

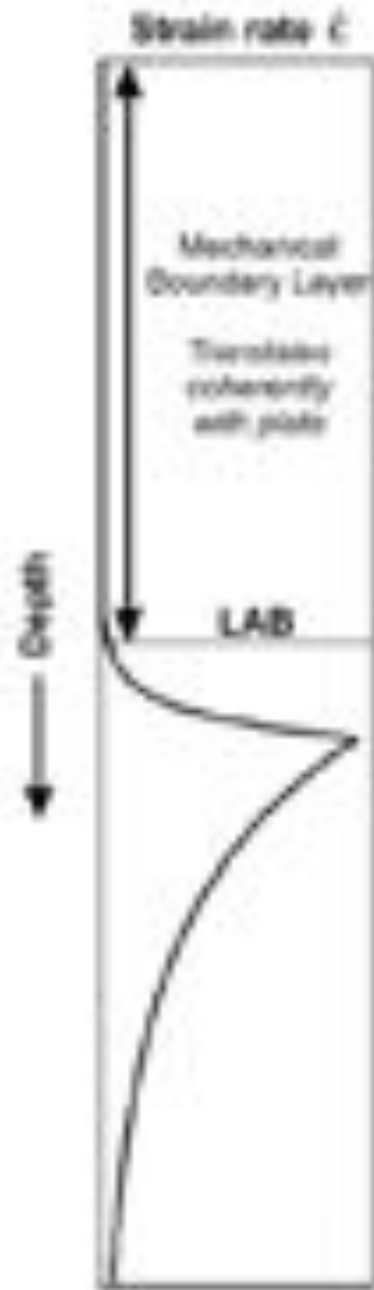
Structure et dynamique du système Lithosphère/Asthénosphère

3-Méthodes sismologiques I: ondes de surface longue période

Barbara Romanowicz - Cours 2013
-Chaire de Physique de l'Intérieur de la Terre
Collège de France
21 Octobre 2013

Différentes définitions de la limite lithosphère- asthénosphère

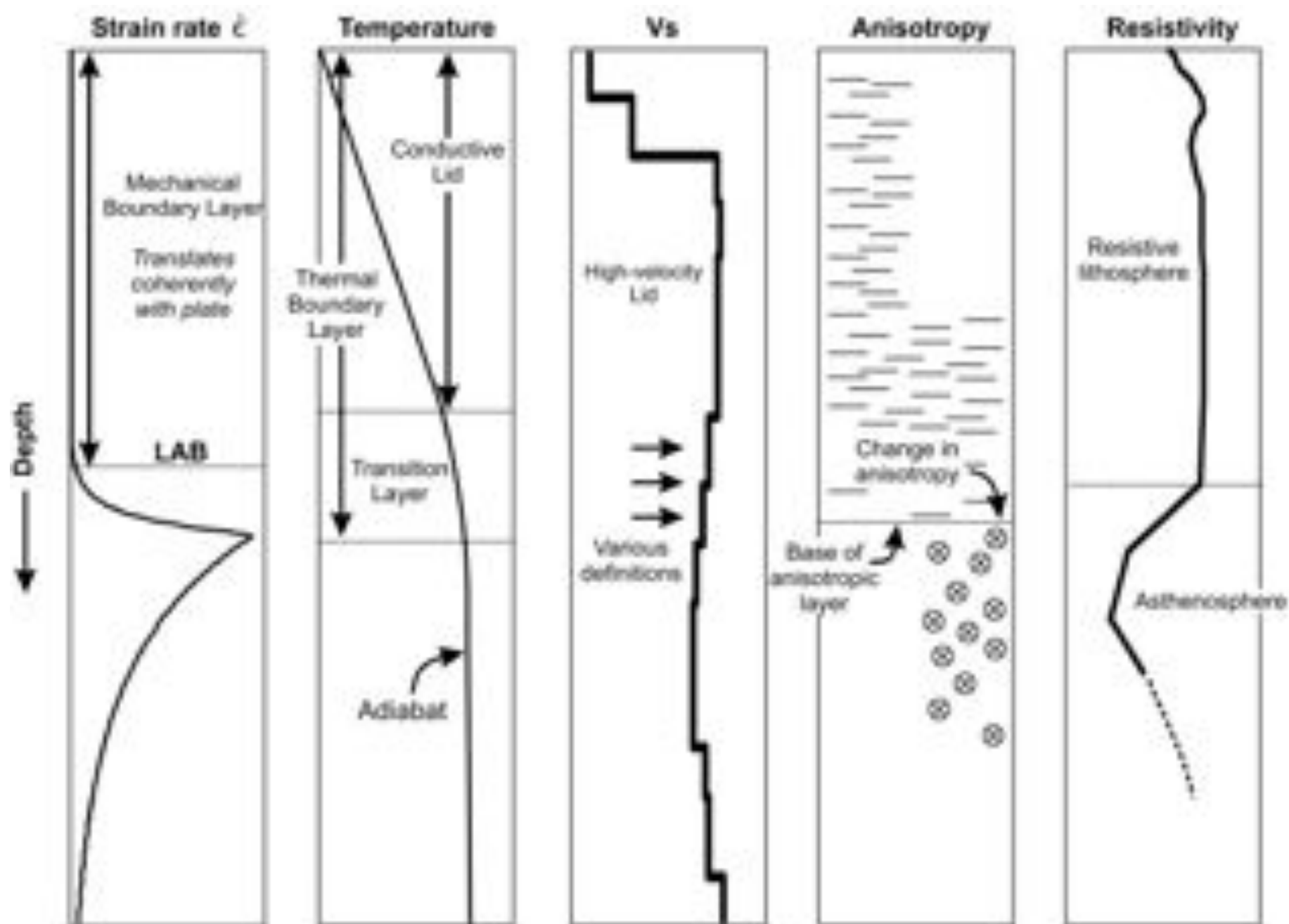
1- Définition mécanique



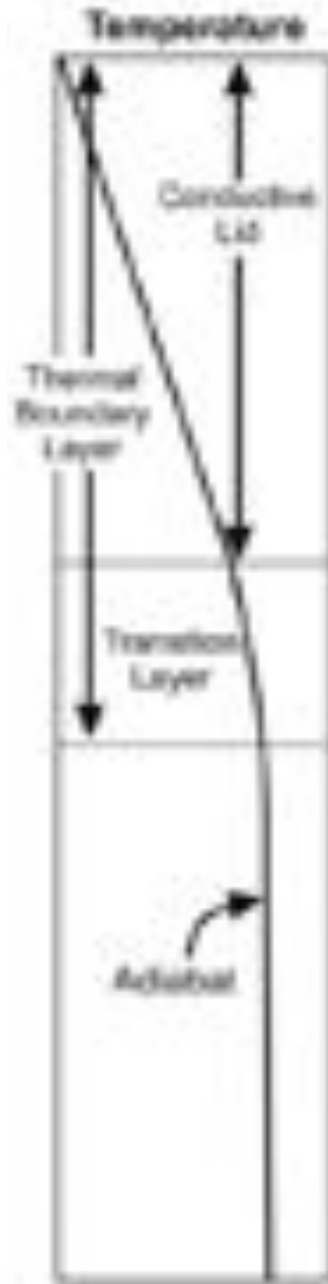
Lithosphère:
Couche limite mécanique non ou peu déformable
Suit le mouvement de la plaque de manière cohérente

Asthénosphère:
Déformation plus importante, maximale juste au dessous
de la LAB

LAB = limite entre la lithosphère et l'asthénosphère



2- Définition thermique



Lithosphère:
Couche limite thermique: dégagement
de la chaleur par conduction

Asthénosphère:

Région convective - variation de la température
en fonction de la profondeur le long de l'adiabat

3a- Définition sismique



Lithosphère: vitesses sismiques rapides

Asthénosphère: zone à faible vitesse

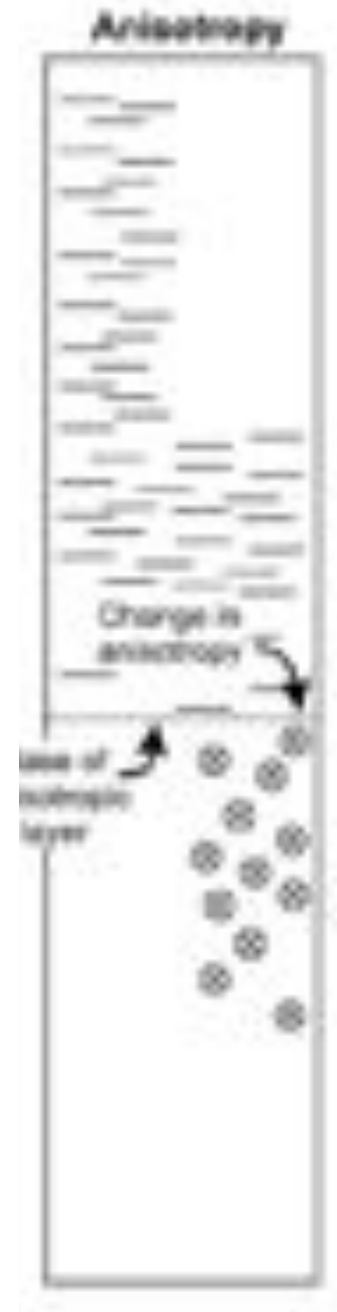
3b- Définition sismique: anisotropie

Lithosphère:

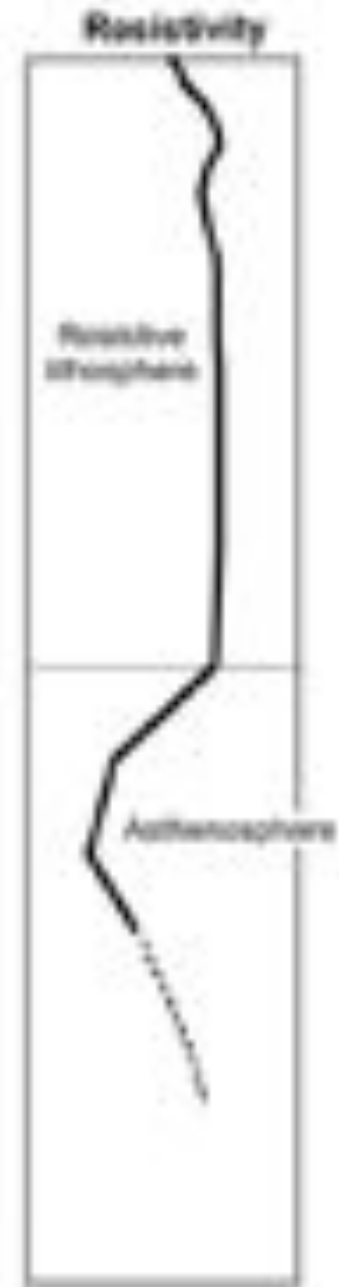
Anisotropie acquise au moment de sa formation: anisotropie "gelée"

Asthénosphère:

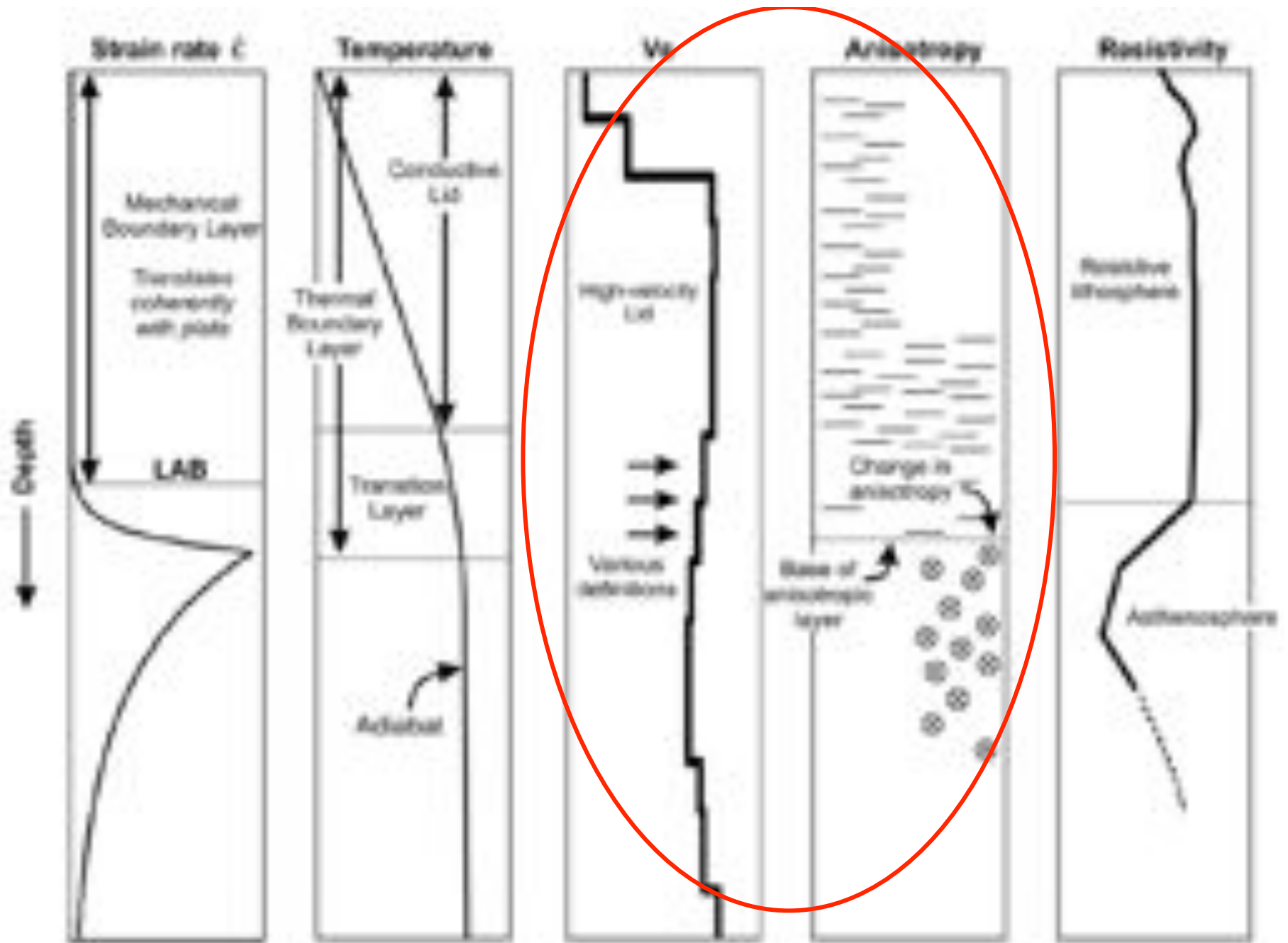
Anisotropie reflète la déformation actuelle - zone de cisaillement entre la plaque et le manteau sous-jacent



4- Définition "électrique": résistivité électrique



- Get better version of the Eaton profiles!

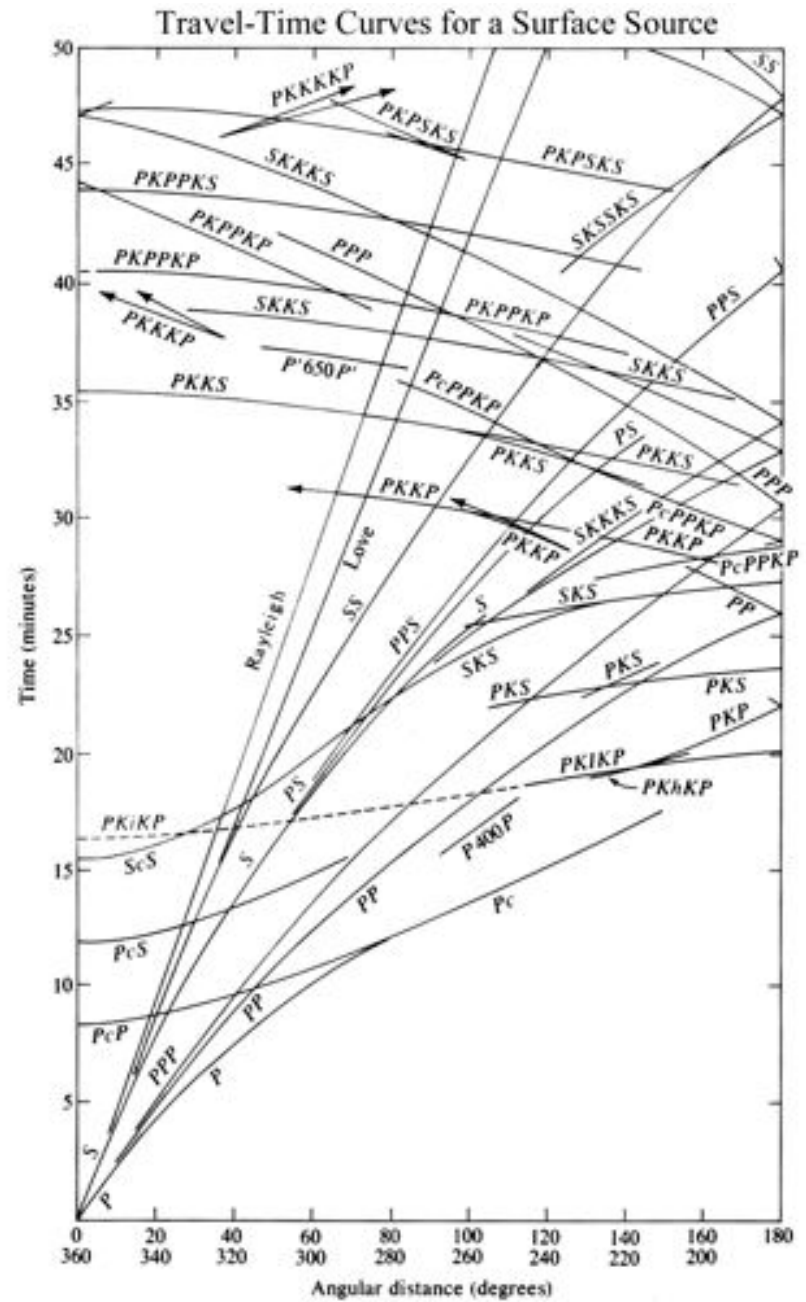
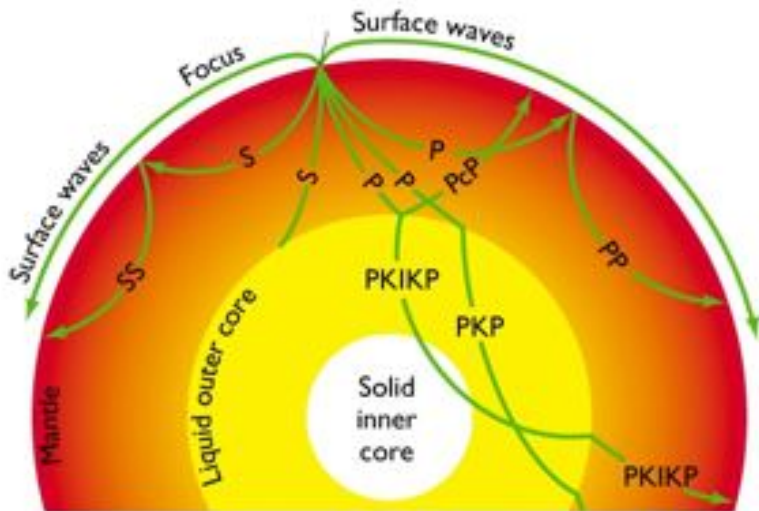
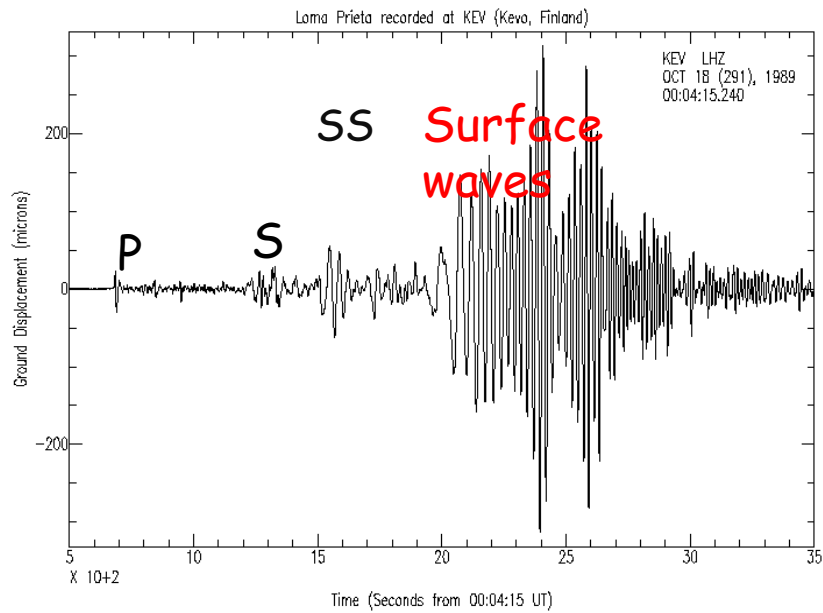


Outils sismologiques:

1- Tomographie sismique longue période

2- "splitting" des ondes SKS (anisotropie Azimuthale)

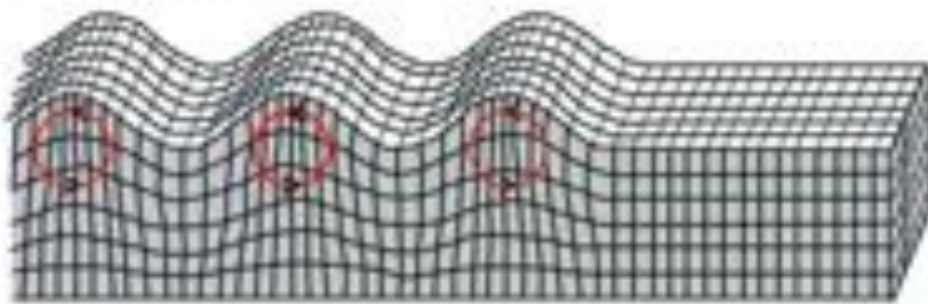
3 - ondes de volume réfléchies ou converties aux discontinuités de structure



From Bolt, B., *Inside the Earth*, San Francisco: W.H. Freeman, 1982.

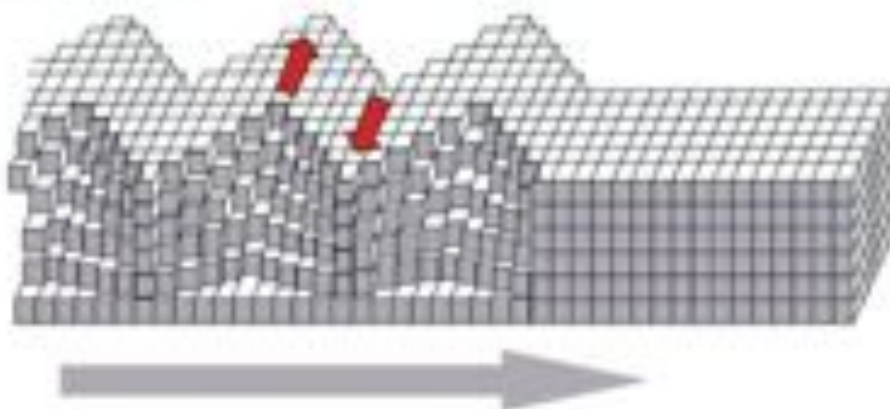
Ondes de surface

- Deux types:
 - Ondes de Rayleigh (R)



• Mouvement de particules elliptique rétrograde dans un plan vertical contenant la direction de propagation
→ sensibles à la structure en V_{sv}
→ observées sur les Composantes Z et R

- Ondes de Love (G)



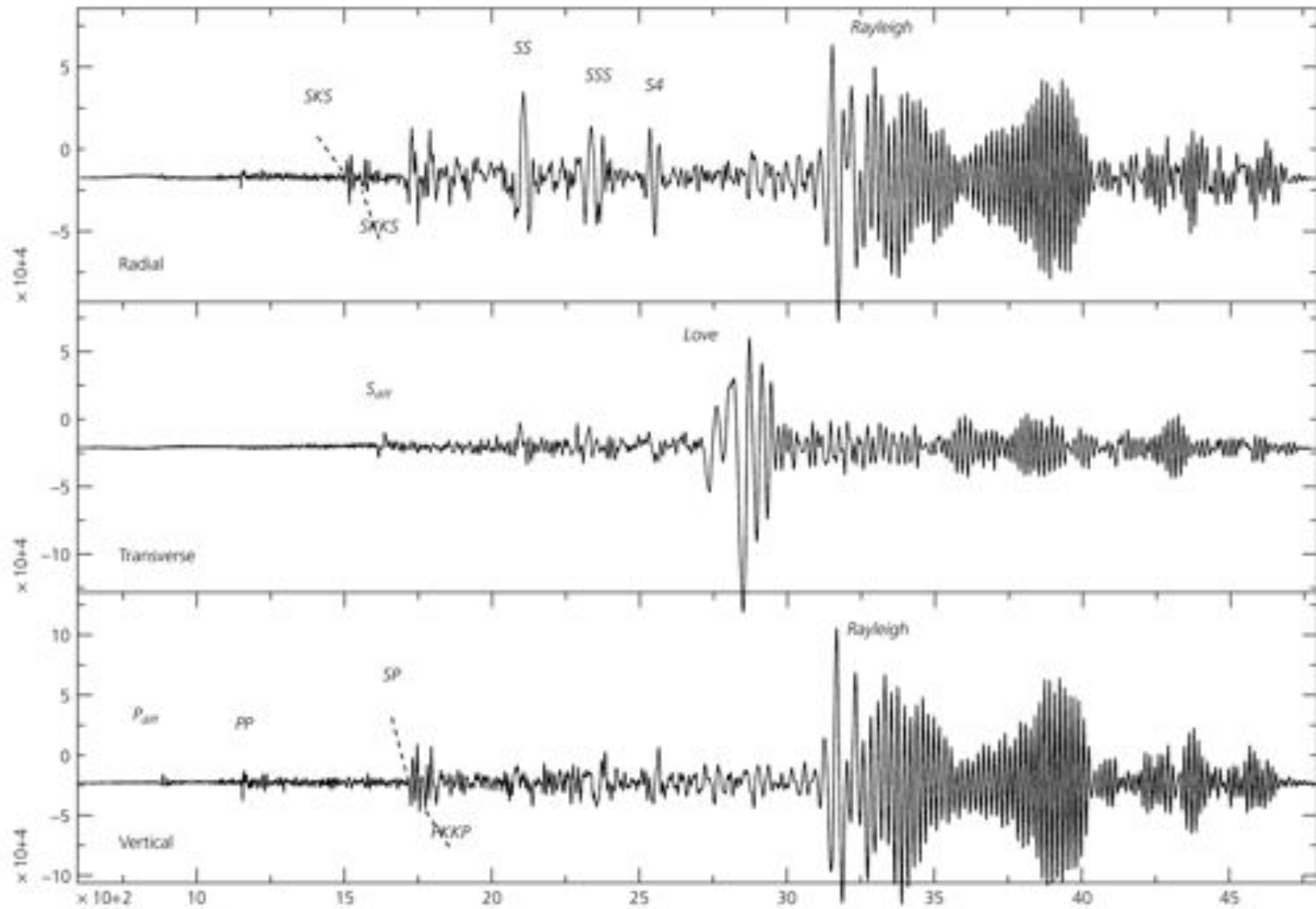
• Mouvement de particules linéaire dans la direction horizontale perpendiculaire contenant la direction de propagation
→ sensibles à la structure en V_{sh}
→ observées sur la composante T (transversale)

Propriétés des ondes de surface

- Ondes sensibles principalement à la vitesse de cisaillement
 - Anisotropie de polarization ($V_{sh} \neq V_{sv}$)
 - Anisotropie azimuthale
- Ondes dispersives (vitesse de propagation dépend de la période)
- La sensibilité à la structure diminue avec la profondeur
 - Dépend de la fréquence et du mode considéré
 - A longue période ($> 30s$) échantillonnent plus profond dans le manteau,
 - A courte période \rightarrow étude de la croûte et de la limite croûte-manteau (région du Moho)
 - A une fréquence donnée, les harmoniques sont sensibles à une profondeur plus importante

Séisme "superficiel"

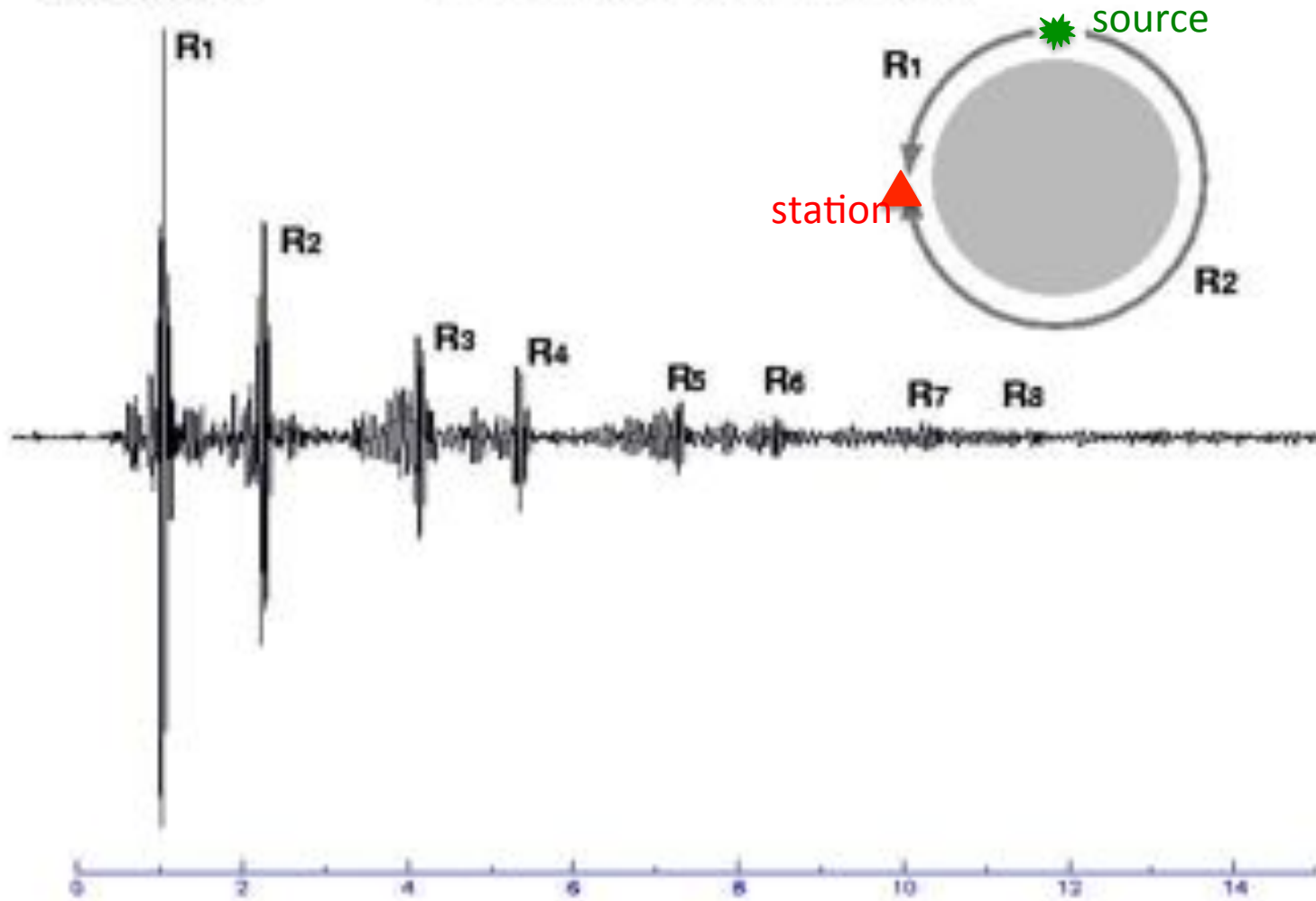
Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.



Temps en secondes x 100

station: CMB
channel: LHZ

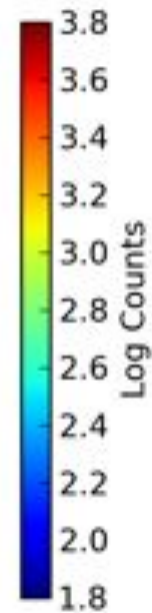
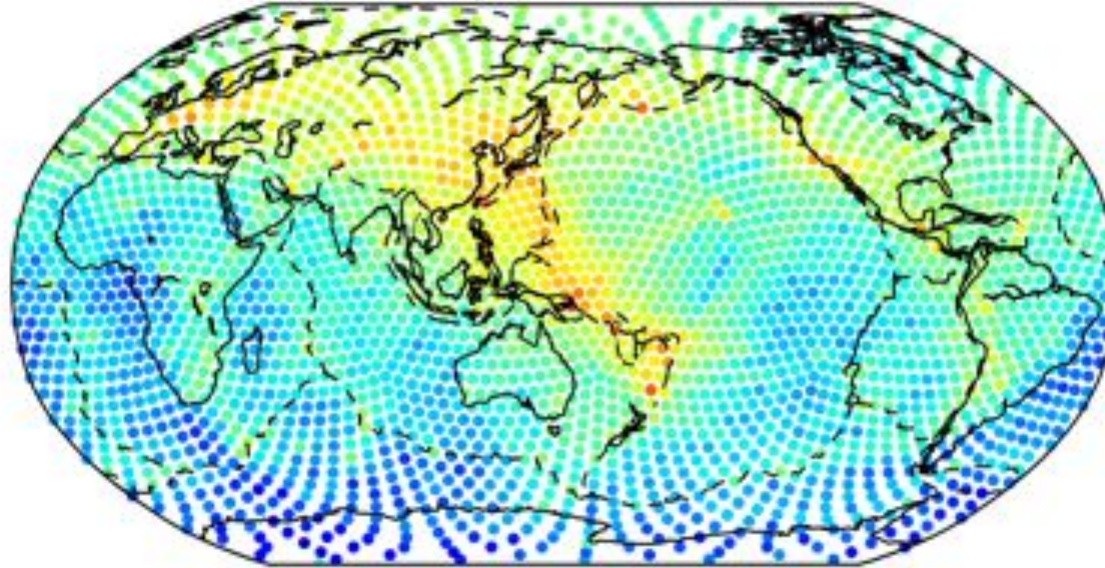
1996/07/11 21:46:39.7 h=15.0km $\Delta=109.7^\circ$ $\phi=32.3^\circ$
Burma-China Border Region Mw=6.8



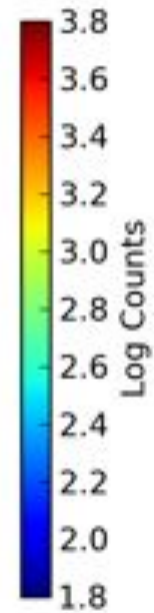
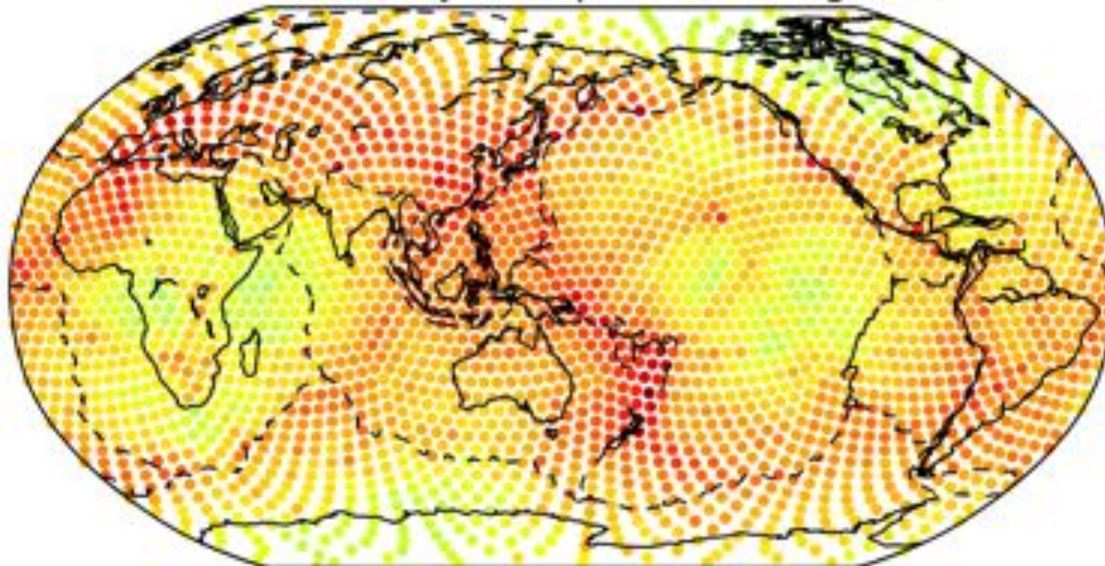
HEURES

SEMum2:
204 events
~ 100,000
wavepackets

Minor-arc paths (unweighted)

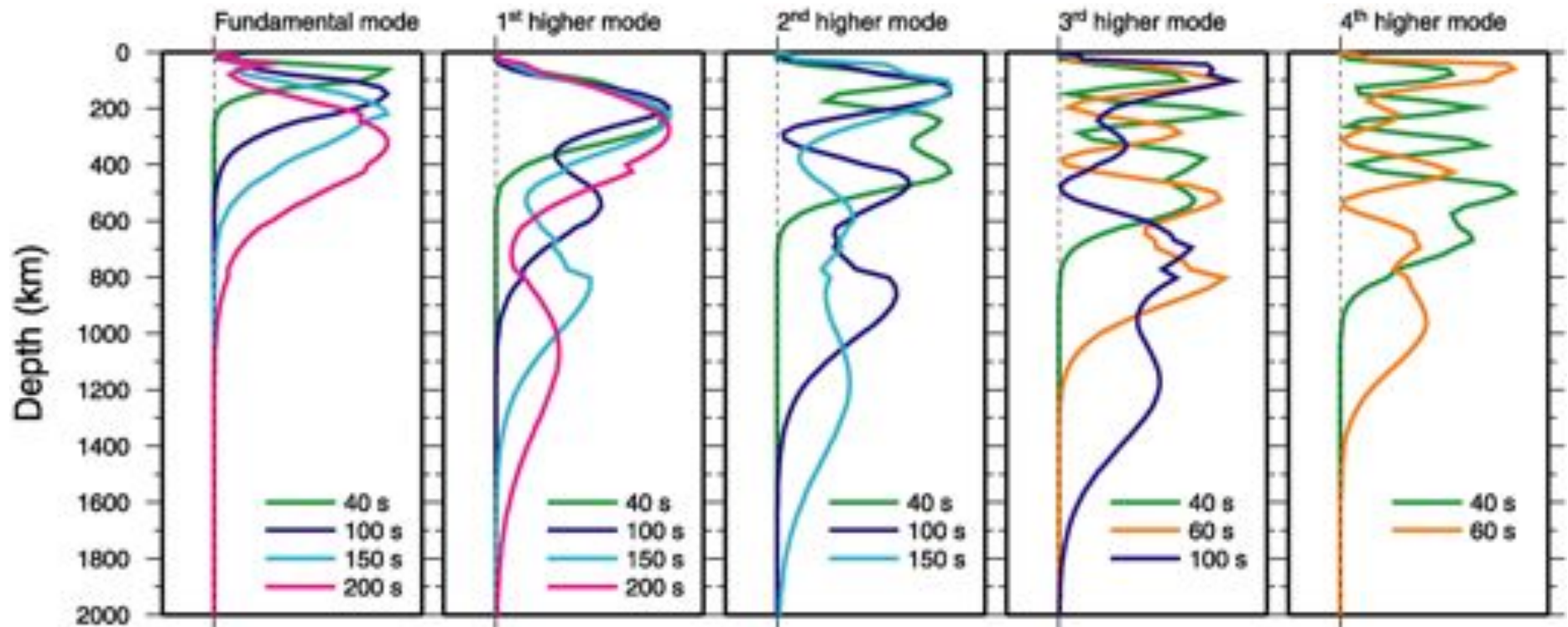


Minor and major-arc paths (unweighted)



Sensibilité à V_s en fonction de la profondeur

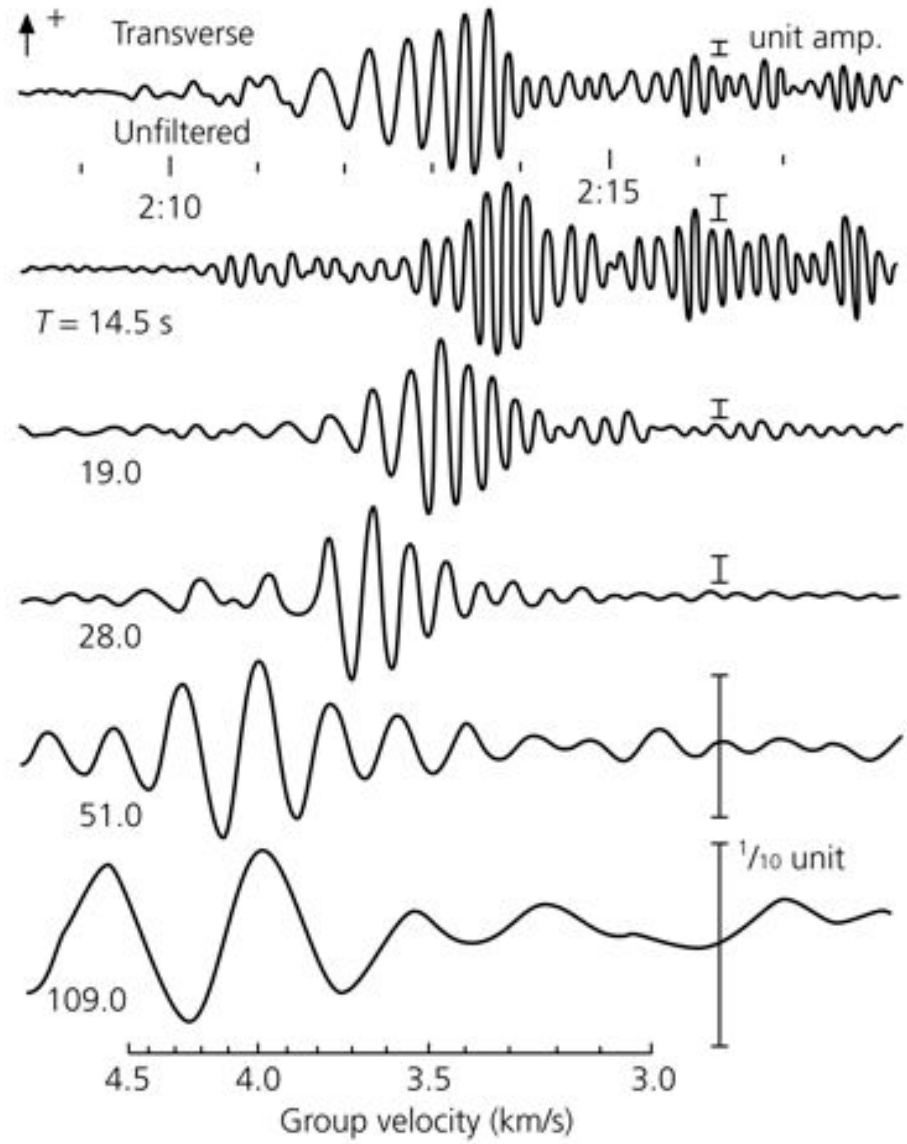
Ondes de Rayleigh



Plot after Ritsema et al, 2004

En incluant les modes harmoniques, on atteint les profondeurs de la zone de transition et du manteau inférieur

Dispersion des ondes de Love: exemple par filtrage fréquentiel



Séisme de Mongolie enregistré au Japon

→ Vitesse de groupe:

- Vitesse de propagation
- de l'énergie

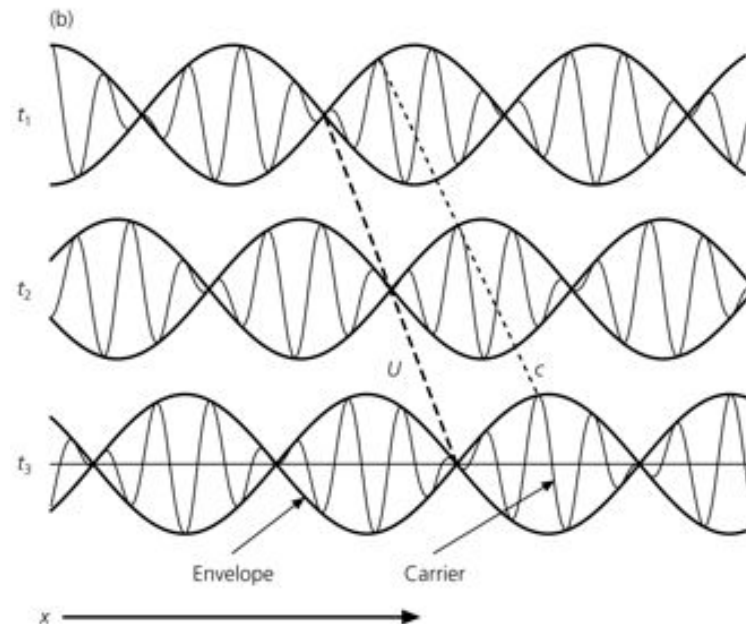
$$U = \frac{d\omega}{dk}$$

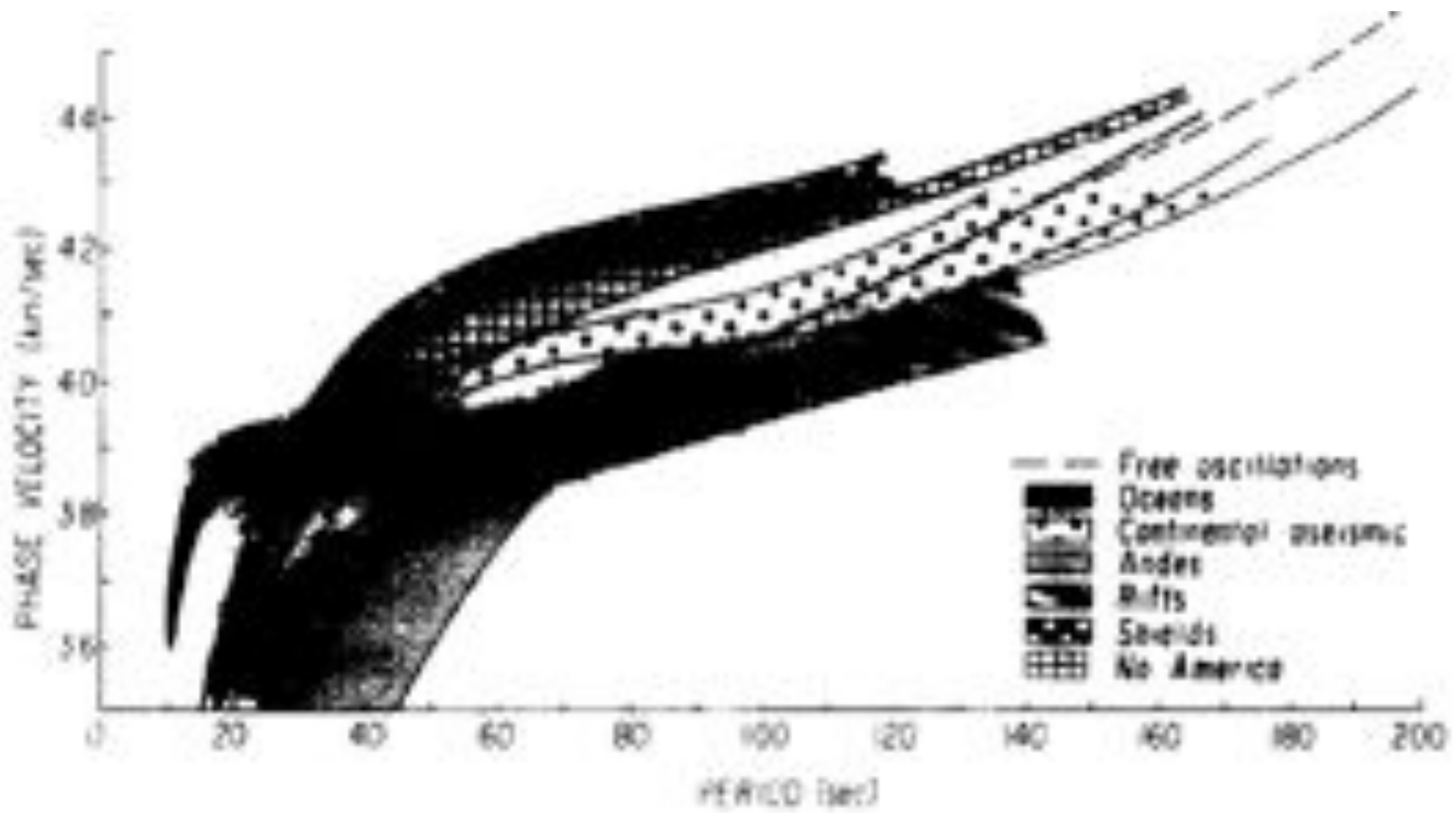
→ Vitesse de phase

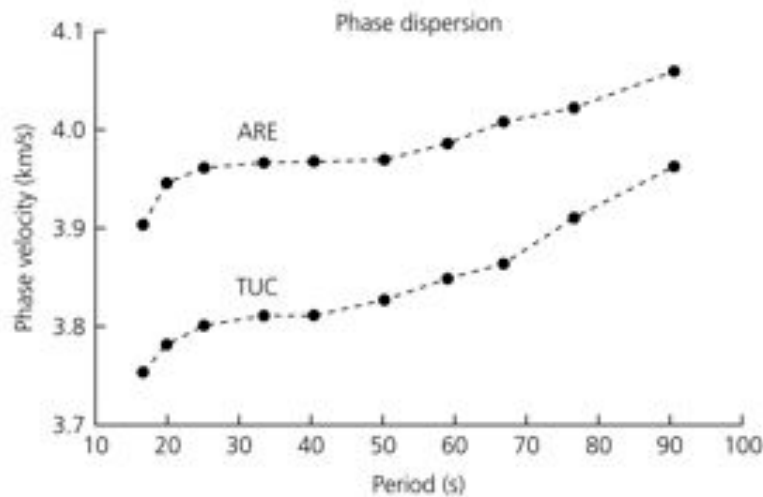
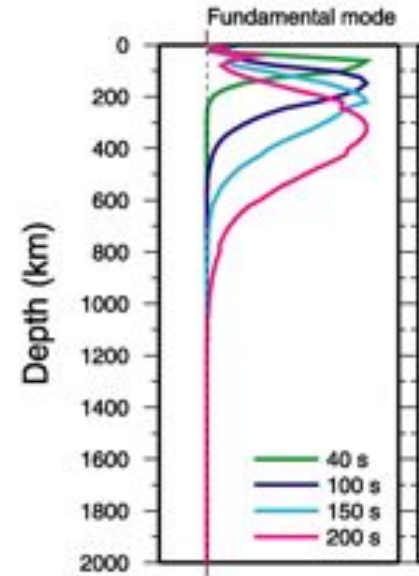
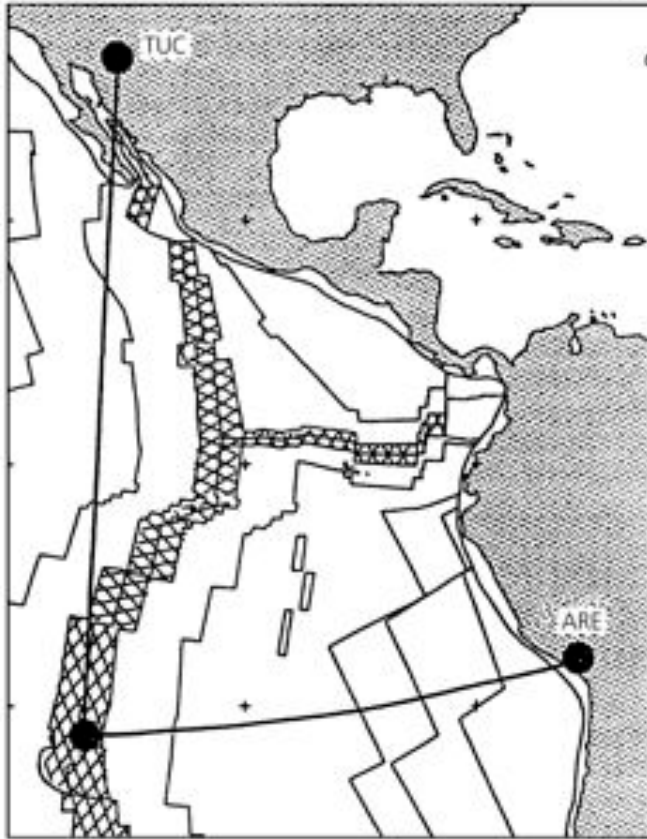
$$C = \frac{\omega}{k}$$

Relation entre vitesse de groupe
et vitesse de phase:

$$U = C + k \frac{dC}{dk} = C + \omega \frac{dC}{d\omega}$$







$$\frac{\delta C}{C}(\omega) = \int_0^a \vec{K}(\omega, r) \delta \vec{m}(r) r^2 dr$$

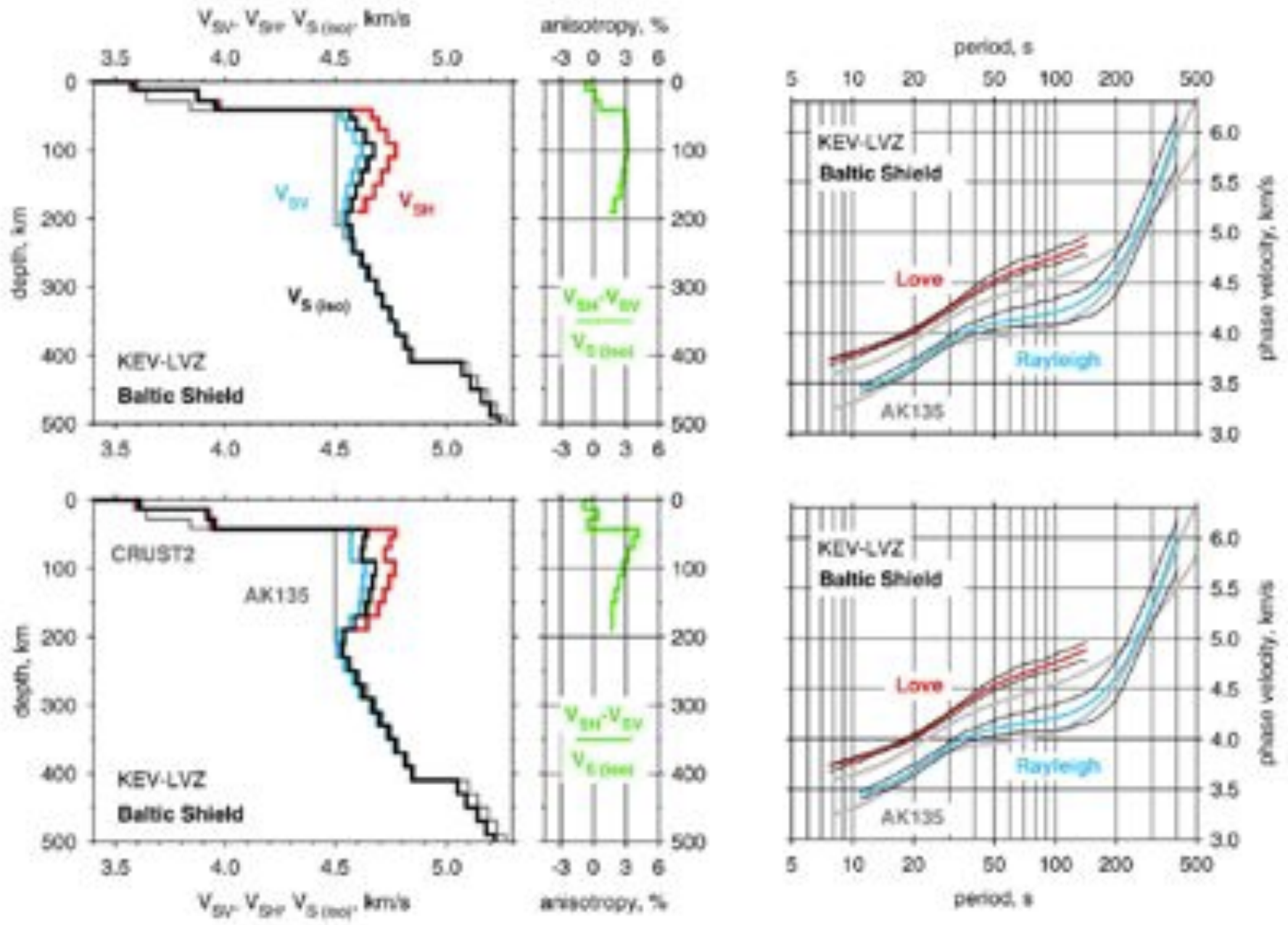
$$\delta \vec{m}(r) = \left(\frac{\delta V_S}{V_S}, \frac{\delta V_P}{V_P}, \frac{\delta \rho}{\rho} \right)$$

$$\vec{K}(\omega, r) = \left(K_S(\omega, r), K_P(\omega, r), K_\rho(\omega, r) \right)$$

$$\frac{\delta C}{C}(\omega) = \int_0^a K_1(\omega, r) \frac{\delta V_S}{V_S}(r) r^2 dr$$

$$K_1 = K_S + a_P K_P + a_\rho K_\rho$$

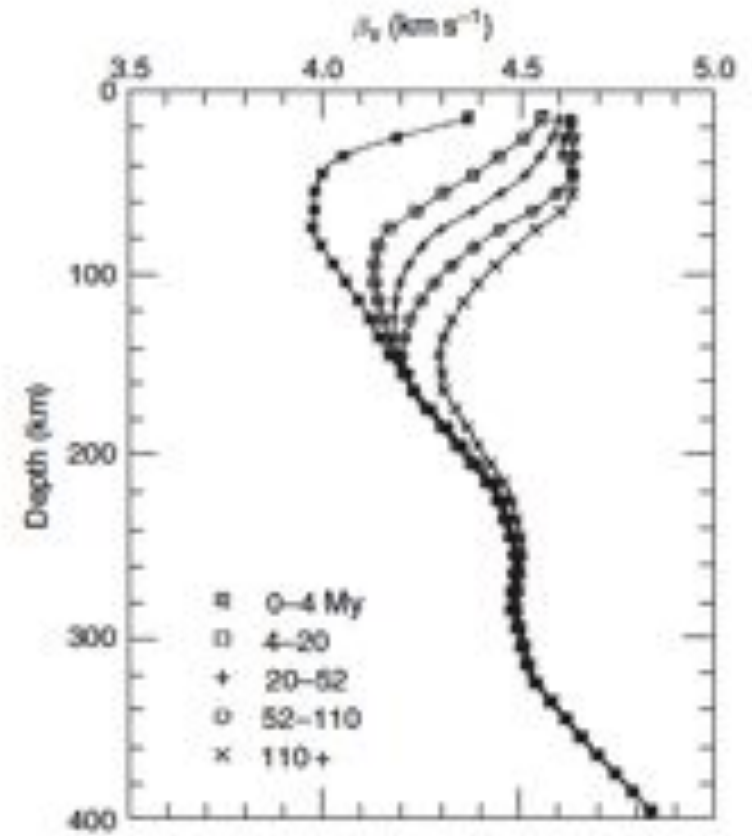
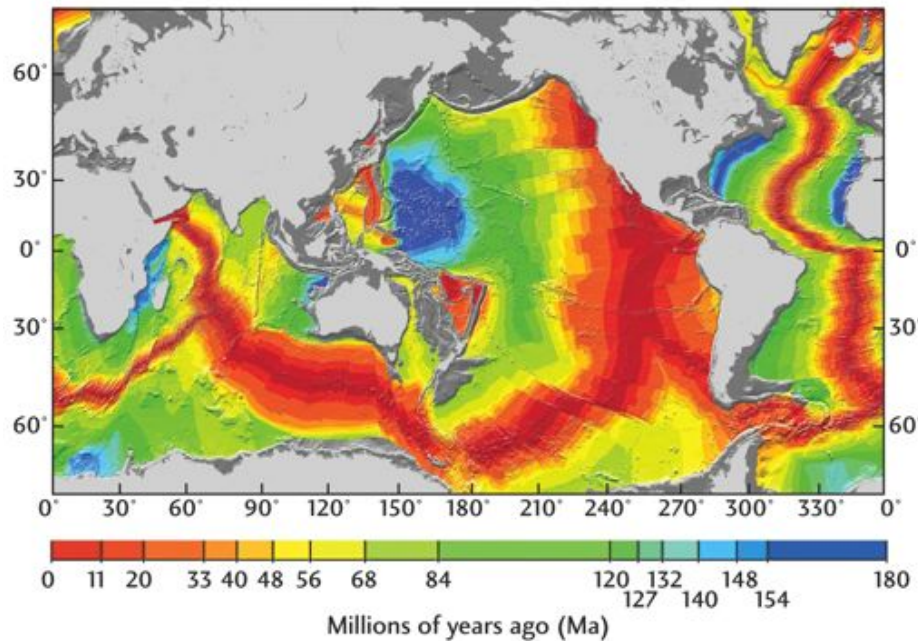
Modèles basés seulement sur la dispersion des ondes de surface ne sont pas “uniques”



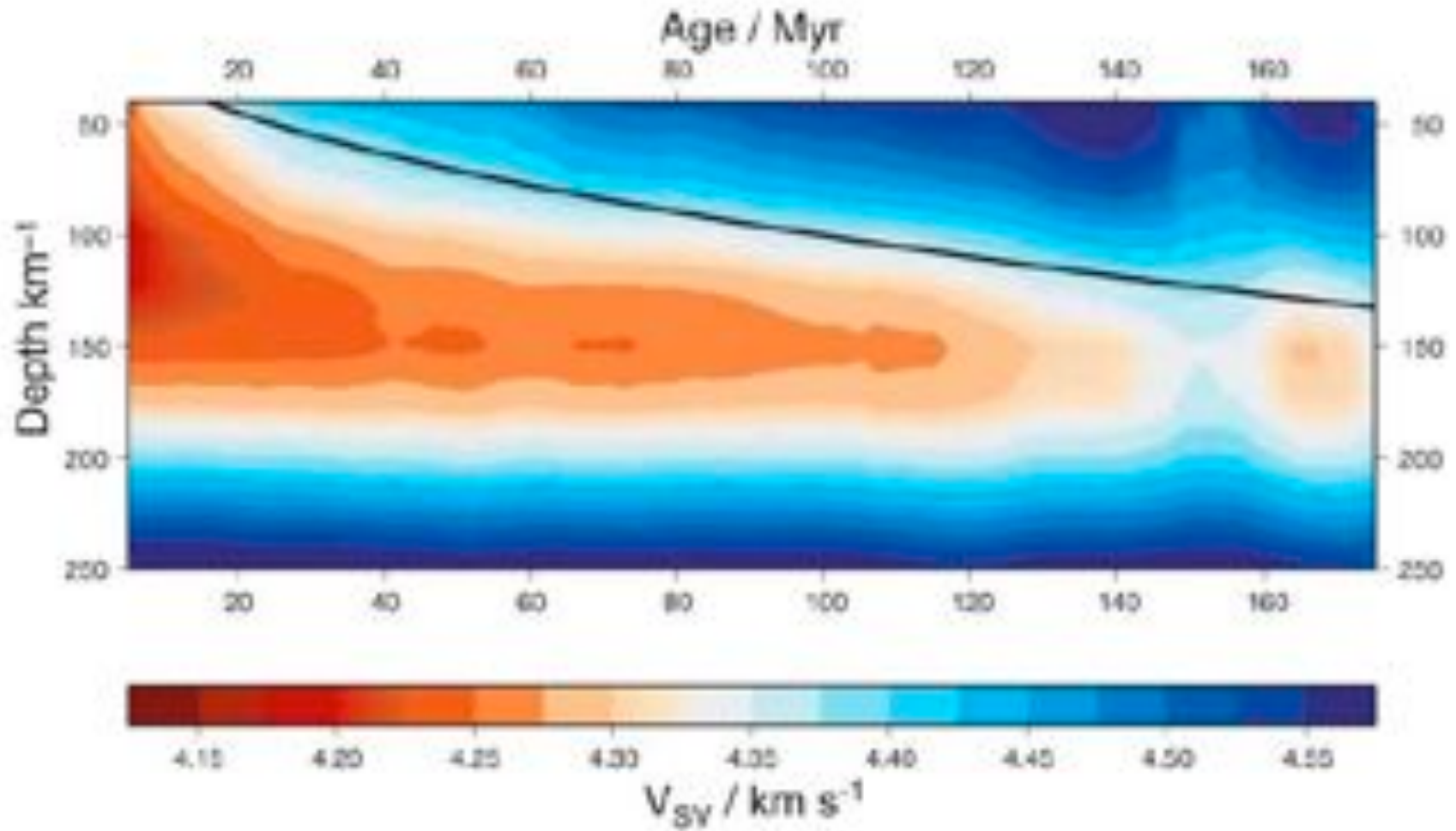
Lebedev et al., 2009

- Gutenberg (1926) fait la découverte de l'existence d'une zone à faible vitesse sismique dans le manteau supérieur (autour de 100 km de profondeur): lithosphère/asthénosphère

Il l'explique par la présence de fusion partielle et de verres
La nature de la zone à faible vitesse (LVZ) est encore controversée de nos jours



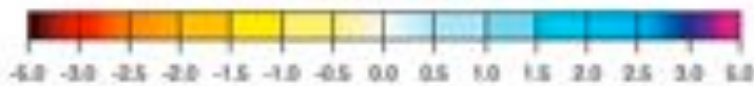
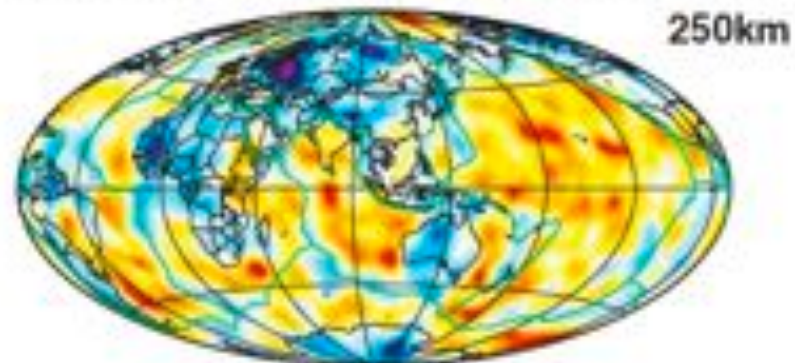
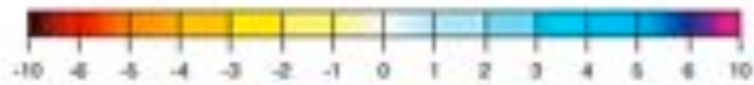
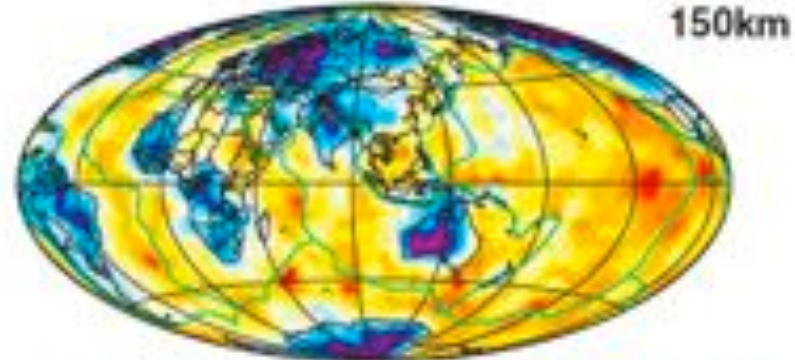
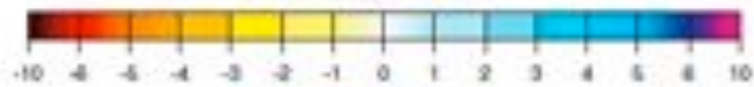
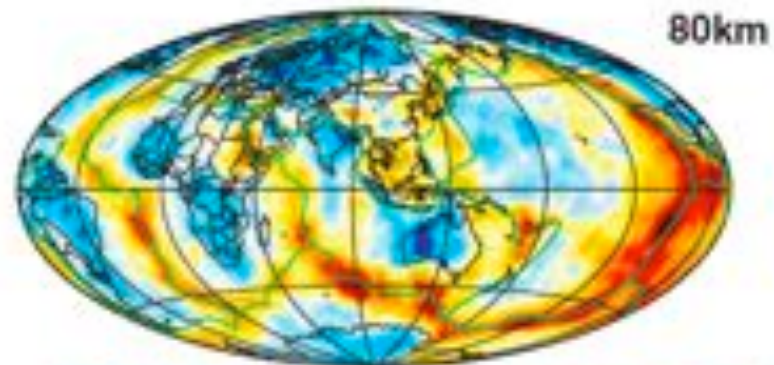
Milieu océanique: Variations de la vitesse V_{sv} en fonction de l'âge



— Base de la couche limite thermique
selon Oldenburg & Parker, 1978

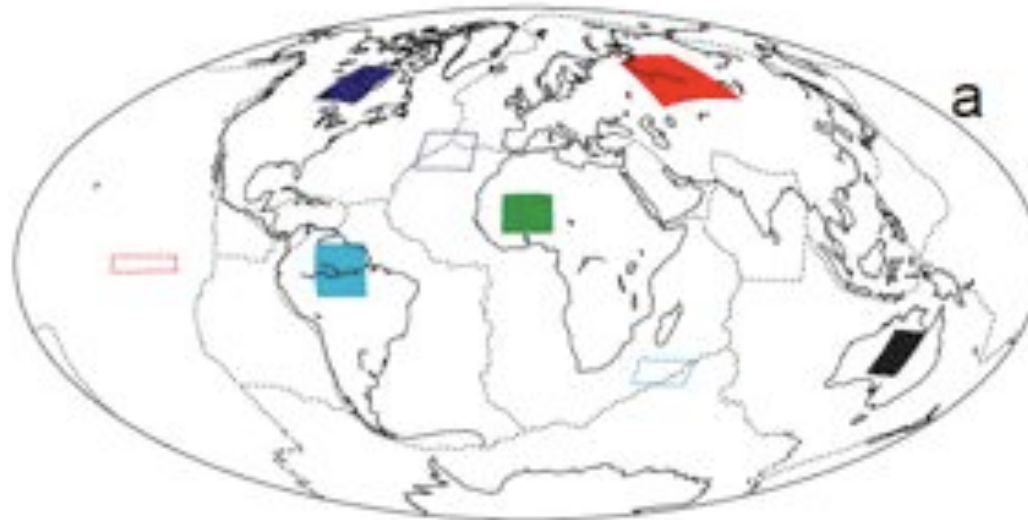
Maqgi et al., 2006

Variations latérales
de la vitesse V_{sv}
par inversion d'ondes
de surface



*Shapiro and
Ritzwoller, 2002*

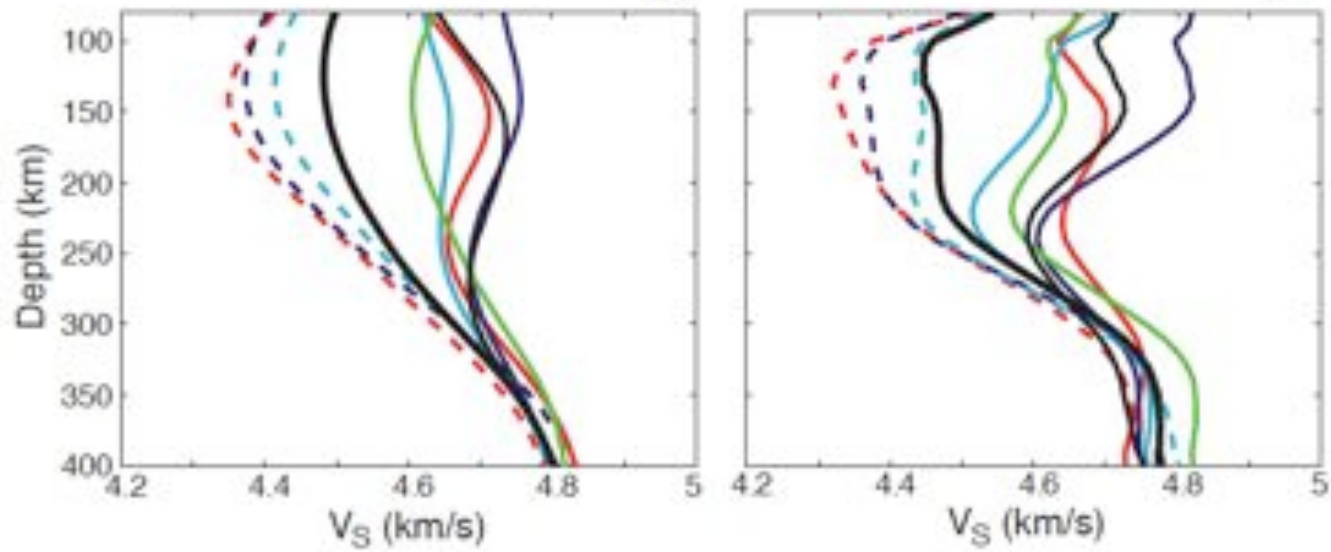
Différences océans/continents



Kustowski et al., 2008

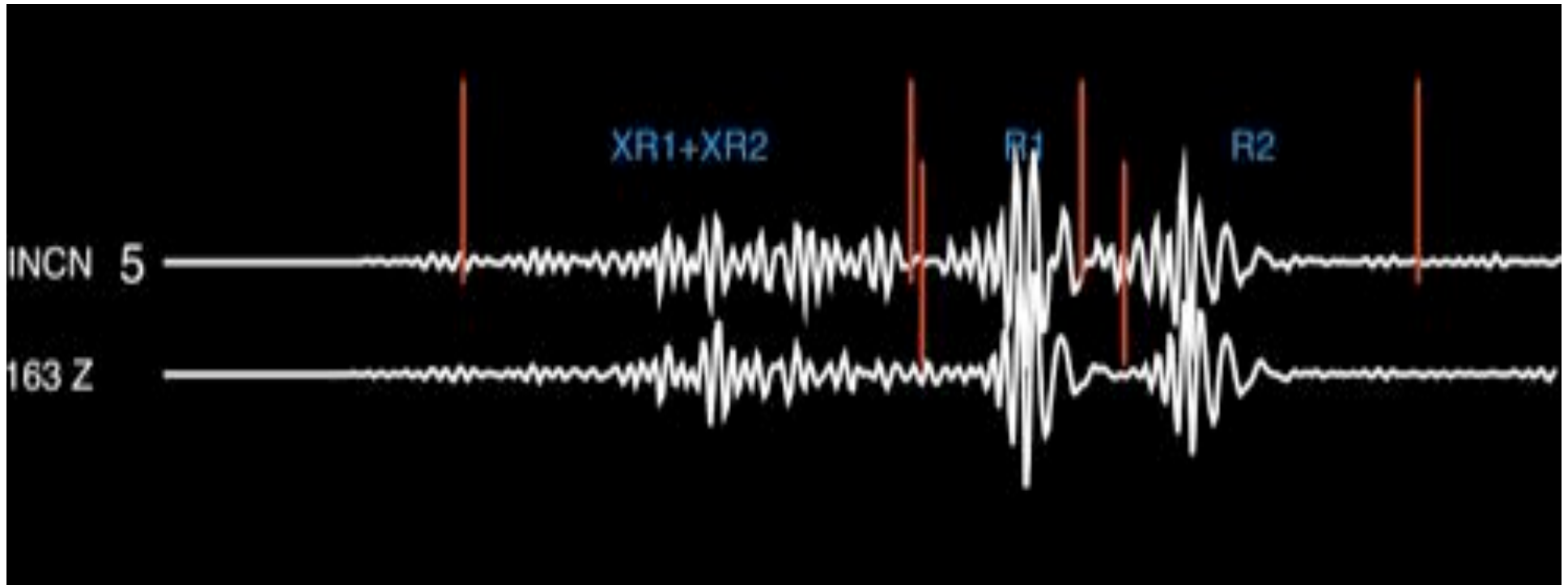
b

Cammarano and Romanowicz, 2007



Romanowicz (2009)

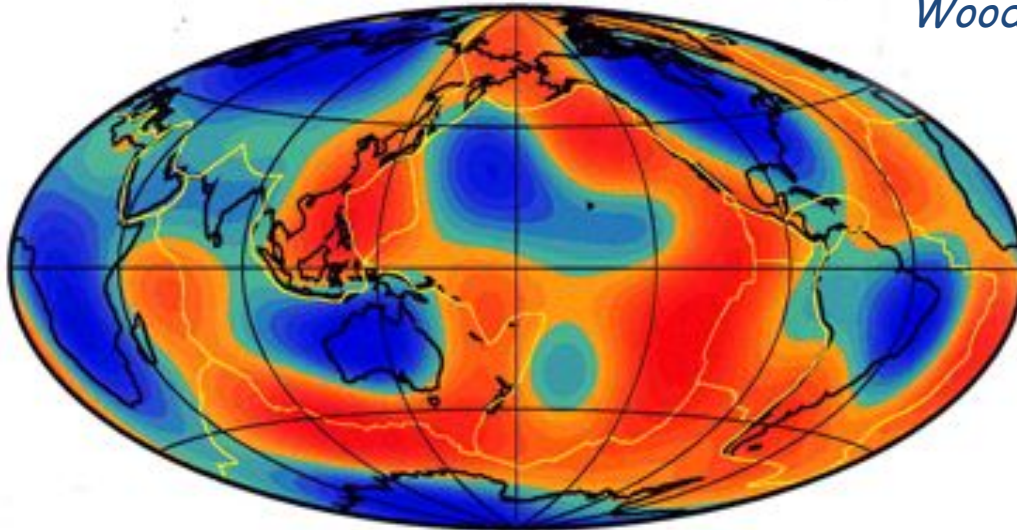
Inversion de la forme d'onde sismique dans l'espace des temps



Les sismogrammes synthétiques peuvent désormais être calculés de manière précise par une méthode numérique (par exemple la "méthode des éléments spectraux")

Model M84C (100 km)

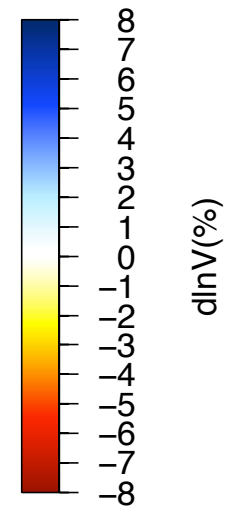
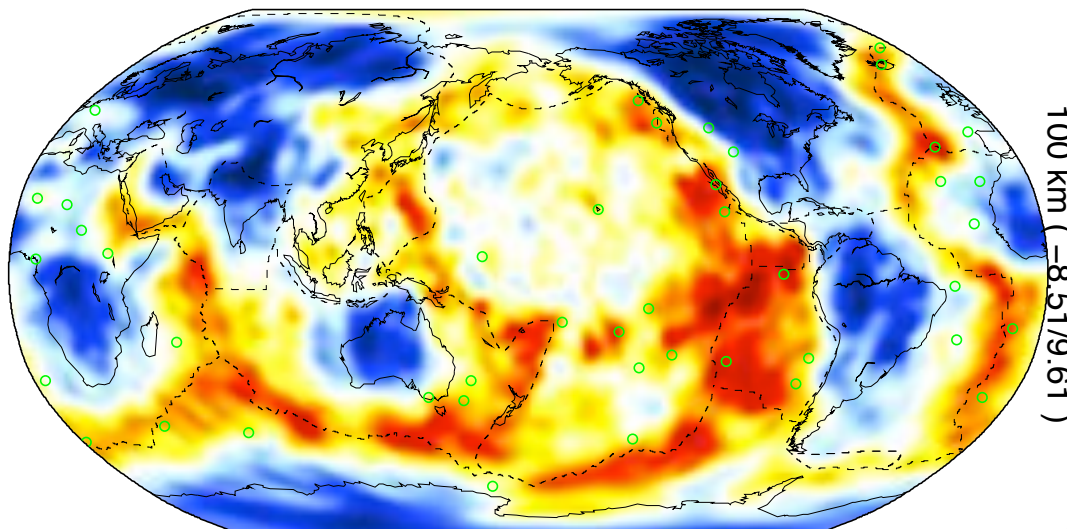
Woodhouse and Dziewonski, 1984



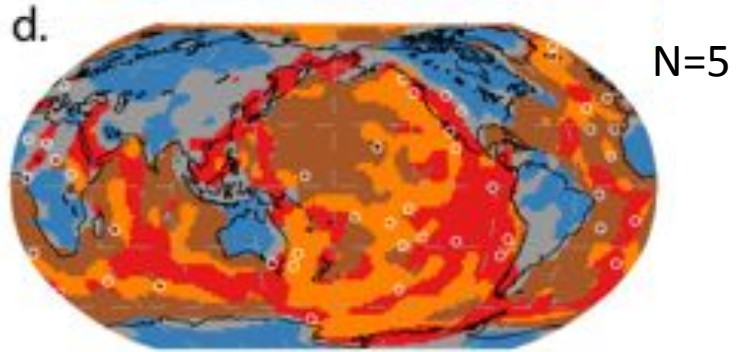
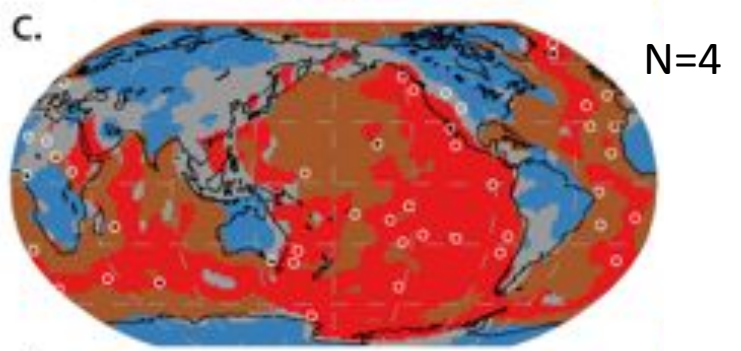
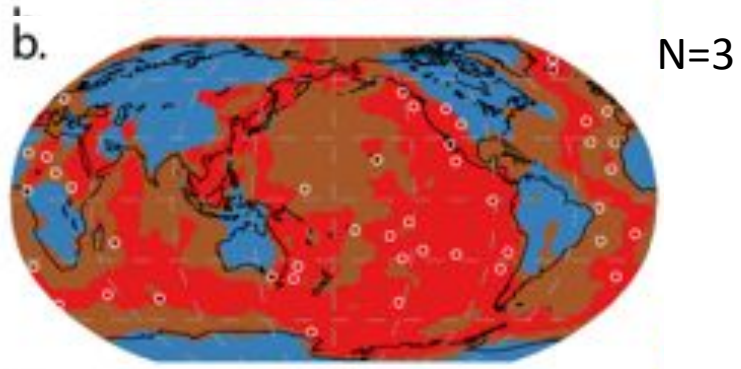
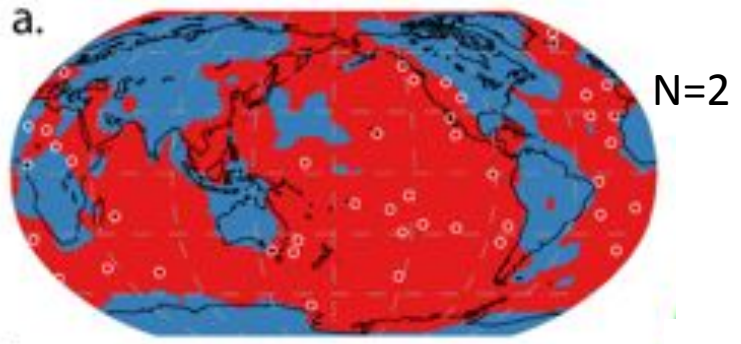
Depth = 100 km



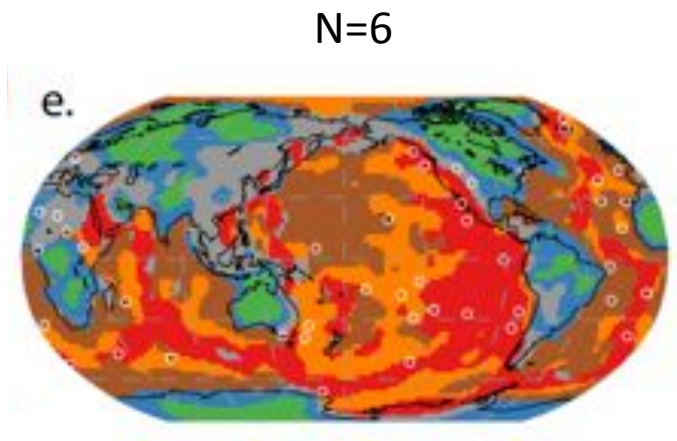
SEM-based model - Berkeley -2010



Lekic and Romanowicz, 2011

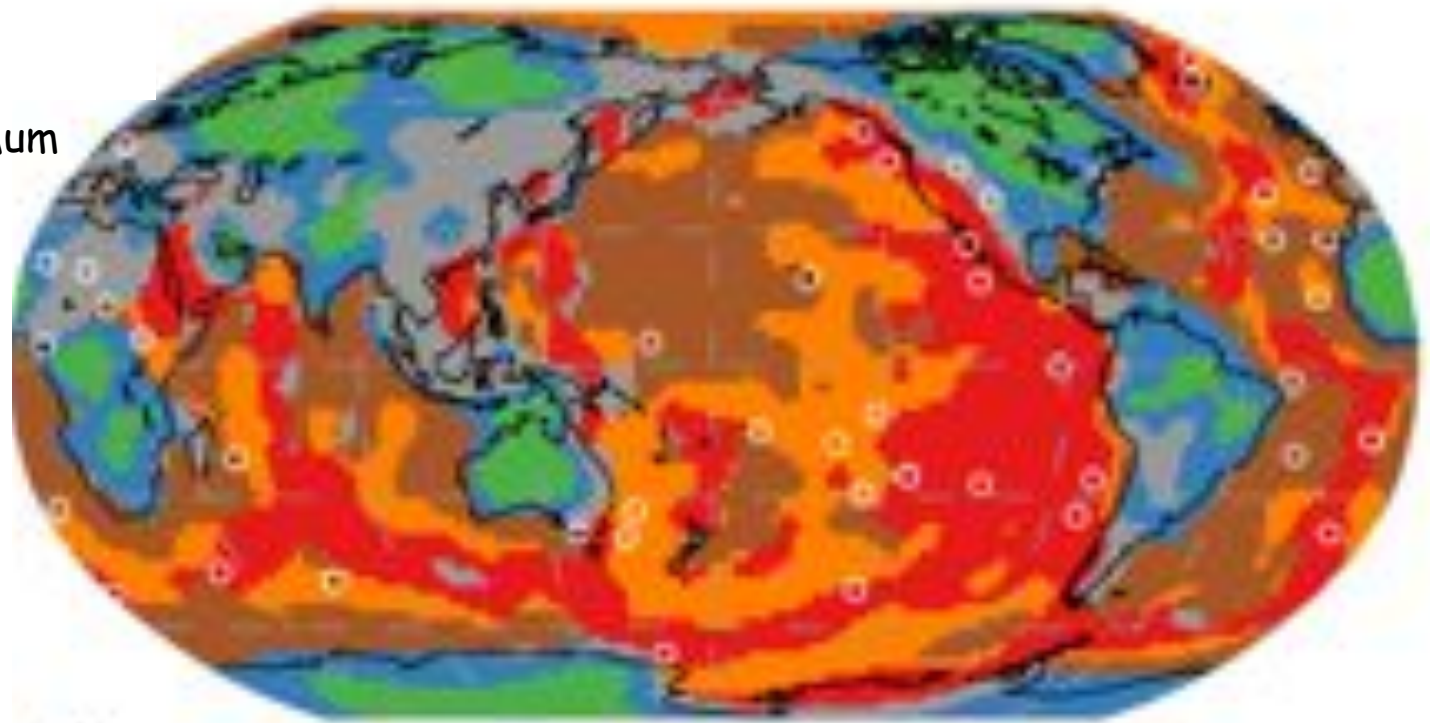


Analyse par la méthode des "clusters"
du modèle SEMum (Lekic and Romanowicz,
2011)



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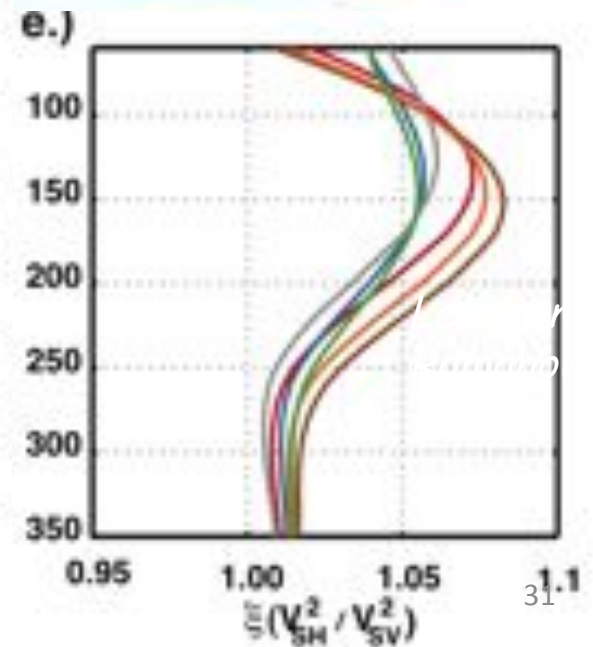
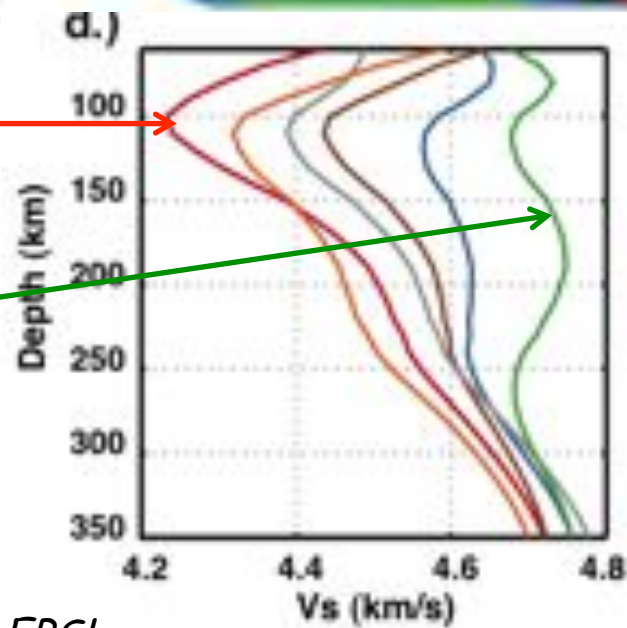
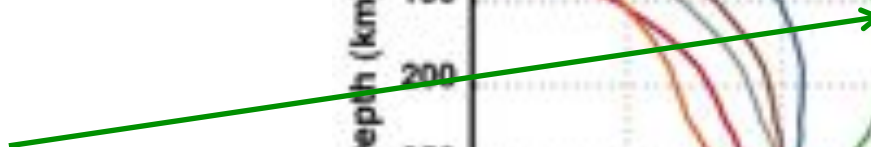
Regionalization of SEMum
based on clustering
analysis
with N=6
regions



Océans jeunes

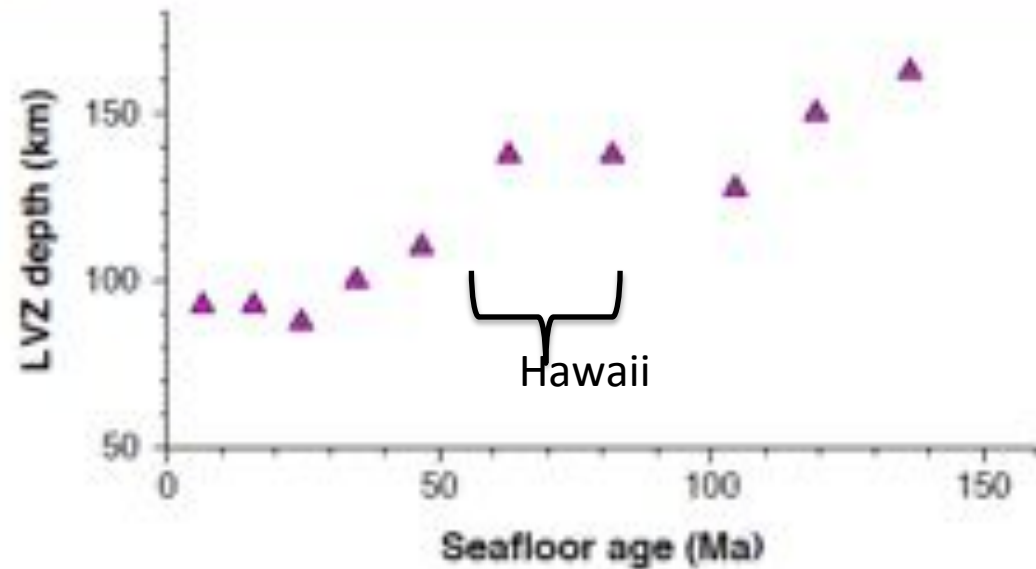


"Cratons"



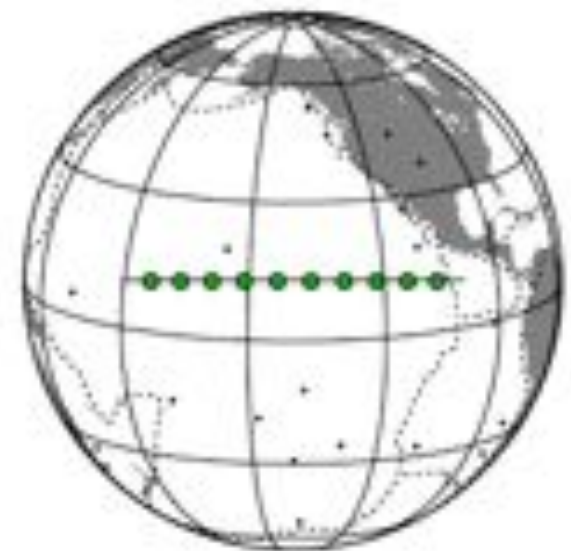
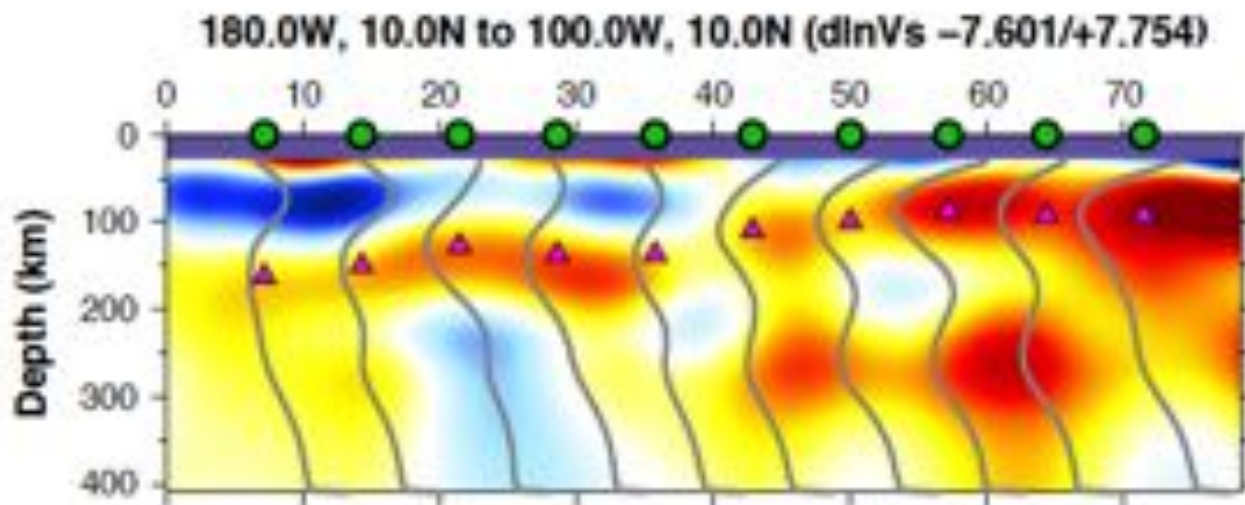
Lekic and Romanowicz, 2011, EPSL

SEMum2.2 model structure



Pacific LVZ structure

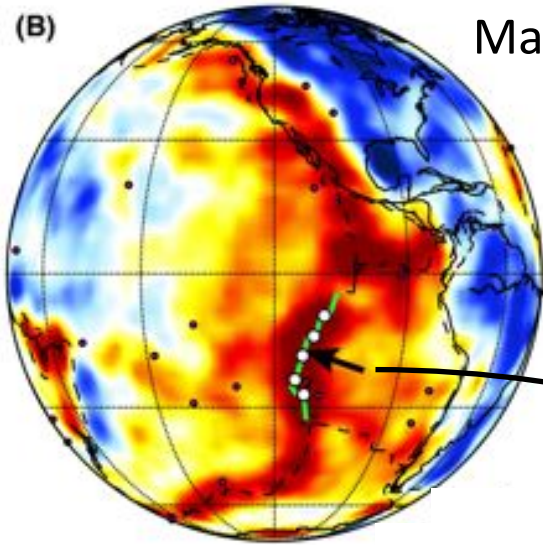
Relationship with seafloor age



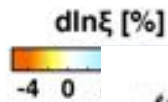
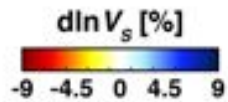
(Ages from Muller, et al. 2009, G^3)

(B)

Map of SEMum2 at 70 km depth

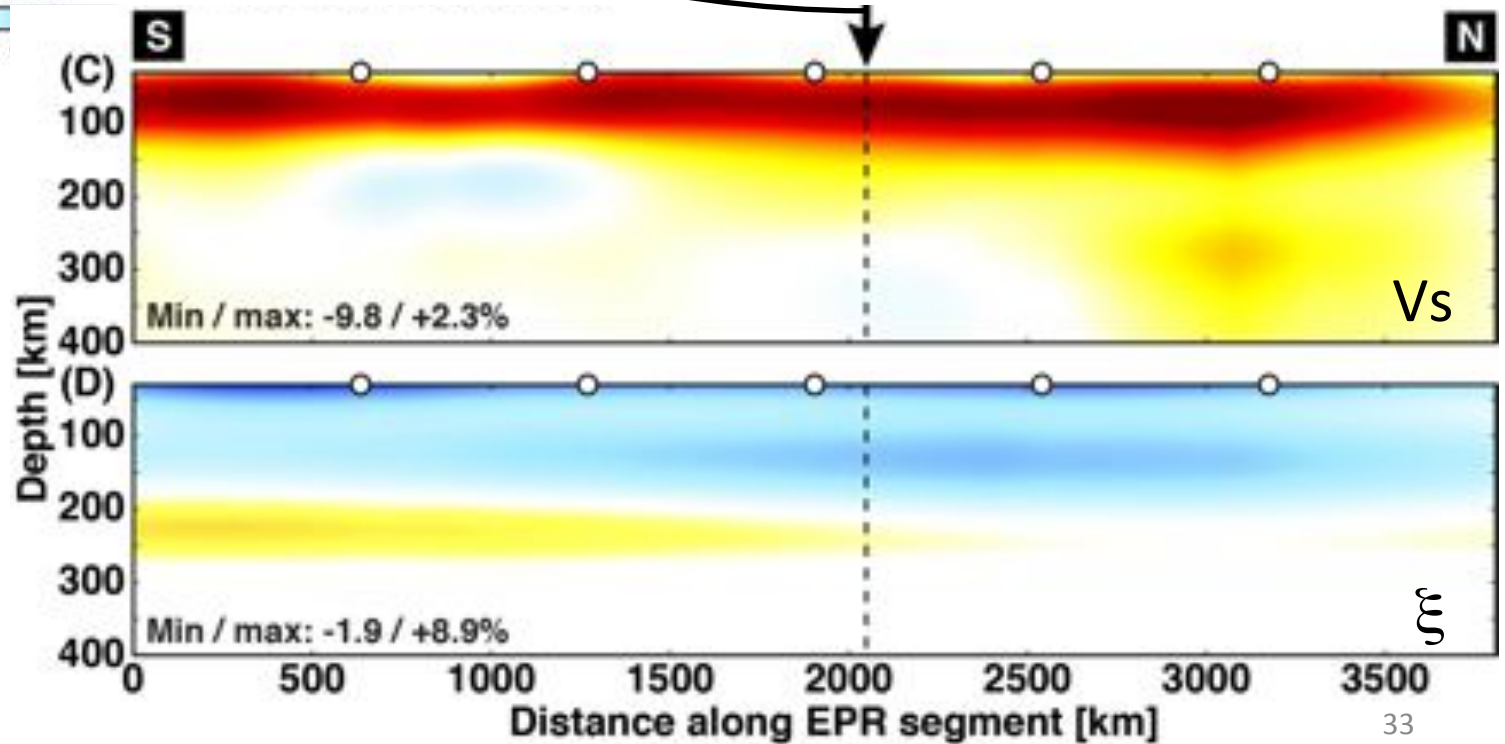


Cross-section along the East Pacific Rise

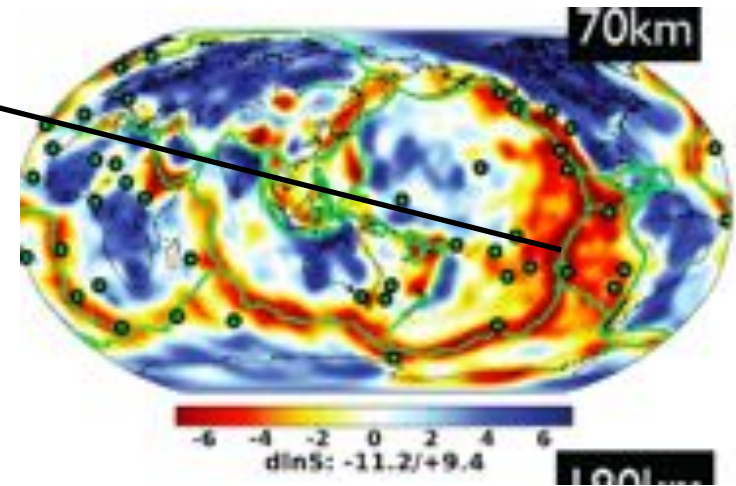
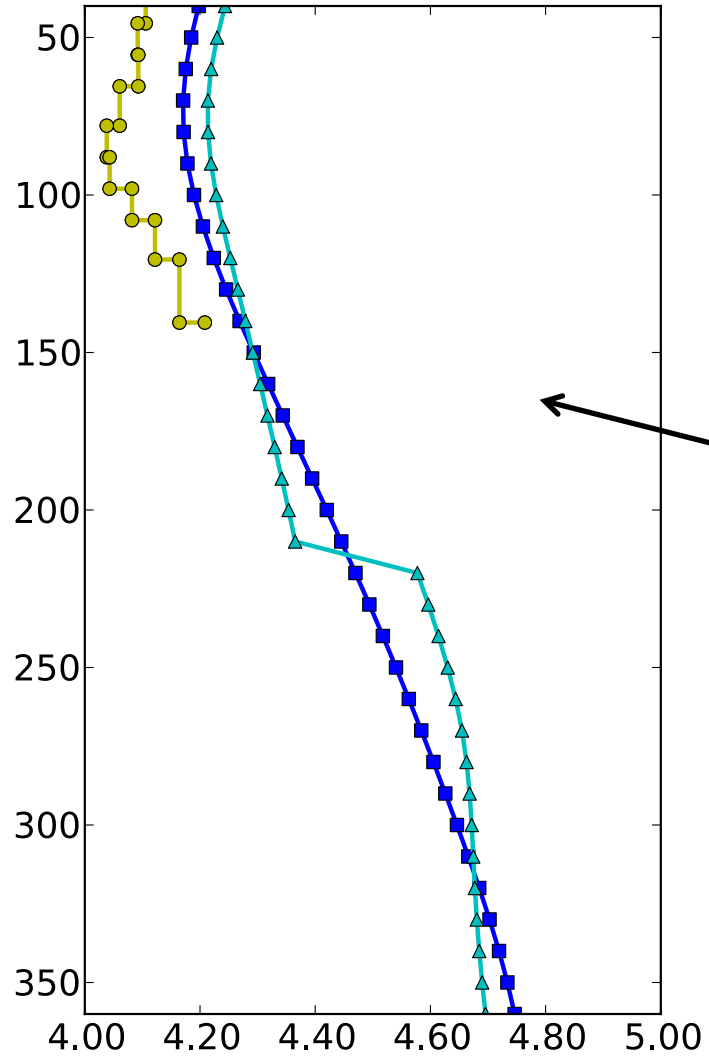


Isotropic velocity

Radial anisotropy

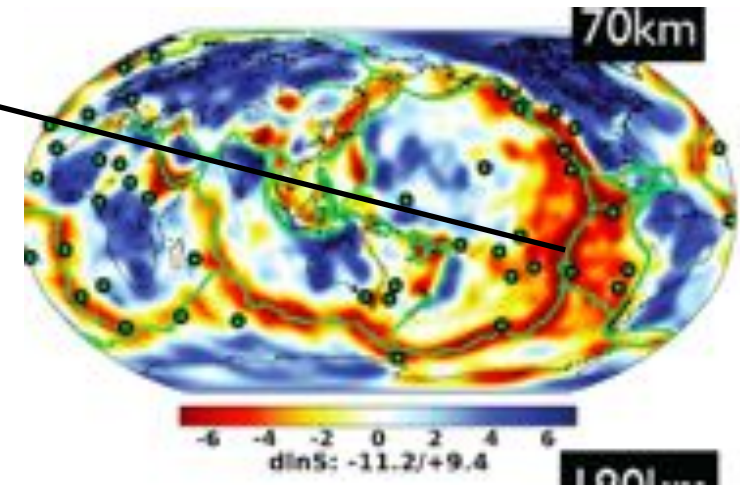
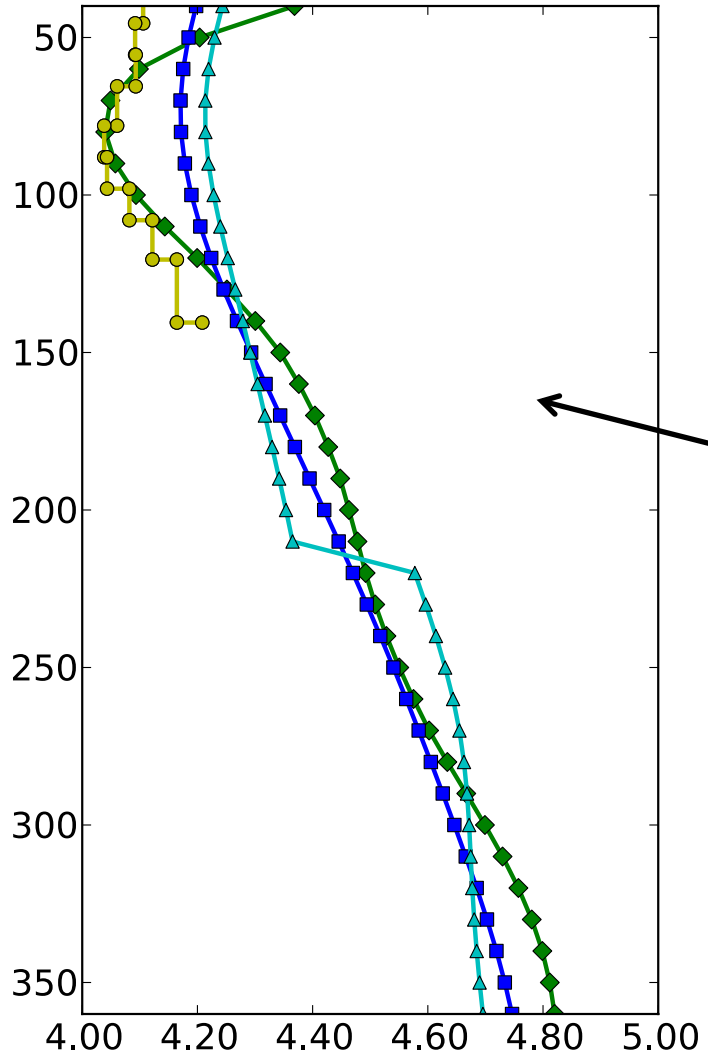


East Pacific Rise



- S362ANI: Kustowski, et al. (2008)
- ▲ S40RTS: Ritsema, et al. (2011)
- Harmon, et al. (2009) (mean)

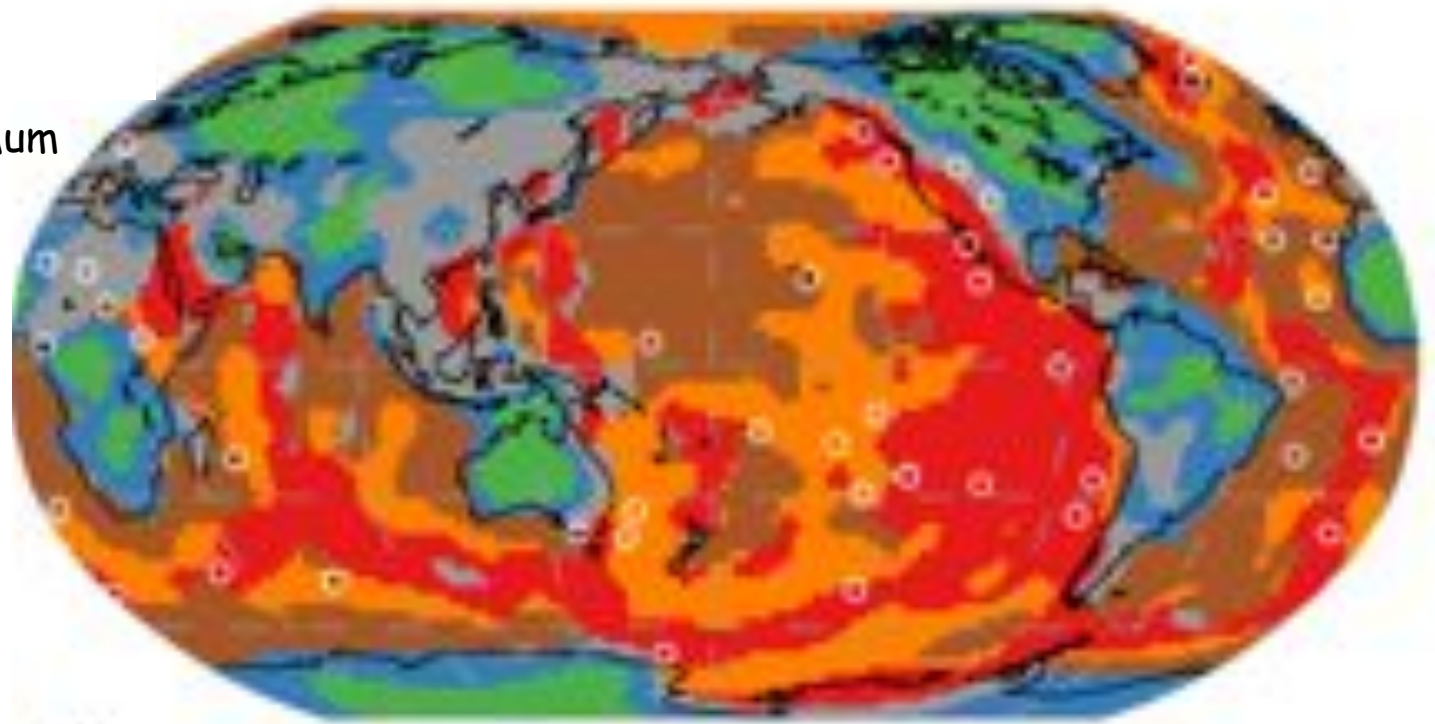
East Pacific Rise



- ◆ SEMum2.2
- S362ANI: Kustowski, et al. (2008)
- ▲ S40RTS: Ritsema, et al. (2011)
- Harmon, et al. (2009) (mean)

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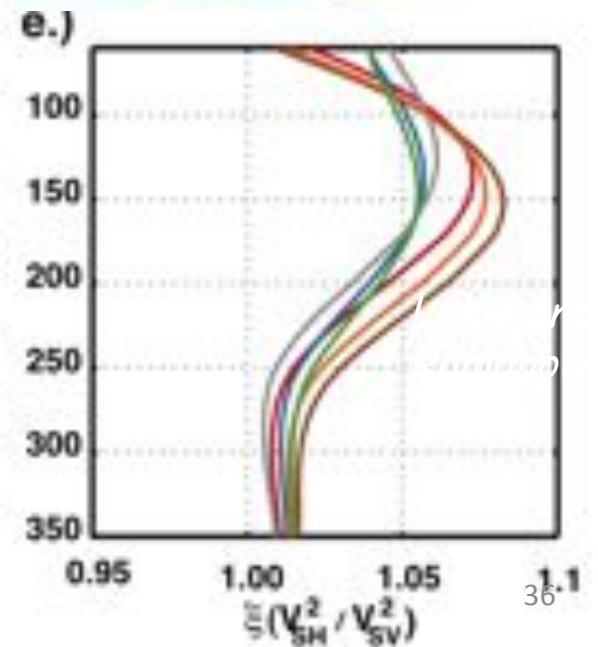
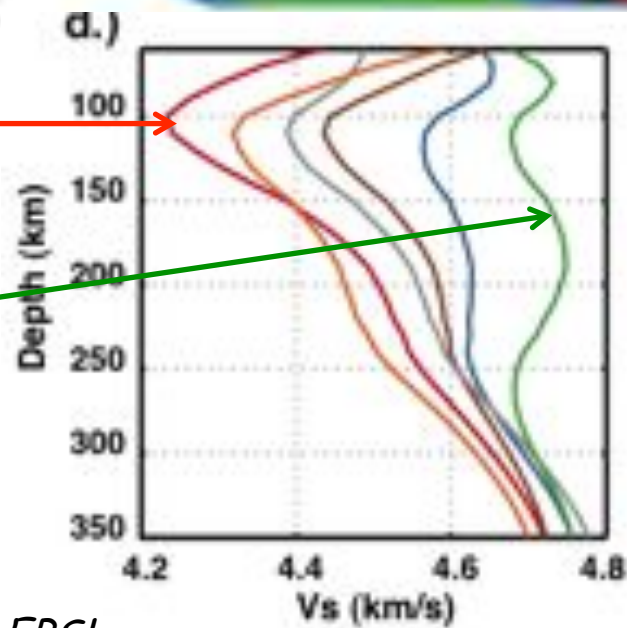
Regionalization of SEMum
based on clustering
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with N=6
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Océans jeunes



"Cratons"

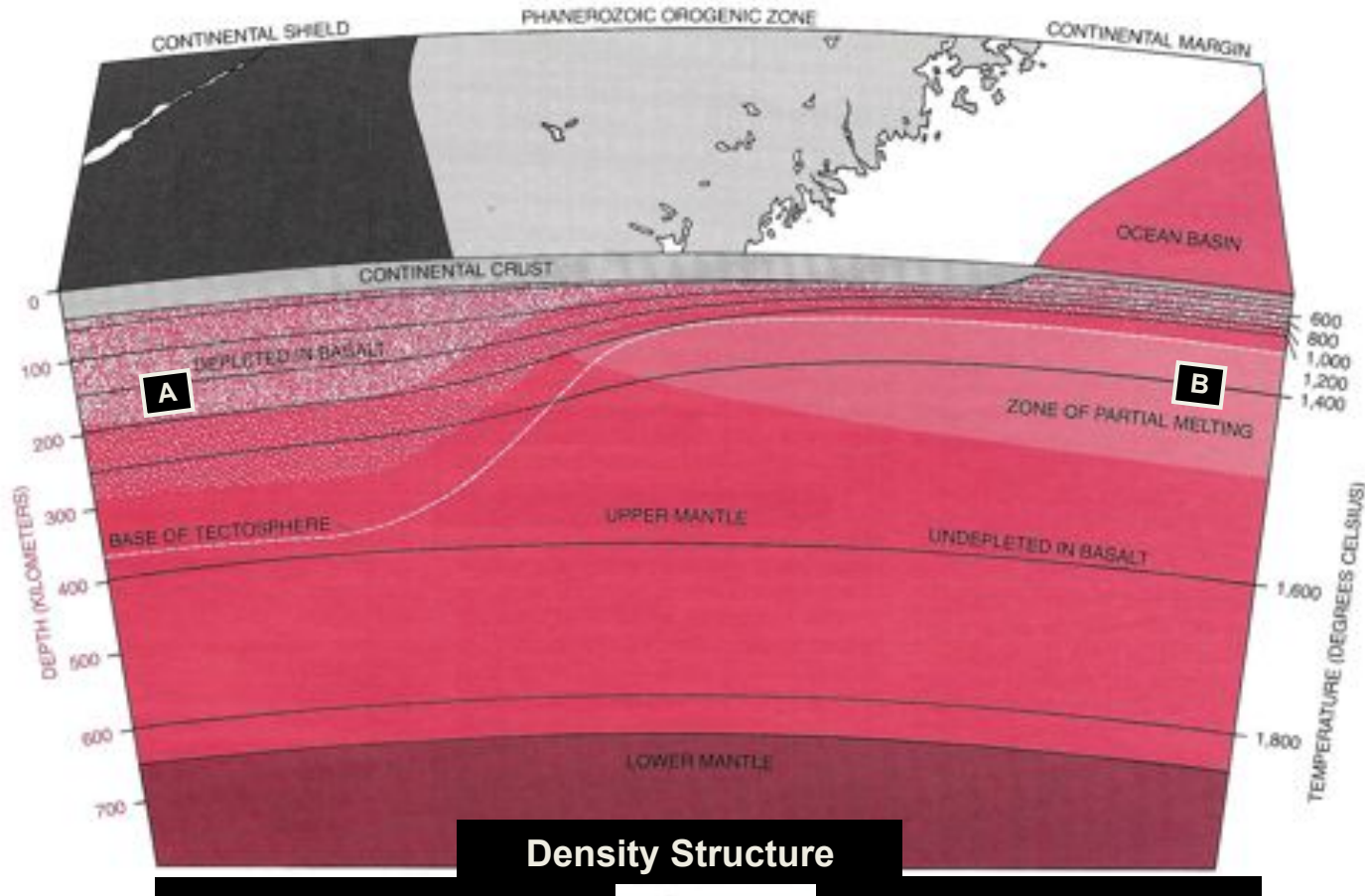


Lekic and Romanowicz, 2011, EPSL

Cratons

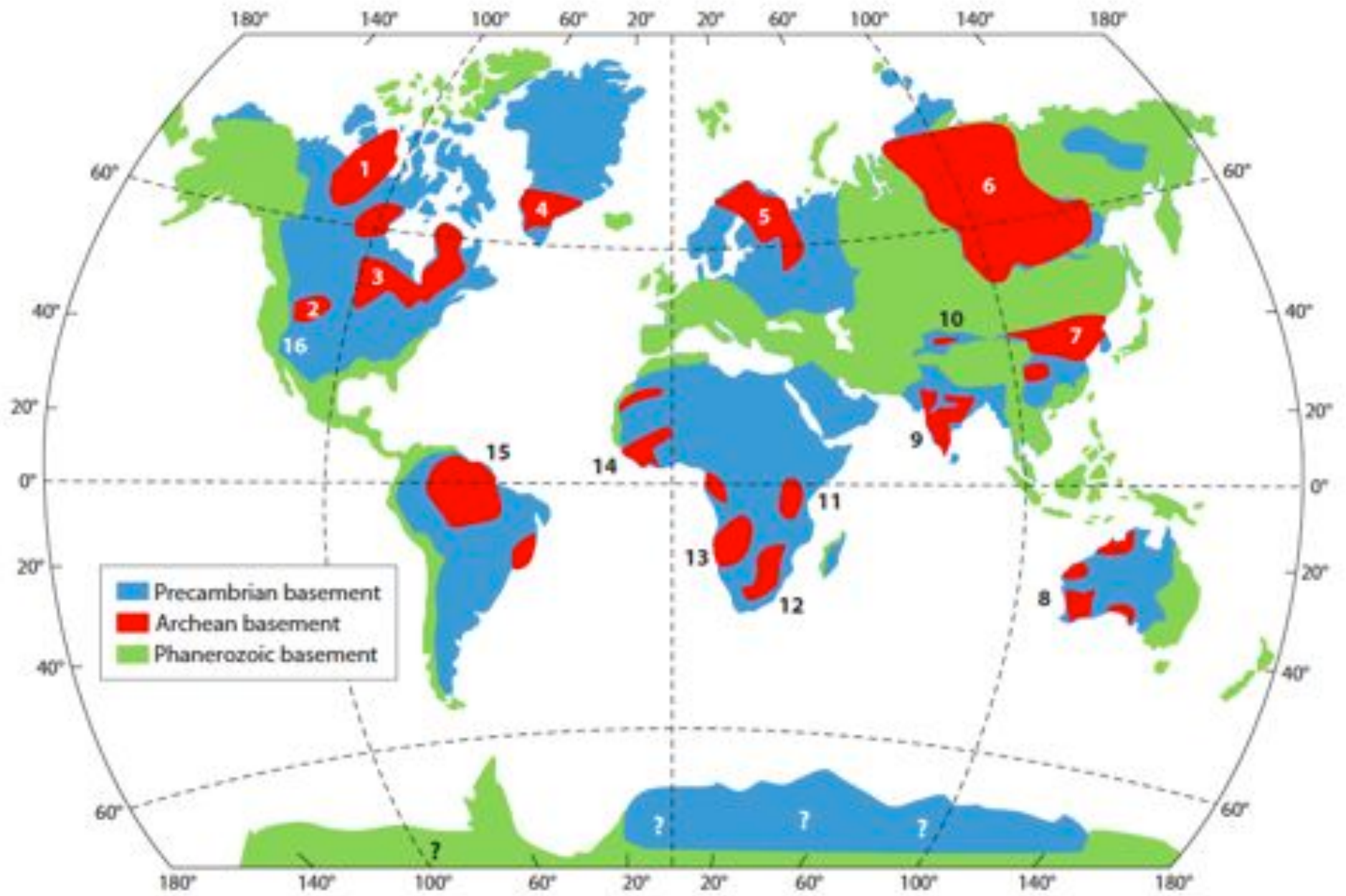
- Parties stables des continents, dont la croûte a été peu déformés depuis l' époque archéenne
- Structure et formation de la lithosphère cratonique:
 - Lithosphère est froide (flux de chaleur, diamants)
 - Vitesses sismiques élevées
 - Pas d'anomalie de gravité
 - Hypothèse "isopycnique": température basse est compensée par une densité faible due à une composition chimique particulière
- Comment ont ils été formés et pourquoi n'ont ils pas été détruits au cours du temps?
- Epaisseur de la lithosphère cratonique

Isopycnic (Equal-Density) Hypothesis



Jordan, Sci. Am., 1979

No positive geoid anomaly above continents: The temperature difference between the cratonic tectosphere and the convecting mantle is density-compensated by the depletion of the tectosphere in Fe and Al relative to Mg by the extraction of mafic fluids.



Lee et al., 2011, *Ann. Rev.*

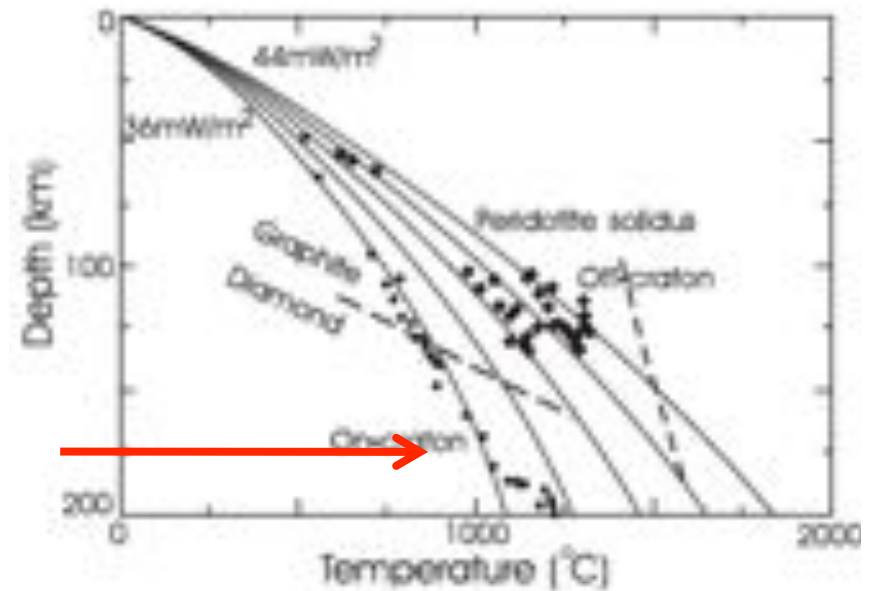
La lithosphère est froide sous les cratons



Xenolith thermobarometry

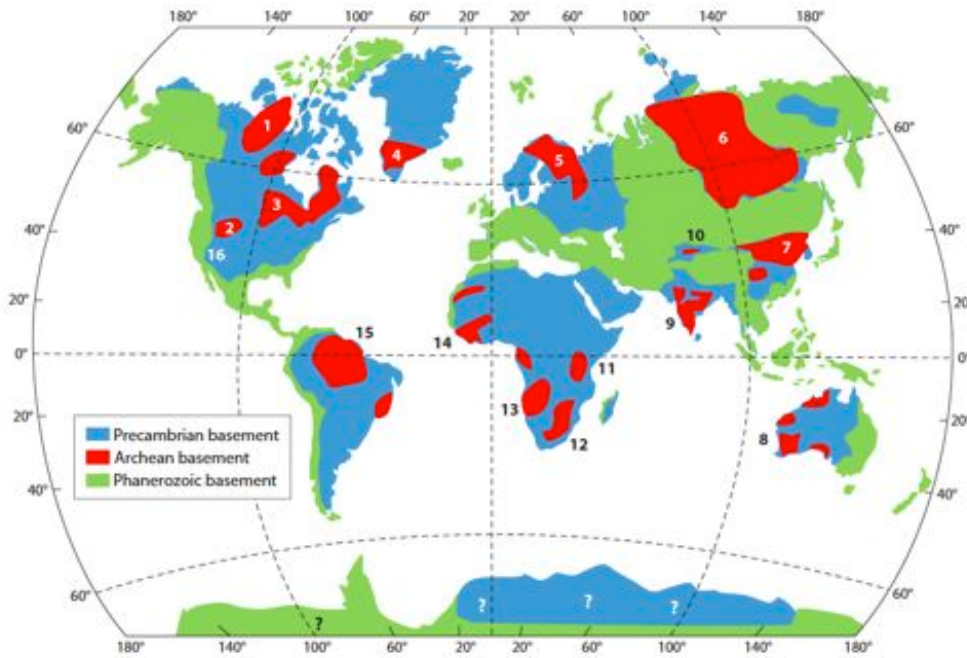
◆ Champs de diamants

From King, *EPSL*, 2005

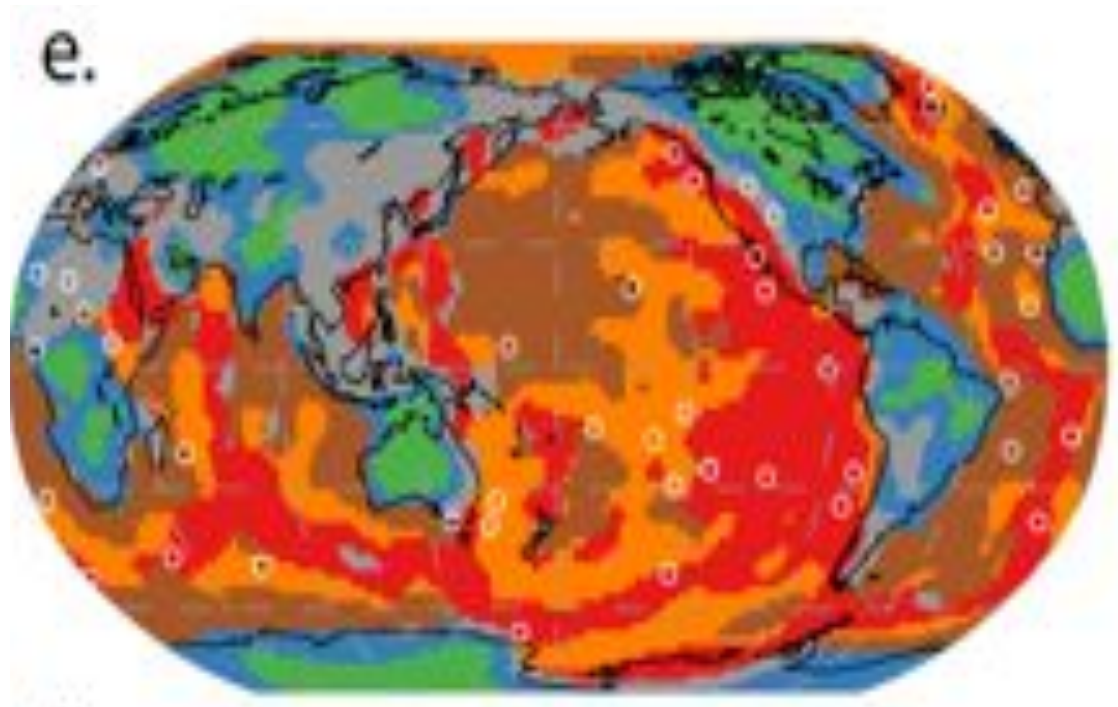


O'Neill and Moresi, 2003

Age de la croûte

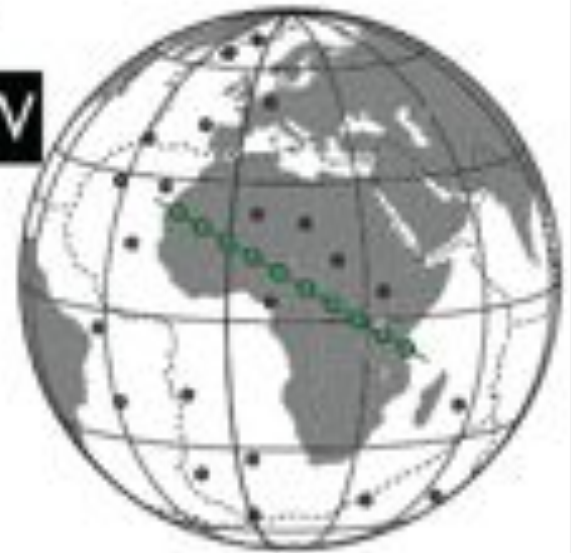
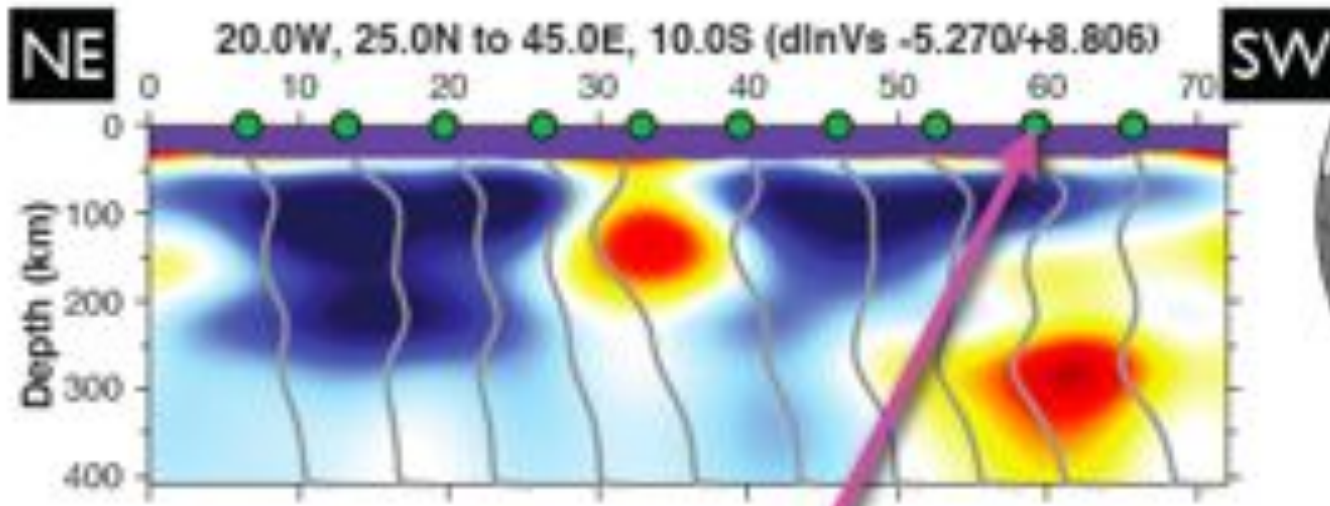


Structure du manteau supérieur



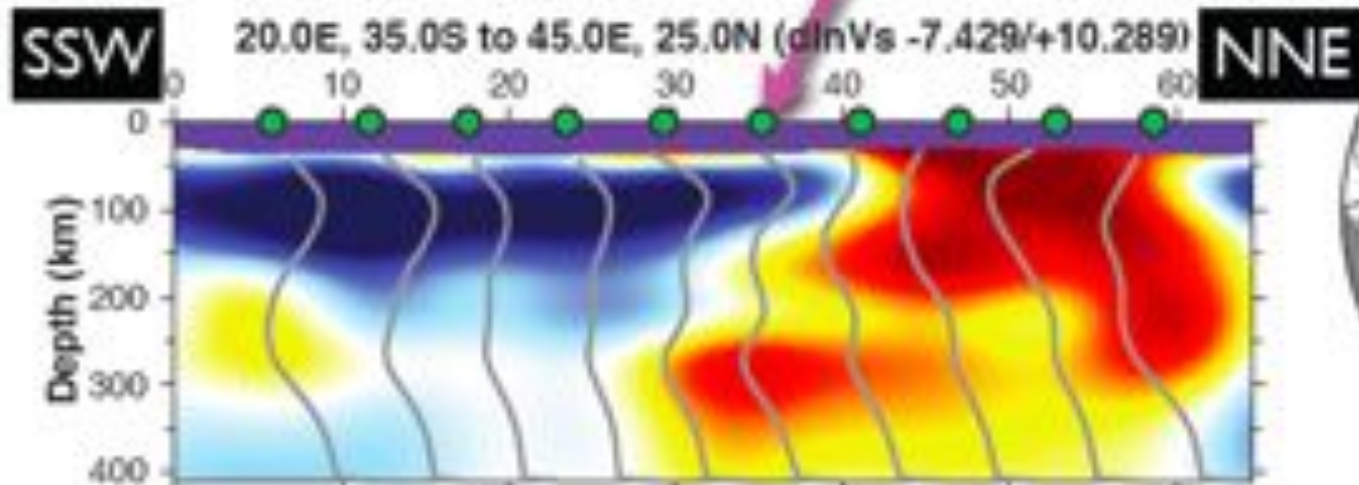
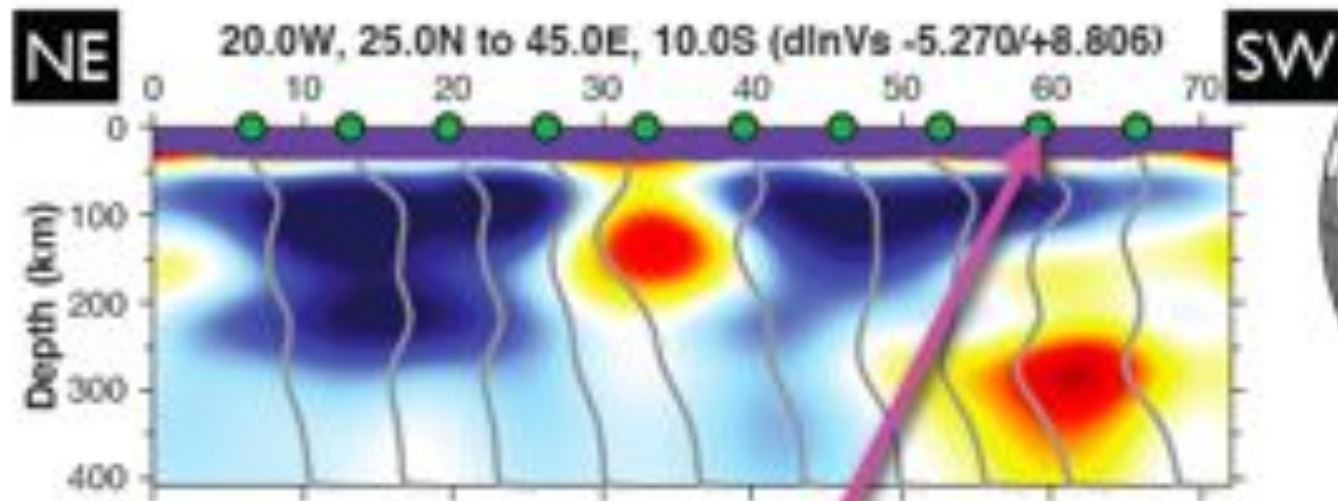
SEMum2.2 model structure

Continental example region: **Africa**

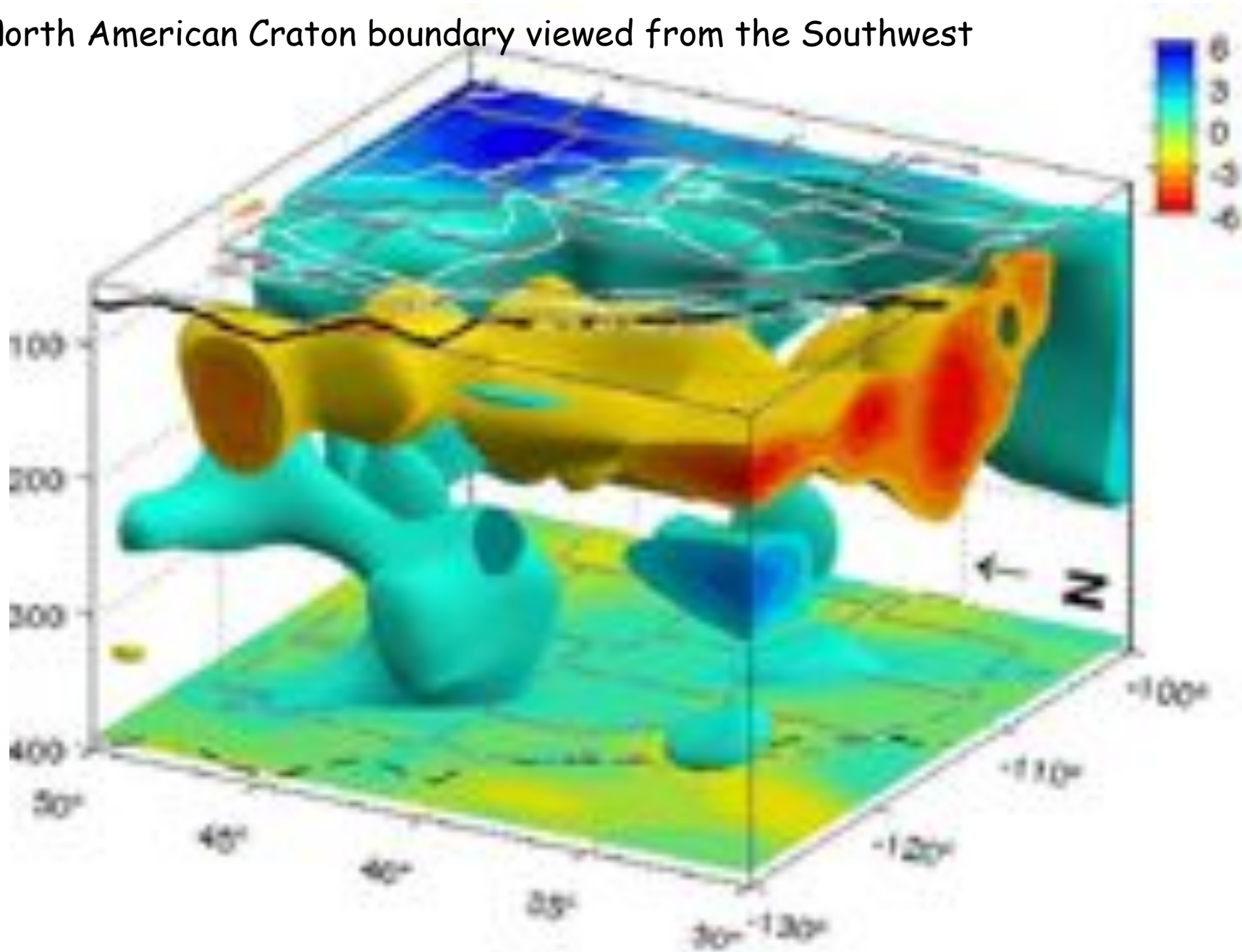


SEMum2.2 model structure

Continental example region: **Africa**



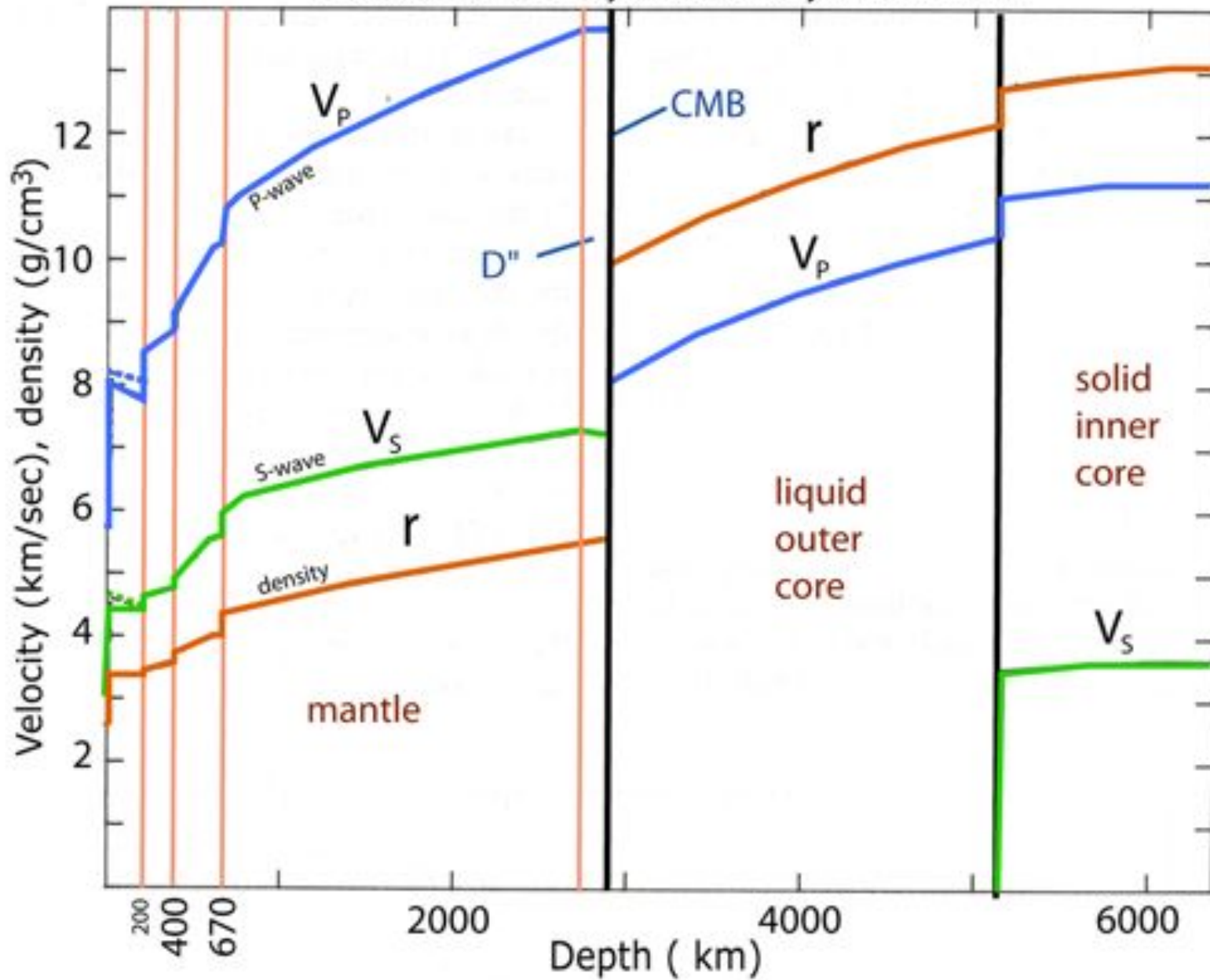
North American Craton boundary viewed from the Southwest



Anisotropie de polarisation (radiale)

- Décrite par 5 paramètres élastiques:
 - A, C, F, L, N (Love, 1911)
 - $L = \rho V_{sv}^2$
 - $N = \rho V_{sh}^2$
 - $A = \rho V_{ph}^2$
 - $C = \rho V_{pv}^2$
 - F représente la vitesse dans une direction intermédiaire
- Les ondes de longue période (de type S) permettent seulement de contraindre (L, N)
 - $\Rightarrow \xi = (V_{sh}/V_{sv})^2$
 - $\delta \ln \xi = 2(\delta \ln V_{sh} - \delta \ln V_{sv})$

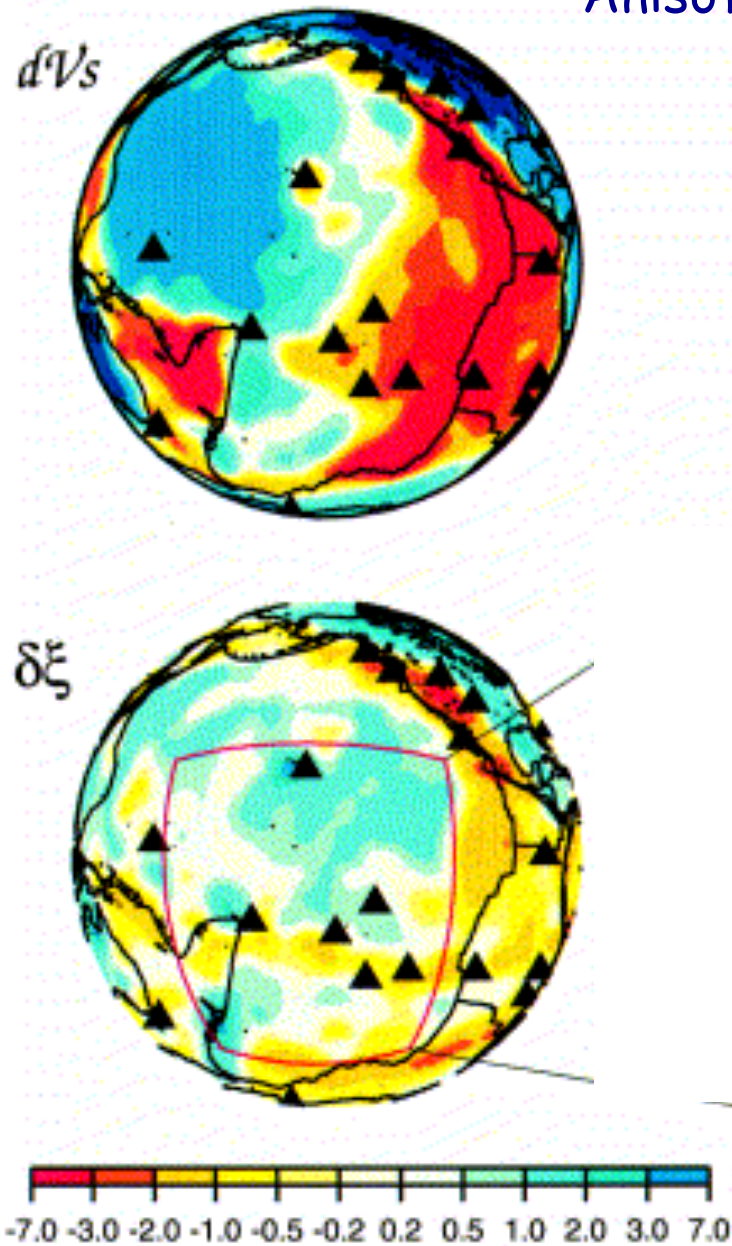
1-D seismic velocity and density in the Earth



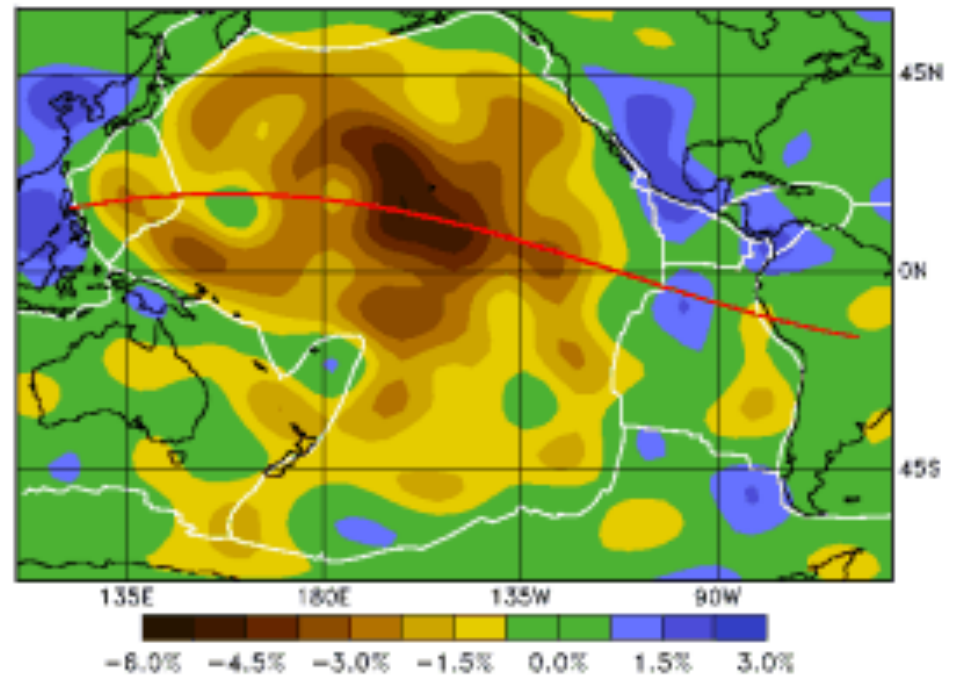
"PREM", Dziewonski and Anderson (1981)

Profondeur = 100 km

Anisotropie radiale dans le manteau supérieur sous les bassins océaniques



Montagner, 2002

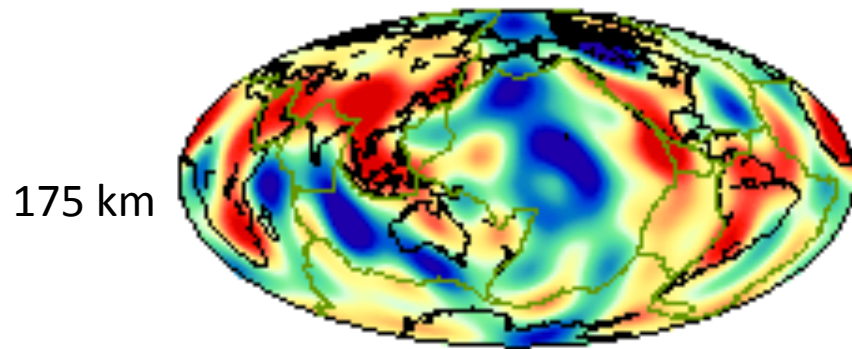


Ekstrom and Dziewonski, 1997

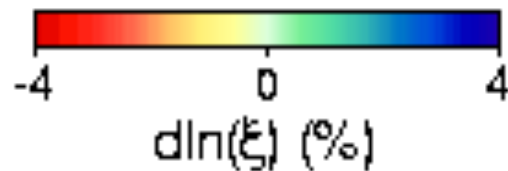
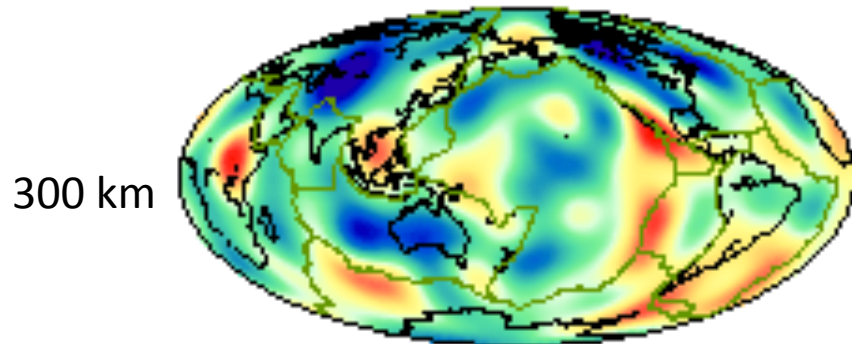
$$\xi = \left(\frac{V_{SH}}{V_{SV}} \right)^2$$

Anisotropie radiale: écarts par rapport au modèle PREM

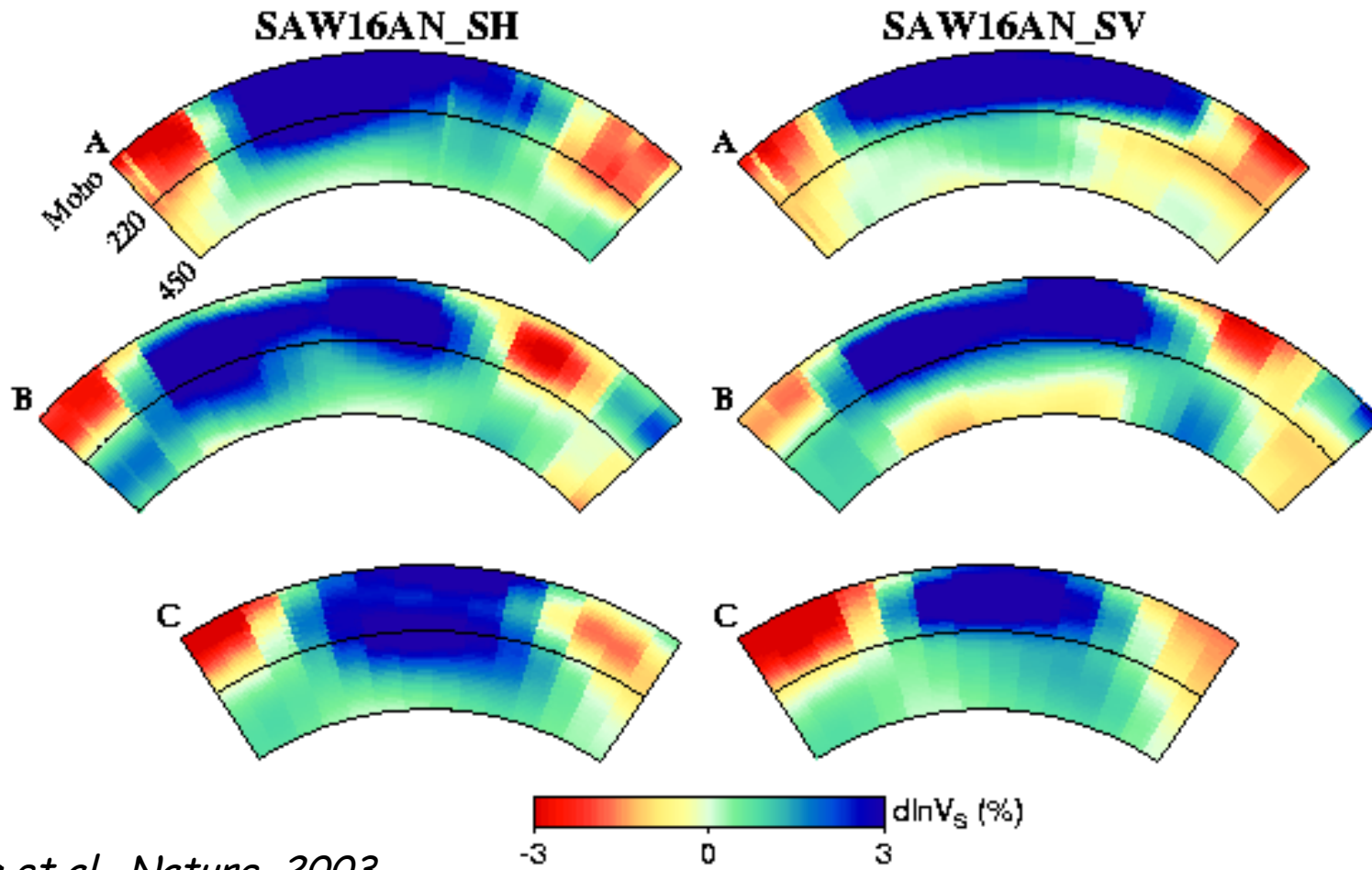
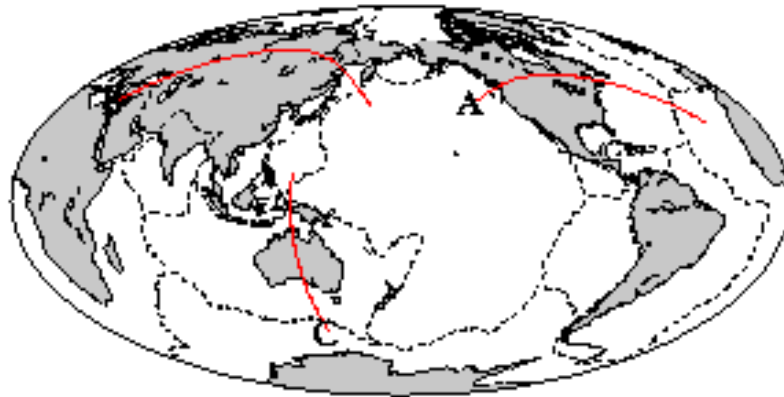
$$d \ln \xi = d\xi / \xi$$



← Moyenne anisotrope de PREM soustraite



$$\xi = \left(\frac{V_{SH}}{V_{SV}} \right)^2$$



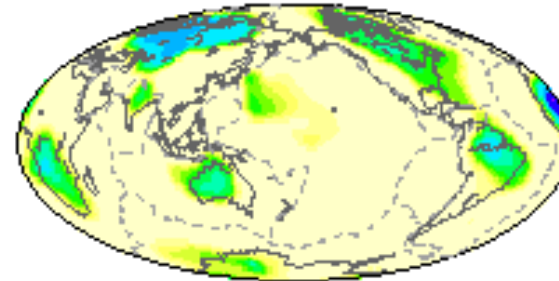
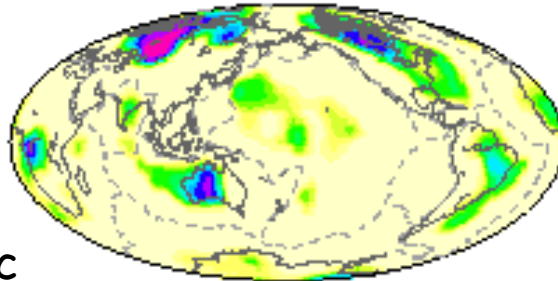
Profondeur maximale où les anomalies de vitesse (vs) sont supérieures à +2%

“modèles SH”

“modèles SV”

SAW16AN_SH

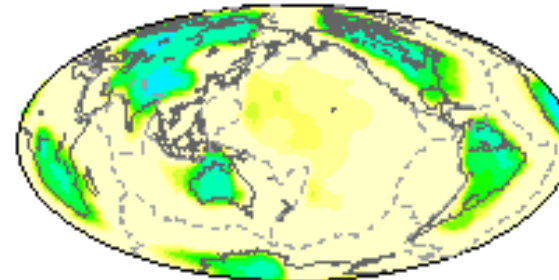
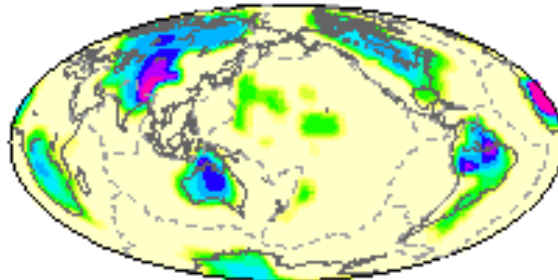
SAW16AN_SV



Radially anisotropic tomography

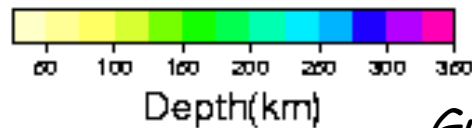
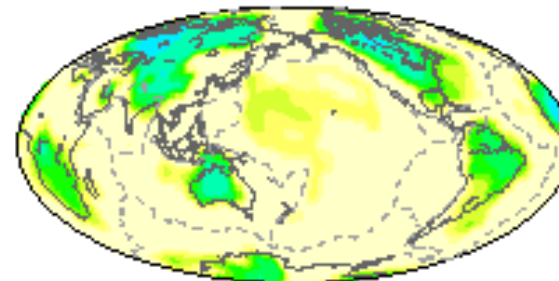
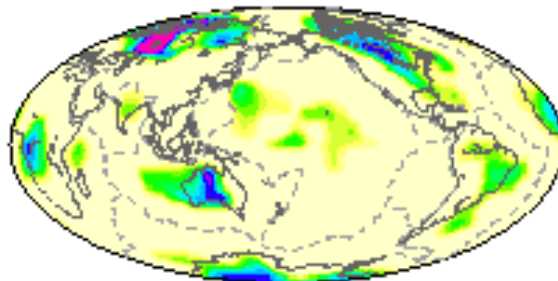
S20A_SH

S20A_SV

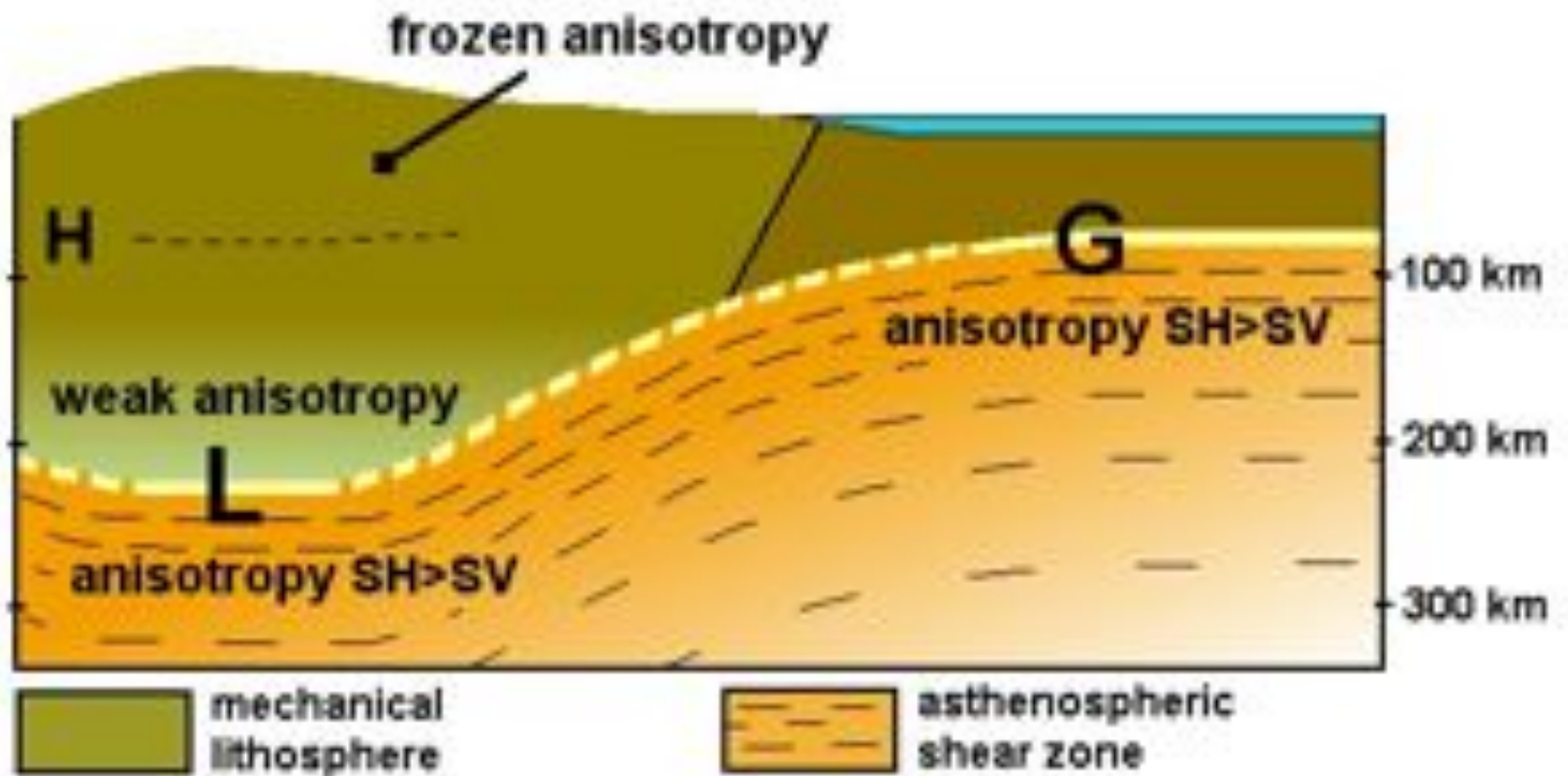


SAW24B16

S20RTS



Gung et al., Nature, 2003



L = LAB = Lithosphere-Asthenosphere boundary

Gung et al., Nature, 2003

Anisotropie azimuthale

- Vitesses sismiques dépendent de la direction de propagation dans le plan horizontal.

$$V(r, \theta, \phi) = a + b \cos 2\psi + c \sin 2\psi + d \cos 4\psi + e \sin 4\psi$$


A, C, F, L, N → anisotropie de polarisation

ψ est l'azimuth, mesuré à partir du Nord dans le sens des aiguilles d'une montre

a, b, c, d, e sont des combinaisons linéaires des éléments du tenseur élastique C_{ijkl}

Vitesses de phase des ondes de Rayleigh:

$$\frac{\delta C}{C}(\theta, \phi, \omega) = \int_0^R (A_0(r, \theta, \phi, \omega) \delta \ln \xi + A_1(r, \theta, \phi, \omega) \cos 2\psi + A_2(r, \theta, \phi, \omega) \sin 2\psi) dr$$



Anisotropie radiale

Montagner and Nataf, 1986

Vitesses de phase des ondes de Rayleigh:

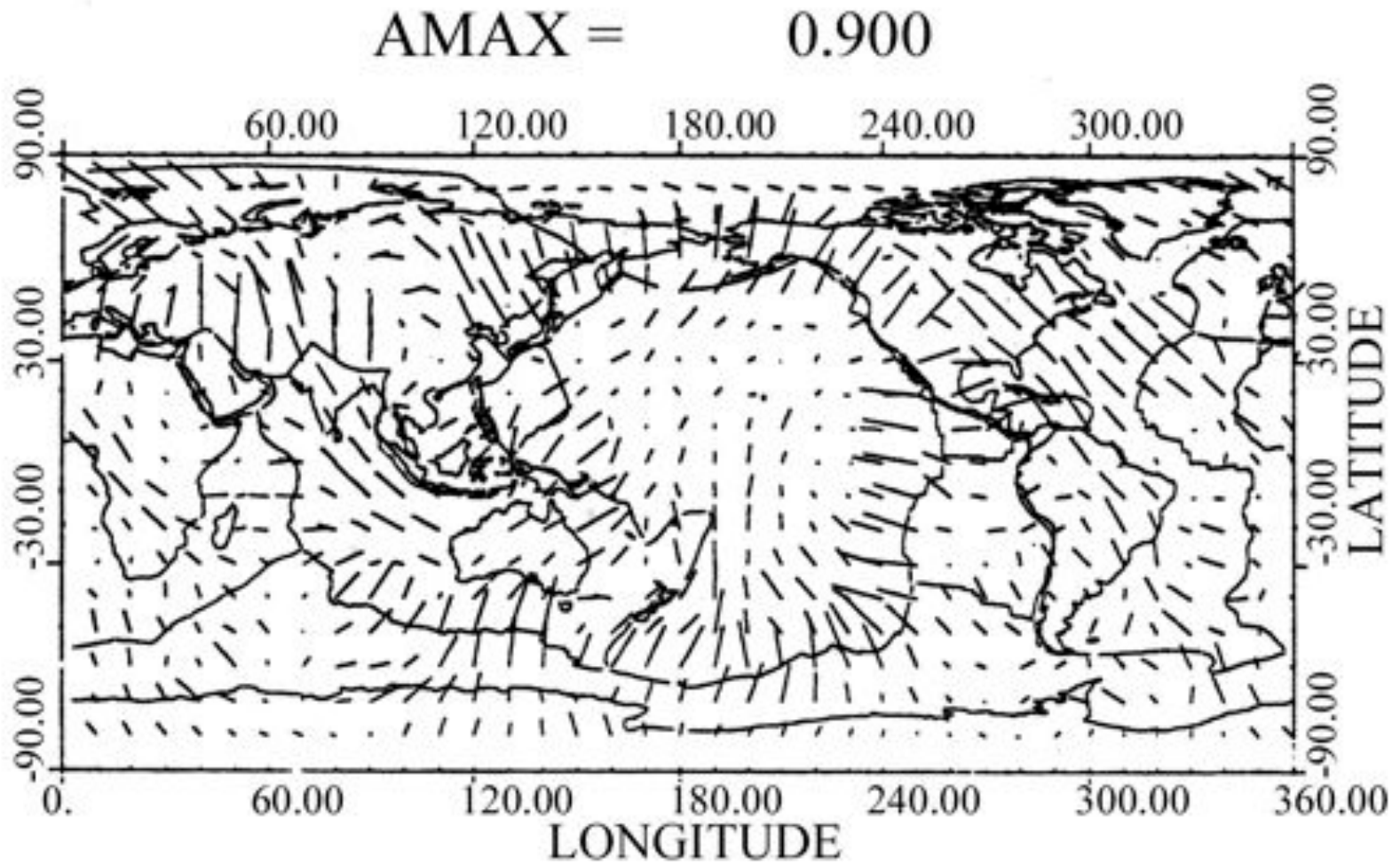
$$\frac{\delta C}{C}(\theta, \phi, \omega) = \int_0^R (A_0(r, \theta, \phi, \omega) \delta \ln \xi + A_1(r, \theta, \phi, \omega) \cos 2\psi + A_2(r, \theta, \phi, \omega) \sin 2\psi) dr$$

Anisotropie radiale ($d \ln \xi$)
(axe de symétrie vertical)

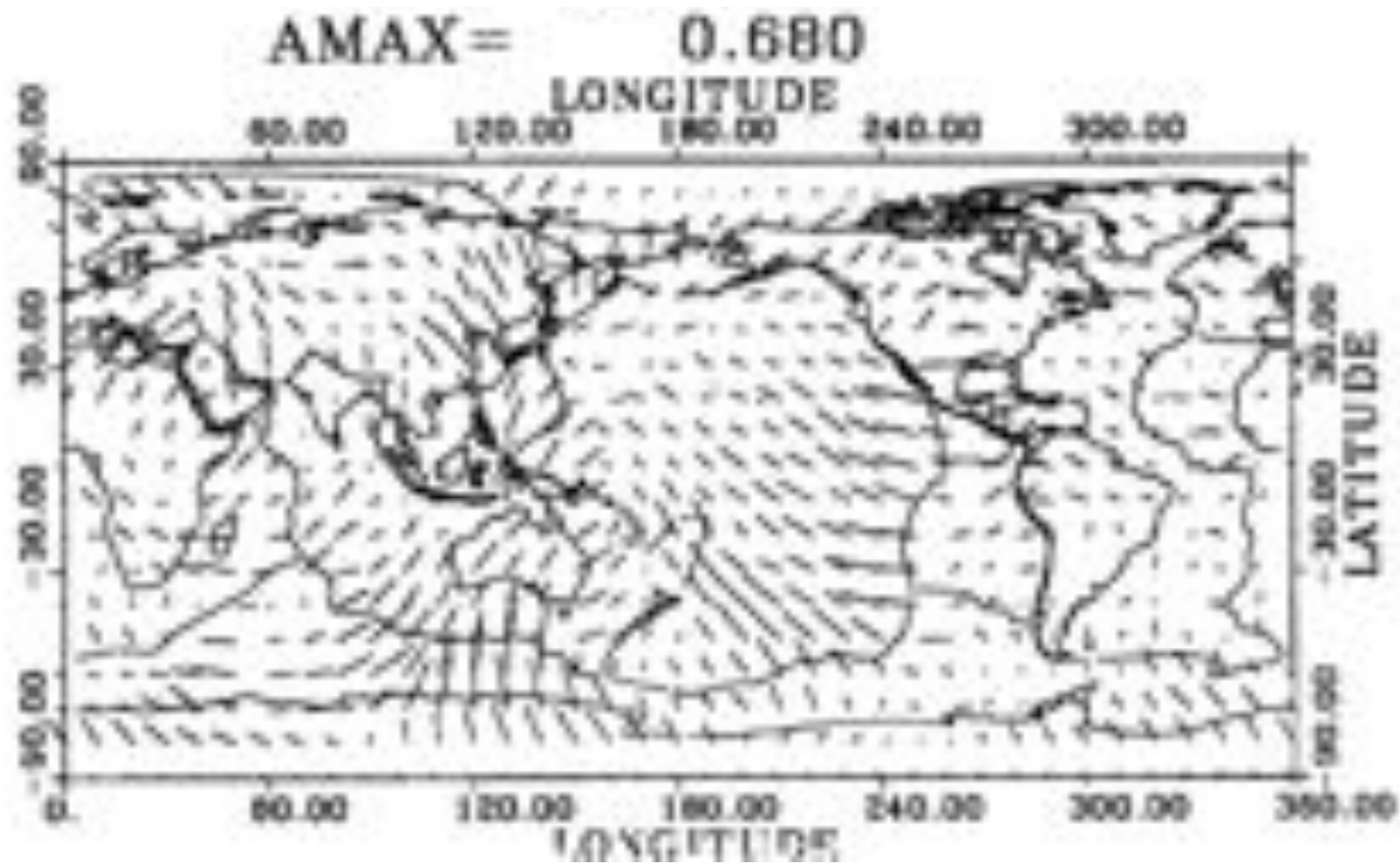
Anisotropie azimuthale (G_c, G_s)
(axe de symétrie horizontal)

Montagner and Nataf, 1986

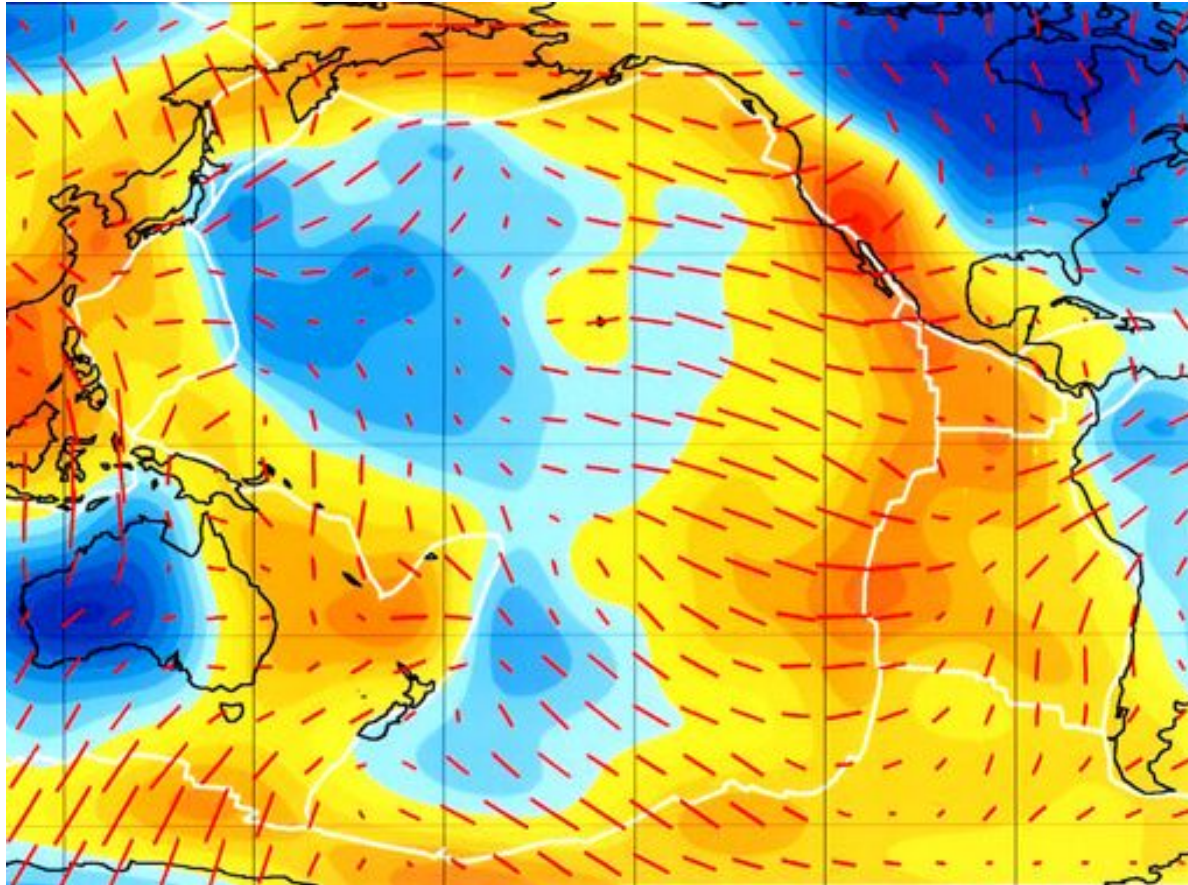
Rayleigh waves $T= 91\text{ s}$



Rayleigh waves $T = 167$ s



Anisotropie azimuthale : ondes de surface



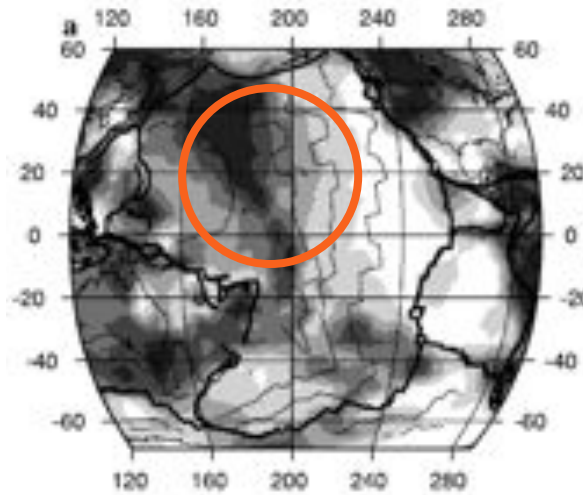
Période= 60 s

Dispersion of Rayleigh waves with 60 second period (most sensitive to depths of about 80-100 km.

Orange is slow, blue is fast. Red lines show the fast axis of anisotropy.

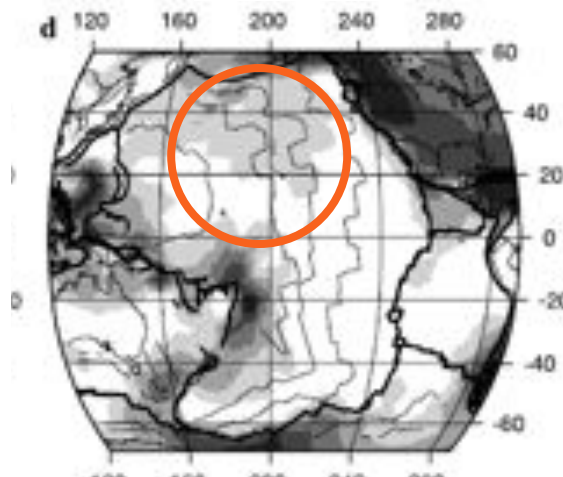
Anisotropie azimuthale: Différence entre la direction rapide et la direction absolue de la plaque

T=25 s

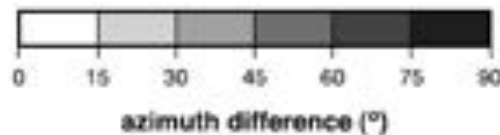


Bassin
Pacifique

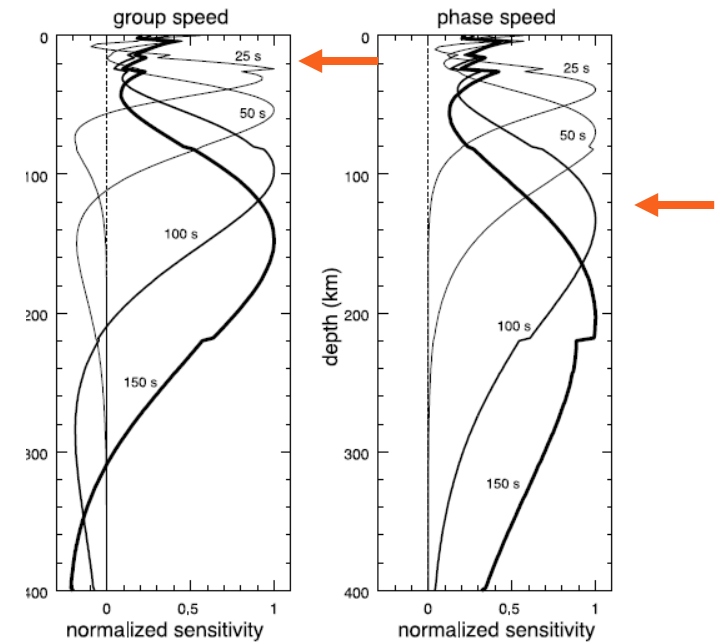
T=150 s



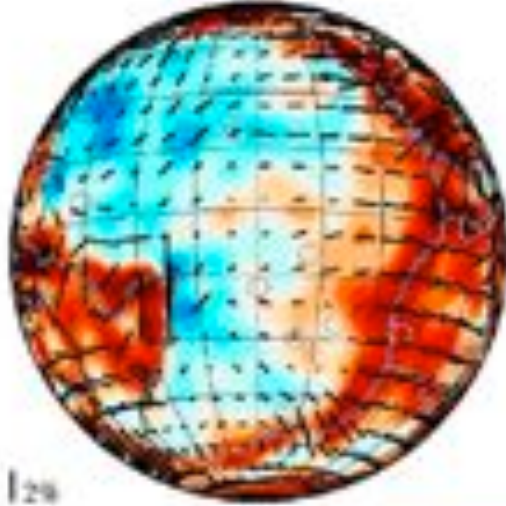
Dispersion des
ondes de
surface



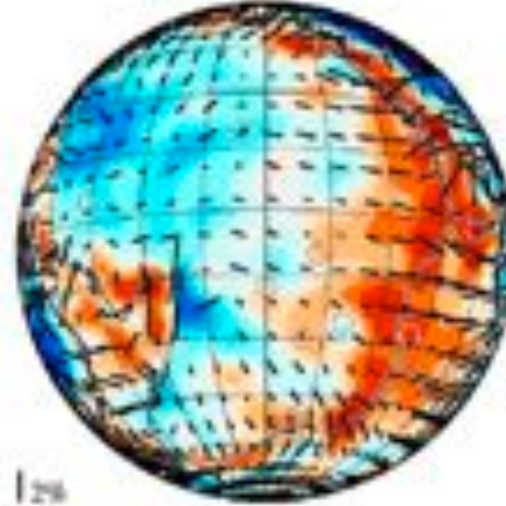
Noyaux de sensibilité



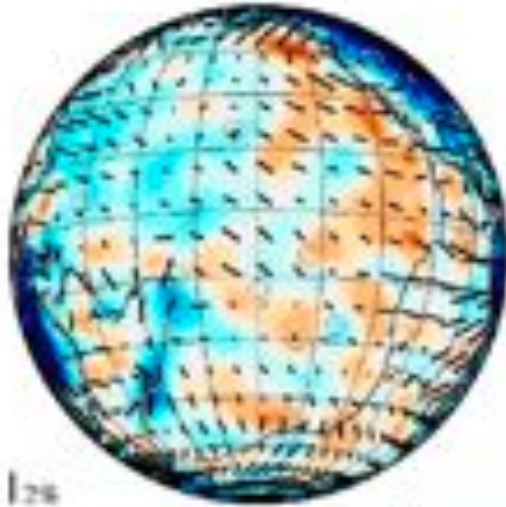
(a) 50 km



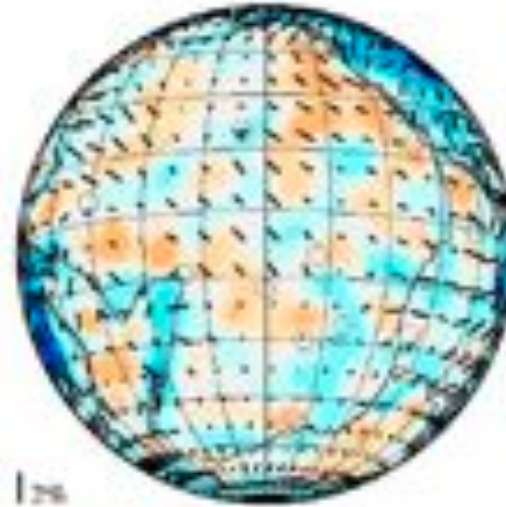
(b) 100 km



(c) 150 km



(d) 200 km



| 4% peak to peak anisotropy

