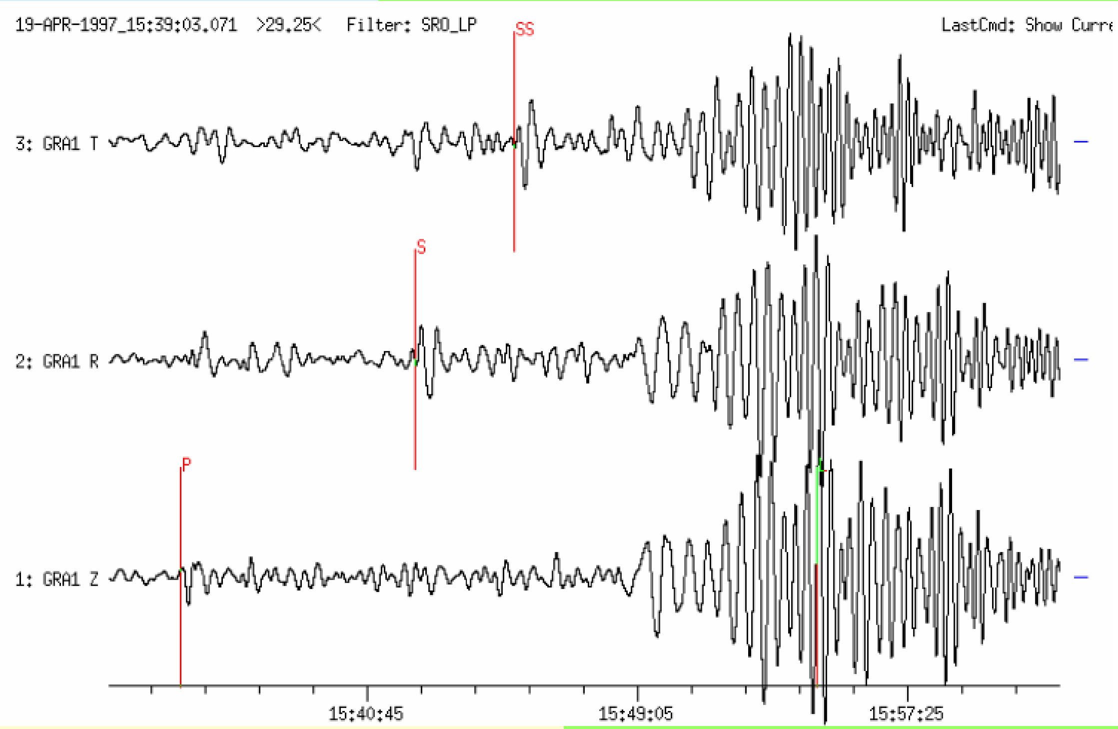
Seismic tomography

Jean Virieux, Pr UJF-IUF

From Paul (2013)
From Amoros (2013)

3C seismograms
at the surface of the Earth



From P. Bormann et al (IASPEI)

- Travel times
- Ray paths and phases
- Seismic tomography

First-arrival signals

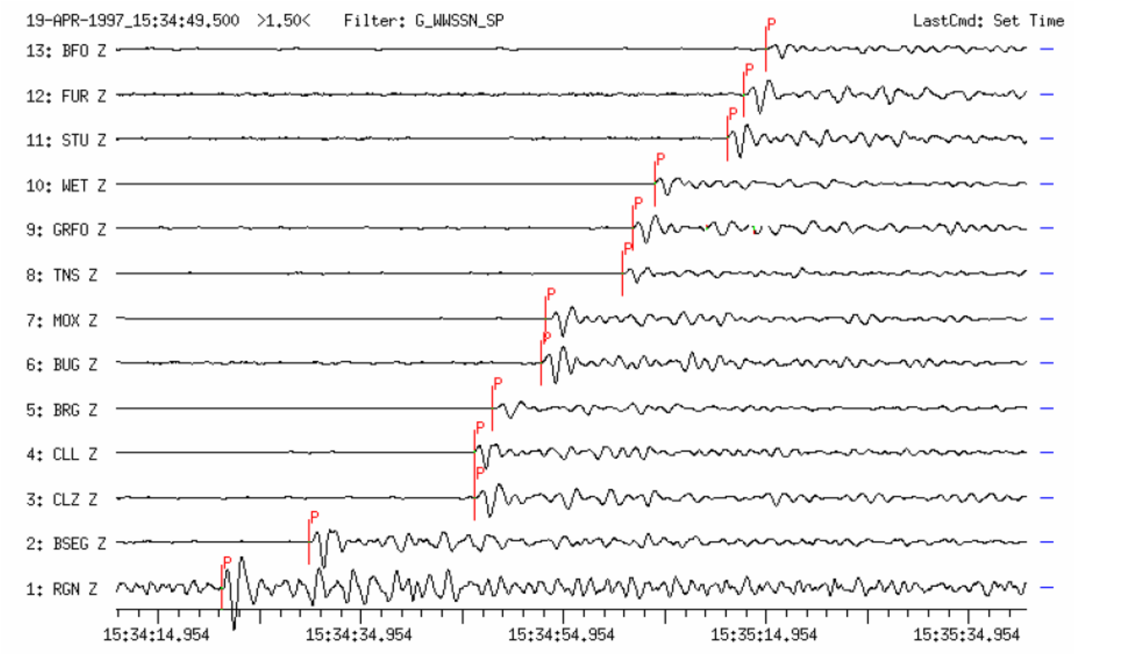
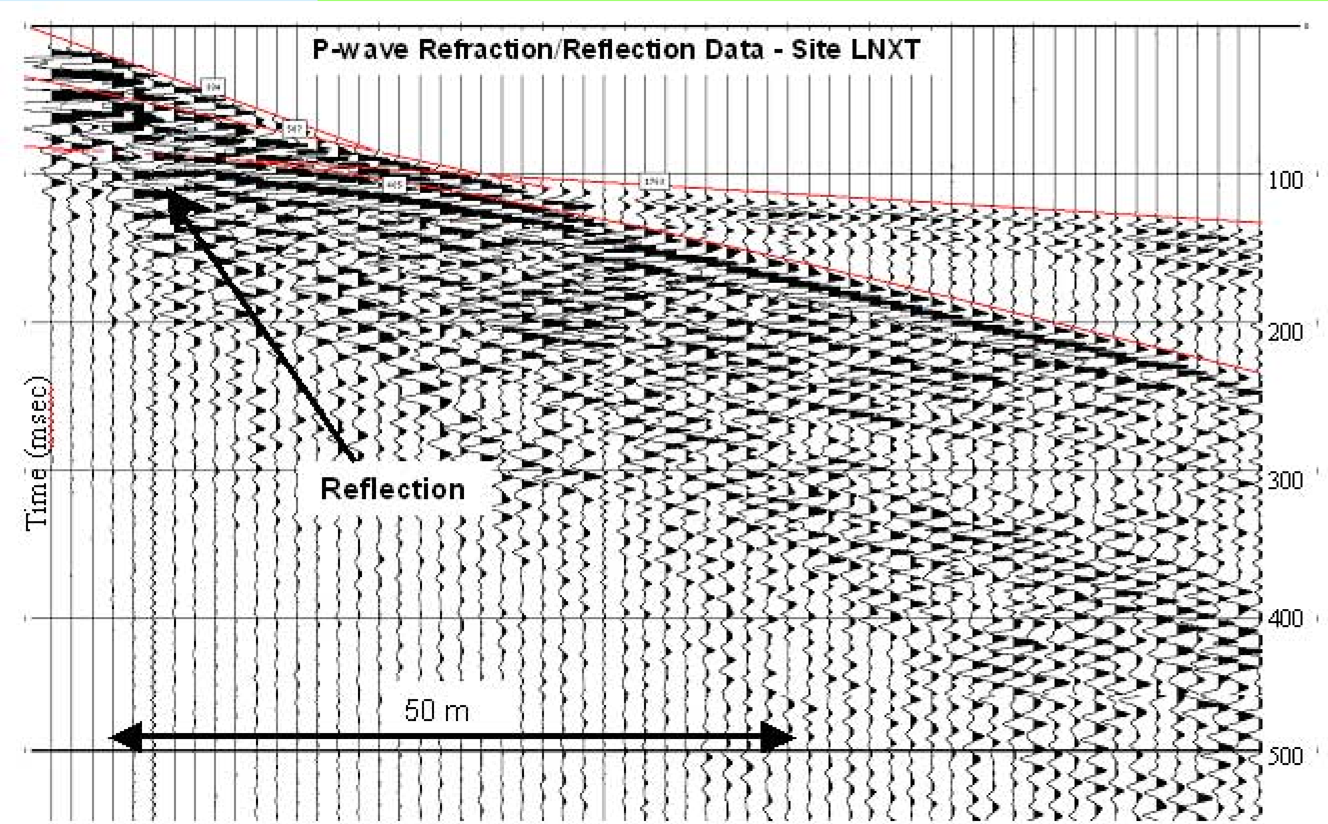


Fig. 11.5 WWSSN-SP vertical-component records of GRSN stations for the same event as in Fig. 11.4. While the P-wave amplitudes vary significantly within the network, the first-motion polarity remains the same.

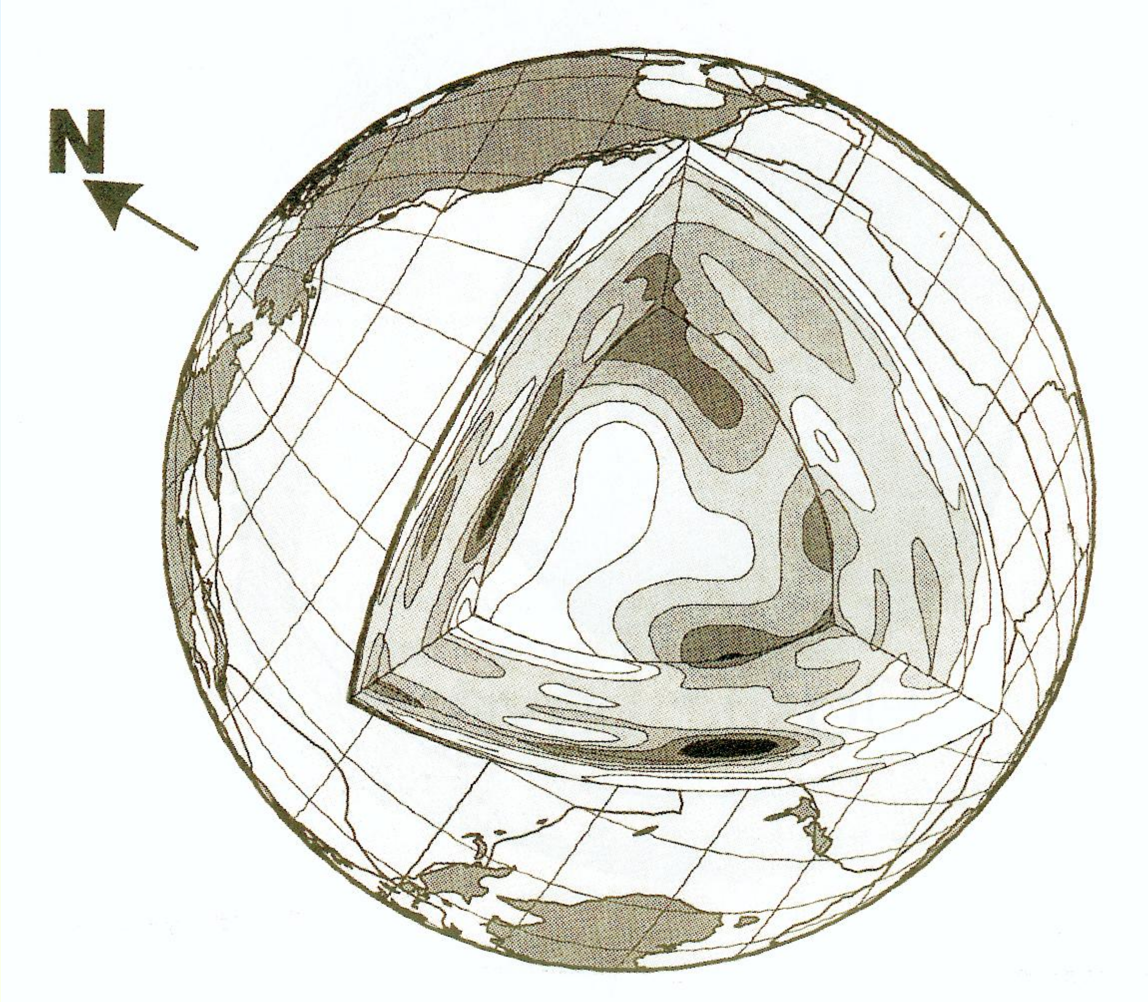
- Travel times
- Ray paths and phases
- Seismic tomography

First-arrival signals



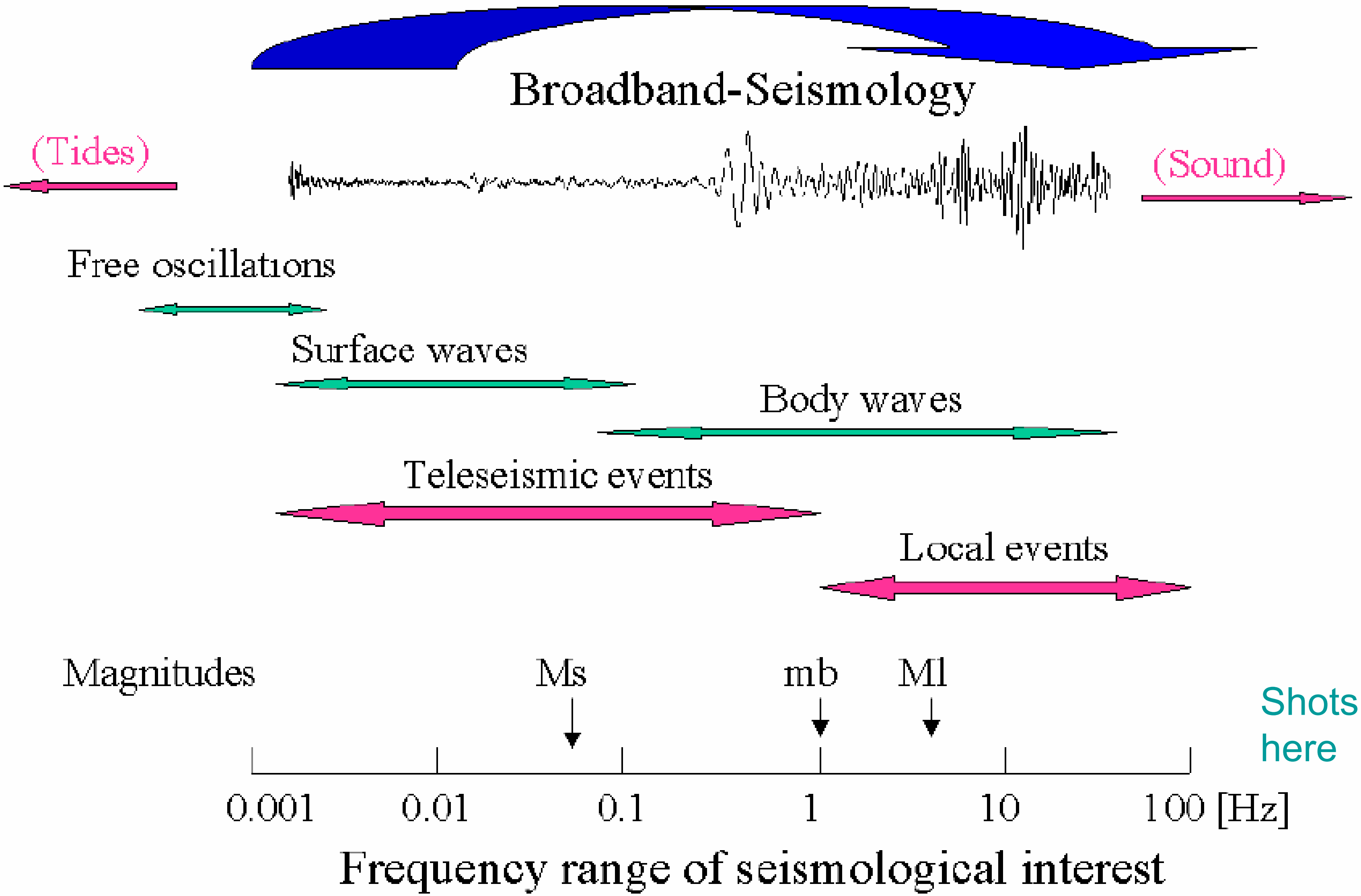
- Travel times
- Ray paths and phases
- Seismic tomography

Earth velocity models?



- Only travel times
- Ray paths and phases
- Seismic tomography

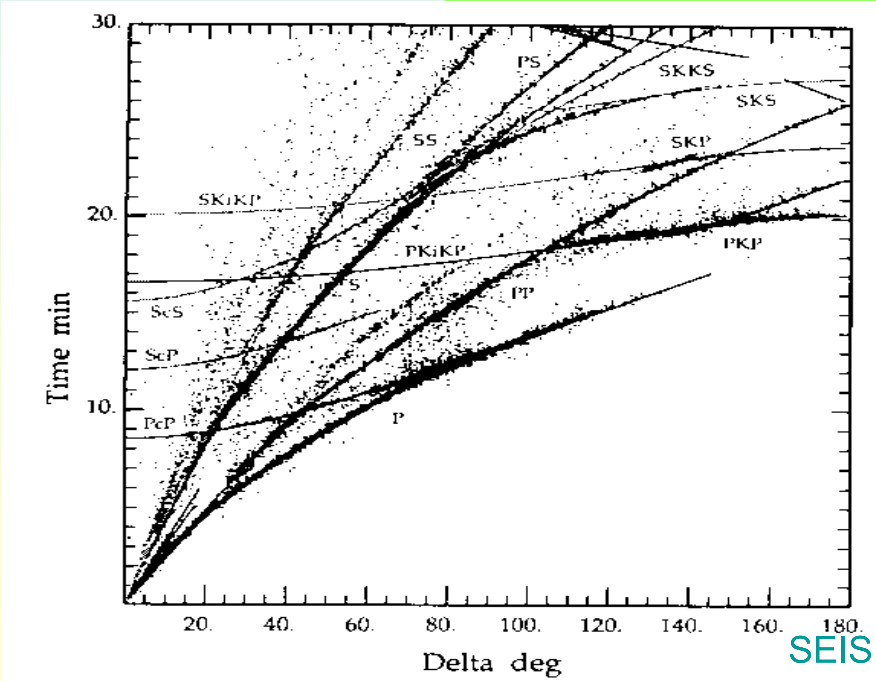
Frequency range in seismology

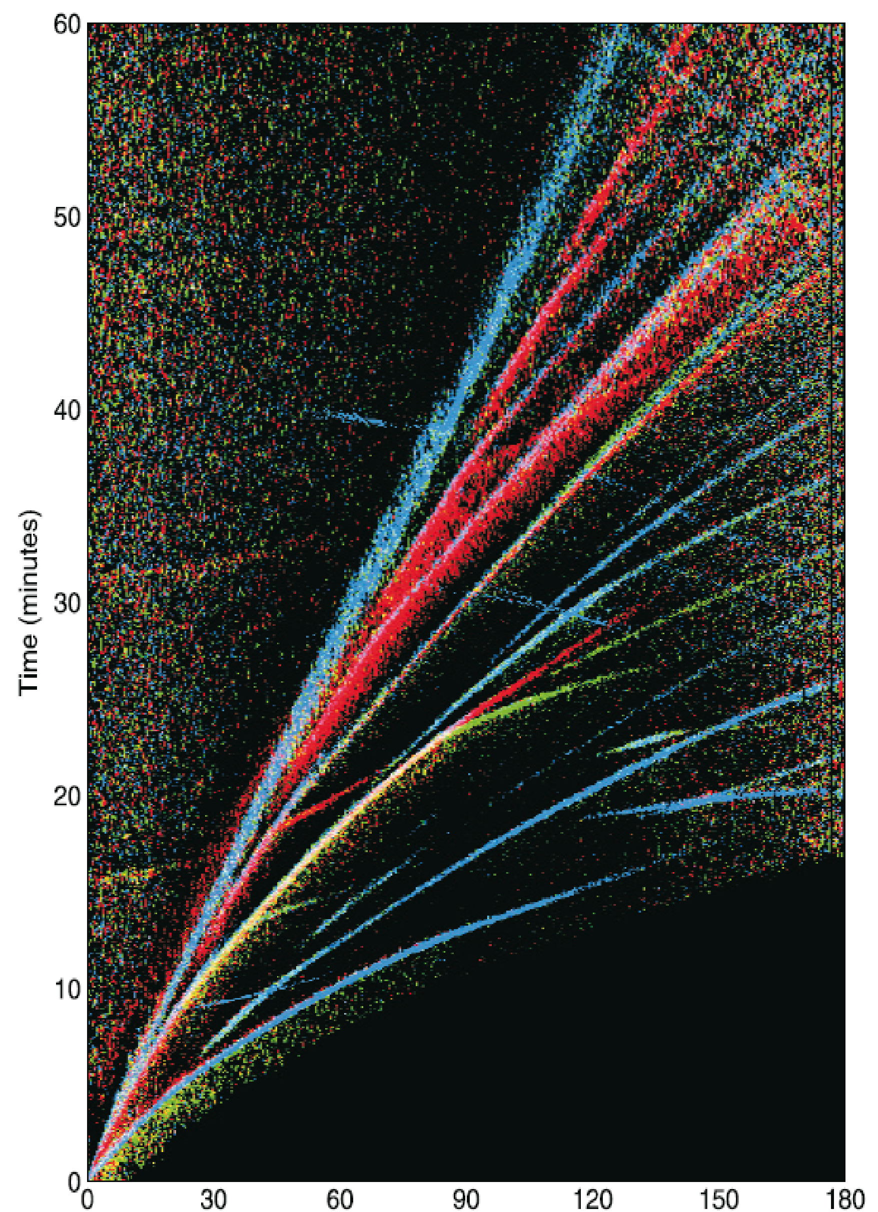


Shots here

Wave packets

Hand-pickings
and automatic pickings



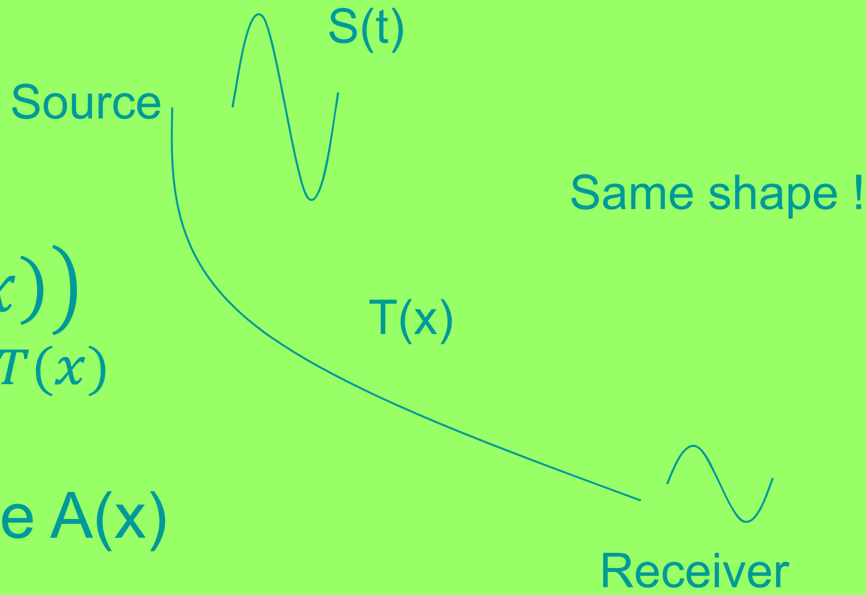


SEISMIC TOMOGRAPHY

Seismogram hierarchy

- Source signal scale
  - Frequency content for the analysis
- Converted phase scale
  - Heterogeneity content
- Total sampling scale
  - Total volume investigation

Translucid Earth



$$u(x,t) = A(x)\,S\big(t - T(x)\big)$$
$$u(x,\omega) = A(x)\,S(\omega)\,e^{i\omega T(x)}$$

Travel-time T(x) and Amplitude A(x)

Diffracting medium: Wavefront preserved

lost wavefront coherence!

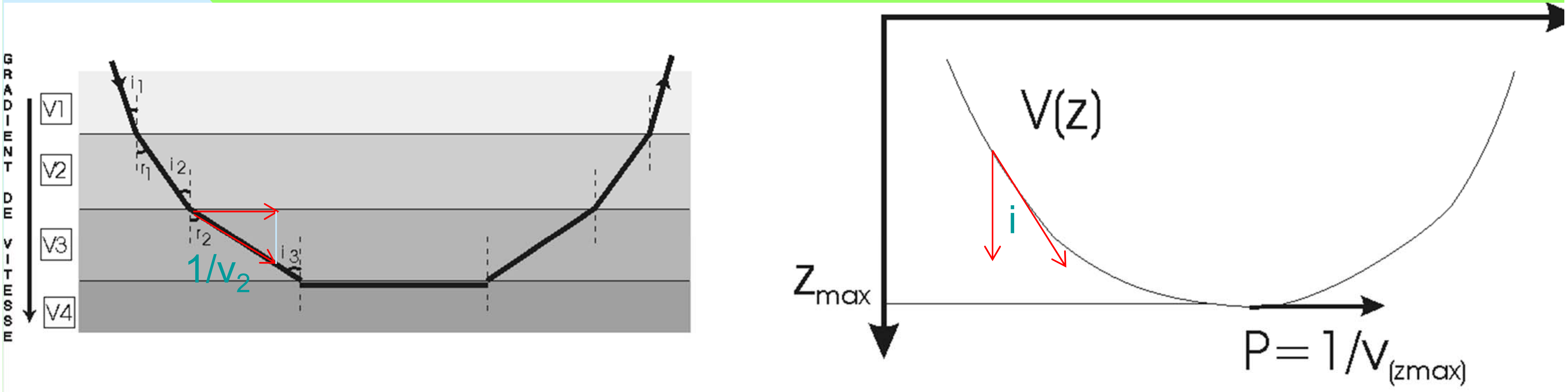
$\omega T(x)$ is sometimes called the phase

- Wavefront: $T(x)=T_0$
- Normal to wavefront: slowness vector **p=gradient of T** with |**p**|=1/v

where v is the local velocity

From discrete to continuous media

Tracing rays?



(a) milieu discret (b) milieu continu

$$\frac{\sin i_1}{v_1} = \frac{\sin i_2}{v_2} = \frac{\sin i_3}{v_3} = p = \text{constante}$$

The variable p is the ray parameter (horizontal component)

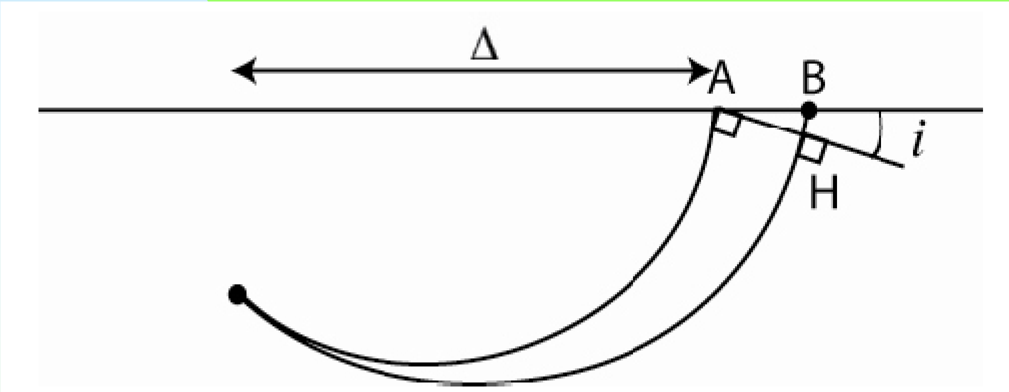
$$\frac{\sin i_{max}}{v_{max}} = \frac{1}{v_{max}} = p$$

z_{max} is the deepest point

The conservation of p at an interface is the Snell-Descartes law …

Ray parameter property

The conservation of p at an interface is the Snell-Descartes law …



Two nearby rays

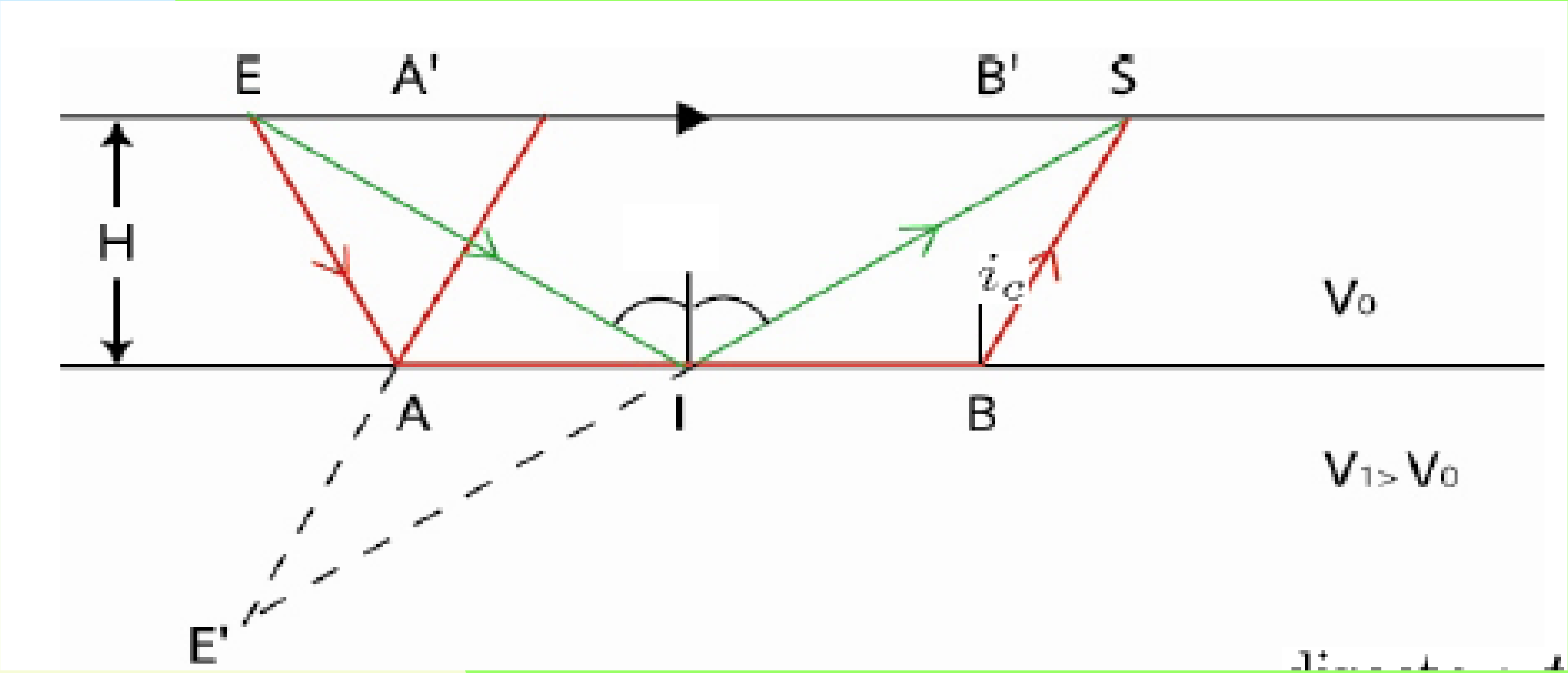
$$AB = \delta x; HB = v\delta t$$

$$\sin i = \frac{HB}{AB} = v\,\frac{\delta t}{\delta x} \Rightarrow p = \frac{\sin i}{v} = \frac{\delta t}{\delta x}$$

The ray parameter p is tangent to the curve $t(x) = t(\Delta)$

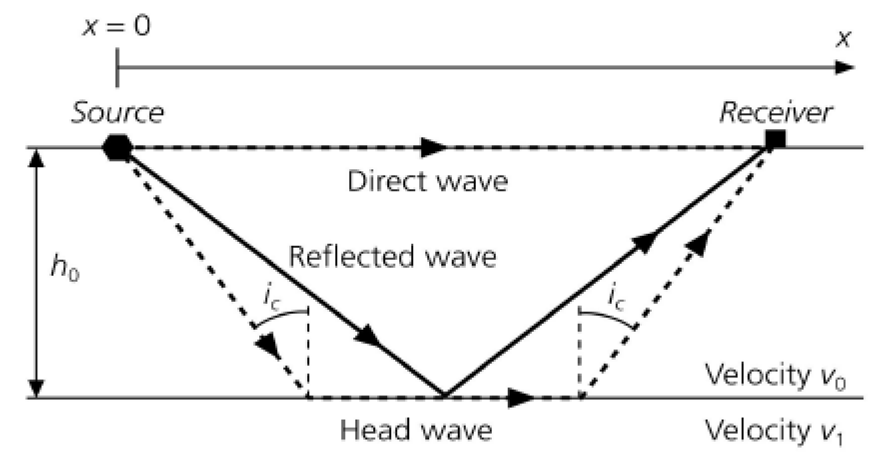
Layered media

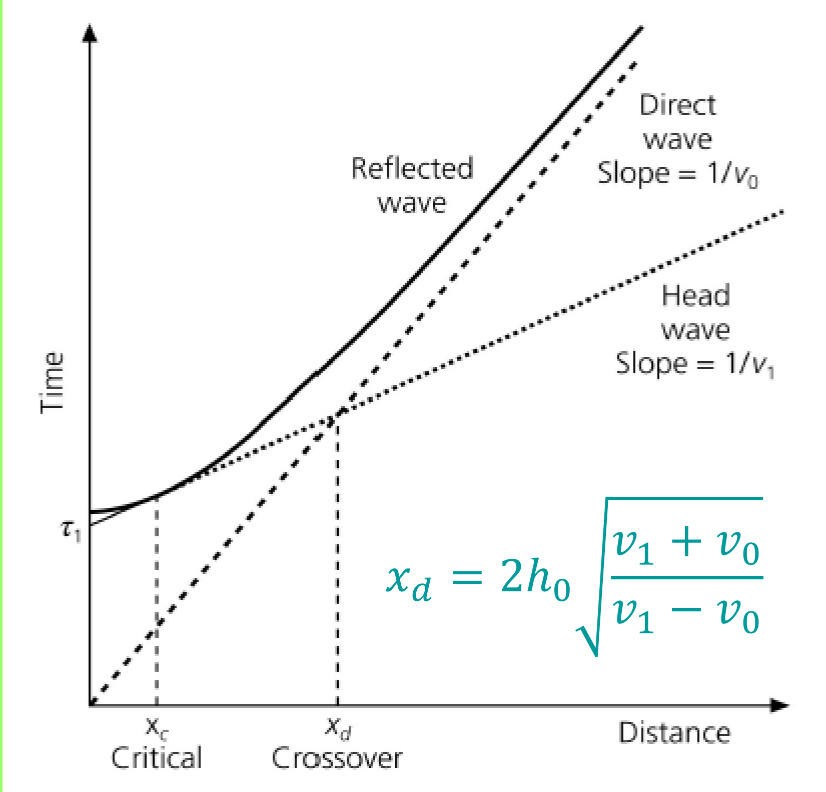
Direct wave
Head wave
Reflected wave



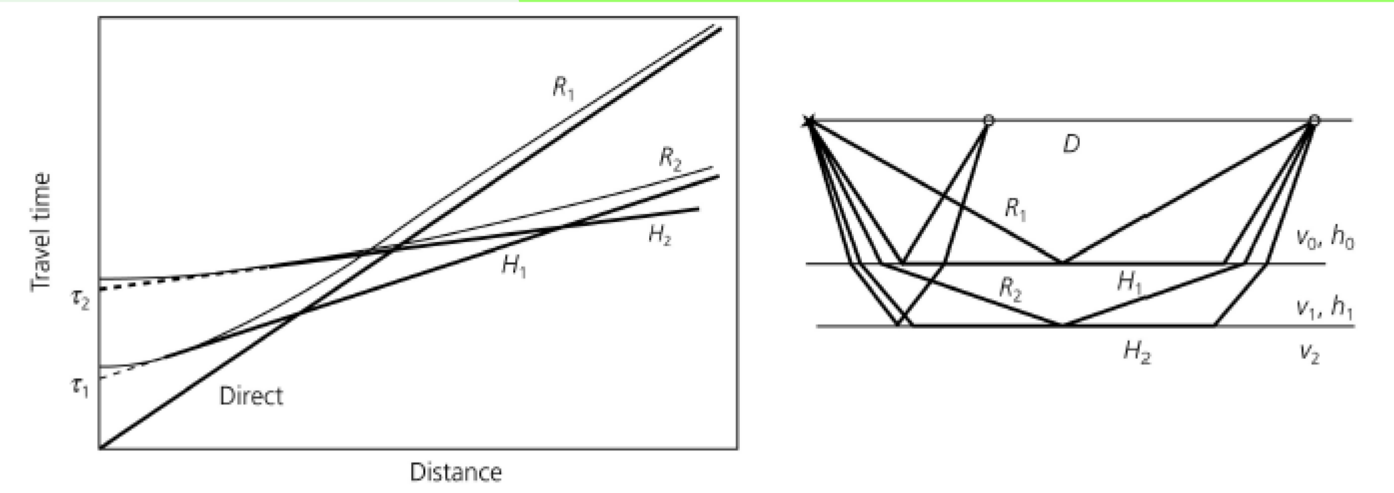
Please trace wavefronts …

Layered media



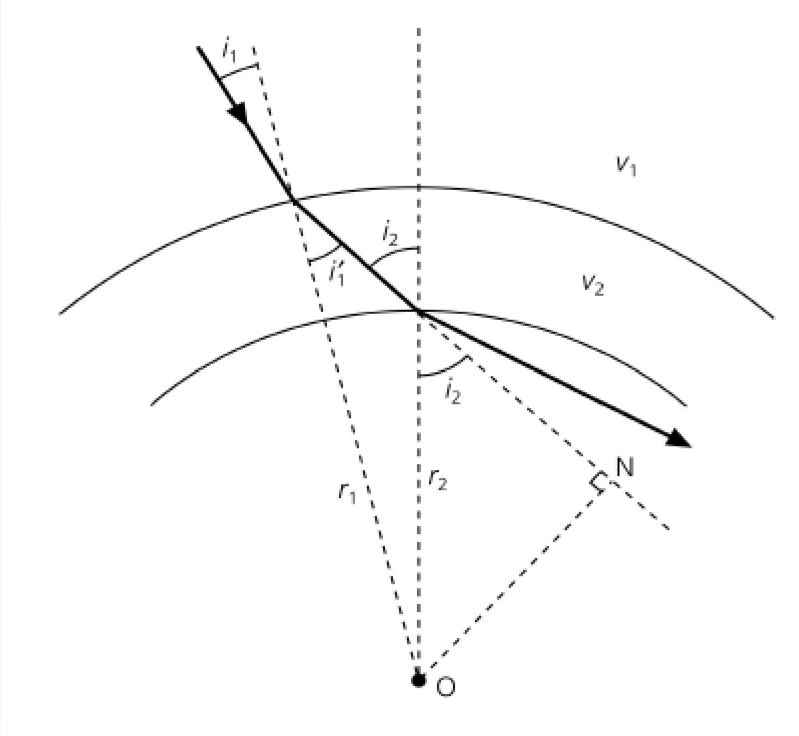


$$x_d = 2h_0\sqrt{\frac{v_1 + v_0}{v_1 - v_0}}$$



Two layers

Spherical Earth



$$ON = r_2 sin i_2 = r_1 sin i'_1$$

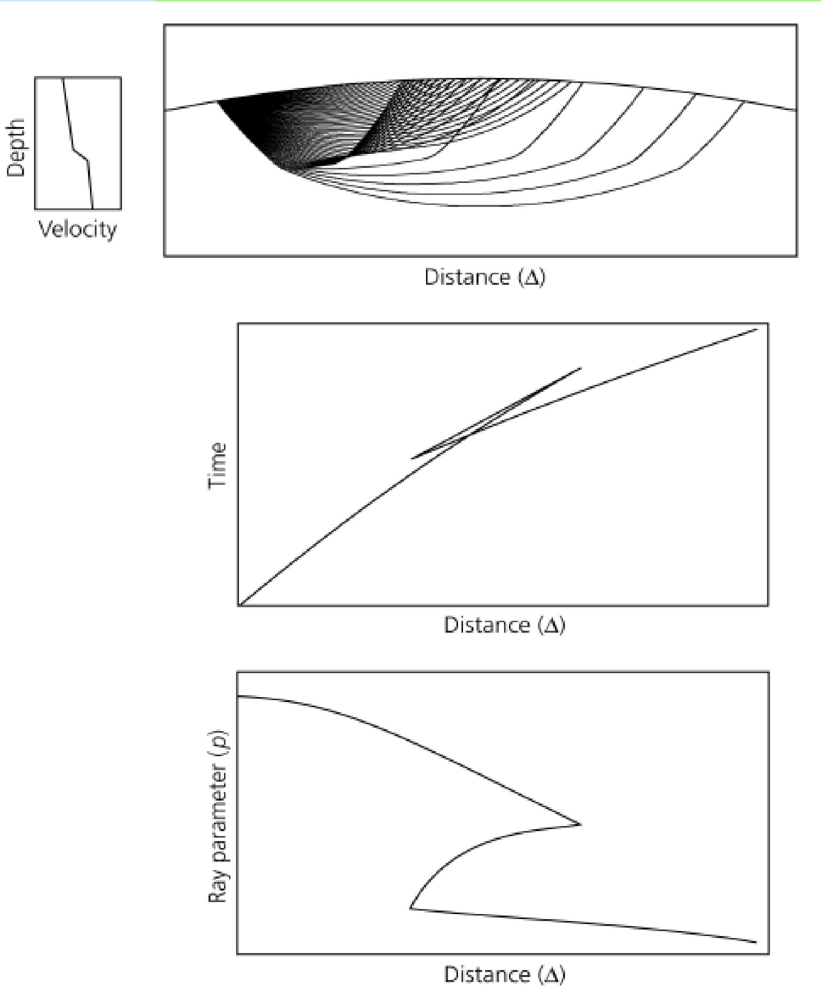
$$\frac{sin i'_1}{v_2} = \frac{sin i_1}{v_1}$$

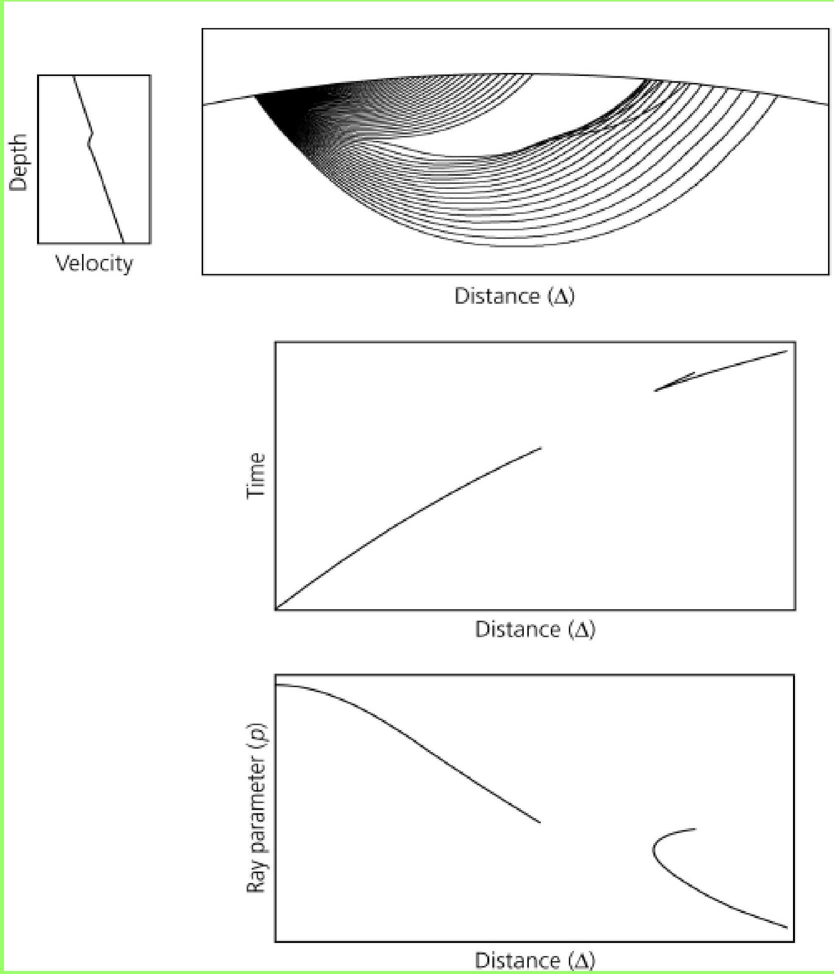
$$\frac{r_1 \sin i_1}{v_1} = \frac{r_2 \sin i_2}{v_2}$$

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

The ray parameter has another definition while it is still preserved at spherical interfaces.

Triplication & shadow zone

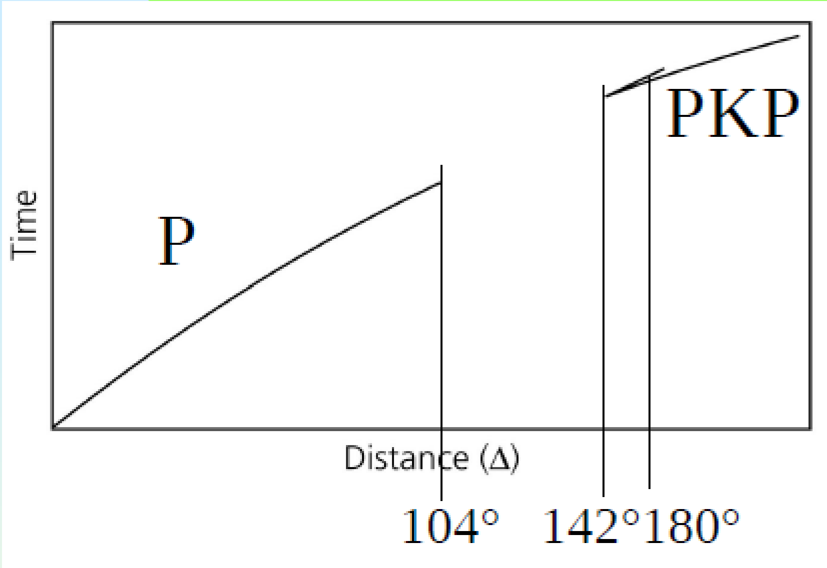


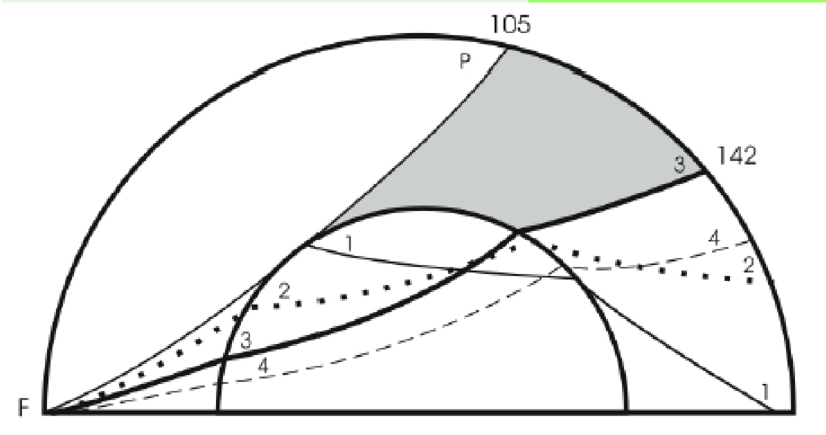


Increase of the velocity: triplication and retrograde branch

Decrease of the velocity: shadow zone (and a retrograde branch)

Shadow zone in the Earth





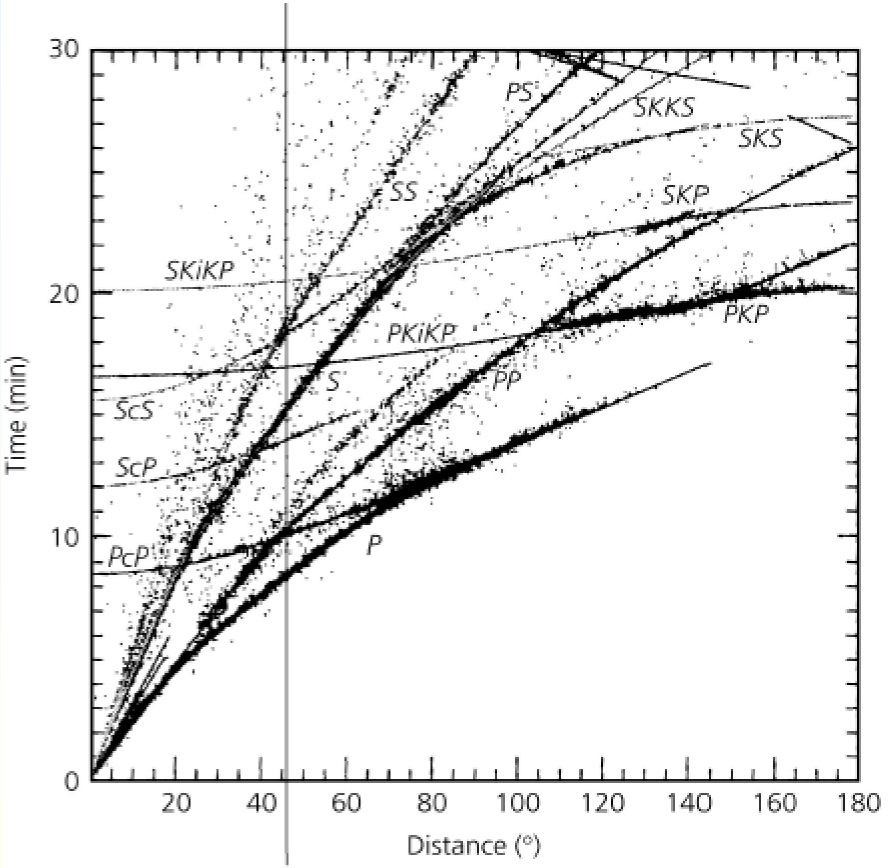
Abrupt decrease of velocity at the CMB (2900 km)

(Oldham, 1906, Gutenberg, 1912)

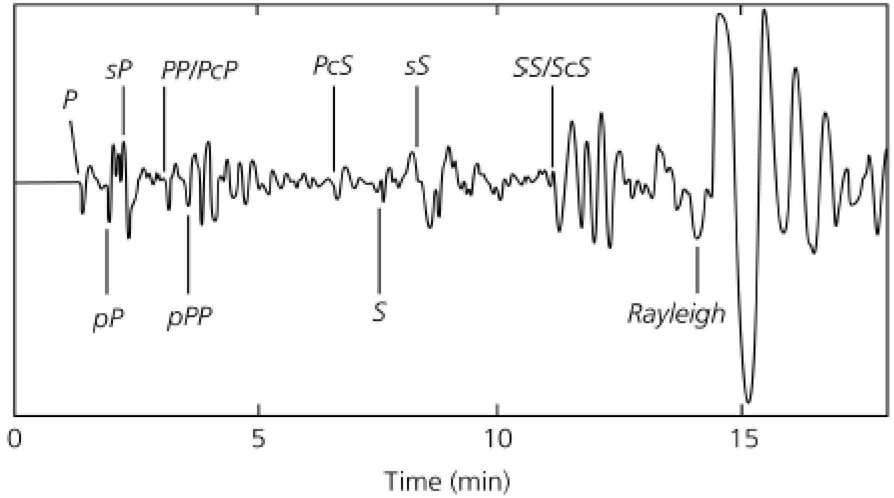
Phase identification?

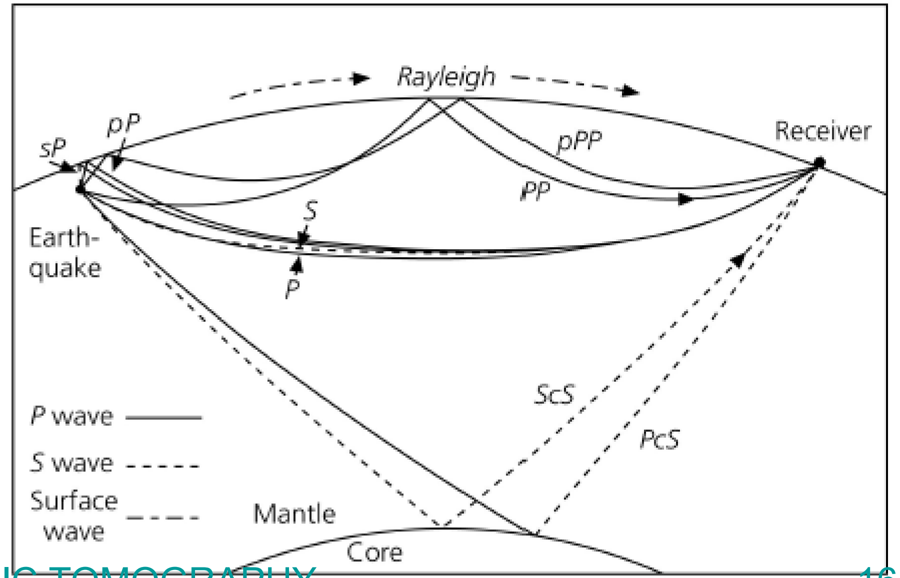
Distance $\Delta = 45°$

Kennett and Engdhal (1991)

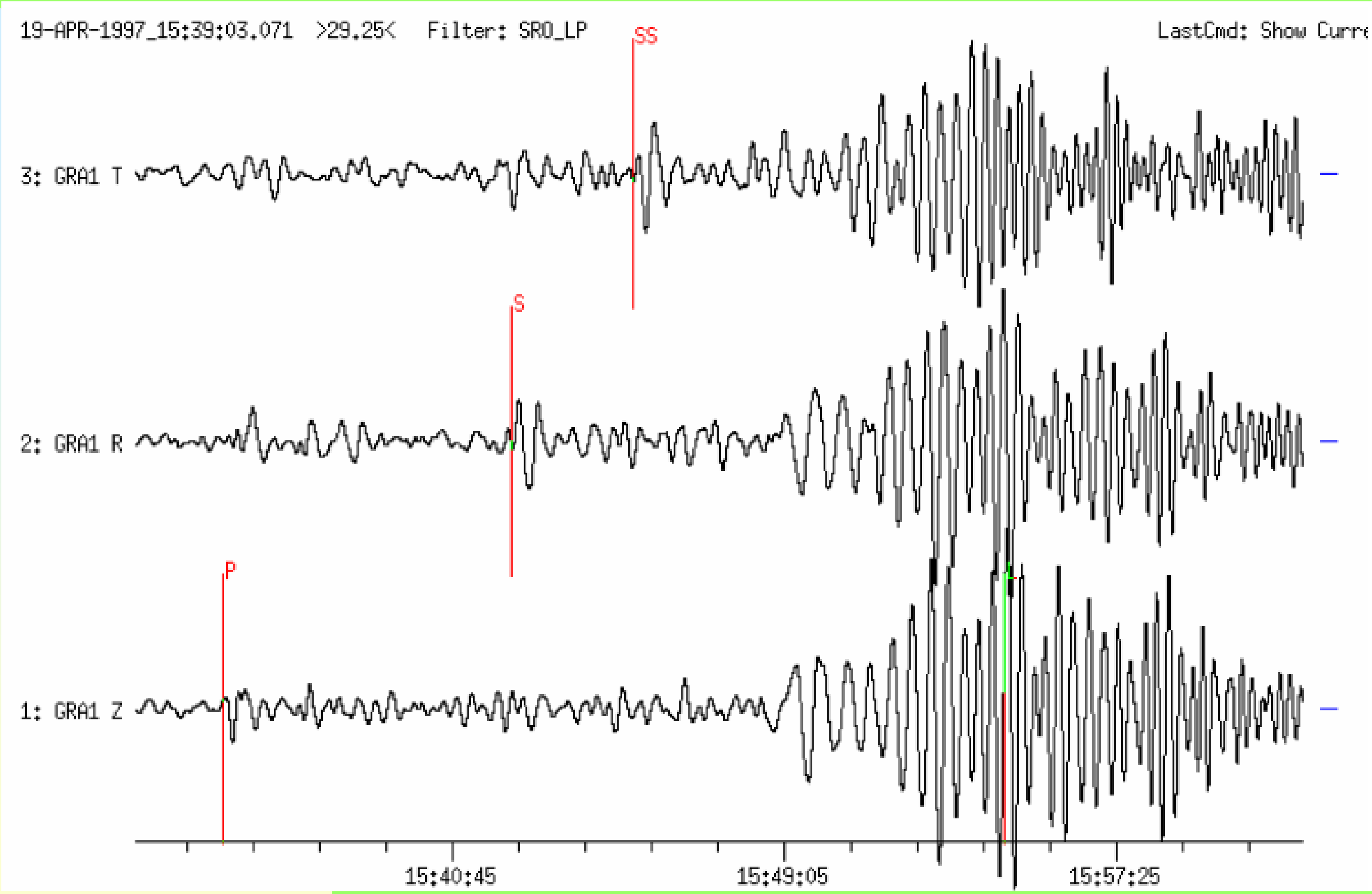


$\Delta = 45°$



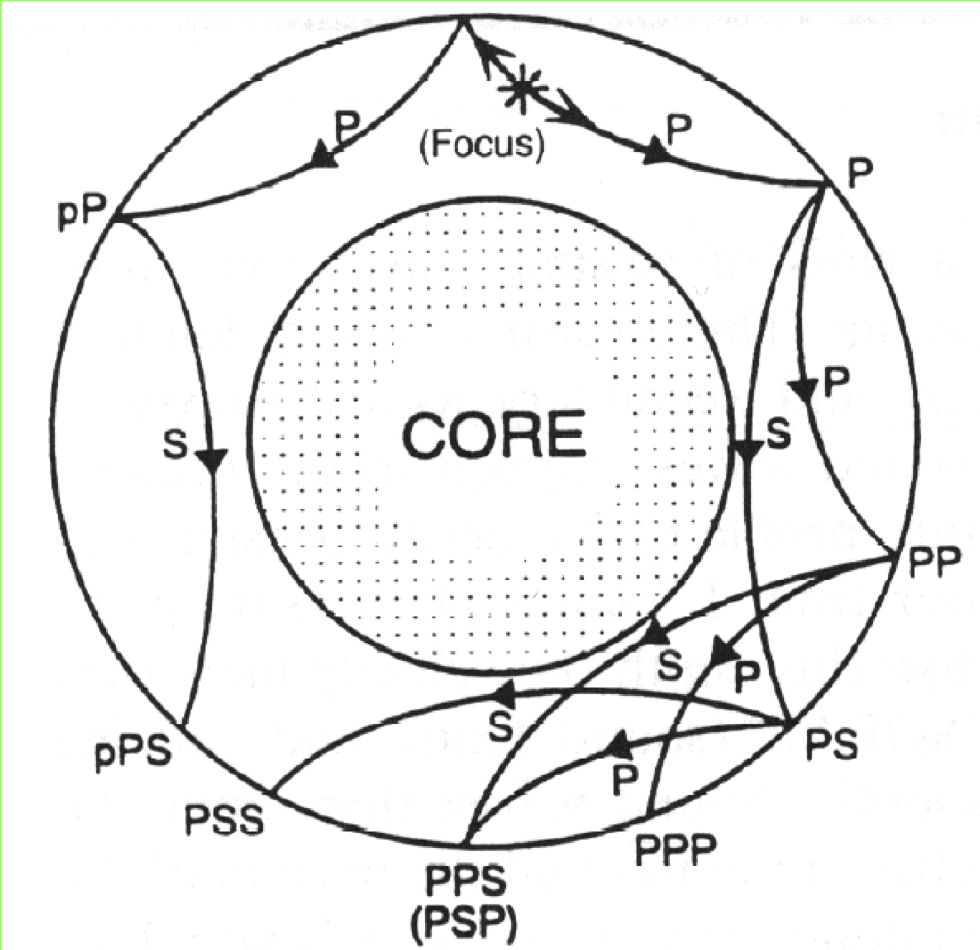


Identify phases ?



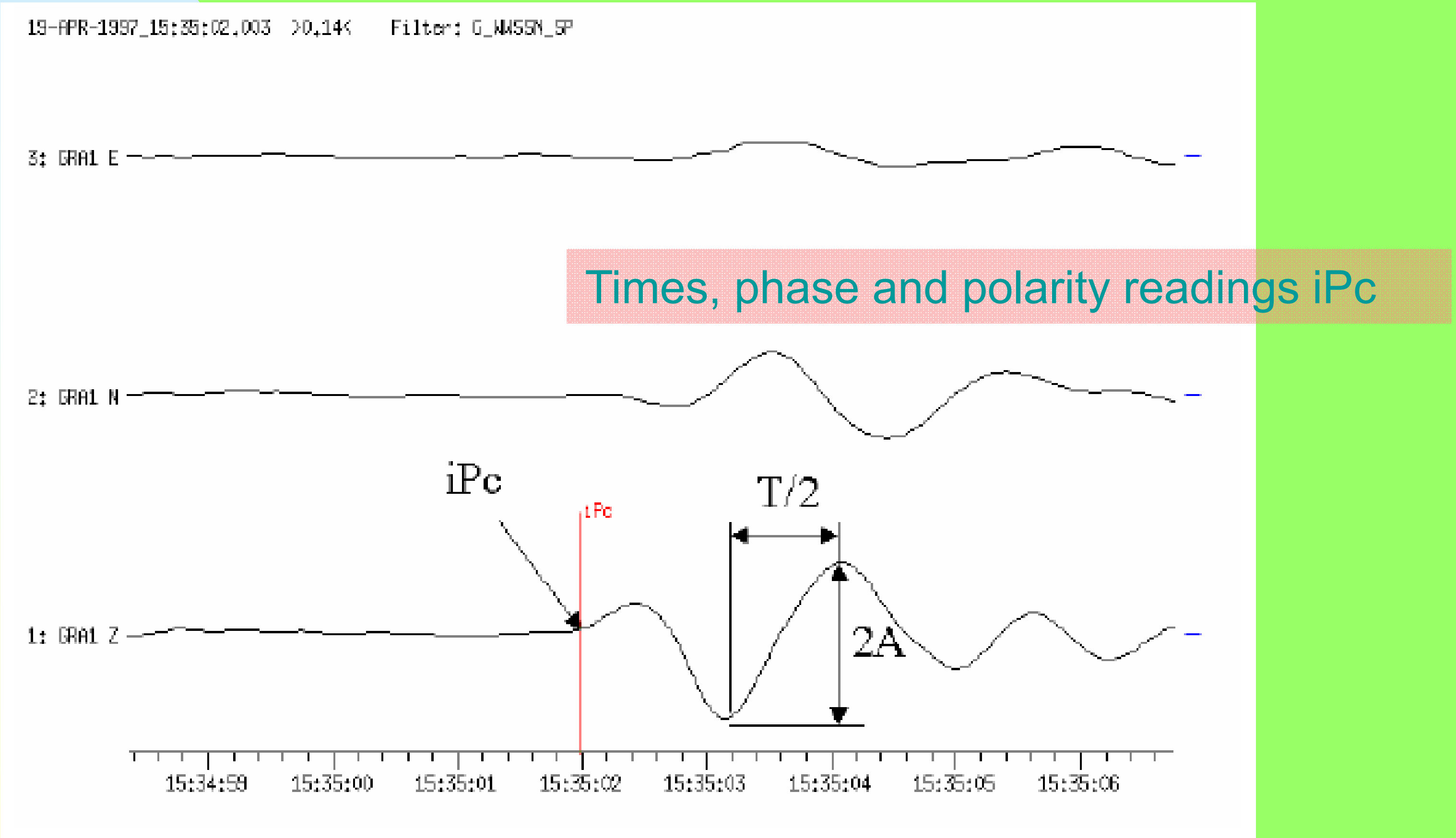
Identify phases ?

Draw the SS phase?



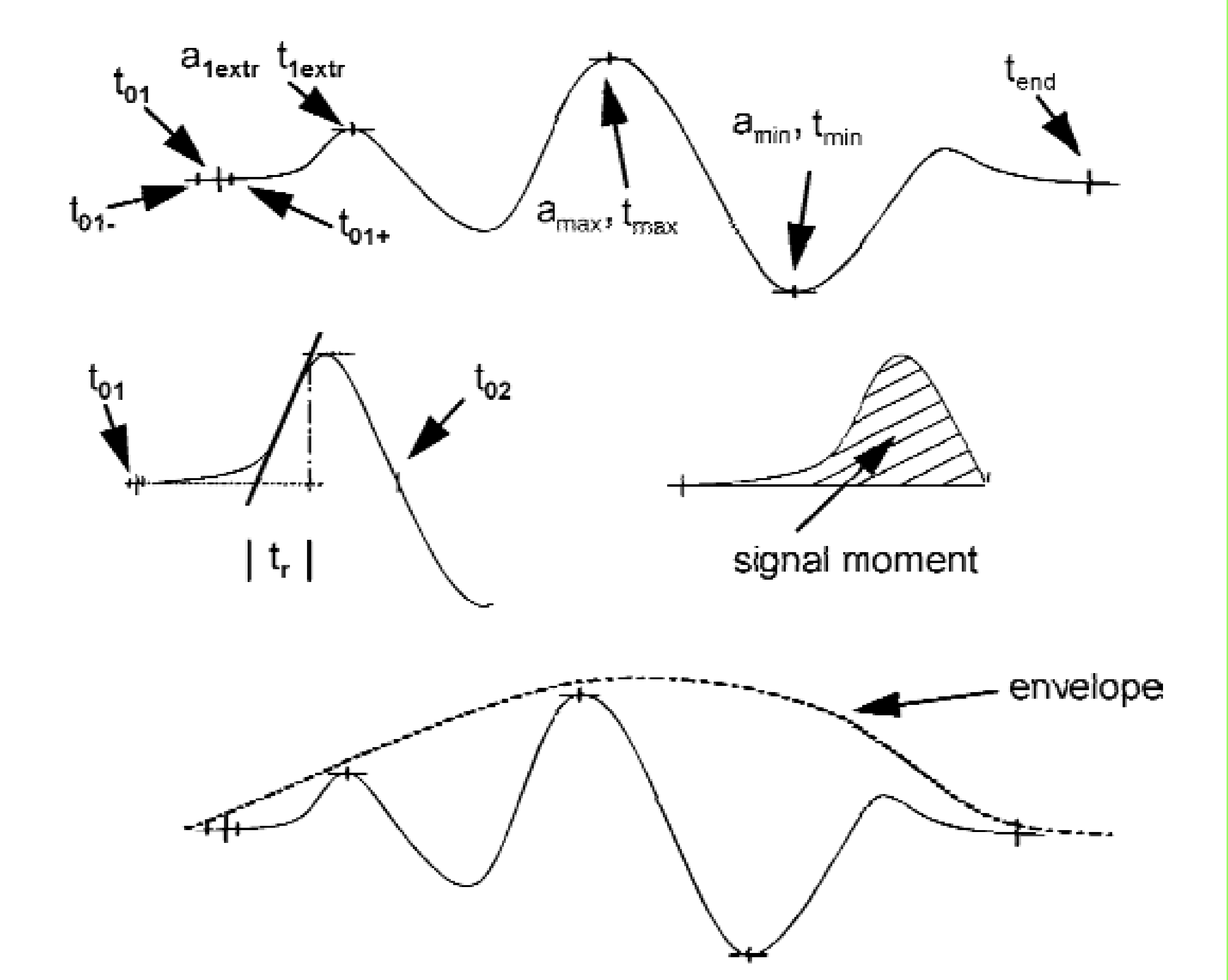
Picking time ?

- Onset time for first-arrival phases?

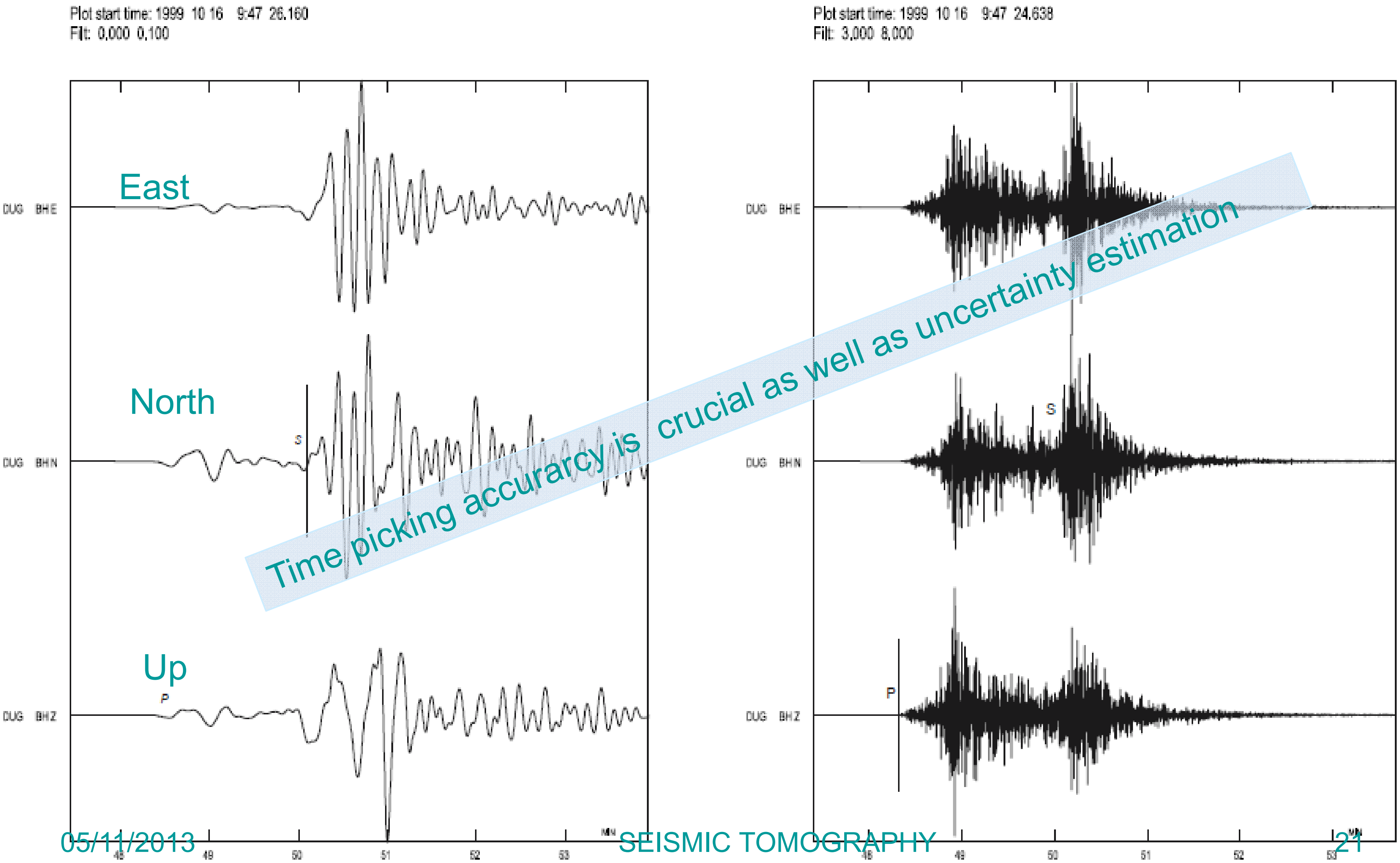


Picking time ?

- Deciphering the waveform



Low-pass or band-pass signals

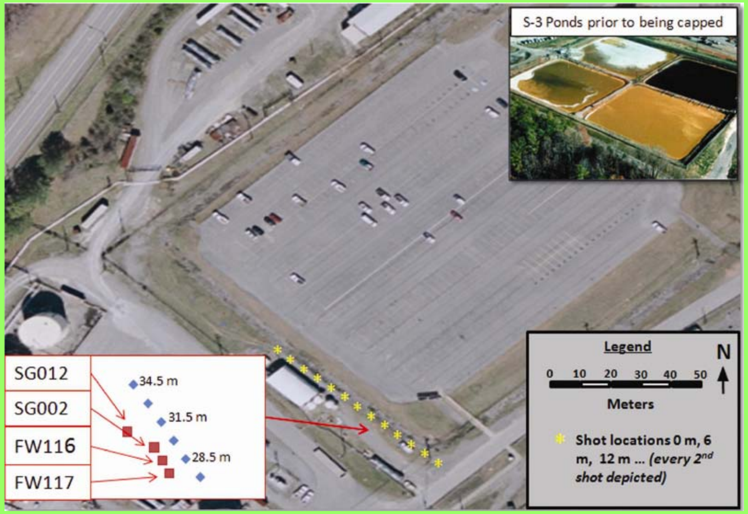


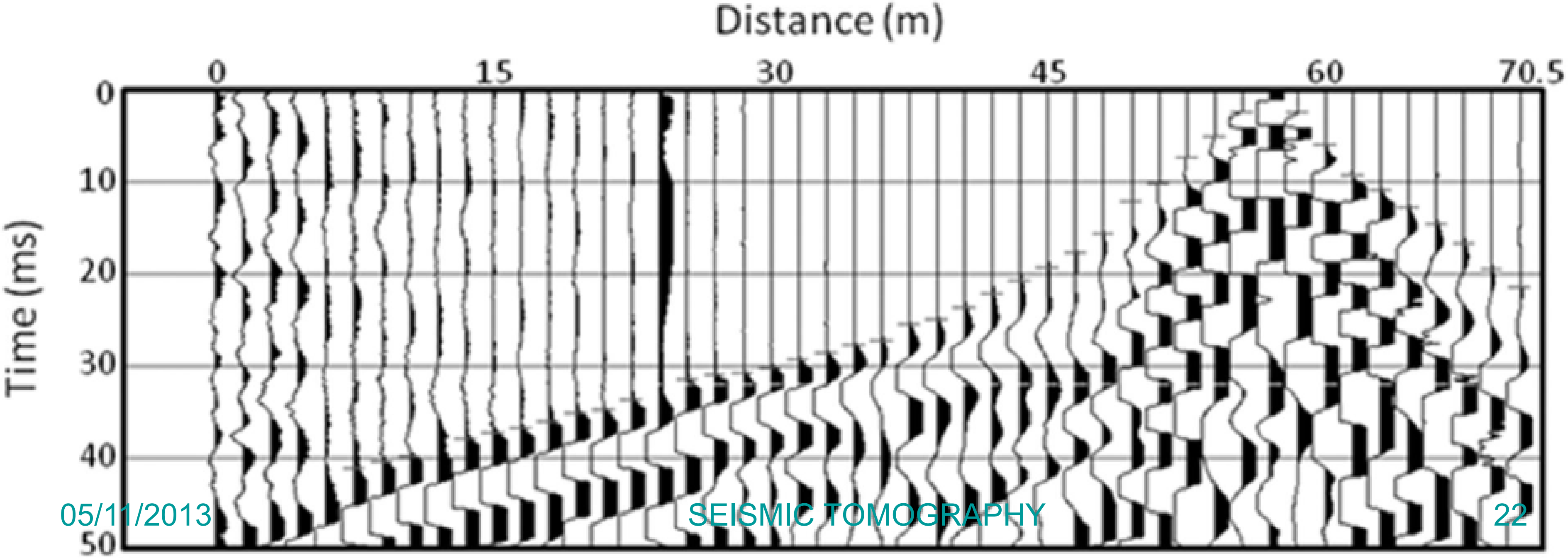
Local shots

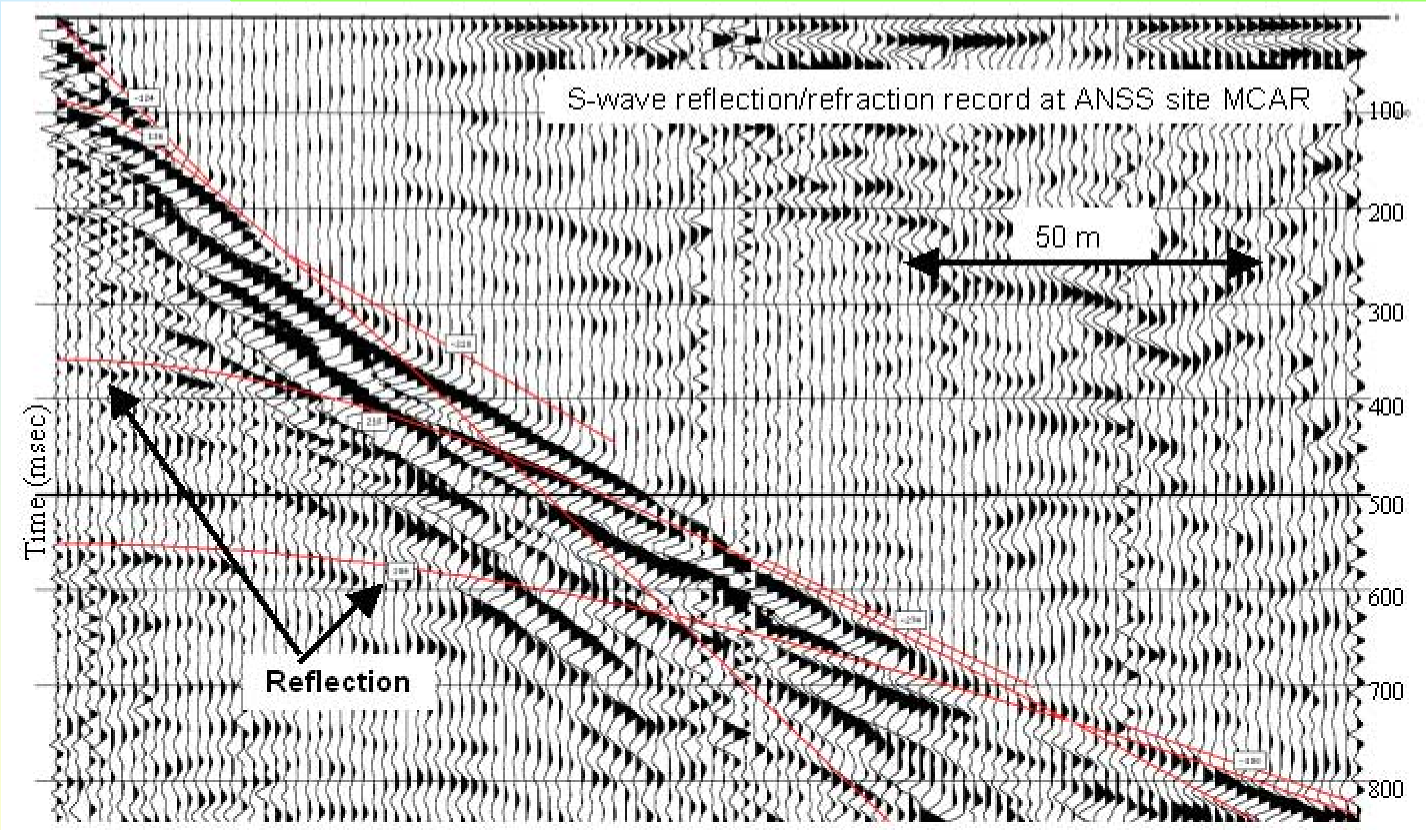
Water ponds below parking !

- Picking onset times

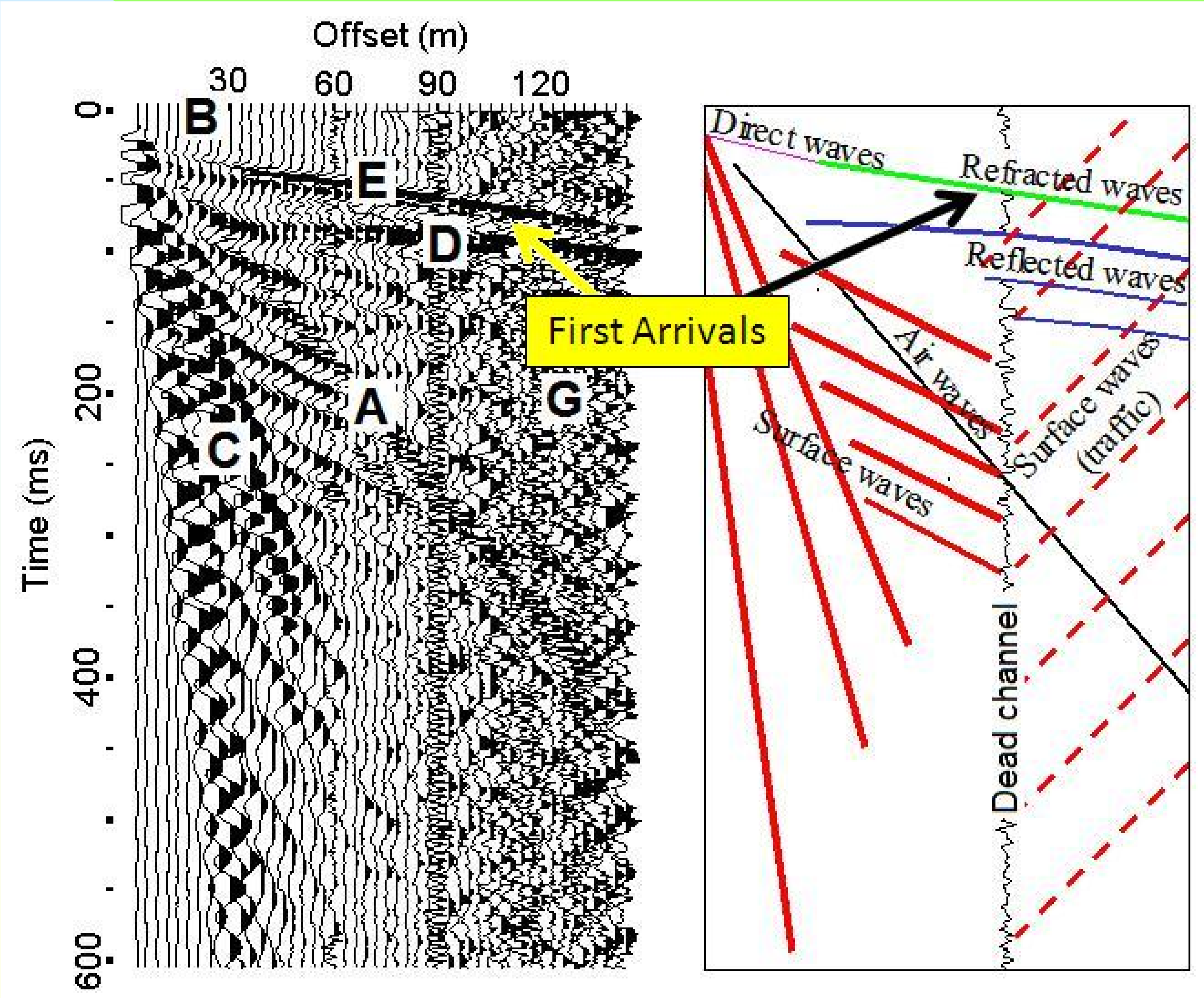
Profile 70.5 m
Geophone distance 1.5 m
Shot 57 m







(From Williams et al, USGS)

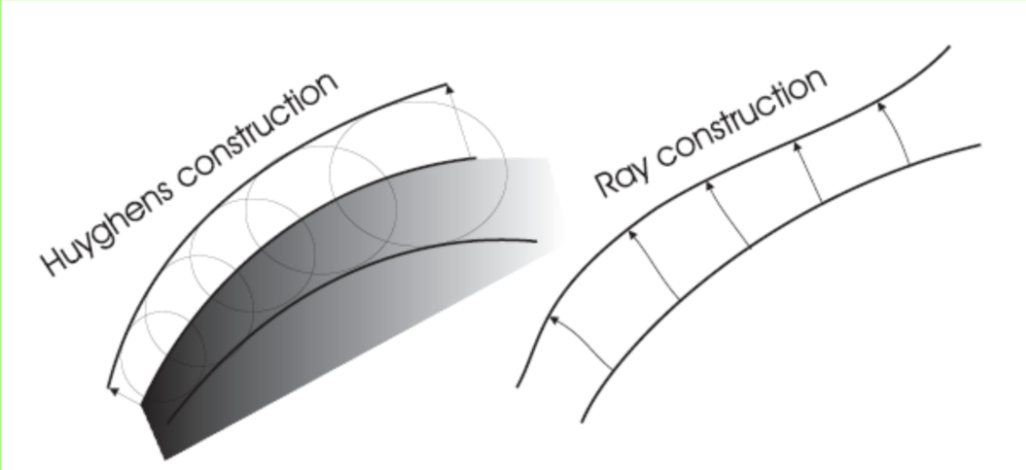


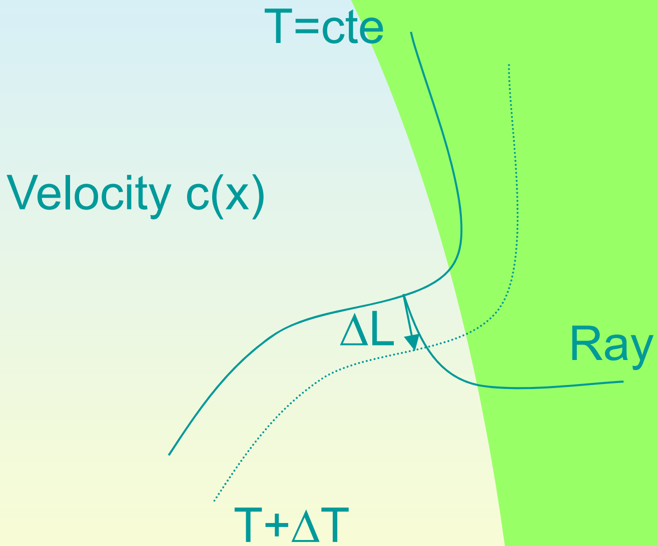
Offset (m)
30
60
90
120
0
200
400
600
Time (ms)
B
E
D
A
G
C
First Arrivals
Direct waves
Refracted waves
Reflected waves
Air waves
Surface waves
Surface waves (traffic)
Dead channel

Eikonal equation

Two simple interpretations of wavefront evolution

Orthogonal trajectories are rays in an isotropic medium





Grad(T)=$\nabla_x T$ orthogonal to wavefront

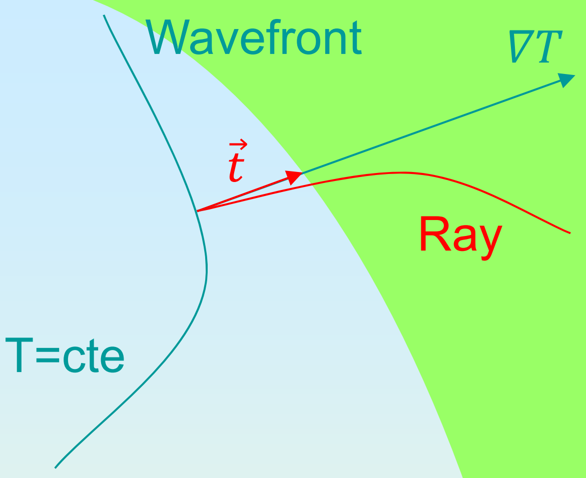
$$c(x) = \frac{\Delta L}{\Delta T} \rightarrow \frac{\Delta T}{\Delta L} = \frac{1}{c(x)} \rightarrow \nabla_x T(x) = \frac{1}{c(x)}$$

Direction ? : abs or square

The orientation of the wavefront could not be guessed from the local information on a specific wavefront

$$(\nabla_x T(x))^2 = \frac{1}{c^2(x)}$$

Ray equation



$\overrightarrow{x(s)}$ *with s as curvilinear abscisse* $\vec{t} = \frac{d\vec{x}}{ds} \rightarrow \|\vec{t}\| = 1$

Evolution of $\vec{x}$ is given by $\frac{d\vec{x}}{ds}$

$\frac{d\vec{x}}{ds} \parallel \nabla T \rightarrow$ $\frac{d\vec{x}}{ds} = c(x)\nabla T(x)$

Evolution of ∇T is given by $\frac{d\nabla T}{ds}$

Ray equations

but the operator $\frac{d}{ds} = \vec{t}.\nabla \ = c\nabla T.\nabla$

and, therefore, $\frac{d\nabla T}{ds} = c\nabla T.\nabla \ (\nabla T)$

leading to $\frac{d\nabla T}{ds} = \frac{c}{2}\nabla(\nabla T.\nabla T) = \frac{c}{2}\nabla(\nabla T)^2 = \frac{c}{2}\nabla(\frac{1}{c^2})$

$$\frac{d\nabla T}{ds} = \nabla(\frac{1}{c(x)})$$

Curvature equation

$$\frac{d}{ds}\left(\frac{1}{c(x)}\frac{d\vec{x}}{ds}\right) = \nabla(\frac{1}{c(x)})$$

We define the slownss vector $\vec{p} = \nabla T(x)$ and the position $\vec{q} = \vec{x}(s)$ along the ray

Various non-linear ray equations

Particule stepping

$$\frac{d\vec{q}(\xi)}{d\xi} = \vec{p}$$

$$\frac{d\vec{p}(\xi)}{d\xi} = \frac{1}{c(\vec{q})}\nabla\frac{1}{c(\vec{q})}$$

$$\frac{dT(\xi)}{d\xi} = \frac{1}{c^2(\vec{q})}$$

$$dT = \frac{1}{c(\vec{q})}ds = \frac{1}{c(\vec{q})^2}d\xi$$

under the condition of the eikonal
$p^2 = 1/c^2(\vec{q})$

ODE to be solved by numerical integration ?

Runge-Kutta integration

Express with slowness

$$u(\vec{q}(\xi)) = \frac{1}{c(\vec{q}(\xi))}$$

$$\frac{d\begin{bmatrix}\vec{q}(\xi)\\ \vec{p}(\xi)\end{bmatrix}}{d\xi} = \begin{bmatrix} 0 & \vec{p}(\xi) \\ \frac{1}{c(\overrightarrow{q(\xi})} \nabla \frac{1}{c(\vec{q}(\xi))} & 0 \end{bmatrix}$$

Second-order RK integration

$$\frac{df}{d\xi} = A(f)$$

Non-linear ray tracing

$$f^{1/2} = f^0 + \frac{\Delta\xi}{2} A(f^0)$$

$$f^1 = f^0 + \Delta\xi \; A\left(f^{1/2}\right)$$

$$\frac{dT(\xi)}{d\xi} = \frac{1}{c^2(\vec{q})}$$

Travel-time computation

How to reconstruct the velocity?

- Forward problem (easy)

    if we know the velocity structure, we can compute travel times and horizontal distances (as well as amplitudes)

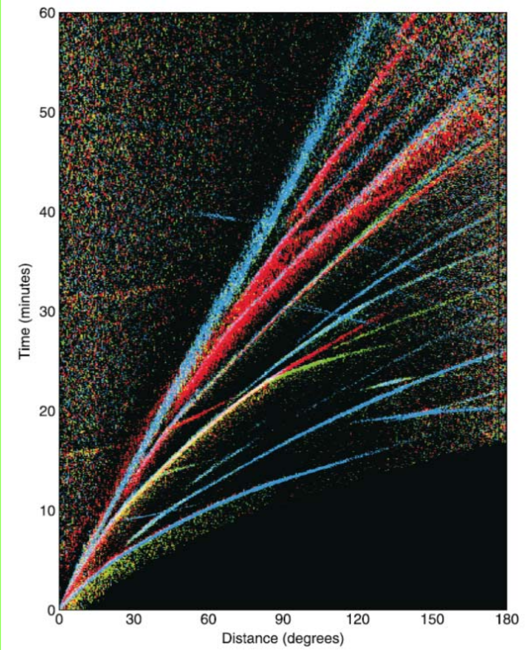
- Inverse problem (difficult)

    From measured travel times (or horizontal distances for a given ray), could we deduce the velocity structure. This is the travel-time tomography or seismic tomography.

    More difficult is the diffraction tomography which uses the waveform or the amplitude of the signal.

Earth reference velocity model

- Harrold Jeffreys and Keith Bullen (1940), (J-B) Remarkable accuracy for teleseismic travel times (below 1%)!
- Herrin et al. (1968), with well located earthquakes.
- Dziewonski and Anderson (1981), Preliminary Reference Earth Model (PREM)
- Kennett and Engdahl (1991), most accurate radially symmetric model (iasp91)
- (2000), The first 3-D reference model with travel times?



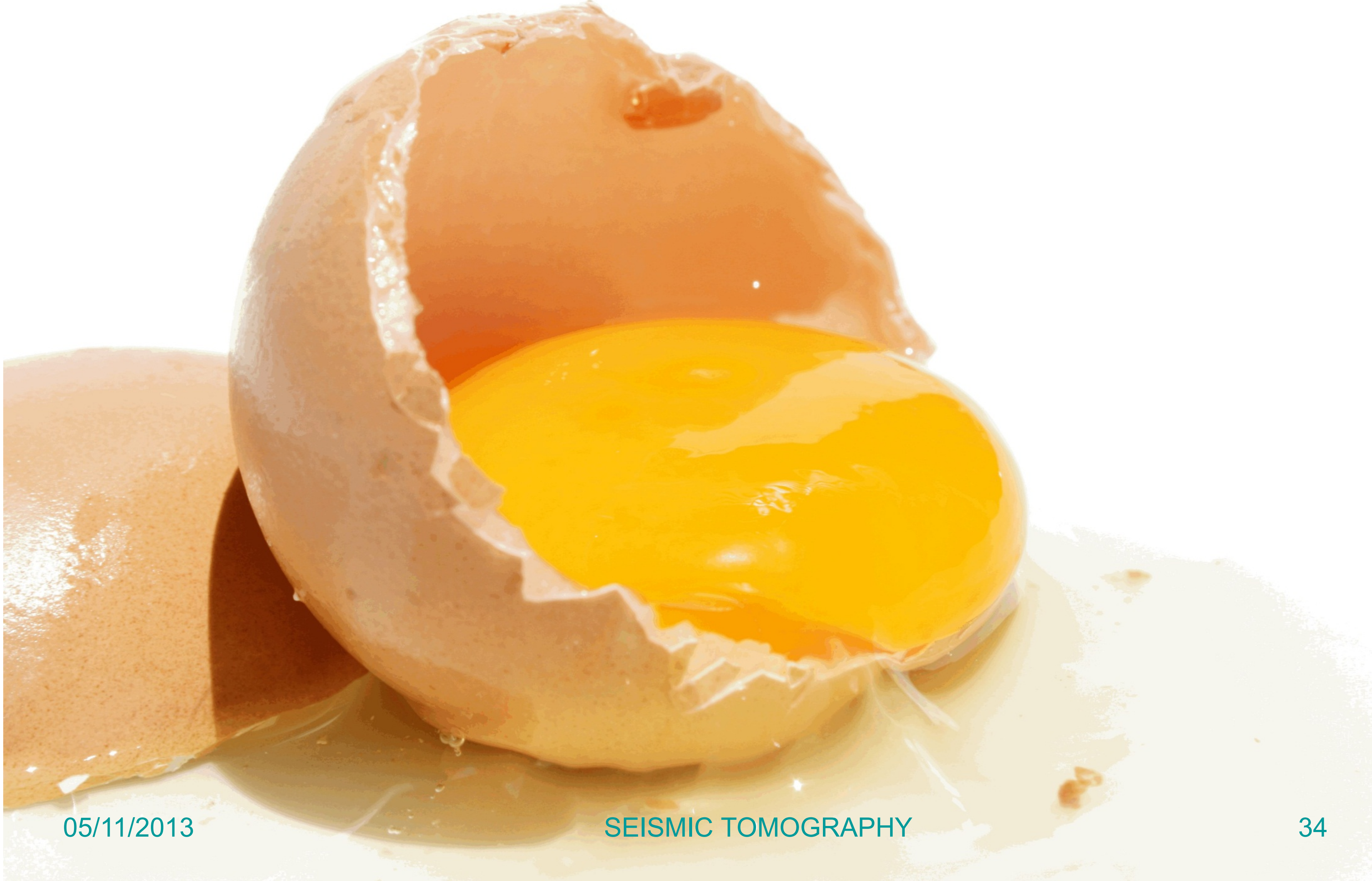
Seismic tomography

- Tomography: a very general problem

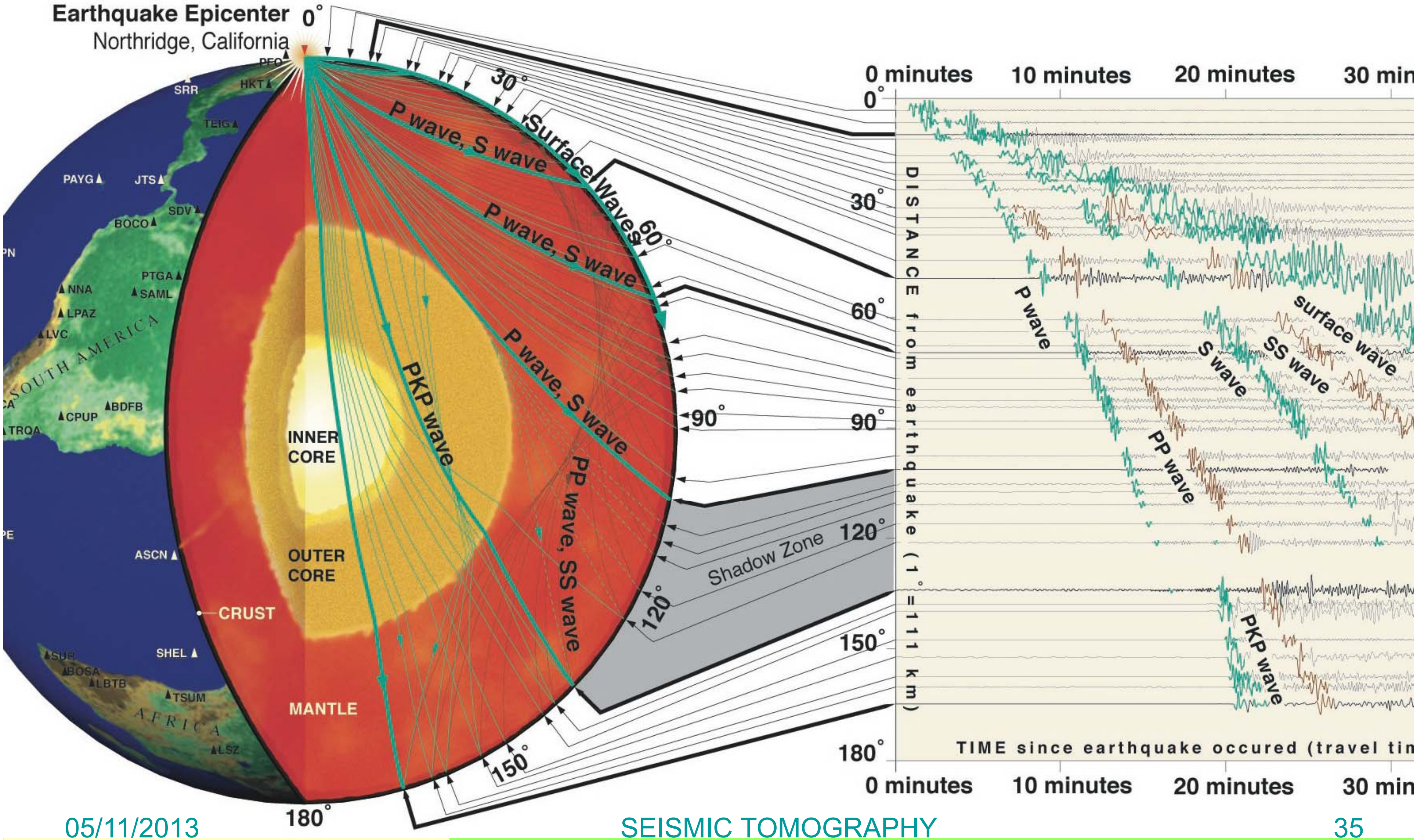
  medical, oceanography, atmosphere
- Very difficult problem when considering travel times.
  - Direct relation between times and velocity profile: only tractable for 1D structure …
- Difficult problem when considering delayed travel times.
  - Perturbation techniques can be used which requires an initial medium as the starting guess.

What is inside ?

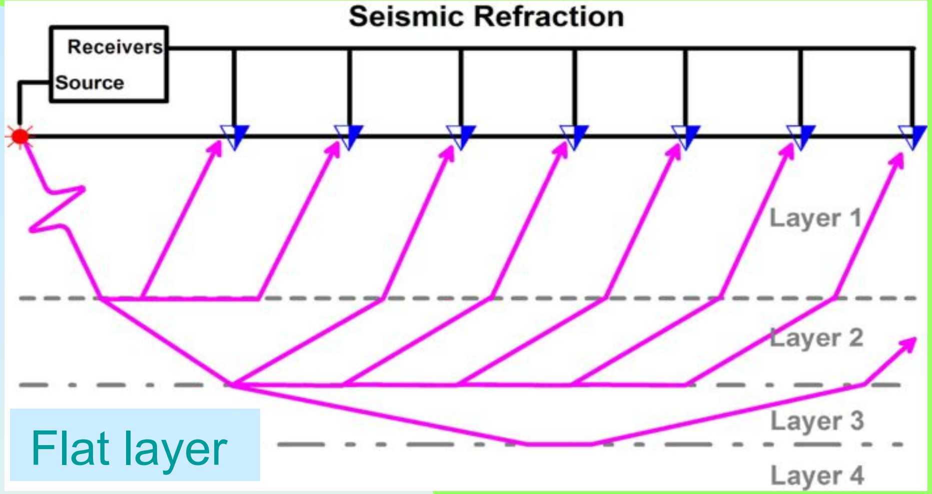
How do you know what is inside?



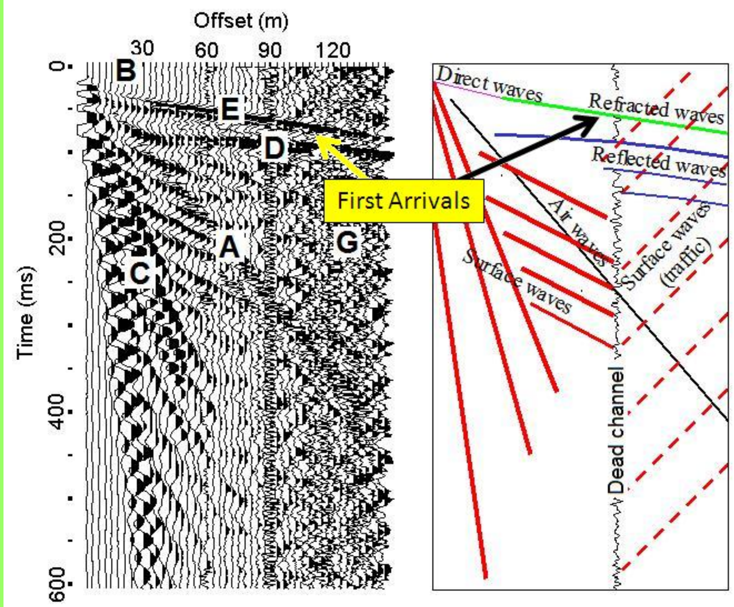
Tomography from travel times ….



Local propagation

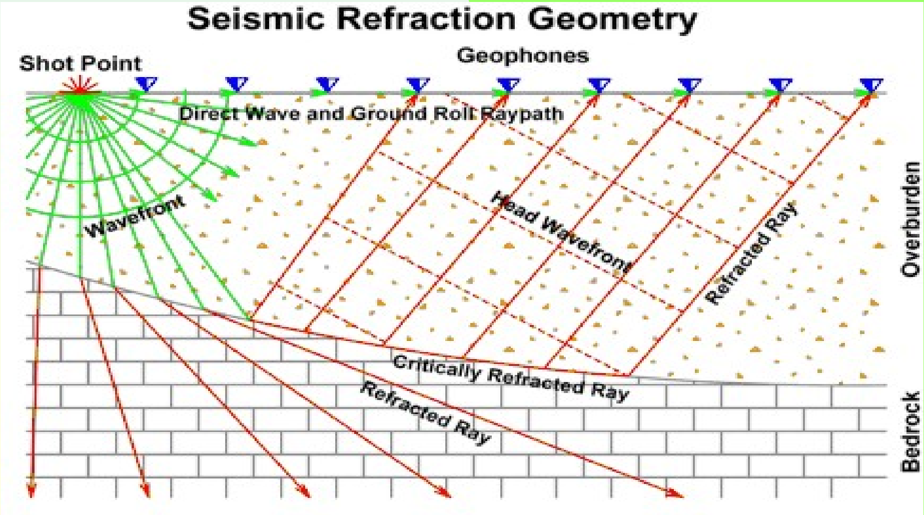


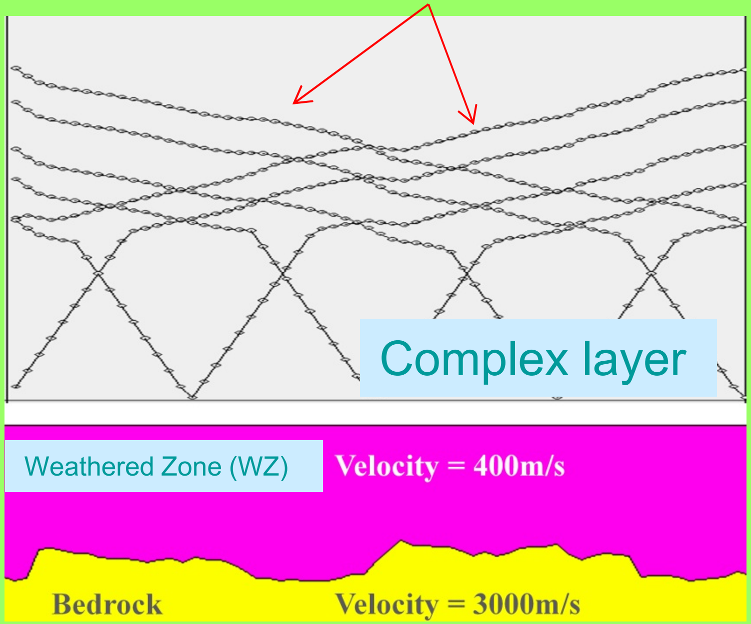
Flat layer



Plus-minus effect

Lateral variations

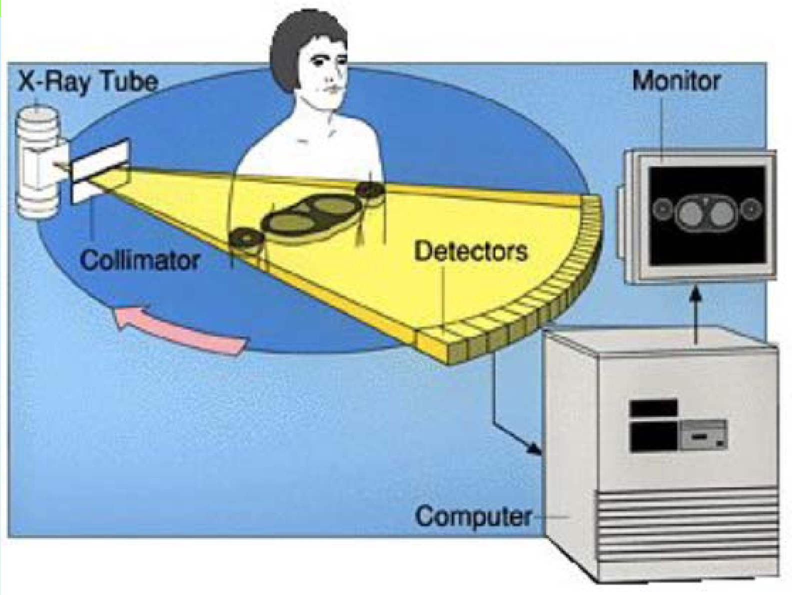




Complex layer

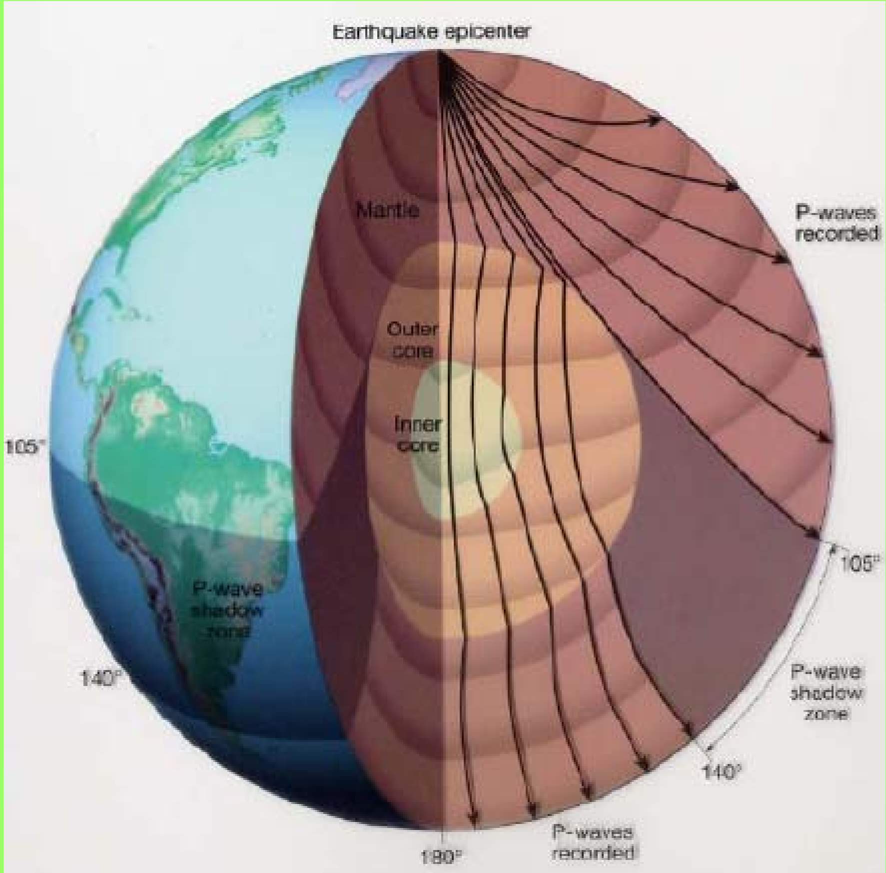
Weathered Zone (WZ)

Medical imaging



X scan: X ray emission, absorption related to density, density reconstruction

Emission of seismic waves, travel times related to velocity, velocity reconstruction

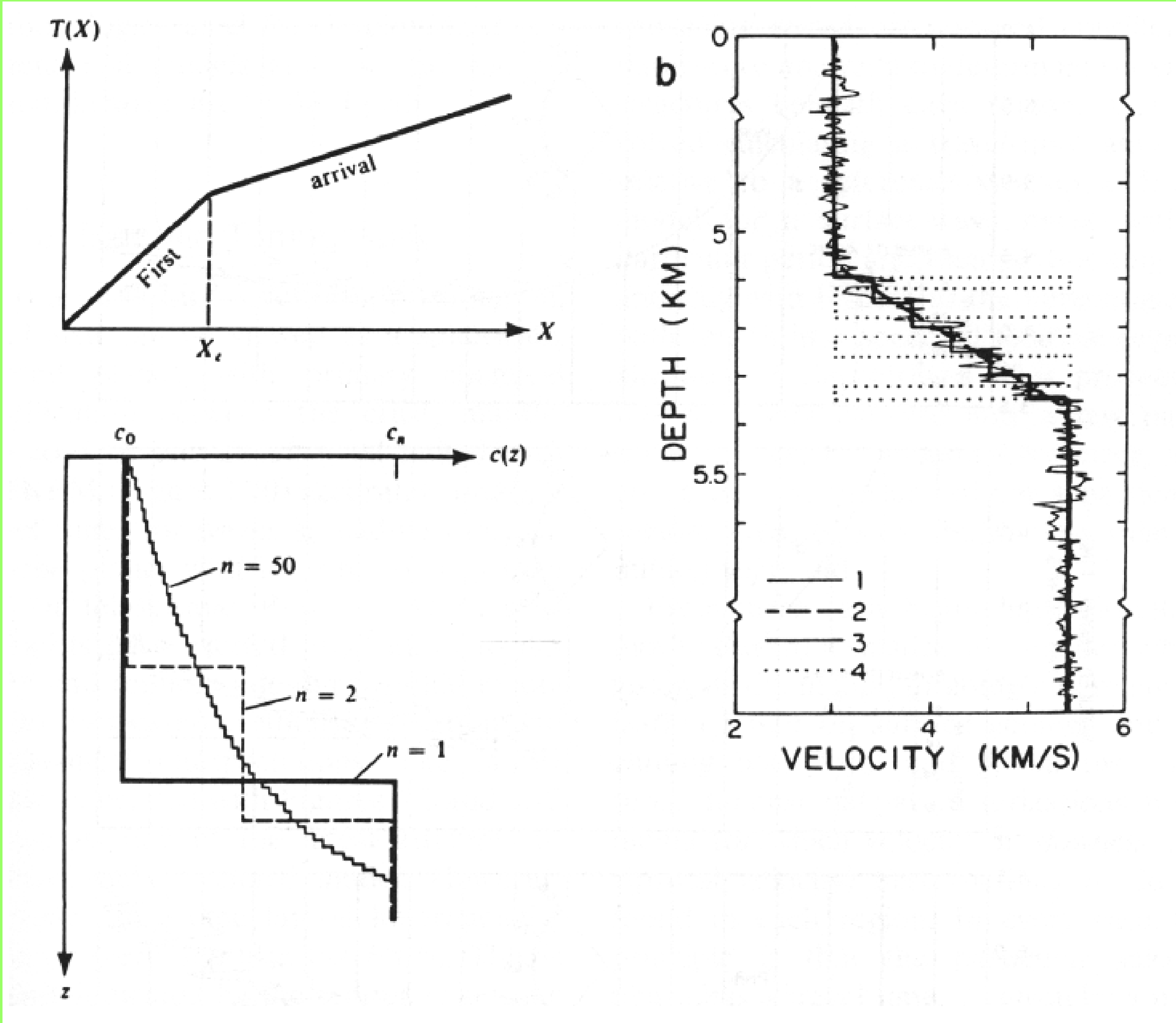


Geophysical imaging

From Paul (2013)

First-arrival times: non-unicity of the reconstruction

A first-arrival travel time curve is compatible with an infinite set of structures …



Aki & Richards (1980)

Velocity field v(z) or slowness u(z)

Ray equations are simpler

$\boldsymbol{q}(\xi), \boldsymbol{p}(\xi)$?

$$\frac{dp_x}{d\xi} = 0; \frac{dp_y}{d\xi} = 0; \frac{dp_z}{d\xi} = u(z)\frac{du(z)}{dz}$$

The horizontal component of the slowness vector is constant: ray tracing is performed in a plan defined by the initial horizontal slowness. We can eliminate y by a simple rotation …

$$\frac{dq_x}{dq_z} = \frac{p_x}{p_z} = \frac{p_x}{\pm\sqrt{u^2(z) - P_X{}^2}}$$

p_x, the ray parameter p, is cte

$$\frac{dp_x}{d\xi} = 0; \frac{dp_z}{d\xi} = u(z)\frac{du(z)}{dz}$$

$$q_x(z_1, p_{x1}) = q_x(z_0, p_{x0}) + \int_{z_0}^{z_1} \frac{p_x}{\sqrt{u^2(z) - p_x{}^2}} dz$$

for a downgoing ray

Herglotz-Wiechert-(Bateman) law for velocity profile v(z)

$$v_a(r_{max}) = \frac{d\Delta}{dt} = {}^1/_p$$

From the tangent at the curve $t(\Delta)$; we can estimate the apparent velocity v_a which is just the velocity at the bottom point of the ray, but we do not know this point …

To get this depth, we need to estimate the apparent velocity for all points from the source to the distance Δ_1.

$$z(\Delta_1) = \frac{1}{\pi}\int_0^{\Delta_1} \arg ch \frac{v_a(\Delta_1)}{v_a(\Delta)} d\Delta$$

Abel problem (1826)

This is valid only for continuous curve and for an increase of velocity. If so, we have a direct relation between depth and velocity

$$\begin{matrix} z(\Delta_1) \\ v_a(\Delta_1) \end{matrix} \Rightarrow z(v) \Rightarrow v(z)$$

HWB inverse law for v(r)

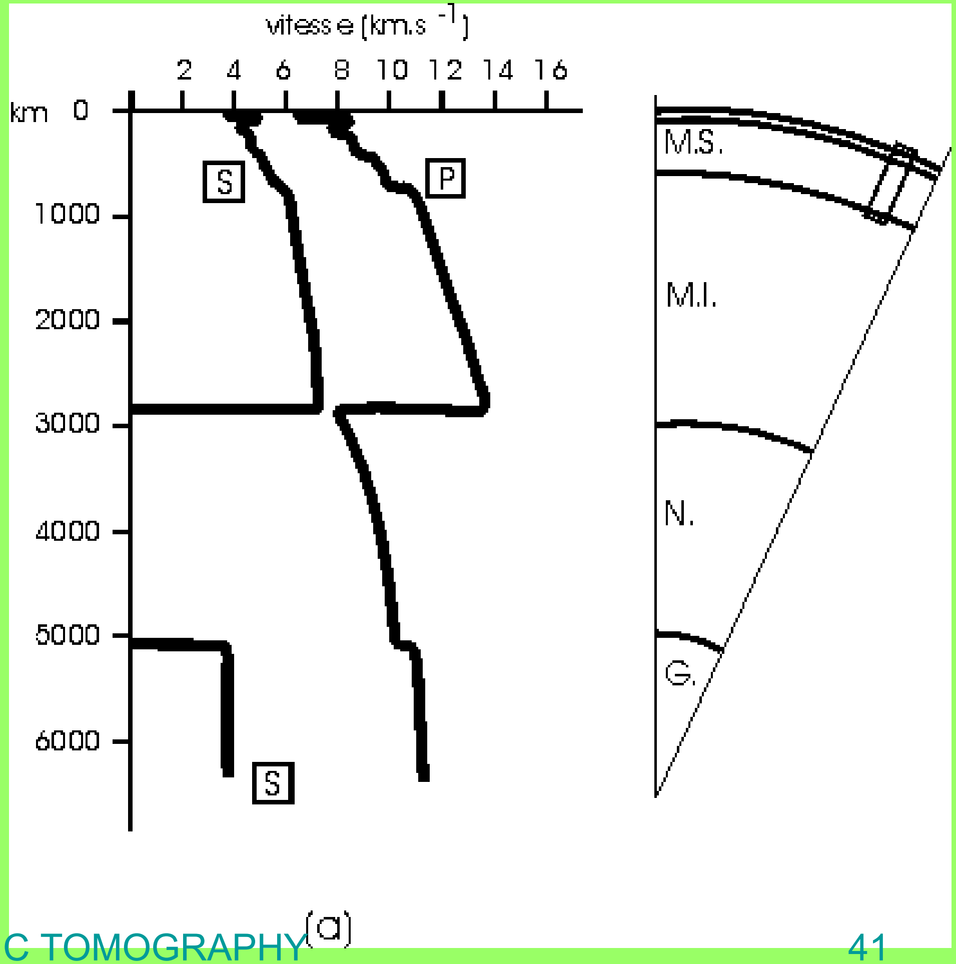
$$\ln\left(\frac{R}{r(\Delta_1)}\right) = \frac{1}{\pi}\int_0^{\Delta_1} \arg ch \frac{p}{\xi_1} d\Delta$$

Spherical Earth

$$slope\ \xi_1 = \frac{dt}{d\Delta})_{\Delta_1} = \frac{r}{v_a(\Delta_1)}$$

$$\begin{matrix} r(\Delta_1) \\ v_a(\Delta_1) \end{matrix} \Rightarrow r(v) \Rightarrow v(r)$$

- Layered structure
- Radial structure

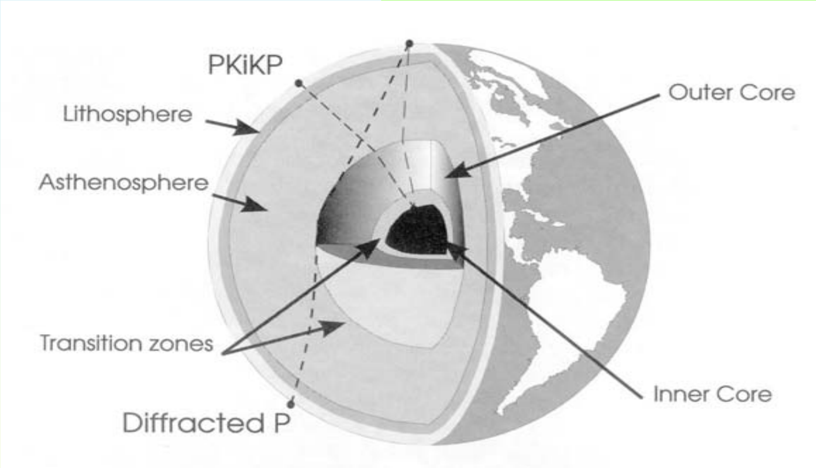


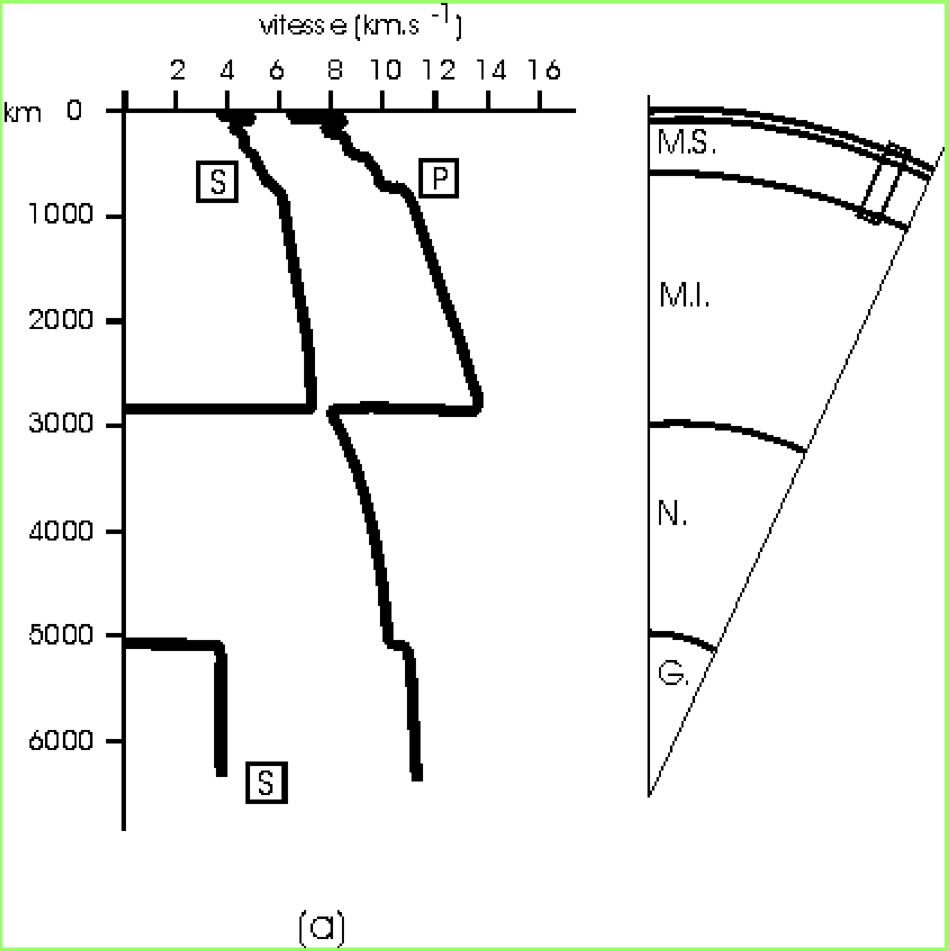
Summary for layered medium

- We may reconstruct an interface at a given depth when considering all waves.
- From first-arrival times, we may build an infinity number of solutions … (direct and head waves only).
- Jump in the velocity profile when a low velocity zone.

Radial Earth structure

- Velocity profile built from travel times





Slight increase of complexity if decrease of velocity

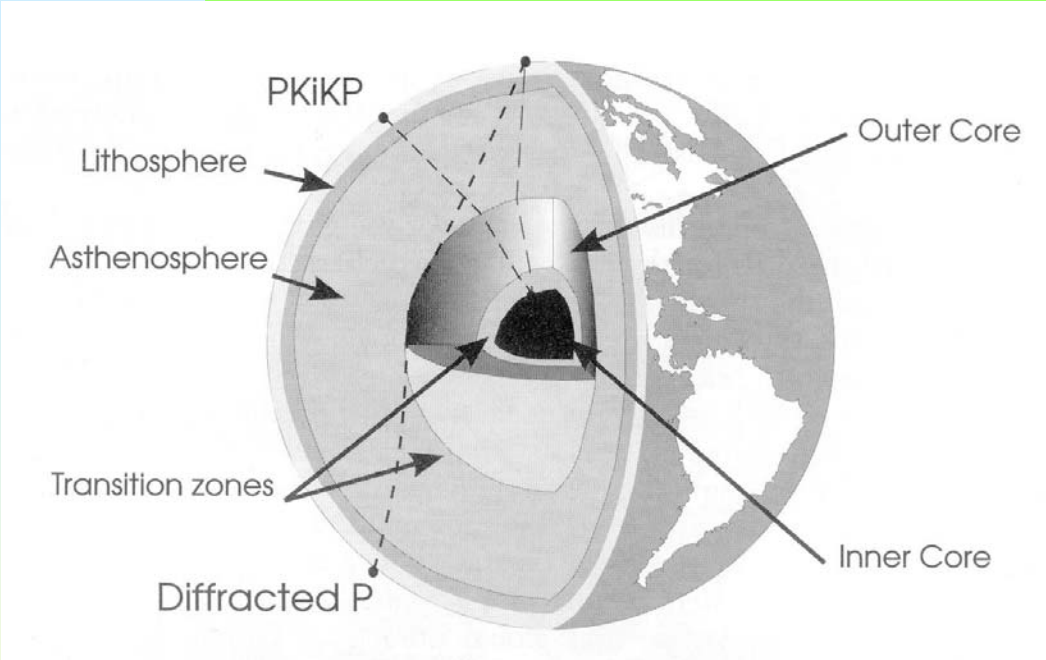
Starting model from the HWB method

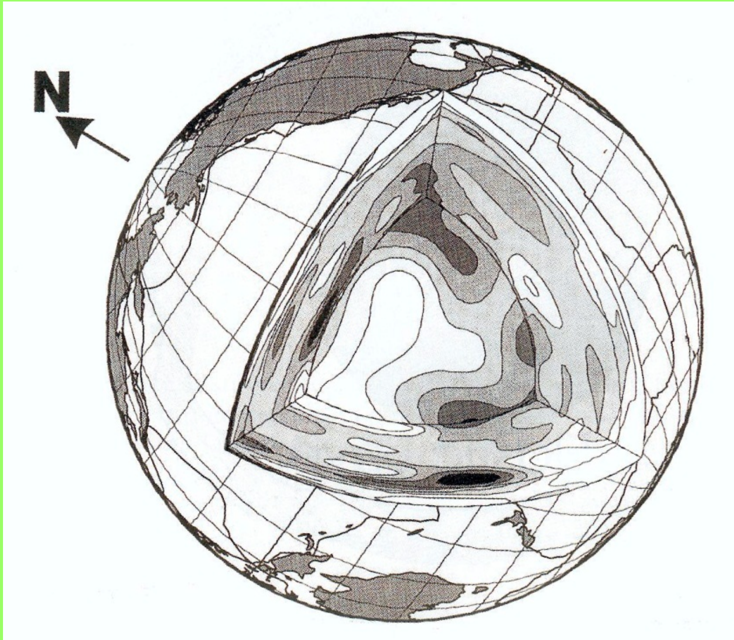
- An initial model has been reconstructed (simple v(z)/v(r))
- The HWB law does not allow the introduction of prior information …

F. Press in 1968 has prefered an exhaustive exploration of all velocity profiles (5 millions at that time). The quality of the profile is simply assessed through a misfit function evaluation as the square sum of observed times ans computed times. The design of the misfit function could introduce other features we may consider such as density and observed inertial moments and so on.

- Full model exploration: grid method, Monte Carlo method, simulated annealing, genetic algorithm, ant path …

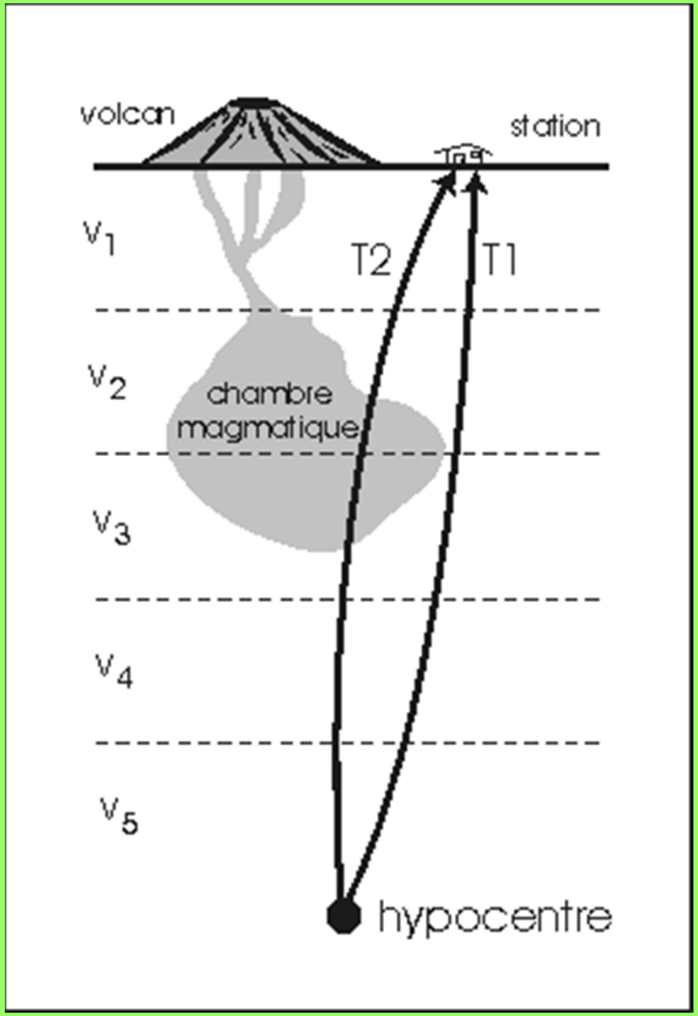
Radial model: not enough!



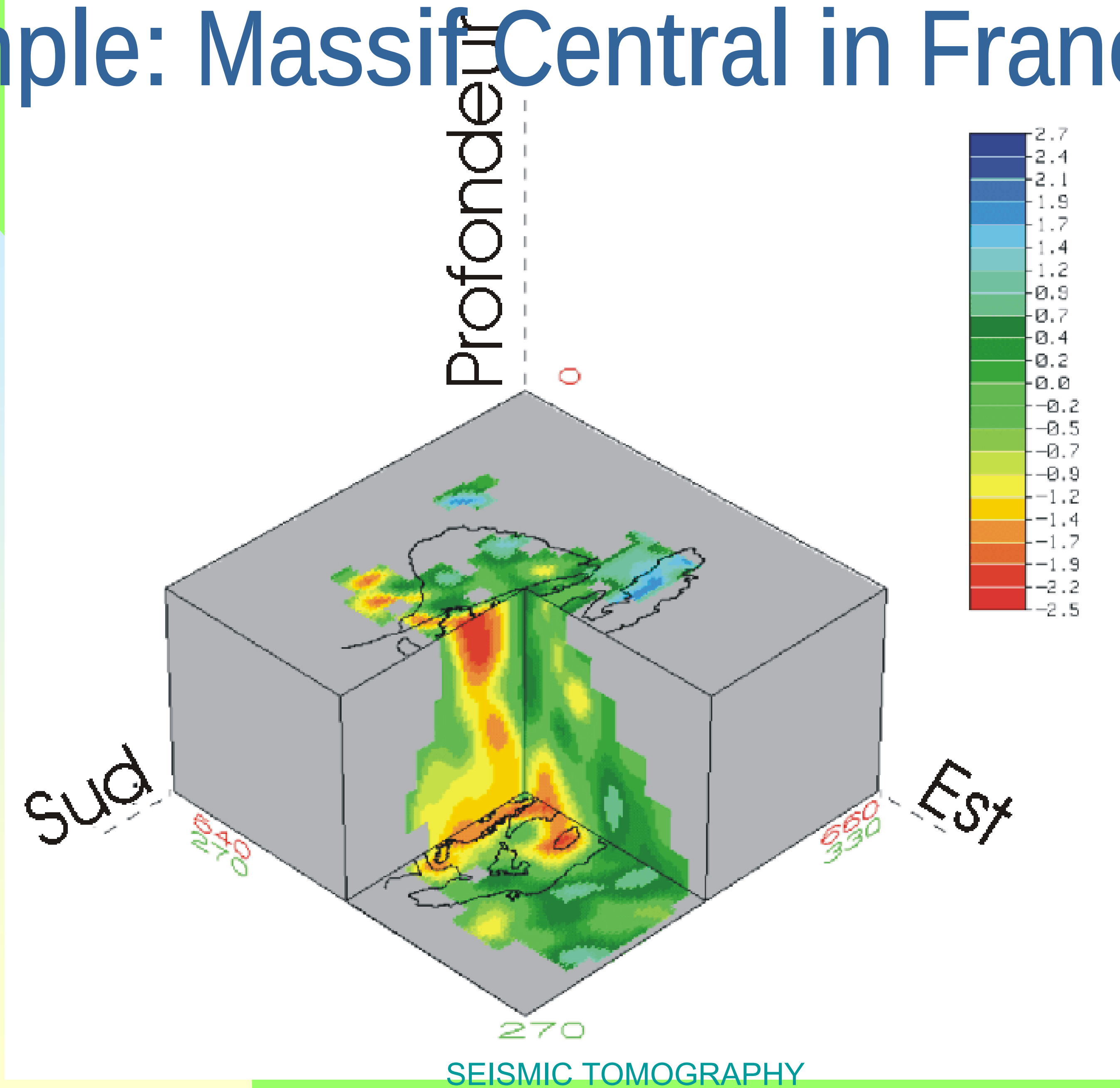


Simpler case: small perturbation

- Initial structure of velocity
- Small variation of velocity or slowness
- Linear approach



Example: Massif Central in France

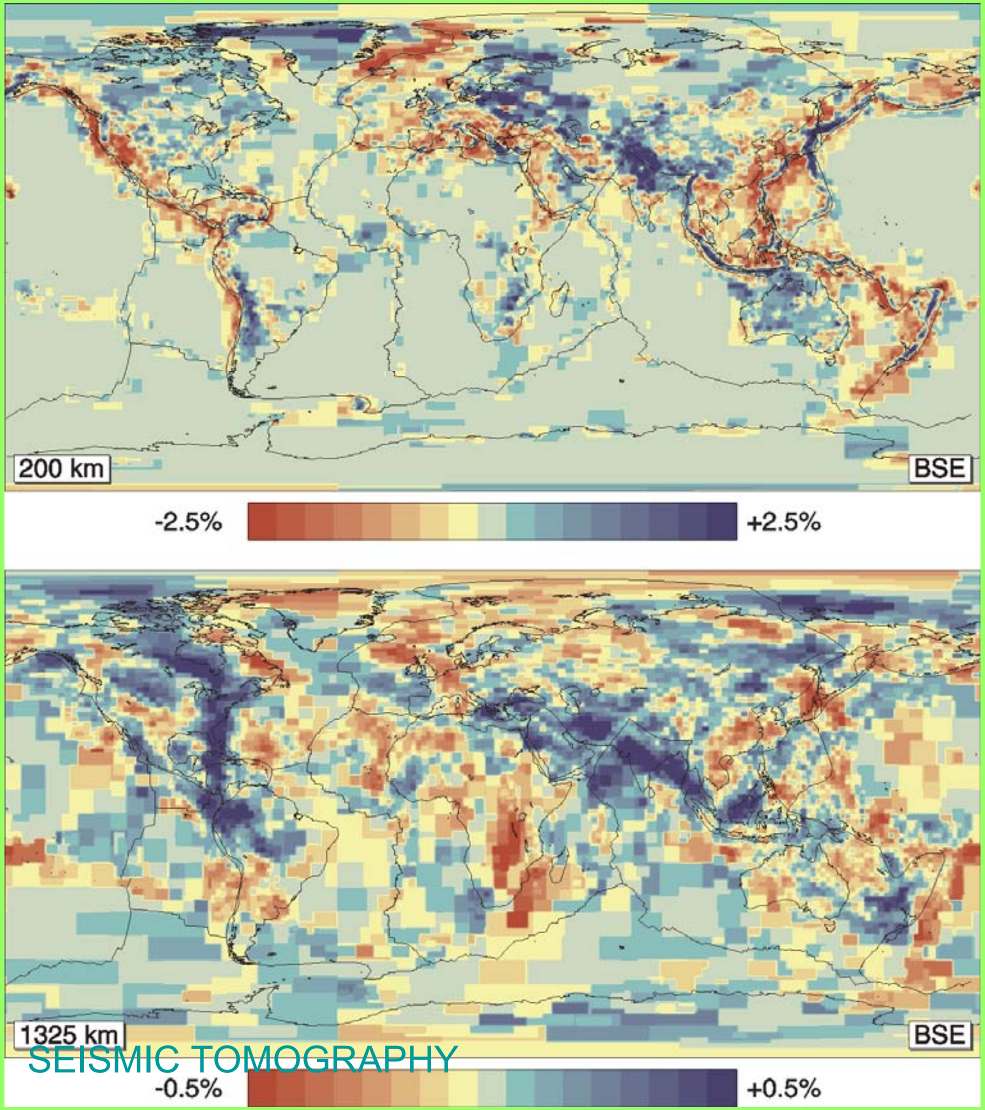


Global seismic tomography

- Velocity variations at 200 km: correlation with superficial structure

- Velocity variations at 1325 km: correlation with geoid

Document W. Spakman



Delayed travel-time tomography

$$t(source, receiver) = \int_{source}^{receiver} u(x, y, z) dl$$

Finding the slowness u(x) from t(s,r) is a difficult problem: only techniques for one variable !

Consider small perturbations $\delta u(x, y, z)$ from a slowness field $u_0(x, y, z)$

$$t(src, rec) = \int_{src}^{rec} u_0(x, y, z) dl + \int_{src}^{rec} \delta u(x, y, z) dl$$

$$t(src, rec) \approx \int_{src_0}^{rec_0} u_0(x, y, z) dl + \int_{src_0}^{rec_0} \delta u(x, y, z) dl$$

$$t(src, rec) - t_0(src, rec) \approx \int_{src_0}^{rec_0} \delta u(x, y, z) dl$$

$$\delta t(src, rec) \approx \int_{src_0}^{rec_0} \delta u(x, y, z) dl$$

This a LINEAR PROBLEM

$$\delta t(s, r) = A(u_0)\, \delta u(x, y, z)$$

Model description

- The model of velocity perturbation (or slowness $\delta u(x,y,z)$) could be described in a regular mesh with values at each node $\delta u_{i,j,k}$. We may define the interpolation function (shape function) for the estimation of slowness perturbation everywhere.
- A simple shape function $h_{i,j,k}$ could be 1 at (i,j,k) and 0 everywhere else.

$$\delta u(x,y,z) = \sum_{cube} \delta u_{i,j,k}\, h_{i,j,k}$$

Linear system

$$\delta u(x,y,z) = \sum_{cube} \delta u_{i,j,k}\, h_{i,j,k}$$

Slowness perturbation description

$$\delta t(src,rec) = \int_{src_0}^{rec_0} dl \sum_{cube} \delta u_{i,j,k}\, h_{i,j,k}$$

$$\delta t(src,rec) = \sum_{cube} \delta u_{i,j,k} \int_{src_0}^{rec_0} dl\, h_{i,j,k}$$

$$\delta t(src,rec) = \sum_{cube} \delta u_{i,j,k} \frac{\partial t}{\partial u}$$

Discretisation of the medium fats the ray

Sensitivity matrice is a sparse matrice

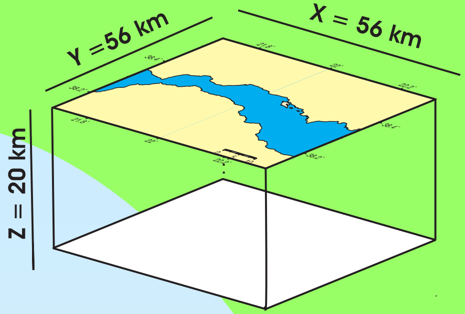
$$\Delta t = A_0 \Delta u$$

Matrice of sensitivity or of partial derivatives

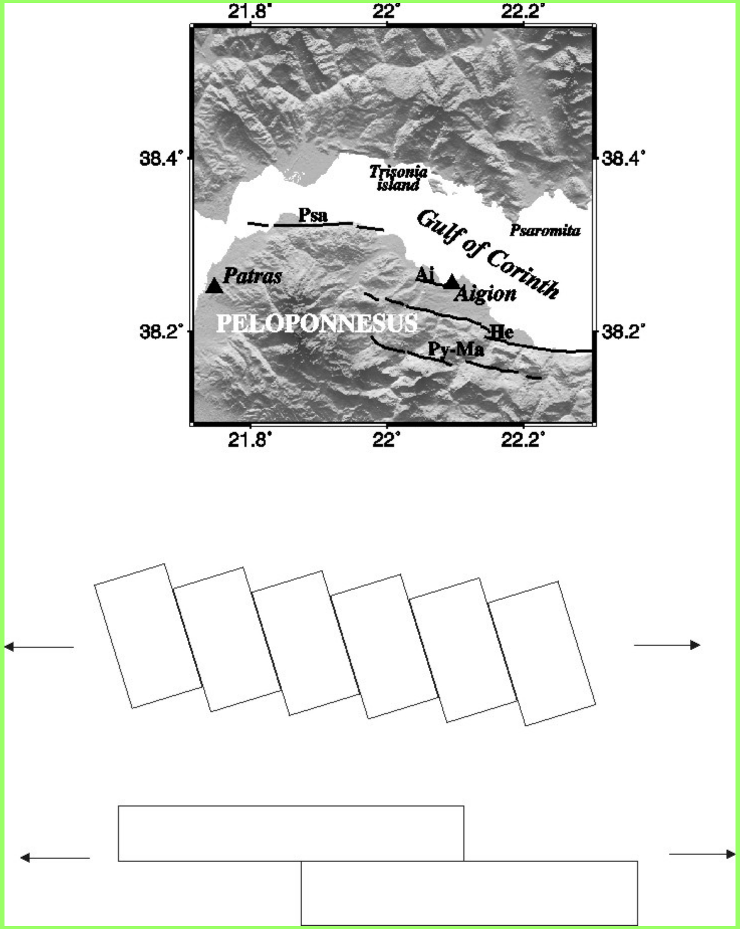
Joint hypo-velocity inversion

$$\delta t(src, rec) = \sum_{cube} \frac{\partial t}{\partial u} \delta u_{i,j,k} + \overrightarrow{p_s}.\overrightarrow{\delta x_s} + 1.\delta t_{0s}$$

$$\begin{bmatrix} \delta t_1 \\ \delta t_2 \\ \delta t_3 \\ \vdots \\ \delta t_{N-2} \\ \delta t_{N-1} \\ \delta t_N \end{bmatrix} = \begin{bmatrix} \partial t/\partial u & 0 & \partial t/\partial u & \cdots & p_{xs} & p_{ys} & p_{zs} & \ldots & 1 \\ 0 & \partial t/\partial u & 0 & \ldots & p_{ys} & p_{ys} & p_{zs} & \cdots & 1 \\ 0 & 0 & 0 & \cdots & p_{ys} & p_{ys} & p_{zs} & \cdots & 1 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \partial t/\partial u & 0 & \partial t/\partial u & \cdots & 0 & 0 & 0 & \ldots & 0 \\ 0 & \partial t/\partial u & \partial t/\partial u & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & \partial t/\partial u & \cdots & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \begin{bmatrix} \delta u_{1,1,1} \\ \delta u_{2,1,1} \\ \delta u_{3,1,1} \\ \vdots \\ \vdots \\ \delta x_s \\ \delta y_s \\ \delta z_s \\ \vdots \\ \delta t_{os} \end{bmatrix} =$$



The Corinth Rift



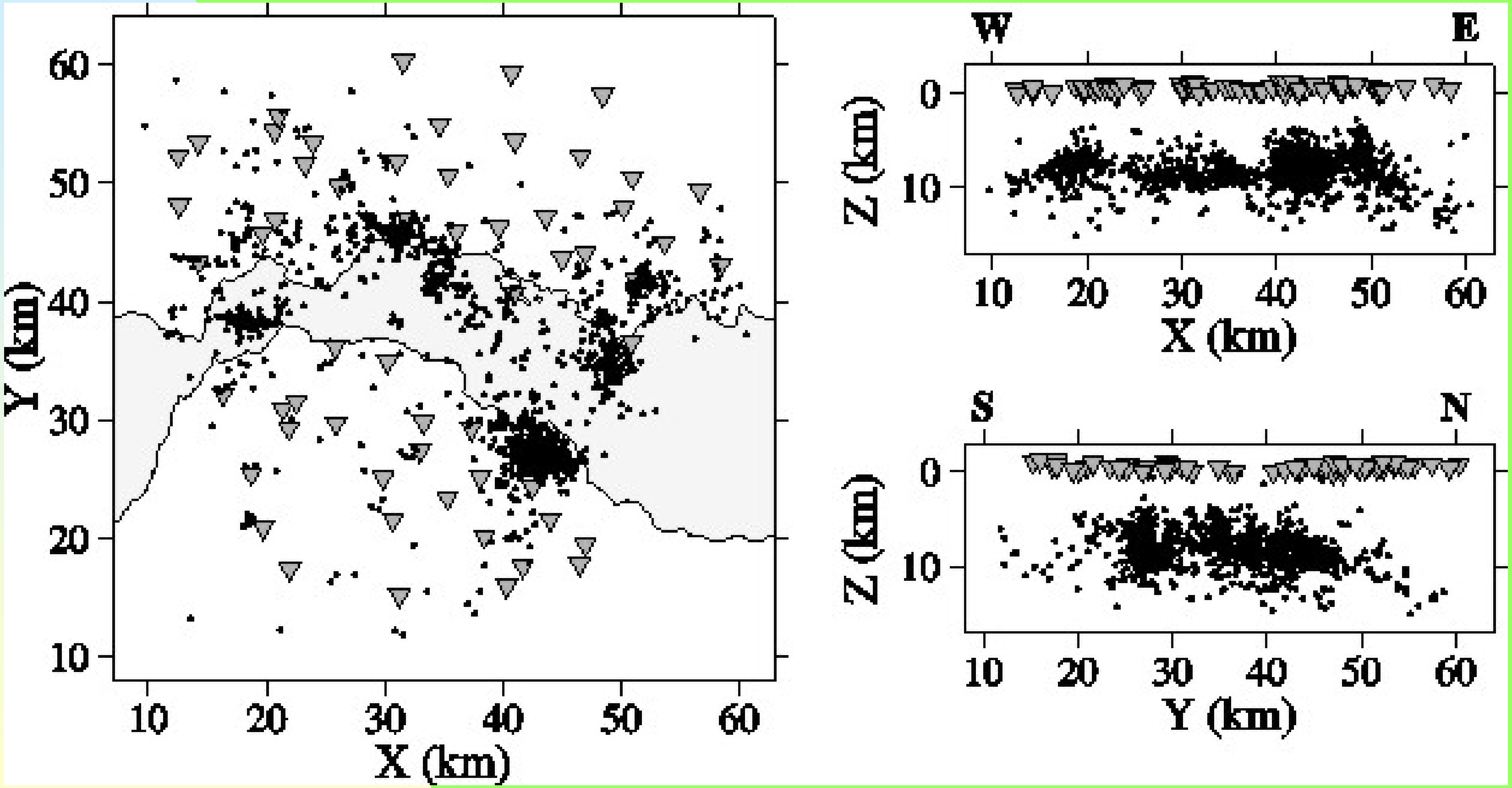
One of the most active intercontinental extension zone

What is the basic mechanism?

How this mechanism could be compatible with physical features

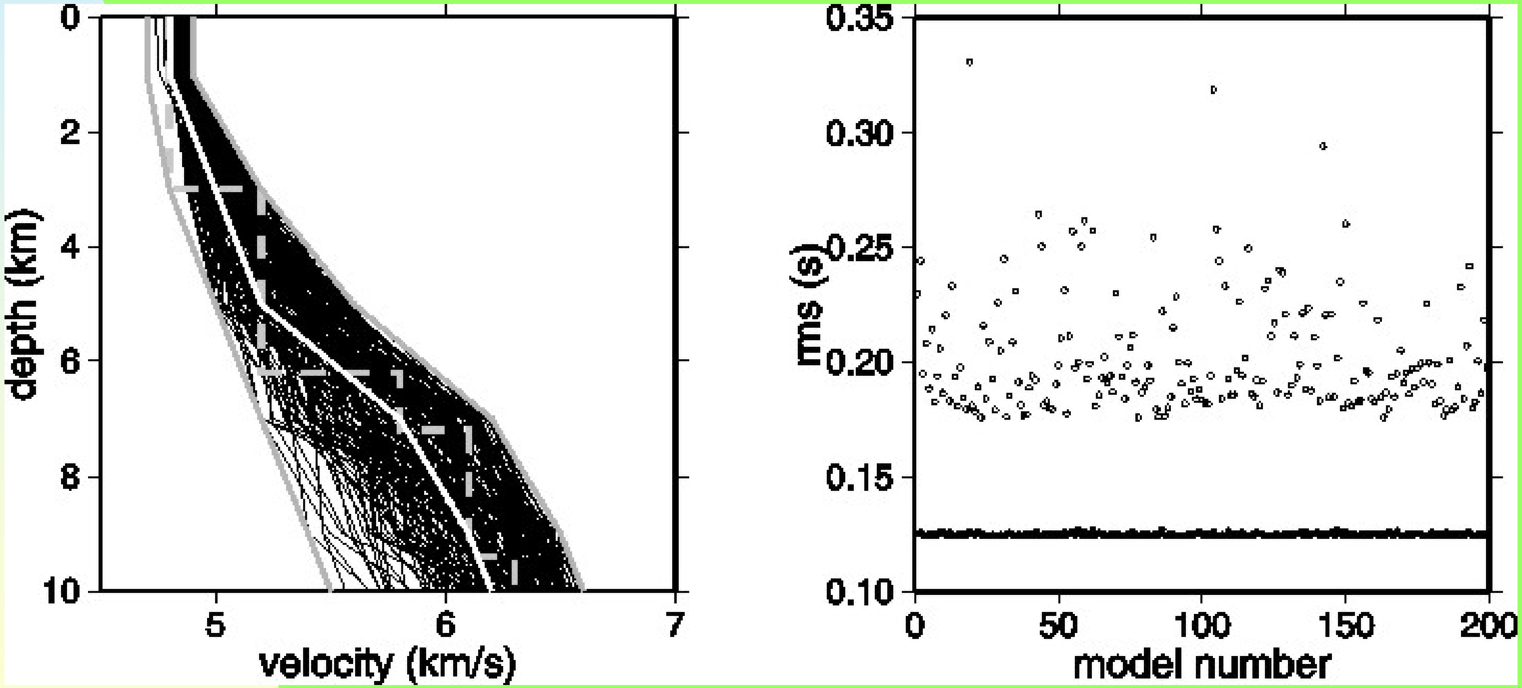
(fracture, fluids, static equilibrium ???)

Field experiment in 1991
and in 2001

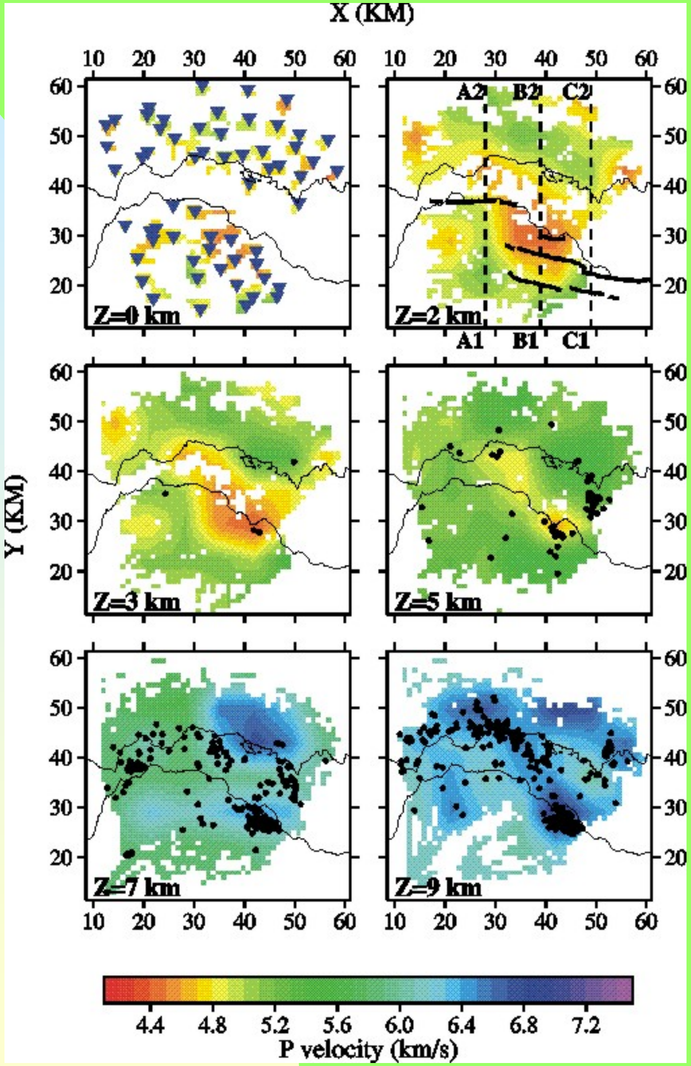


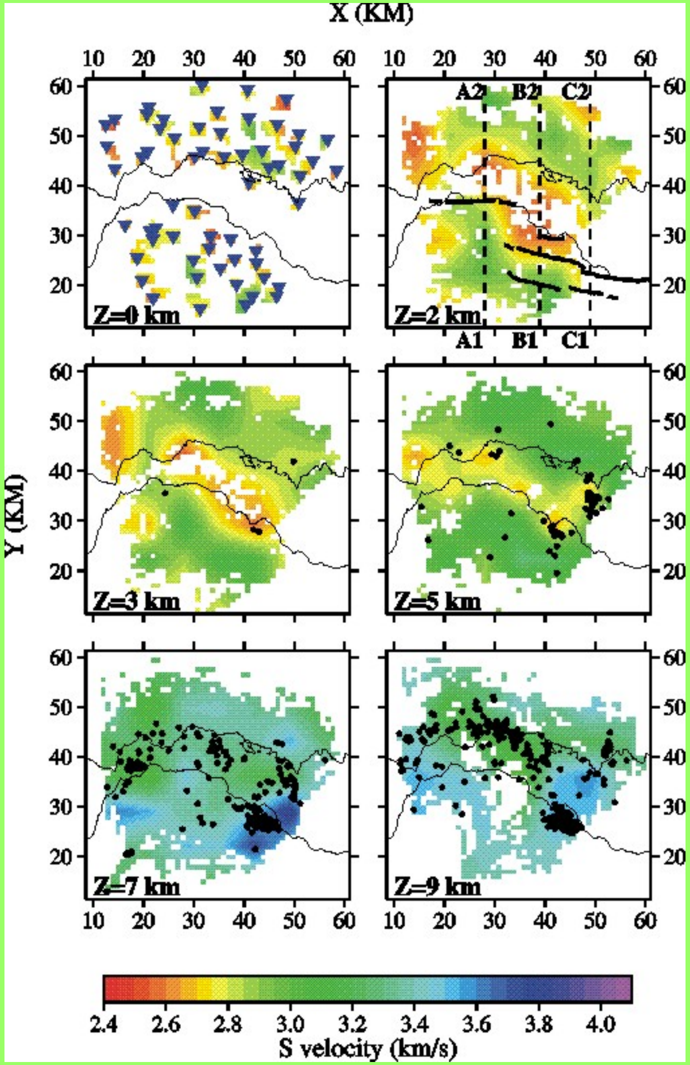
1D velocity reconstruction

HWB method or random sampling



Velocity structure Horizontal cross-sections

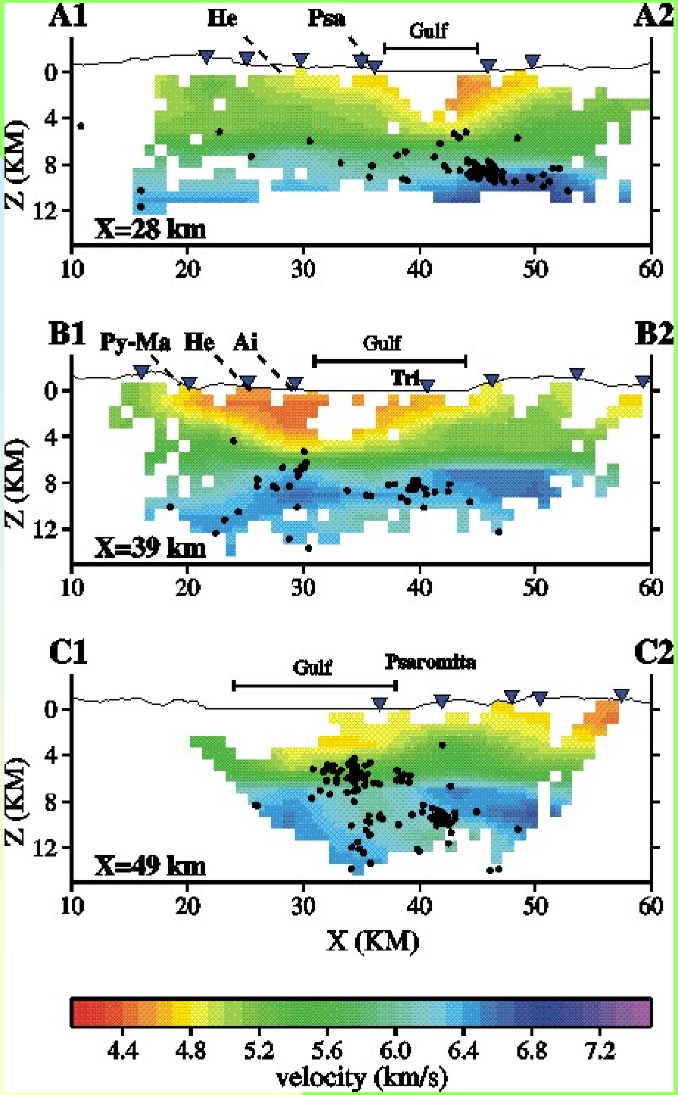




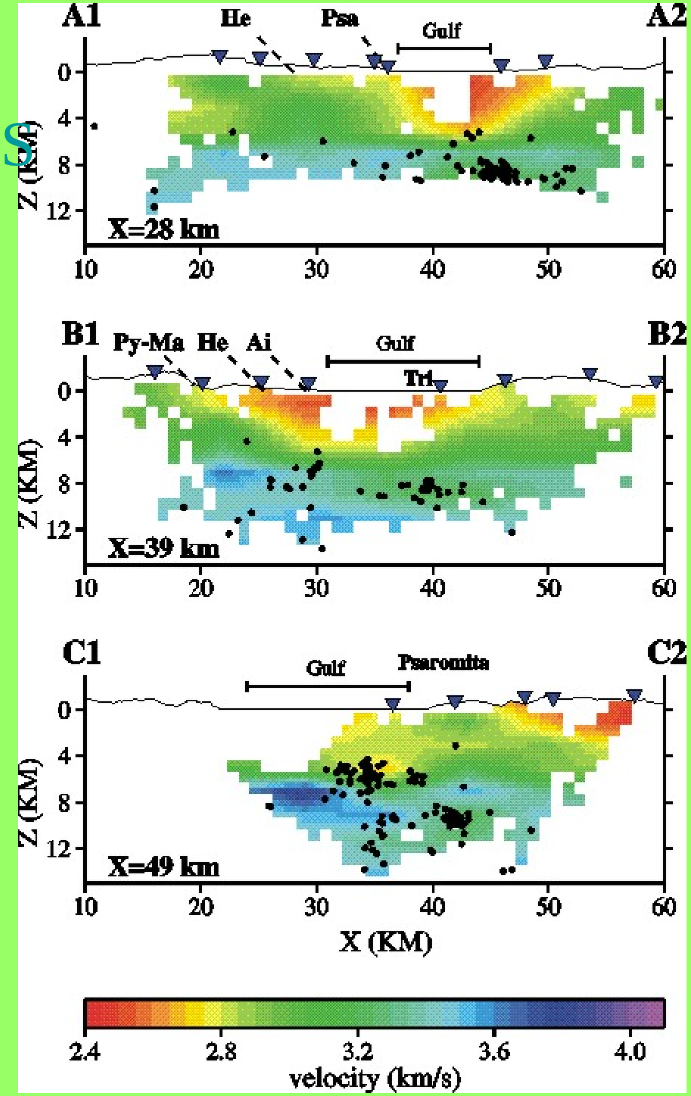
Velocity structure

Vertical sections

P



S



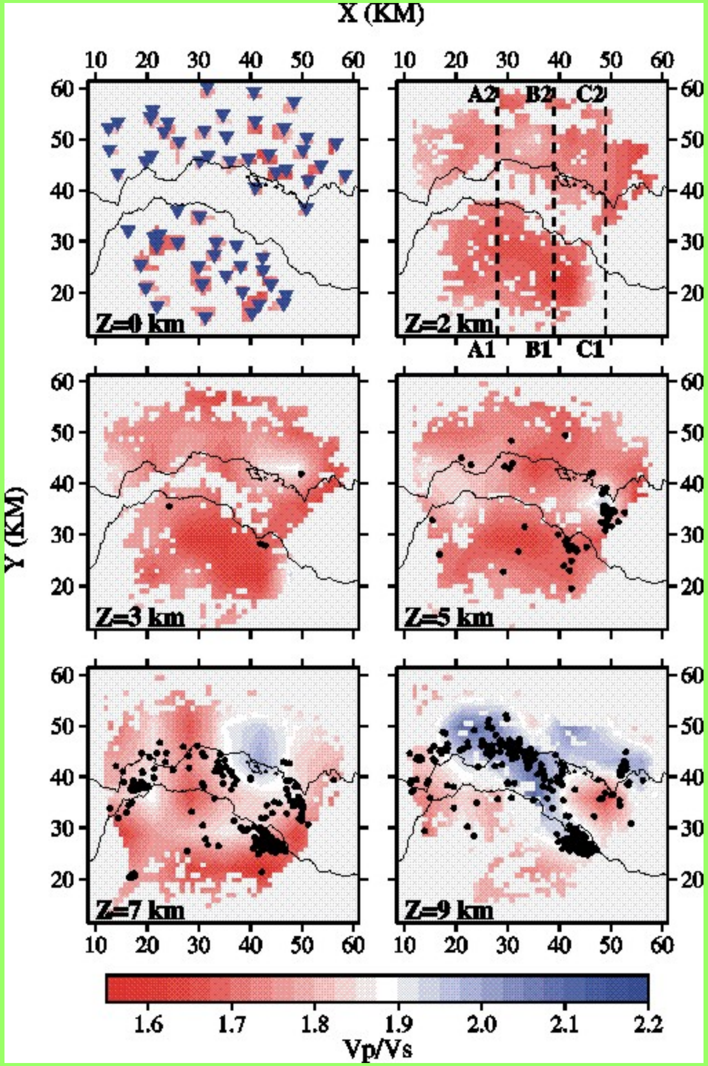
Ratio Vp/Vs: a proxy for fluids?

Few attributs can be deduced from Vp and Vs reconstructions in order to identify features related to specific mechanisms

- Ratio Vp/Vs connected to fluid saturation

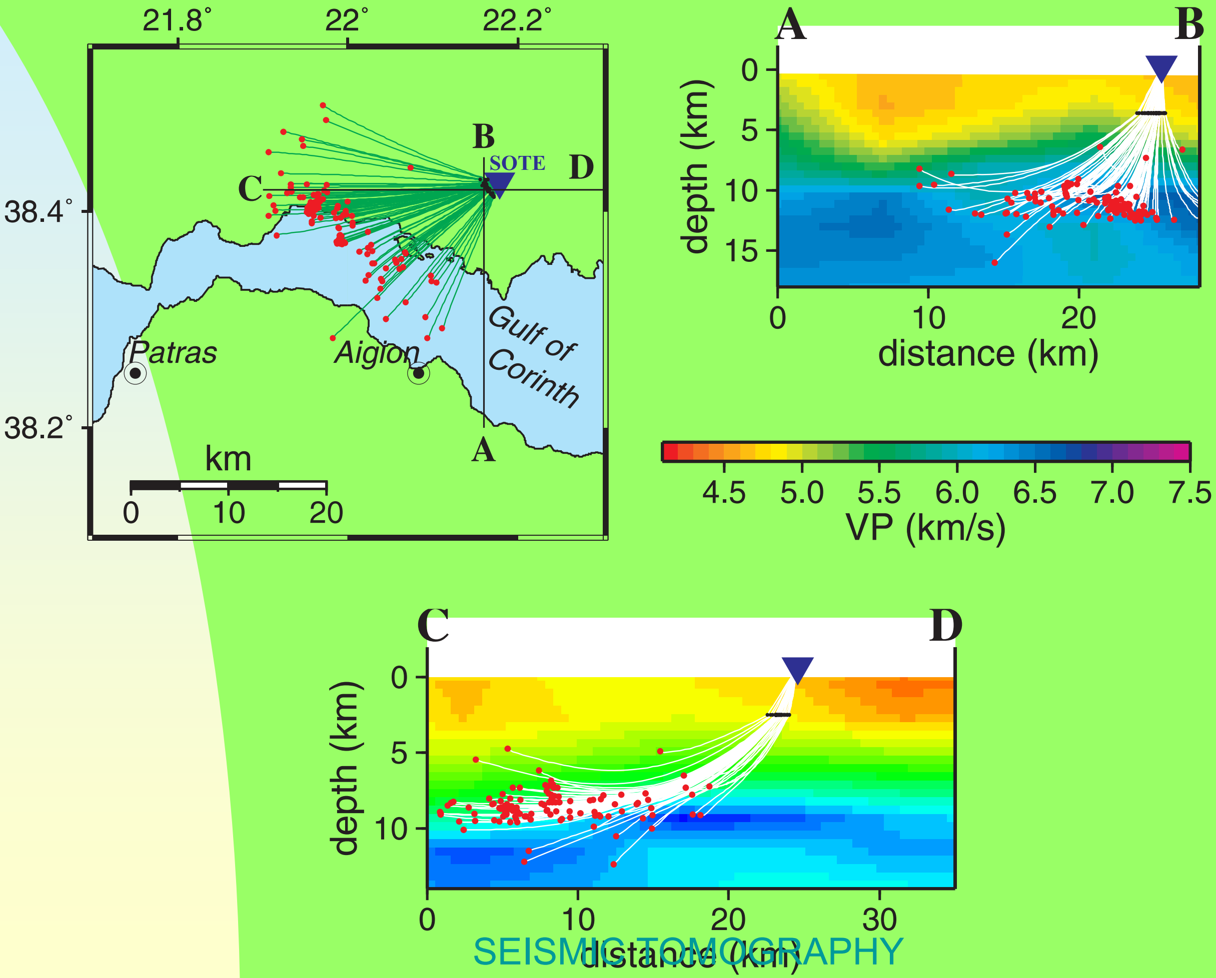
- Product Vp*Vs connected to porosity

This may lead to select the second mechanism of opening the continental margin …



Where are converted phases?

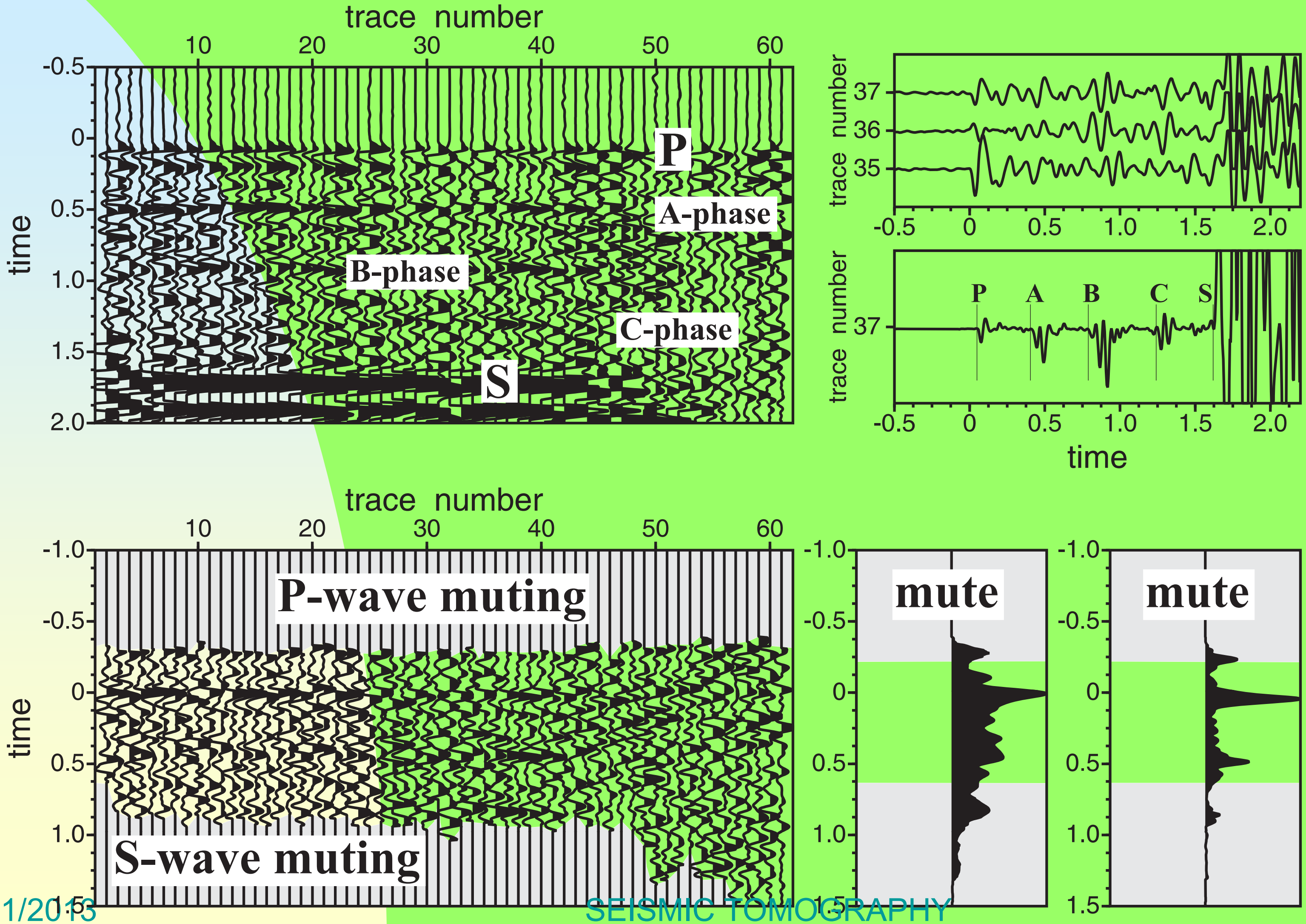
Similar to receiver function technique in connection with migration method



Phase analysis

- Amplitude versus offset (AVO)
- Receiver function method
- Beamforming

Seismic energy between P and S phases?



Alps tomography

In the last five decades, the deep structure of the Alps has been probed by every geophysical method applicable, and the resulting amoint of data is unmatched for any other oregen (Kissling, 1993)

- Bouguer anomaly
- Active seismic profiles (refraction, reflection, wide-angle reflection)
- Passive seismic experiments

Tirs à l'explosif dans le lac Nègre (Mercantour)

Alors que la majeure partie des chaînes méditerranéennes résultent de la subduction de l'Afrique sous l'Europe, les Alpes sont dans la situation inverse avec le "sous-charriage" (underthrusting) de l'Europe sous l'Adria

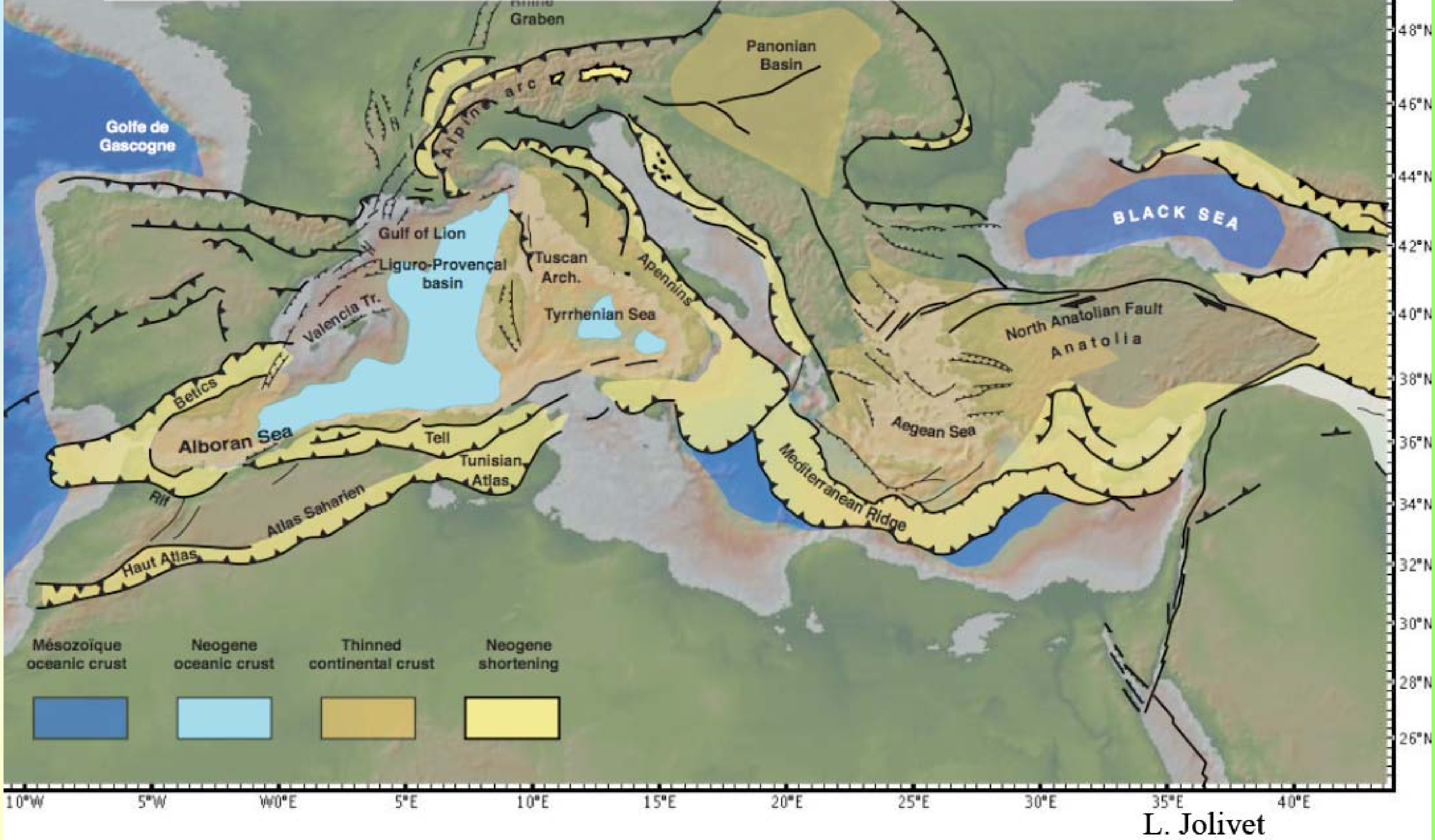


Figure I.11

Tirs à l'explosif du Lac Nègre pour sismique réfraction (1 à 25 T, 1958)

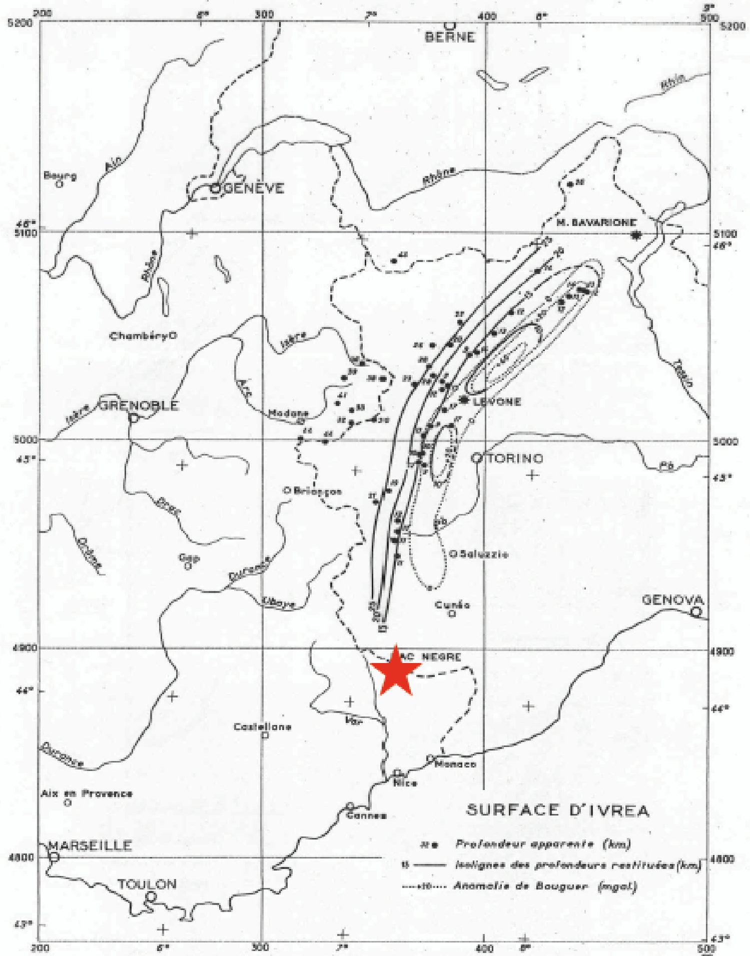


Figure VI.11
Profondeurs apparentes et isolignes des profondeurs restituées de la surface d'Ivrea.

Map of isobaths of the Ivrea surface (7.4 km/s reflector at 10 km depth at least)

Reflection Seismics (ECORS-CROP)

a) Sismique réflexion verticale

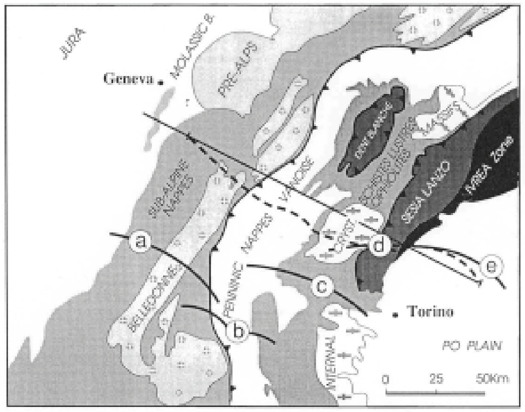


Fig. 1. – Location of the ECORS-CROP traverse (dashed line) through the western Alps. The curved segments represent the fans of mirror points of the WAR experiment and the straight continuous line, the projection of gravity data shown in cross section in figure 5 (note that the gravity profile extends further west than the ECORS-CROP traverse).

Localisation et résultats du profil de sismique réflexion verticale ECORS-CROP (Nicolas et al., 1990)

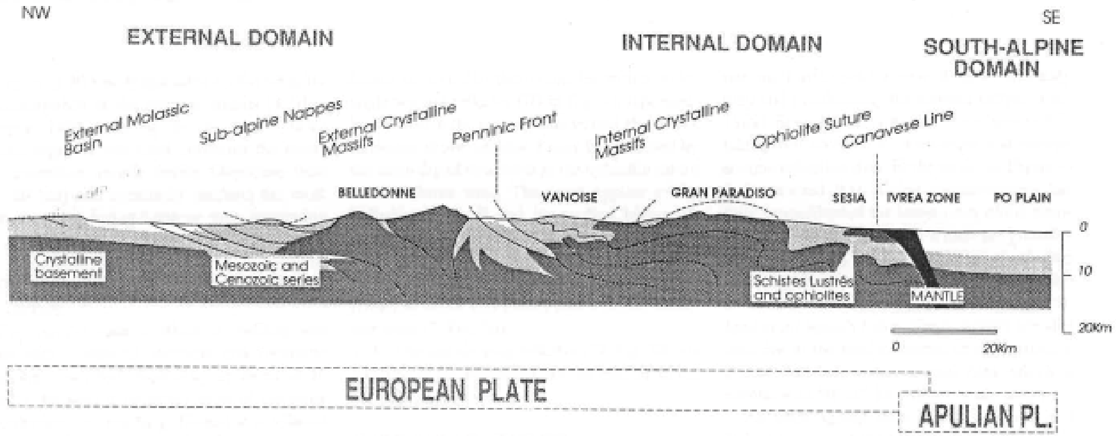


Figure 2. Simplified geologic cross section along ECORS-CROP geophysical traverse (after P. Vialon, *in* ECORS-CROP, 1986).

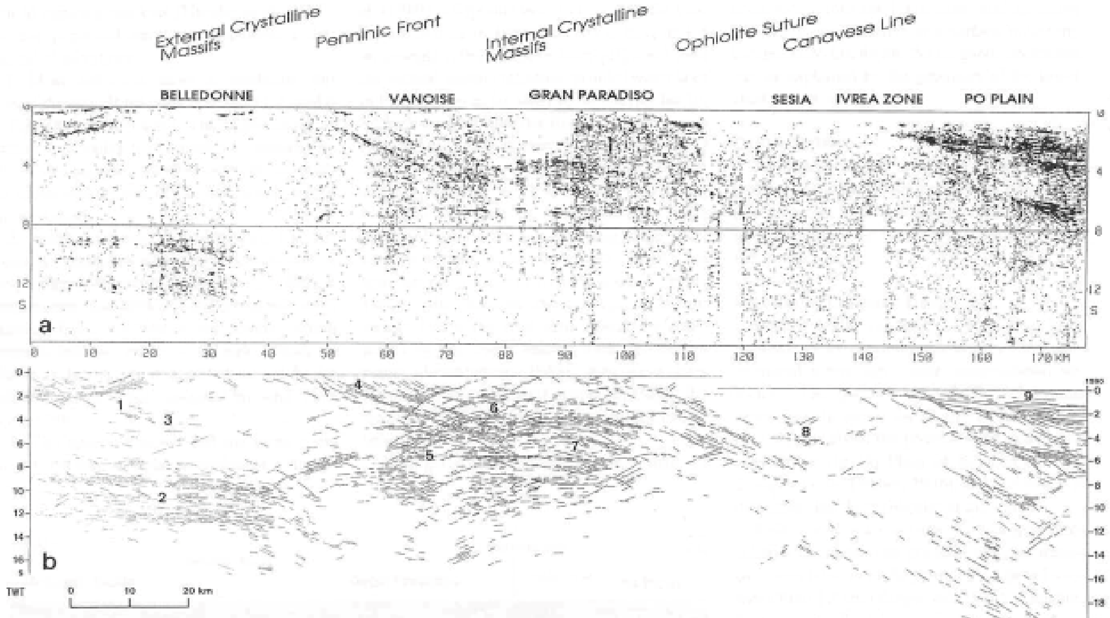
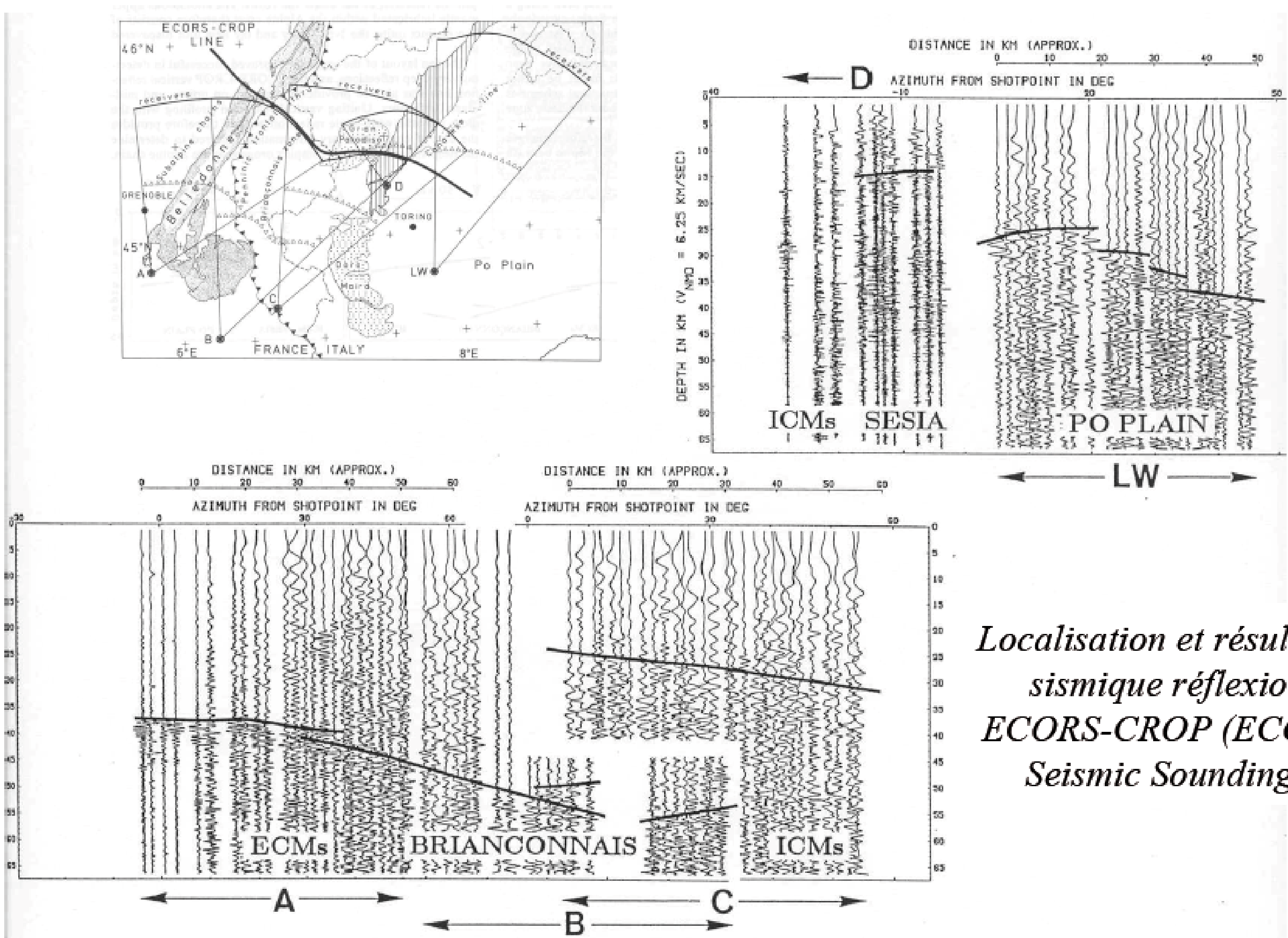


Figure 3. Vertical seismic-reflection profile of ECORS-CROP traverse through western Alps. a: Coherency-filtered stacked seismic section. Coherency is measured in moving window of 15 traces for slopes ranging from 0 to 0.25 s/km and displayed if larger than constant threshold. White stripes correspond to zones dominated by strong coherent noise where coherency has not been displayed (Marthelot, 1990). b: Line drawing of most prominent reflectors (Damotte et al., 1990). See text for explanation of numbered reflectors.

Wide-angle seismic profile

b) Sismique réflexion grand-angle



Localisation et résultats des profils de sismique réflexion grand-angle ECORS-CROP (ECORS-CROP Deep Seismic Sounding Group, 1990)

Gravimetry-seismics

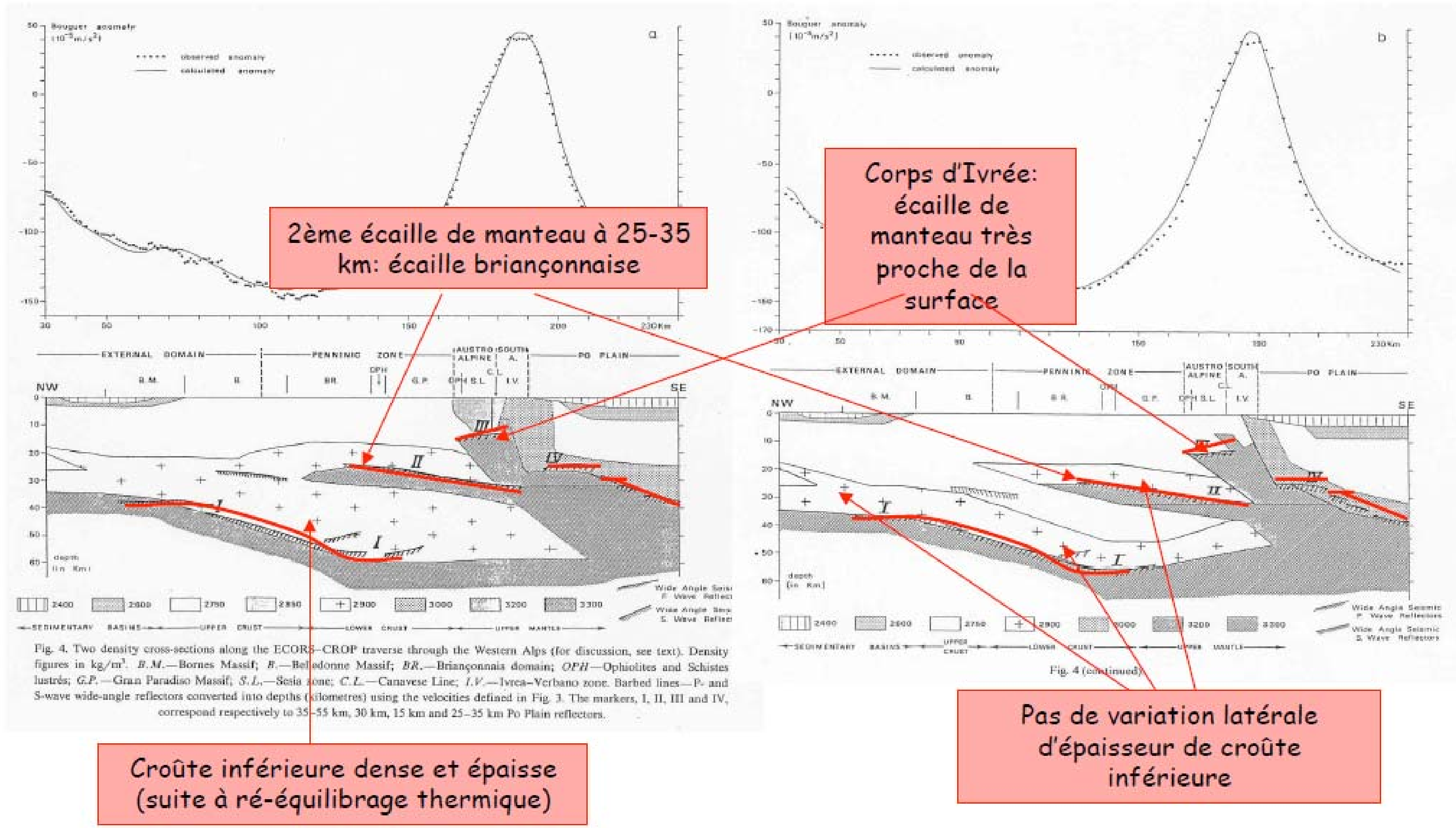


Fig. 4. Two density cross-sections along the ECORS–CROP traverse through the Western Alps (for discussion, see text). Density figures in kg/m³. *B.M.*—Bornes Massif; *B.*—Belledonne Massif; *BR.*—Briançonnais domain; *OPH*—Ophiolites and Schistes lustrés; *G.P.*—Gran Paradiso Massif; *S.L.*—Sesia zone; *C.L.*—Canavese Line; *I.V.*—Ivrea–Verbano zone. Barbed lines—P- and S-wave wide-angle reflectors converted into depths (kilometres) using the velocities defined in Fig. 3. The markers, I, II, III and IV, correspond respectively to 35–55 km, 30 km, 15 km and 25–35 km Po Plain reflectors.

(Bayer et al., 1989)

Different interpretations

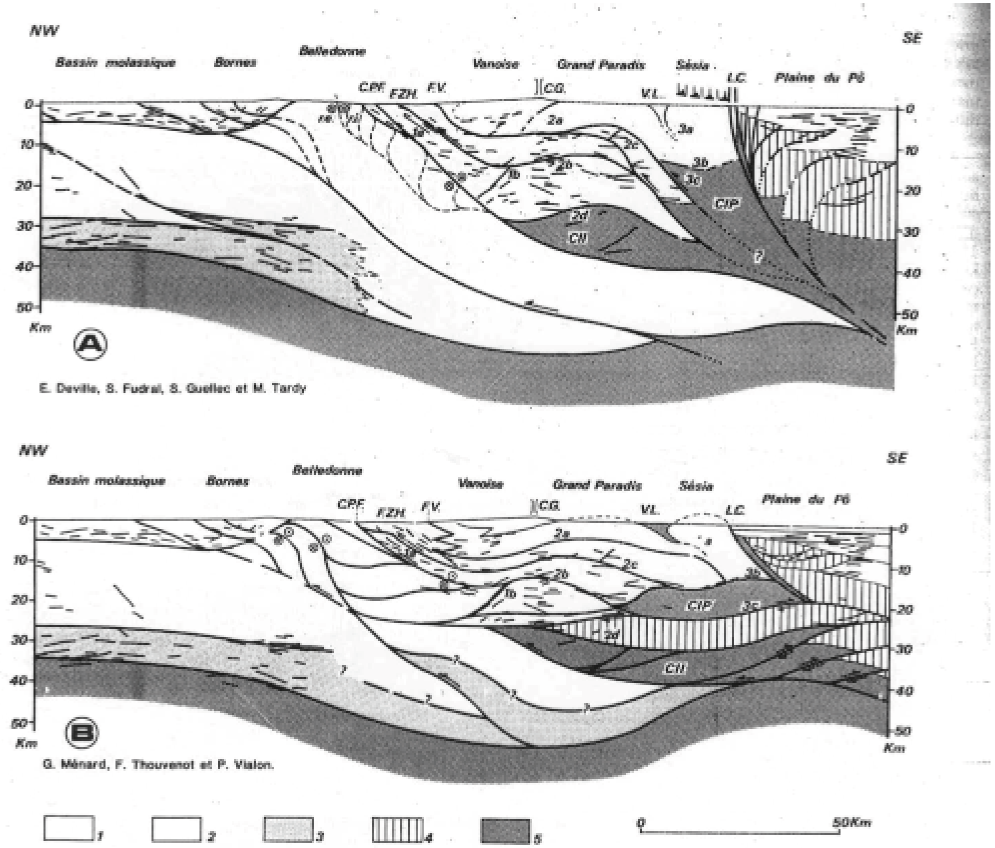


FIG. 6. – Deux schémas interprétatifs possibles du profil sismique migré ECORS CROP Alpes dans lesquels le chevauchement du massif cristallin externe de Belledonne est lié à un écaillage crustal profond et externe.
A. – Dans ce premier modèle (E.D., S.F., S.G. et M.T.) où la collision alpine induit un système d'écailles lithosphériques en procharriages vers le nord-ouest, l'écaille du corps d'Ivréa inférieur est reliée au Chevauchement pennique frontal et l'écaille du corps d'Ivréa principal au front des unités à métamorphismes HP de Vanoise.
B. – Dans ce second modèle (G.M., F.T. et P.V.) où des charriages en retour reprennent tardivement les procharriages du domaine pennique, le corps d'Ivréa principal détaché, flotte en arrière et au-dessus du corps d'Ivréa inférieur. Ce dernier est surmonté de croûte sud alpine (en place ou substituée).
1 : couvertures sédimentaires et métasédimentaires; 2 : croûte continentale supérieure européenne ou croûte européenne indifférenciée; 3 : croûte inférieure litée; 4 : croûte continentale sud-alpine; 5 : manteau; C.G. : col de la Galise; C.I.I. : corps d'Ivréa inférieur; C.I.P. : corps d'Ivréa principal; C.P.F. : chevauchement pennique frontal; F.V. : front des unités à métamorphisme HP de Vanoise; F.Z.H. : front de la zone houillère; L.C. : ligne du Canavese; r.e. : rameau externe de Belledonne; r.i. : rameau interne de Belledonne; V.L. : écailles de Viu-Locana.

(Tardy et al., 1990)

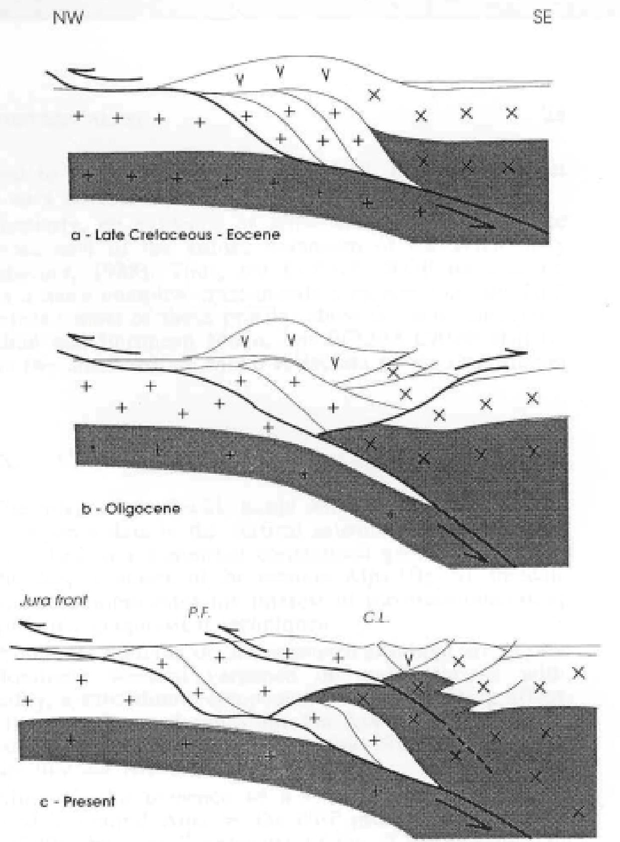
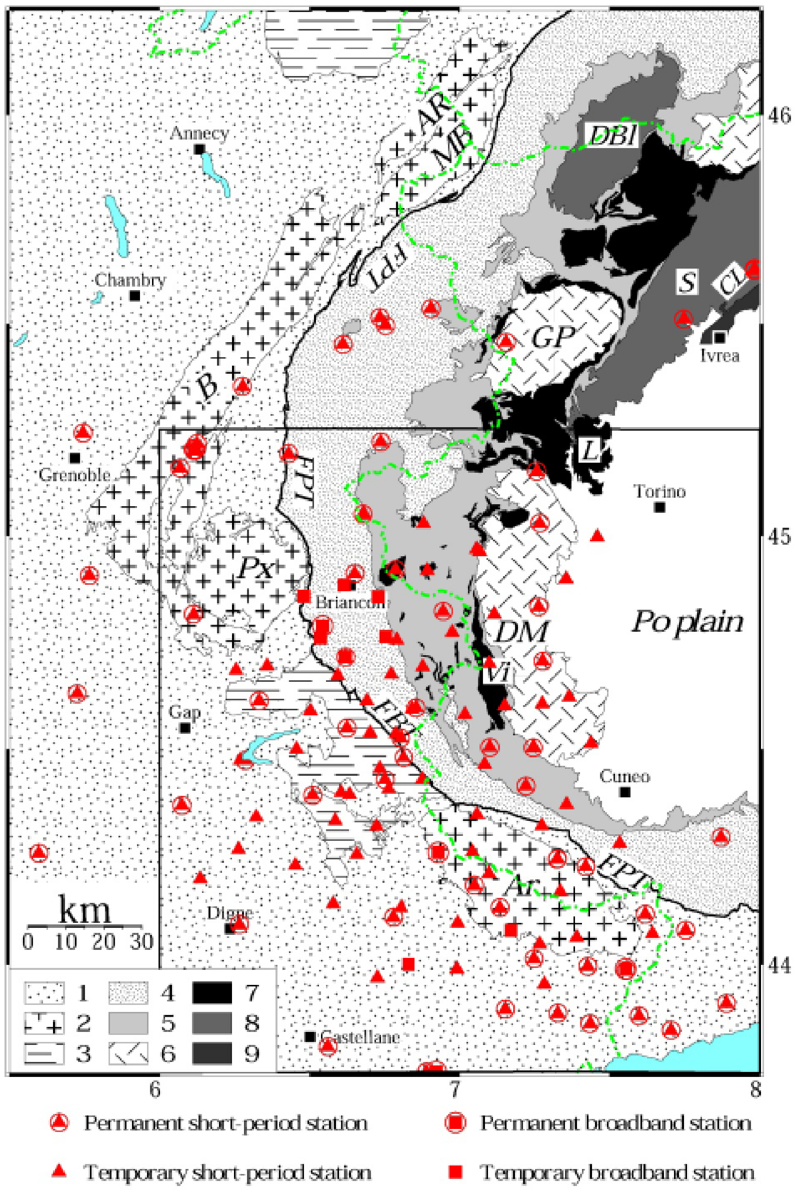


FIG. 8. – Alternative schema for the ECORS-CROP traverse implying in (a) a crustal accretionary wedging by thick-skinned imbrication of upper and lower crust, followed in (b) by mantle indentation and back thrusting, and in (c) by west-oriented thrust. Same decoration as in figure 7 [Roure *et al.*, this volume].

(Nicolas et al., 1990)

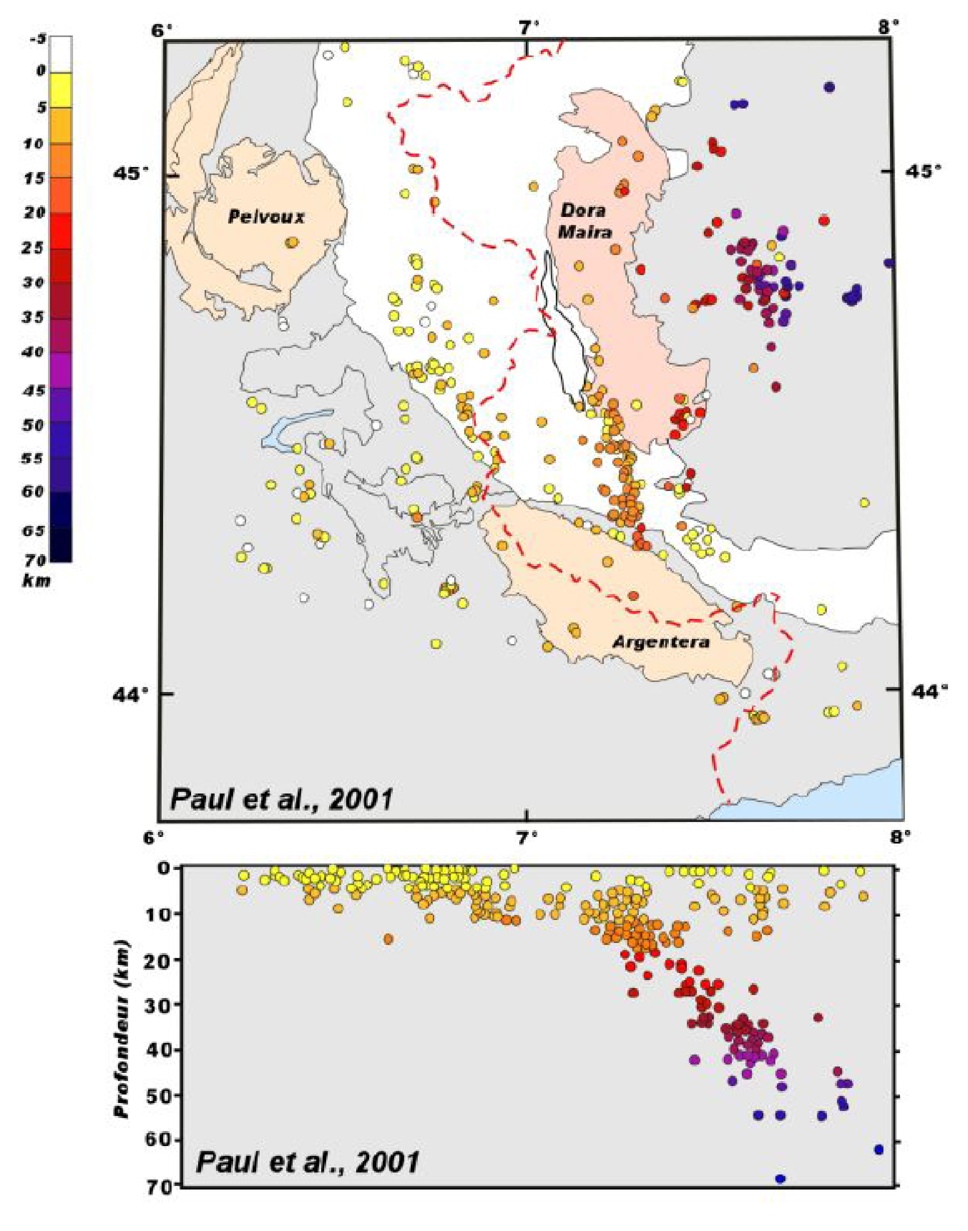
Joint hypo-velocity inversion

- Réseau sismologique temporaire de 67 stations + 59 stations permanentes, en France et Italie
- 550 séismes locaux
- ~15 000 temps d'arrivée (P+S)
- Grille: au mieux 5 km x 5 km x 5 km au centre du réseau

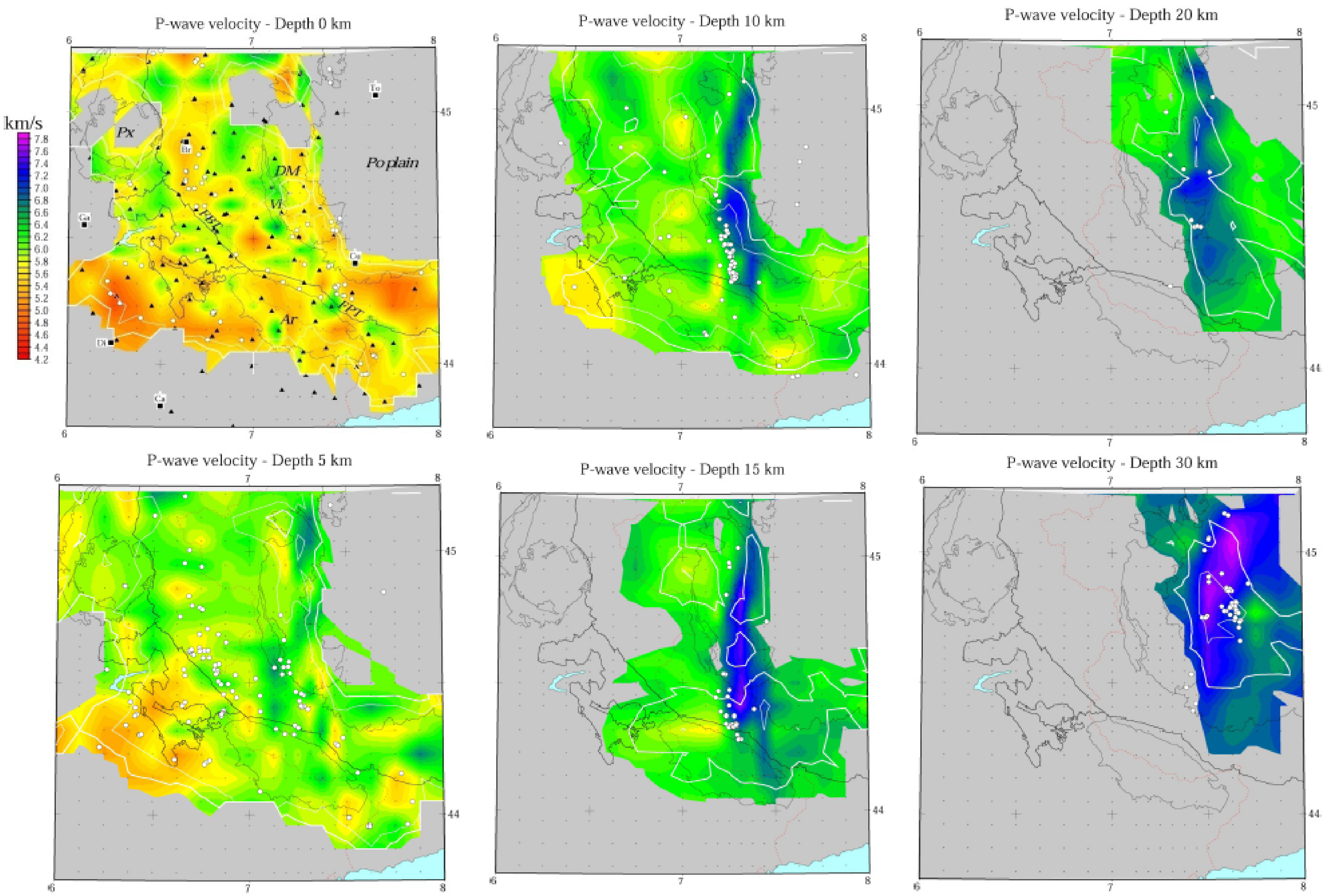


(Paul et al., 2001)

Localisation des séismes utilisés pour la tomographie crustale, en carte et en coupe



Vp maps at # depths



(Paul et al., 2001)

Recent interpretation

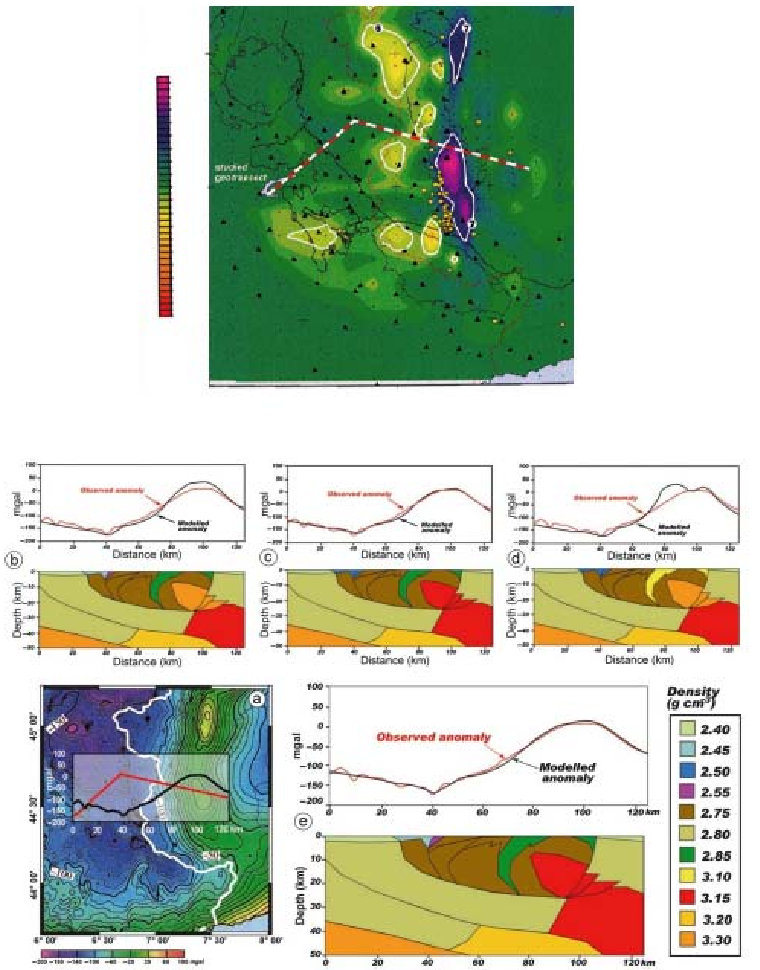


Fig. 6 Models of the gravity effect calculated for the interpretative cross-section. Three models with different rock density values are presented. The model showing the best fit between the observed and the modelled anomaly is presented in the enlarged picture. The studied geotransect (red line) is located on the Bouguer gravity map of Masson et al. (1999). The black line represents the gravity profile along the geotransect.

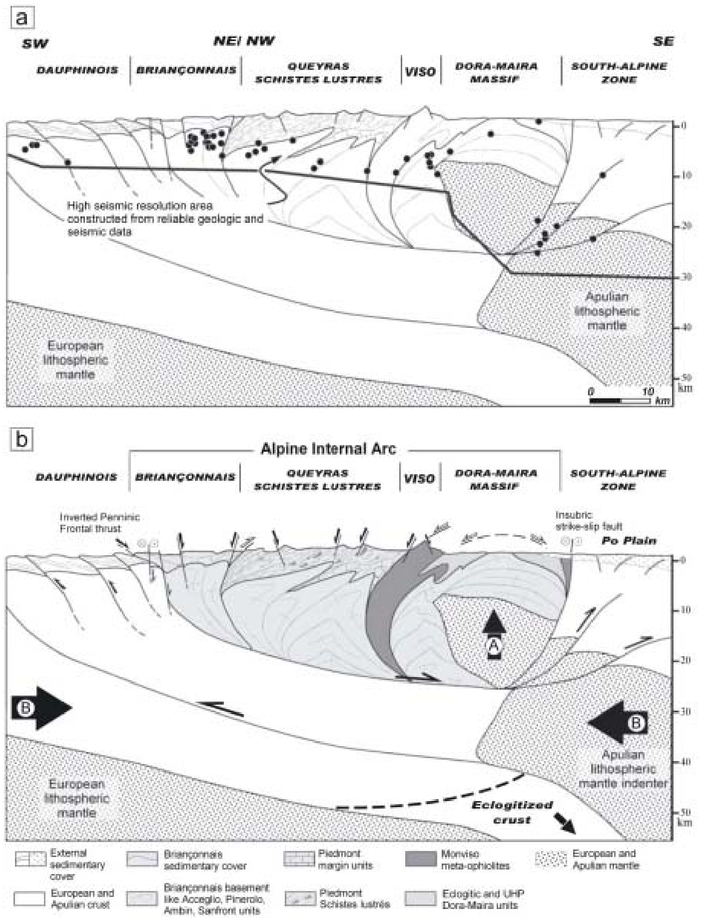
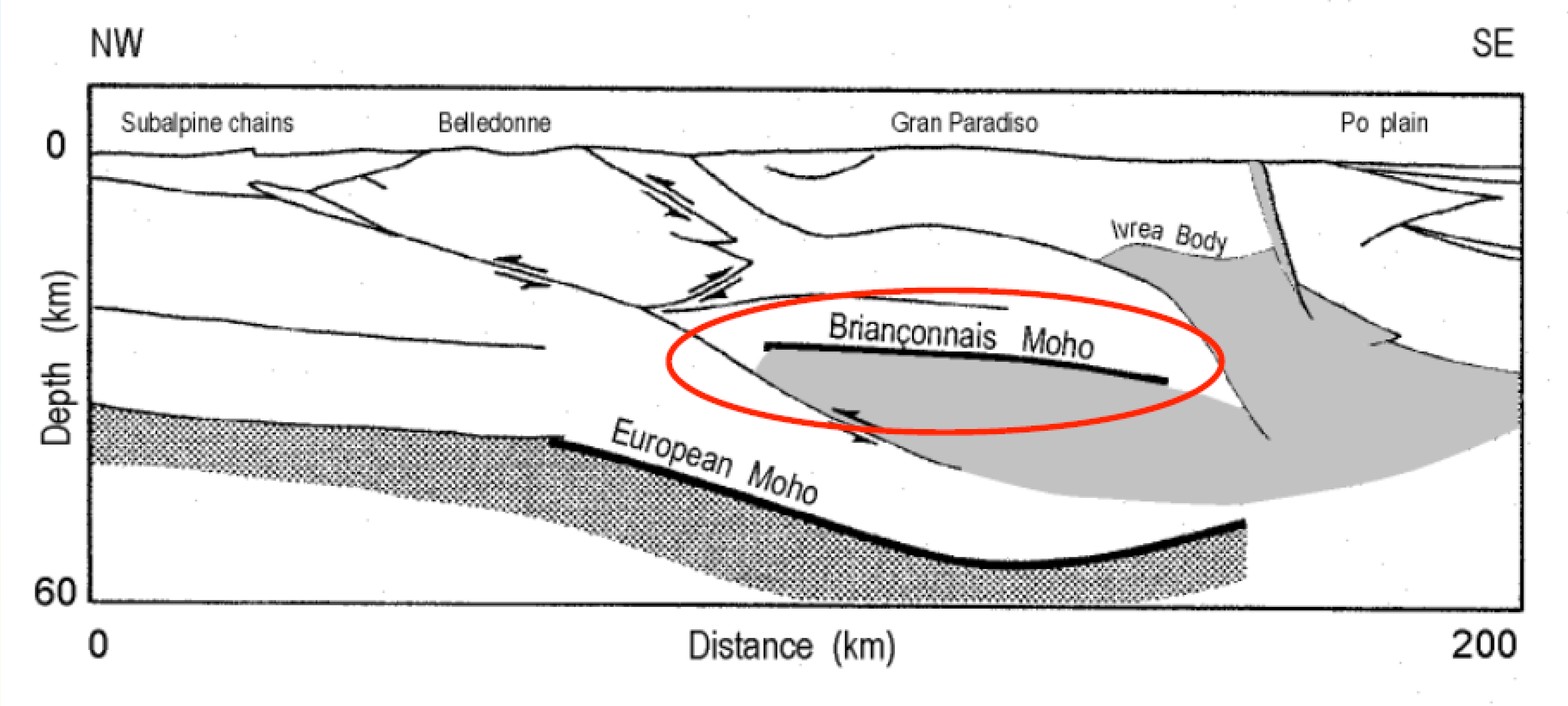


Fig. 4 Interpretative crustal-scale cross-section of the south-western Alps. (a) Cross-section showing the high seismic resolution area with the localization of earthquake hypocentres (black circles) with respect to the main geological and tectonic boundaries. (b) Cross-section with the main geological units and kinematics indicators, the upper part of the Apulian mantle (arrow A) acts as an indenter and the lower part (arrow B) transfers the compression onto the external arc (European foreland).

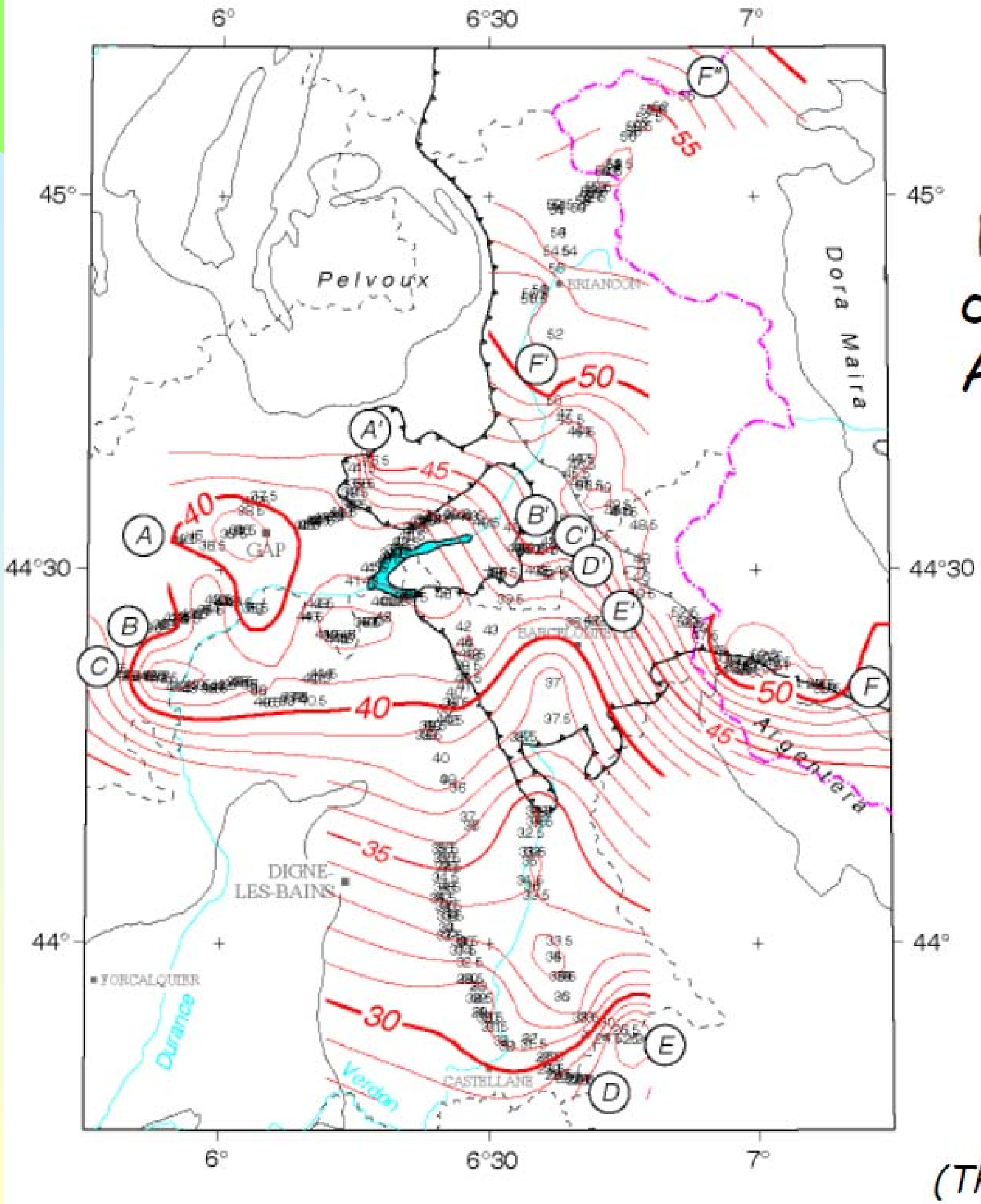
(Lardeaux et al., 2006)

Brianconnais Moho?

(Thouvenot et al, 2007)



Very weak signature if there is any moho: importance of the quality control



Résultat: une nouvelle carte du Moho sous les Alpes sud-occidentales

Interesting result of this experiment …

(Thouvenot et al., 2007)

WORKFLOW of FATT

- Selection of an enough fine grid
- Selection of the a priori model information
- Selection of an initial model
- FMM and BRT for 2PT-RT
- Time and derivatives estimation
- LSQR inversion
- Update the model
- Uncertainty analysis
- Geodynamic or geotechnical interpretation

THANK YOU !

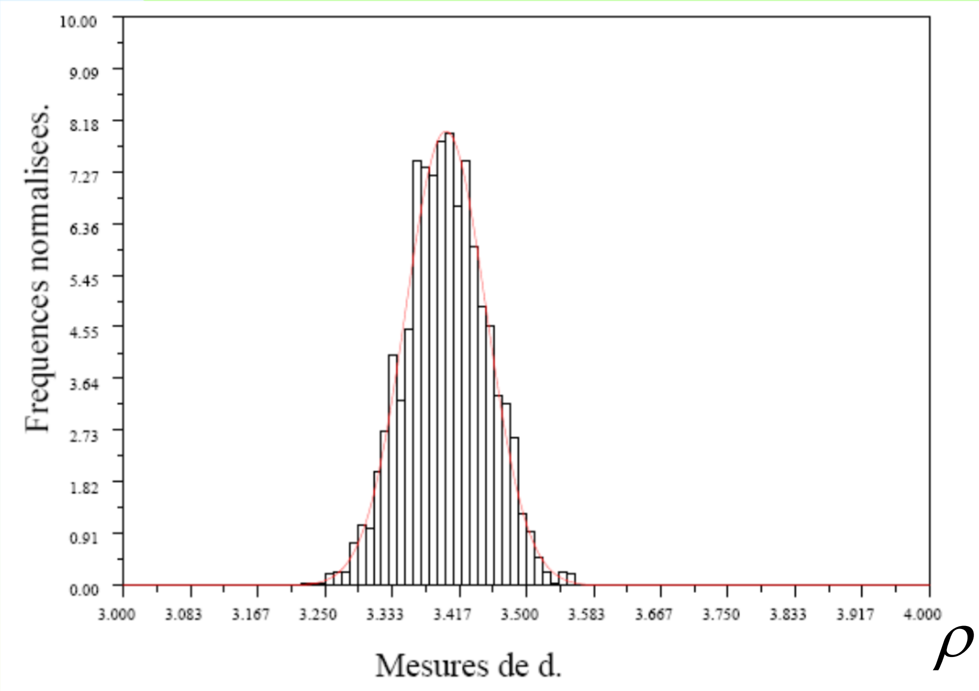
Many figures have come from other people: could they forgive me if I have not mentionned their names.

Other methods of exploration

- Grid search
- Monte-Carlo (ponctual or continuous)
- Genetic algorithm
- Simulated annealing and co
- Tabou method
- Natural Neighboring method

Probability density

Data space



$$\rho(d,m) = \rho_D(d)\rho_M(m)$$

The probability density in the model space is related to the

Different informations