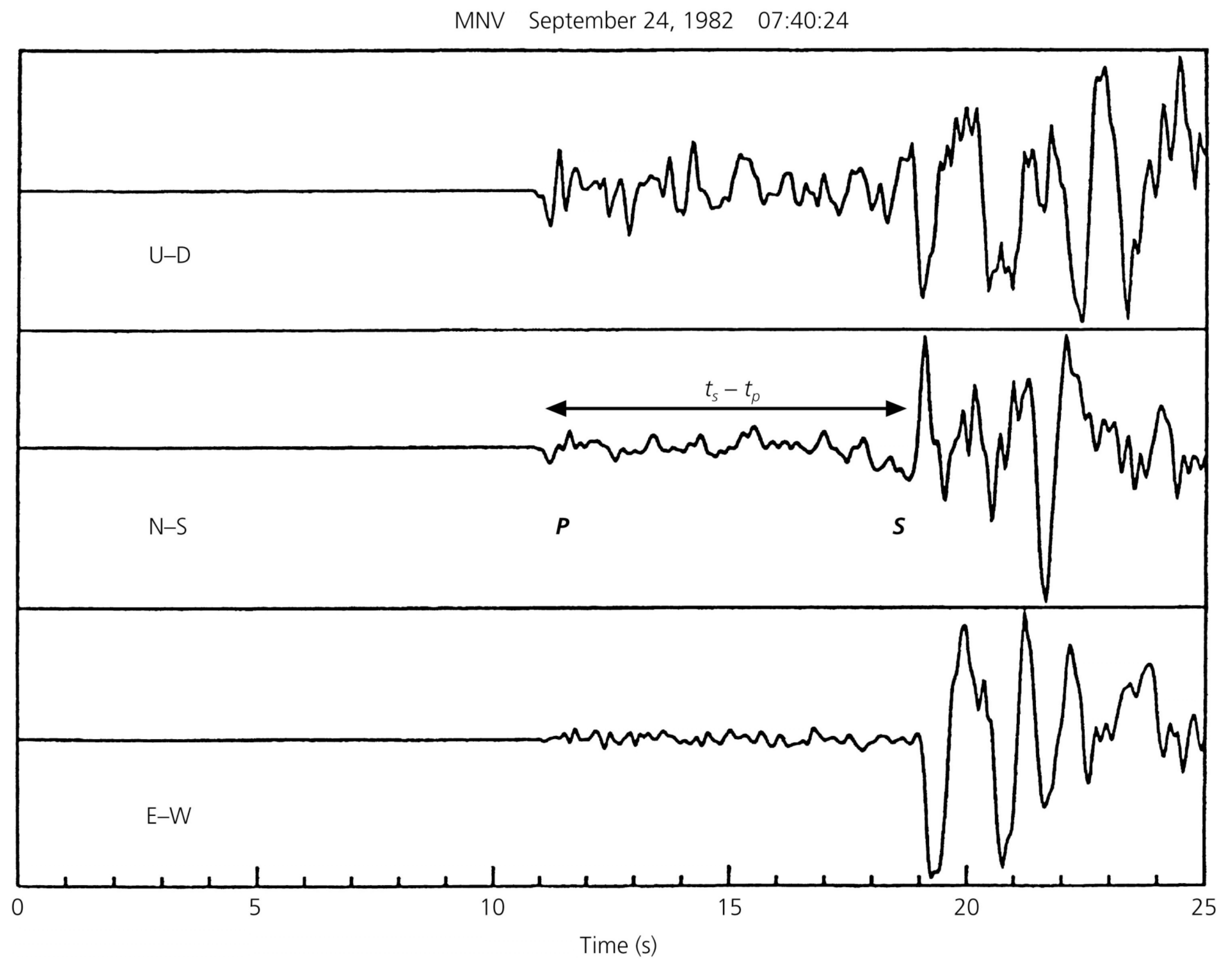
COMPRESSIONAL (P) WAVE SPEED V_P DEPENDS ON BOTH MODULI BUT *SHEAR* (S) WAVE SPEED V_S DEPENDS ON ONLY SHEAR MODULUS

P WAVES TRAVEL FASTER (ABOUT 1.7x) THAN S WAVES

S WAVES CANNOT TRAVEL THROUGH LIQUID ($\mu = 0$) LIKE OUTER CORE

IN CRUST, V_P ABOUT 5.5 km/s - 12,375 miles/hr

Figure 2.4-9: Seismograms recorded 64 km from a small, shallow earthquake.



For close distances (horizontal propagation):

$$t_s = x/3.2 \qquad t_p = x/5.5$$

$$t_s - t_p = x(1.0/3.2 - 1.0/5.5) = x/7.6$$

THREE COMPONENTS OF GROUND MOTION

P & S waves appear differently

Figure 2.4-8: Seismograms at two Japanese stations above an earthquake.

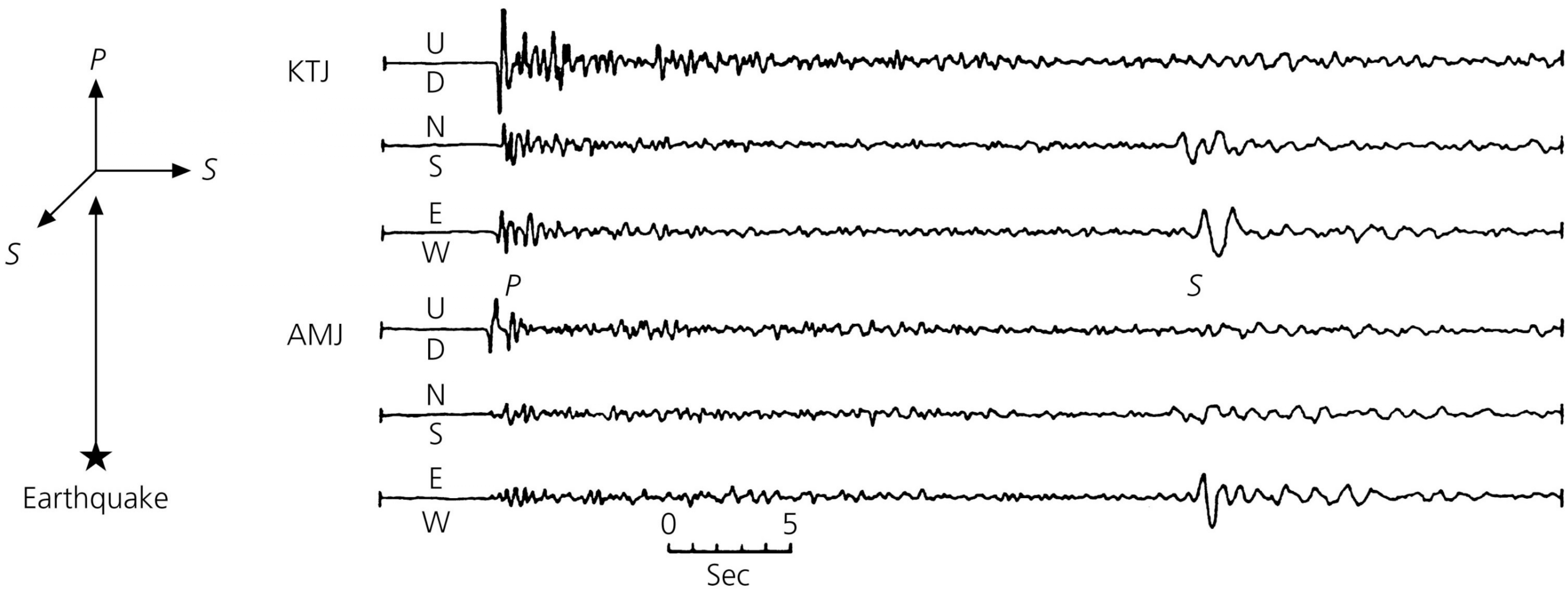
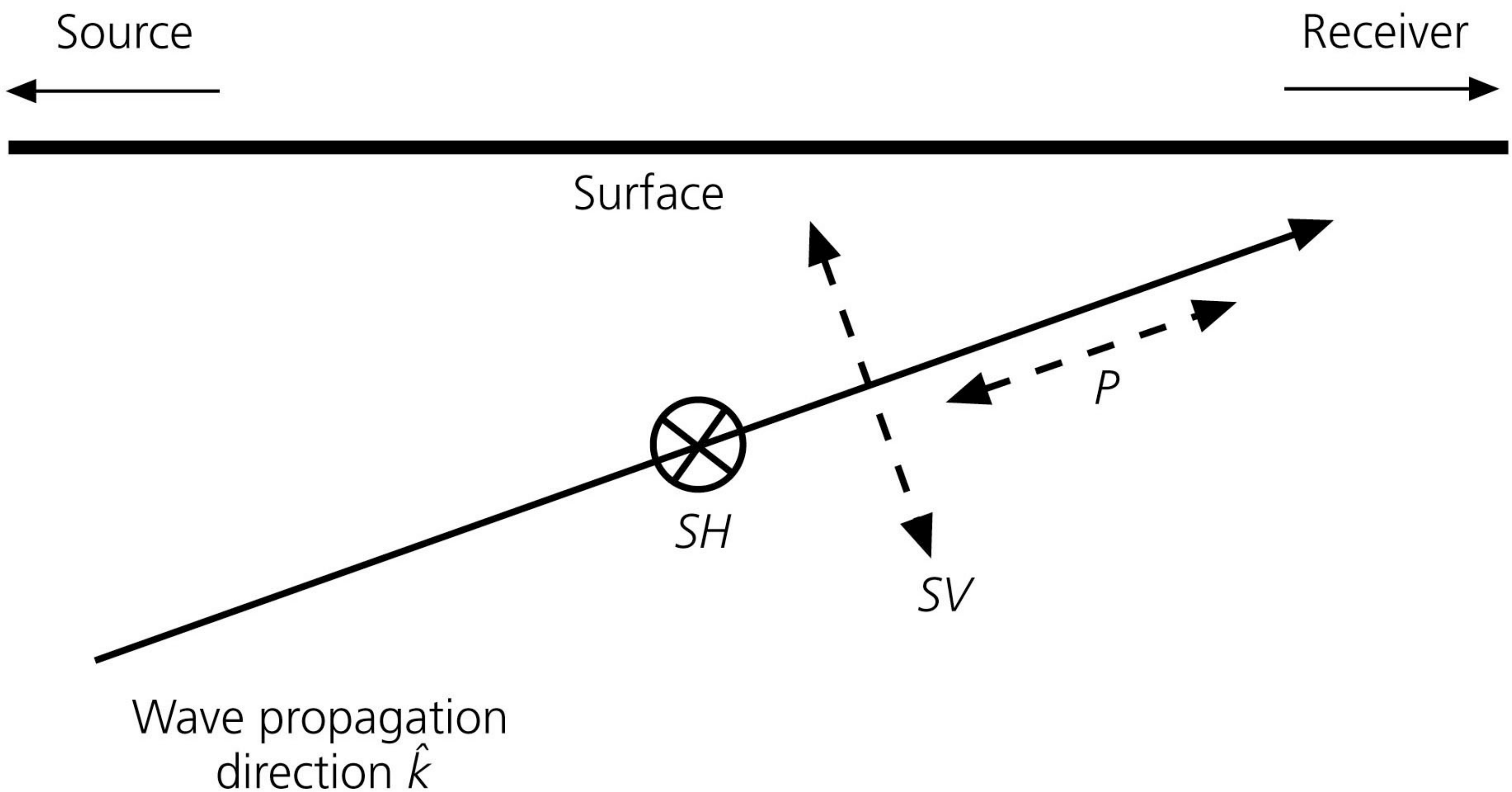
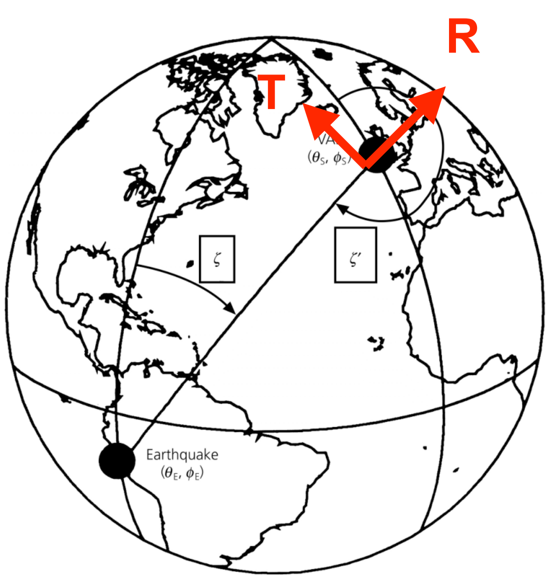


Figure 2.4-4: Displacements for *P*, *SV*, and *SH*.



RADIAL & TRANSVERSE HORIZONTAL COMPONENTS



$$\begin{pmatrix} u_R \\ u_T \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} u_{EW} \\ u_{NS} \end{pmatrix}$$

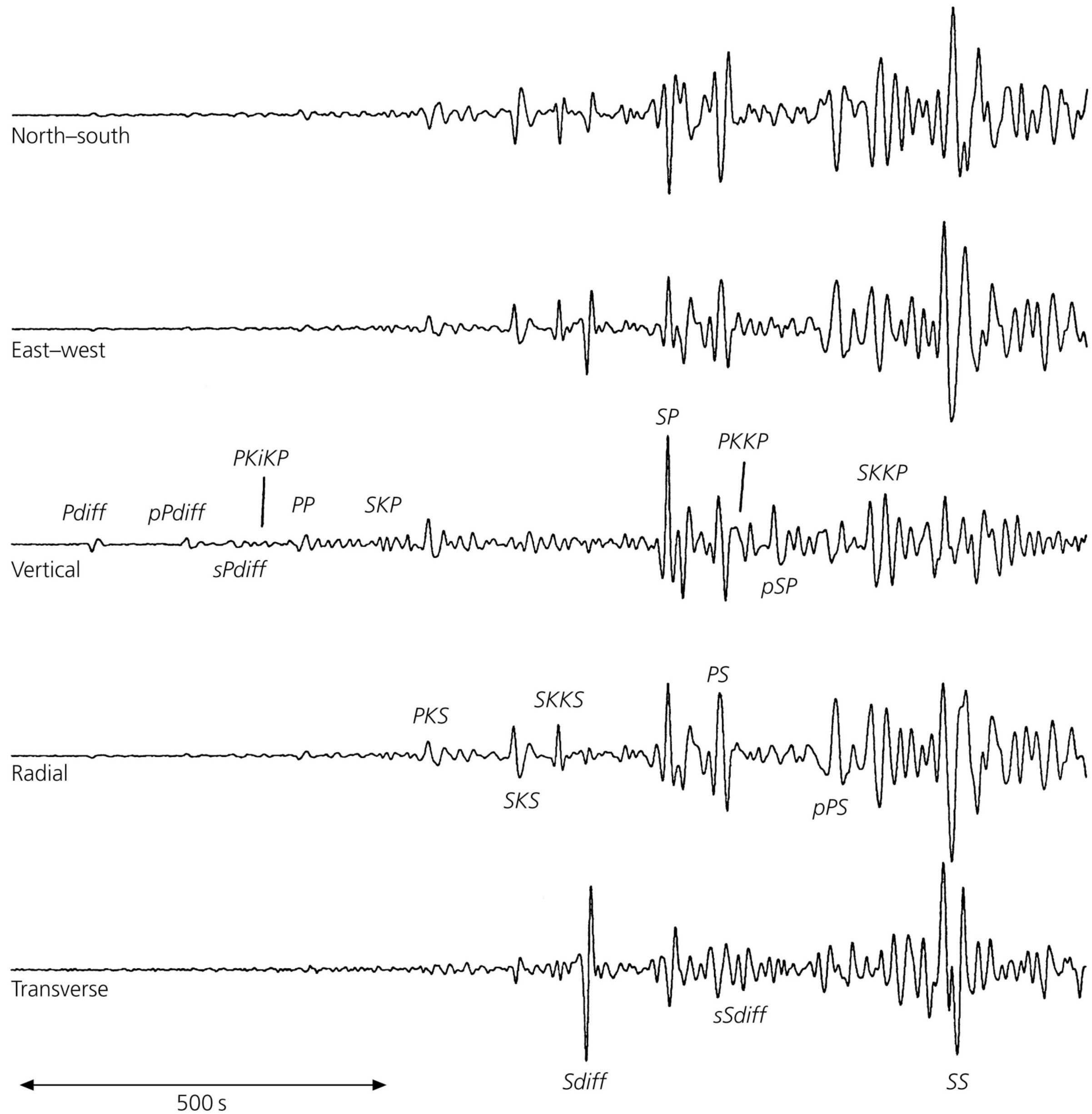
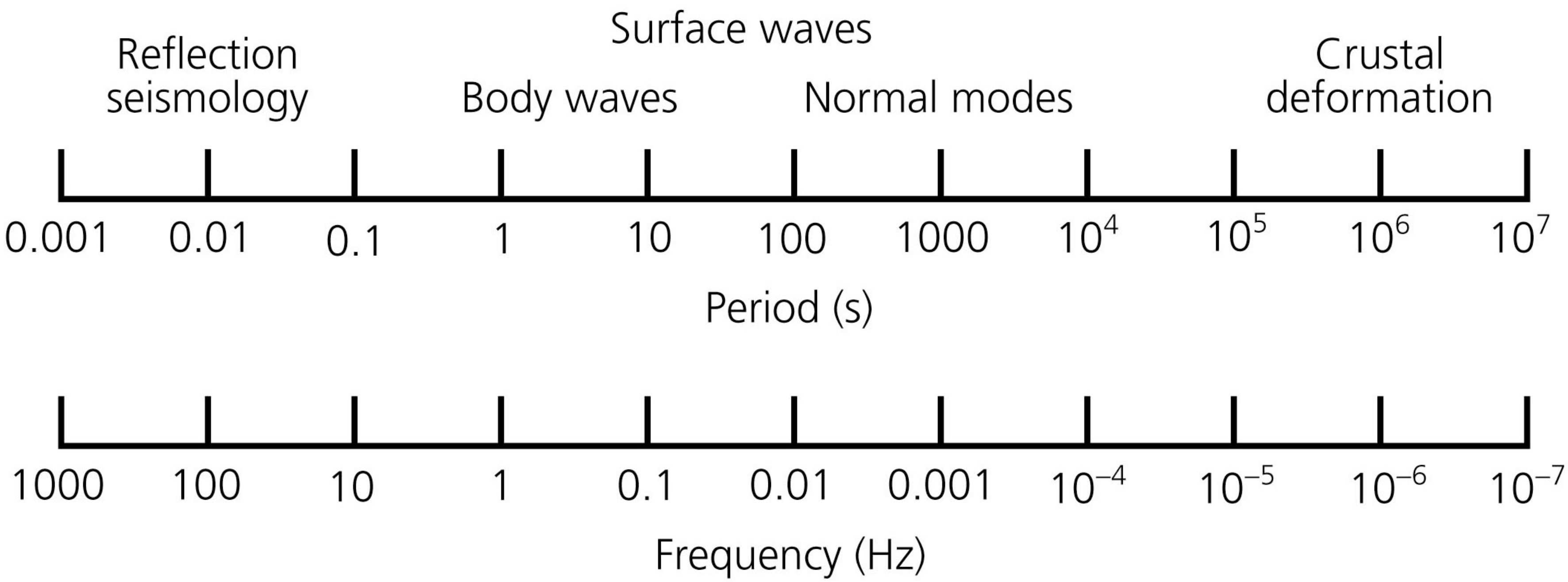


Figure 2.4-7: Seismic spectrum for various studies.



electromagnetic spectrum

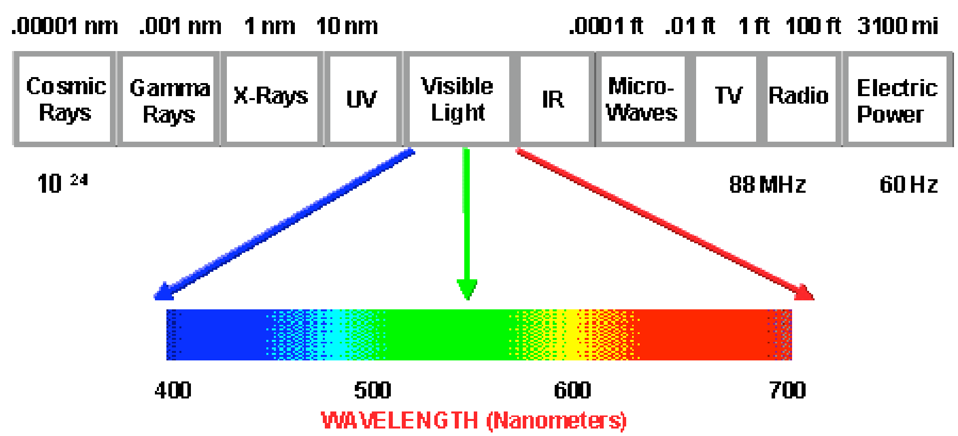
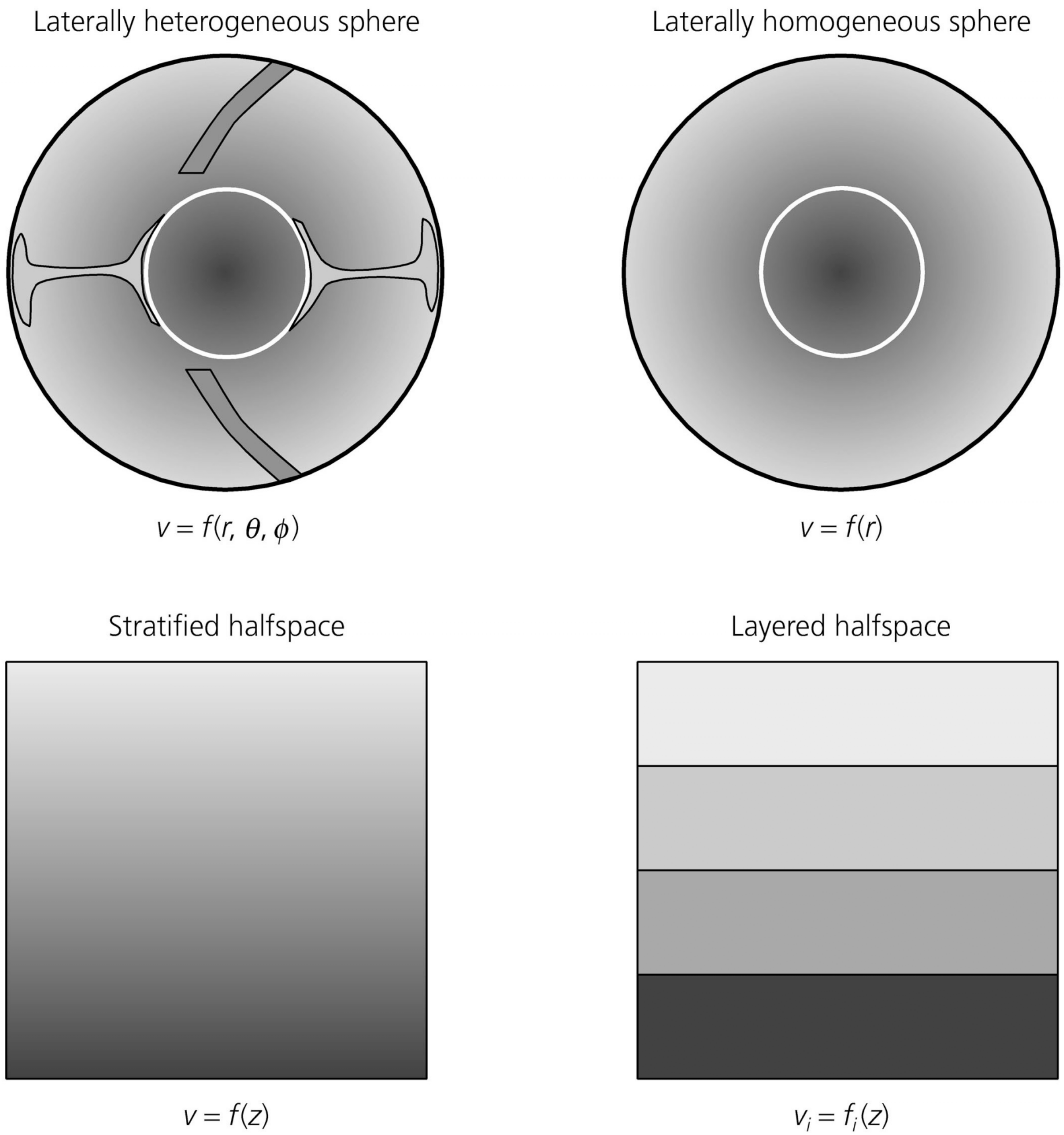
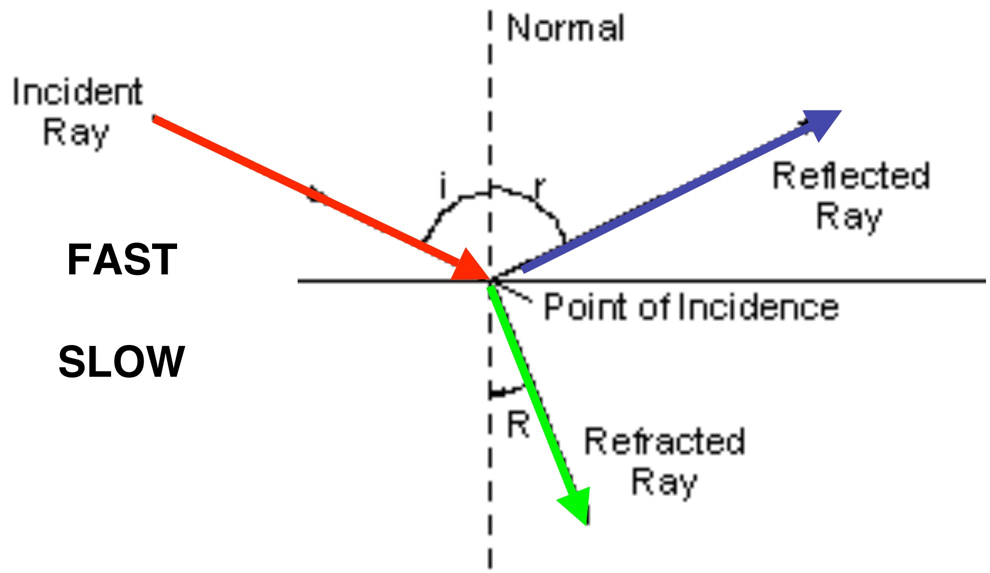


Figure 2.5-1: Some examples of earth models used in seismology.



AS SEISMIC WAVES TRAVEL FROM MATERIAL OF ONE SPEED AND DENSITY TO ANOTHER

INCIDENT (INCOMING) WAVES ARE REFLECTED AND TRANSMITTED (REFRACTED)



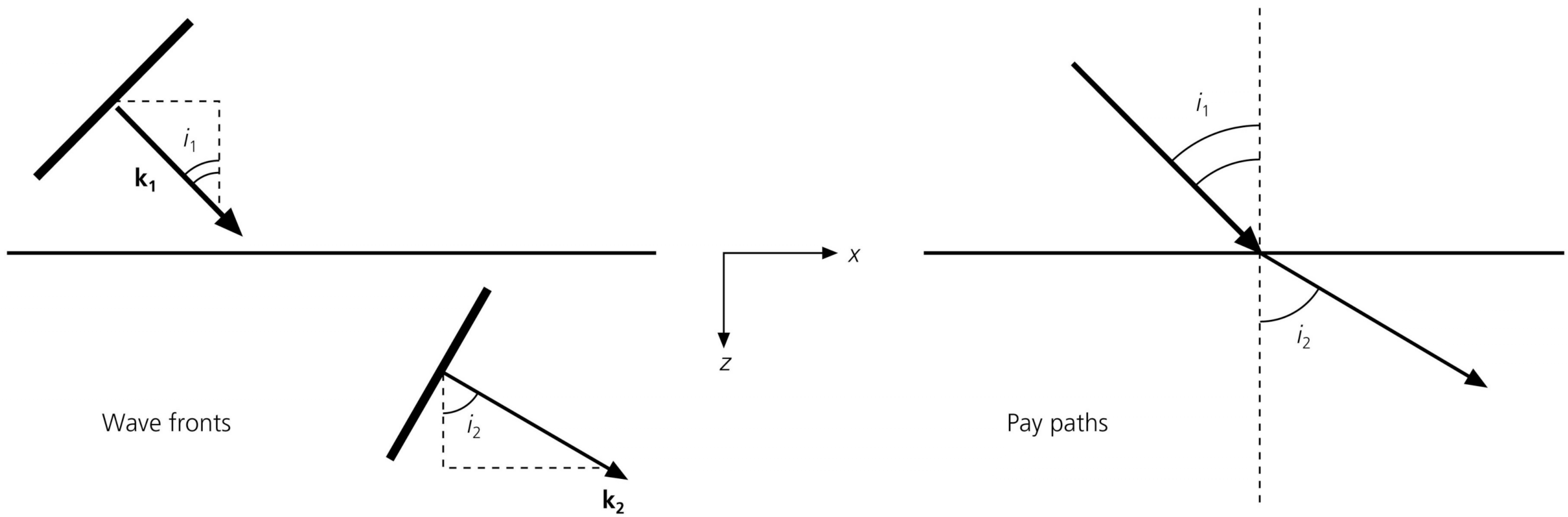
BOTH THE ANGLES AND SIZE (AMPLITUDE) OF WAVES CHANGE, DEPENDING ON VELOCITY AND DENSITY CHANGE

THIS EFFECT LETS US STUDY EARTH STRUCTURE

(AND IS USED IN LENSES, EYEGLASSES, ETC. FOR LIGHT)

TRAVELLING BETWEEN MEDIA OF DIFFERENT VELOCITIES, WAVES BEND AND CHANGE AMPLITUDE

Figure 2.5-4: Change in wave front and direction during refraction.



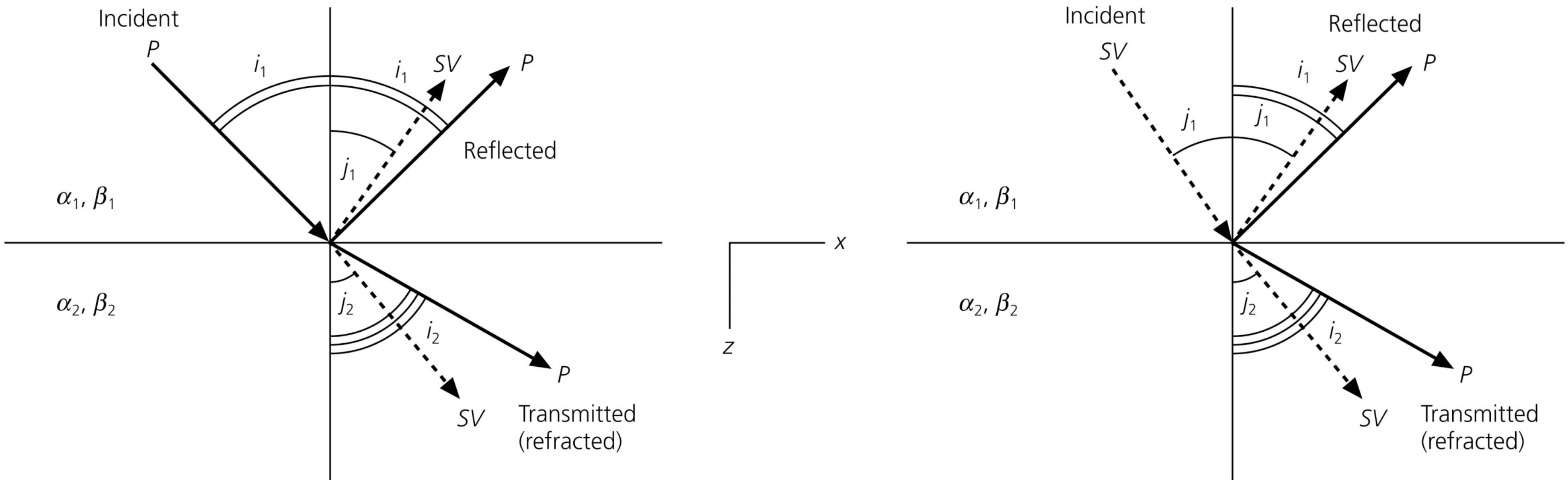
Snell's law in a flat medium:

$$\sin i_1 / v_1 = \sin i_2 / v_2$$

Hence ray parameter $p = \sin i / v$

is constant along a ray

Figure 2.5-5: Transmitted and reflected waves for incident *P* and *SV* waves.



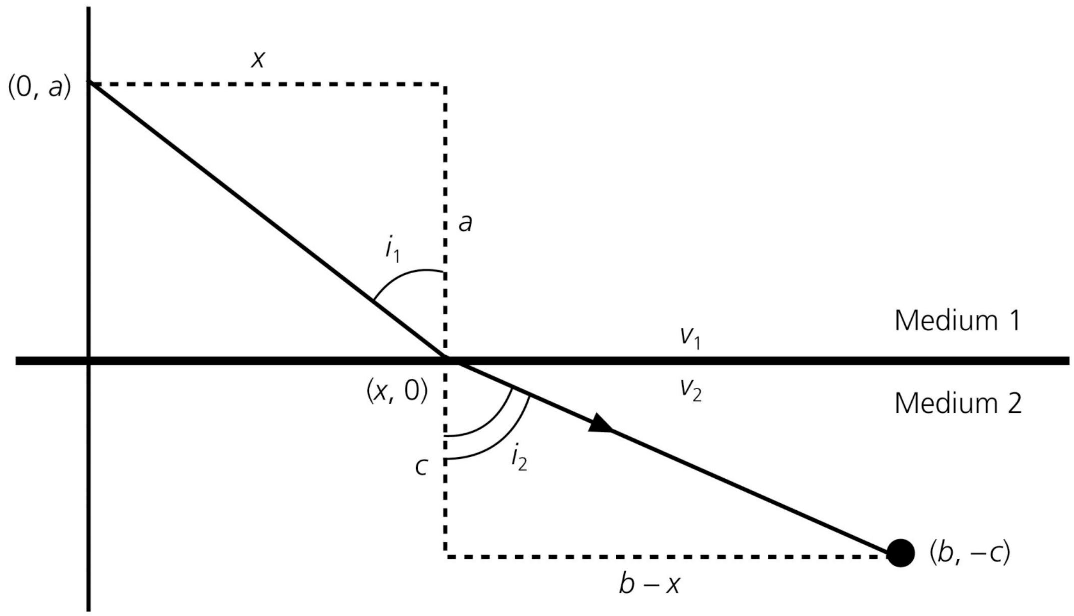
Snell's law:

$$c_x = \frac{\alpha_1}{\sin i_1} = \frac{\beta_1}{\sin j_1} = \frac{\alpha_2}{\sin i_2} = \frac{\beta_2}{\sin j_2}$$

FROM FASTER TO SLOWER MATERIAL- REFRACTED WAVES BENDS TOWARDS VERTICAL

FROM SLOWER TO FASTER MATERIAL- REFRACTED WAVES BENDS TOWARDS HORIZONAL

Figure 2.5-14: Derivation of Snell's law using Fermat's principle.



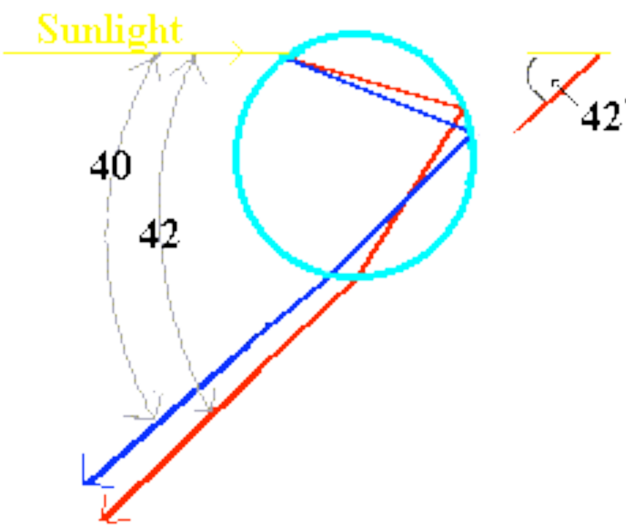
$$T(x) = \frac{(a^2 + x^2)^{1/2}}{v_1} + \frac{((b-x)^2 + c^2)^{1/2}}{v_2}$$

$$\frac{dT(x)}{dx} = \frac{x}{v_1\,(a^2 + x^2)^{1/2}} - \frac{(b-x)}{v_2\,((b-x)^2 + c^2)^{1/2}} = \frac{\sin i_1}{v_1} - \frac{\sin i_2}{v_2} = 0$$

Snell's law: $\dfrac{\sin i_1}{v_1} = \dfrac{\sin i_2}{v_2}$

SNELL'S LAW DESCRIBES OTHER FAMILIAR EFFECTS

DIFFERENT COLORS (WAVELENGTHS) OF LIGHT TRAVEL AT DIFFERENT SPEEDS IN WATER OR GLASS, SO REFRACTED AT DIFFERENT ANGLES



RAINDROPS CAUSE THE RAINBOW.

THIS IS WHY YOU ONLY SEE A RAINBOW WHEN THE SUN IS BEHIND YOU

TSUNAMI SPEED IN DEEP WATER of depth d

$c = (gd)^{1/2}$

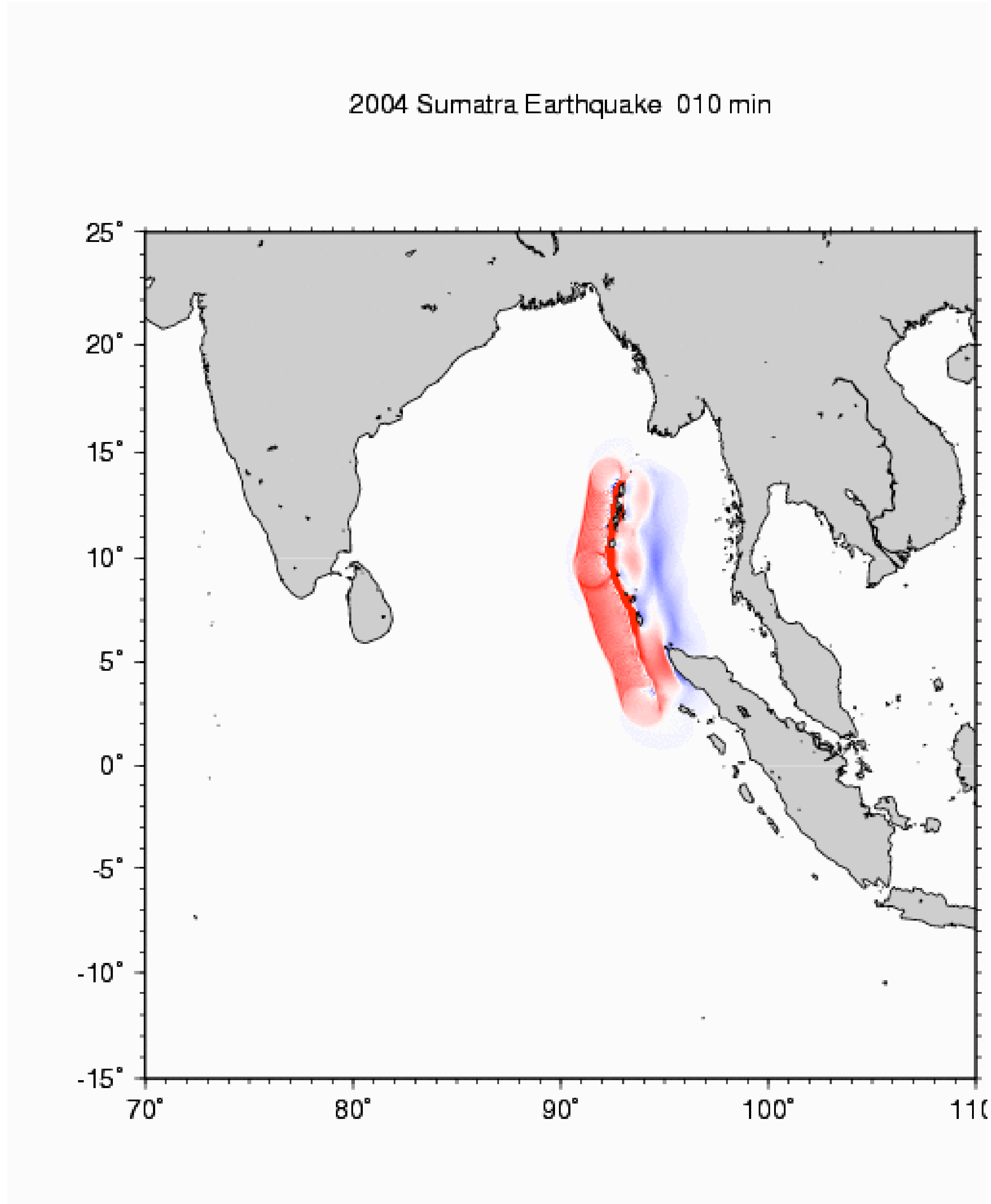
$g = 9.8\ m/s^2 \quad d = 4000\ m$

$c = 200\ m/s = 720\ km/hr = 450\ mph$

In open ocean, wavelength long (~100 km), amplitude small (~50 cm)

As wave slows in shallow water, wavelength decreases & amplitude grows

Maximum amplitude radiated at right angle to fault



staff.aist.go.jp/kenji.satake/animation.gif

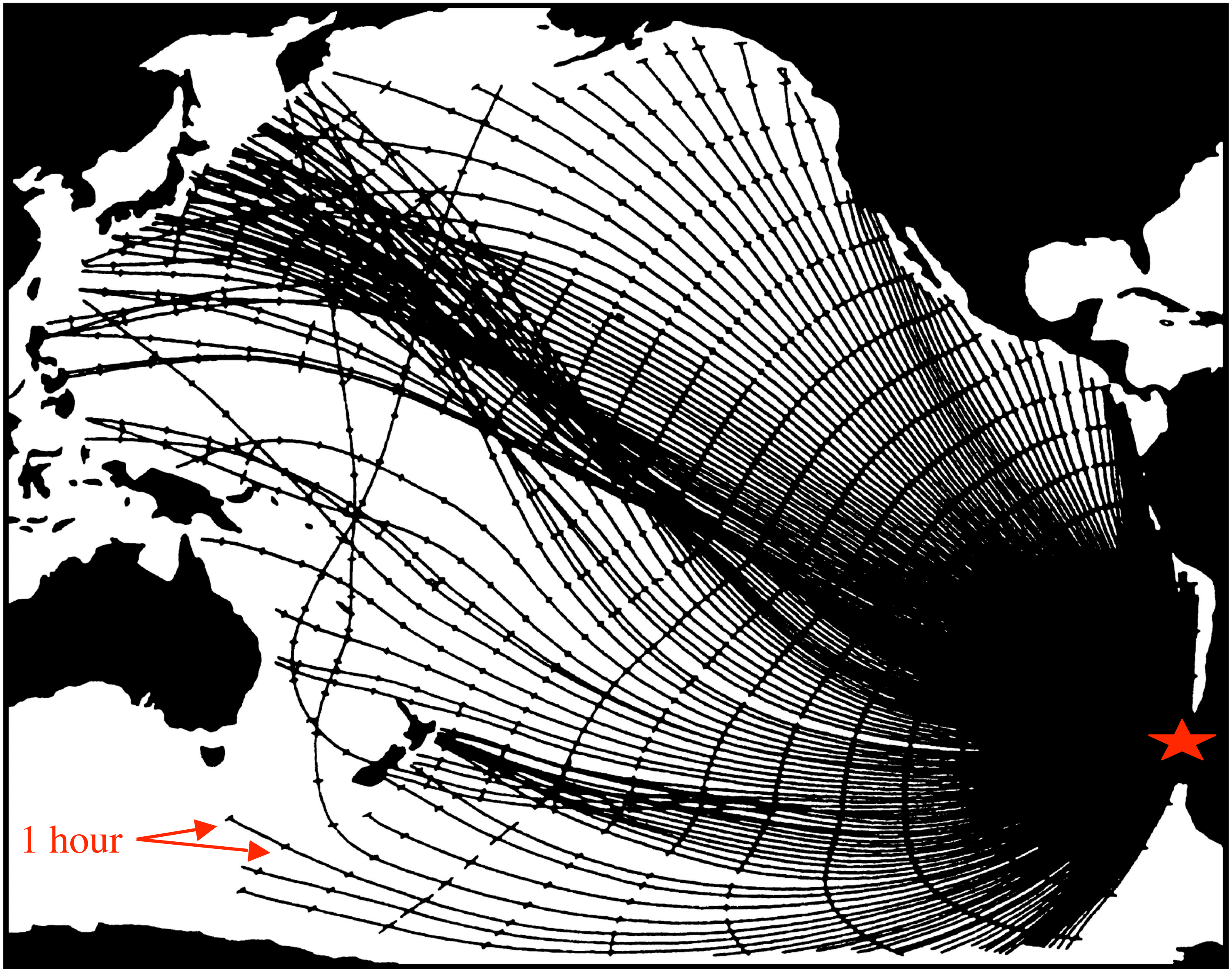
TRACE RAY PATHS USING SNELL'S LAW

RAYS BEND AS WATER DEPTH CHANGES

FIND WHEN WAVES ARRIVE AT DIFFERENT PLACES

DENSITY OF WAVES SHOWS FOCUSING & DEFOCUSING

Figure 2.8-9: Ray paths for tsunami generated by the 1960 Chile earthquake.



Okal, 1987

CRITICAL ANGLE

Transmitted P:

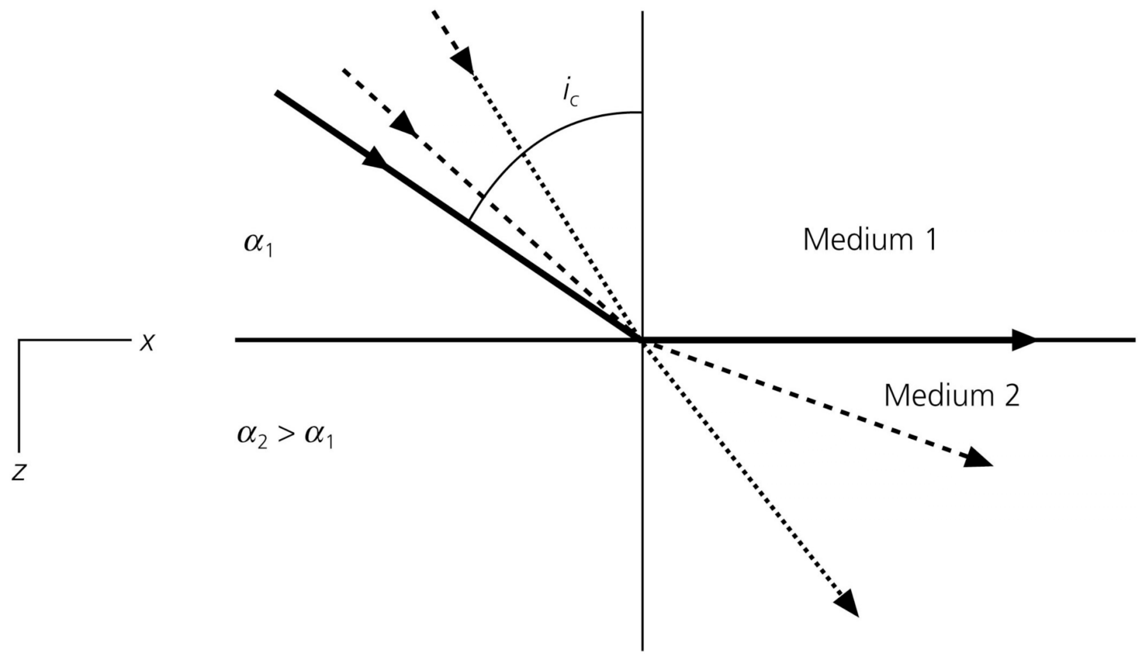
$$\frac{\sin i_1}{\alpha_1} = \frac{\sin i_2}{\alpha_2}$$

If $i_2 = 90°$,

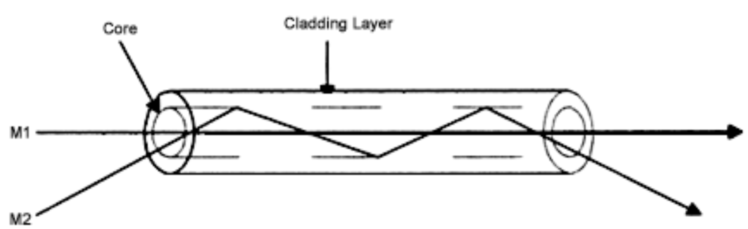
$$\frac{\sin i_1}{\alpha_1} = \frac{1}{\alpha_2}$$

$$\sin\, i_c = \alpha_1/\alpha_2 \qquad \text{or} \qquad i_c = \sin^{-1}(\alpha_1/\alpha_2)$$

Figure 2.5-7: Critical angle for *P* waves incident upon a boundary.

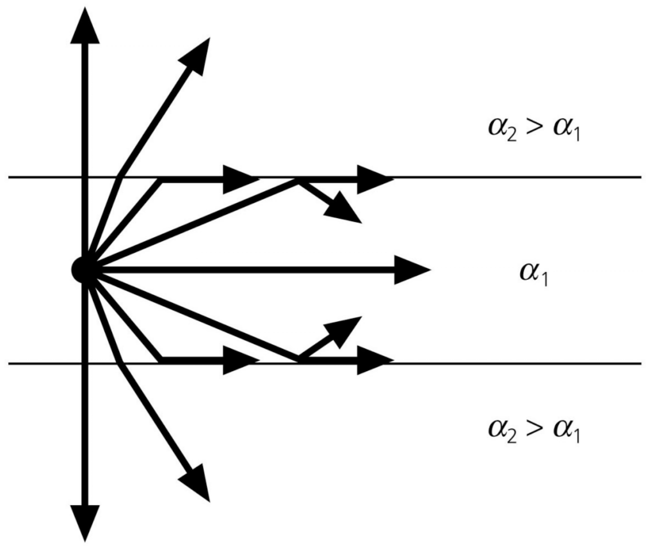


Total Internal reflection



OTHER APPLICATIONS- FIBER OPTICS- LIGHT "TRAPPED" IN A LOW VELOCITY FIBER

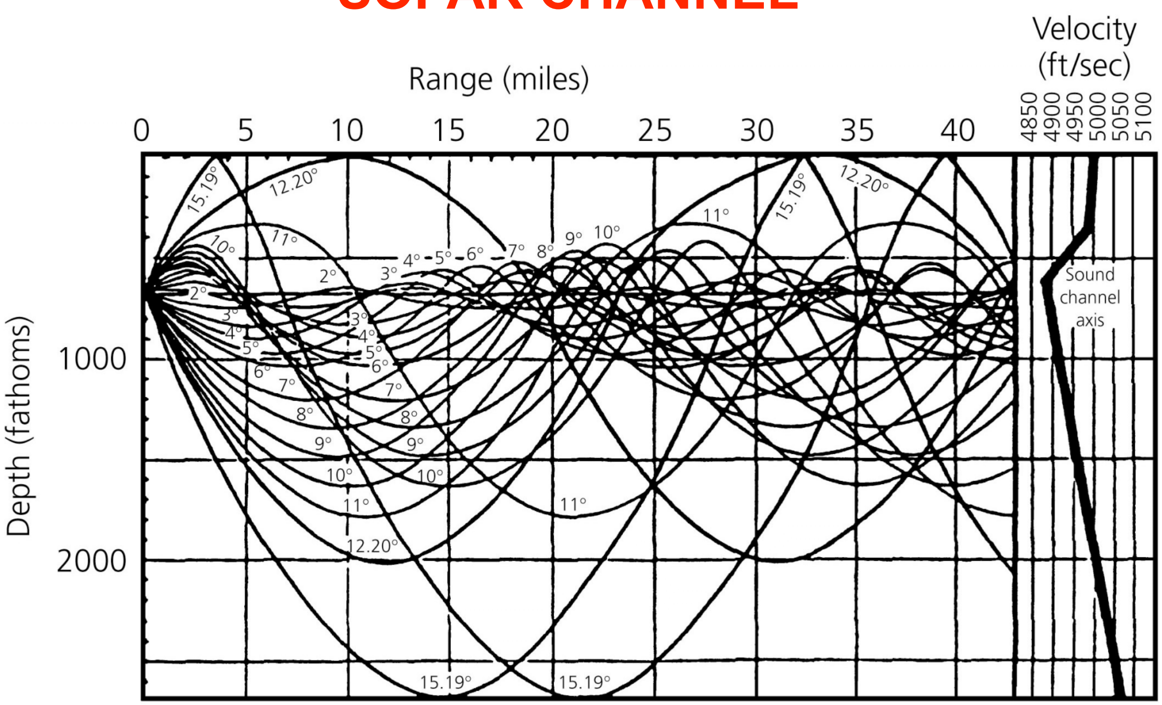
Figure 2.5-11: Propagation of waves in a low-velocity channel.



SOSUS

The "Secret Weapon" of Undersea Surveillance

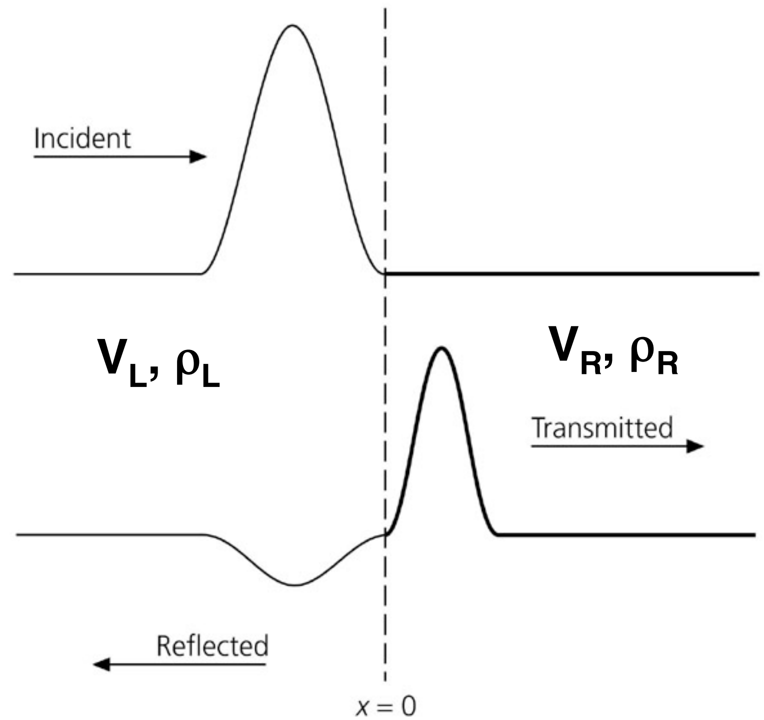
SOFAR CHANNEL



REFLECTION (R) AND TRANSMISSION (T) COEFFICIENTS

RATIO OF AMPLITUDES (SIZE) AS WAVES TRAVEL FROM MATERIAL OF ONE SPEED (V) AND DENSITY (ρ) TO ANOTHER

Figure 2.2-5: Transmitted and reflected wave pulses.



TRANSMISSION COEFFICIENT.

Transmitted/Incident

REFLECTION COEFFICIENT:

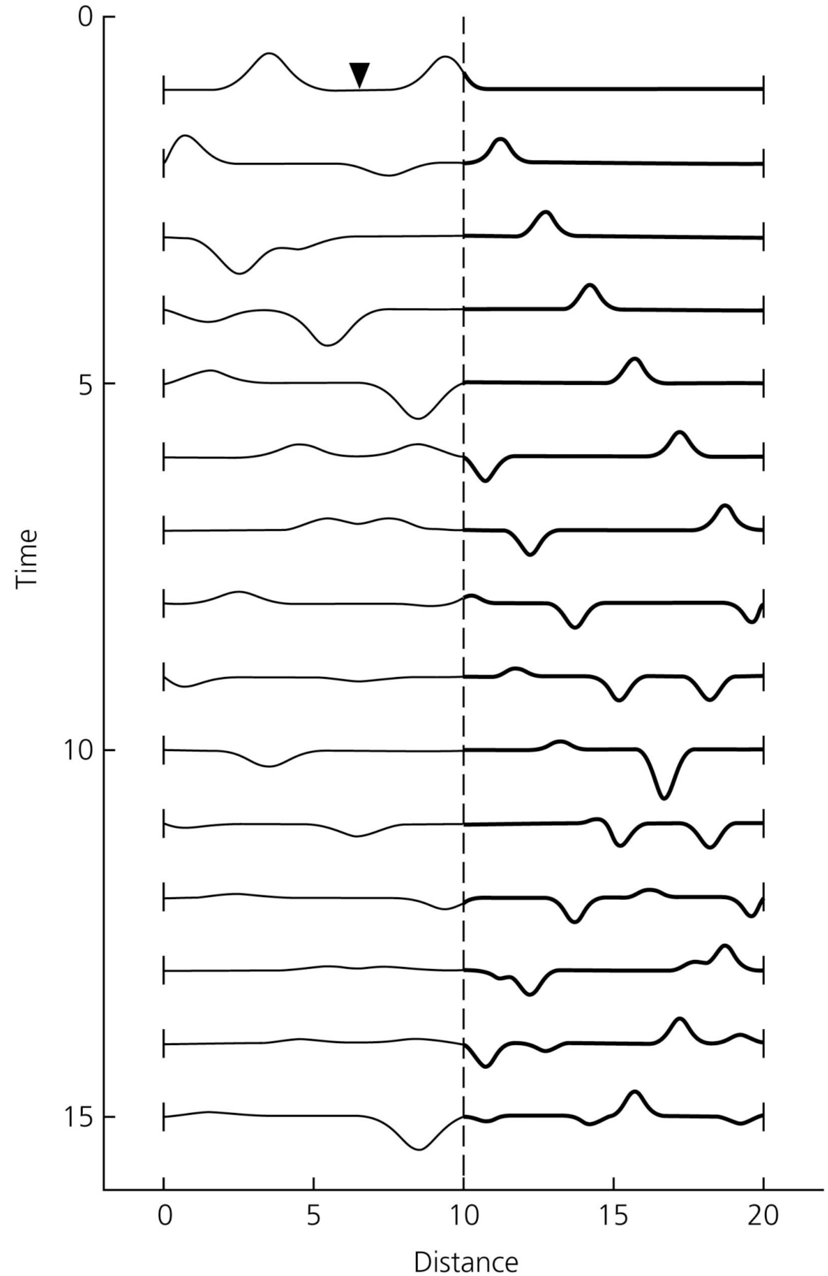
Reflected/Incident

$$T_{LR} = \frac{2\,\rho_L v_L}{\rho_L v_L + \rho_R v_R}$$

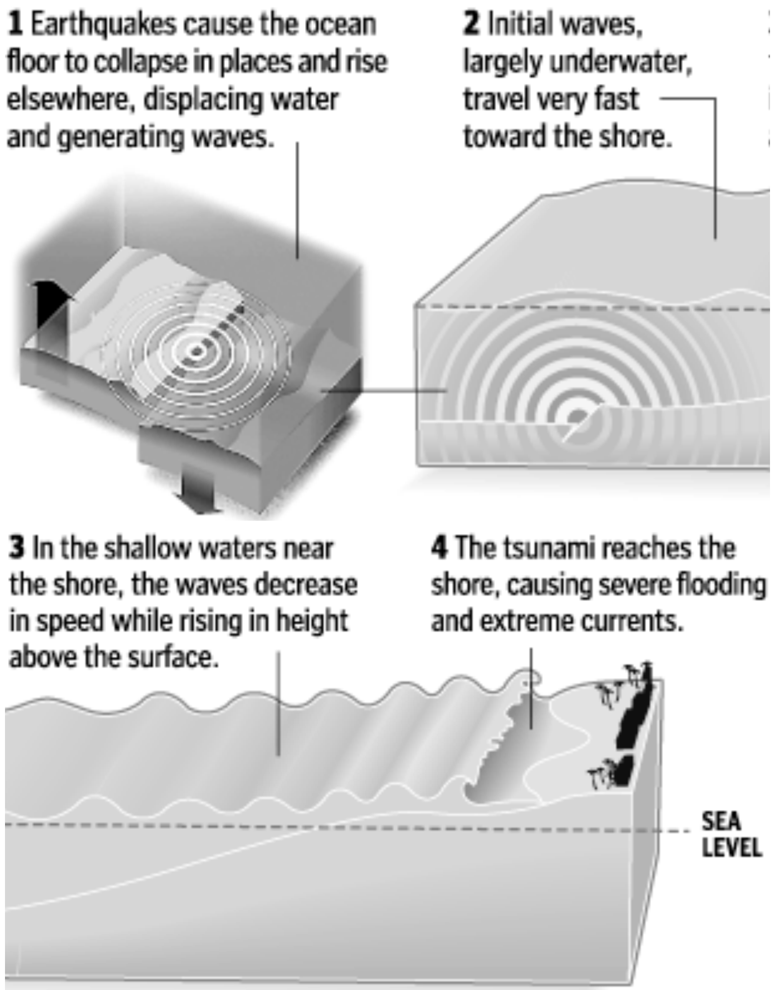
$$R_{LR} = \frac{\rho_L v_L - \rho_R v_R}{\rho_L v_L + \rho_R v_R}$$

http://www.earth.northwestern.edu/people/seth/demos/STRING/string.html

Figure 2.2-6: Waves on a string of two different densities.

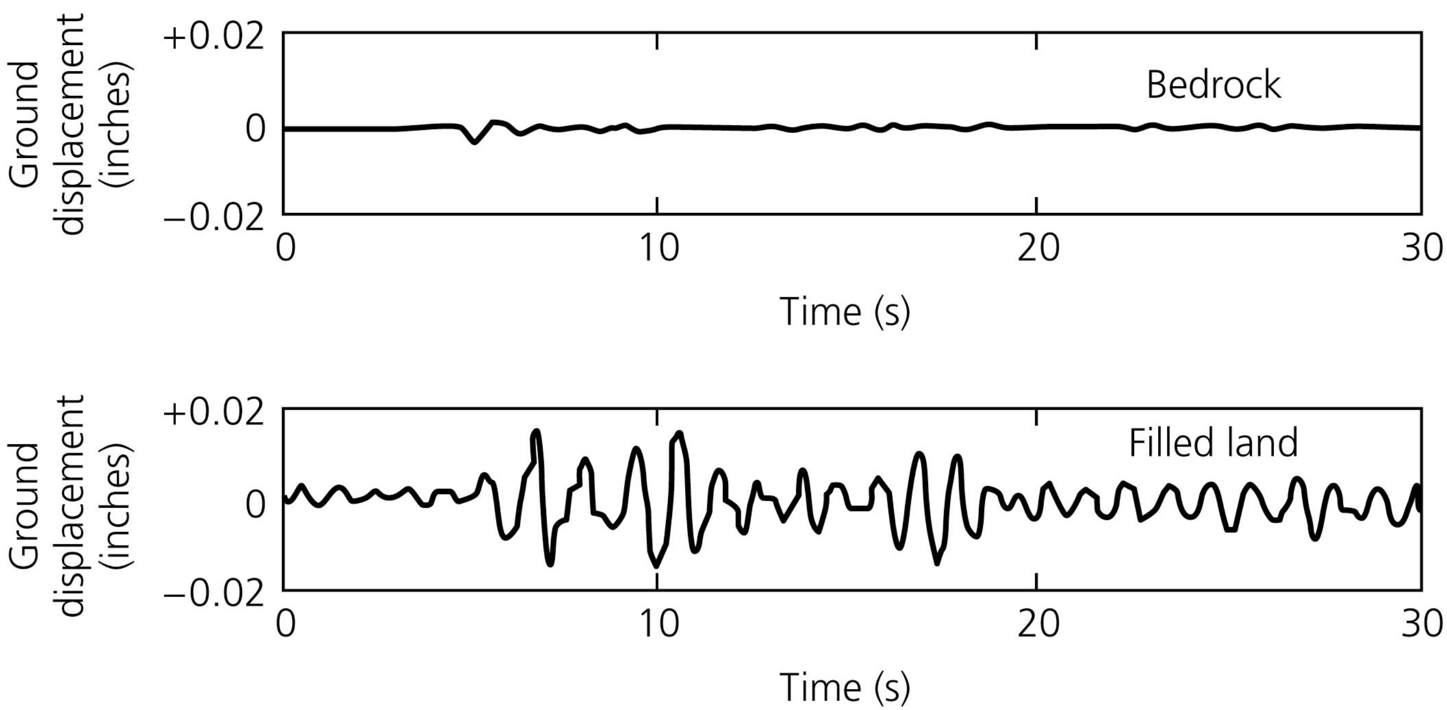


TSUNAMI wave speed = (water depth *x* acceleration of gravity)$^{1/2}$



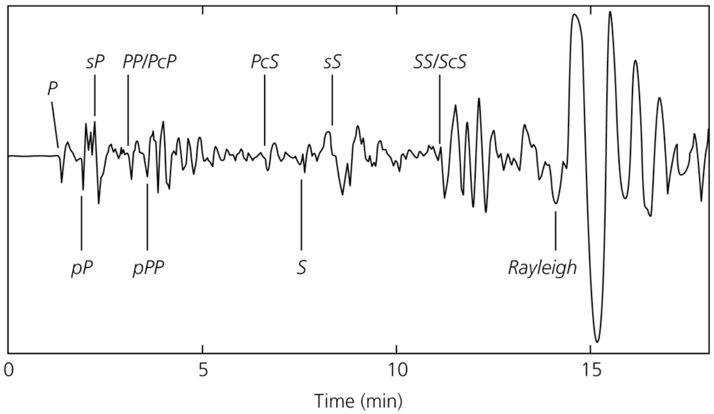
KHAO LAK, THAILAND DECEMBER 26, 2004

Figure 2.4-10: Ground displacement from the 1989 Loma Prieta earthquake.



TRAVEL TIME CURVES

Figure 1.1-3: Example of seismogram,



showing accompanying ray paths.

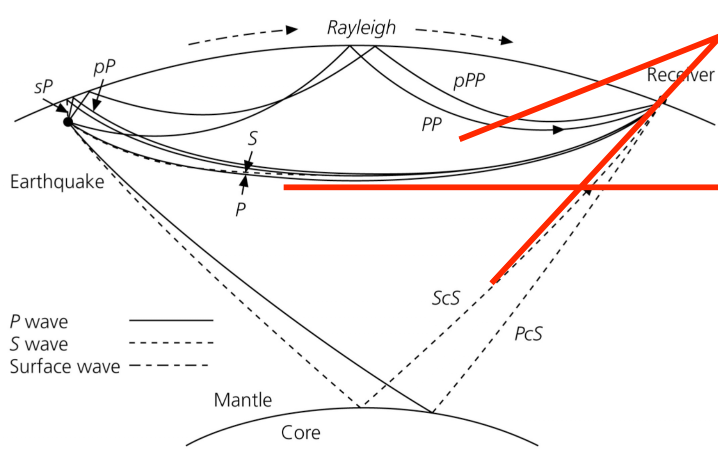


Figure 3.5-3: Travel time data and curves for the IASP91 model.

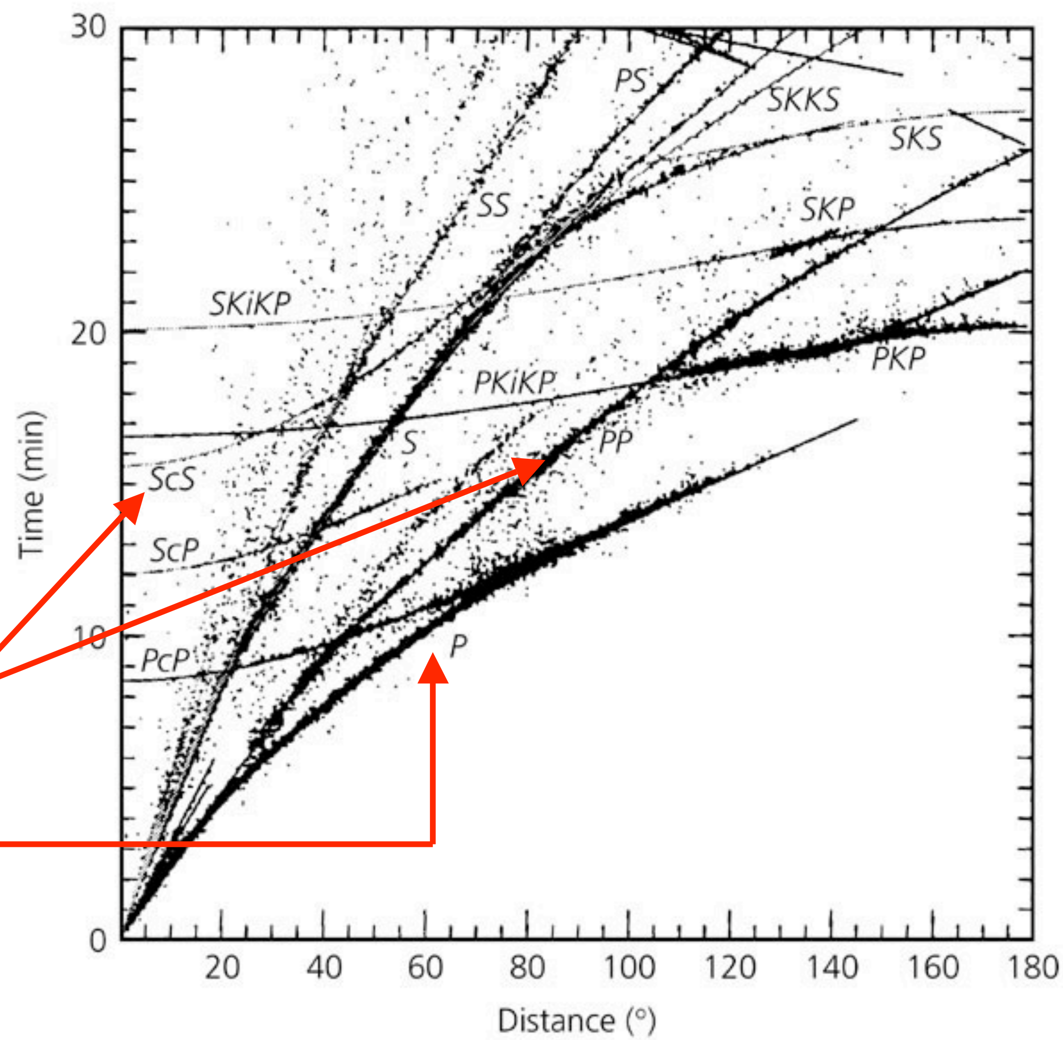


Figure 3.5-5: Illustration of various body wave phases.

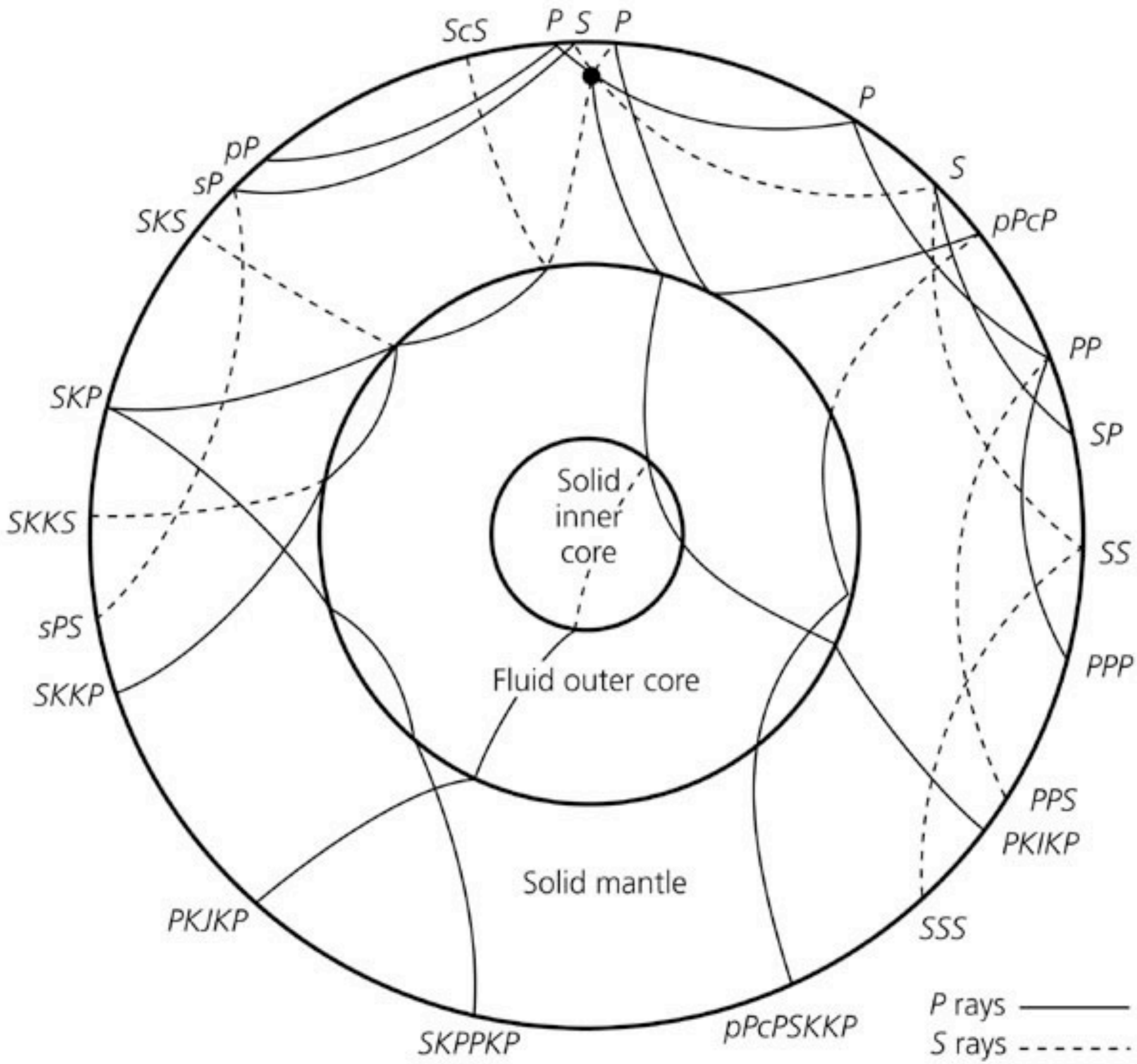
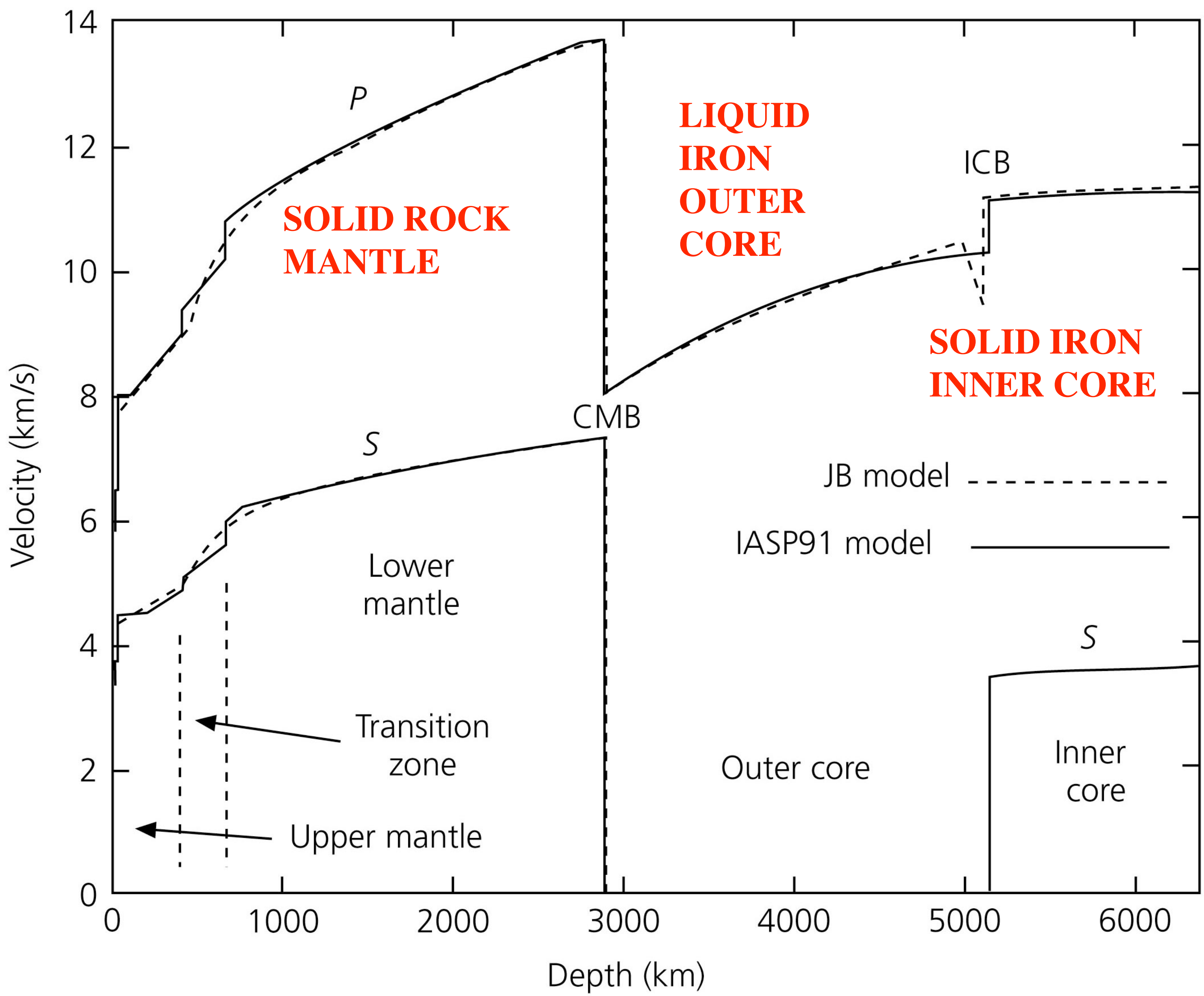
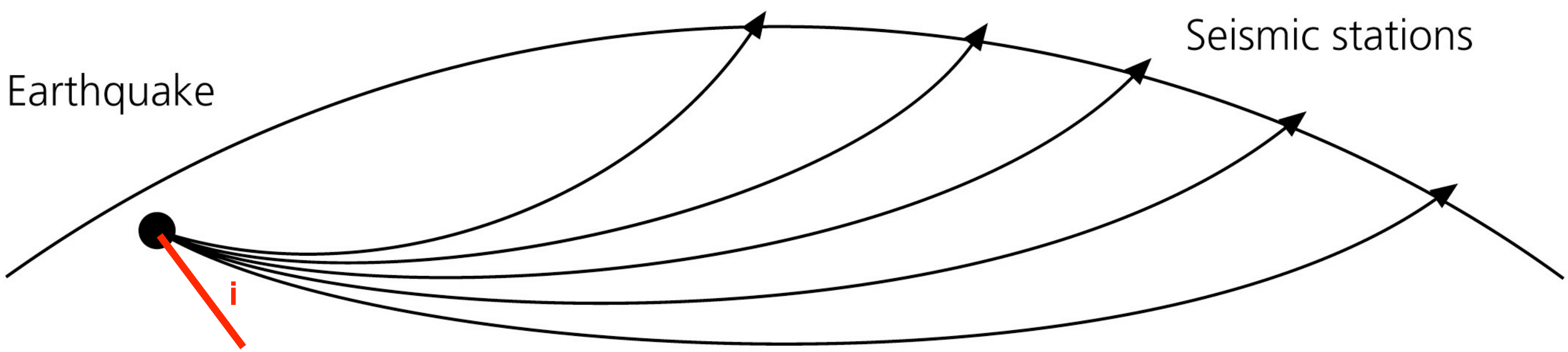


Figure 3.5-1: Comparison of the J-B and IASP91 earth models.



SEISMIC RAY PATHS BEND AS VELOCITY INCREASES WITH DEPTH

Figure 1.1-2: Schematic ray paths for an increase in seismic velocity with depth.

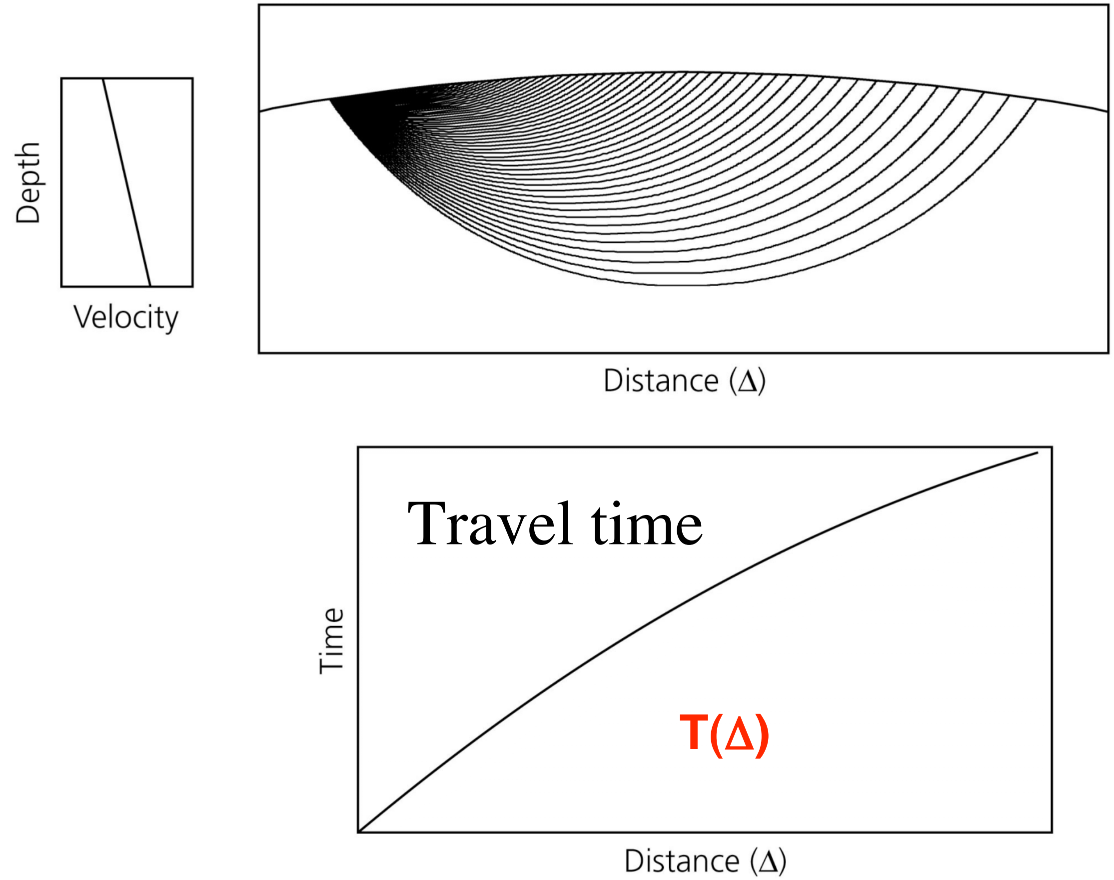


Snell's law for spherical earth with velocity v at radius r

Ray turns to incidence angle i so ray parameter p is constant along the ray

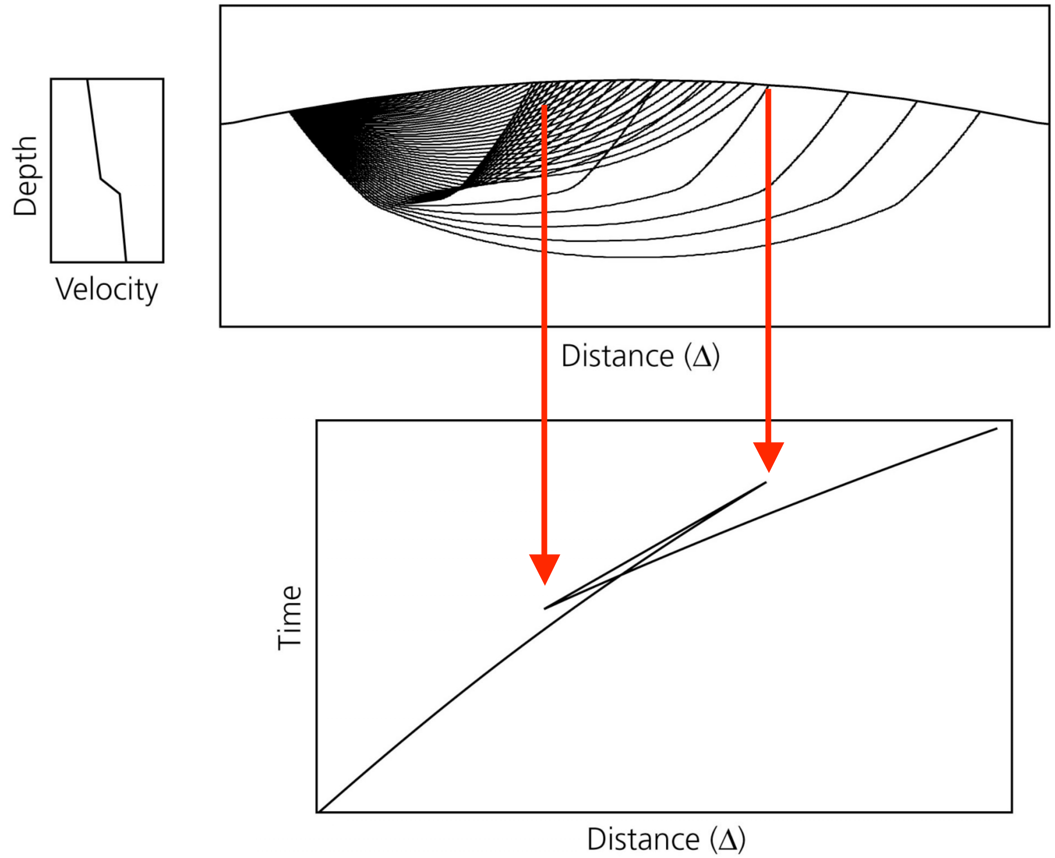
$$p = \frac{r \sin i}{\mathrm{v}}$$

Figure 3.4-5: Ray path effects for increasing velocity.



$$p = r \sin i / v$$
$$= dT / d\Delta$$

Figure 3.4-6: Ray path triplication effects for a velocity increase.



$p = r \sin i / v = dT/ d\Delta$

Rapid velocity increase causes triplication

Multiple rays at same distance

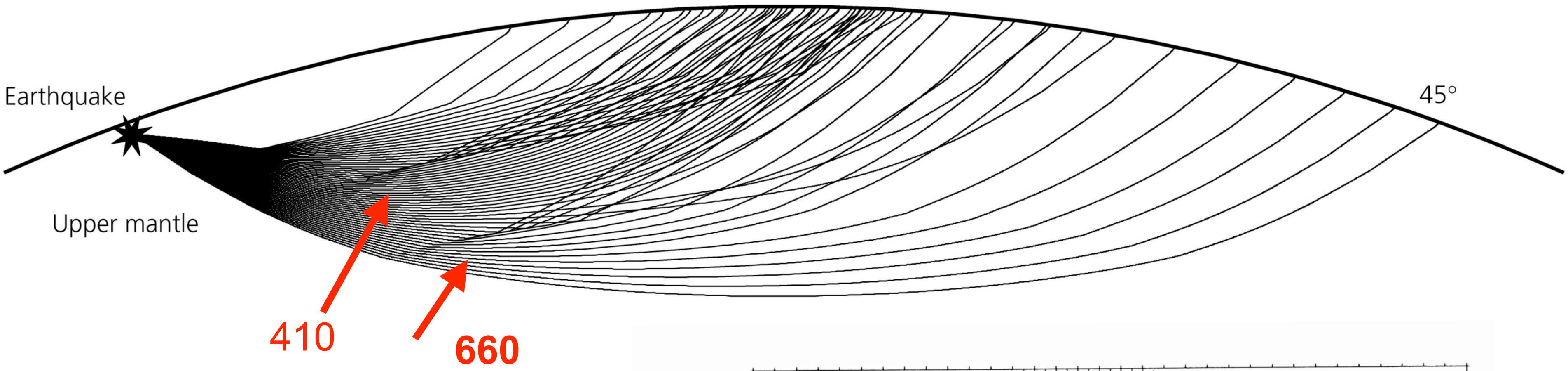
Expect high amplitudes where rays are concentrated, and low amplitudes where rays are sparse.

Mathematically, the concentration of rays is proportional to $di/d\Delta$, the range of incidence angles for the rays that arrive in a given distance.

$$\frac{d^2 T}{d\Delta^2} = \frac{dp}{d\Delta} = \frac{d(r \sin i/\mathrm{v})}{d\Delta} = \frac{r}{\mathrm{v}} \cos i \, \frac{di}{d\Delta}$$

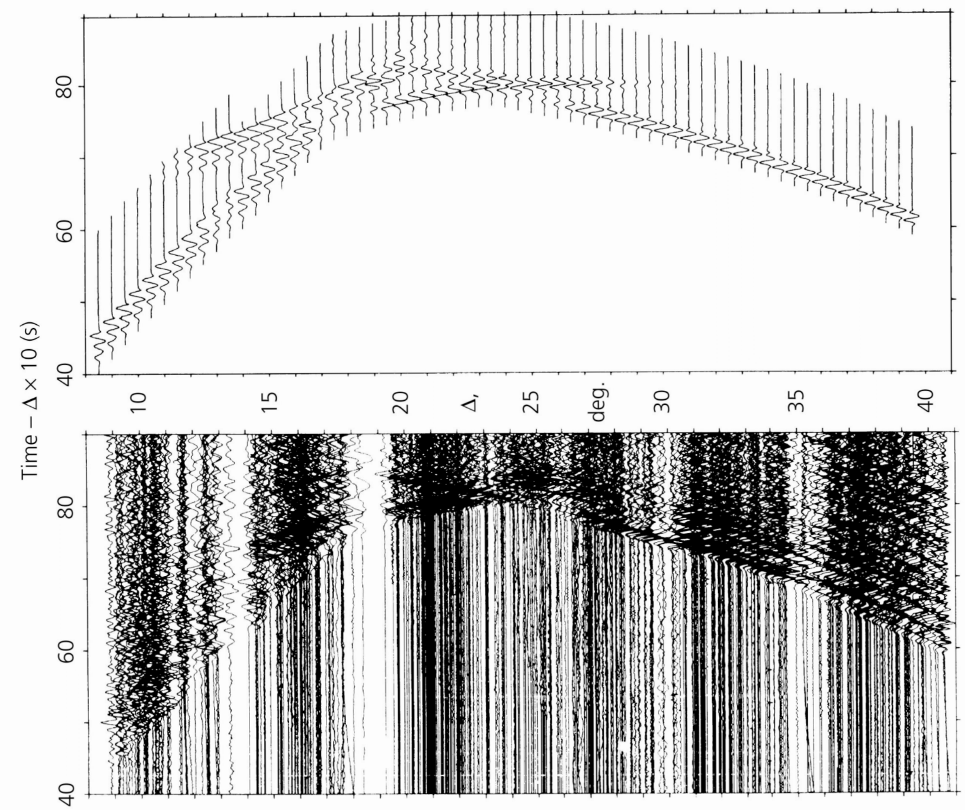
The amplitude is proportional to the second derivative of the travel time curve, or the derivative of the $p(\Delta)$ curve.

Figure 3.5-12: Ray paths for *P* waves through the upper mantle.



Transition zone between upper & lower mantles bounded by 410 and 660 km discontinuities

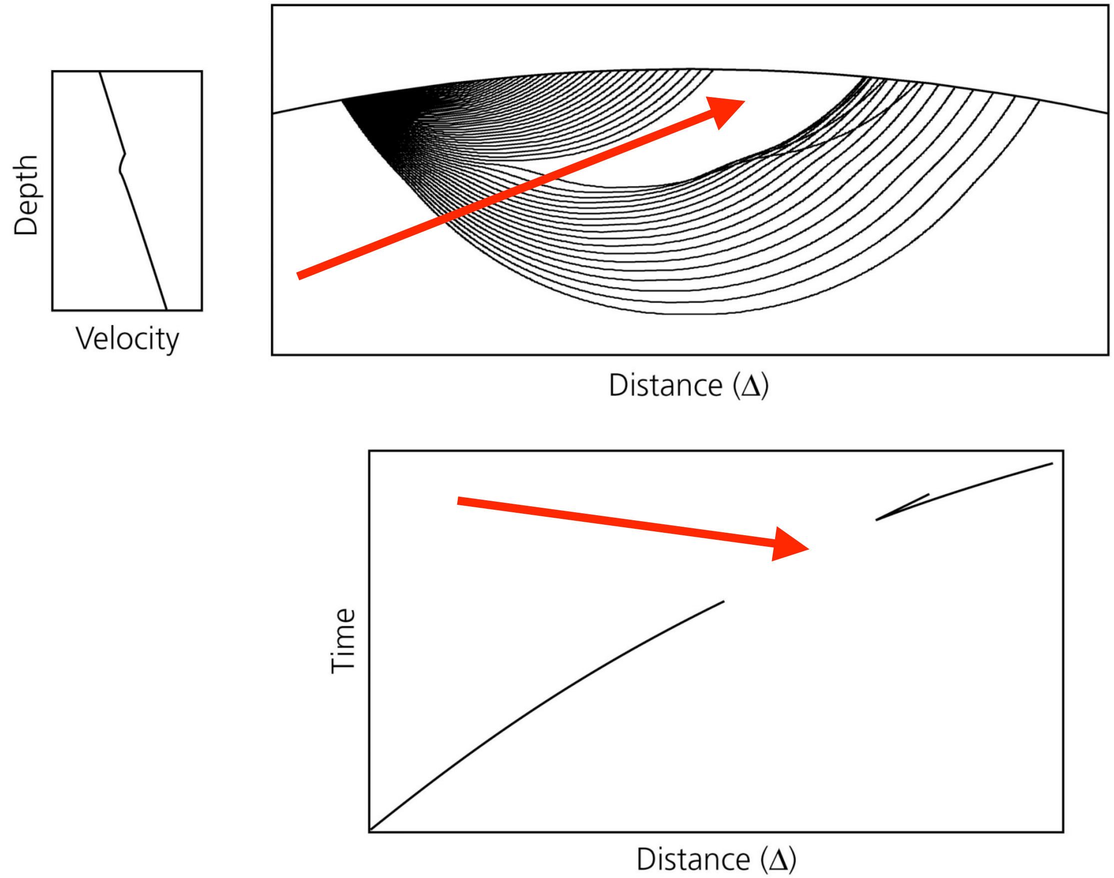
Velocity increases due to mineral phase changes



3.5-13: Seismic array study of upper mantle structure.

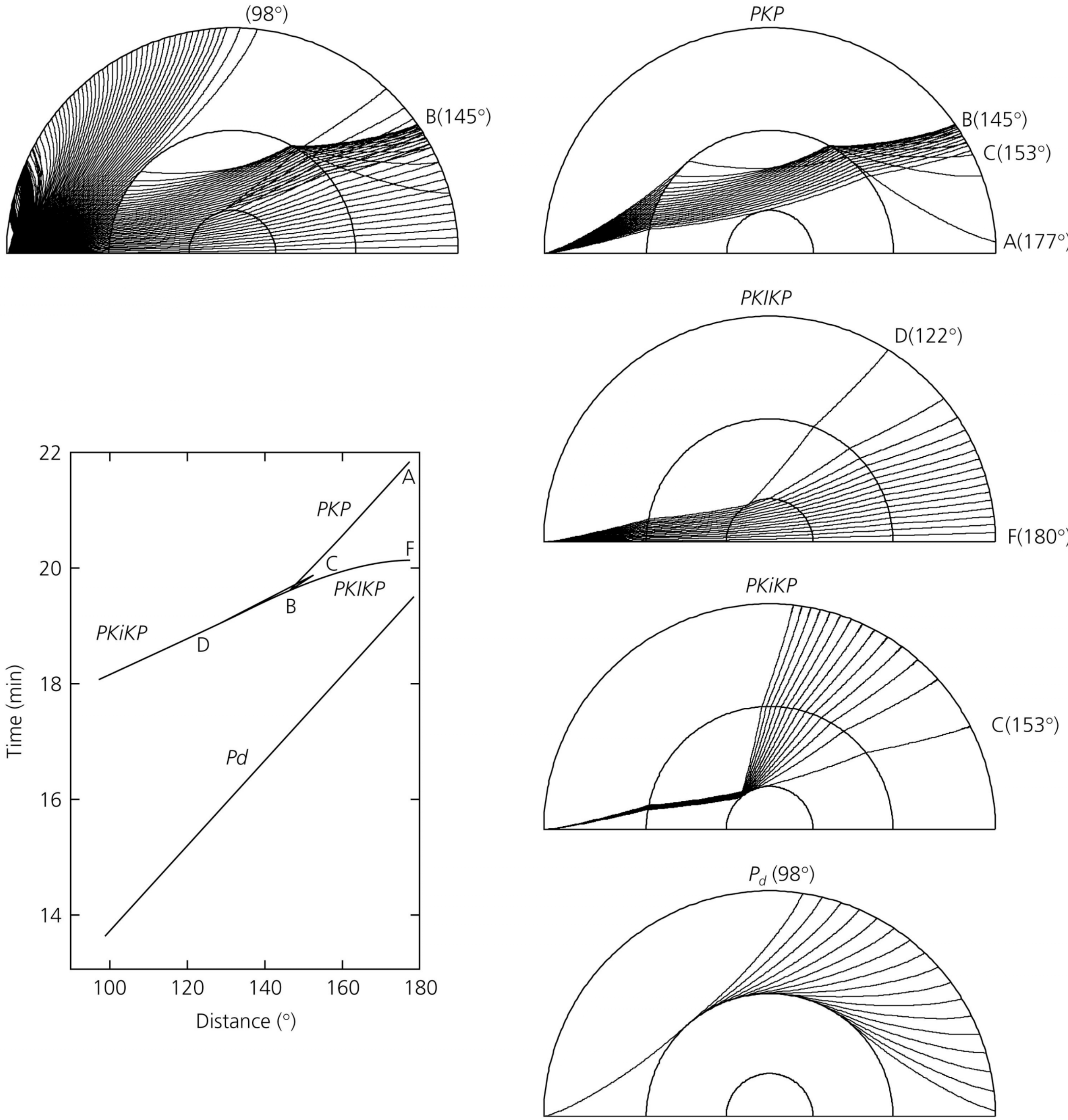
$$p = r \sin i / v = dT / d\Delta$$

Figure 3.4-7: Ray path shadow-zone effects for a velocity decrease.



Low velocity zone causes shadow zone - no rays arrive

Figure 3.5-7: Ray paths and travel times for major core phases.



HUYGEN'S PRINCIPLE

Treat every point on wave front as source of new circular wavefront

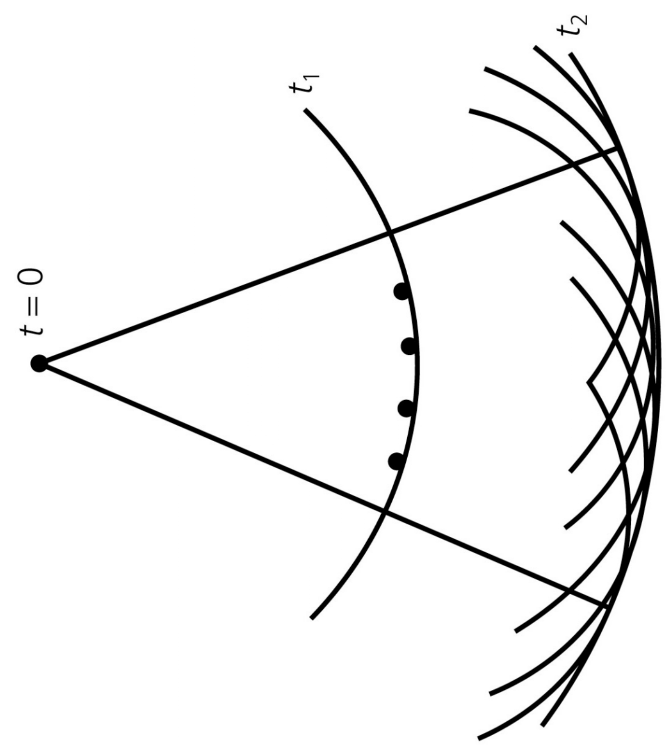


Figure 2.5-15: Huygens' generation of circular wave fronts.

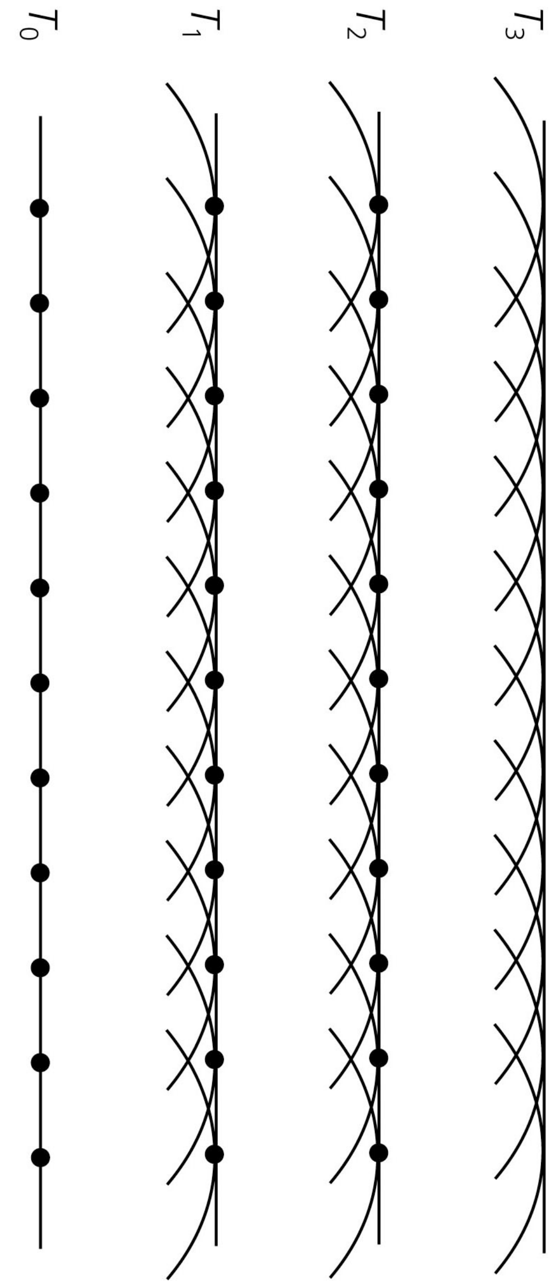
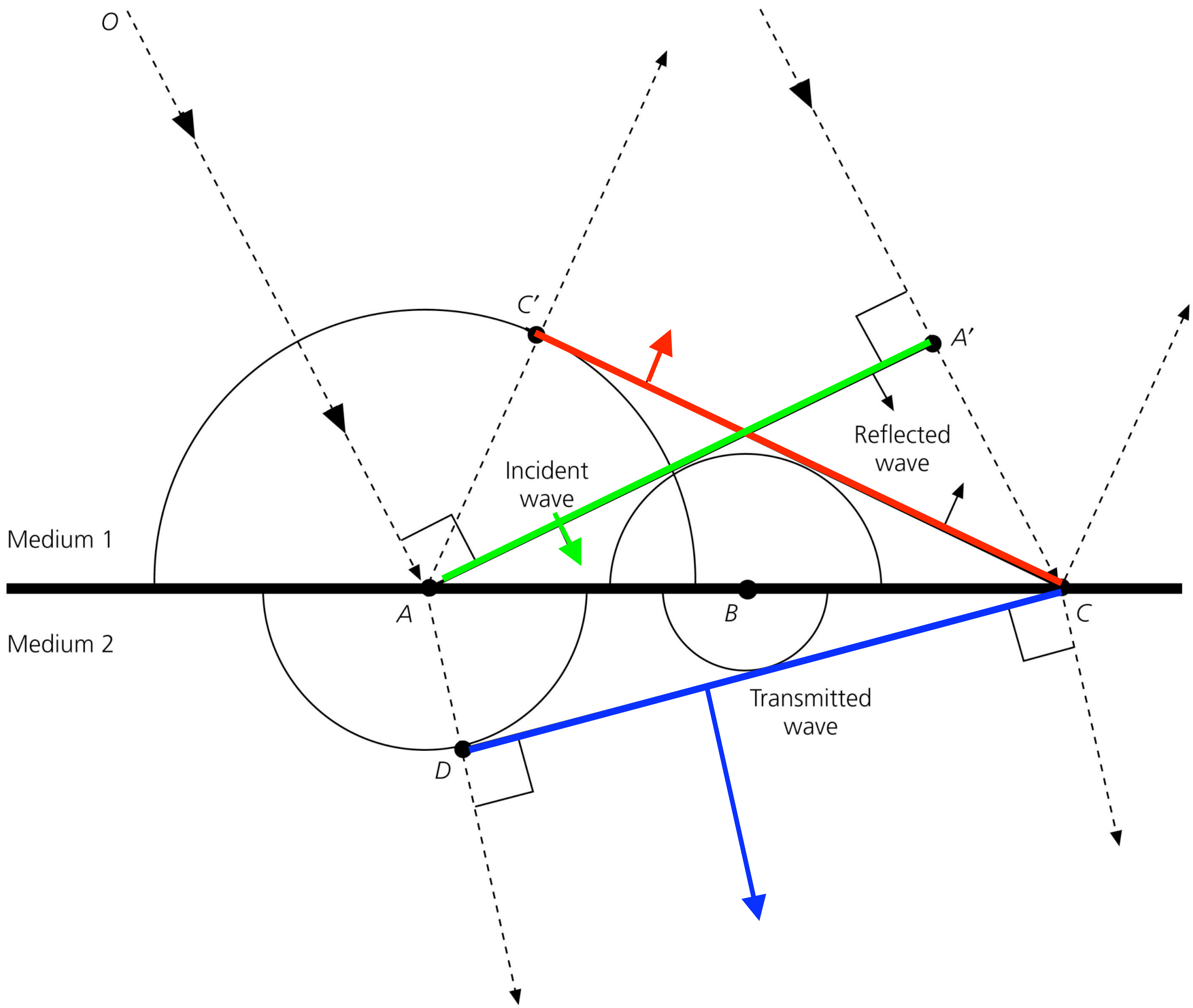


Figure 2.5-16: Huygens' principle for the propagation of a straight wave front.

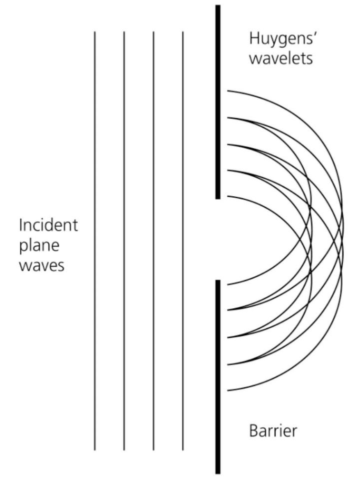
Figure 2.5-17: Derivation of Snell's law using Huygens' principle.

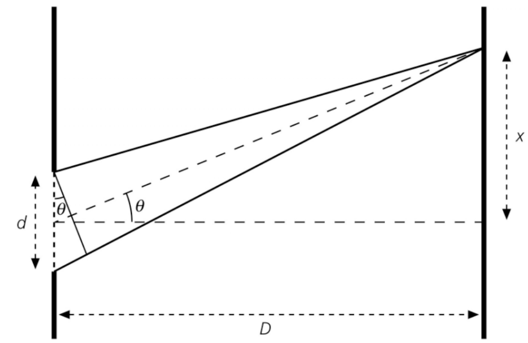


DIFFRACTION: ENERGY ARRIVES WHERE THERE'S NO GEOMETRIC (SNELL'S LAW) PATH

Process is frequency dependent: long wavelengths (long periods) diffract more

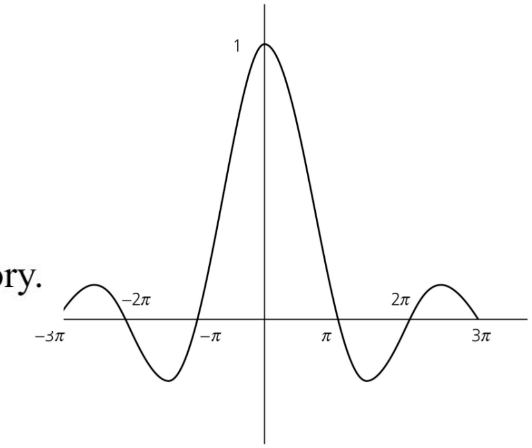
Figure 2.5-18: Single-slit diffraction.





Destructive interference when (for $D >> d$): $\lambda/2 = d \sin\theta \approx dx_0/D$

Actual diffraction pattern is: $\dfrac{\sin\zeta}{\zeta}$ where $\zeta = 2\pi dx/\lambda D$



Diffraction is described by Huygens' principle, but not geometric ray theory.

SURFACE WAVES

LOVE: SH

RAYLEIGH: P-SV

Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.

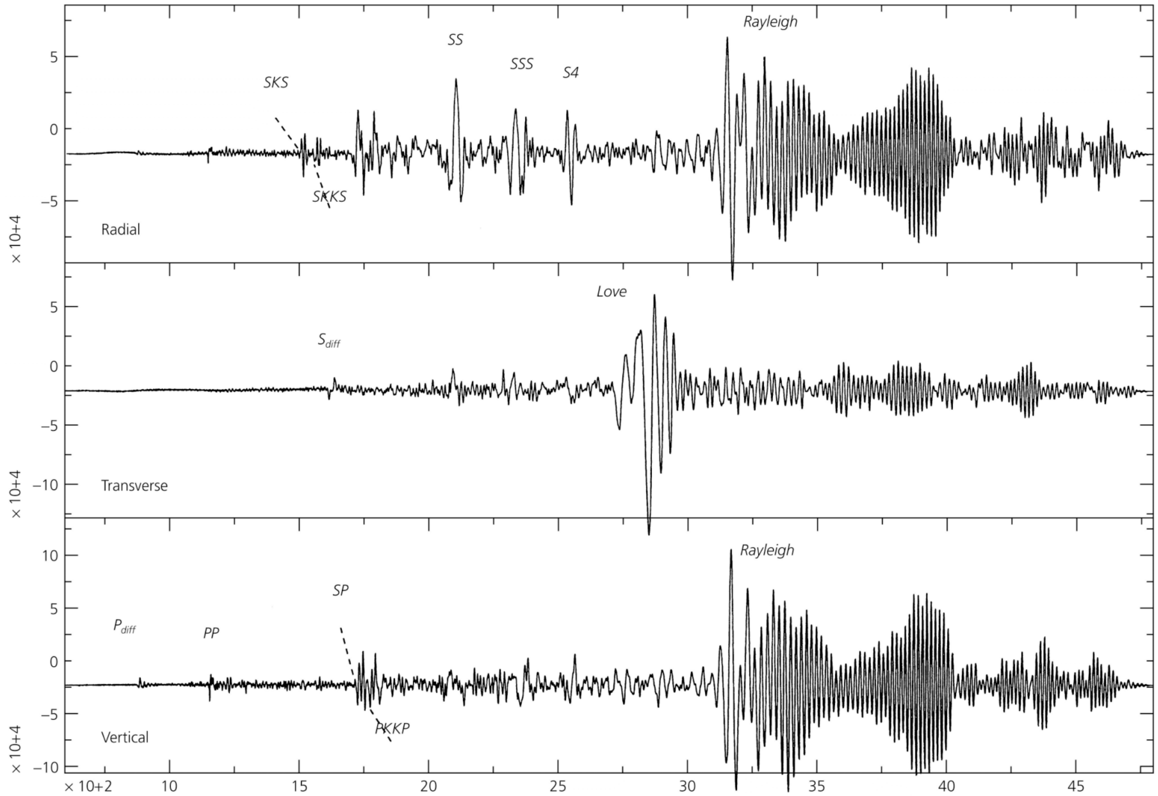


Figure 2.7-2: Geometry for Love and Rayleigh wave motions.

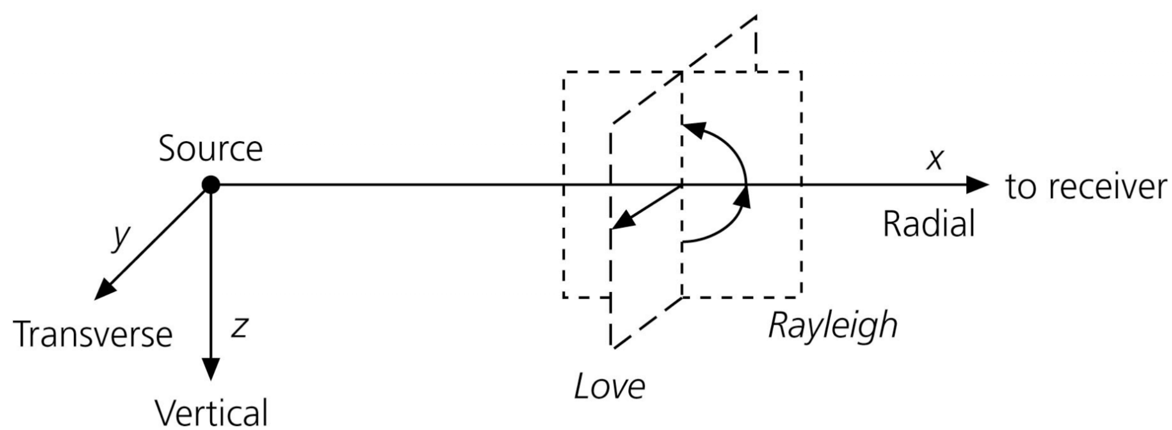
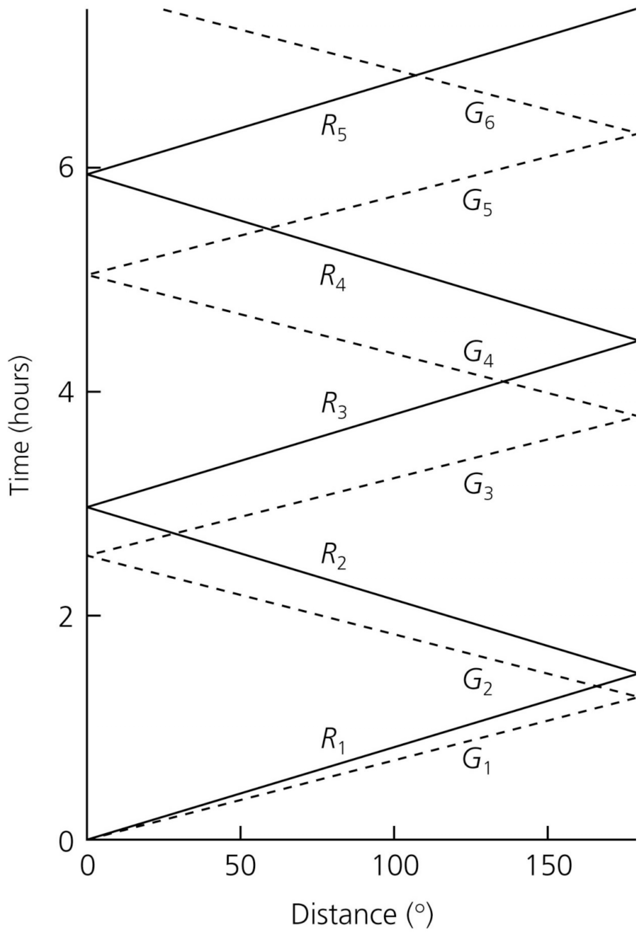
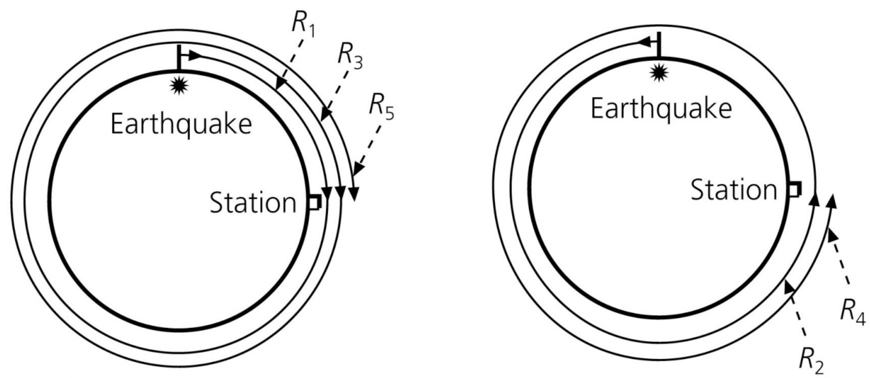


Figure 2.7-3: Multiple surface waves circle the earth.

Figure 2.7-4: Six-hour stacked IDA record se





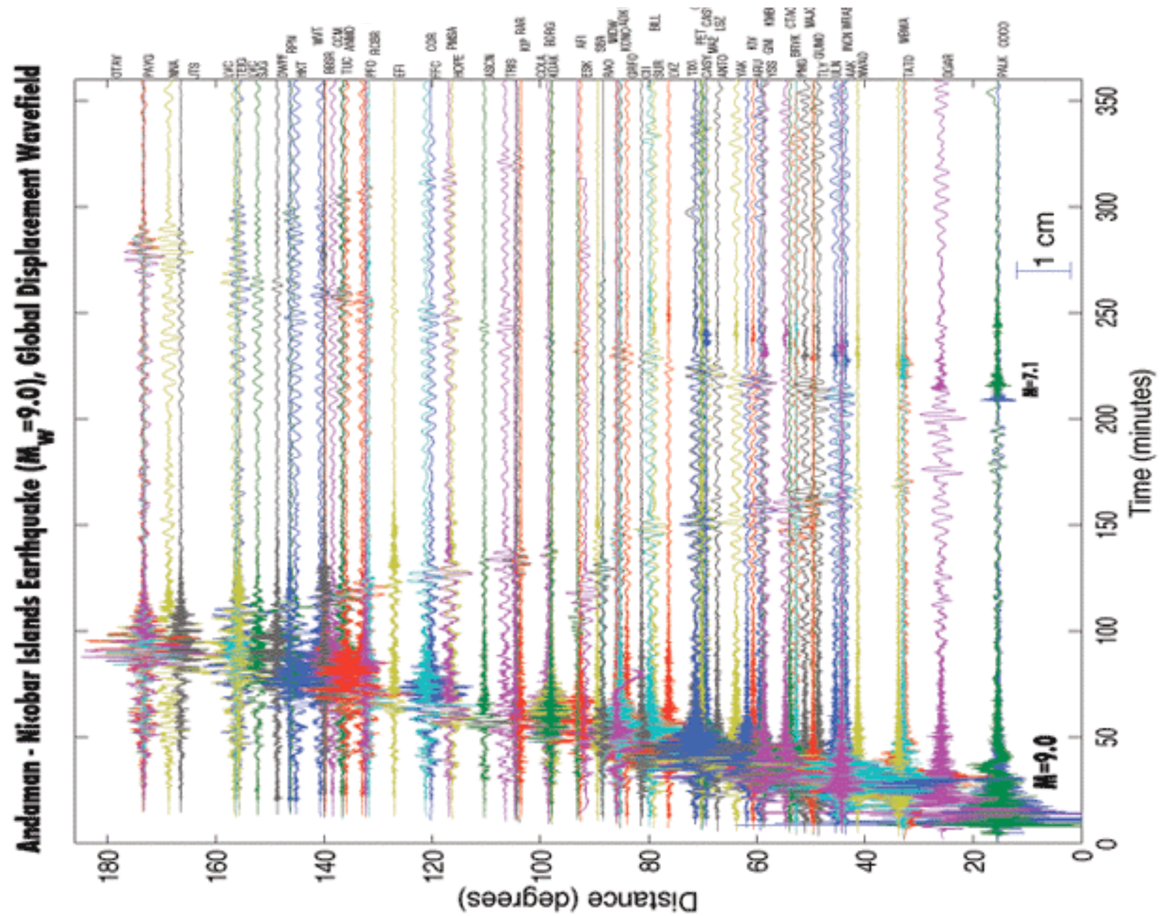
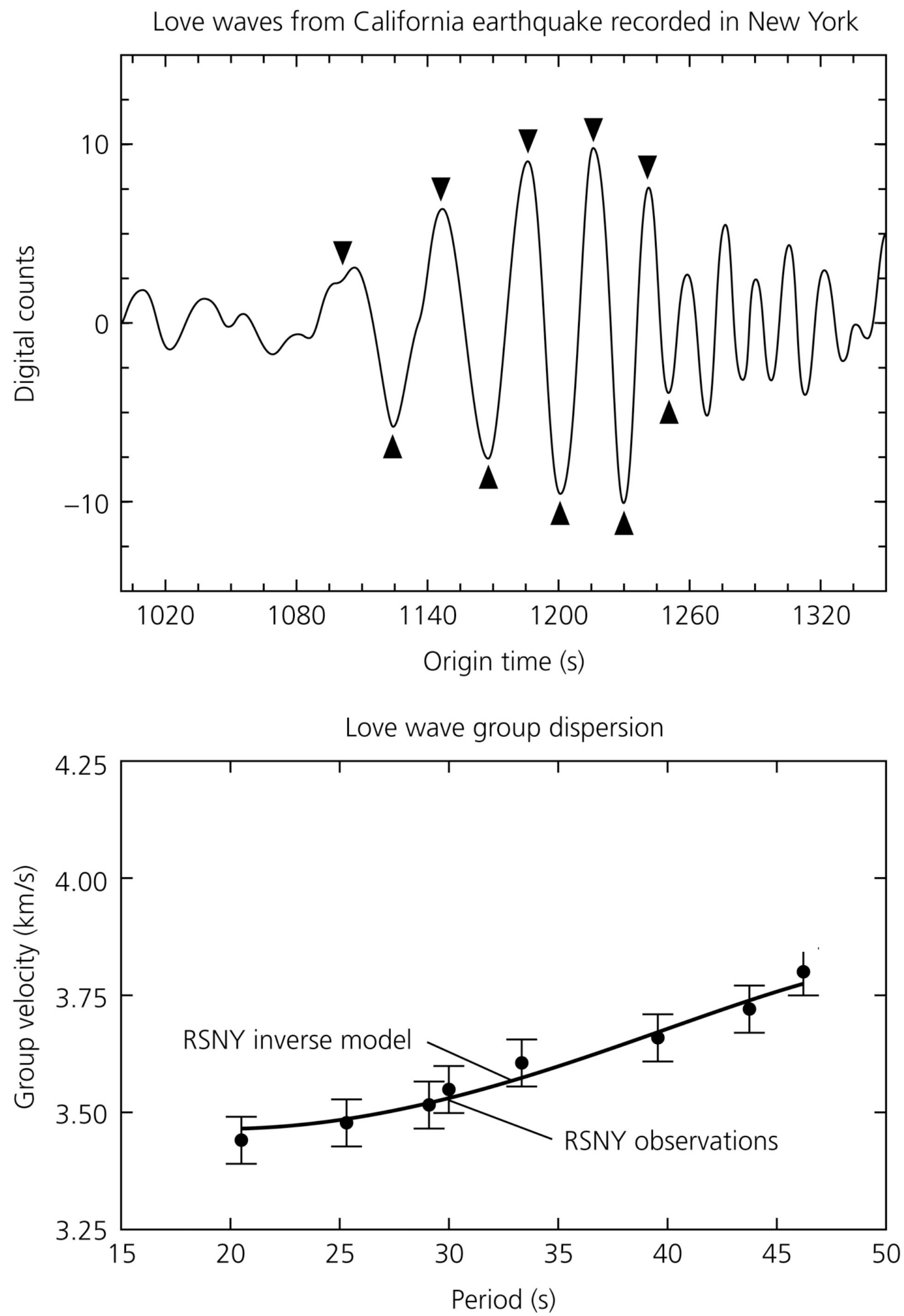


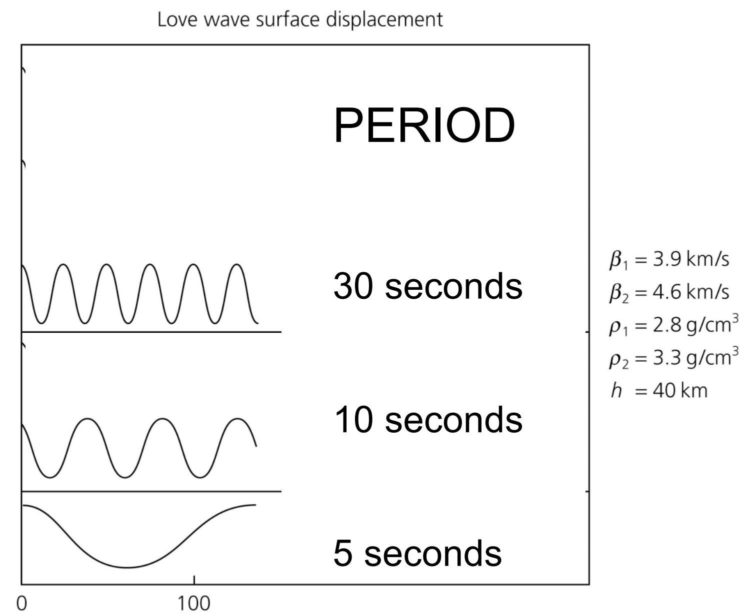
Figure 2.8-3: Example of calculating Love wave group velocity dispersion.

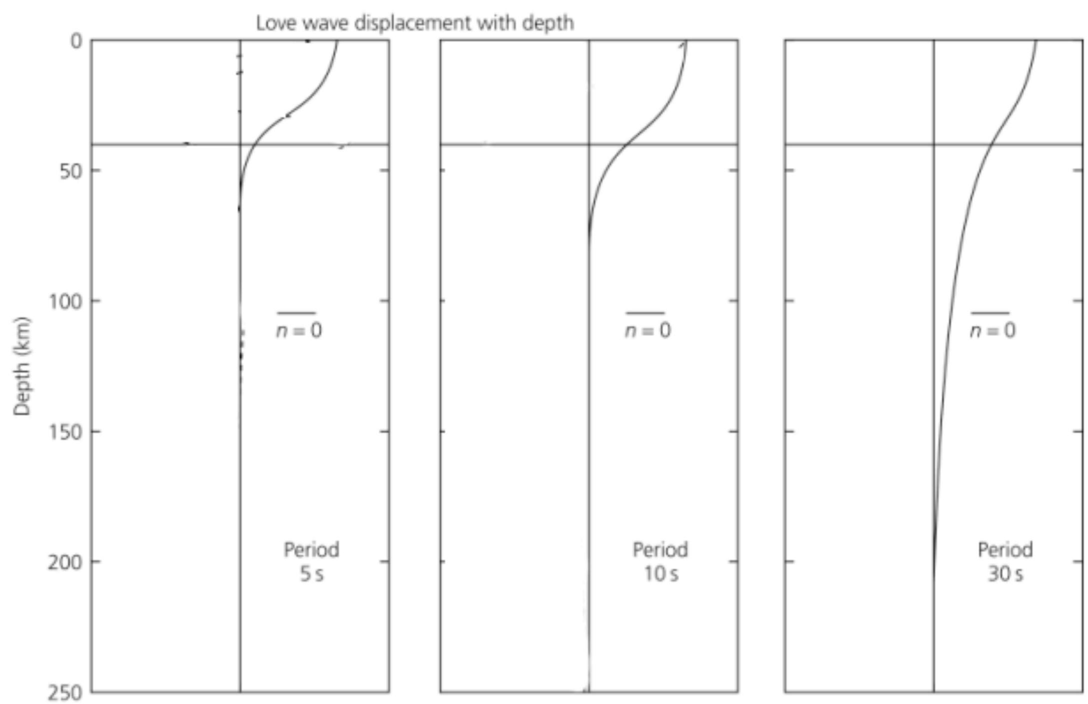


The wave oscillates as $\cos(k_x r_{\beta_1} z)$ in the layer, but decays exponentially as $\exp(-k_x r^*_{\beta_2} z)$ in the half-space.

The vertical sensitivities of the modes are the eigenfunctions.

Figure 2.7-10: Displacements of for Love waves in a layer over a halfspace.



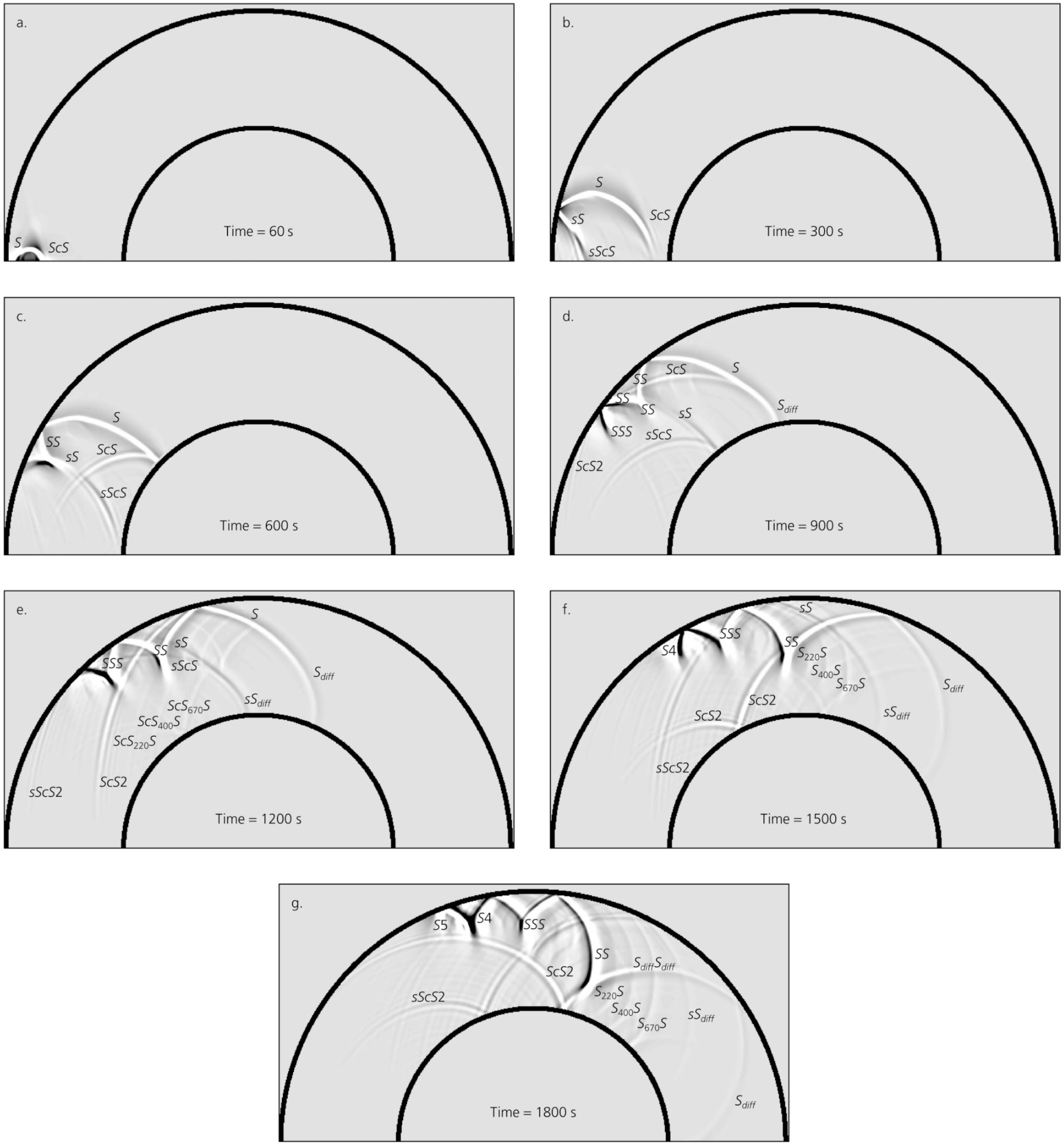


LONGER PERIODS HAVE LONGER WAVELENGTHS

AND SO "SEE" DEEPER INTO HIGHER VELOCITY MATERIAL

GEOMETRICAL DISPERSION DIFFERS FROM PHYSICAL DISPERSION (prism)

Figure 3.5-19: Snapshots of a synthetic *SH* wave field at various times.



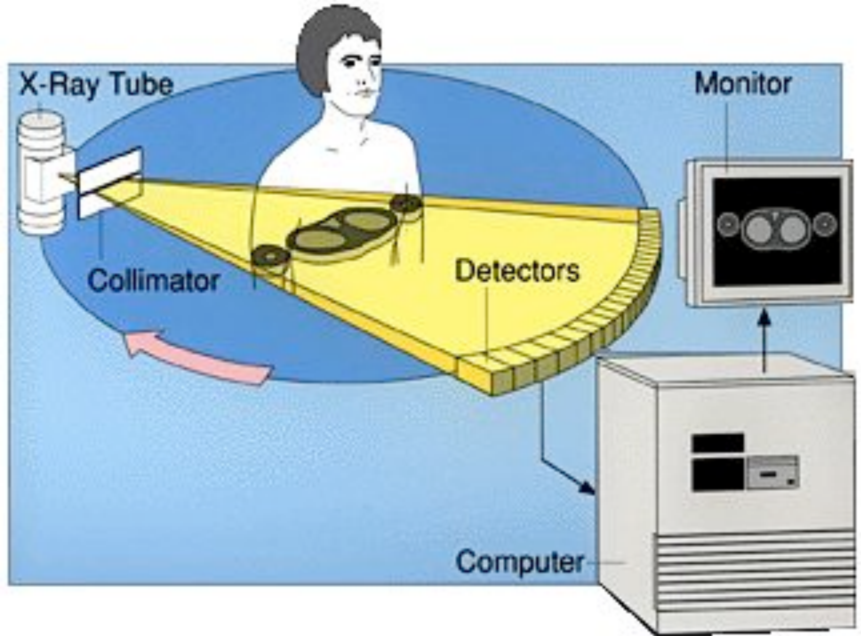
TOMOGRAPHY ("SLICE PICTURE")

BEAMS TRAVEL THROUGH OBJECT AT MANY DIFFERENT ANGLES

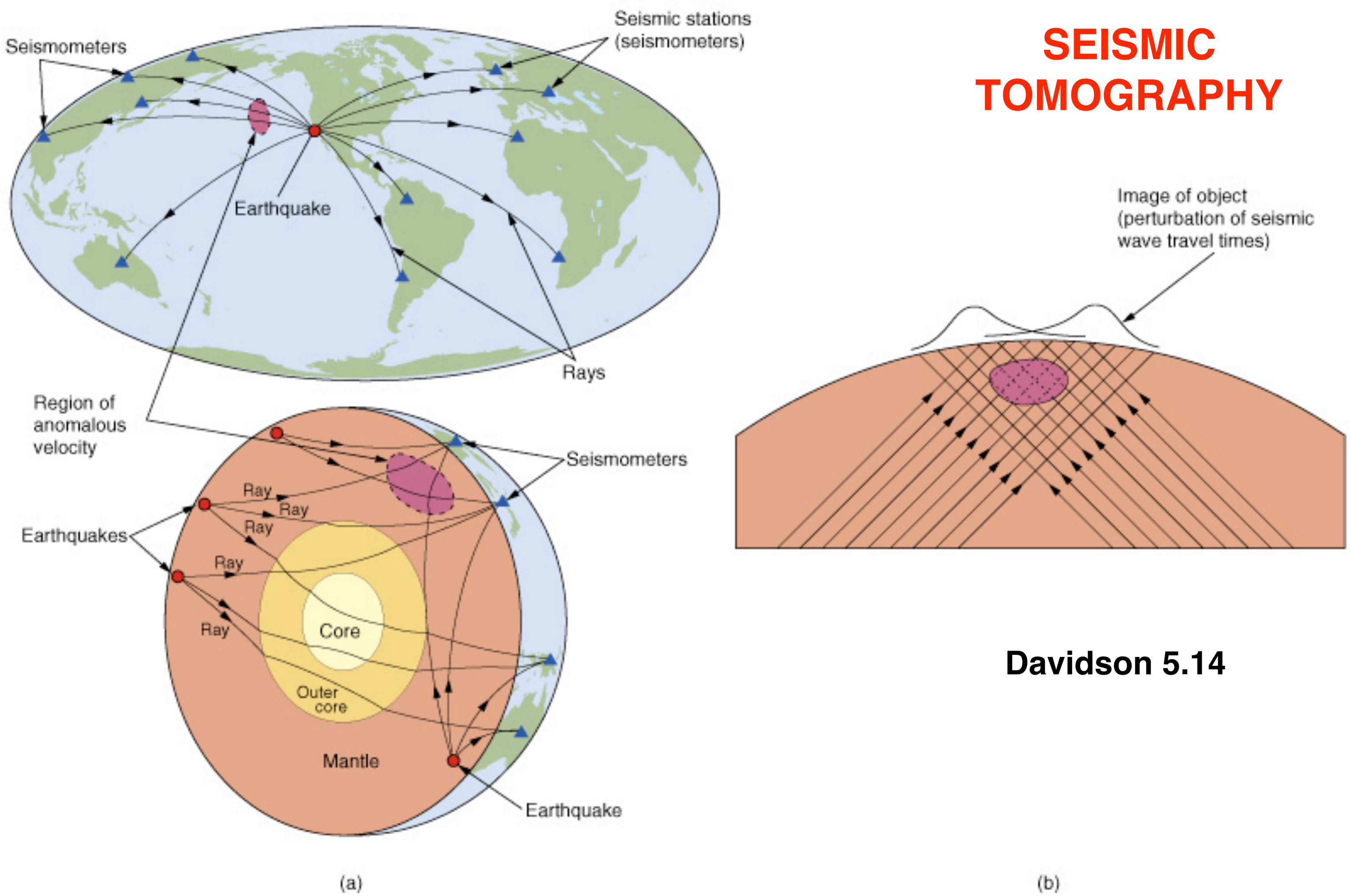
COMBINE BEAMS FOR DETAILED PICTURE OF VARIATIONS INSIDE OBJECT

(CAT= COMPUTED AXIAL TOMOGRAPHY)

MEDICAL TOMOGRAPHY USES X-RAYS (ELECTROMAGNETIC RADIATION) TO "SEE" VARIATIONS IN ABSORPTION DUE TO BONES, TISSUE ETC



SEISMIC TOMOGRAPHY

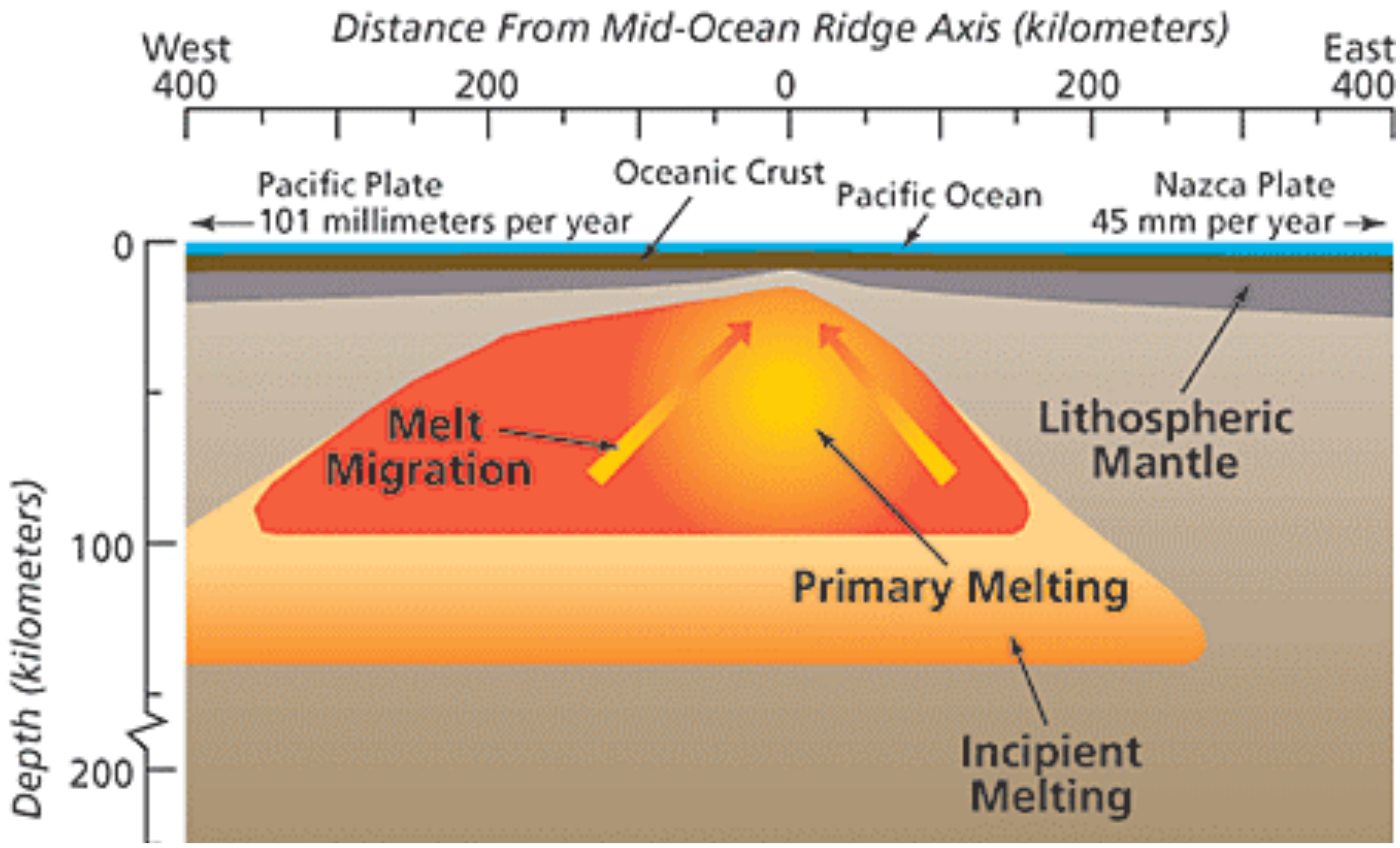


Davidson 5.14

SEISMIC WAVES TRAVEL THROUGH THE EARTH ON MANY DIFFERENT PATHS

COMBINE PATHS FOR A DETAILED PICTURE OF VELOCITY VARIATIONS INSIDE

SEISMIC TOMOGRAPHY OF MIDOCEAN RIDGE
HOT UPWELLING MAGMA HAS LOW VELOCITY



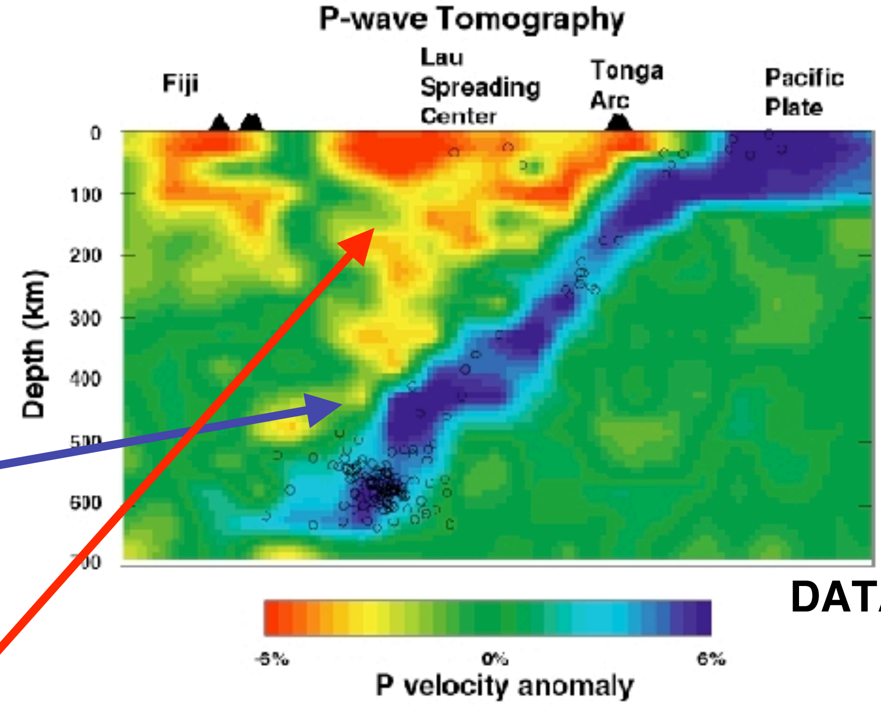
Forsyth et al, 1998

TOMOGRAPHY SHOWS THERMAL STRUCTURE OF SUBDUCTING PLATE (SLAB)

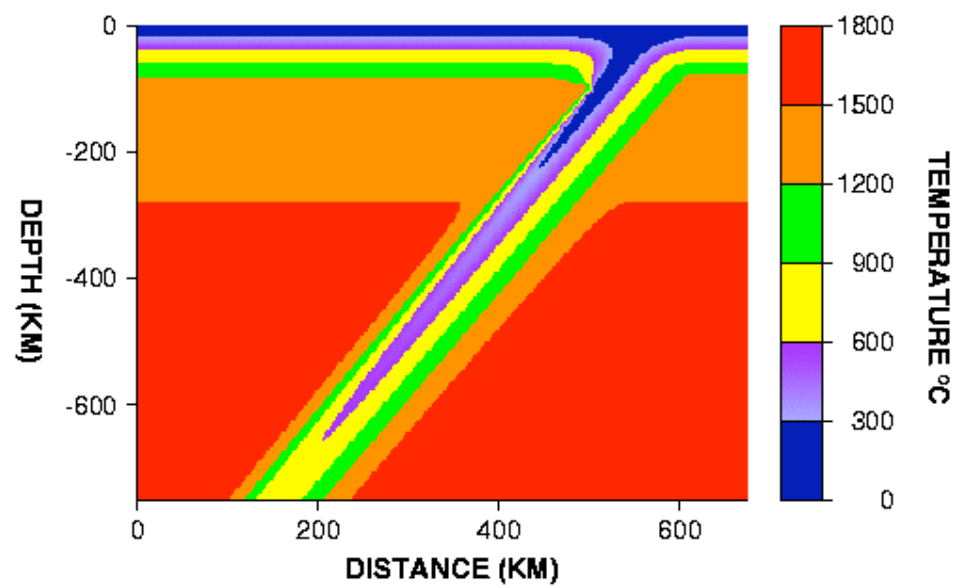
COLD (HIGH SEISMIC VELOCITY) OCEANIC PLATE SUBDUCTS INTO WARMER (LOWER SEISMIC VELOCITY) MANTLE

WARM REGION OF BACK ARC MELTING CAUSES VOLCANOES

SLAB HEATS UP SLOWLY (MILLIONS OF YEARS)



DATA

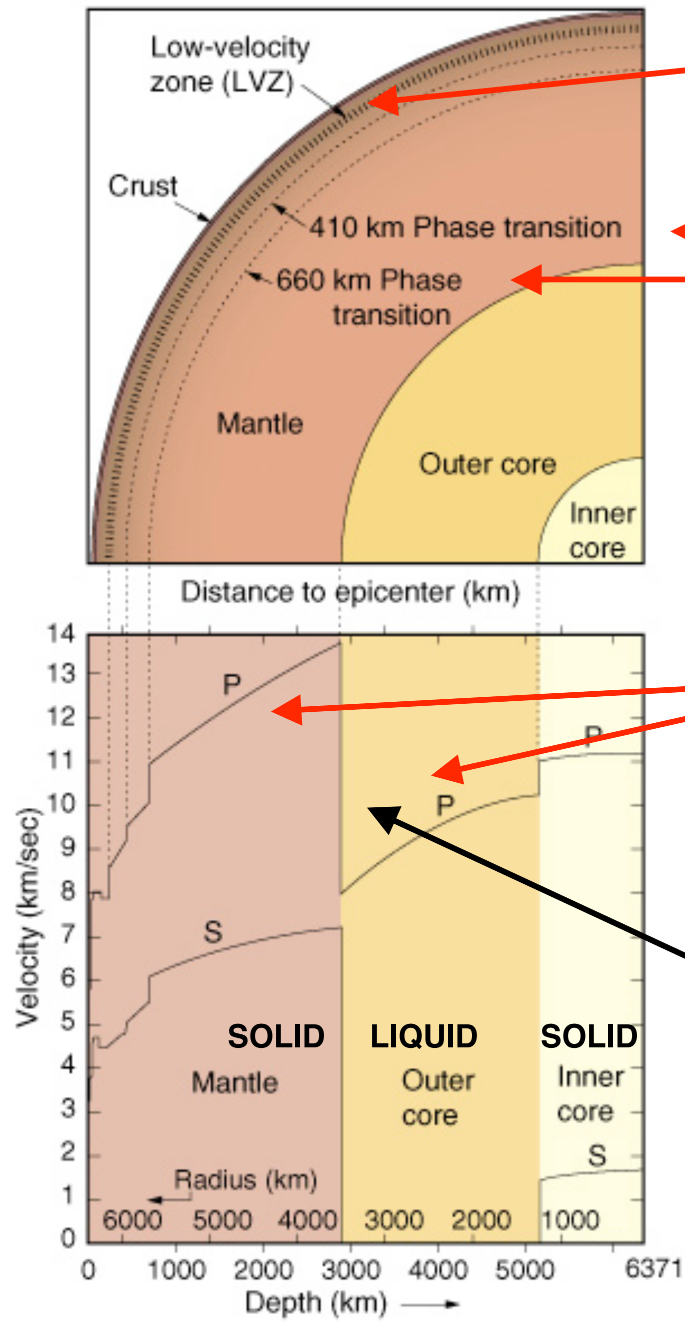


TEMPERATURE MODEL

ANALYSES OF TRAVEL TIME CURVES GIVE VELOCITIES, COMPOSITIONS, AND CHANGES WITH DEPTH

4 MAJOR REGIONS:

CRUST, MANTLE, OUTER CORE, INNER CORE



Near melting at base of plates

Rapid velocity increase

Smooth velocity increase

Velocity decrease

Davidson 5.8

Earth's mass:

$g = GM/a^2$

Because $g = 9.8$ m/s^2, $G = 6.67 \times 10^{-11}$ Nm^{2}kg^{-2}, and $a = 6371$ km,

we get $M_{Earth} = 5.97 \times 10^{24}$ kg.

The average density, ρ_o, is found by dividing the mass by the volume:

$$\rho_o = M / \left[(4/3)\pi a^3 \right] \approx 5.5 \text{g/cm}^3$$

This value is significantly higher than the density of the surface rocks (about 3 g/cm^3).
(Evidence for a core of denser material)

Because density varies with depth, the mass varies with depth as

$$M = 4\pi \int_0^a \rho(r) r^2 dr$$

TRAVEL TIME CURVES GIVE VELOCITY AT DEPTH

TO DETERMINE COMPOSITION, NEED TO KNOW WHAT MATERIALS COULD EXIST AT THOSE DEPTHS (PRESSURES) AND TEMPERATURES THAT WOULD HAVE OBSERVED VELOCITIES

PRESSURE = DENSITY x DEPTH x ACCELERATION OF GRAVITY

SO PRESSURE INCREASES WITH DEPTH

3 km depth => 1000 ATMOSPHERES

400 km => 133,000 ATMOSPHERES, ~1500˚C

CORE-MANTLE BOUNDARY (2900 km) => 1.3 million ATMOSPHERES, ~3700˚C

CENTER OF EARTH (6371 km) => 3.5 million ATMOSPHERES, ~4200˚C

MATERIALS BEHAVE *VERY* DIFFERENTLY AT THESE CONDITIONS THAN AT SURFACE

INCREASE OF PRESSURE WITH DEPTH HAS TWO EFFECTS

- STEADY COMPRESSION (SQUISHING) OF MATERIAL MAKES IT STRONGER AND DENSER AND SO INCREASES VELOCITY GRADUALLY WITH DEPTH IN UPPER (100-410 km depth) AND LOWER (660-2900 km depth) MANTLE

- AT APPROPRIATE PRESSURE AND TEMPERATURE CONDITIONS MINERALS TRANSFORM TO DENSER PHASES, CAUSING THE RAPID VELOCITY INCREASES (DISCONTINUITIES) AT 410 AND 660 km depth

SIMULATING EARTH'S INTERIOR

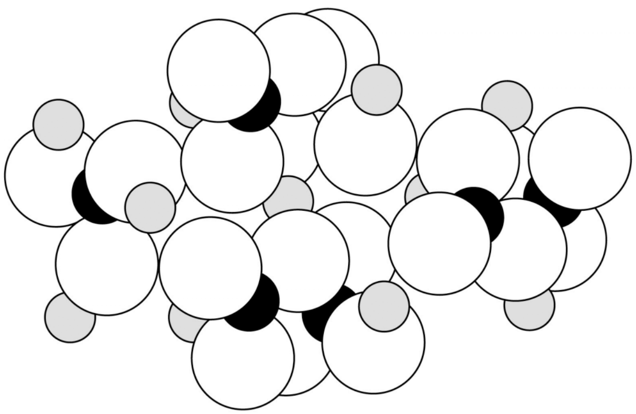
Lab experiments

Pressure = Force/Area

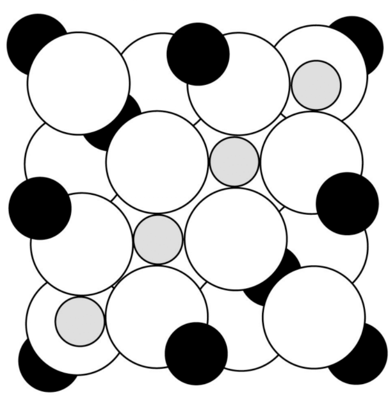
Piston Cylinder - reach upper mantle conditions

Figure 3.8-10: Crystal structures of a α olivine and γ-spinel.

Olivine

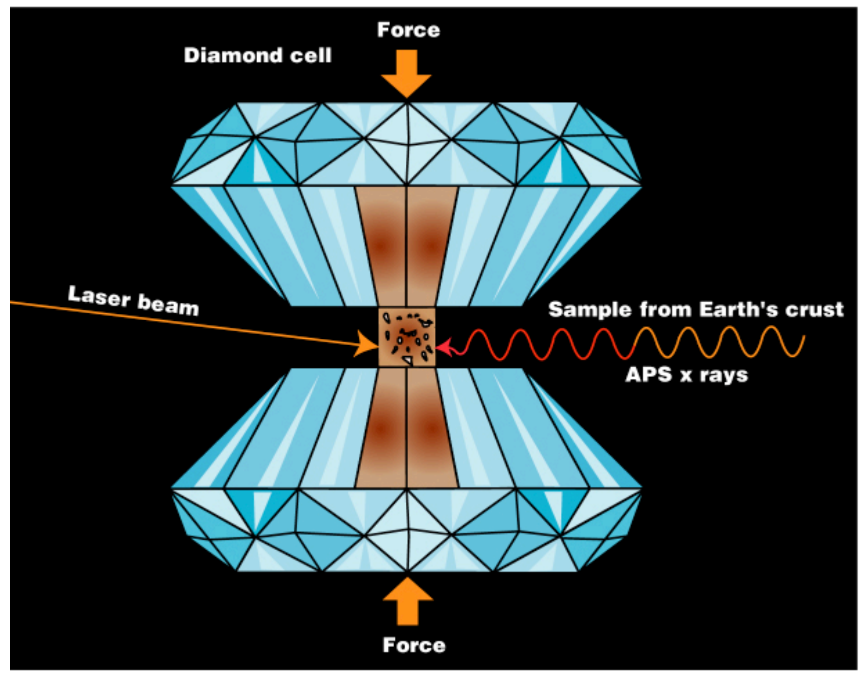


Spinel structure



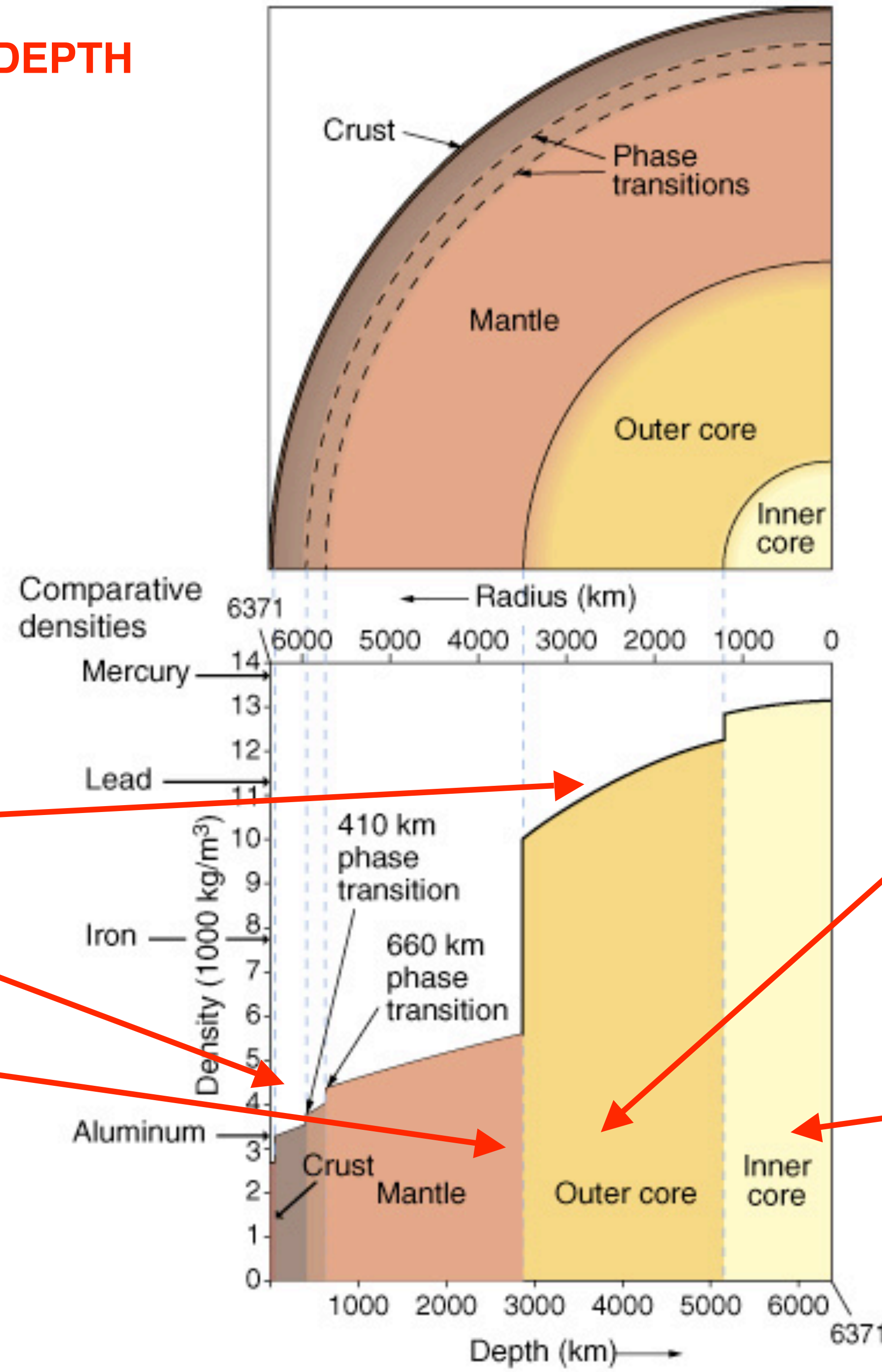
410 km: olivine to spinel phase change

8% denser



Diamond cell - reach core conditions

DENSITY INCREASES WITH DEPTH



COMBINED EFFECT OF:

Compression (squishing) - slow increase

Phase changes - sharp increase

Changes in composition

Dense mostly iron liquid

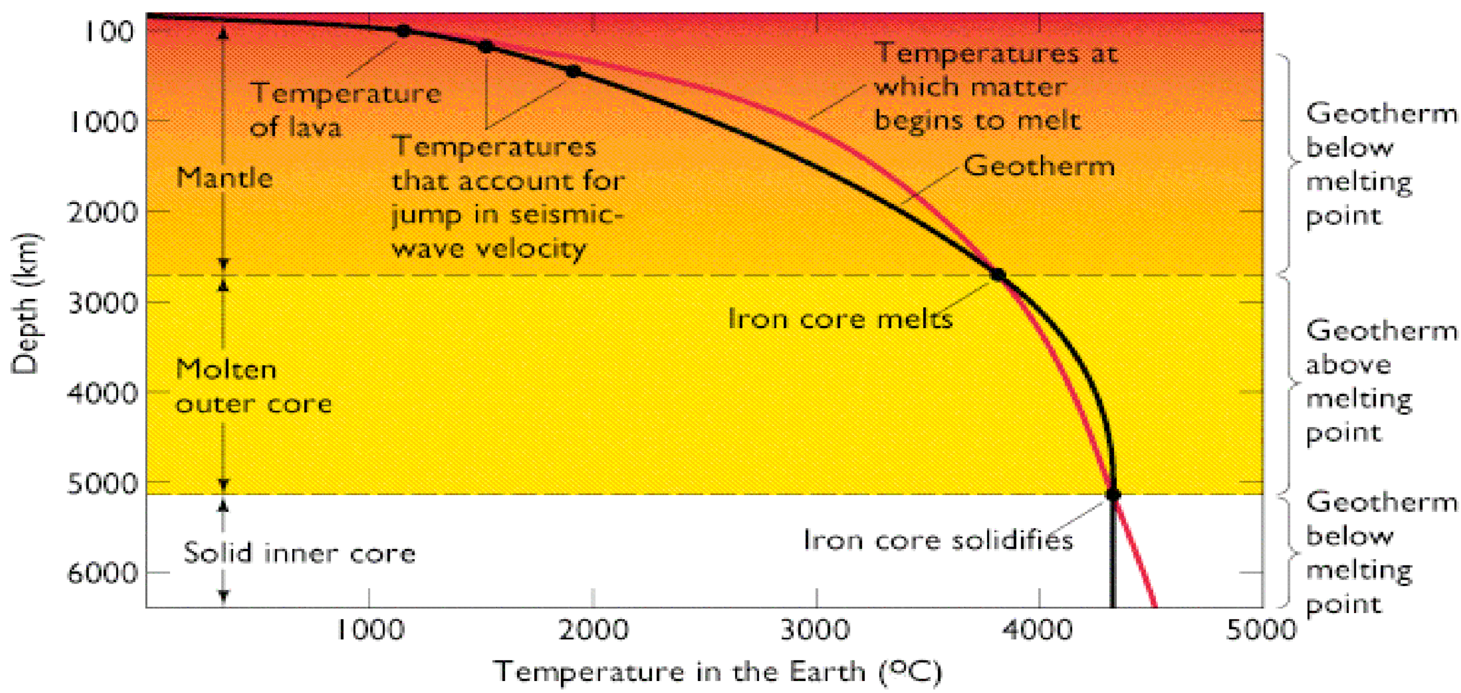
Denser solid iron

Davidson 5.2

TEMPERATURES IN THE EARTH - GEOTHERM

BELOW MELTING CURVE (SOLIDUS) IN MANTLE AND SOLID INNER CORE

ABOVE MELTING CURVE IN LIQUID OUTER CORE



SOLID

LIQUID

SOLID

Transition zone between upper & lower mantles bounded by 410 and 660 km discontinuities

Velocity increases due to mineral phase changes

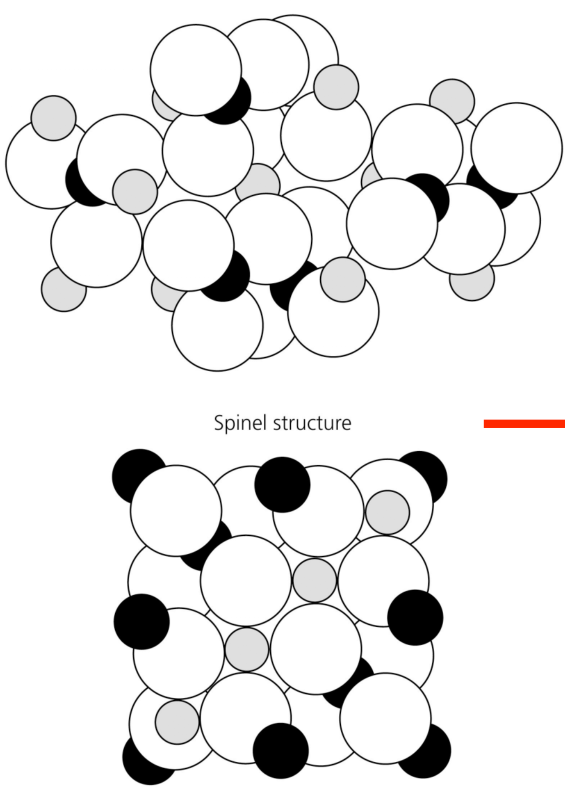


Figure 3.8-8: Predicted mineral assemblages for the mantle.

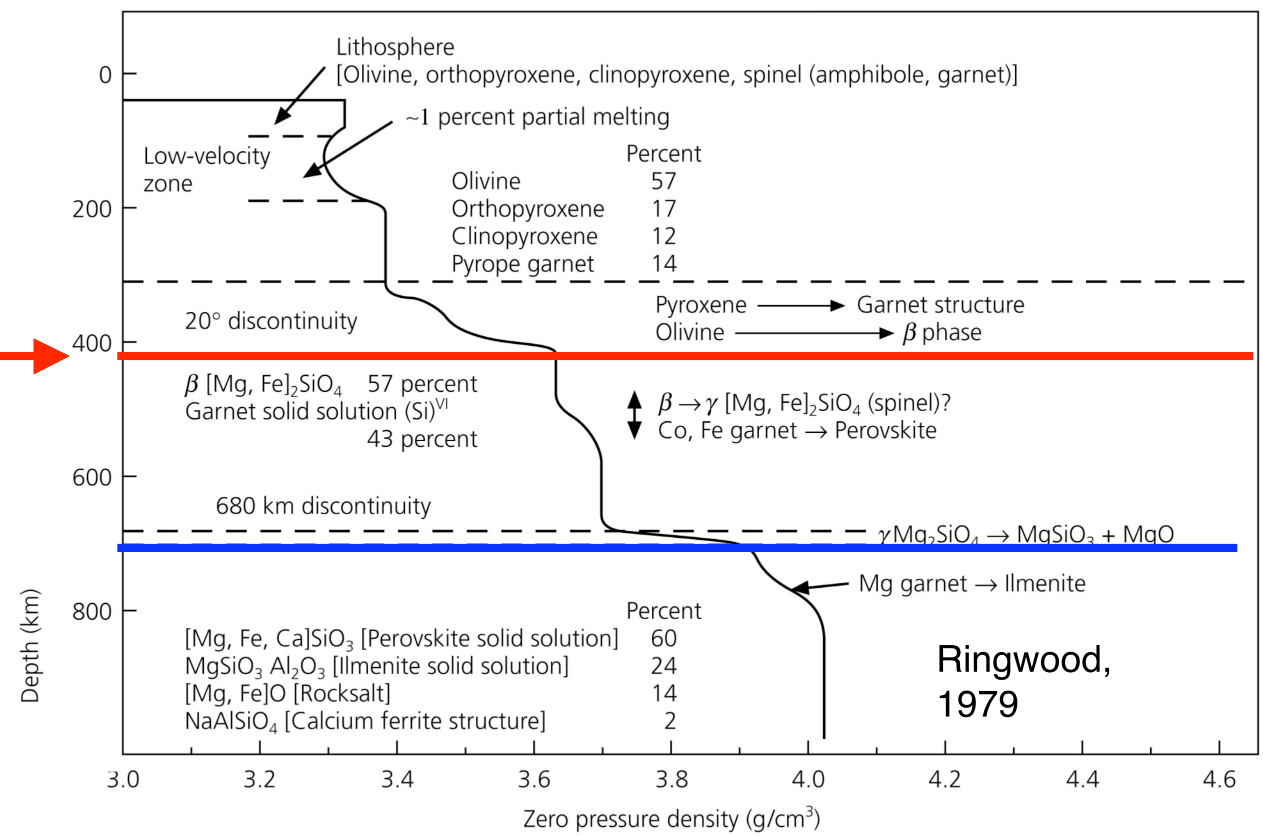
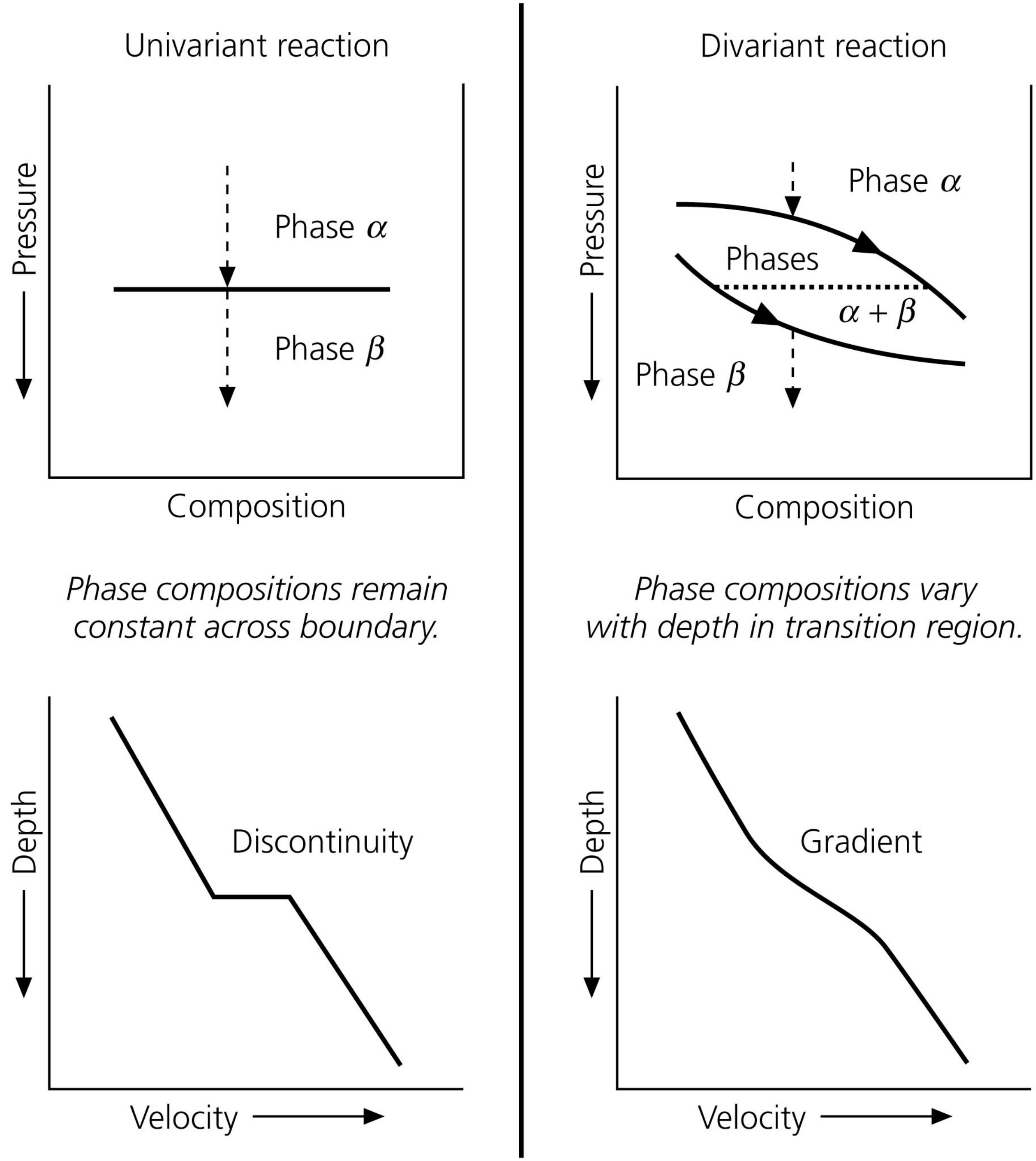


Figure 3.8-11: Effect of phase changes on velocity structure.



SOLID INNER CORE FREEZES FROM OUTER CORE

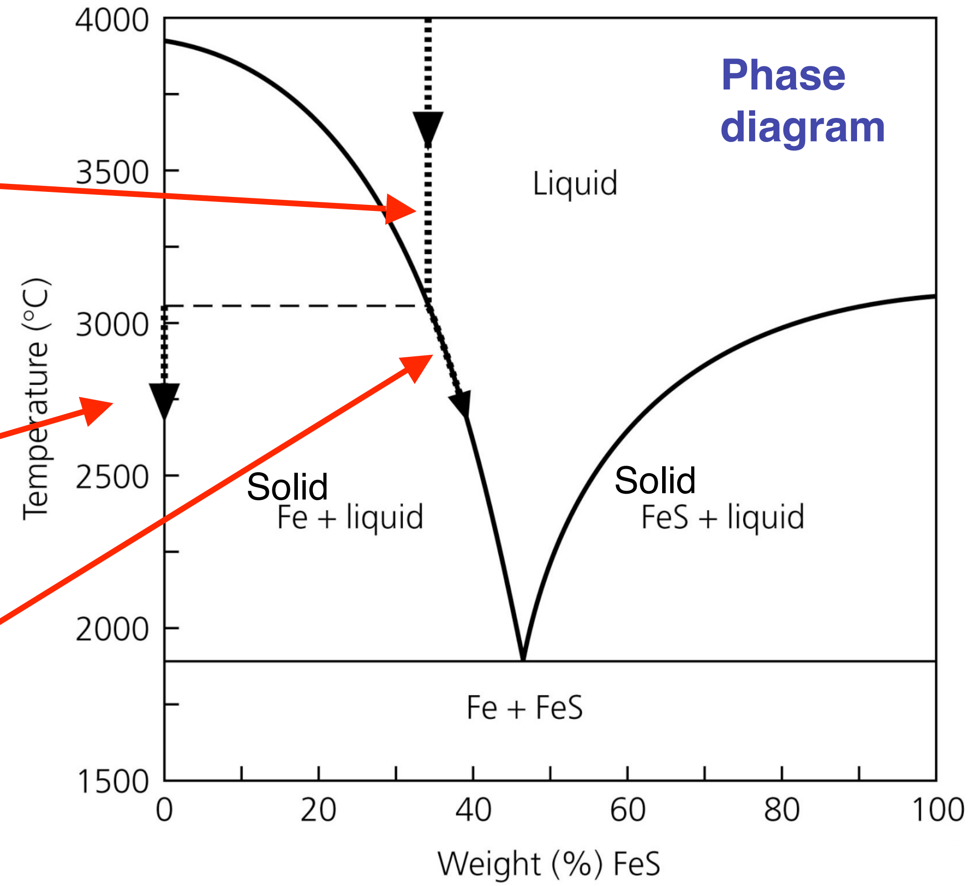
Fractional crystalization as earth cools

Liquid core containing iron (Fe) and Sulphur (S) cools

Solid iron core freezes out

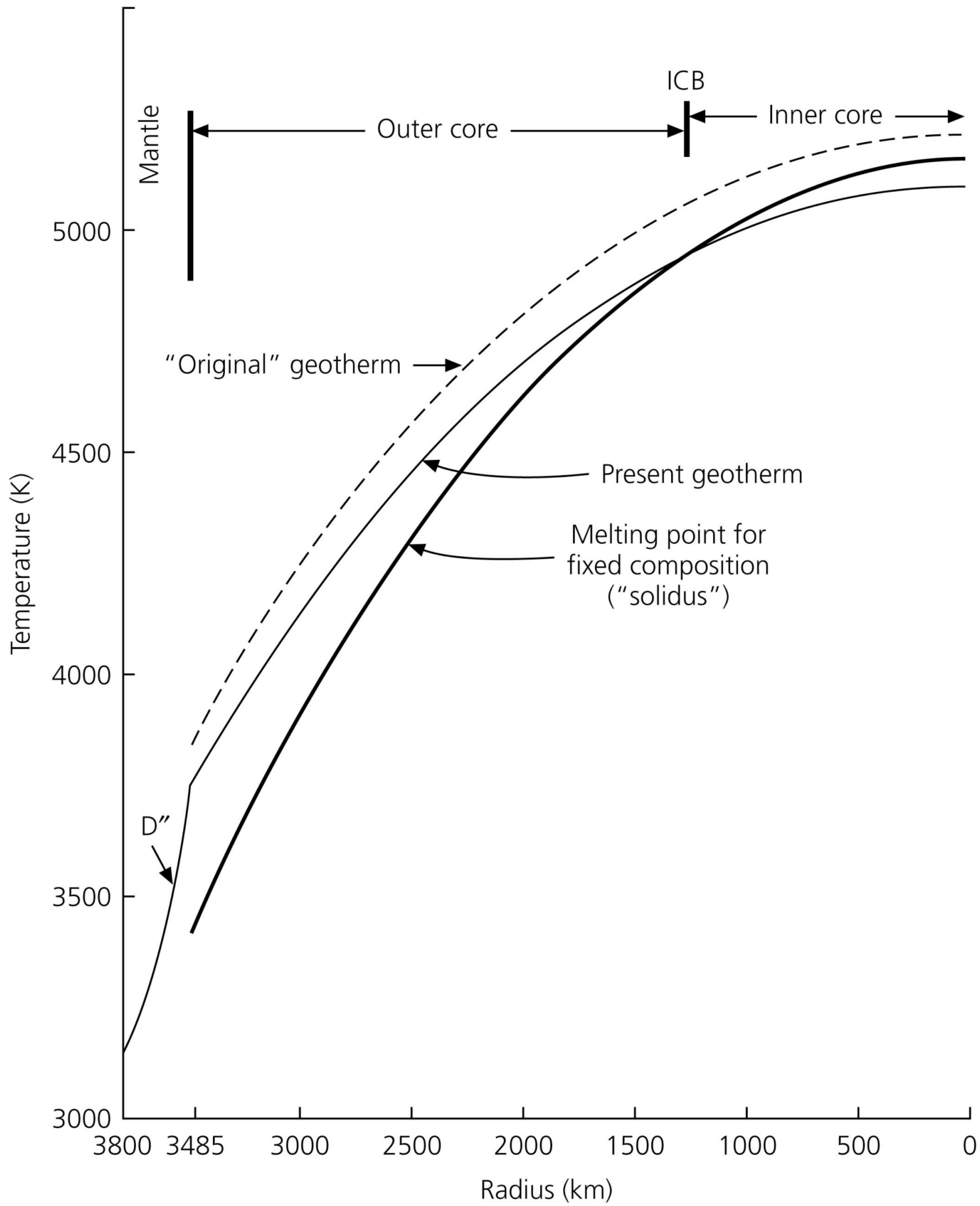
Remaining liquid core enriched in S

Composition of inner & outer cores differ



Heat released by freezing and gravitational energy released as the denser solid sinks drive convection in the outer core and thus generate magnetic field

Figure 3.8-15: Geotherm and solidus for the core.



EARTH: A GIANT HEAT ENGINE

“Heat is the geological lifeblood of planets”

Figure 5.1-1: Cartoon of plate tectonics.

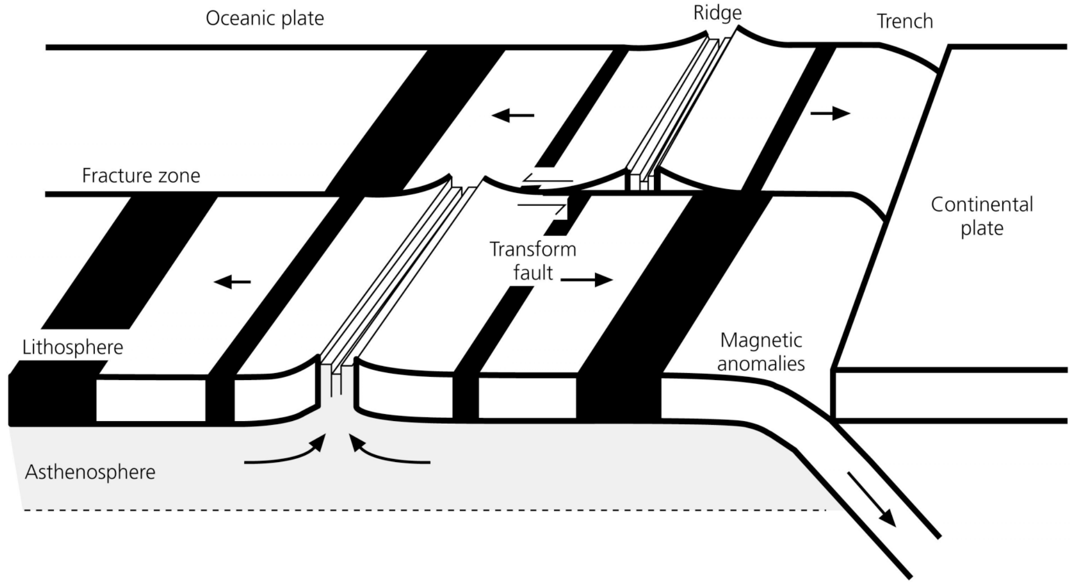
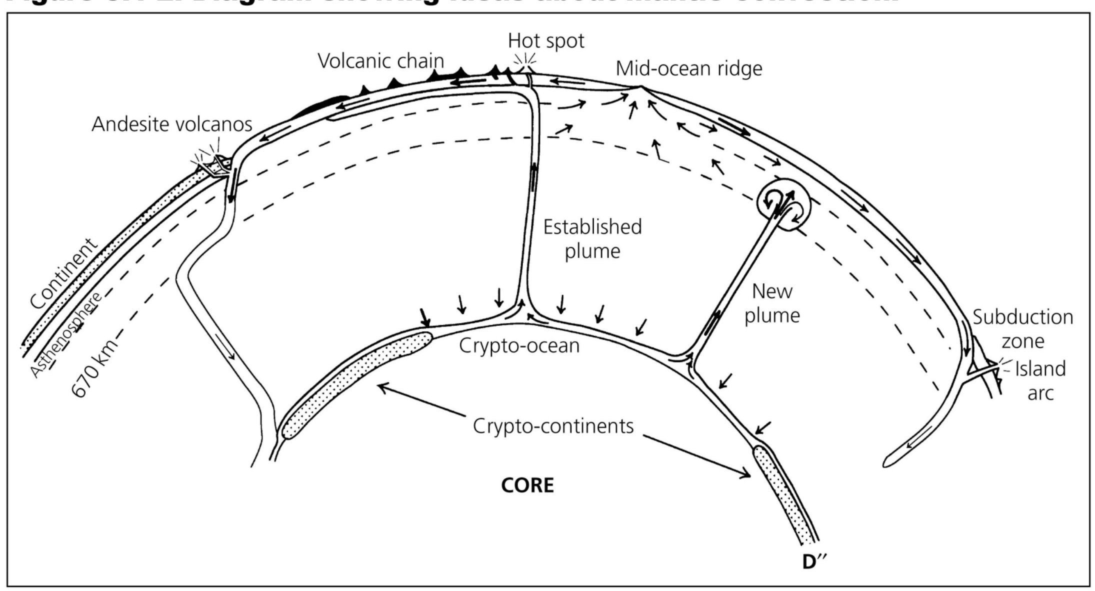


Figure 5.1-2: Diagram showing ideas about mantle convection.



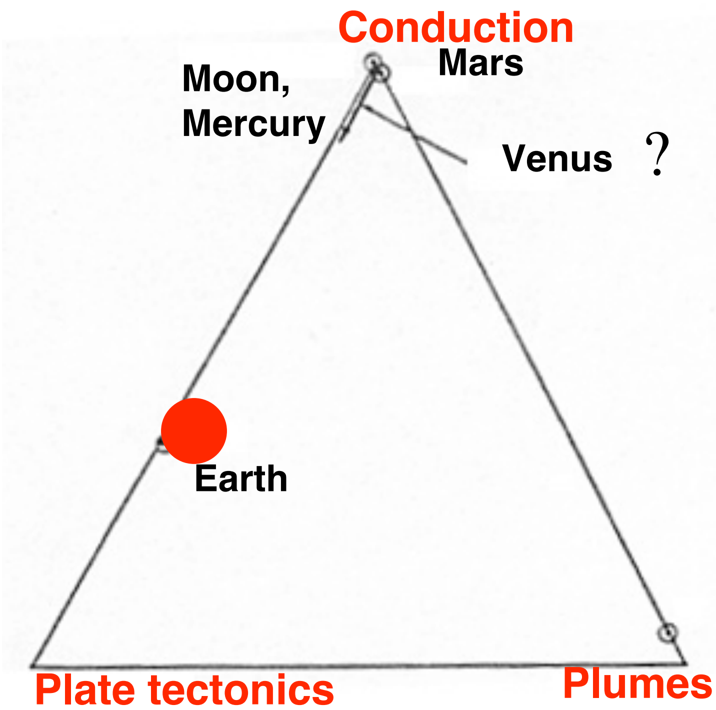


Plate tectonics makes Earth different

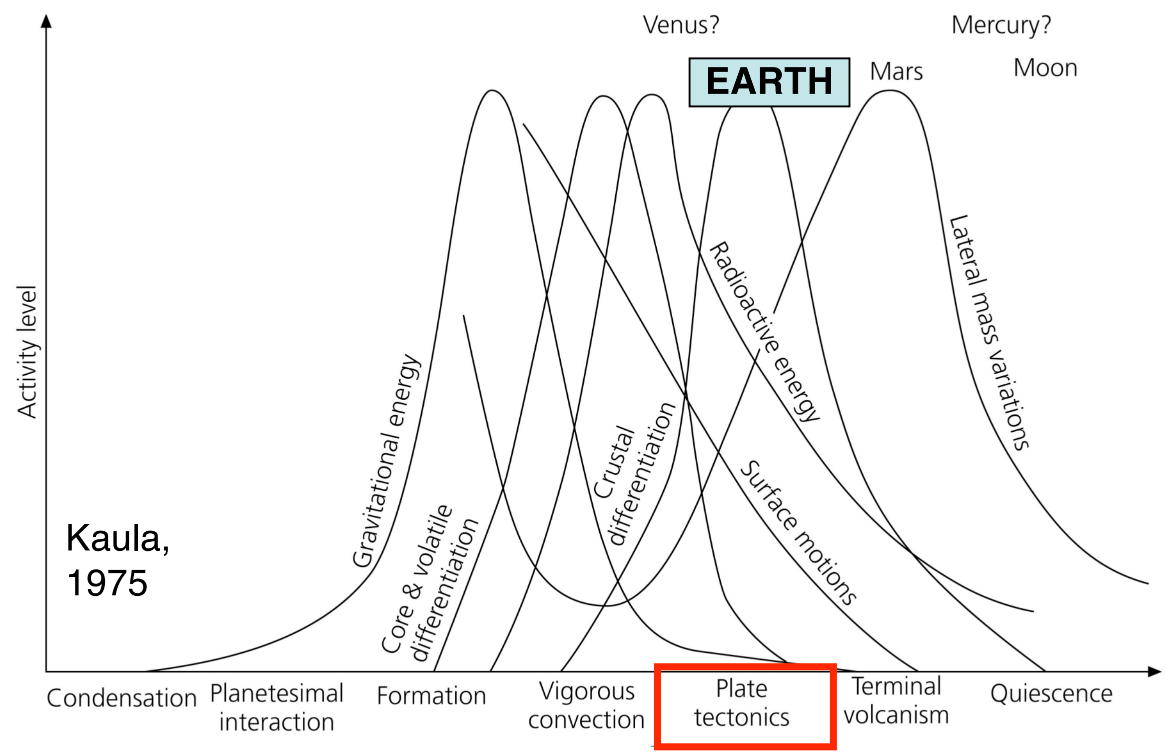
Seafloor topography and heat flow indicate Earth's heat loss primarily (~70%) by plate tectonics, with ~25% by conduction

Grossly similar sister planets, Mars and Venus, seem conduction-dominated: large-scale plate tectonics appears absent, at least at present

Mars may have had plate tectonics, now stopped, perhaps due to both cooling & loss of water (which reduces rock strength & thus may be needed for plate tectonics)

Venus may still be hot with episodic overturns rather than steady-state plate tectonics

PLATE TECTONICS CHARACTERIZES EARTH RELATIVE TO OTHER PLANETS



Terrestrial (inner) planets may follow similar life cycle with stages including formation, early convection and core formation, plate tectonics, terminal volcanism, and quiescence.

Evolution driven by available energy sources as planets cool with time. Planets formed at about the same time but are at different stages in their life cycles. (Consider human and dog born on the same date).

Earth in middle age with active plate tectonics

Moon & Mars old, dead, inactive - “one plate planets”

DEAD MOON & MARS

Seismological & other data suggest moon now has a thick lithosphere and is tectonically inactive

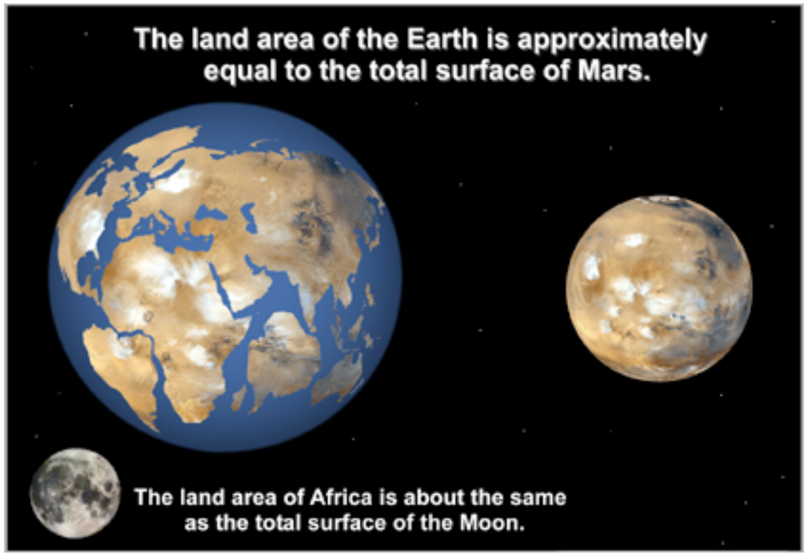
Lost much of its heat, presumably because of small size, which favors rapid heat loss.

Expect the heat available from gravitational energy of accretion and radioactivity to increase as the planet`s volume, whereas rate of heat loss should depend on surface area

remaining heat = available / loss ~ $(4/3)\pi r^3 \;/\; 4\pi r^2 = r/3$

Larger planets would retain more heat and be more active

Mercury and Mars, larger than the moon but smaller than earth, should have also reached their old age with little further active tectonics.



Remember, always, the words of Francis Birch (1952)

Ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few examples of equivalents follow:

High-pressure form	Ordinary meaning
certain	dubious
undoubtedly	perhaps
positive proof	vague suggestion
unanswerable argument	trivial objection
pure iron	uncertain mixture of all the elements