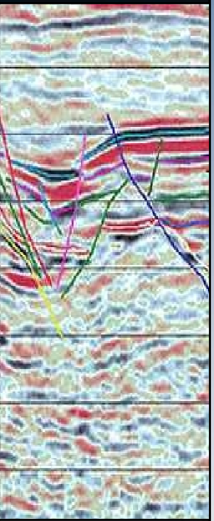


Refraktionsseismik

- Zweischichtfall
  - Laufzeitdiagramme
  - Inversionsproblem
- Dreischichtfall
- Geneigte Schicht
- N-Schichtfall
- Anwendungen
- Seismische Tomographie

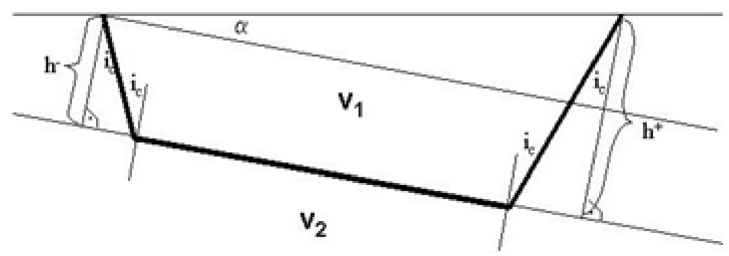
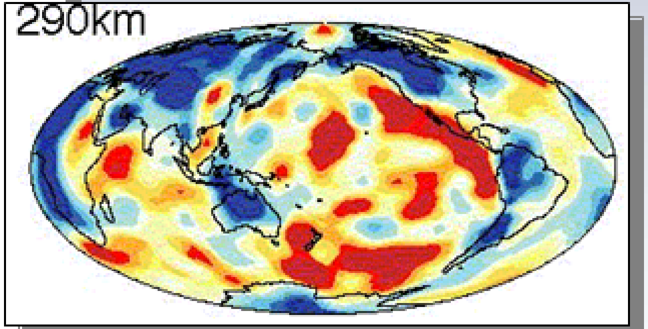
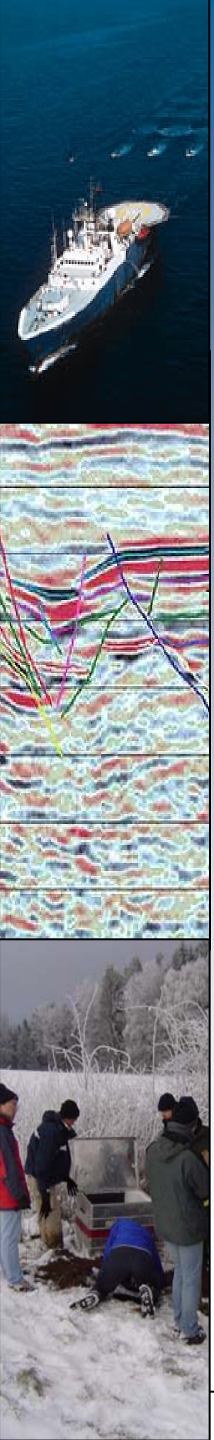


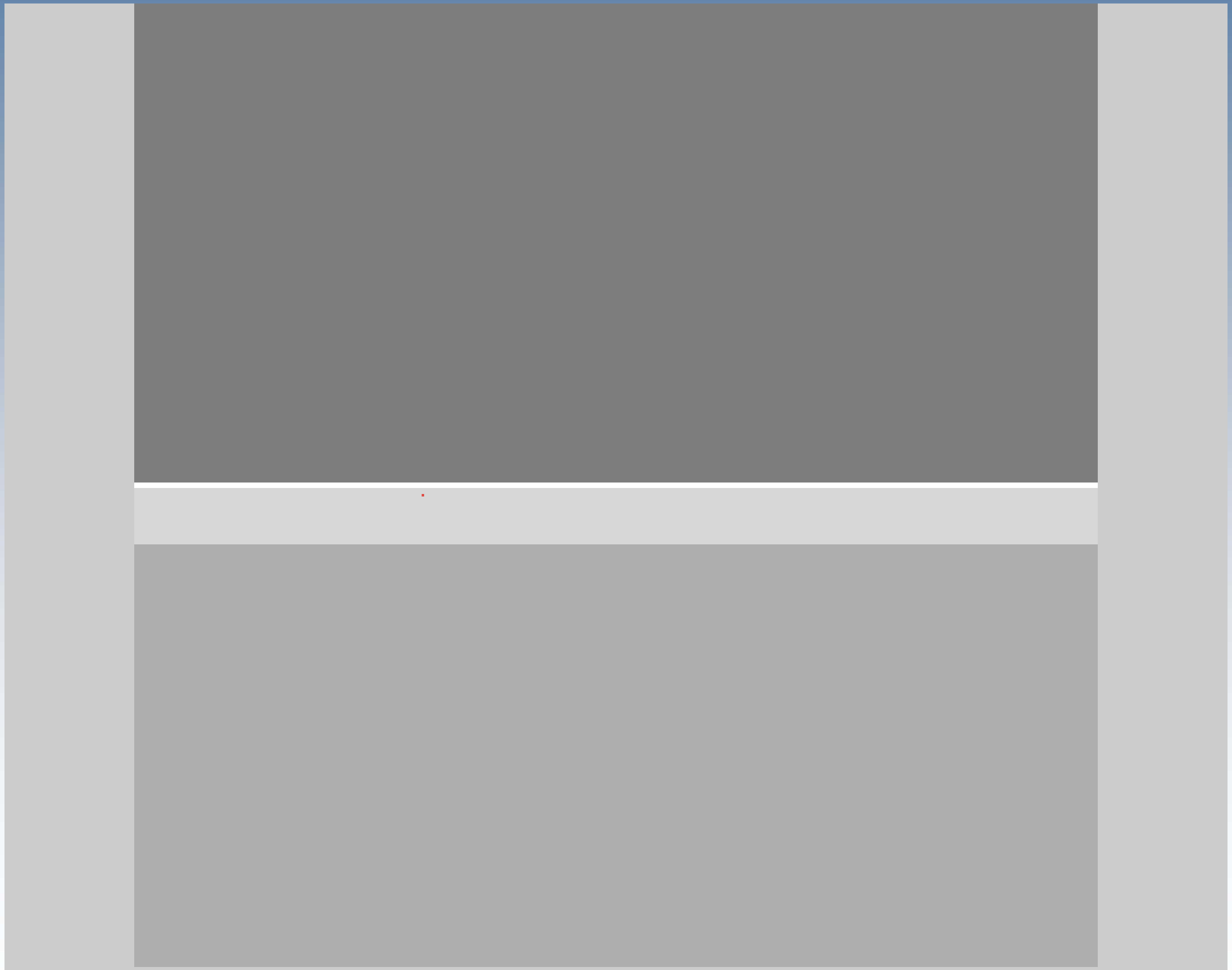
Figure 5: Refracted ray path for the inclined 2-layer case.

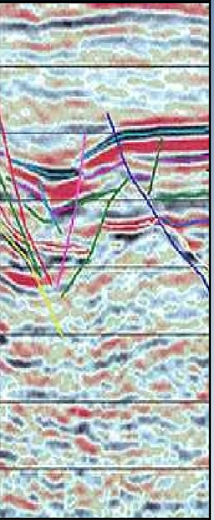


Theorie zu diesem Kapitel als Skript erhältlich (in Englisch) -> download

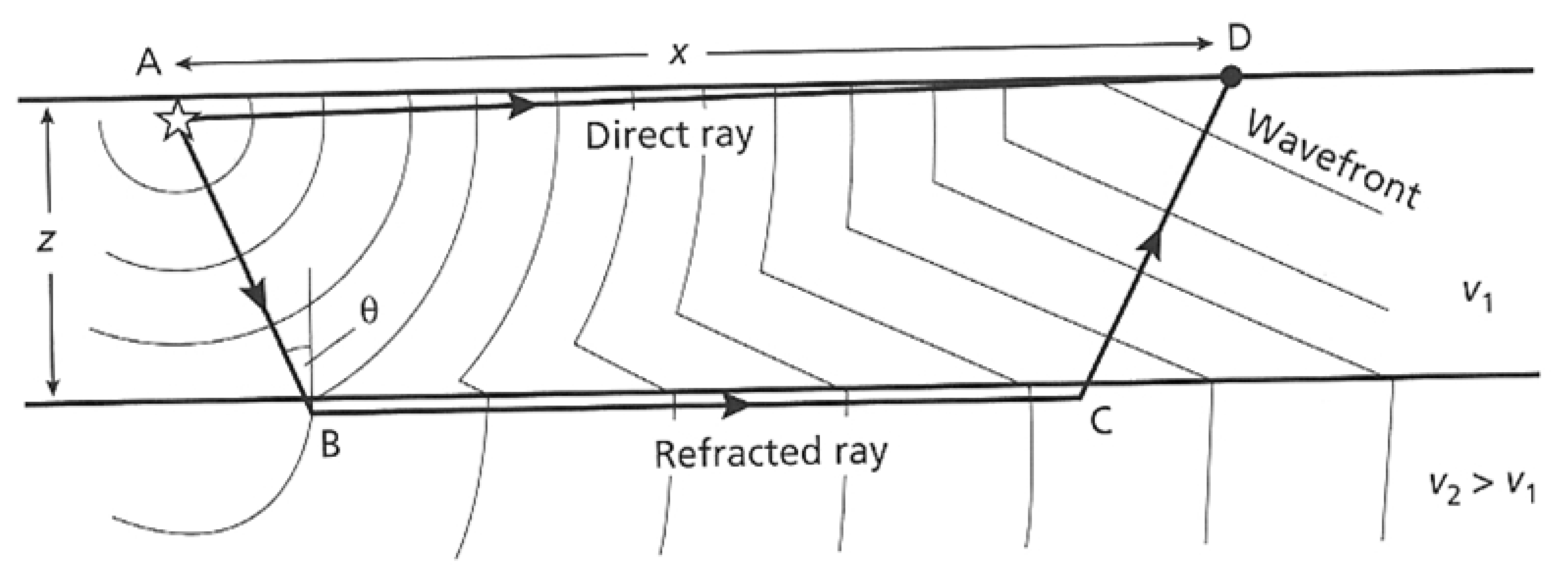


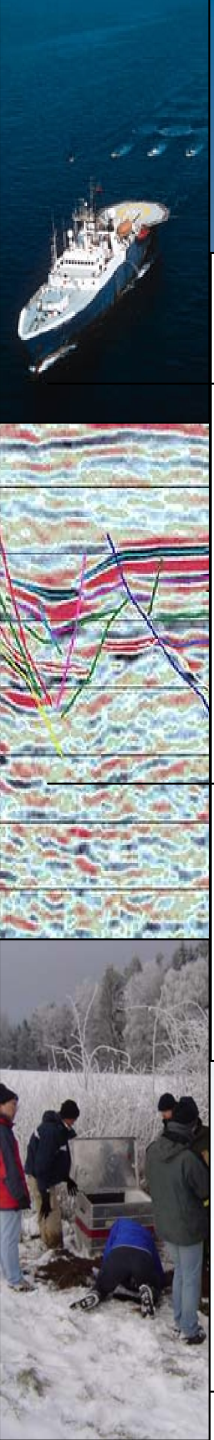
Snapshots and Seismogramme:
Refraktierte Wellen



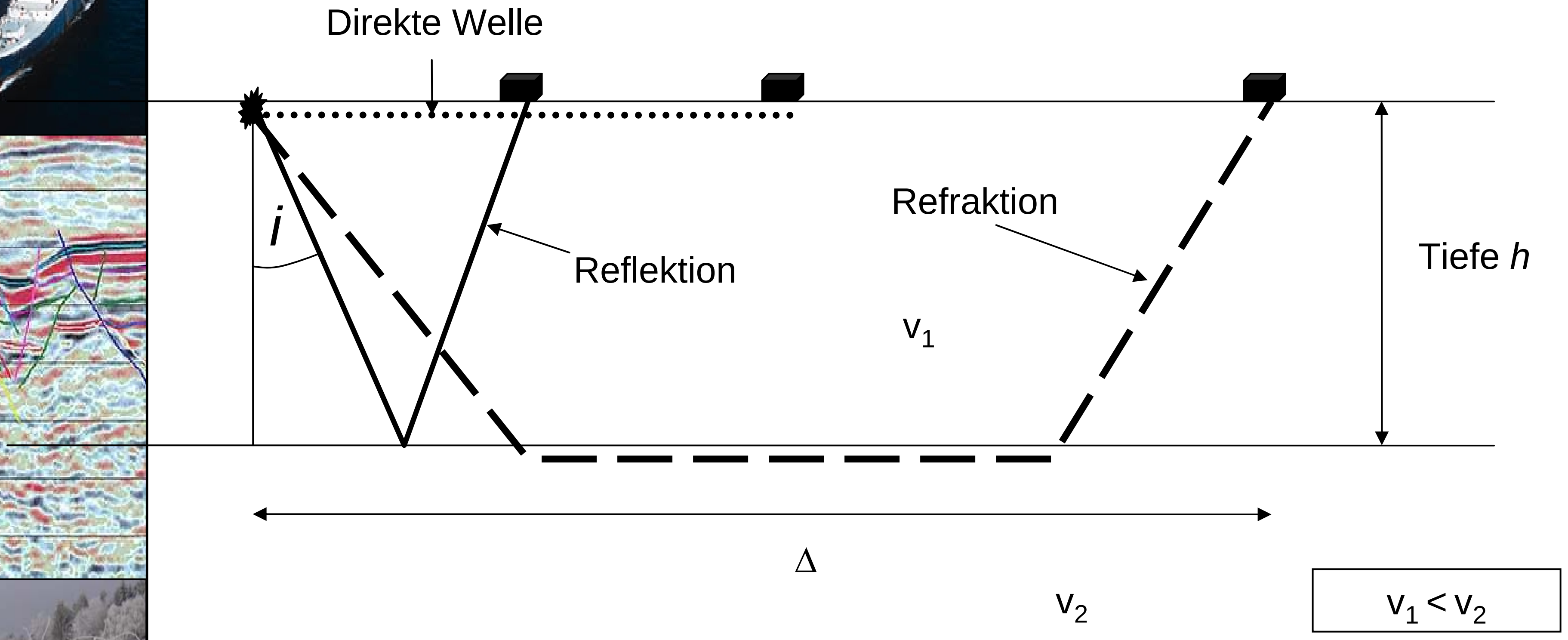


Strahlen und Wellenfronten

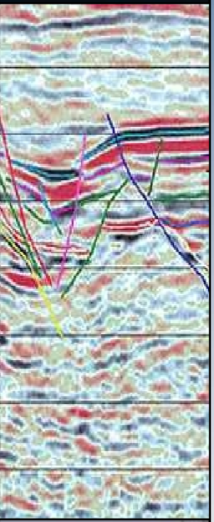




Refraktionsprofil



Geometrie des Reflexions/Refraktionsexperiments. Drei Phasen werden bei größeren Distanzen beobachtet: die direkte Welle, die reflektierte Welle und die refraktierte Welle.



Refraktionsexperiment: Ankunftszeiten

Direkte Welle

$$\boxed{t_{dir} = \Delta / v_1}$$

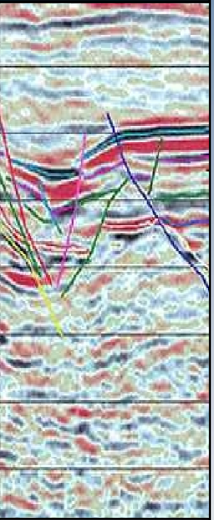
Reflektierte Welle

$$\boxed{t_{refl} = \frac{2}{v_1}\sqrt{(\Delta/2)^2 + h^2}}$$

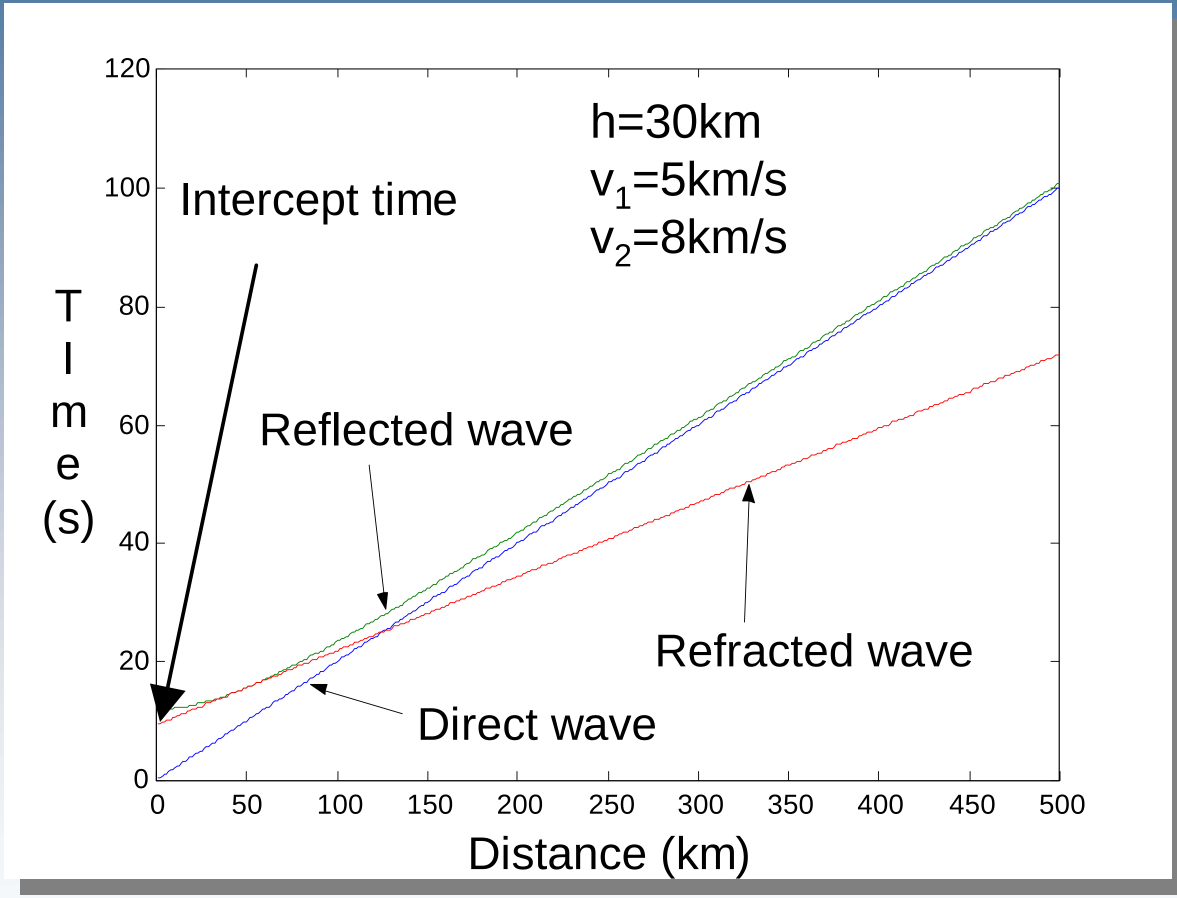
Refraktierte Welle

$$\boxed{t_{refr} = \frac{2h\cos i_c}{v_1} + \frac{\Delta}{v_2} = t_{refr}^{i} + \frac{\Delta}{v_2}}$$

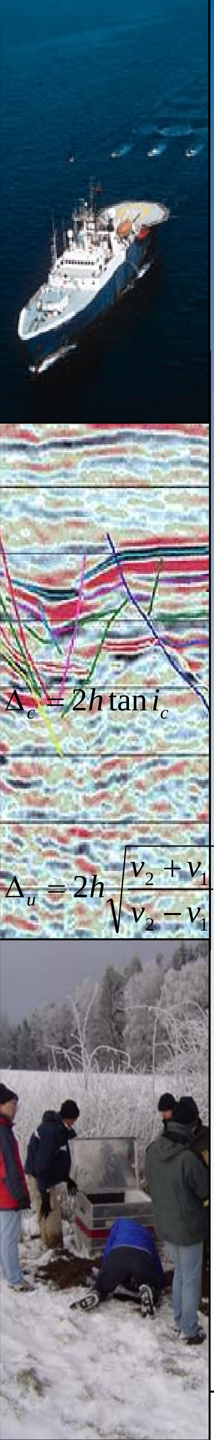
Interzeptzeit



Zweischichtfall
Laufzeitdiagramm



Dies würde einem einfachen Modell der Kruste und des oberen Mantels entsprechen.



Kritische Distanz
Überholdistanz

Die kritische Distanz Δ_c ist die Entfernung, bei der die refraktierte Welle gemäß der Strahlentheorie erstmals beobachtet werden kann (tatsächlich wird sie wegen finitem Frequenzgehalt schon bei kleineren Entfernungen beobachtet). Die kritische Distanz ergibt sich aus

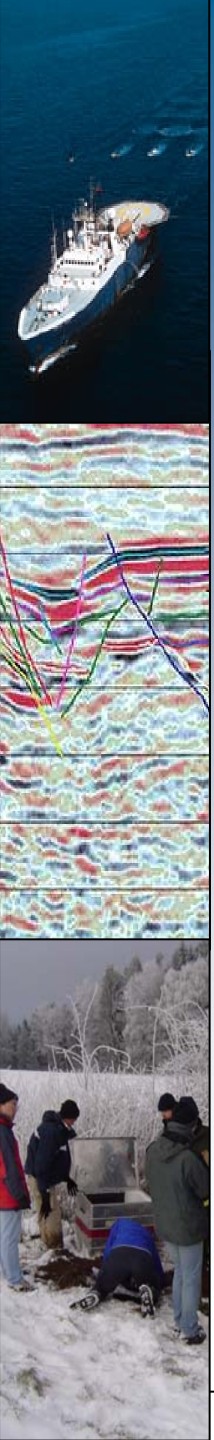
kritische Distanz

$$\Delta_c = 2h \tan i_c$$

der kritische Winkel i_c ist gegeben durch das Snellius Gesetz. Wenn wir die Laufzeit der direkten Welle mit der Laufzeit der refraktierten Welle gleichsetzen ergibt sich die

Überholdistanz

$$\Delta_{ü} = 2h\sqrt{\frac{v_2+v_1}{v_2-v_1}}$$



Das Inversionsproblem
Erdmodell aus Laufzeitkurven

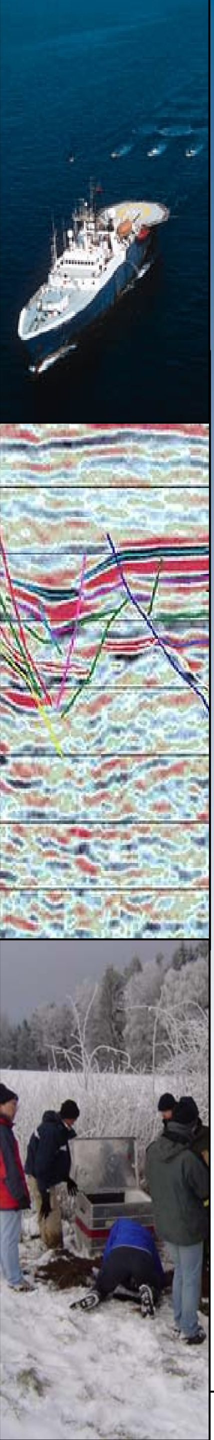
- Bestimme v_1 aus der Steigung ($1/v_1$) der direkten Welle
- Bestimme v_2 aus der Steigung ($1/v_2$) der refraktierten Welle
- Bestimme kritischen Winkel aus v_1 und v_2.
- Lies Interzeptzeit t_i aus Laufzeitkurve der refraktierten Welle
- Bestimme Tiefe h mit

$$h = \frac{v_1 t_i}{2 \cos i_c}$$

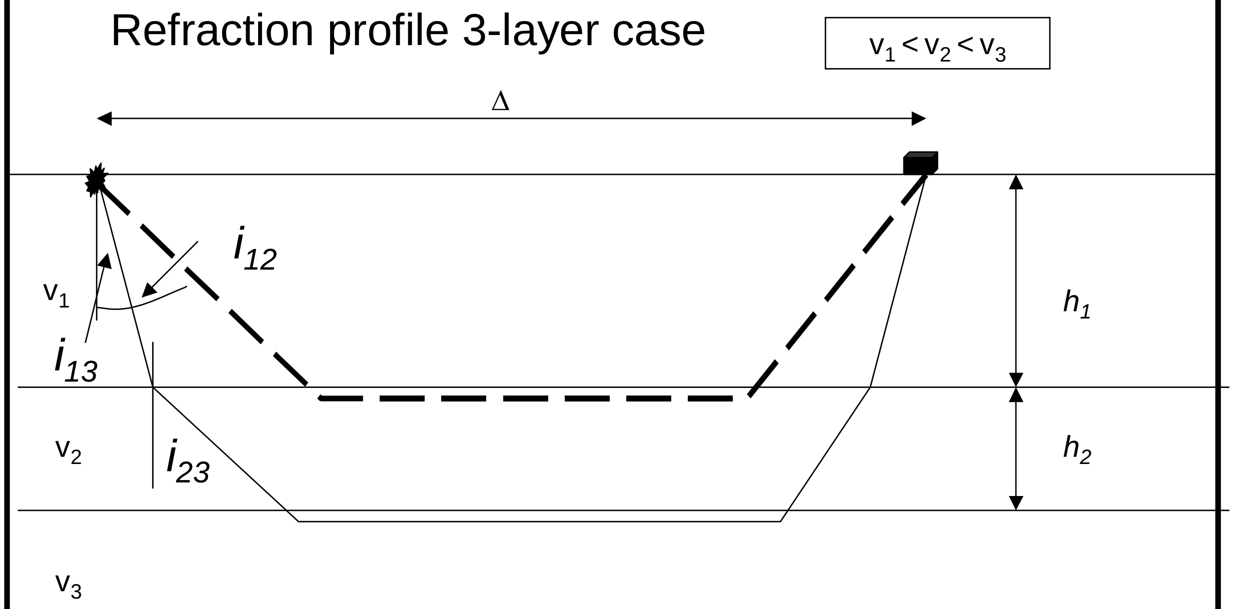
oder

- Ermittle Überholdistanz aus Laufzeitkurve und bestimme h mit

$$\Delta_{ü} = 2h \sqrt{\frac{v_2 + v_1}{v_2 - v_1}}$$

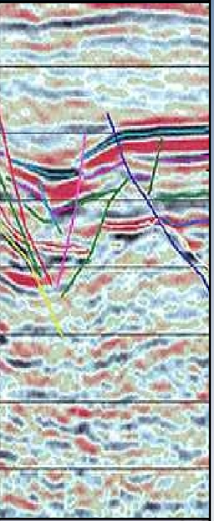


Dreischichtfall


Refraction profile 3-layer case

Wir brauchen Ankunftszeiten für

- Direkte Welle
- Refraktionen


Dreischichtenfall
Ankunftszeiten

Direkte Welle

$$\boxed{t_1 = \Delta / v_1}$$

Refraktion in Schicht 2

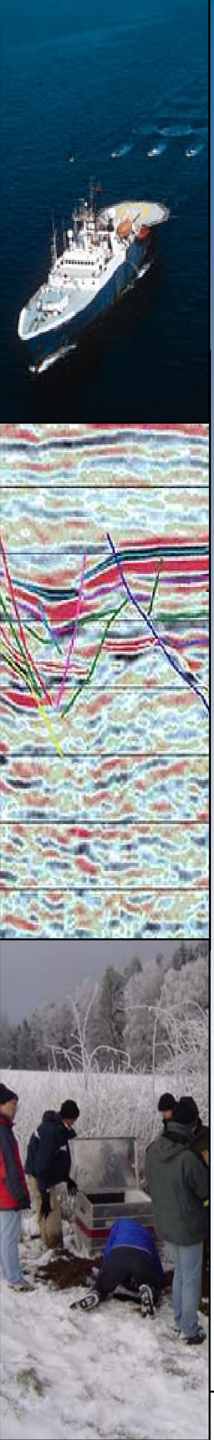
$$\boxed{t_2 = \frac{2h_1 \cos i_{12}}{v_1} + \frac{\Delta}{v_2} = t^{i2} + \frac{\Delta}{v_2}}$$

Refraktion in Schicht 3

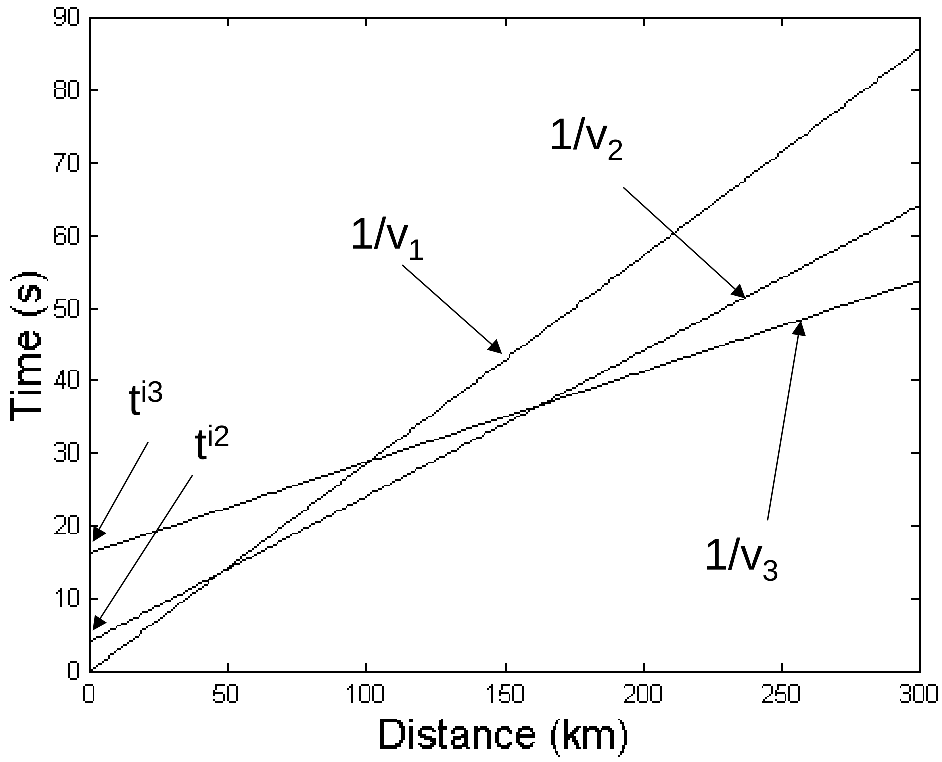
$$\boxed{t_3 = \underbrace{\frac{2h_1 \cos i_{13}}{v_1} + \frac{2h_2 \cos i_{23}}{v_2}}_{t^{i3}} + \frac{\Delta}{v_3} = t^{i3} + \frac{\Delta}{v_3}}$$

mit …

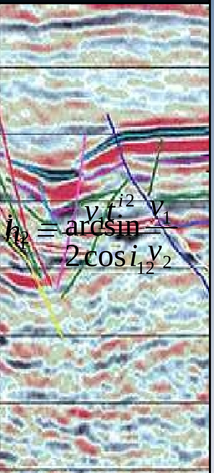
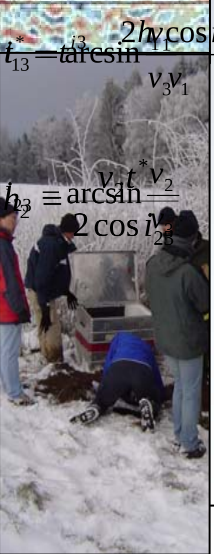
$$\boxed{\frac{\sin i_{13}}{v_1} = \frac{\sin i_{23}}{v_2} = \frac{\sin i_{33}}{v_3} = \frac{1}{v_3}}$$



Dreischichtfall
Laufzeitkurven



Travel-time diagram for the 3-layer case

Das Inversionsproblem
Dreischichtfall

- Bestimme Geschwindigkeiten v_{1-3} aus Steigungen ($1/v_{1-3}$) der Laufzeitkurven
- Lies Interzeptzeit t^{i2} der Refraktion in Schicht 2.
- Bestimme Höhe h_1 mit der Gleichung für t_2 damit ,

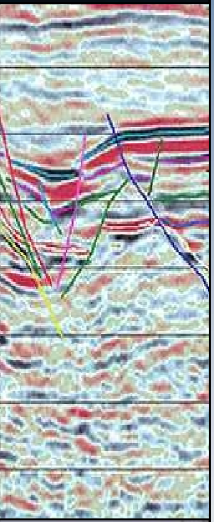
$$h_1 = \frac{v_1 t^{i2}}{2\cos i_{12}} \qquad \text{where} \qquad i_{12} = \arcsin\frac{v_1}{v_2}$$

- Lies Interzeptzeit t^{i3} der Refraktion in Schicht 3.
- Berechne mit h_1 eine Zwischeninterzeptzeit t^*

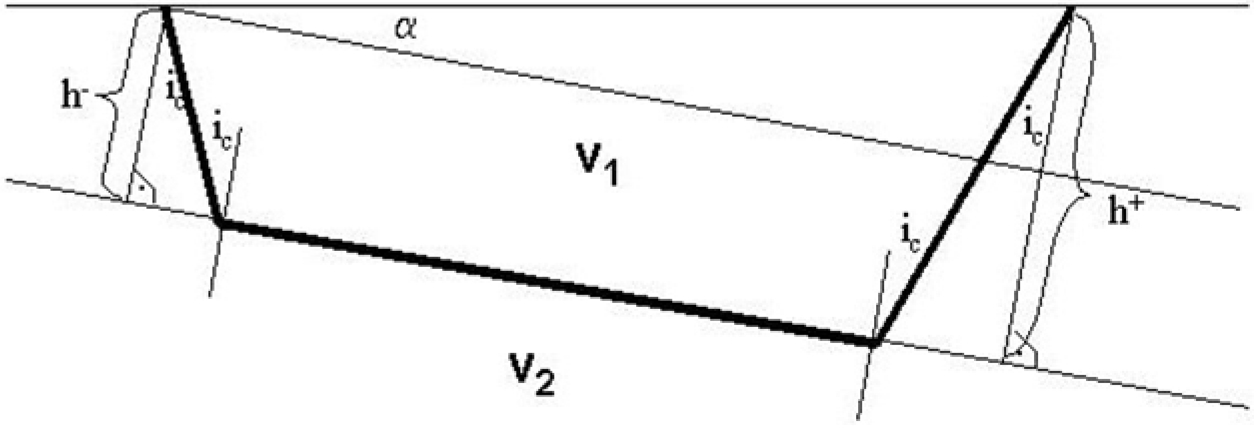
$$t^* = t^{i3} - \frac{2h_1\cos i_{13}}{v_1} \qquad \text{where} \qquad i_{13} = \arcsin\frac{v_1}{v_3}$$

- Mit t^* berechne h_2 der Schicht 2

$$h_2 = \frac{v_2 t^*}{2\cos i_{23}} \qquad \text{mit} \qquad i_{23} = \arcsin\frac{v_2}{v_3}$$

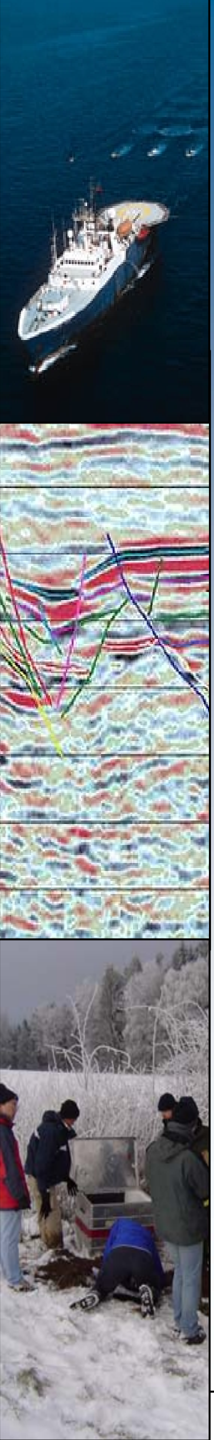




Geneigte Schicht

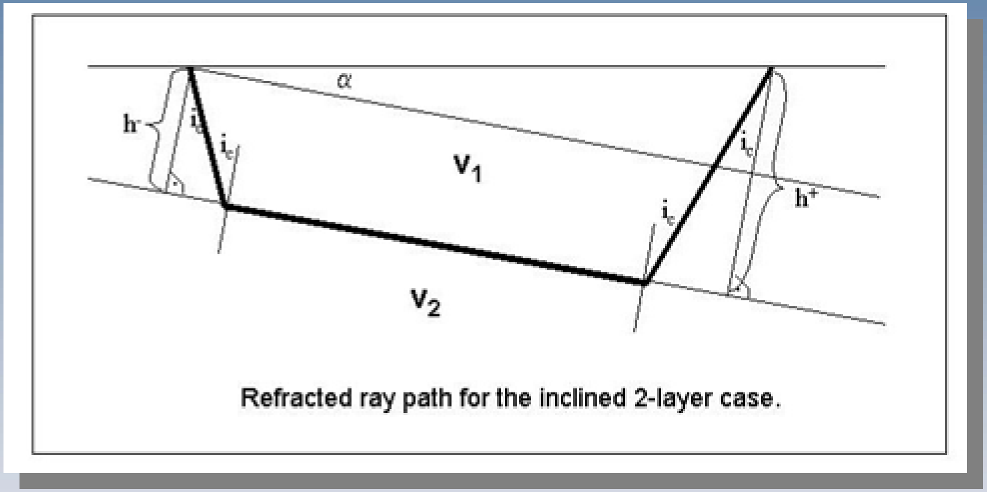


Refracted ray path for the inclined 2-layer case.

Mit dieser asymmetrischen Anordnung benötigen wir Schüsse von beiden Seiten um h^+ und h^- zu bestimmen.



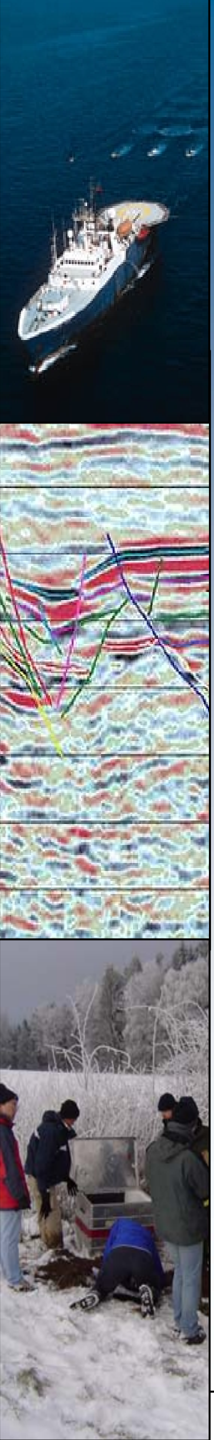
Geneigte Schicht
Laufzeiten



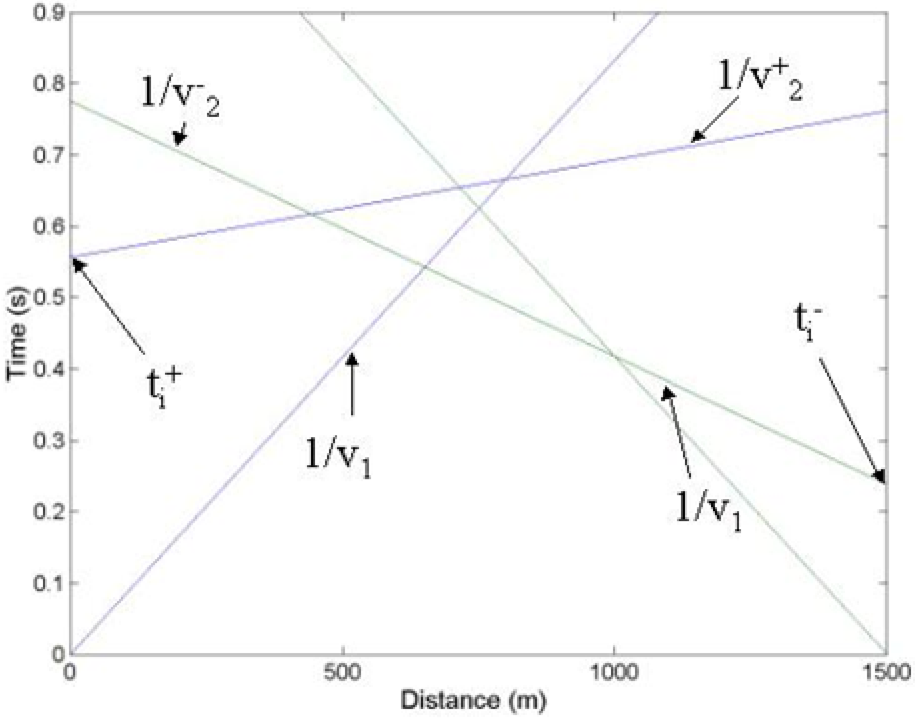
Refracted ray path for the inclined 2-layer case.

$$t_{refr}^{-} = \frac{2h^{-}\cos i_c}{v_1} + \frac{\sin(i_c + \alpha)}{v_1}\Delta = t_i^{-} + \frac{1}{v_2^{-}}\Delta$$

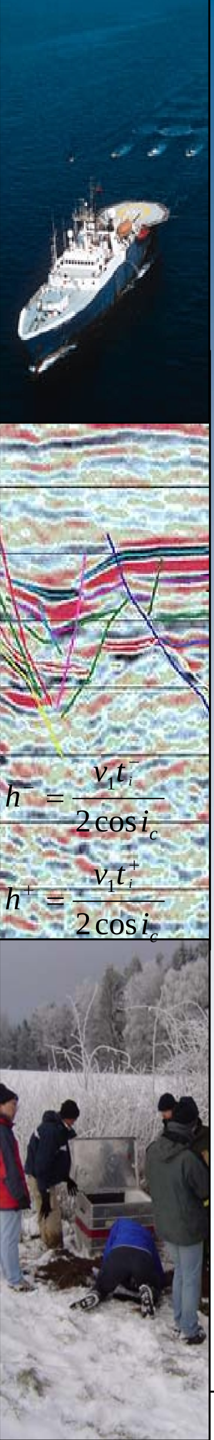
$$t_{refr}^{+} = \frac{2h^{+}\cos i_c}{v_1} + \frac{\sin(i_c - \alpha)}{v_1}\Delta = t_i^{+} + \frac{1}{v_2^{+}}\Delta$$



Geneigte Schicht
Laufzeitkurven



Travel-time diagram for the inclined-layer case for the model in the previous figure.



Inversionproblem

Geneigte Schicht

- Bestimme Geschwindigkeiten v_1 and $v_2^{+/-}$ aus den Steigungen der Laufzeitkurven.

- Bestimme α and v_2 über:

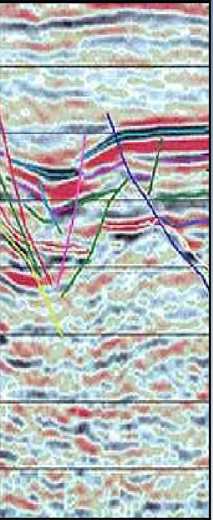
$$\boxed{\begin{aligned} \sin(i_c+\alpha) &= \frac{v_1}{v_2^-} \Rightarrow i_c+\alpha = \arcsin\frac{v_1}{v_2^-} \\ \sin(i_c-\alpha) &= \frac{v_1}{v_2^+} \Rightarrow i_c-\alpha = \arcsin\frac{v_1}{v_2^+} \end{aligned}}$$

$$\boxed{\begin{aligned} \frac{(i+\alpha)+(i-\alpha)}{2} &= i \Rightarrow v_2 = \frac{v_1}{\sin i} \\ \frac{(i+\alpha)-(i-\alpha)}{2} &= \alpha \end{aligned}}$$

- Lies Interzeptzeiten t_i^+ and t_i^- aus den Laufzeitkurven. Bestimme die Distanz von der Schichtgrenze mit

$$\boxed{\begin{aligned} h^- &= \frac{v_1 t_i^-}{2\cos i_c} \\ h^+ &= \frac{v_1 t_i^+}{2\cos i_c} \end{aligned}}$$

- Zeichne Kreise um die Schusspunkte mit Radius $h^{+/-}$ und finde die Tangente dazu -> Schichtgrenze



Der n-Schicht-Fall

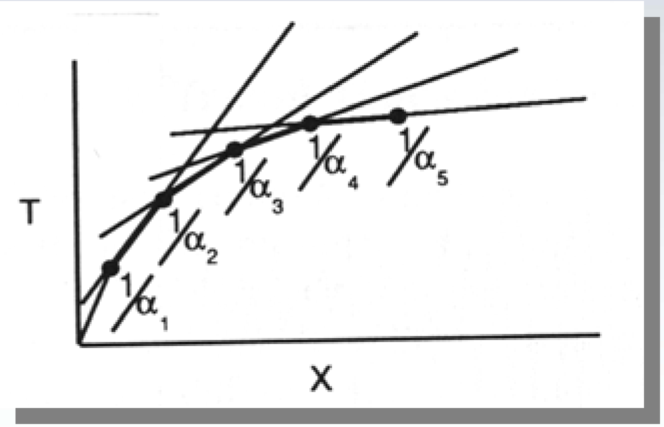
$$t_2 = \frac{2h_1 \cos i_{12}}{v_1} + \frac{\Delta}{v_2} = t^{i2} + \frac{\Delta}{v_2}$$

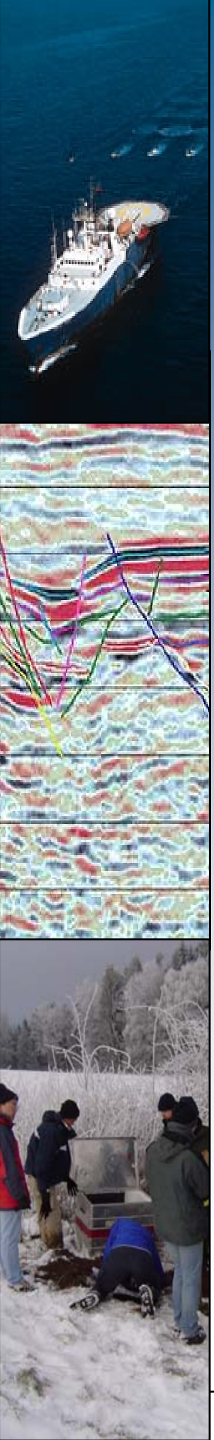
$$t_3 = \underbrace{\frac{2h_1 \cos i_{13}}{v_1} + \frac{2h_2 \cos i_{23}}{v_2}}_{t^{i3}} + \frac{\Delta}{v_3} = t^{i3} + \frac{\Delta}{v_3}$$

Dies lässt sich erweitern auf n Schichten:

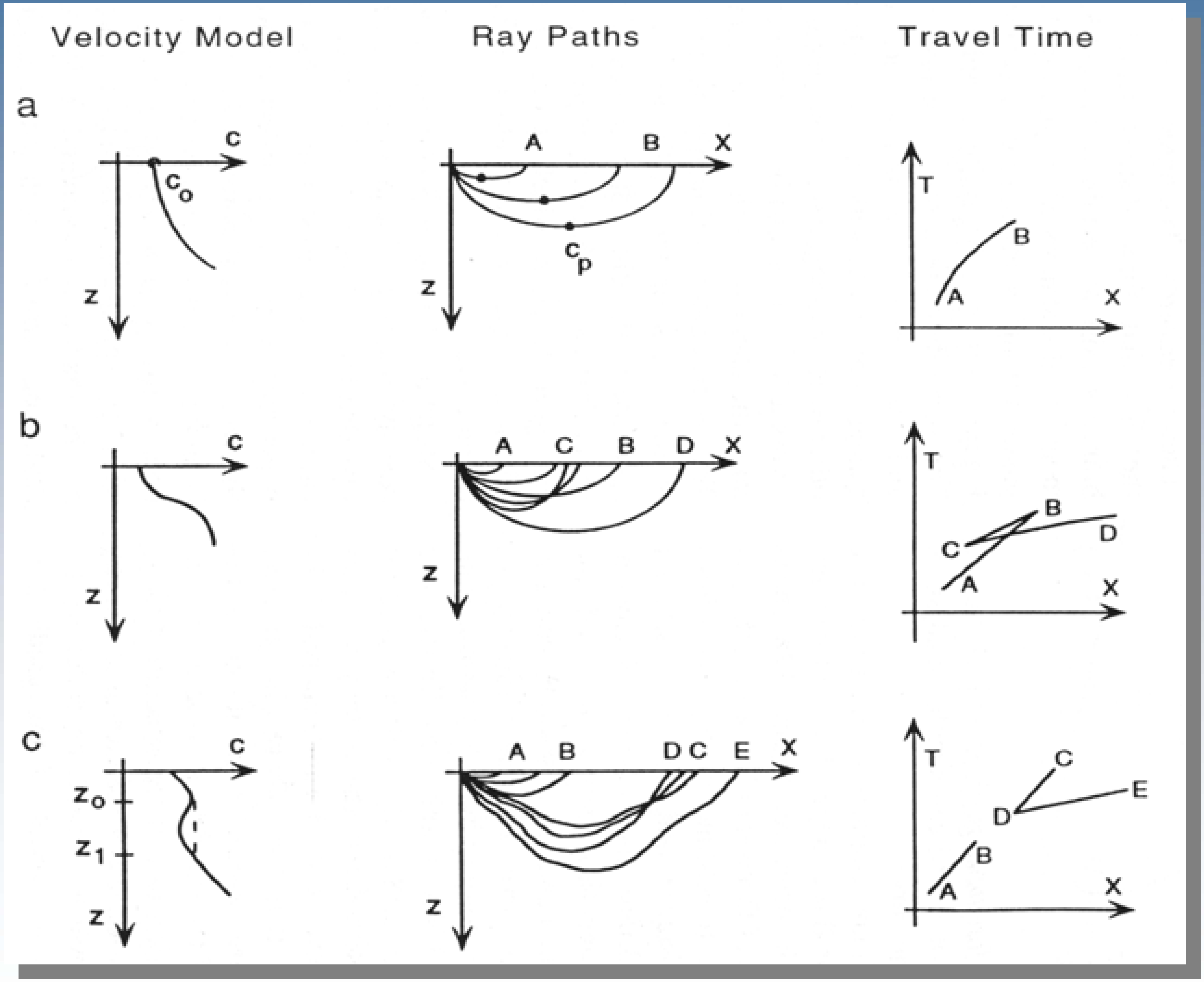
$$t_n = \frac{\Delta}{v_n} + \sum_{i=1}^{n-1} \frac{2h_i \cos i_{in}}{v_i}$$

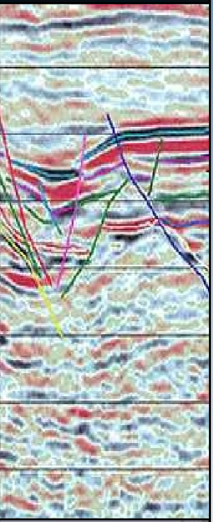
$$i_{in} = \sin^{-1}\left(\frac{v_i}{v_n}\right)$$



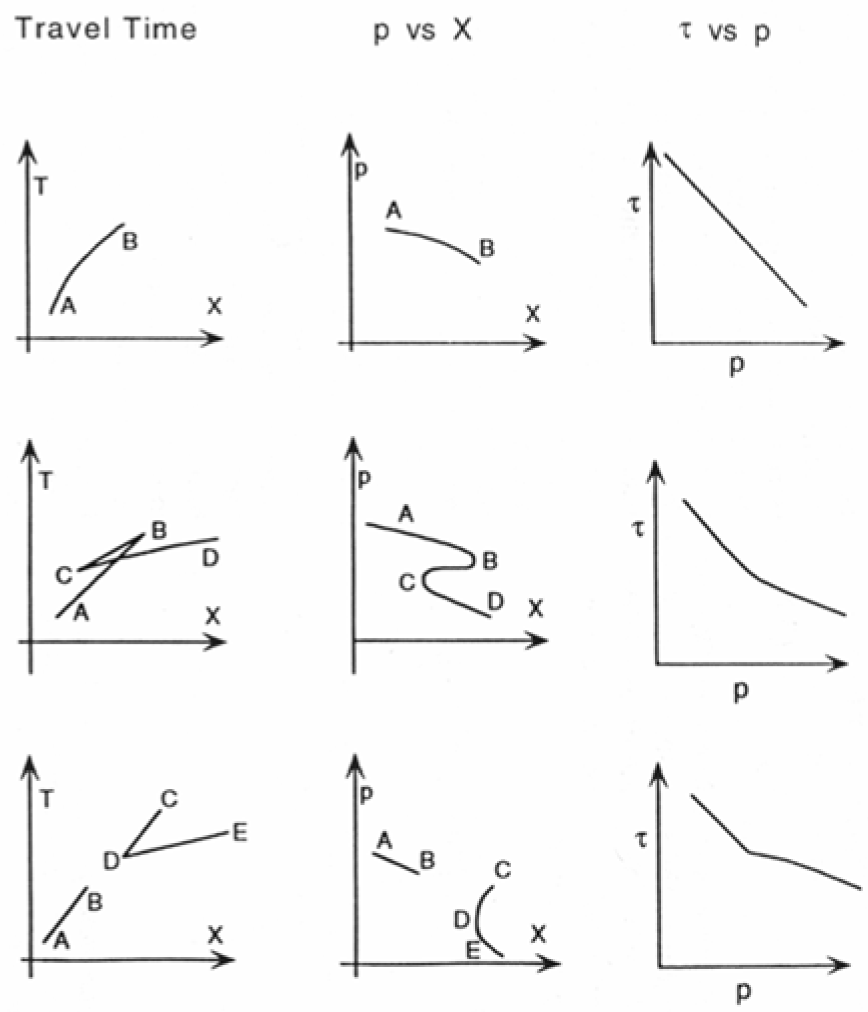


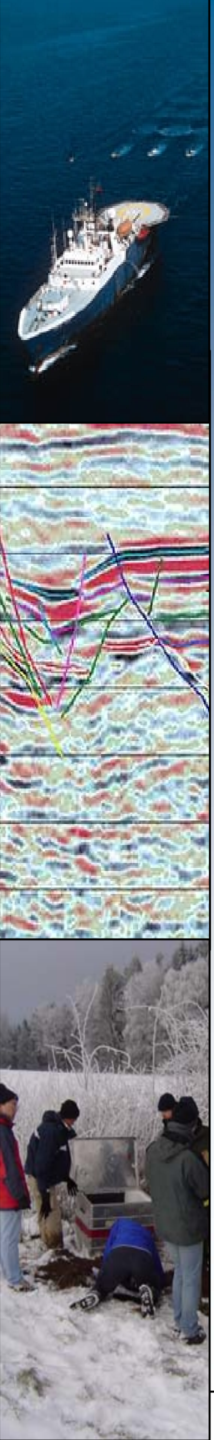
Kontinuierliche Geschwindigkeitsmodelle



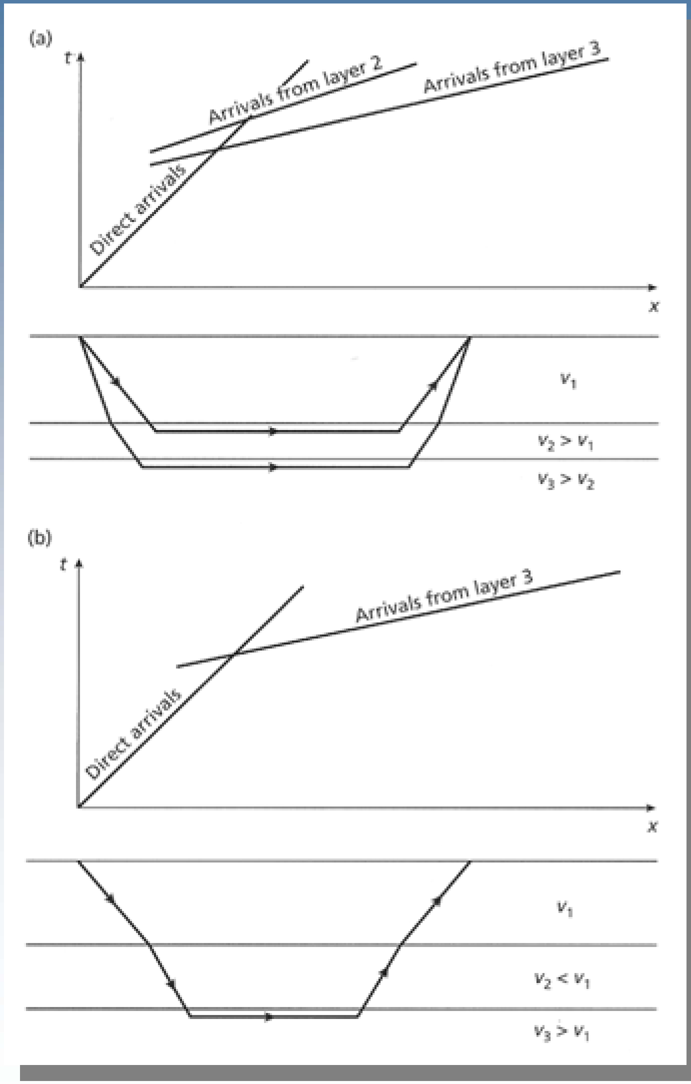


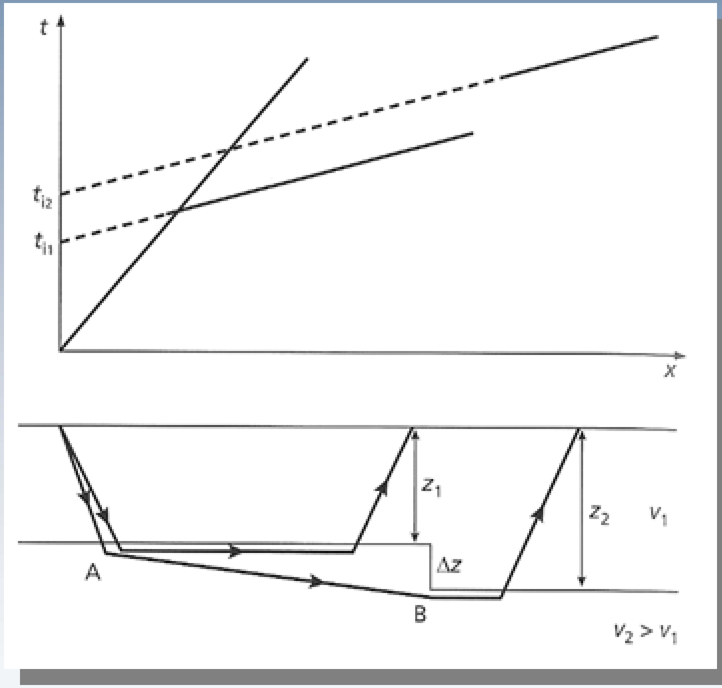
$\tau(p)$ Darstellung

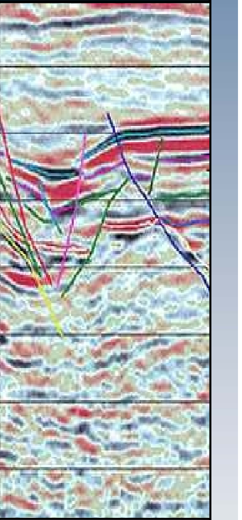




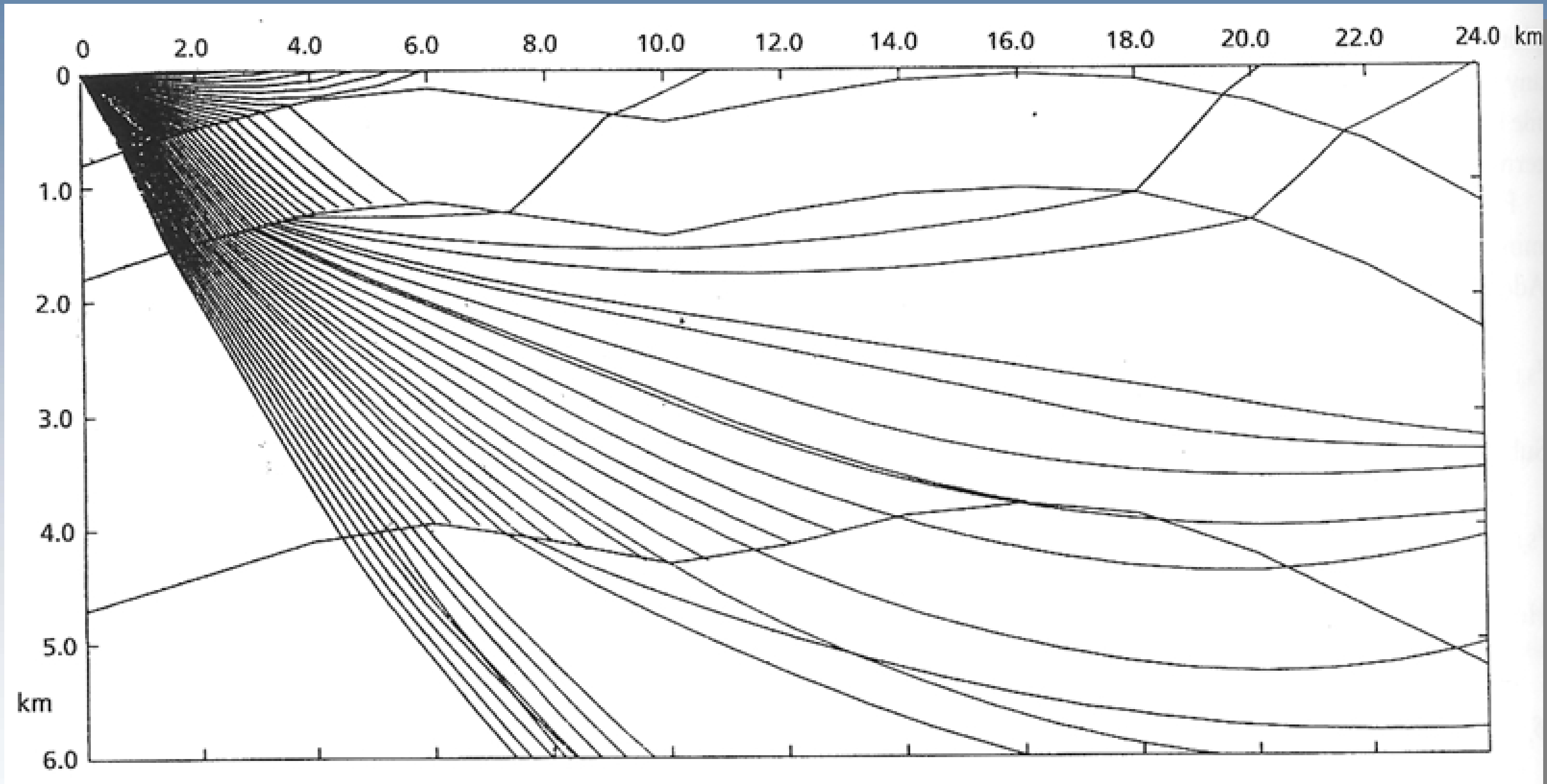
Verborgene Schichten – Verwerfungen



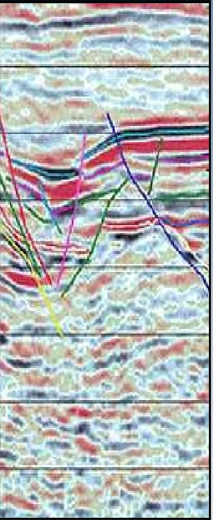


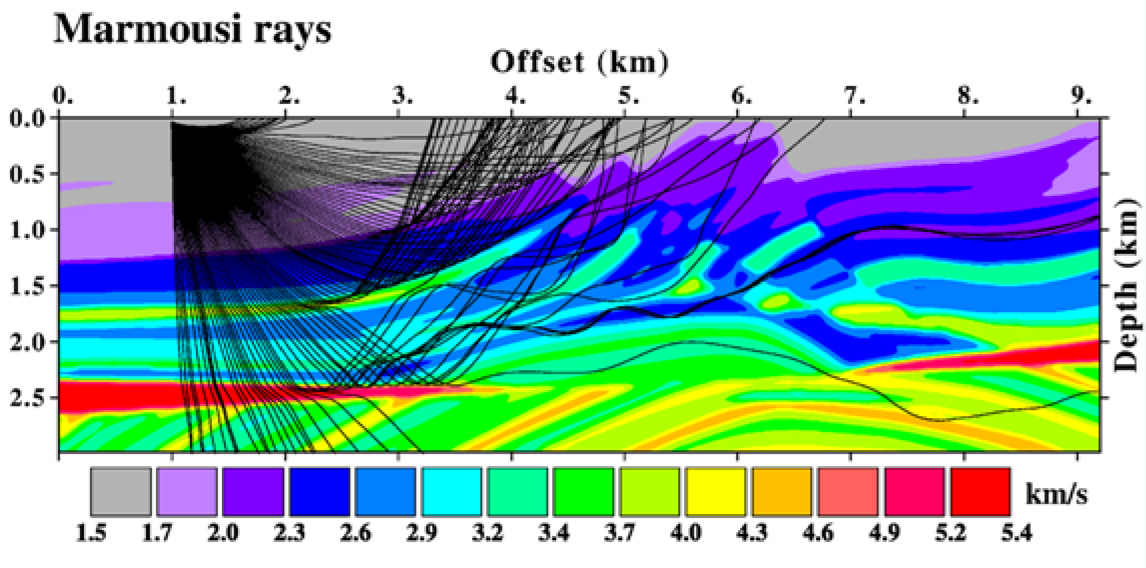


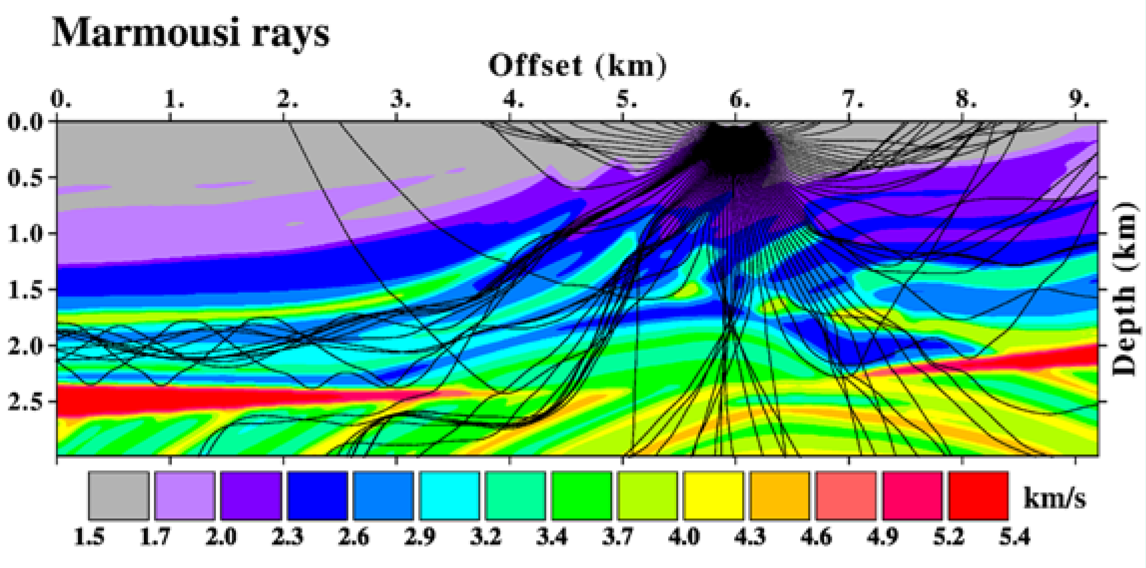
Strahlen in komplexen Modellen

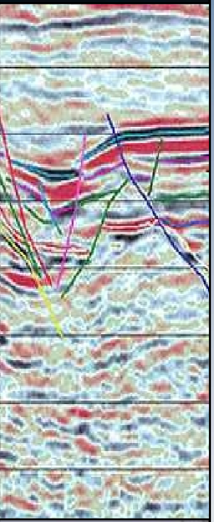


Realistisches Reservoir Modell (Marmousi)

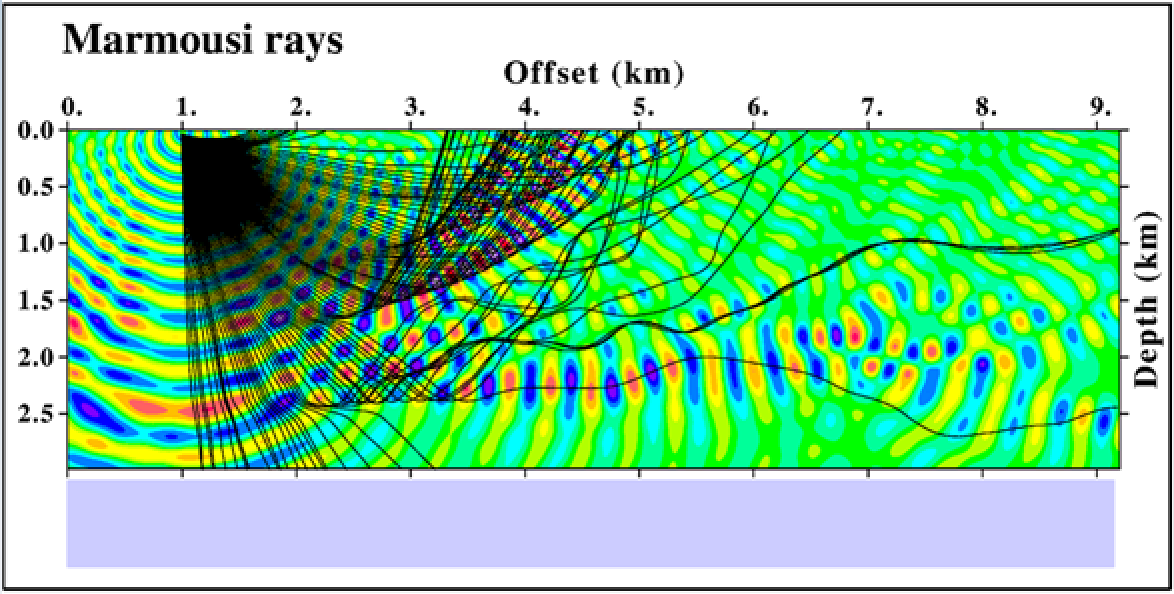


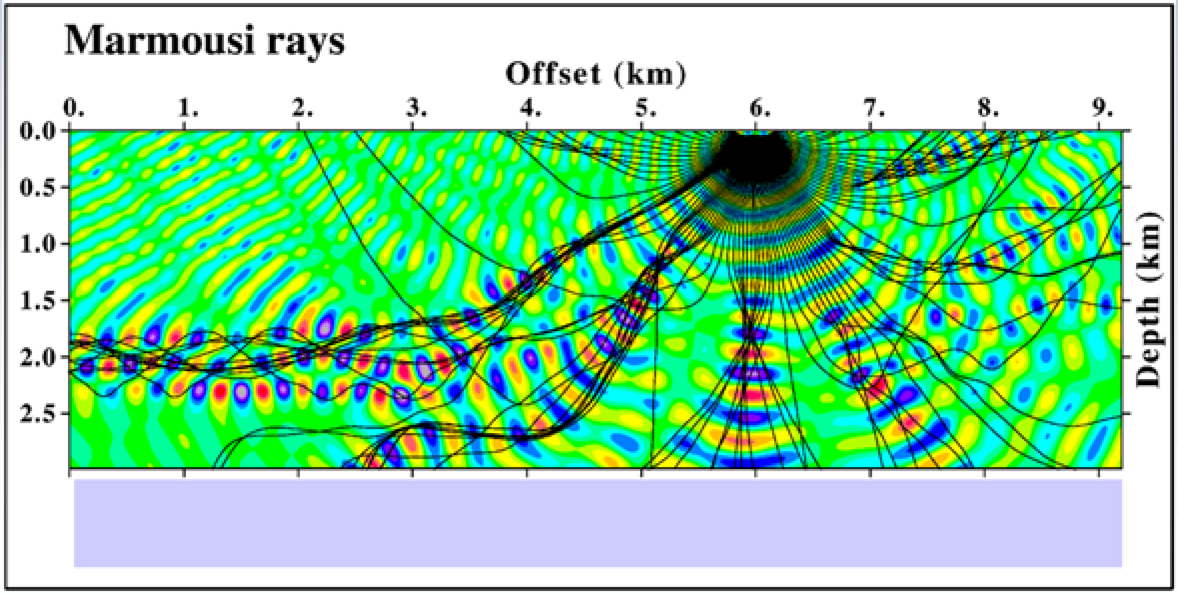


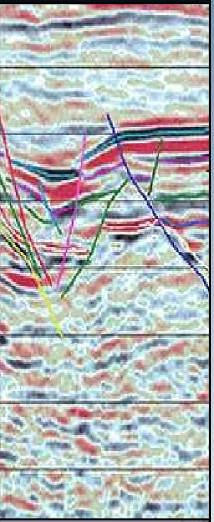




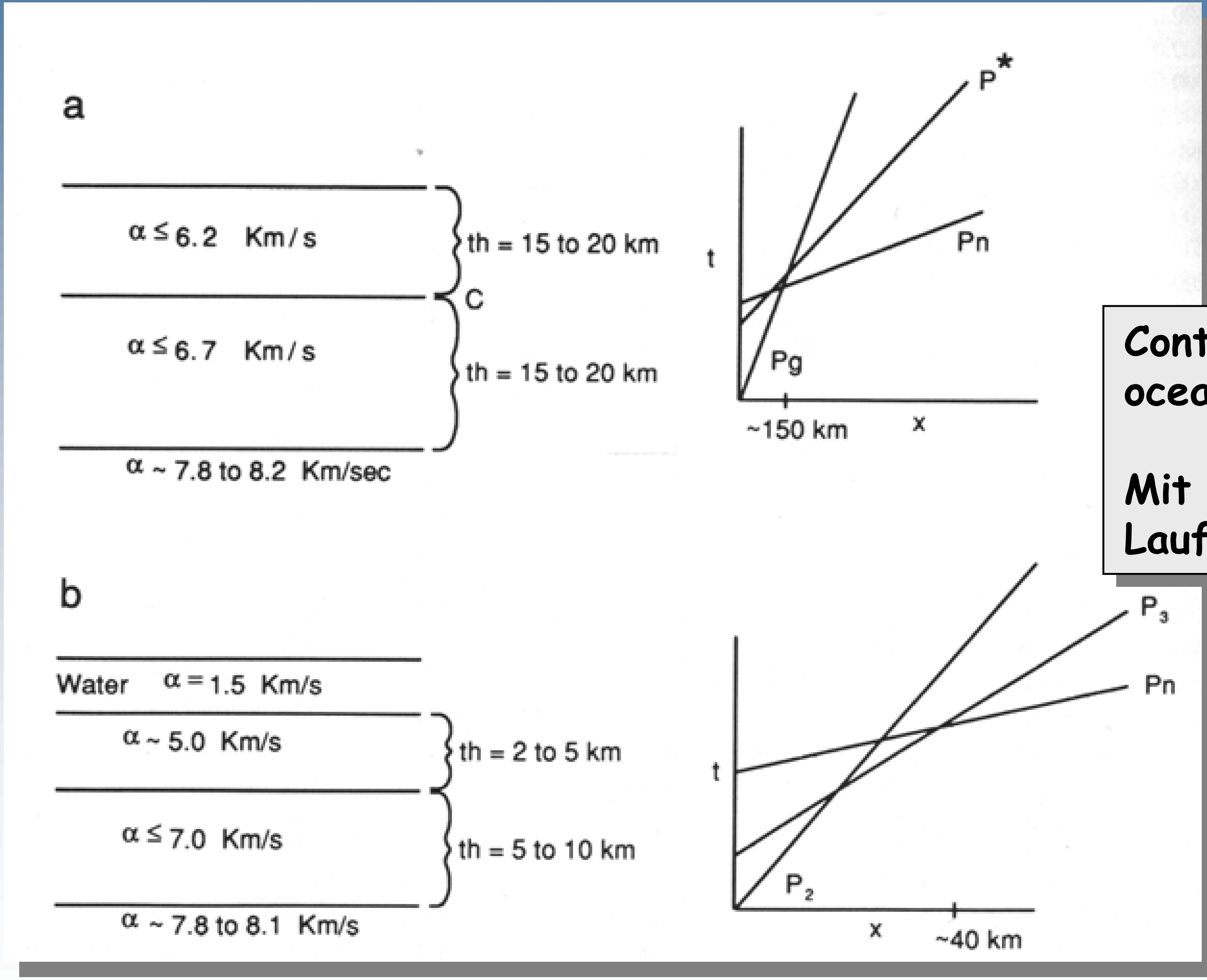
Vergleich mit Simulation





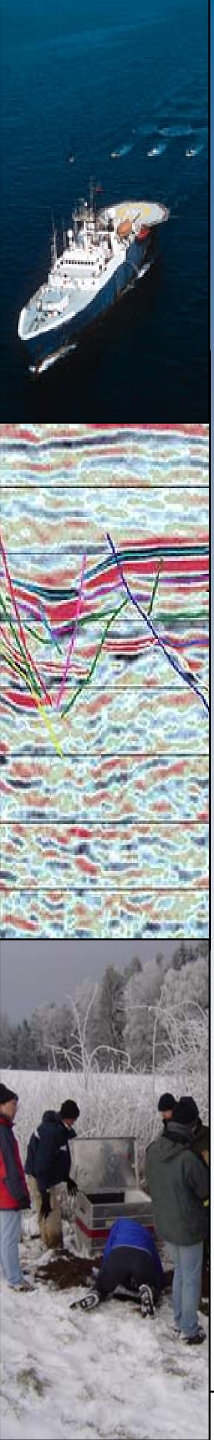


Beispiel: Erdkruste



Continental crust (a)
oceanic crust (b)

Mit entsprechenden Laufzeiten



The Erdkruste: Minerale und Geschwindigkeiten

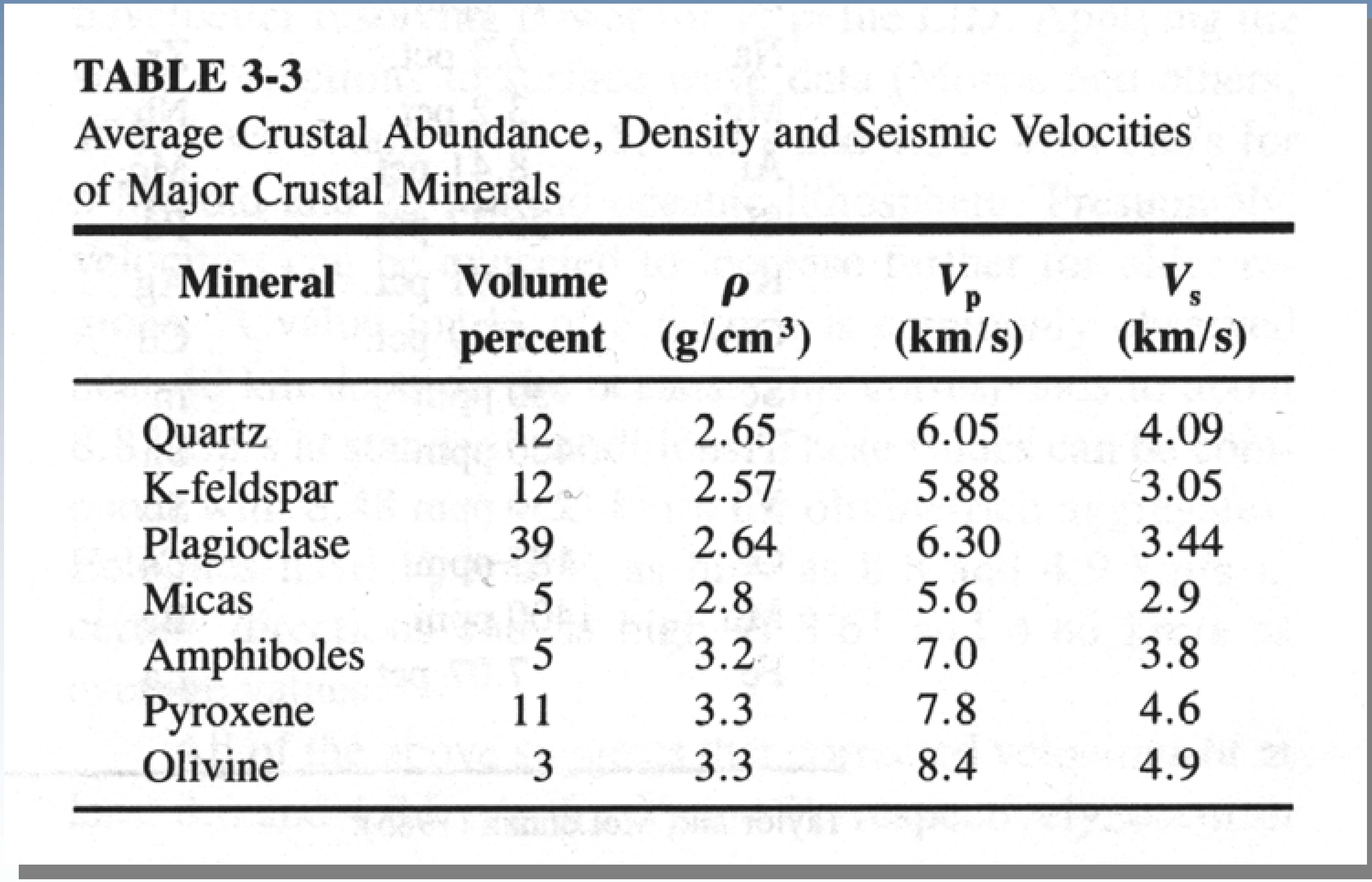
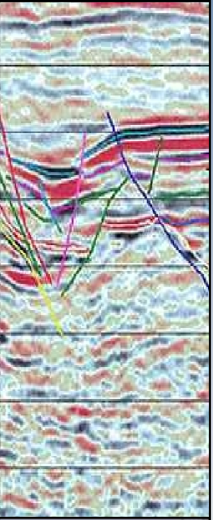


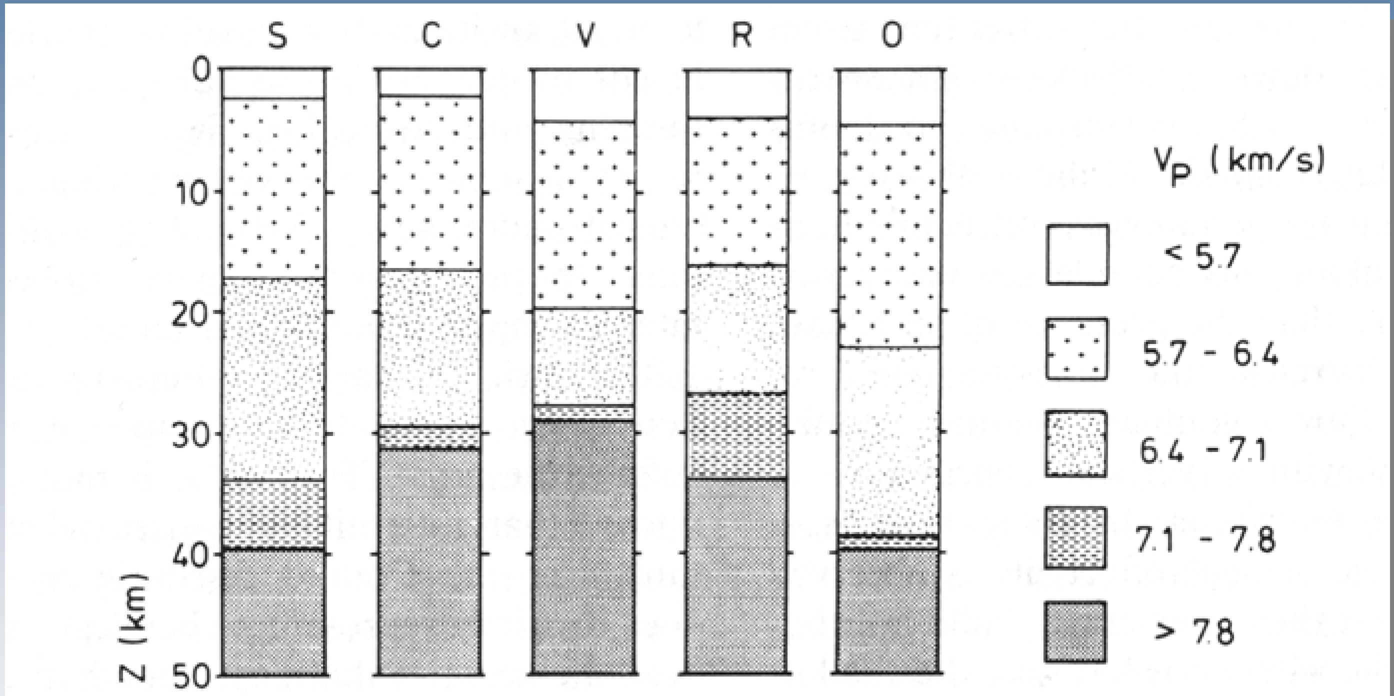
TABLE 3-3

Average Crustal Abundance, Density and Seismic Velocities of Major Crustal Minerals

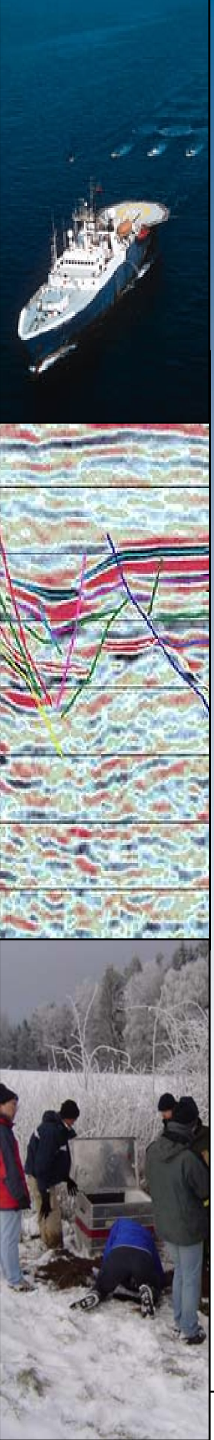
Mineral	Volume percent	ρ (g/cm^3)	V_p (km/s)	V_s (km/s)
Quartz	12	2.65	6.05	4.09
K-feldspar	12	2.57	5.88	3.05
Plagioclase	39	2.64	6.30	3.44
Micas	5	2.8	5.6	2.9
Amphiboles	5	3.2	7.0	3.8
Pyroxene	11	3.3	7.8	4.6
Olivine	3	3.3	8.4	4.9



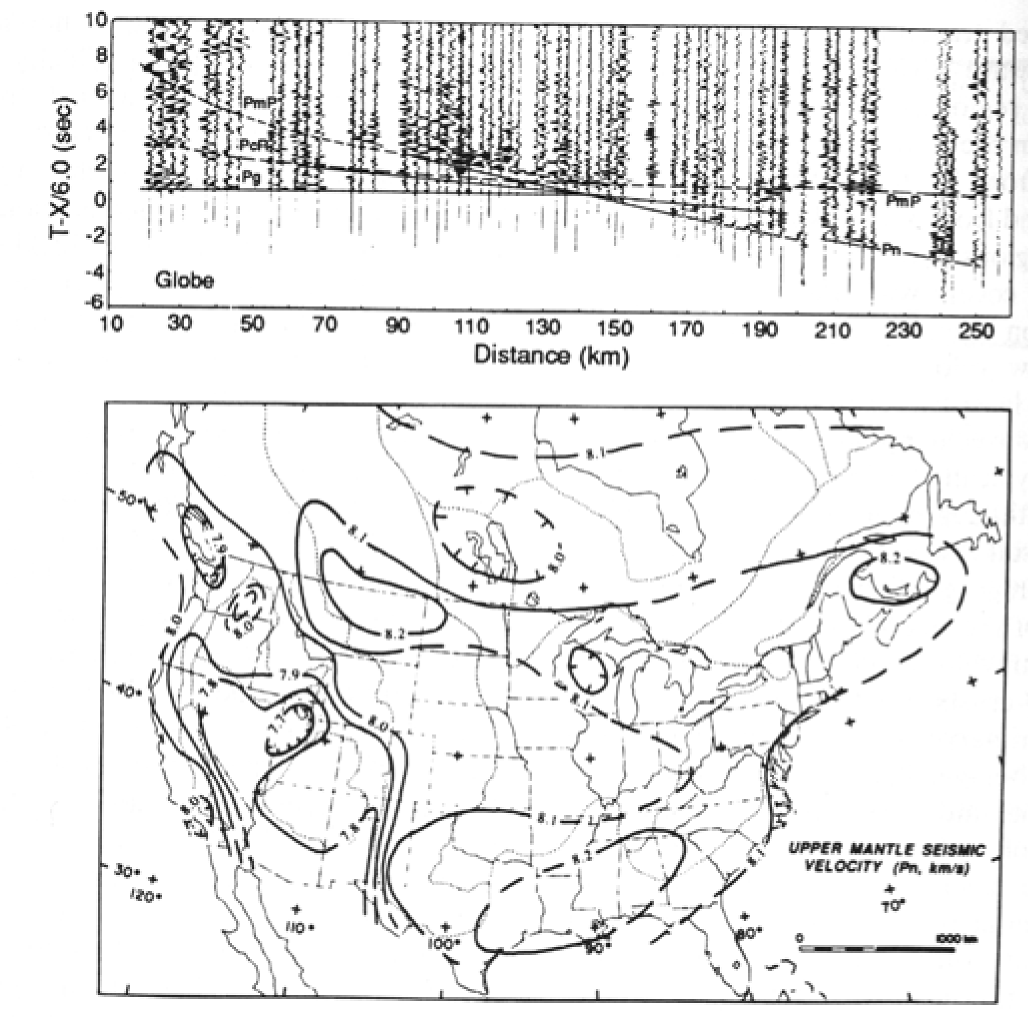
Erdkruste: Typen



S shields, C Caledonian provinces, V Variscan provinces, R rifts, O orogens

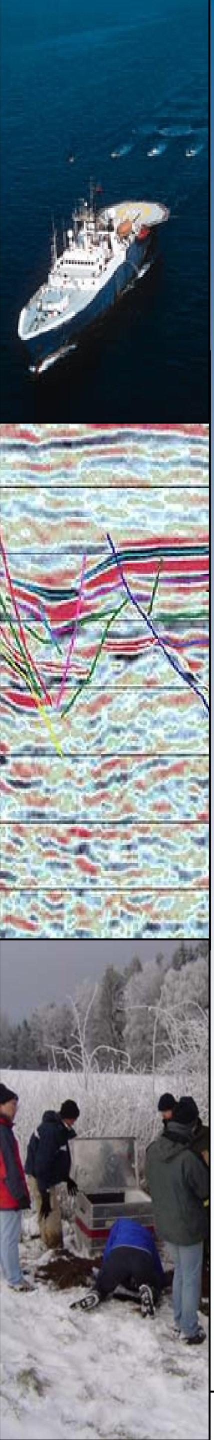


Die Erdkruste:
Refraktionsexperimente

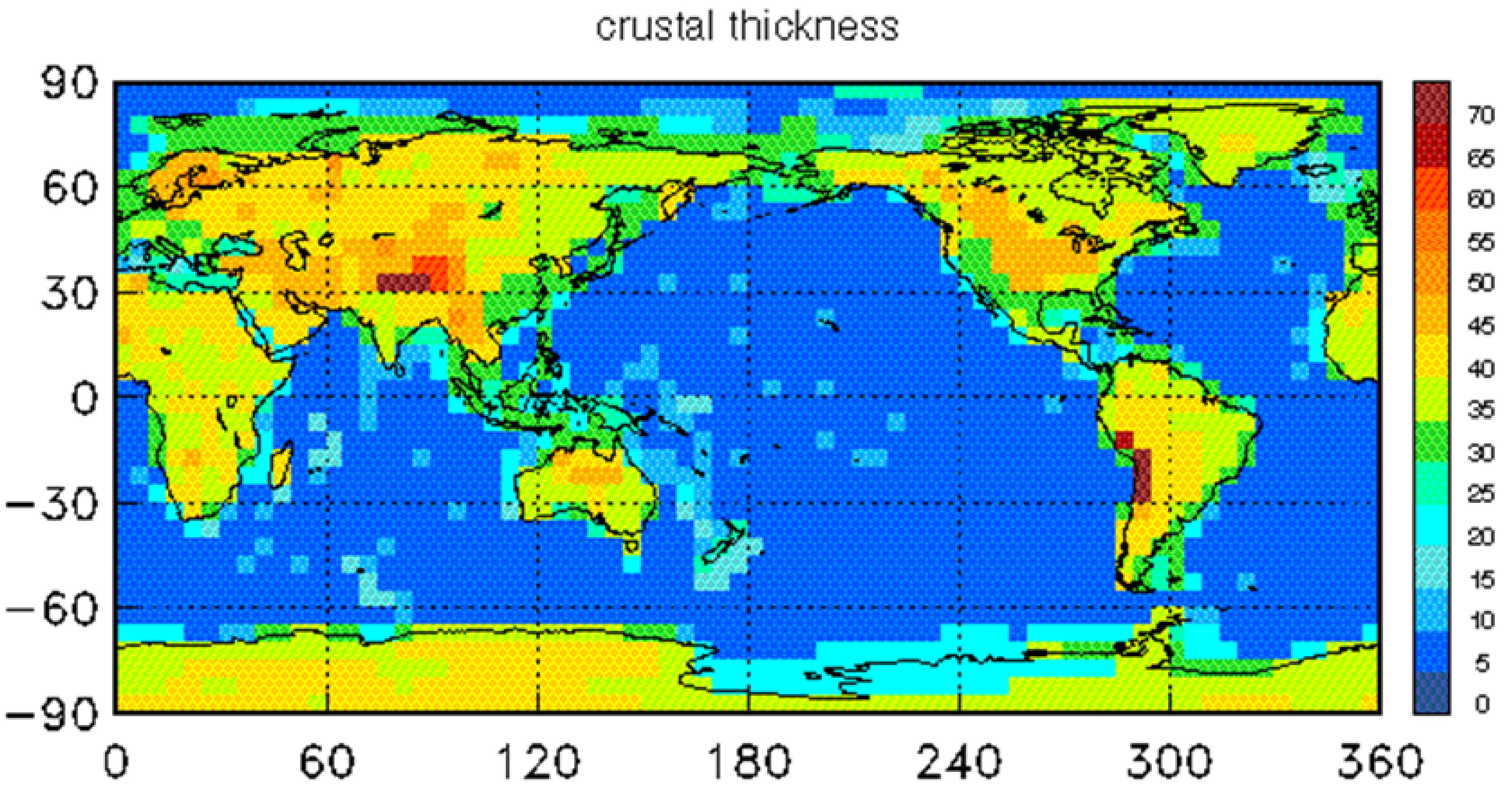


Profil über N-Amerika:

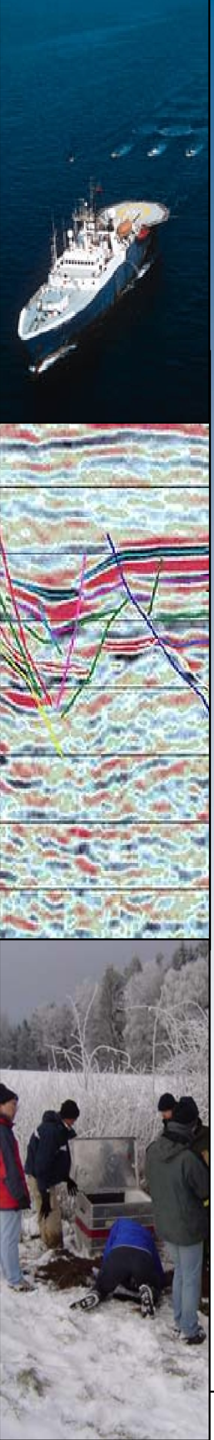
PmP Moho Reflektion
Pn Moho Refraktion
Pg Direkte P-Welle



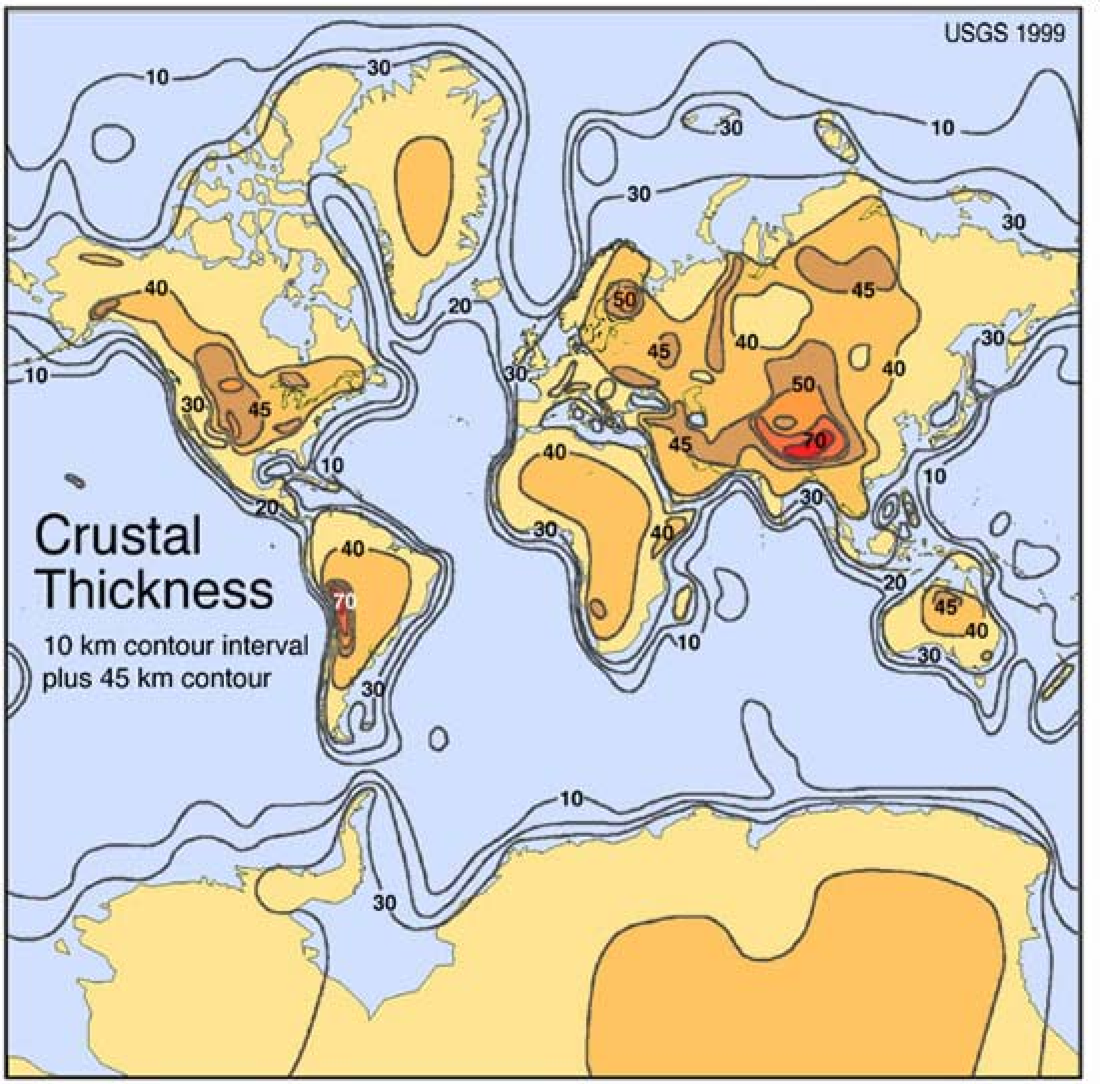
Globales Krustenmodell

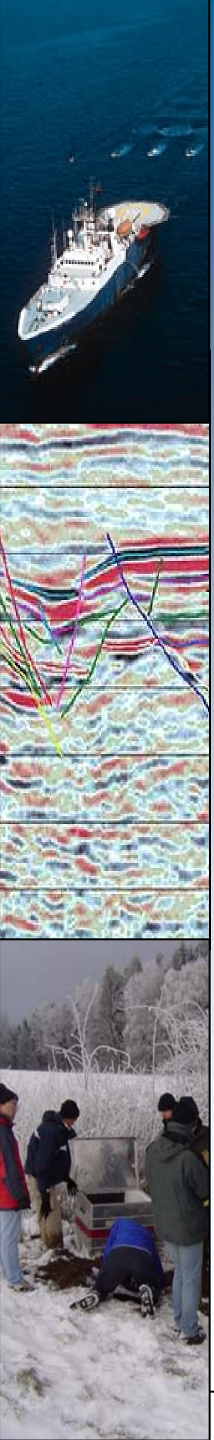


Krustendicke in km kompiliert aus seismischen Daten

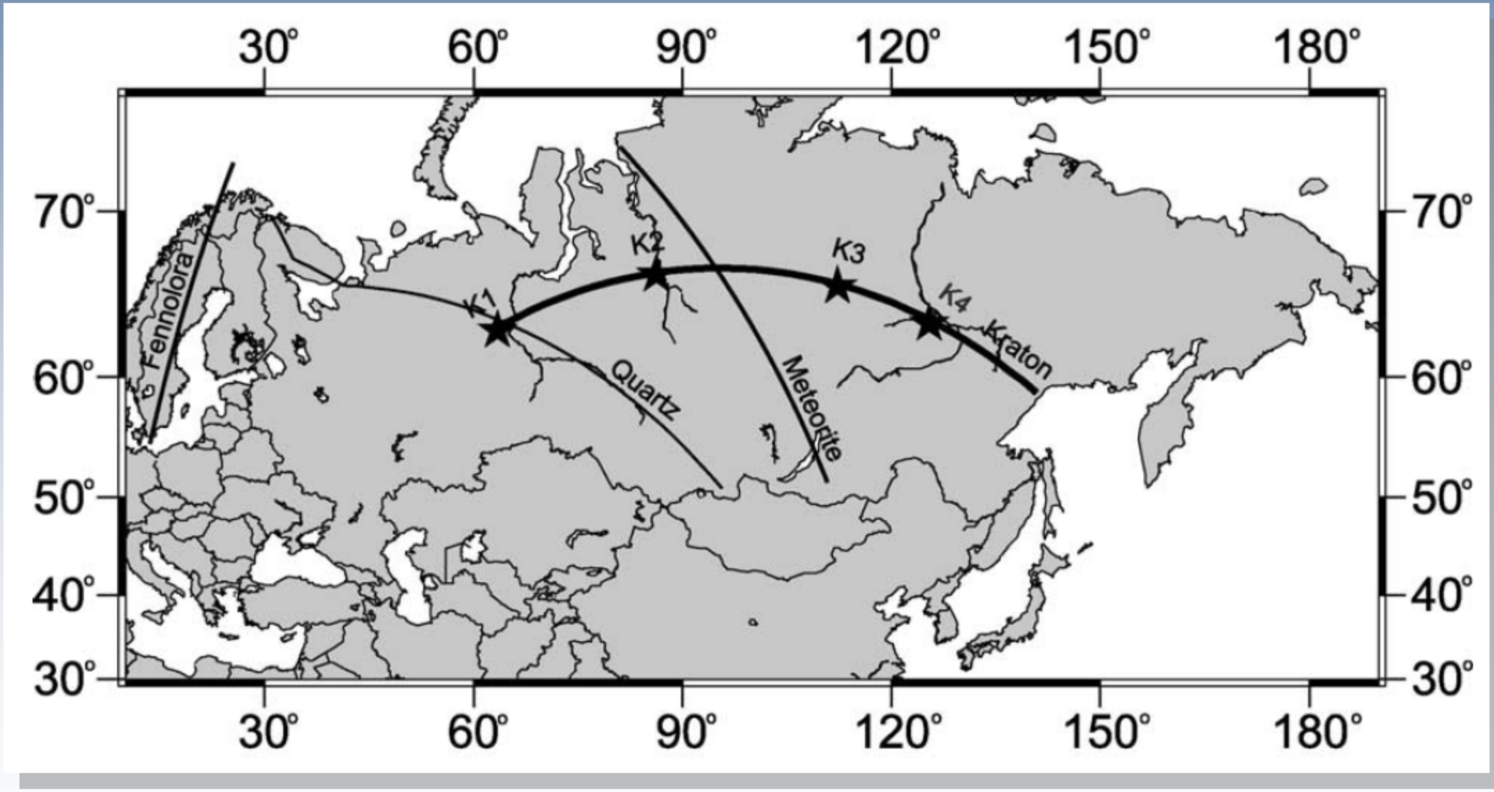


Moho Depth

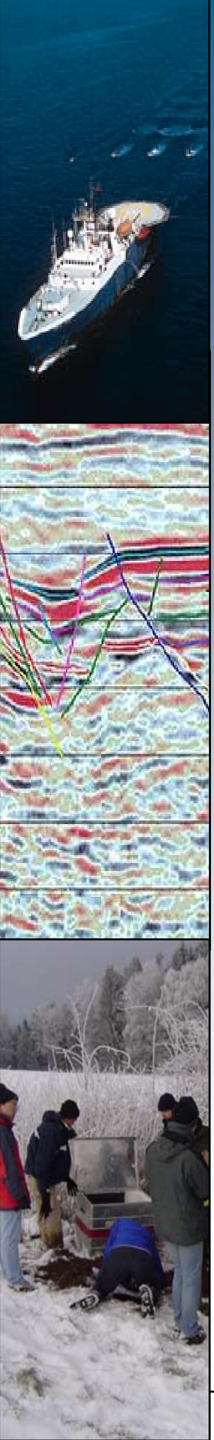

USGS 1999
Crustal Thickness
10 km contour interval
plus 45 km contour
10
30
20
40
45
50
70



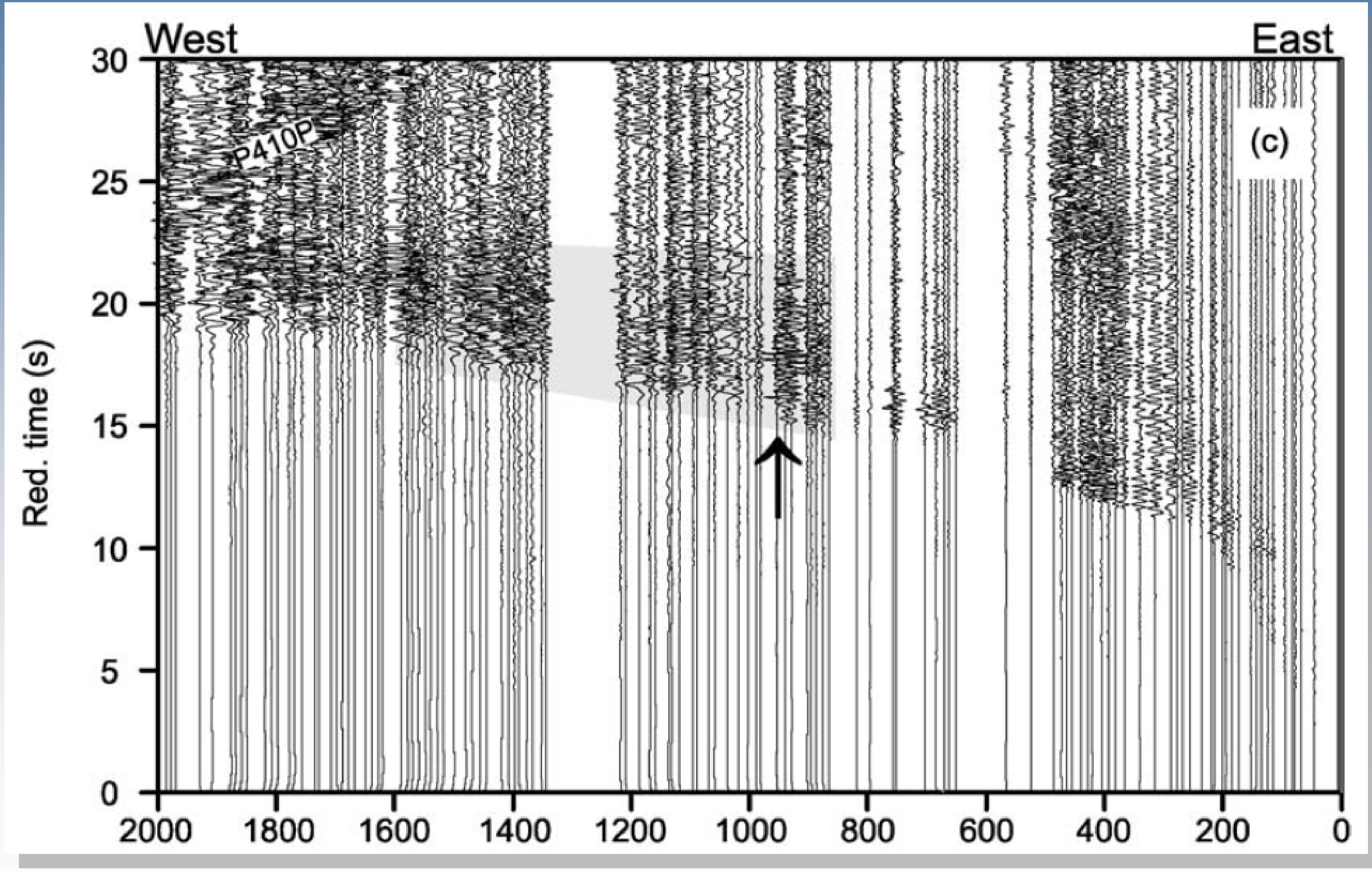
Peaceful nuclear explosions (PNEs)

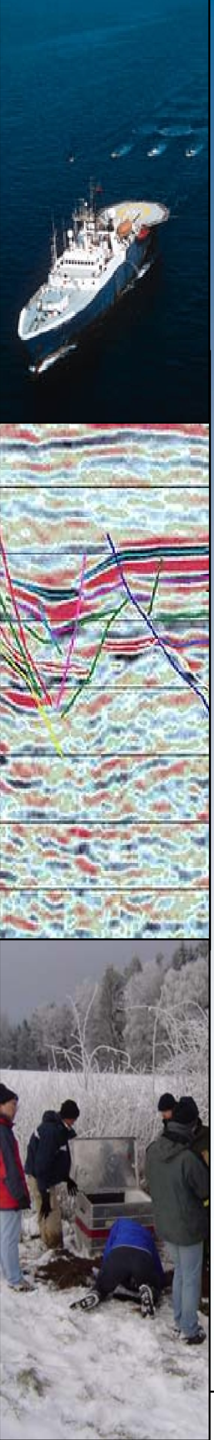


PNE figures from Nielsen et al. 2002

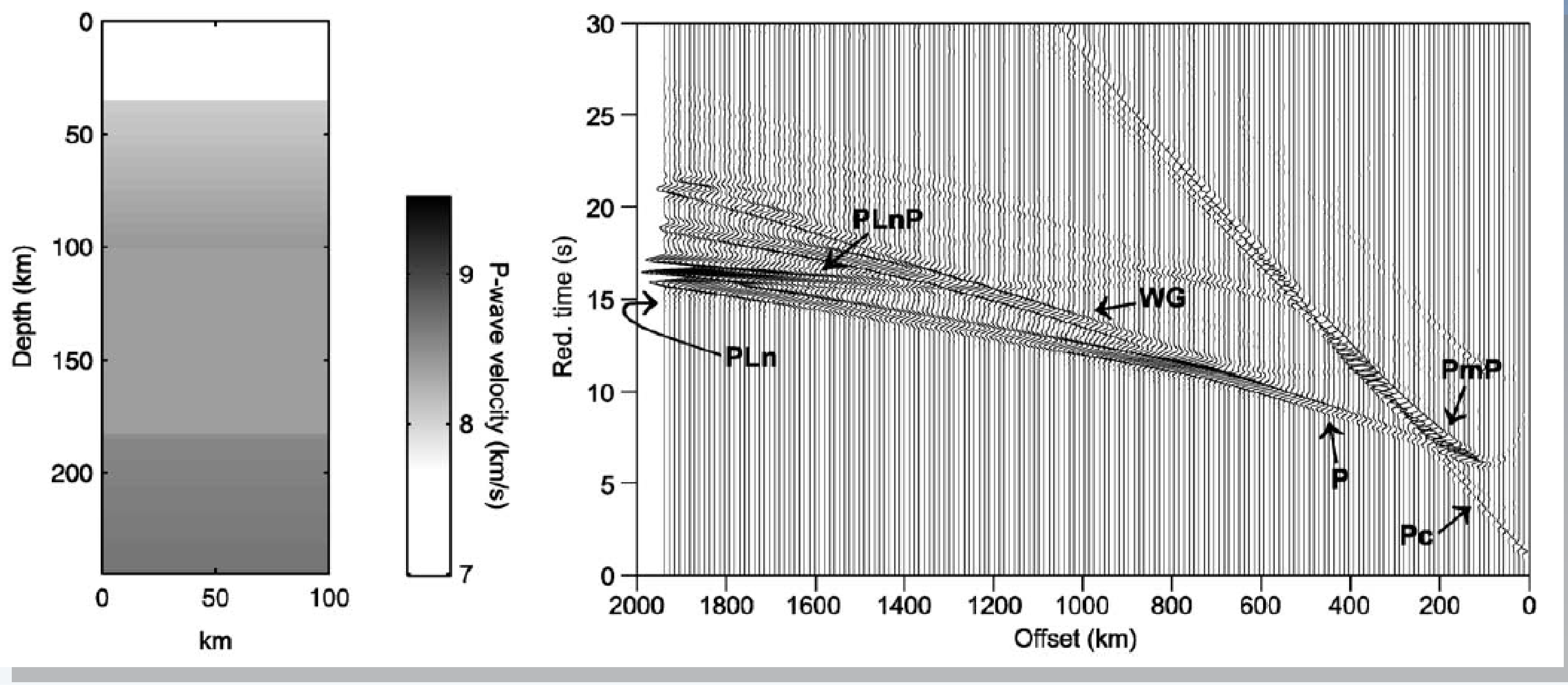


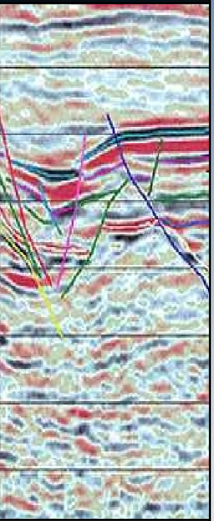
Seismograms



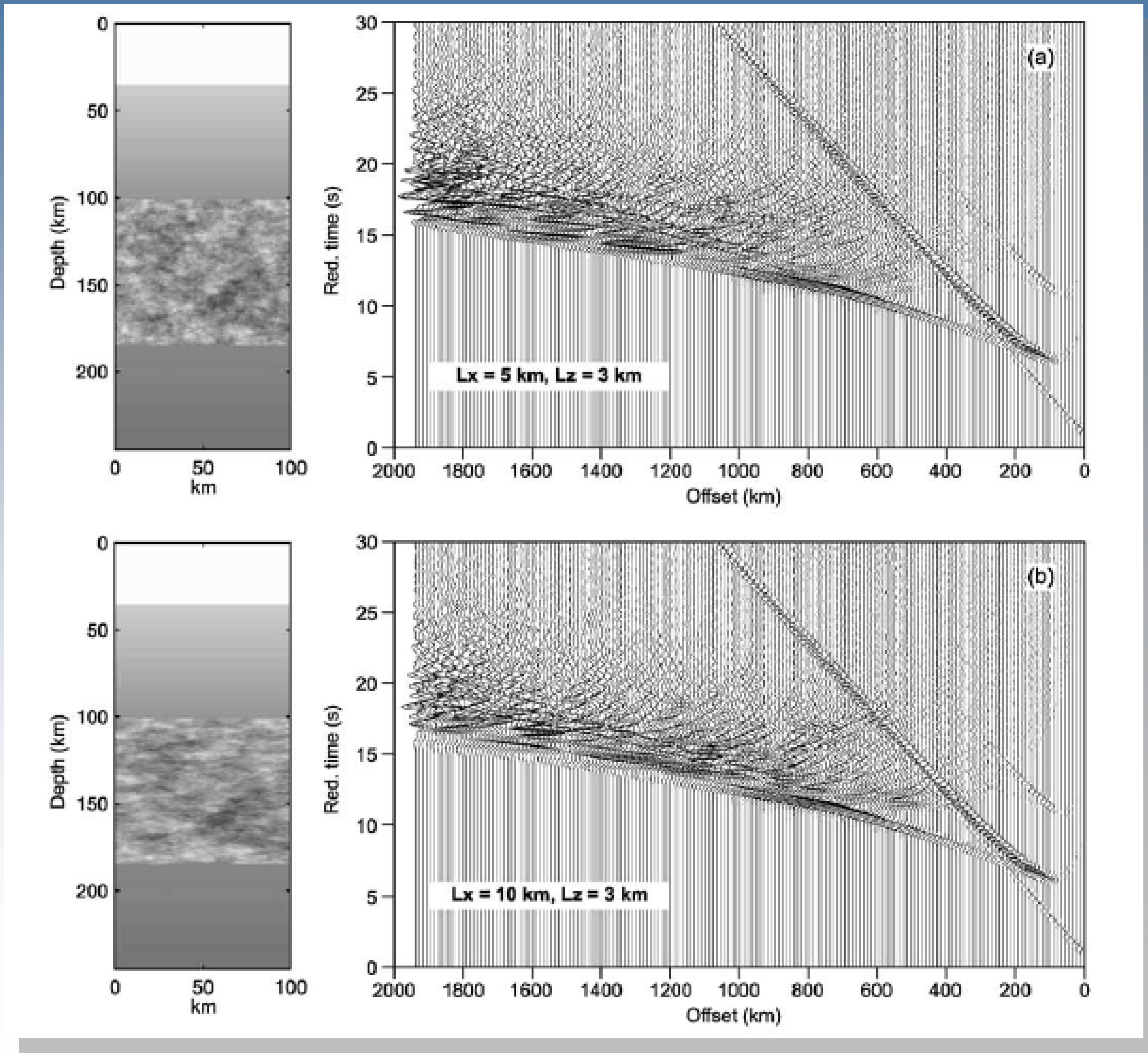


Synthetic seismograms

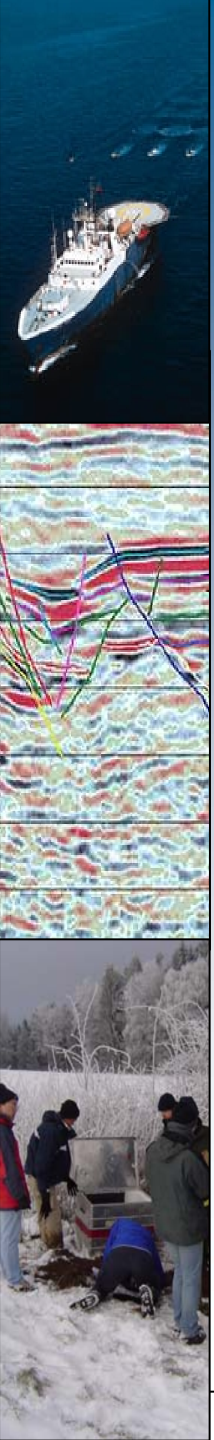


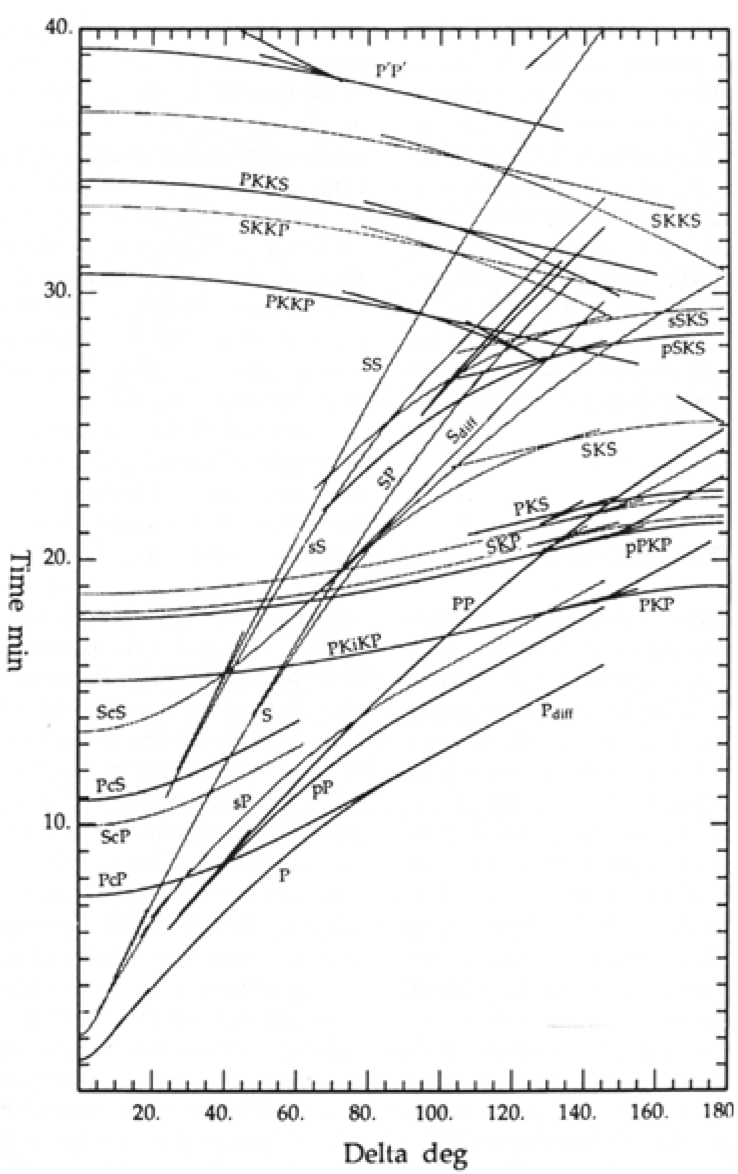


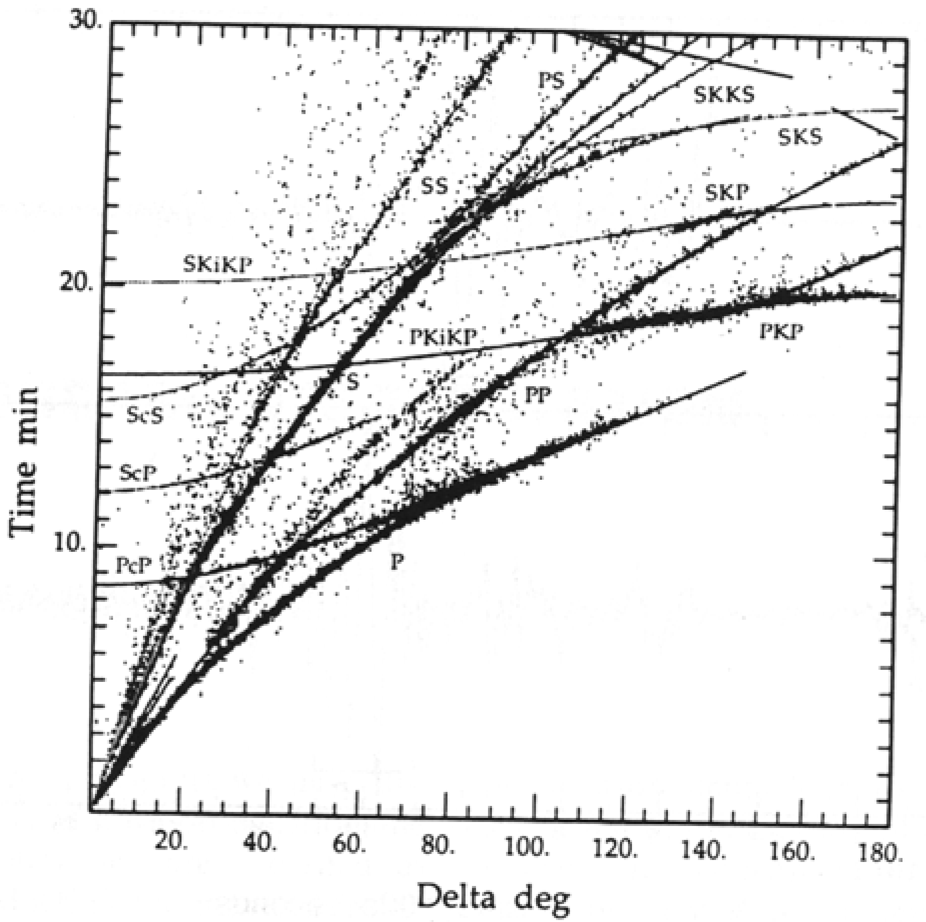
Modelling with random media

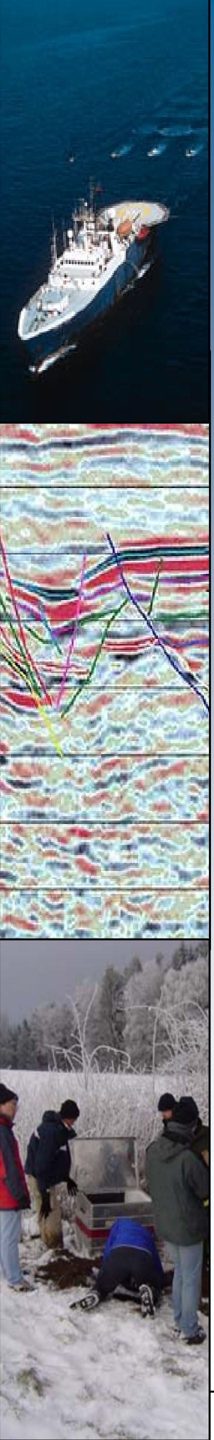


Globale Seismologie
Laufzeiten









Seismische Tomographie

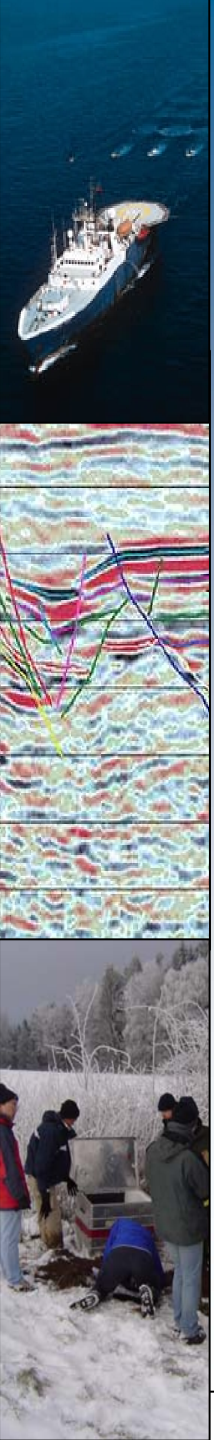
.

Angenommen wir haben eine Menge Laufzeitmessungen (verschiedene Messstationen, verschiedene Erdbeben, verschiedene seismische Phasen)

Im Allgemeinen suchen wir das Erdmodell m, welches die Differenz der beobachteten mit den berechneten Laufzeiten minimiert

$$\sum_{traveltimes} T_{obs} - T_{theory}(m) = Min!$$

Für kugelsymmetrische Medien kann dieses Problem analytisch gelöst werden.

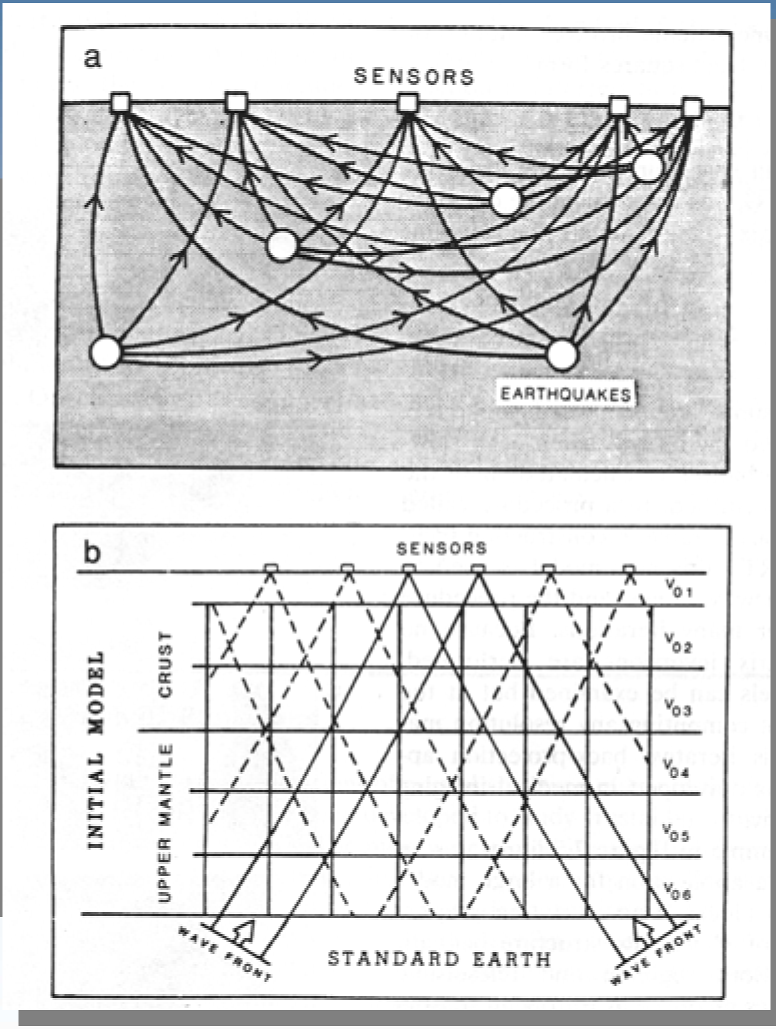


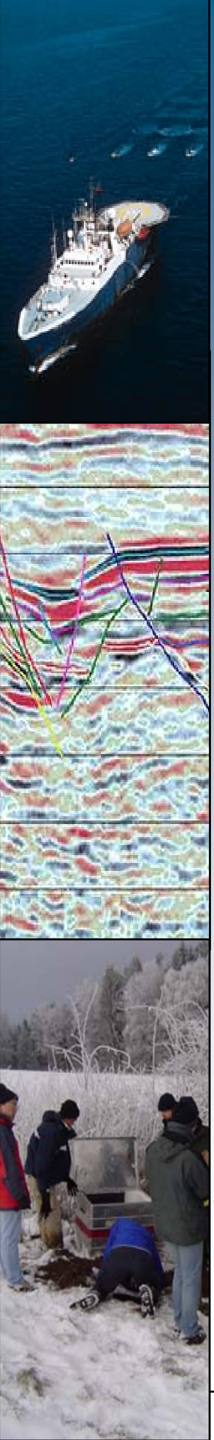
Seismische Tomographie

Die 3D Variationen der seismischen Geschwindigkeiten enthalten wertvolle Informationen über die Dynamik des Erdinnen.

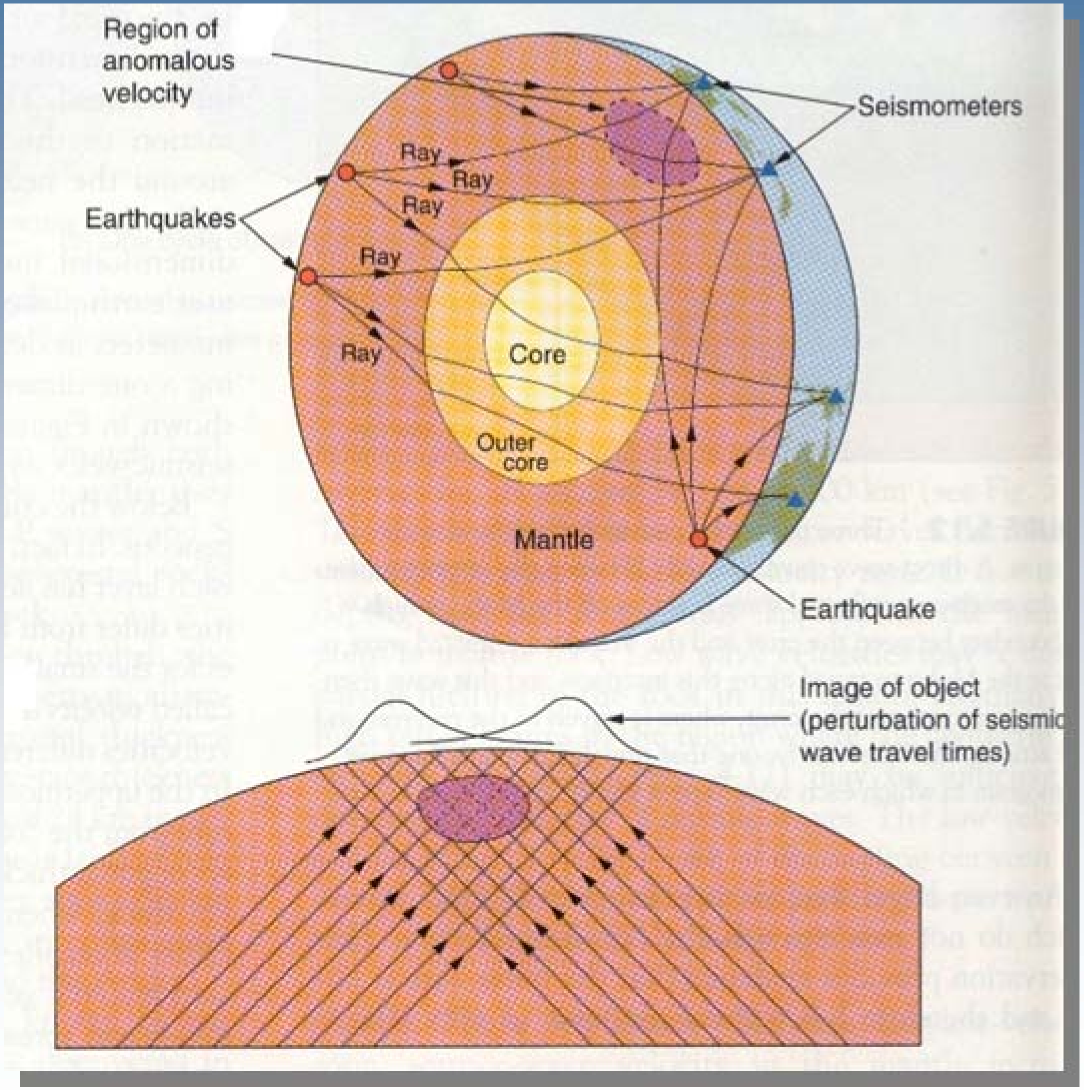
Seismische Tomographie zielt darauf ab, die Perturbationen der Geschwindigkeiten um ein Referenzmodell zu finden.

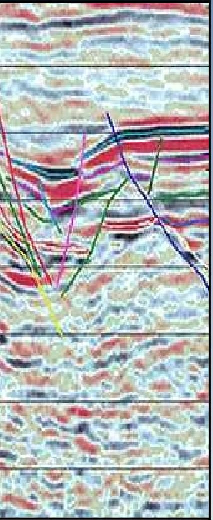
Gibt es Unterschiede zur medizinischen Tomographie?



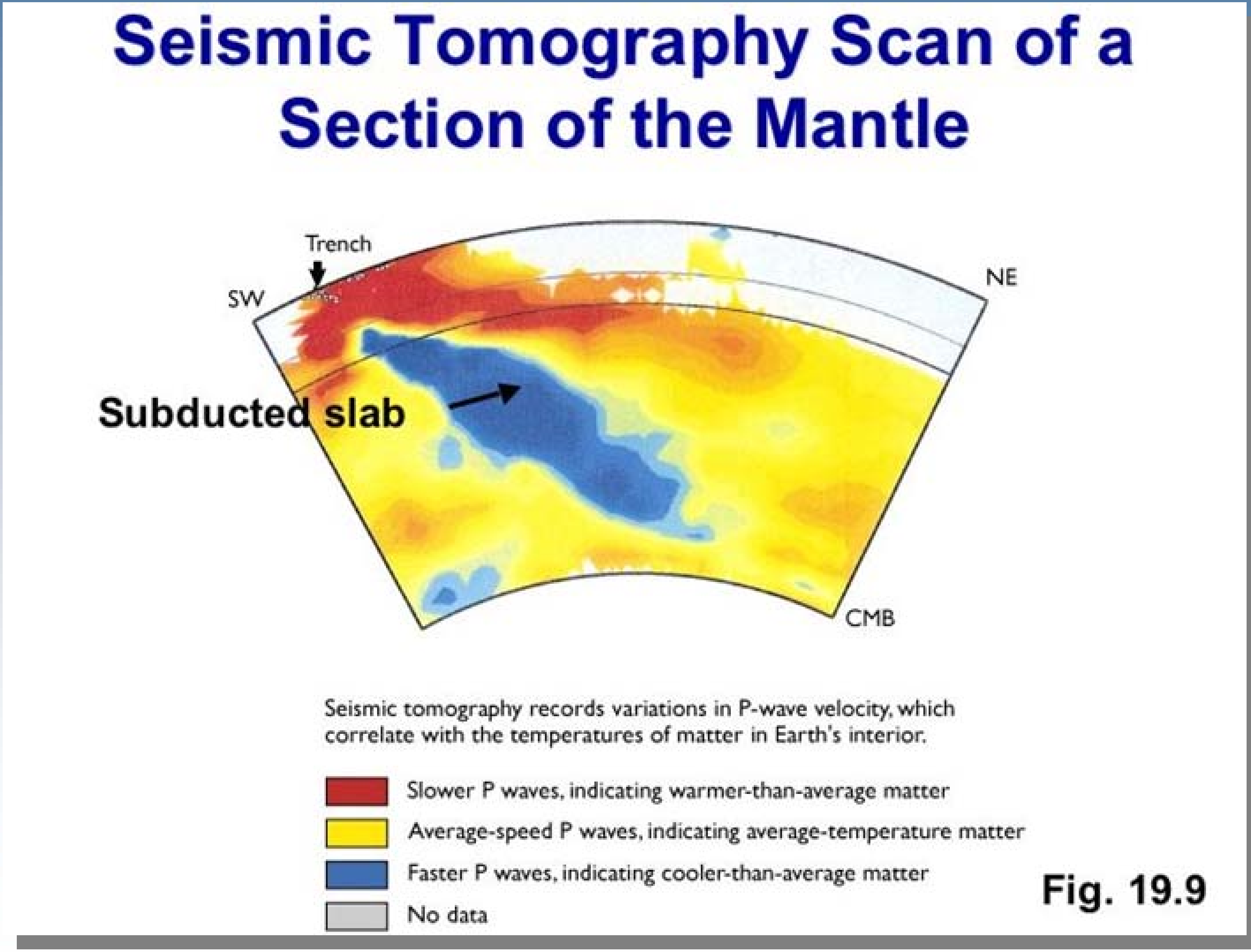


Globale Tomographie





Beispiel

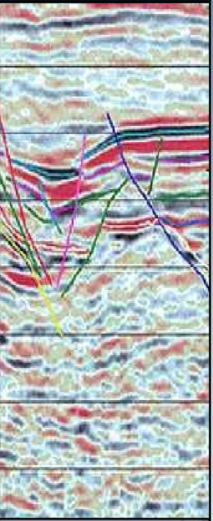


Seismic Tomography Scan of a Section of the Mantle

Seismic tomography records variations in P-wave velocity, which correlate with the temperatures of matter in Earth's interior.

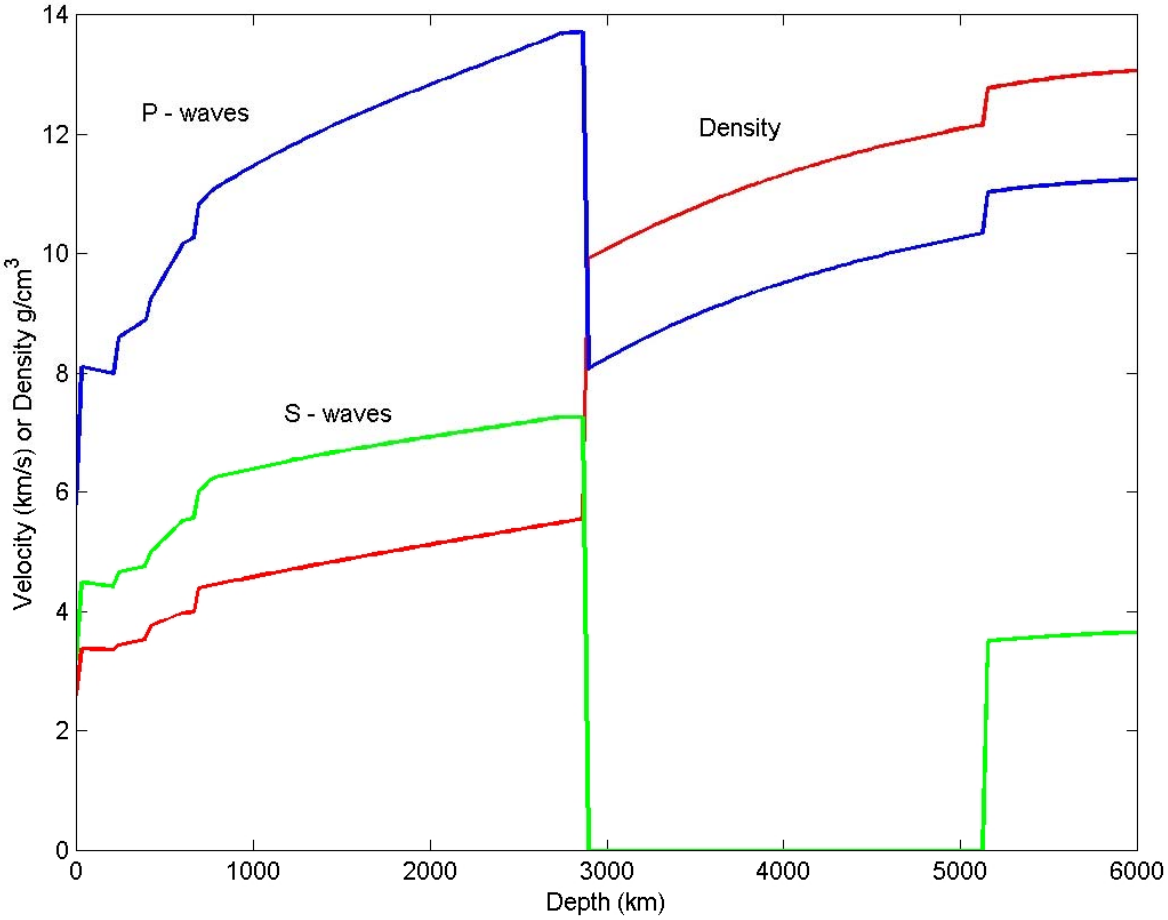
- 🟥 Slower P waves, indicating warmer-than-average matter
- 🟨 Average-speed P waves, indicating average-temperature matter
- 🟦 Faster P waves, indicating cooler-than-average matter
- ⬜ No data

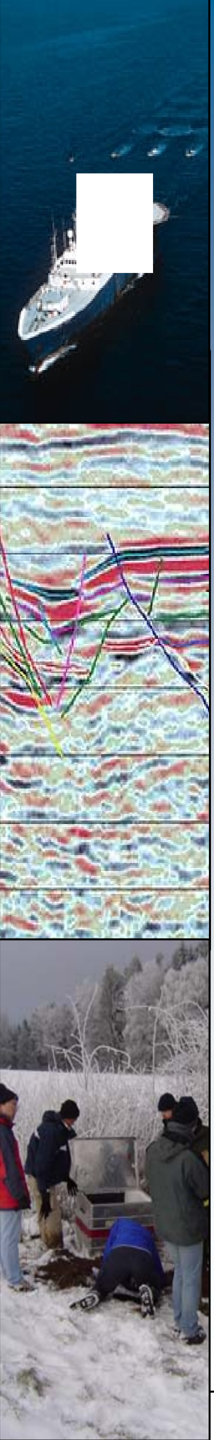
Fig. 19.9



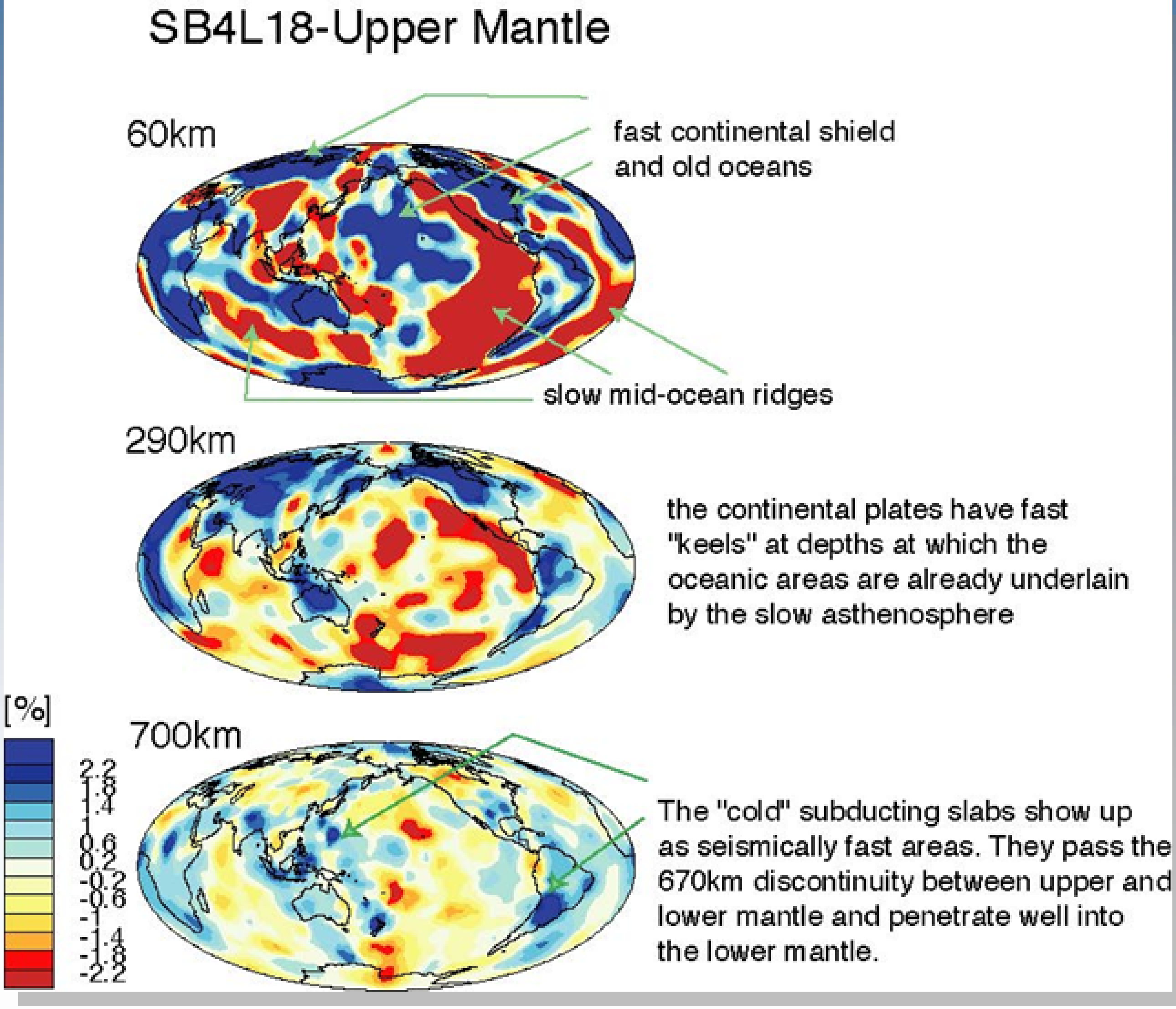
PREM: velocities and density

PREM: Preliminary Reference Earth Model (Dziewonski and Anderson, 1981)





Upper mantle: 3-D structure

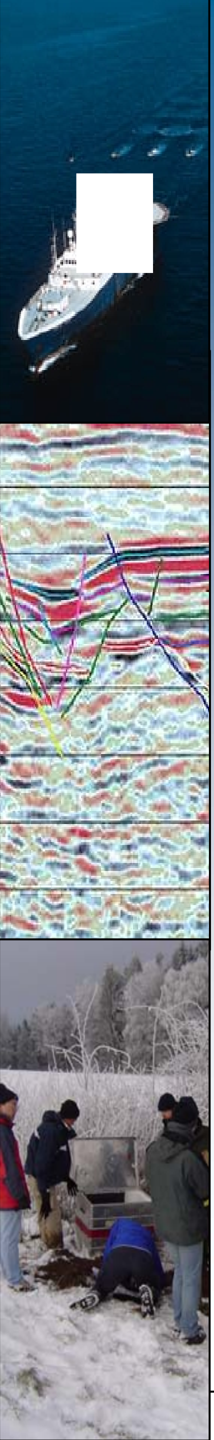


fast continental shield and old oceans

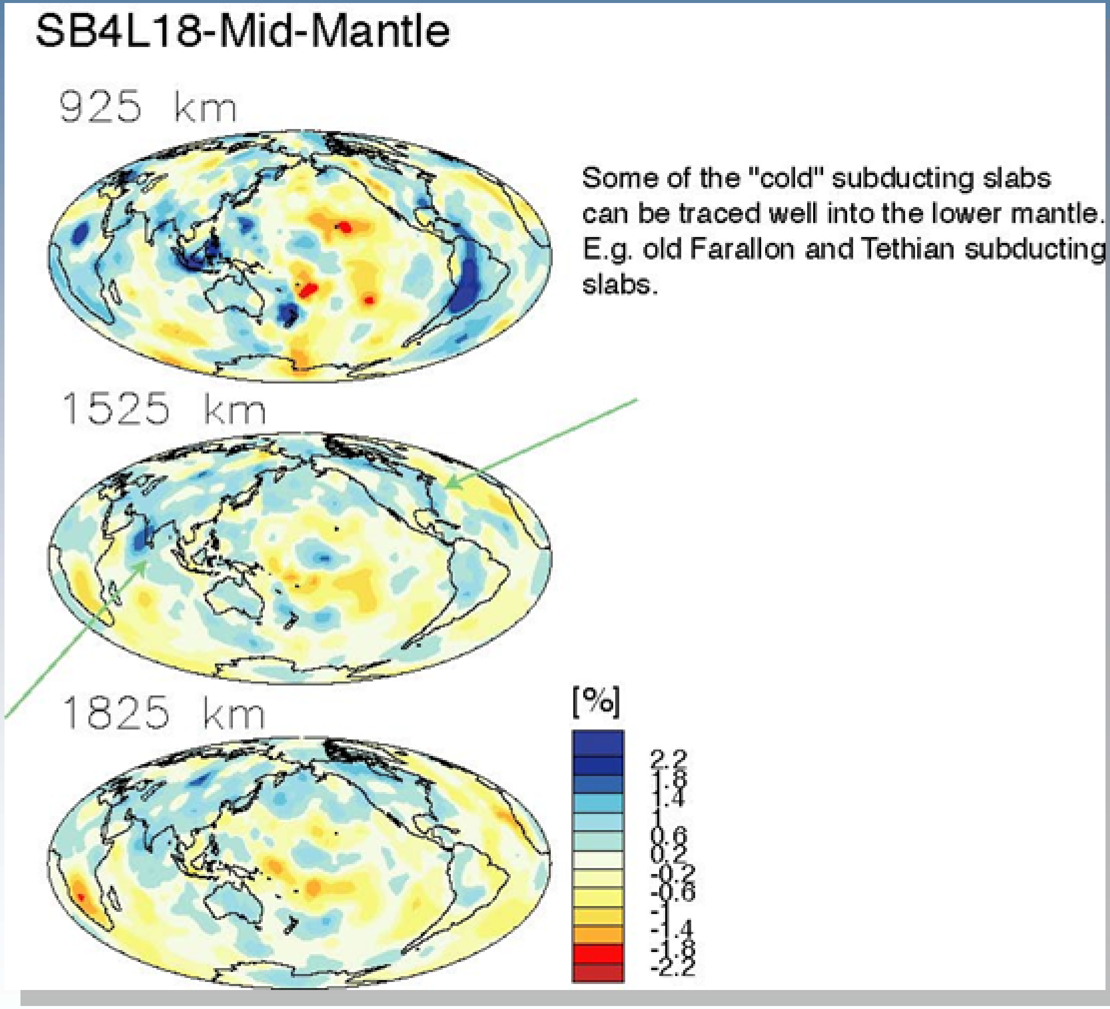
slow mid-ocean ridges

the continental plates have fast "keels" at depths at which the oceanic areas are already underlain by the slow asthenosphere

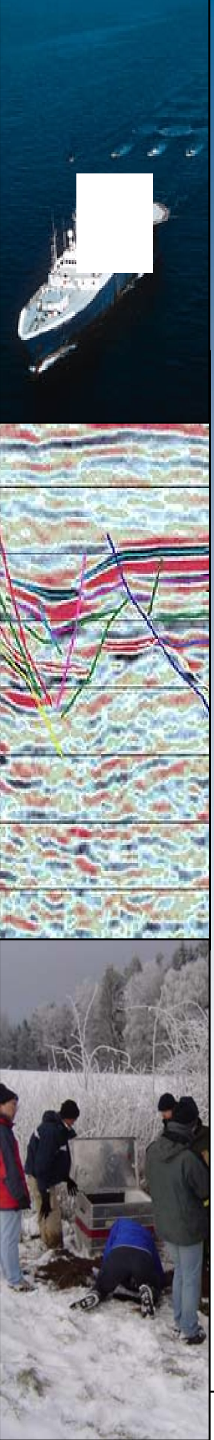
The "cold" subducting slabs show up as seismically fast areas. They pass the 670km discontinuity between upper and lower mantle and penetrate well into the lower mantle.



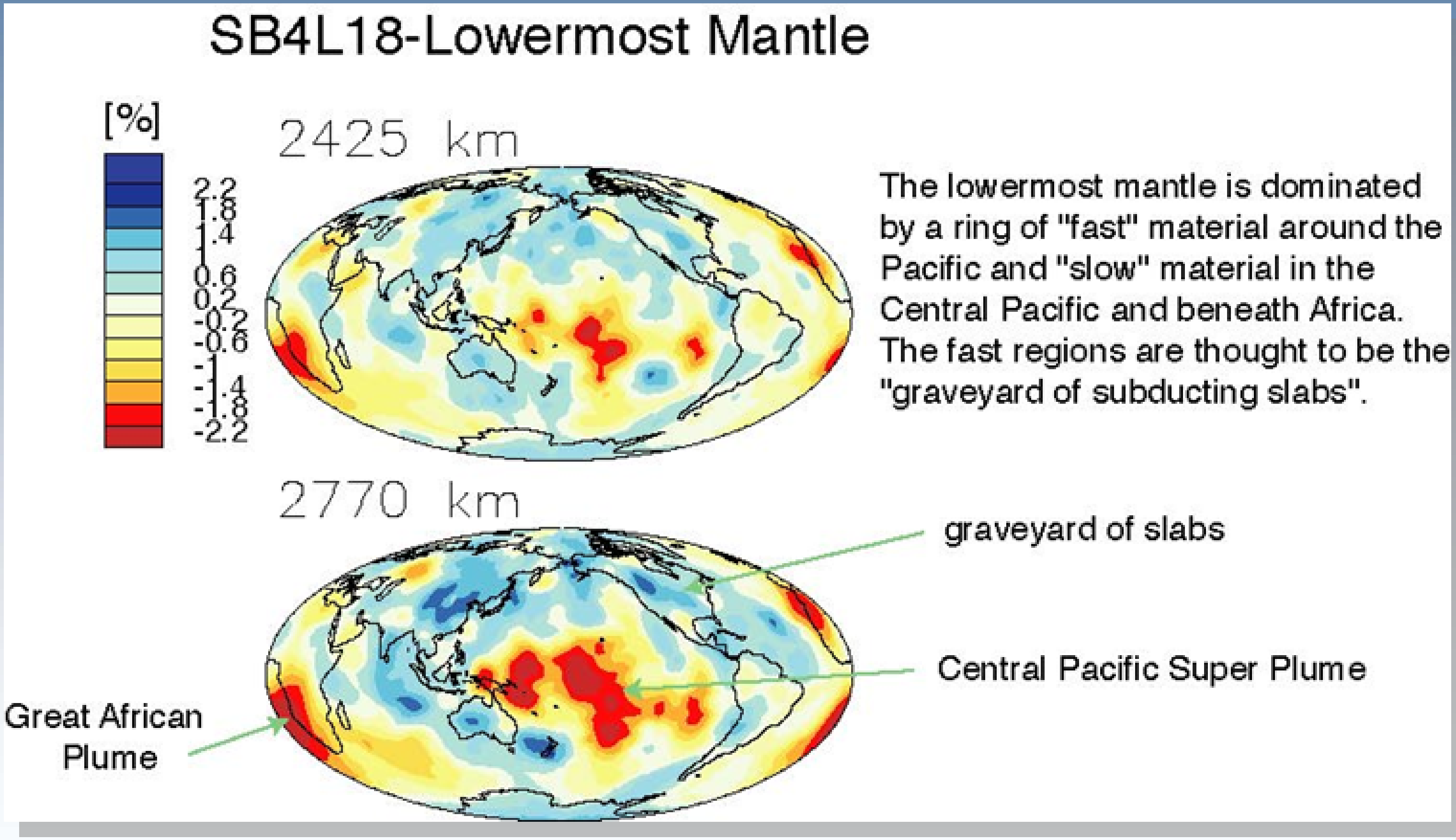
Mid-mantle: 3-D structure



Some of the "cold" subducting slabs can be traced well into the lower mantle. E.g. old Farallon and Tethian subducting slabs.

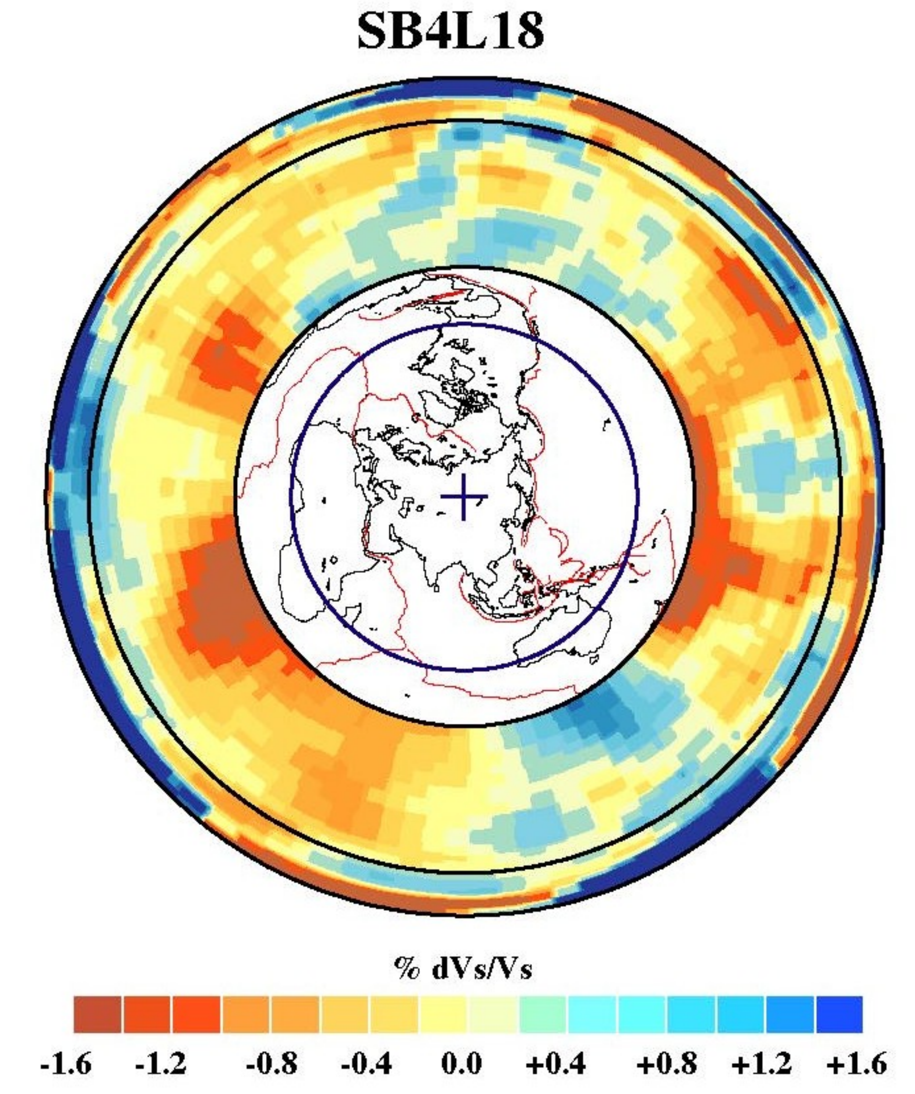


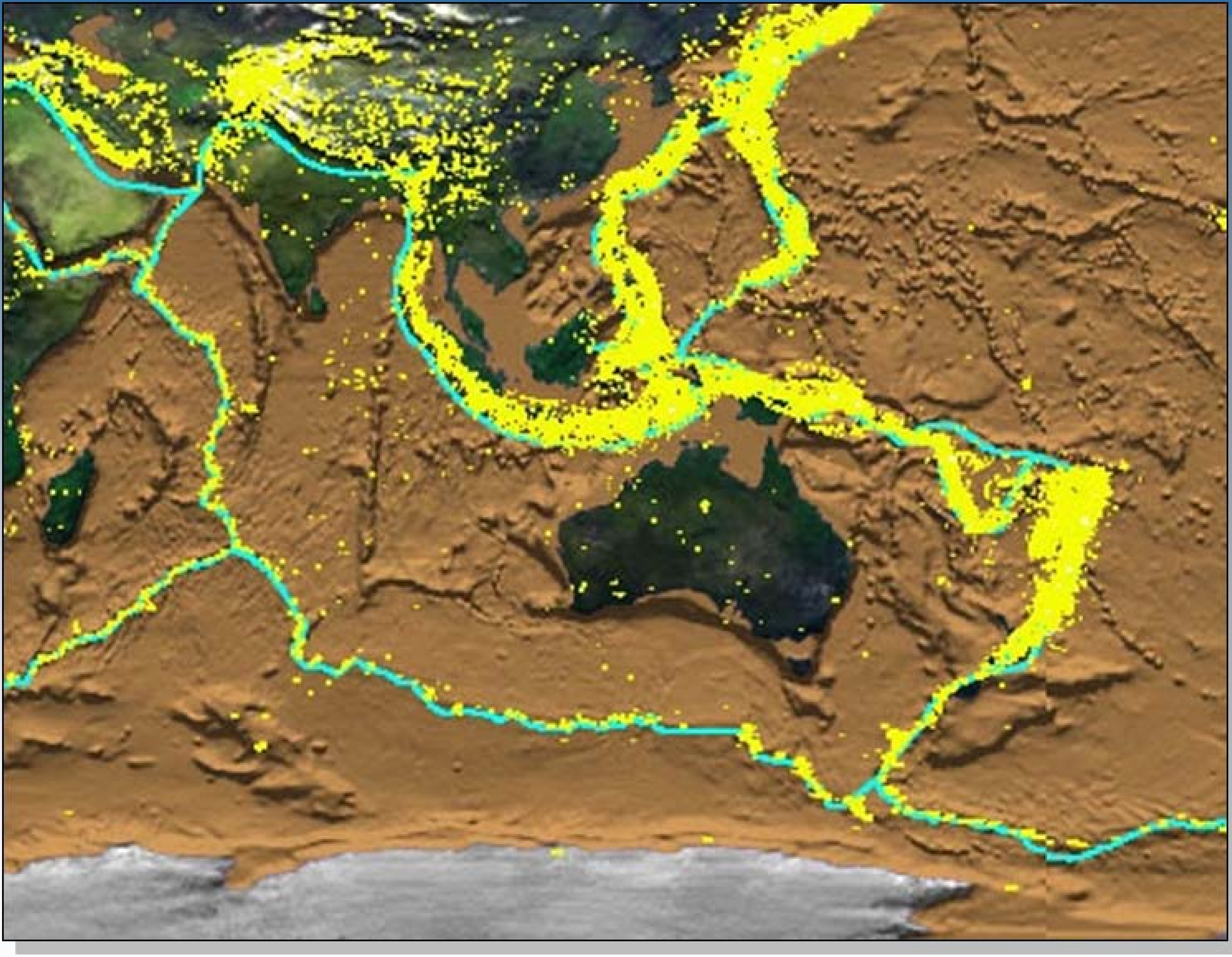
Lower Mantle: 3-D structure

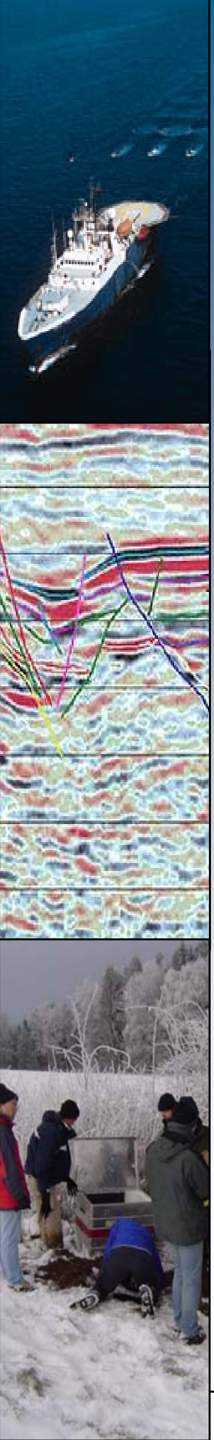


The lowermost mantle is dominated by a ring of "fast" material around the Pacific and "slow" material in the Central Pacific and beneath Africa. The fast regions are thought to be the "graveyard of subducting slabs".

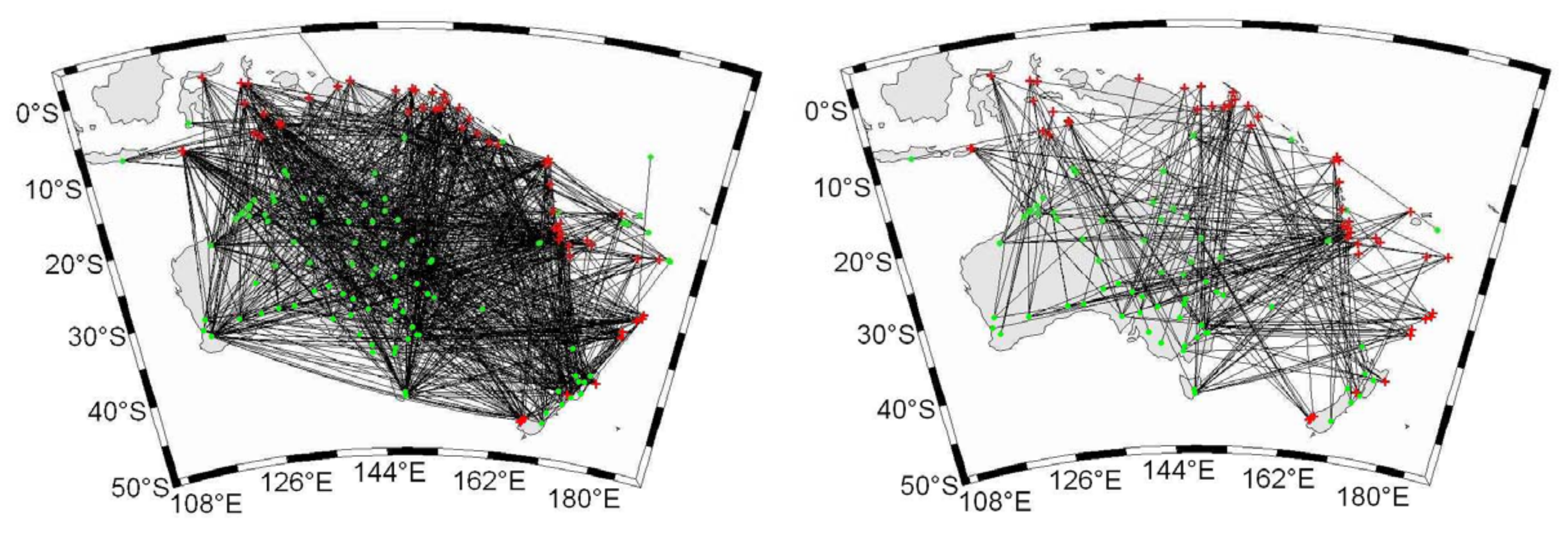
Global Cut: 3-D structure





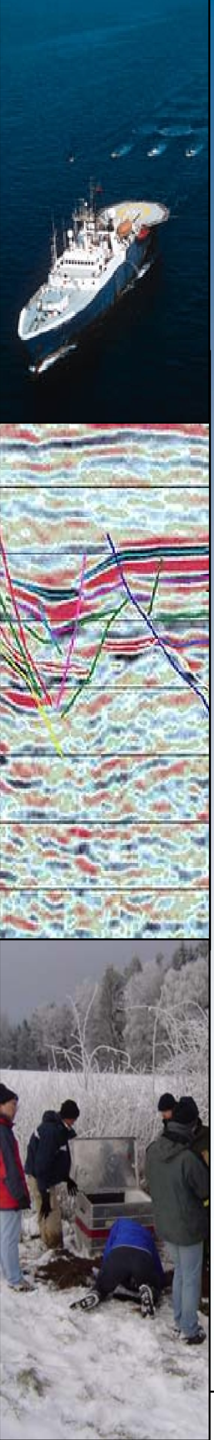


Ray coverage

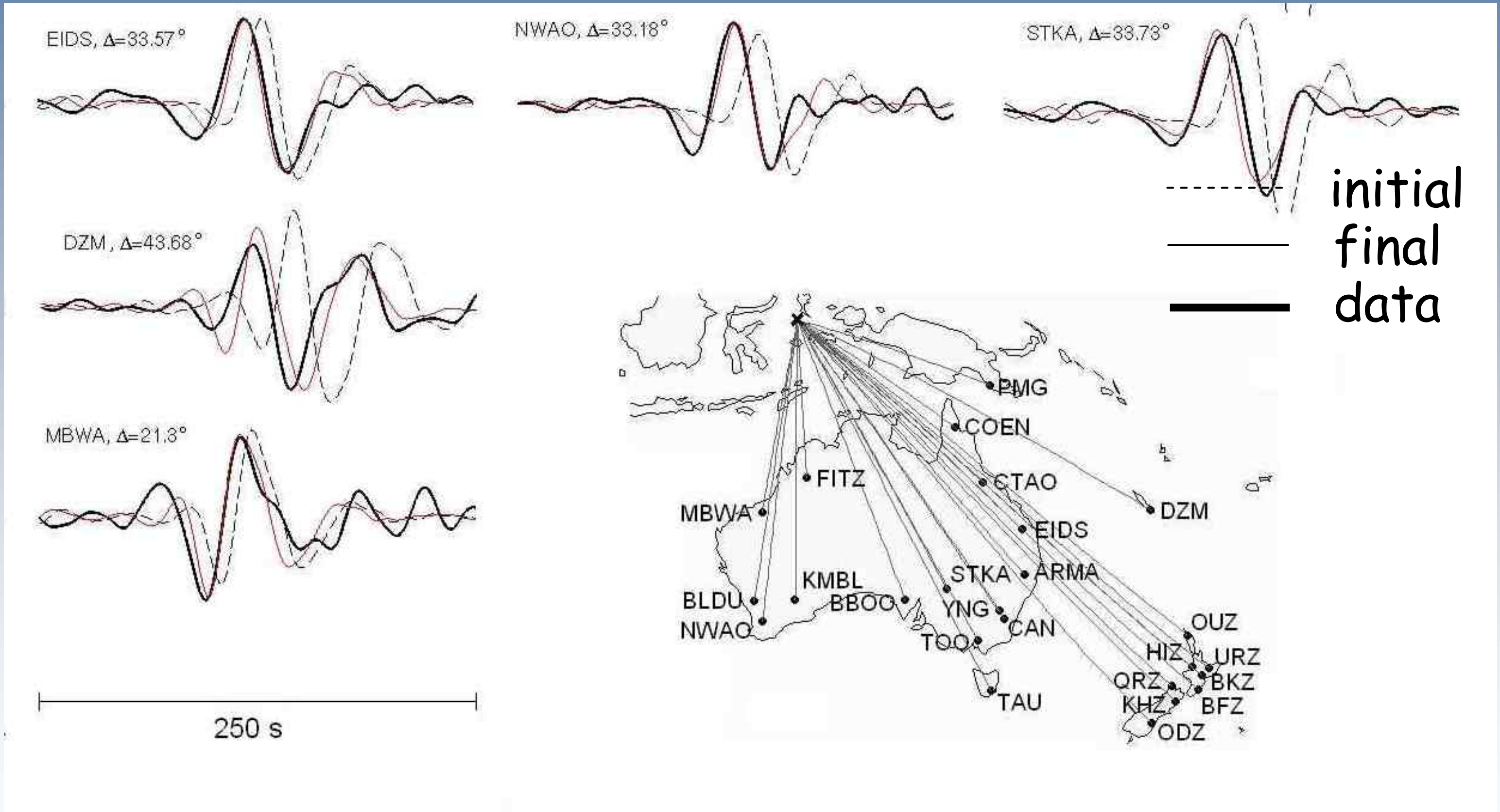


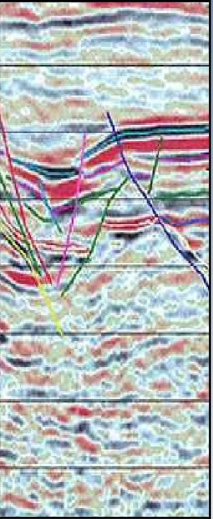
Rayleigh waves

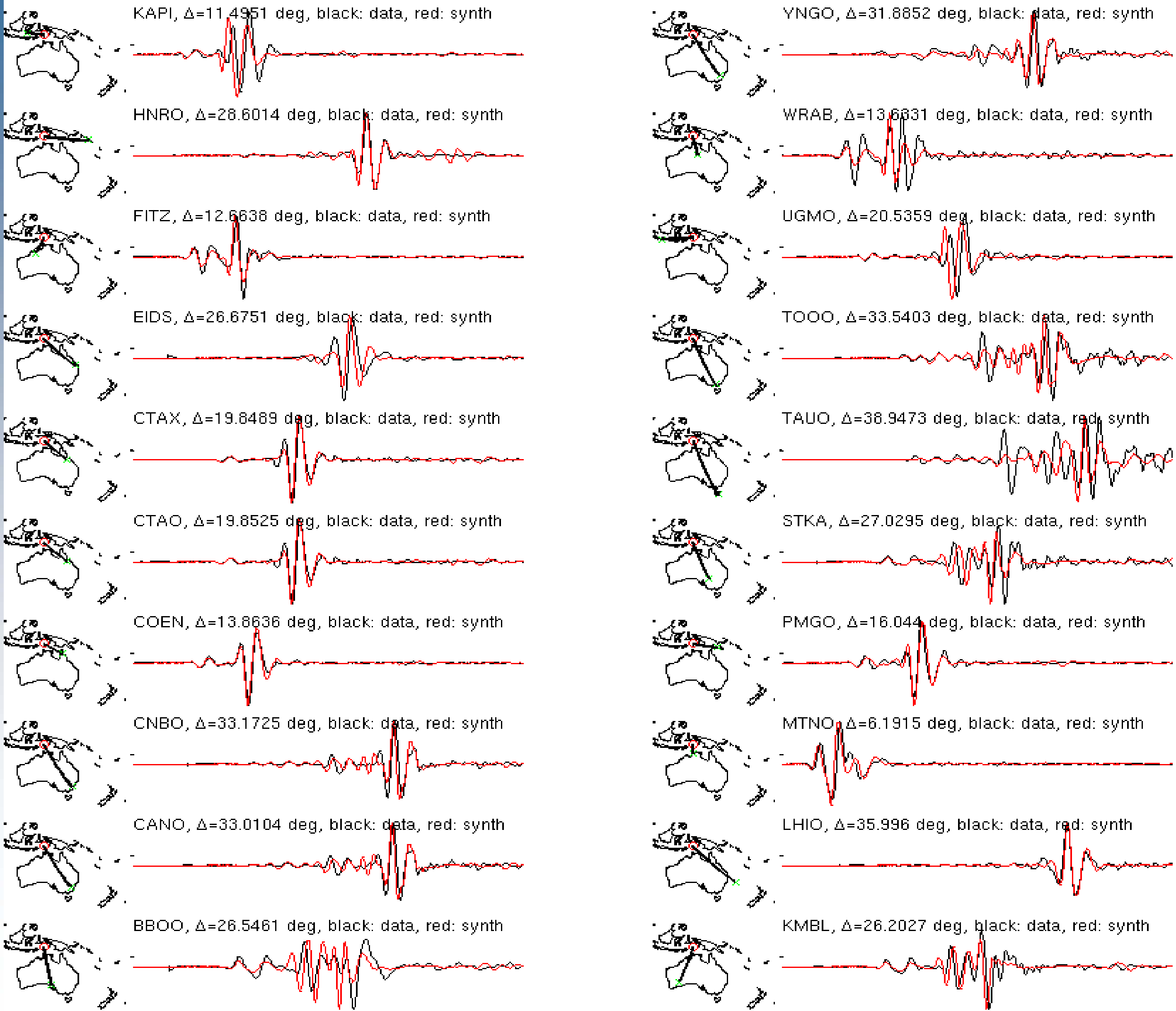
S waves

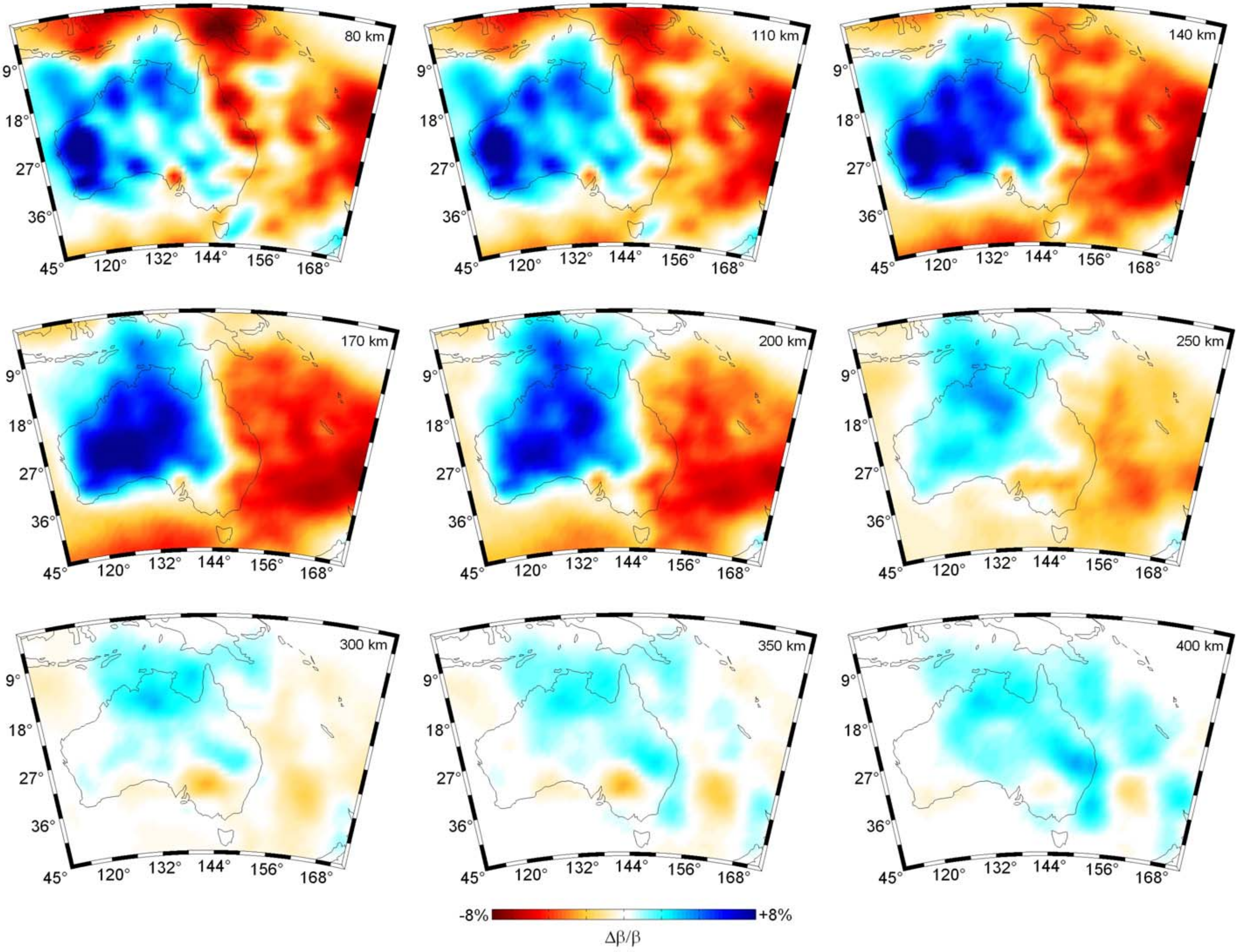


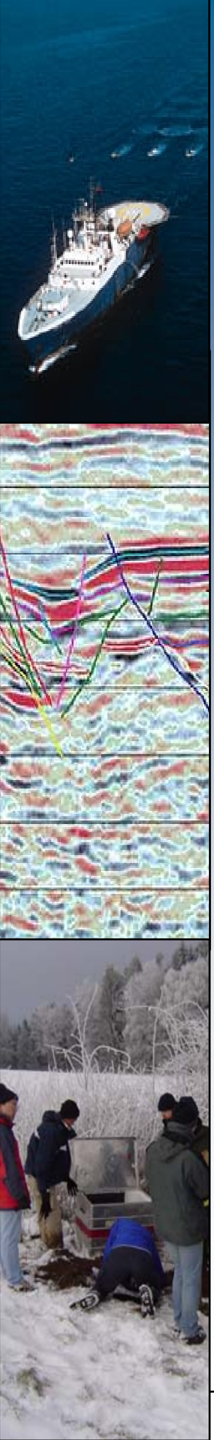
Misfit reduction (single event)






KAPI, Δ=11.4951 deg, black: data, red: synth
HNRO, Δ=28.6014 deg, black: data, red: synth
FITZ, Δ=12.6638 deg, black: data, red: synth
EIDS, Δ=26.6751 deg, black: data, red: synth
CTAX, Δ=19.8489 deg, black: data, red: synth
CTAO, Δ=19.8525 deg, black: data, red: synth
COEN, Δ=13.8636 deg, black: data, red: synth
CNBO, Δ=33.1725 deg, black: data, red: synth
CANO, Δ=33.0104 deg, black: data, red: synth
BBOO, Δ=26.5461 deg, black: data, red: synth
YNGO, Δ=31.8852 deg, black: data, red: synth
WRAB, Δ=13.6831 deg, black: data, red: synth
UGMO, Δ=20.5359 deg, black: data, red: synth
TOOO, Δ=33.5403 deg, black: data, red: synth
TAUO, Δ=38.9473 deg, black: data, red: synth
STKA, Δ=27.0295 deg, black: data, red: synth
PMGO, Δ=16.044 deg, black: data, red: synth
MTNO, Δ=6.1915 deg, black: data, red: synth
LHIO, Δ=35.996 deg, black: data, red: synth
KMBL, Δ=26.2027 deg, black: data, red: synth


80 km
110 km
140 km
170 km
200 km
250 km
300 km
350 km
400 km
9°
18°
27°
36°
45°
120°
132°
144°
156°
168°
-8%
+8%
Δβ/β



Zusammenfassung Refraktionsseismik

- Wenn sich die Geschwindigkeiten mit der Tiefe erhöhen beobachtet man Refraktionen
- Refraktionen breiten sich im schnelleren Medium in horizontaler Richtung aus und strahlen zur Oberfläche
- Refraktierte Wellen erlauben die Bestimmung der Geschwindigkeits-Tiefenverteilung
- Die Verallgemeinerung des Konzept für 3D Medien führt zur seismischen Tomographie
- Tomographische Abbildungen können große Unsicherheiten enthalten wegen ungenügender Strahlabdeckung oder verdeckter Regionen (zB Niedriggeschwindigkeitszonen etc.)
- Die Zukunft liegt in der direkten Modellierung der gesamten beobachteten Wellenformen -> Wellenformtomographie