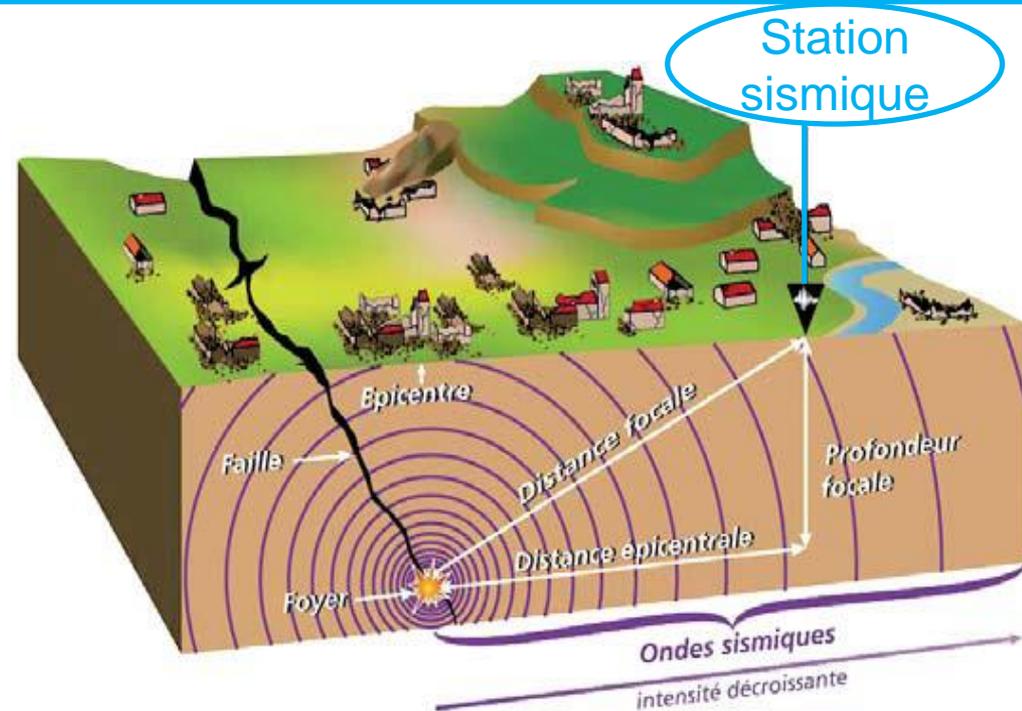
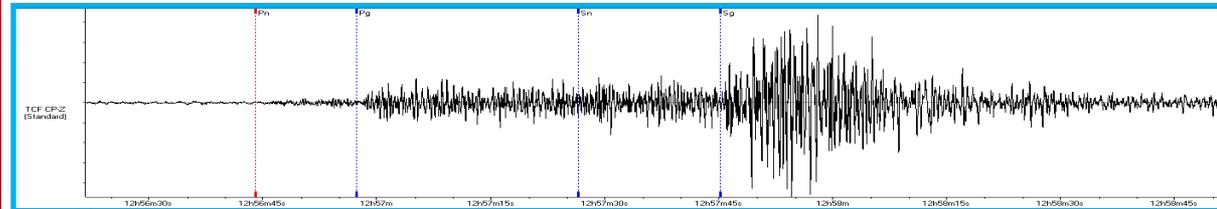


# The seismic source

## La source sismique

Bruno Hernandez

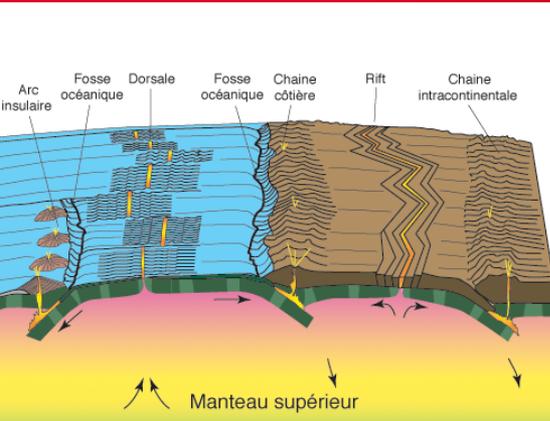
DE LA RECHERCHE À L'INDUSTRIE



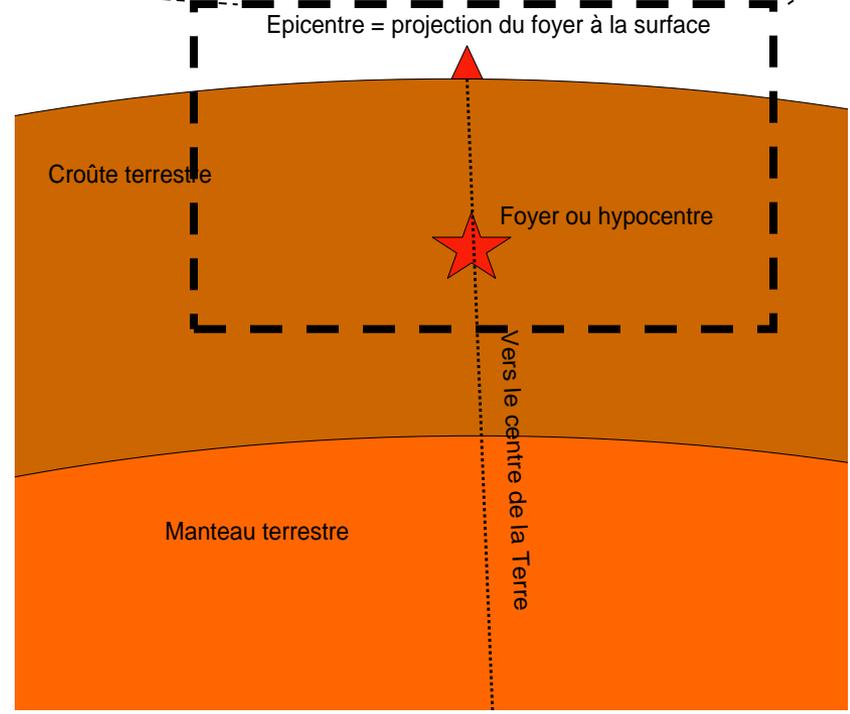
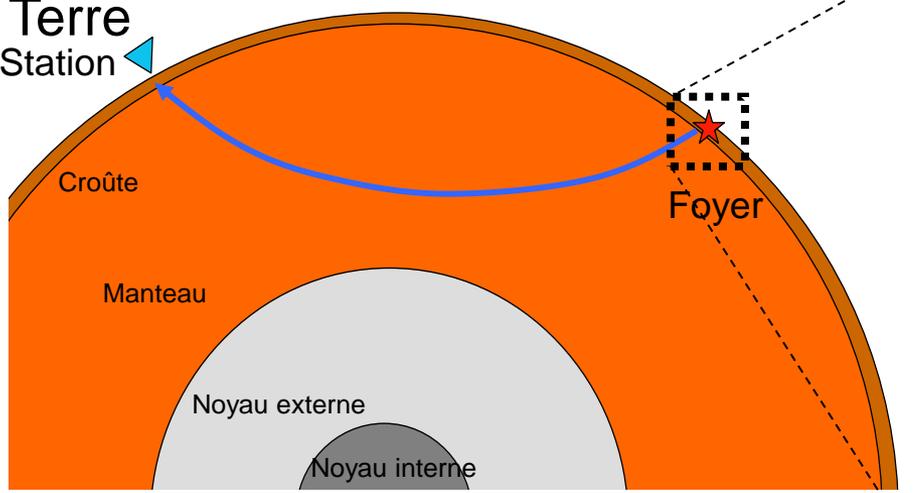
www.cea.fr

Séminaire « sismologie pour les tsunamis »

## La rupture sismique



- Les ondes générées par le séisme se propagent à l'intérieur de la Terre

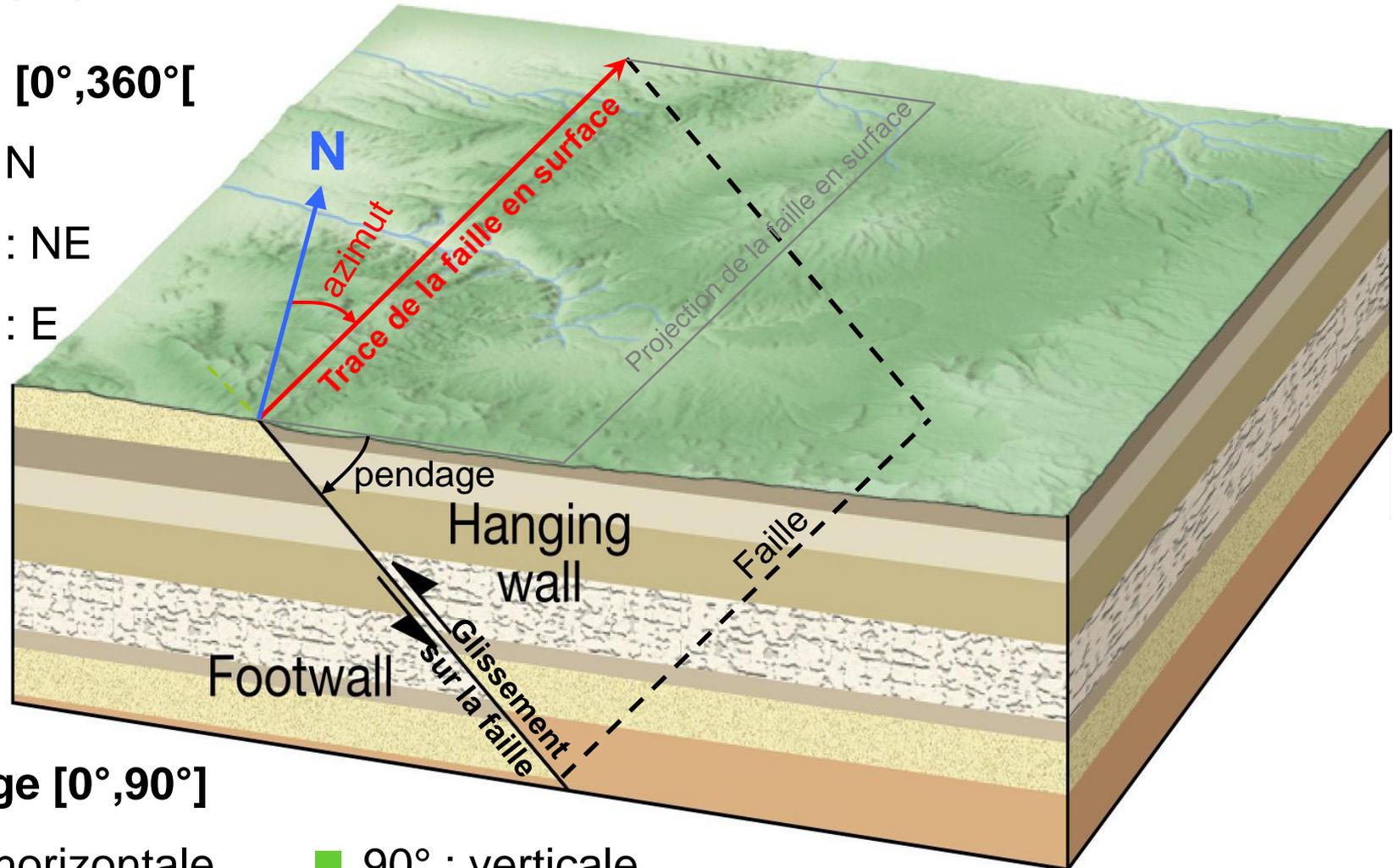


## Géométrie de la faille : cas d'une faille plane

- Quand on regarde la faille selon son azimut, elle pend sur la droite (Hanging wall à droite et Footwall à Gauche).

- Azimut  $[0^\circ, 360^\circ[$

- $0^\circ$  : N
- $45^\circ$  : NE
- $90^\circ$  : E



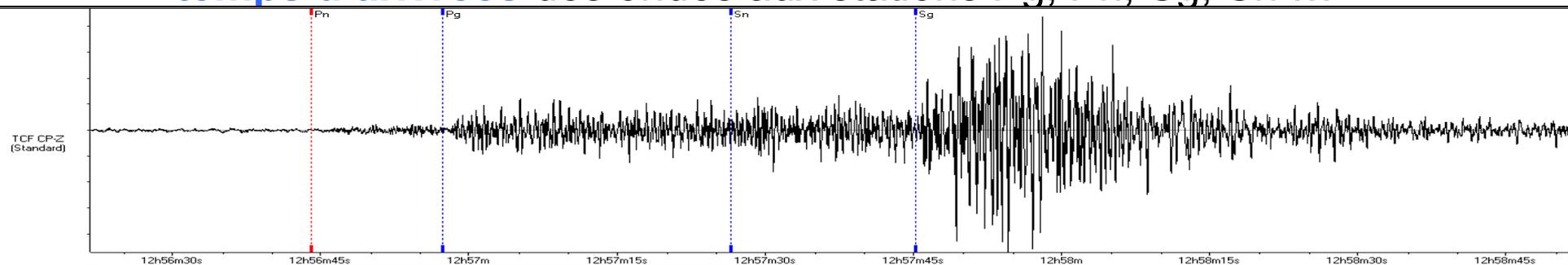
- Pendage  $[0^\circ, 90^\circ[$

- $0^\circ$  : horizontale
- $90^\circ$  : verticale

## Localisation de l'Hypocentre

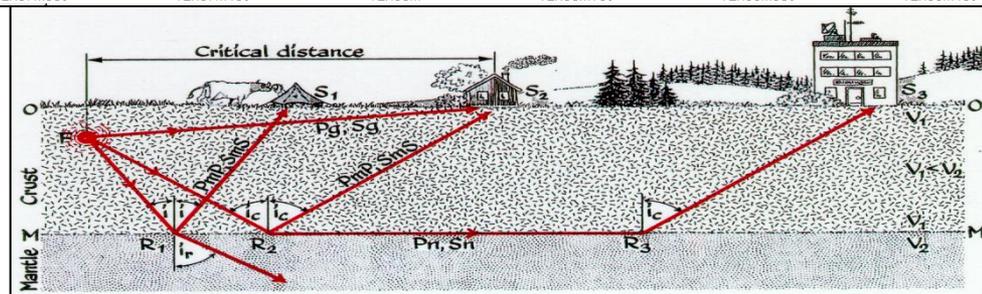
- des données :

- temps d'arrivées des ondes aux stations Pg, Pn, Sg, Sn ...



- des hypothèses :

- un modèle de terre



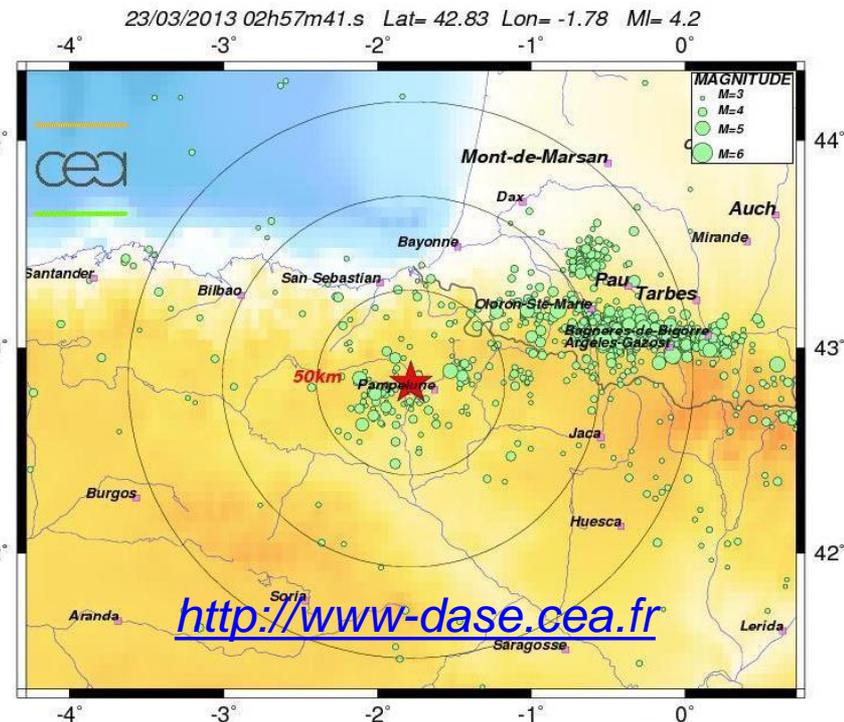
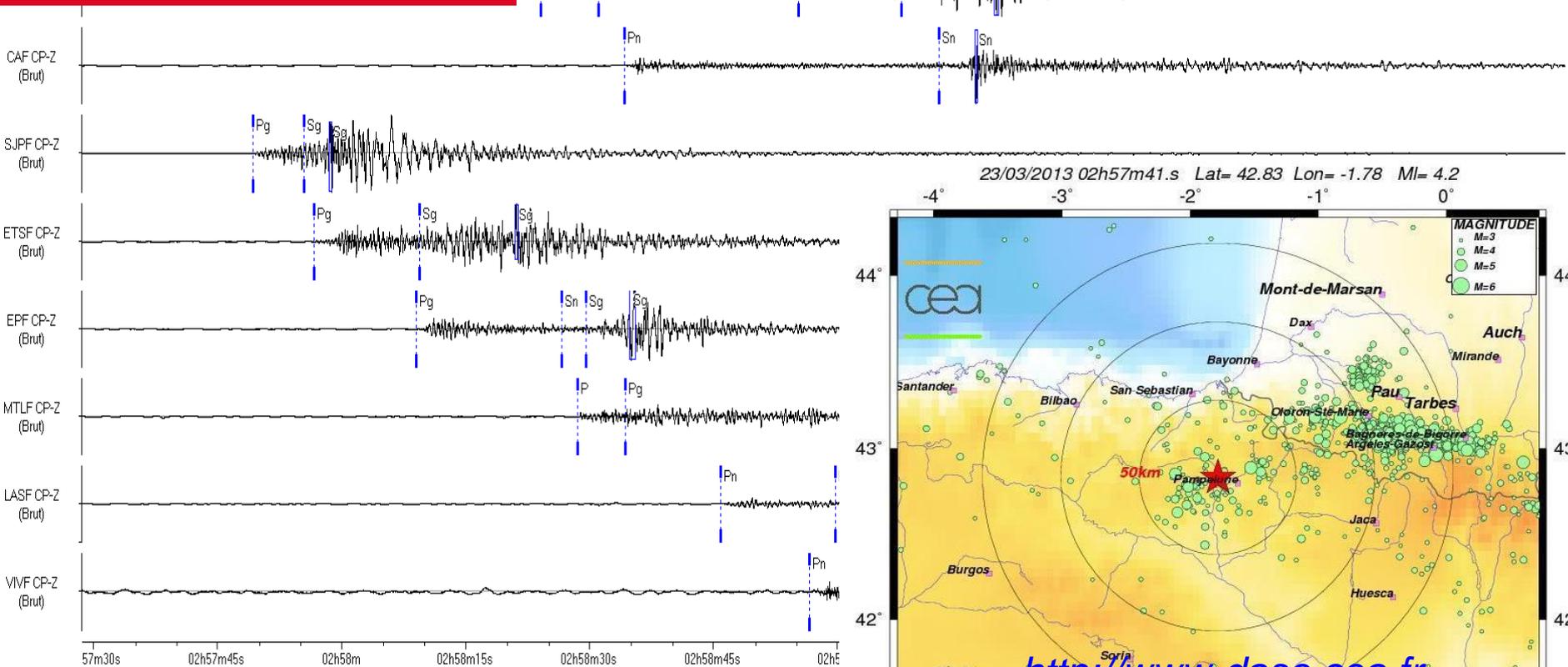
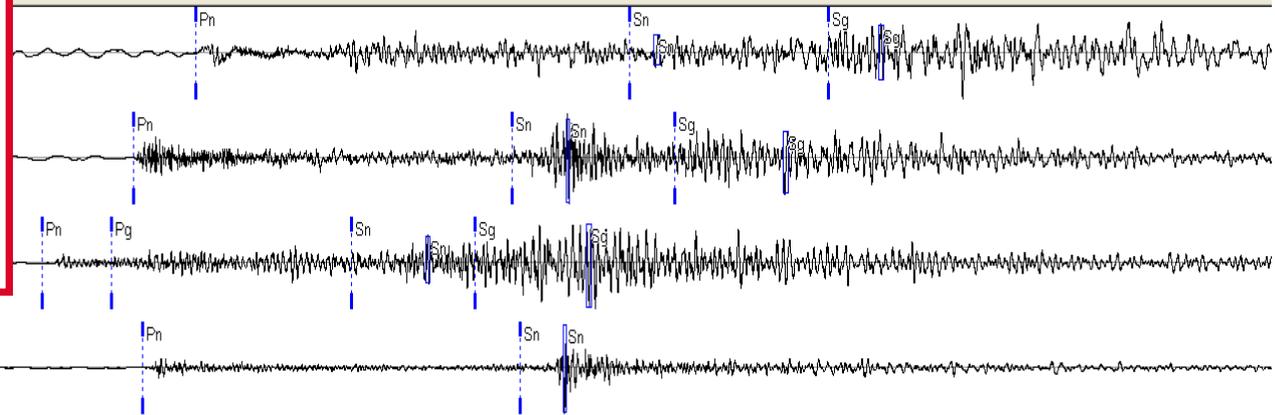
Avec les vitesses de propagation dans les couches géologiques pour calculer des temps d'arrivées théoriques

- des inconnues à estimer (**latitude, longitude, profondeur et  $t_0$** )

- par un processus de convergence vers les paramètres de l'hypocentre par minimisation des résidus entre les données observées et valeurs calculées

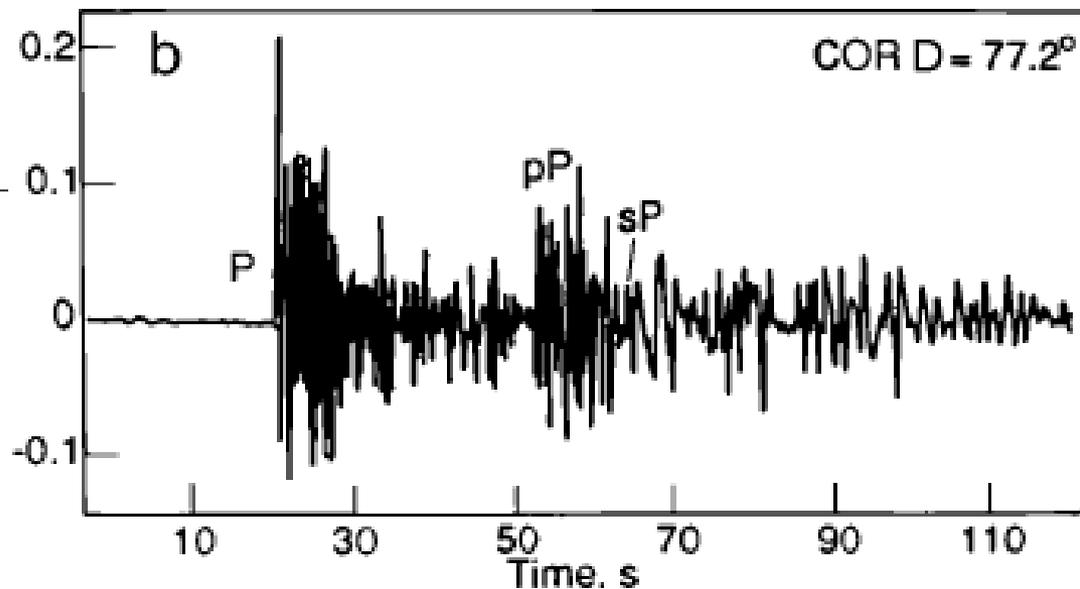
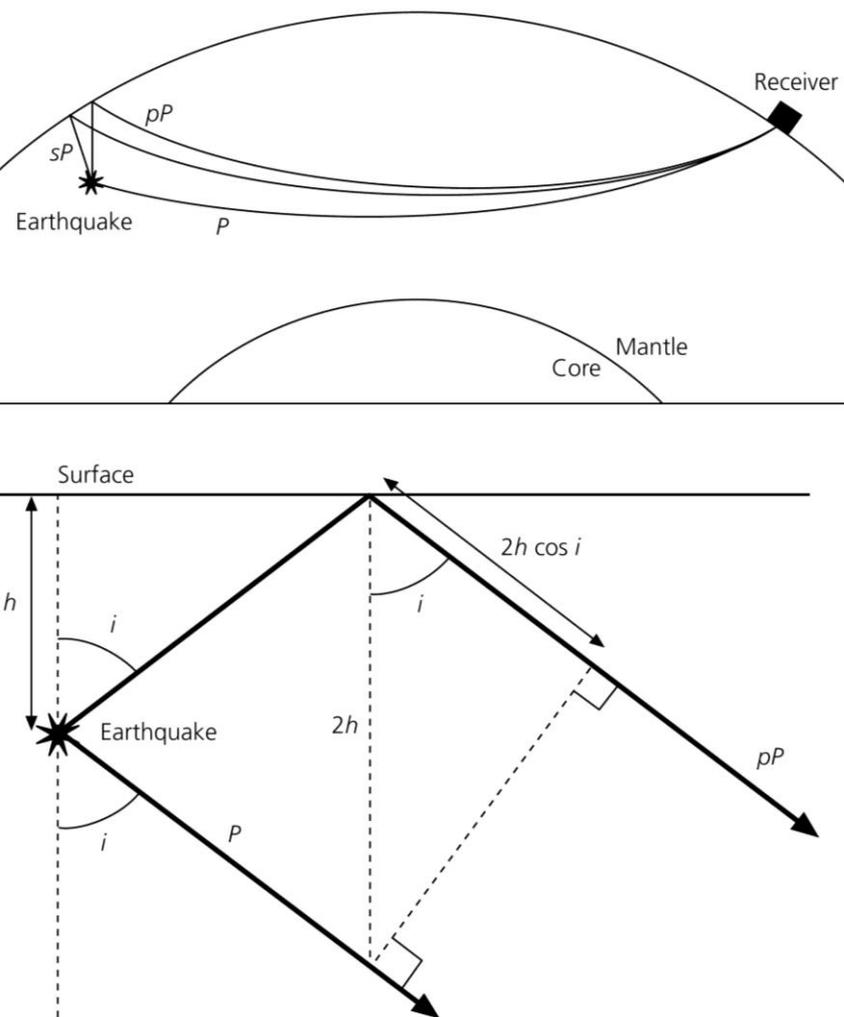
## Localisation des hypocentres

**23/03/2013 02:57:41 TU**  
**Pampelune (Espagne)**  
**Latitude = 42.83**  
**Longitude = -1.78**  
**Magnitude = 4.2 (MI)**



## Détermination de la profondeur focale

- A distance télé-sismique, l'analyse des phases  $pP$  et  $sP$ 
  - permet de mieux déterminer la profondeur hypocentrale



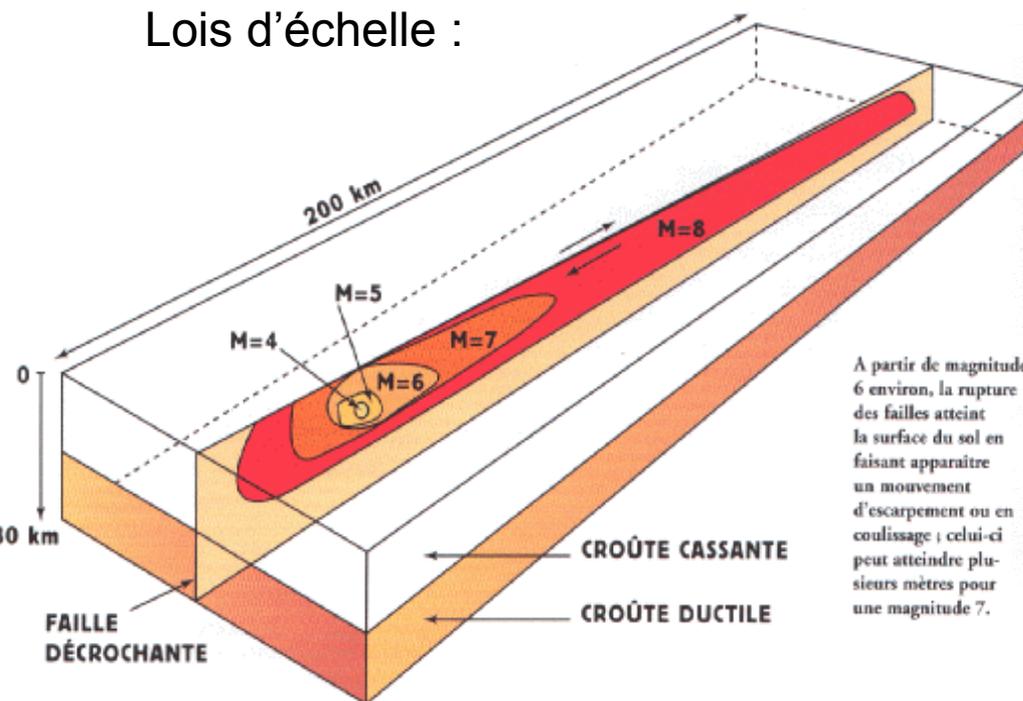
# Magnitude et surface de rupture

La magnitude (énergie libérée au foyer) dépend directement :

- de la surface du plan de faille
- de la longueur du déplacement sur la faille

La magnitude est une quantité logarithmique qui a été introduite afin de quantifier simplement l'énergie libérée par les séismes.

Lois d'échelle :



A partir de magnitude 6 environ, la rupture des failles atteint la surface du sol en faisant apparaître un mouvement d'escarpement ou en coulissage ; celui-ci peut atteindre plusieurs mètres pour une magnitude 7.

Magnitude	Longueur de faille	Coulissage moyen	Durée de rupture
9	800 km	15 m	250 s
8	200 km	5 m	60 s
7	50 km	1 m	15 s
6	10 km	20 cm	3 s
5	3 km	5 cm	1 s
4	1 km	1 cm	0,3 s

Variabilité : 50 %

## Les Magnitudes

- La magnitude est une notion empirique introduite par Richter en 1935
  - C'est une échelle ouverte (il existe des magnitudes négatives...)
    - ✉ La limite inférieure est fixée par le seuil de détection du capteur et au niveau de bruit de fond à la station sismique.
    - ✉ La limite supérieure observée sur terre est de 9,5 (1960, Chili)
  - un gain de 2 unités sur la magnitude correspond à une multiplication de l'énergie d'un facteur 1000.
- Il existe en fait plusieurs formules de calcul spécifiques à **l'onde sismique** utilisée, à la **fréquence** de cette onde, à la **distance épacentrale**, au **niveau d'énergie de la source**...
  - Magnitude locale  $M_L$
  - Magnitude de durée  $M_D$
  - Magnitude des ondes de Volume  $m_b$
  - Magnitude des ondes de Surface  $M_S$
  - Magnitude du moment sismique  $M_W$
  - ...

## Magnitudes : principales formules

**$M_L$**  Magnitude locale (ondes S, période  $\sim 1$  s,  $\Delta < 20^\circ$ )

$$M_L = \log_{10} A_{\max}(\Delta) - \log A_0(\Delta) \text{ (définition de Richter, 1935)}$$

$$M_L = \log_{10} (A_{\max}/T) + C_0(\Delta) \text{ (} C_0 \text{ : correction de distance)}$$

**$M_D$**  Magnitude de durée (t : durée du signal,  $\Delta < 300$  km)

$$M_D = a + b \log_{10}(t) + c(\Delta) \text{ (remplace } M_L \text{ si saturation)}$$

**$m_b$**  Magnitude de volume (ondes P, période  $\sim 1$  s,  $\Delta > 20^\circ$ )

$$m_b = \log_{10}(A_{\max}/T) + Q(\Delta, h)$$

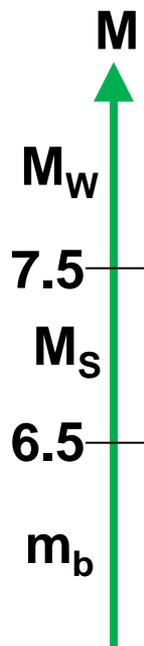
**$M_S$**  Magnitude de surface (ondes R, période  $\sim 20$  s,  $20^\circ < \Delta < 90^\circ$ )

$$M_S = \log_{10}(A_{\max}/T) + 1,66 \log_{10}(\Delta) + 3,3 \text{ (} h < 80 \text{ km)}$$

**$M_W$**  Magnitude de moment (Kanamori, 1977)

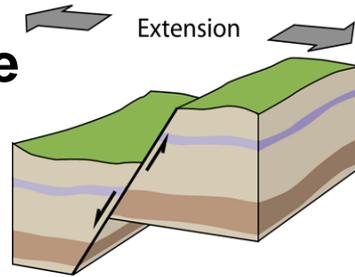
$$M_W = \frac{2}{3} \log_{10}(M_0) - 6,06 \text{ (} M_0 \text{ : moment sismique en N.m)}$$

avec  $M_0 = \mu \cdot S \cdot \Delta u$  ( $\mu$  : rigidité, S : surface de la faille,  $\Delta u$  : glissement).

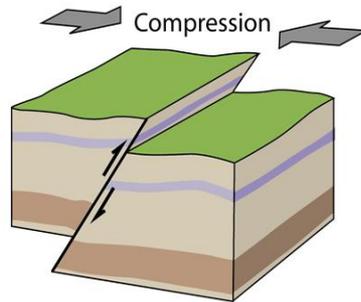


## Les familles de failles

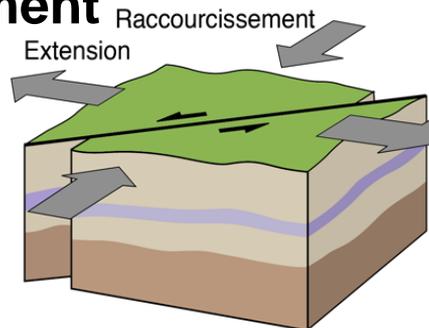
- **Faille normale**



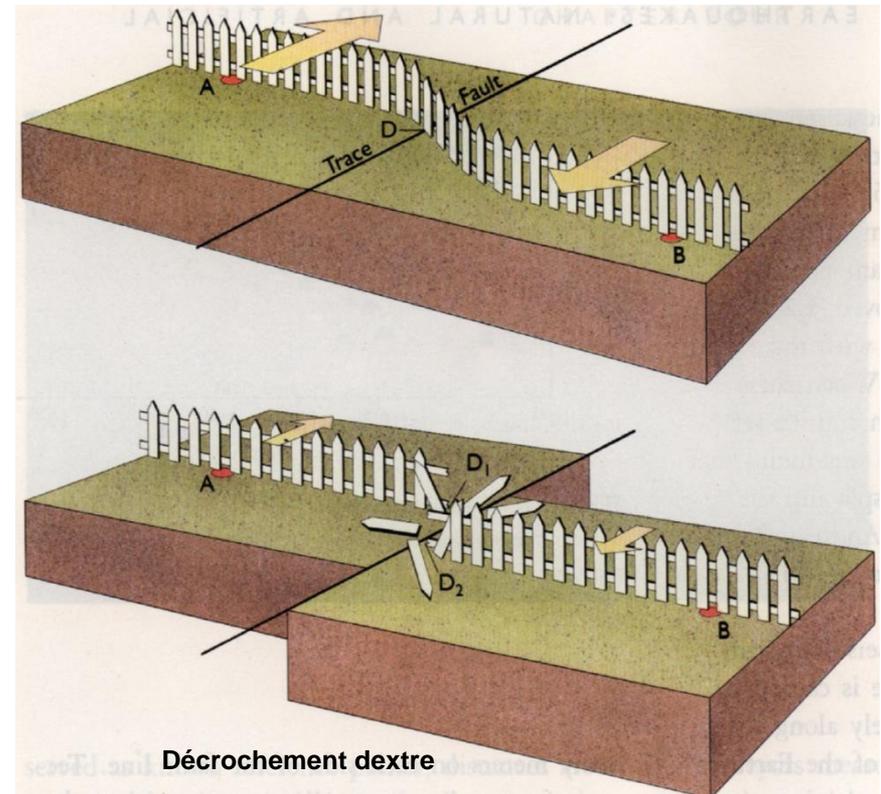
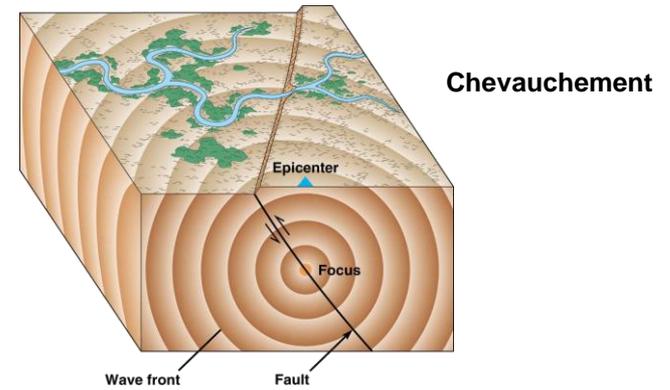
- **Faille inverse**



- **Décrochement**



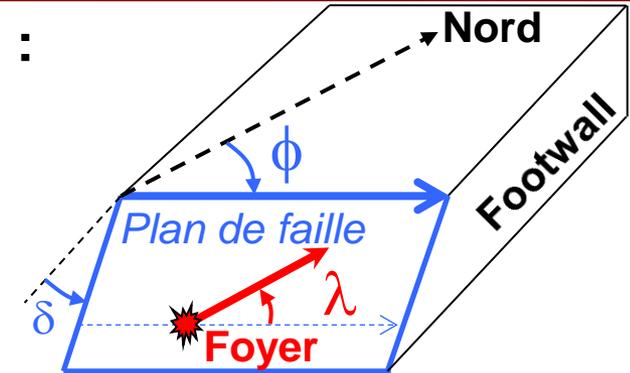
Décrochement senestre



Décrochement dextre

## Mécanisme au Foyer : conventions

- **Géométrie de la faille, 2 angles  $\phi$  et  $\delta$  :**
  - $\phi$  : Azimut [ $0^\circ, 360^\circ$ ] (strike)
  - $\delta$  : Pendage [ $0^\circ, 90^\circ$ ] (dip)



**$\lambda$  (rake) : angle du glissement (du hanging wall par rapport au footwall) dans le plan de faille ]-180°, 180°]**

$\lambda = 90^\circ$  : pur mécanisme en faille inverse

$\lambda = -90^\circ$  : pur mécanisme en faille normale

$\lambda = 0^\circ$  : pur mécanisme en décrochement sénestre

$\lambda = 180^\circ$  : pur mécanisme en décrochement dextre

$\lambda > 0^\circ$  : composante inverse

$\lambda < 0^\circ$  : composante normale

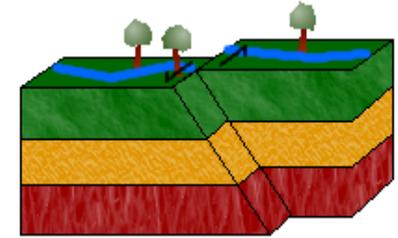
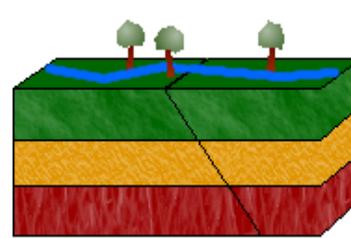
$-90 < \lambda < 90^\circ$  : composante sénestre

$-180 < \lambda < -90^\circ \cup 90^\circ < \lambda < 180^\circ$  : composante dextre

## Mécanisme au Foyer : exemples

### Mécanisme décrochant

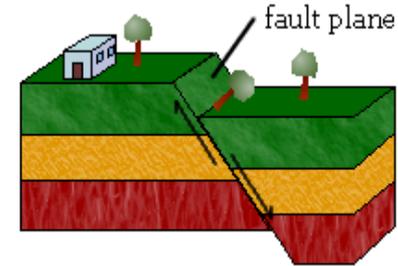
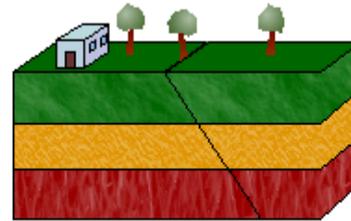
$\lambda = 0^\circ$  : sénestre pur



Décrochement sénestre

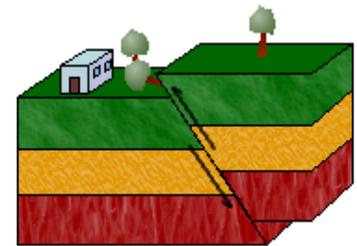
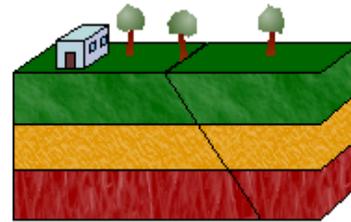
### Mécanisme normal

$\lambda = -90^\circ$  : normal pur



### Mécanisme inverse

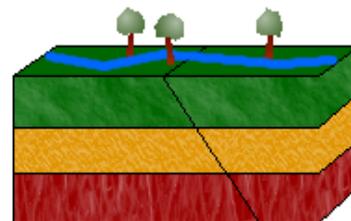
$\lambda = 90^\circ$  : inverse pur



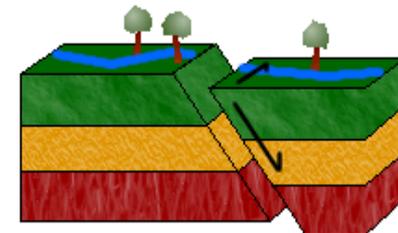
→ shortening ←

### Mécanisme oblique

$\lambda = -45^\circ$  : normal sénestre



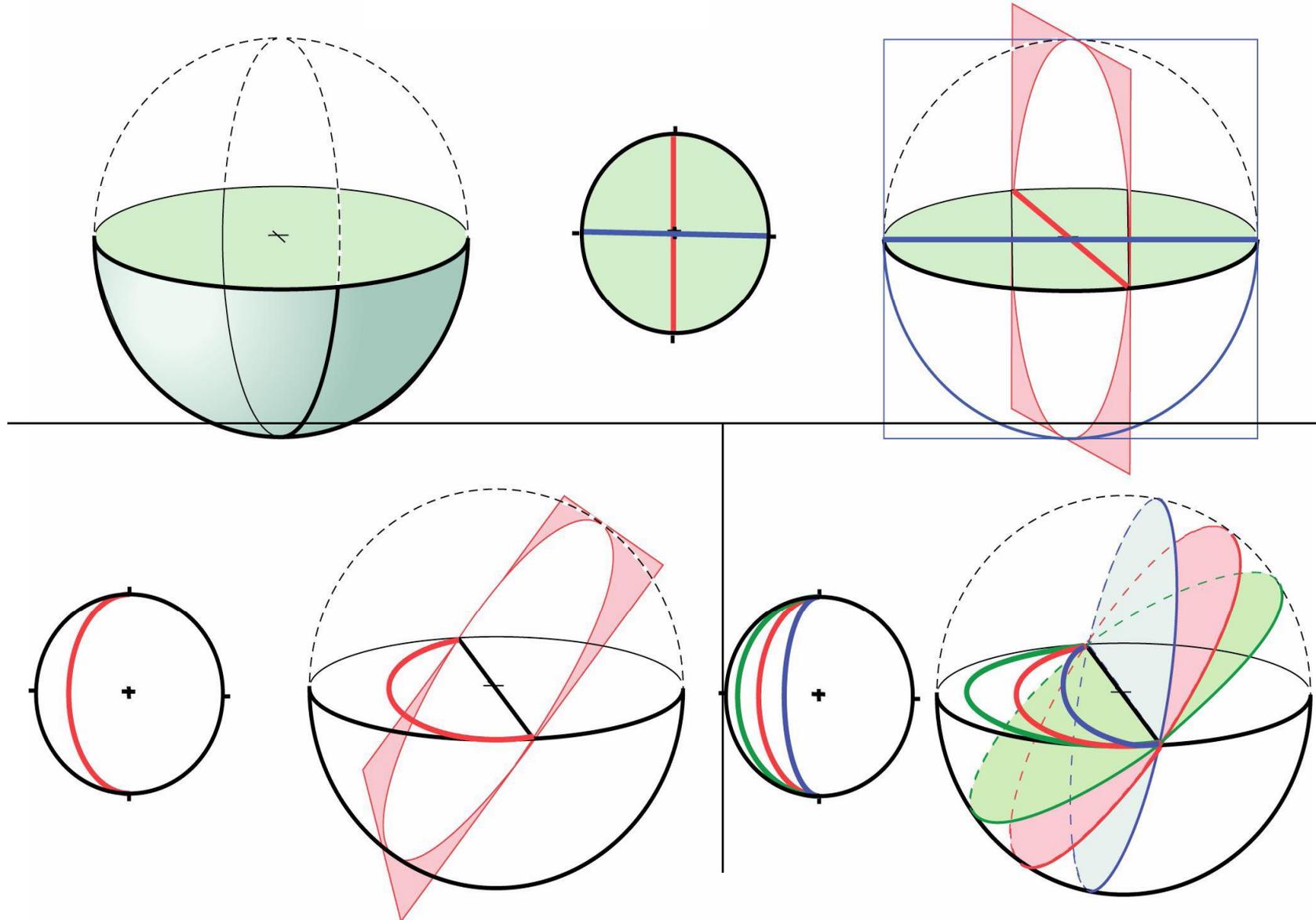
Chevauchement



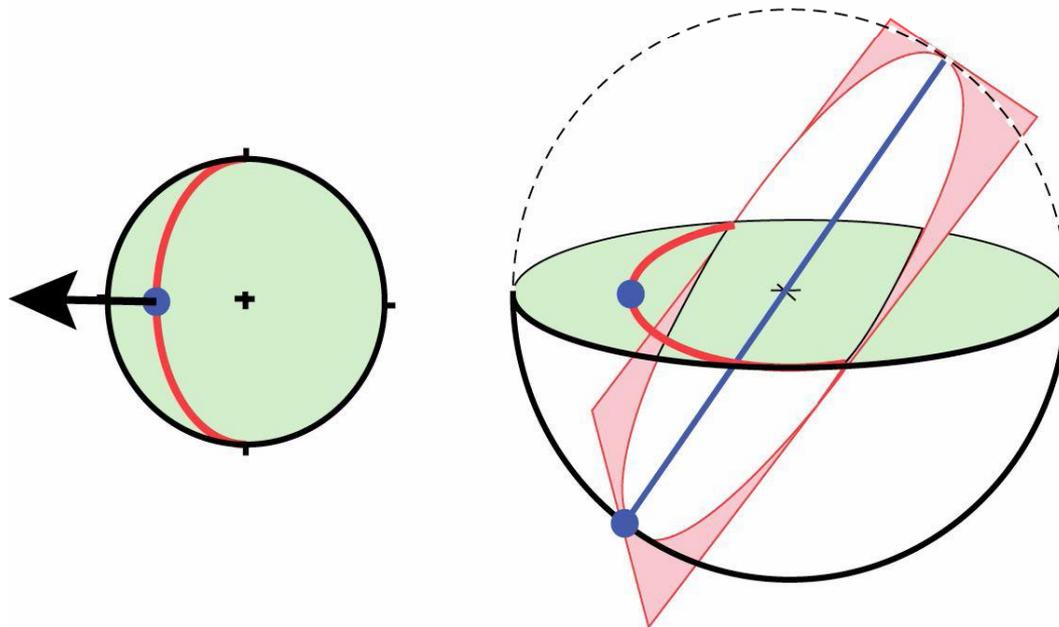
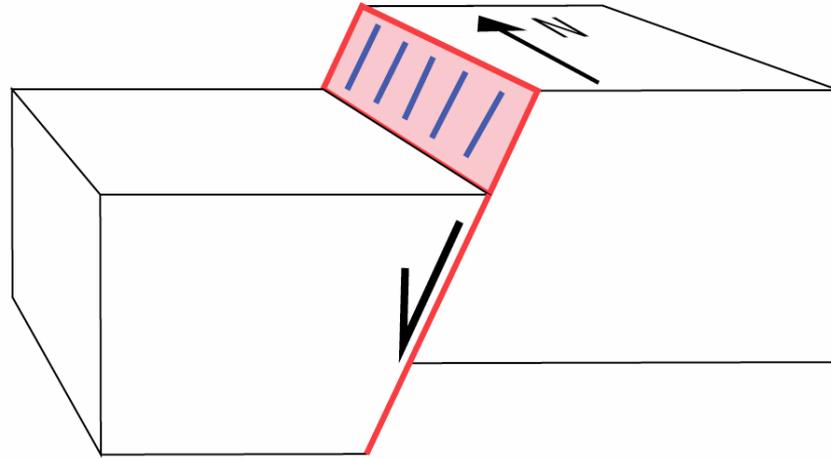
Normal sénestre

# Stereographic projection of the fault

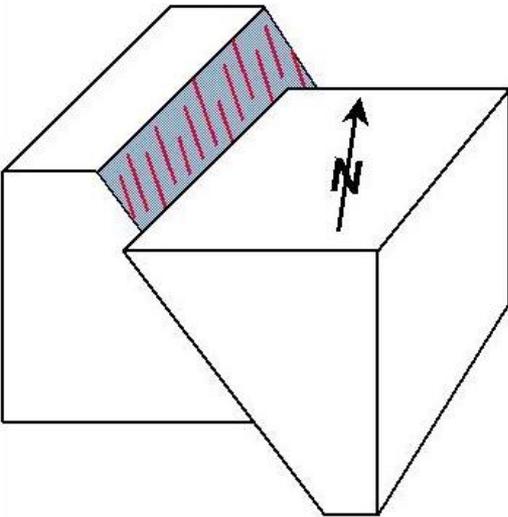
## Projection stéréographique : géométrie du plan de faille



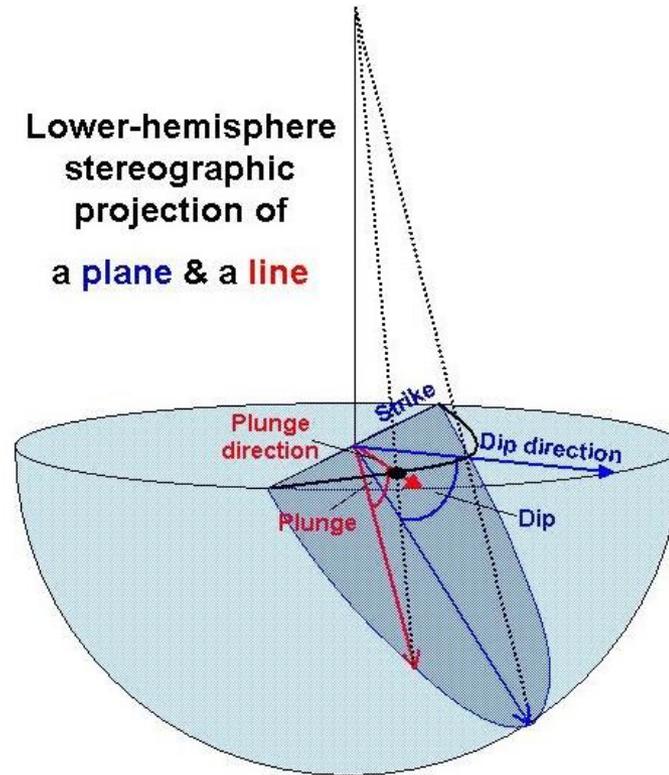
## Projection stéréographique : direction du glissement



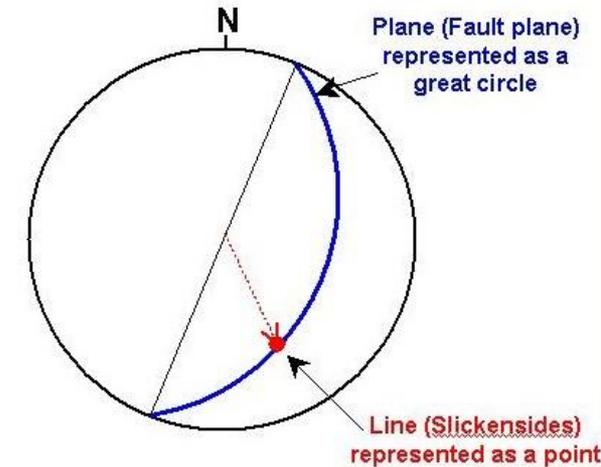
Oblique normal fault with **slickensides** on the fault plane



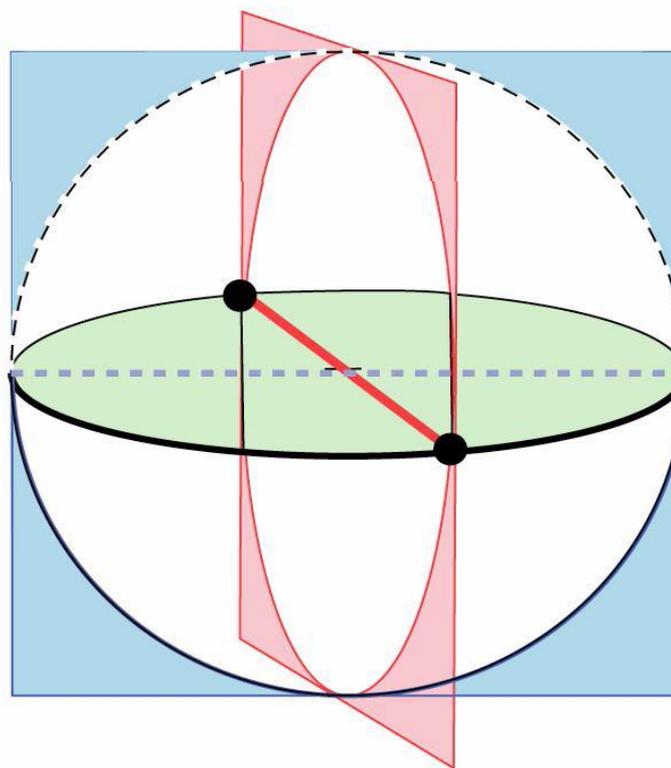
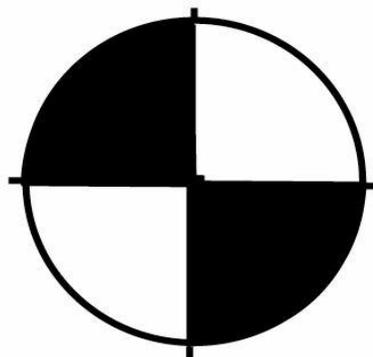
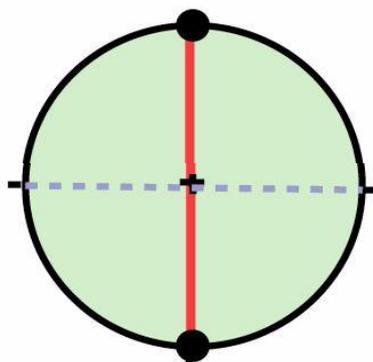
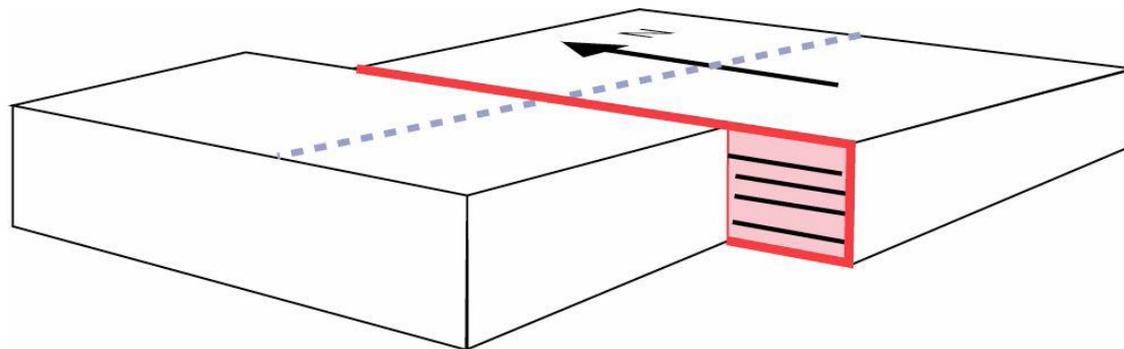
Lower-hemisphere stereographic projection of a plane & a line



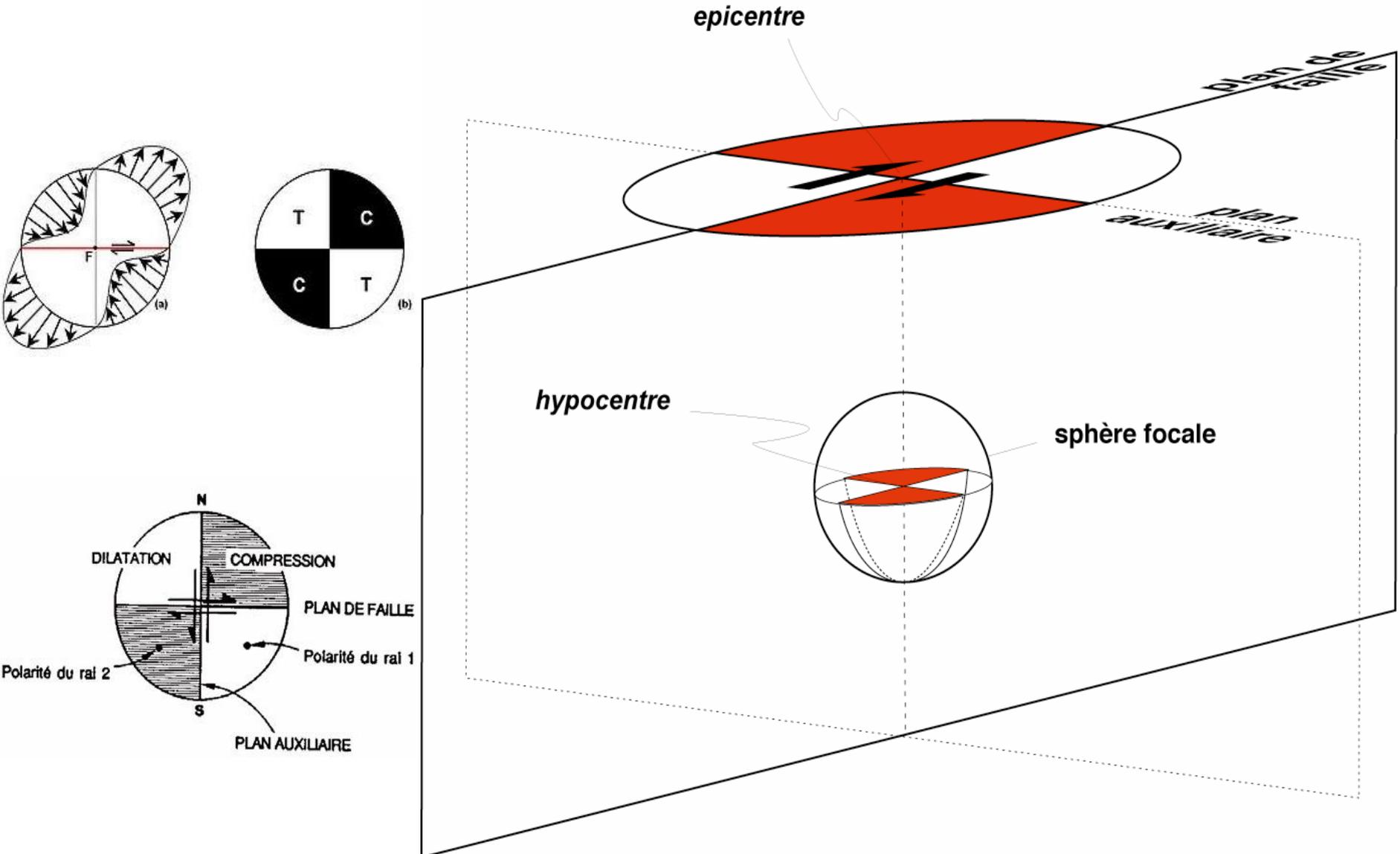
Representation of 3D structures on a plane



## Projection stéréographique : mécanisme au foyer

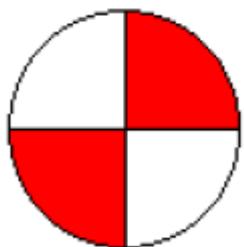


## Projection stéréographique : mécanisme au foyer

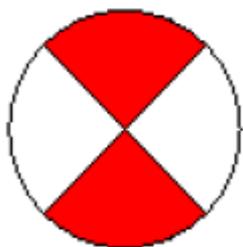


## Tenseur des moments et sphère focale

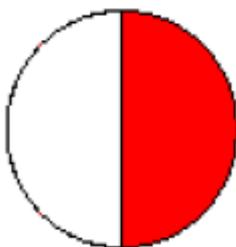
Correspondance entre le tenseur des moments et la sphère focale



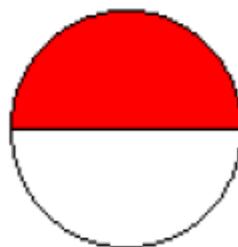
M1



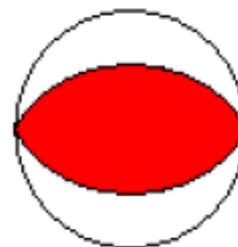
M2



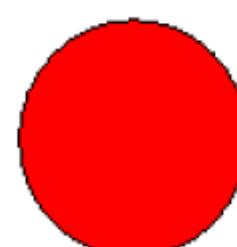
M3



M4



M5

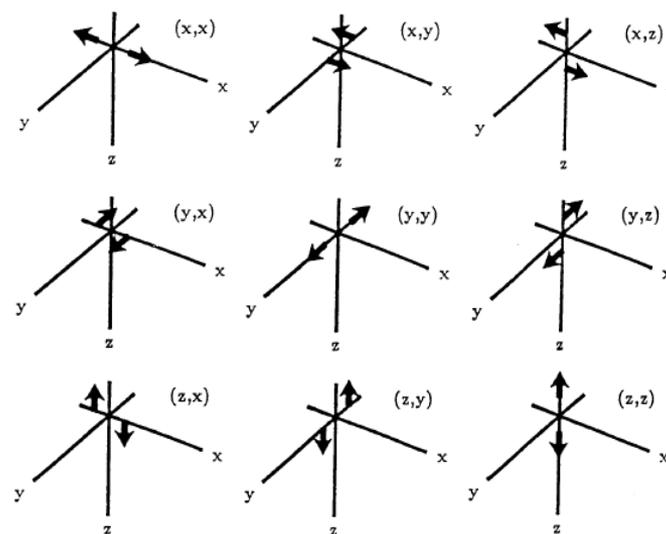


M6

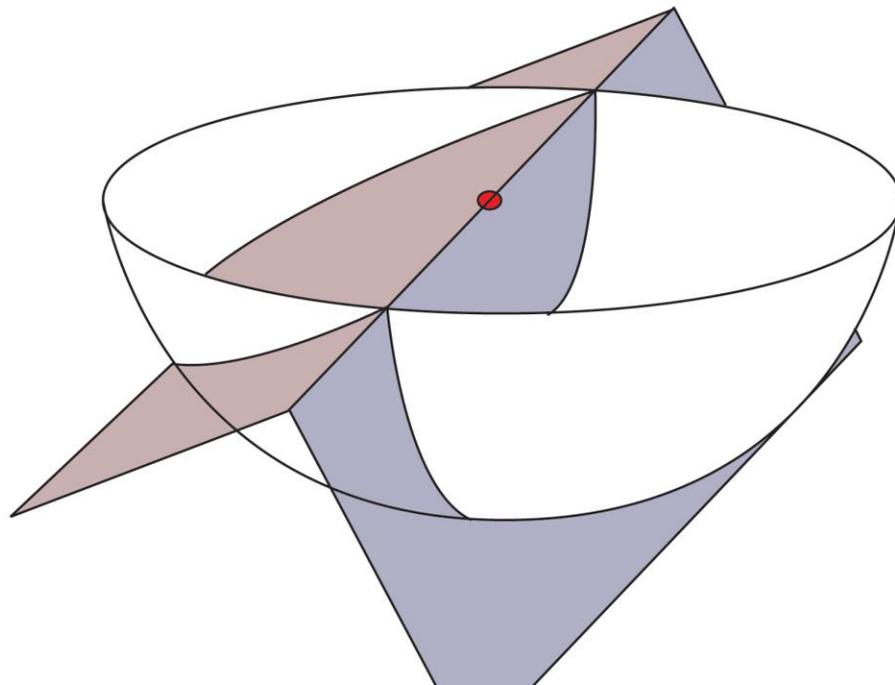
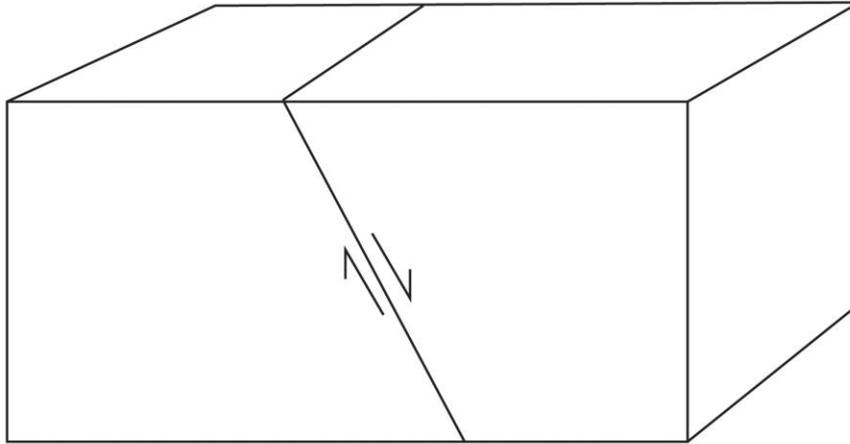
$$M_1: \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}; \quad M_2: \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix}; \quad M_3: \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$M_4: \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}; \quad M_5: \begin{bmatrix} -1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad M_6: \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

moments élémentaires



## Projection stéréographique : mécanisme au foyer



## Radiation des ondes à la source (séisme – explosion)

### Séisme – glissement sur une faille

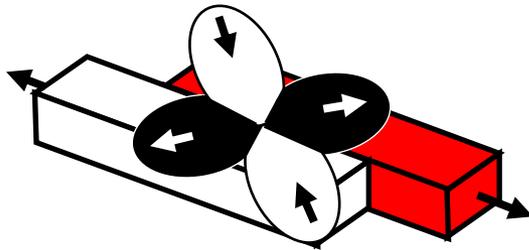


Diagramme de radiation compression (ondes P)

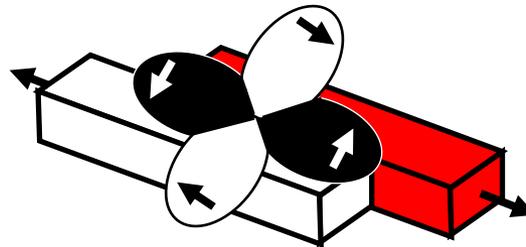
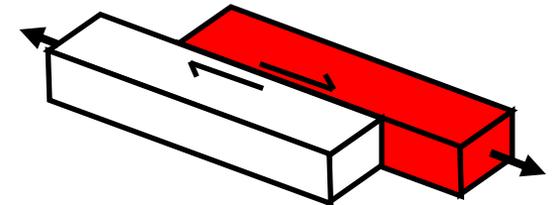
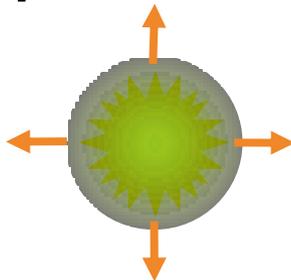


Diagramme de radiation cisaillement (ondes S)



Pas de changement de volume

### Explosion – compression radiale



Compression (ondes P)

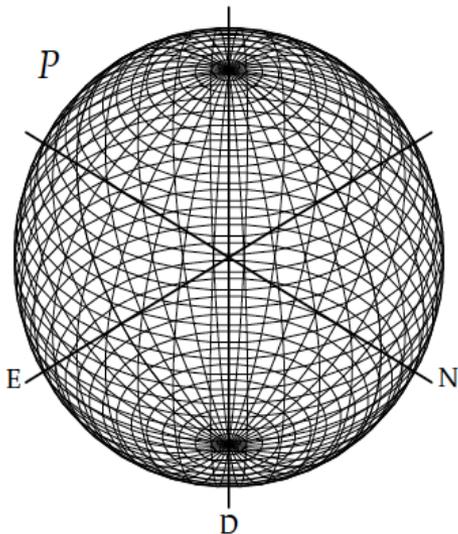
Pas de radiation en cisaillement



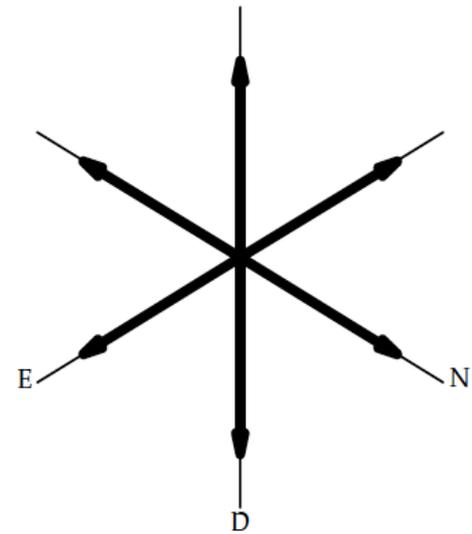
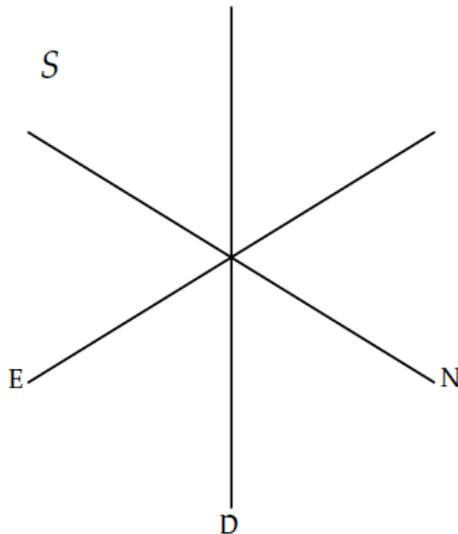
Changement de volume

● Explosion

### Ondes P

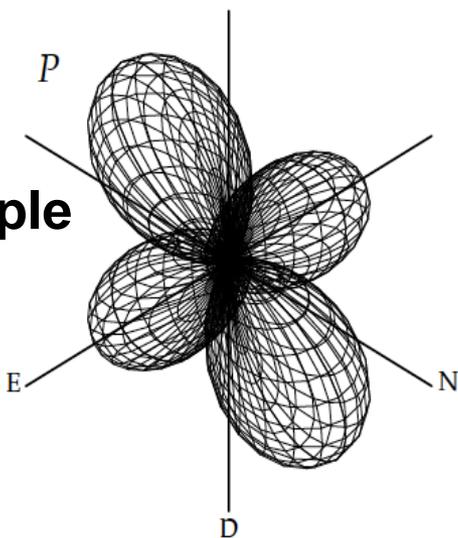


### Ondes S

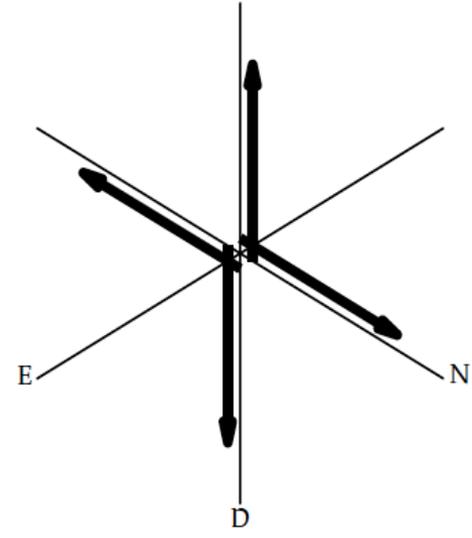
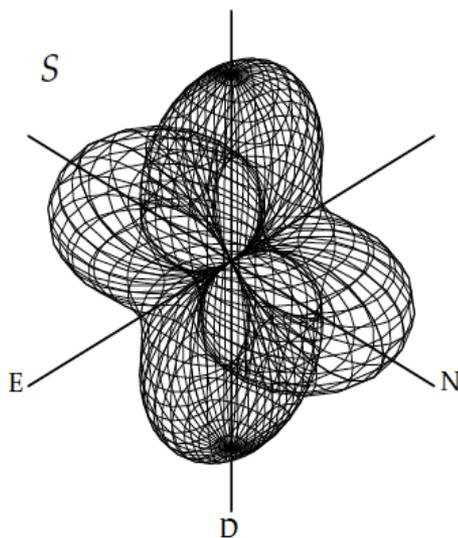


● Double couple

### Ondes P



### Ondes S



## Rayonnement de ondes sismiques

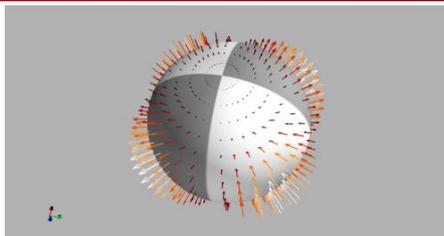


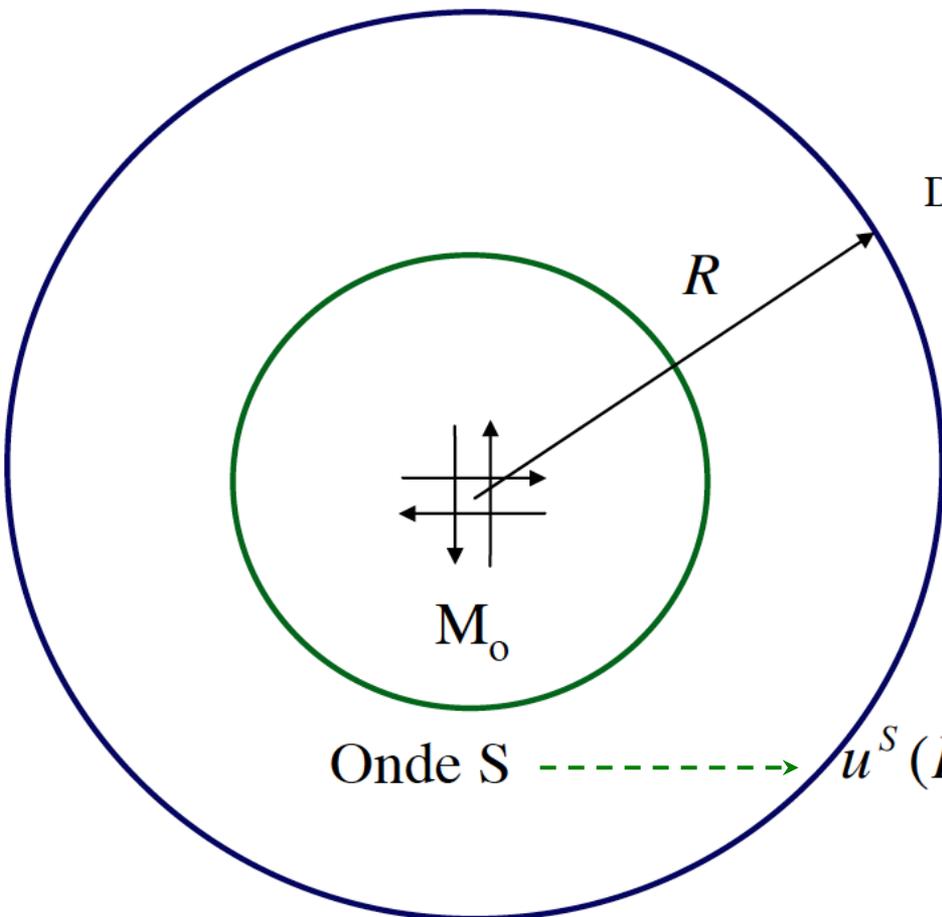
Diagramme de rayonnement

Onde P

$$u^P(R, t) = \frac{1}{4\pi\rho\alpha^3} \frac{1}{R} \mathcal{R}^P(\theta, \varphi) \dot{M}_0(t - R/\alpha)$$

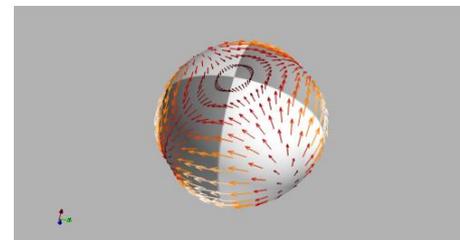
Divergence Géométrique

Signal sismique



Onde S

$$u^S(R, t) = \frac{1}{4\pi\rho\beta^3} \frac{1}{R} \mathcal{R}^S(\theta, \varphi) \dot{M}_0(t - R/\beta)$$



## Tenseur des moments (sous-éléments)

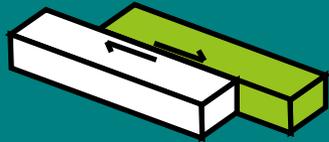
Modèle

Source

Tenseur M

Couples

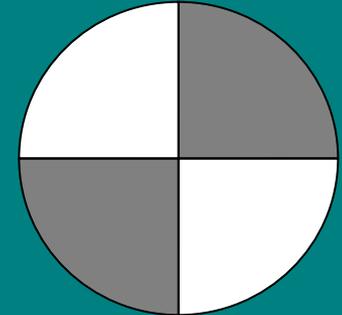
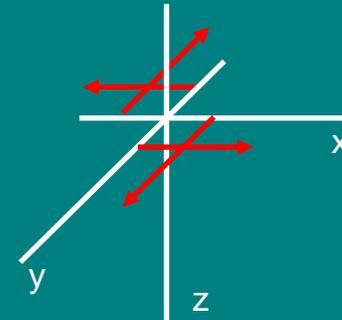
Mécanisme



Décrochement  
Strike-slip

DC  
(Double-couple)

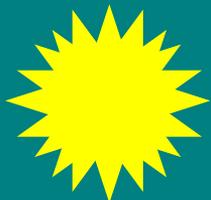
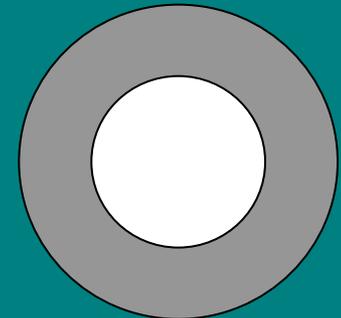
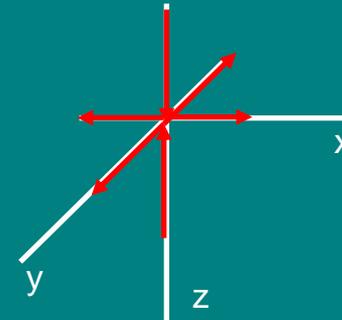
$$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



Ring Fault

CLVD  
(Compensated  
linear vector  
dipole)

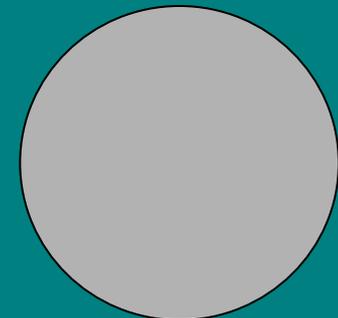
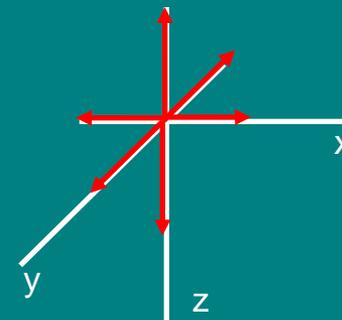
$$\begin{pmatrix} \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \\ 0 & 0 & -1 \end{pmatrix}$$



Explosion

Isotrope

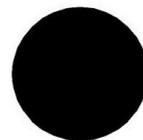
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



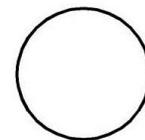
## Tenseur des moments et mécanismes associés

**Explosion - Implosion**

$$\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

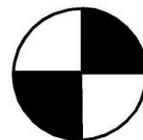


$$-\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

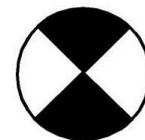


**Double couple (séismes)**

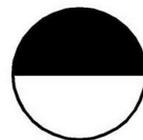
$$-\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



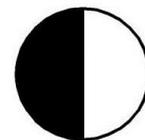
$$\frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



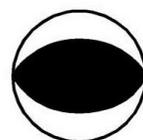
$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}$$



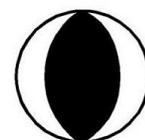
$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$$



$$\frac{1}{\sqrt{2}} \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

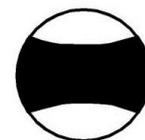


**CLVD**

$$\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



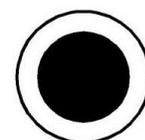
$$\frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$$\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$



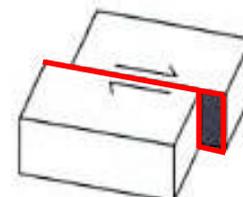
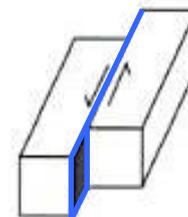
$$-\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$



## Mécanisme au foyer et sphère focale

- Mécanisme décrochant

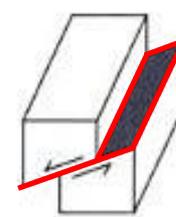
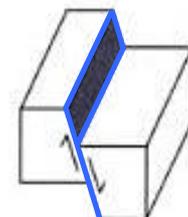
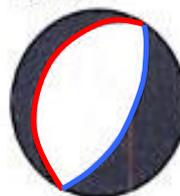
Strike Slip



Décrochement sénestre Décrochement dextre

- Mécanisme normal

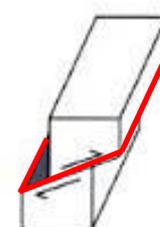
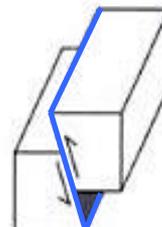
Normal



Normal à fort pendage Normal à faible pendage

- Mécanisme inverse

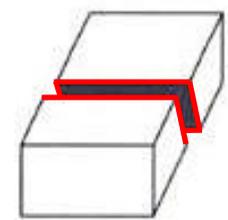
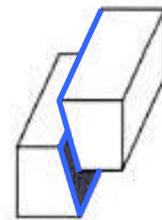
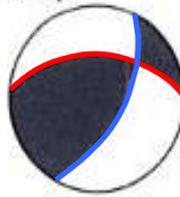
Reverse



Chevauchement à fort pendage Chevauchement

- Mécanisme oblique

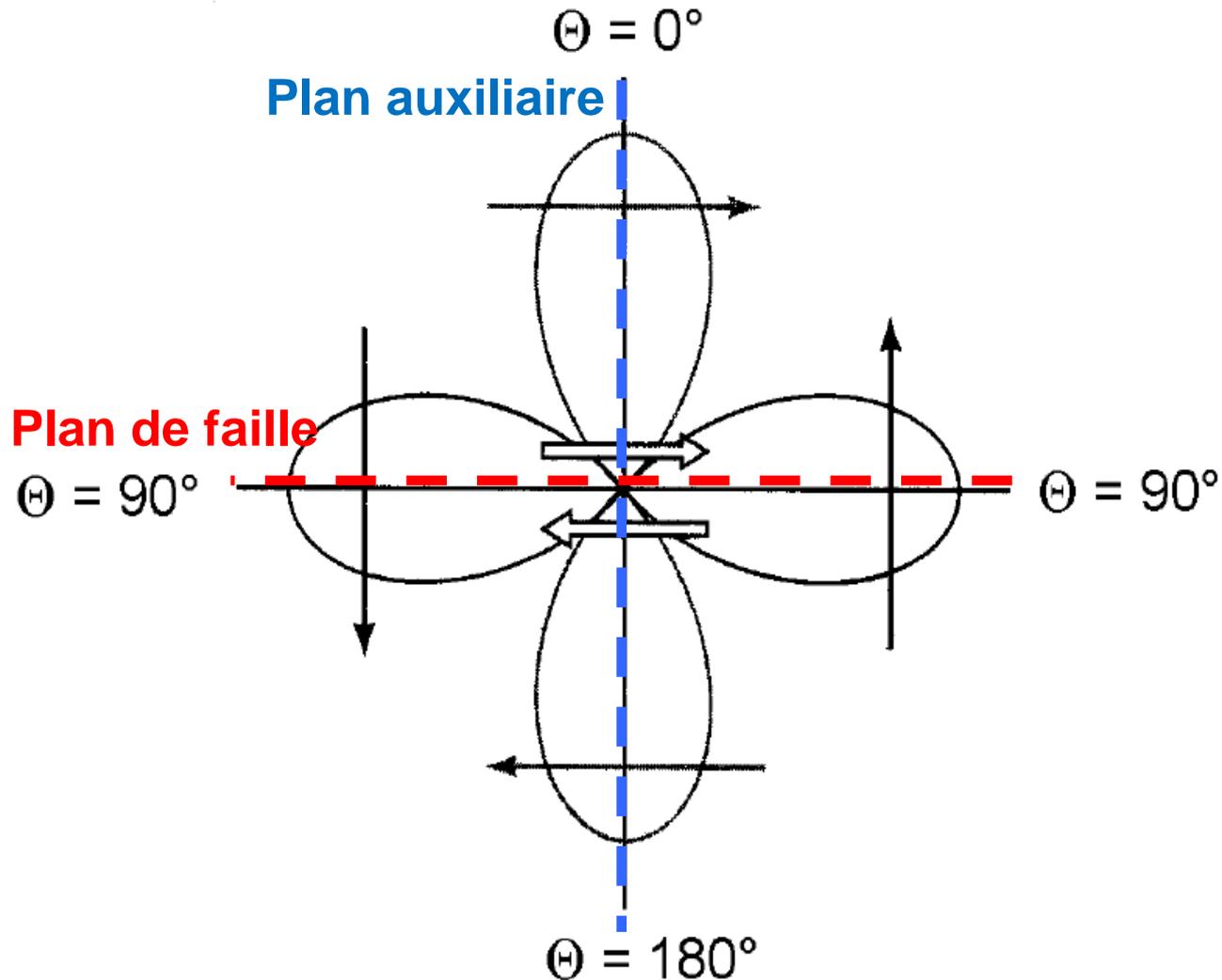
Oblique



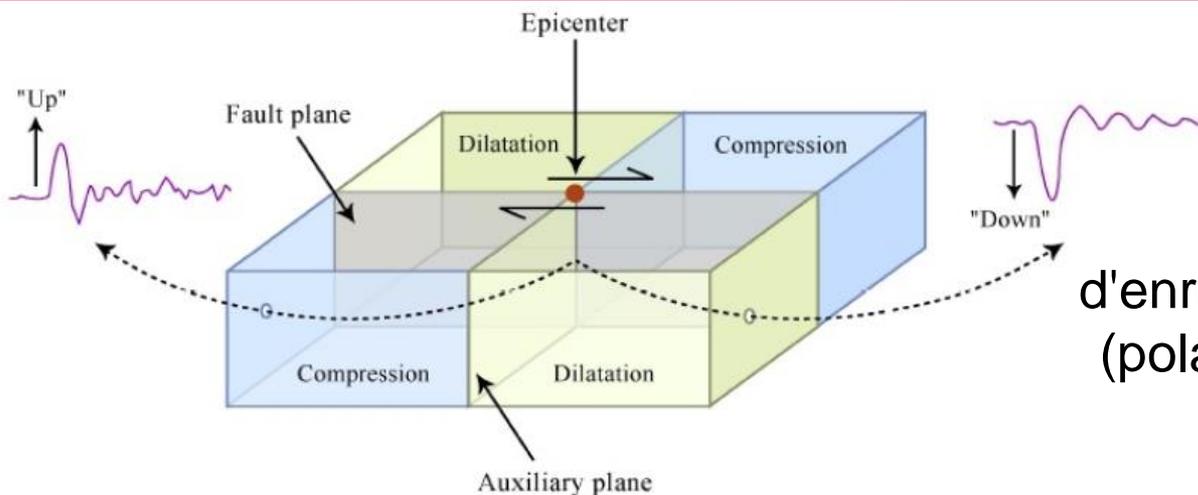
Chevauchant sénestre Chevauchant dextre

## Le double couple

Deux plans nodaux perpendiculaires (plan de faille et plan auxiliaire)

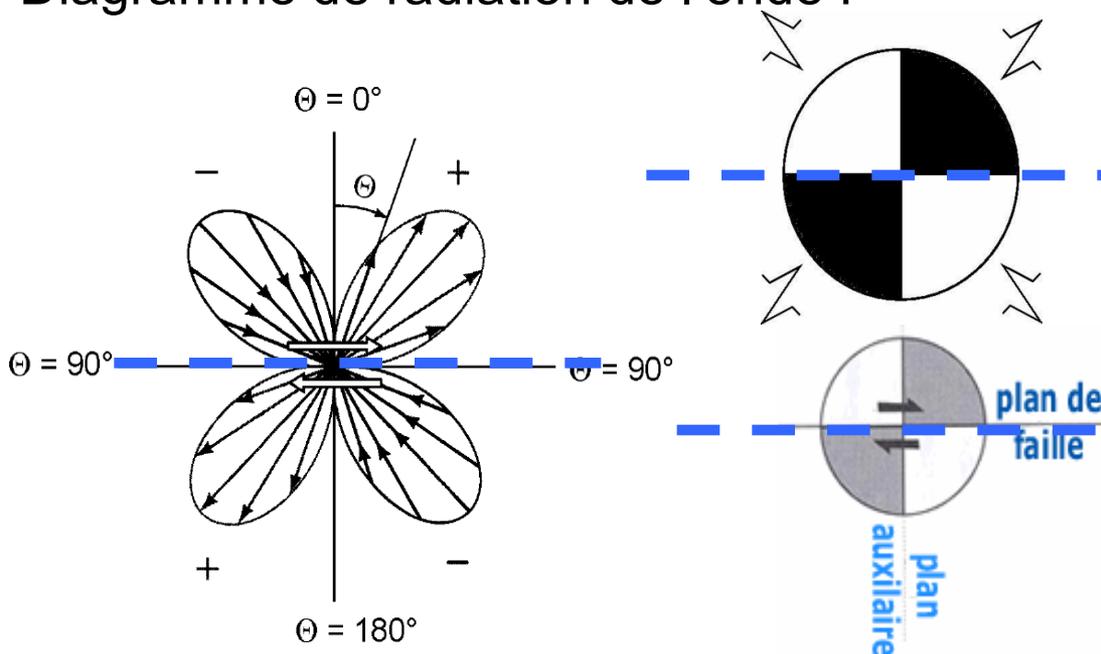


## Mécanisme au foyer et sens de premier mouvement



Mouvement des stations d'enregistrement lors d'un séisme (polarité de premier mouvement)

### Diagramme de radiation de l'onde P

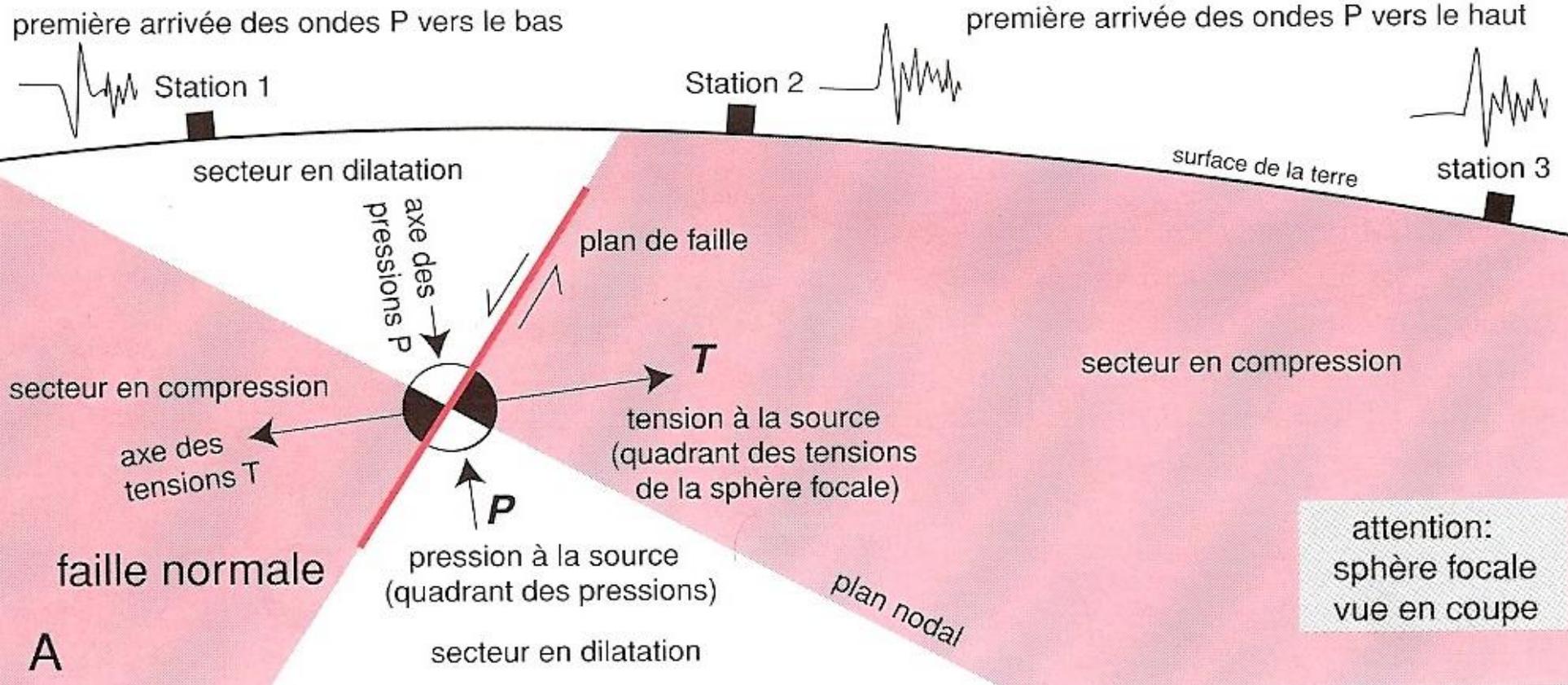


Si le premier pic reçu sur le sismogramme est vers le haut, alors le premier mouvement est en compression.

2 quadrants en compression (en noir)

2 quadrants en dilatation (en blanc)

## Mécanisme au foyer et sens de premier mouvement



A

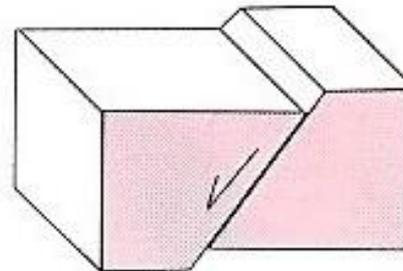
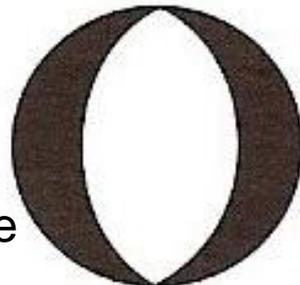
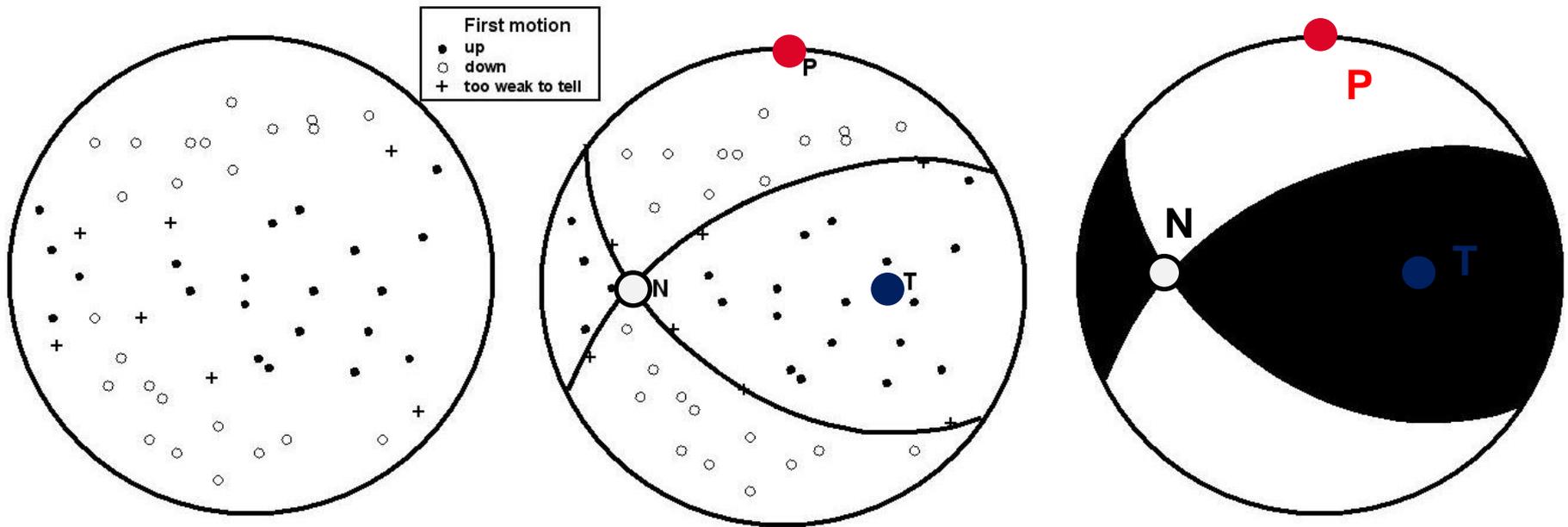


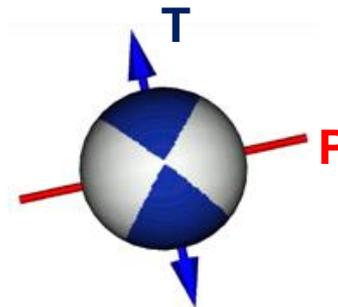
Diagramme 3D

Sphère focale vue en carte

## Détermination des plans nodaux et des axes P, T et N

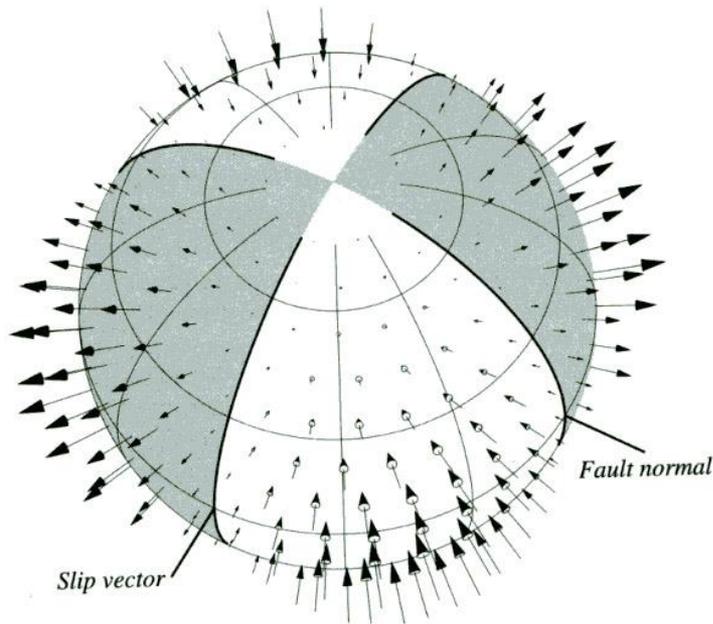


**axe P** : au centre du secteur blanc,  
**axe T** : au centre du secteur sombre,  
 Axe N : intersection des plans nodaux



## Mécanisme au foyer et sens de premier mouvement

A partir des polarités des ondes P, on peut déterminer le mécanisme au foyer.

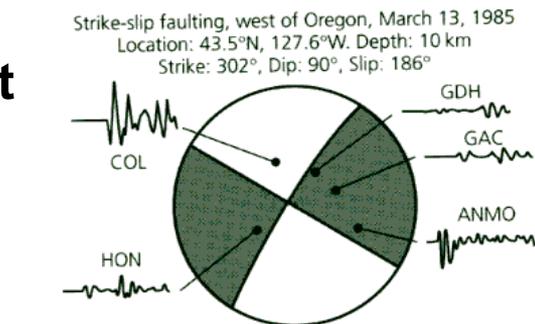
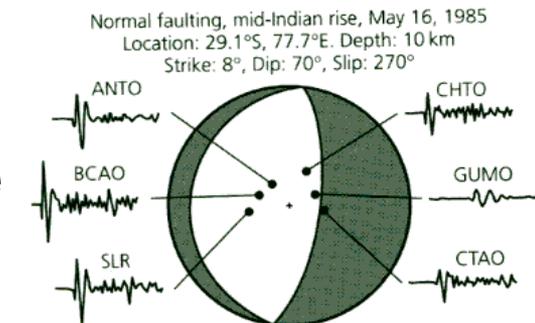
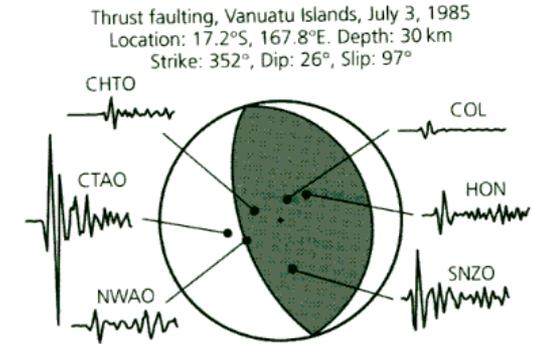


amplitudes des ondes P

● **Faïlle inverse**

● **Faïlle normale**

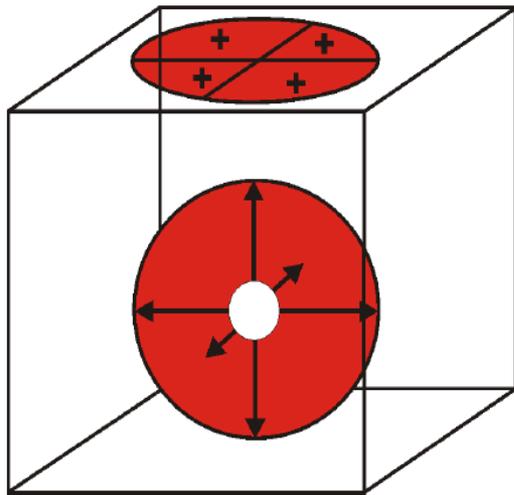
● **Décrochement**



0 120 240  
(s)

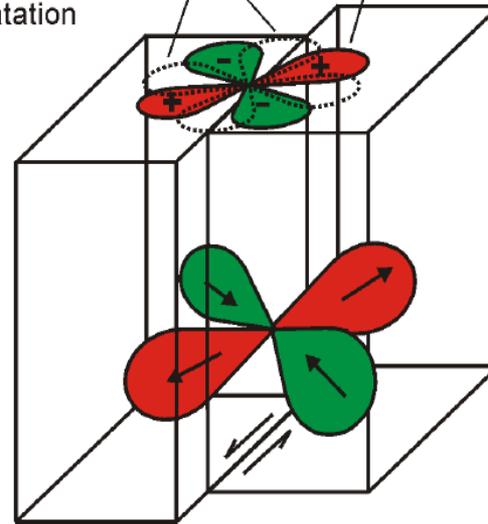
## Mécanisme au foyer et sphère focale

Explosion



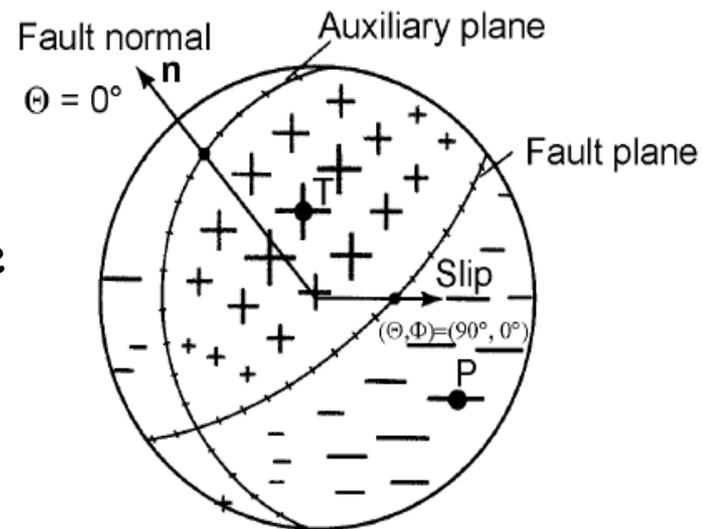
SH- & Love-waves P- & Rayleigh-waves

+ Compression  
- Dilatation



Double couple

Sphère focale : Sphère centrée sur la source et découpée en secteurs compressifs (+) et extensifs (-)





## Tenseur des moments sismiques

Expression des moments sismiques pour une source sismique double-couple en fonction des paramètres de la source  
(Aki et Richards, 1980)

$$M_{xx} = -M_0(\sin\delta \cos\lambda \sin 2\phi + \sin 2\delta \sin\lambda \sin^2\phi)$$

$$M_{xy} = M_0(\sin\delta \cos\lambda \cos 2\phi + 0.5 \sin 2\delta \sin\lambda \sin 2\phi)$$

$$M_{xz} = -M_0(\cos\delta \cos\lambda \cos\phi + \cos 2\delta \sin\lambda \sin\phi)$$

$$M_{yy} = M_0(\sin\delta \cos\lambda \sin 2\phi - \sin 2\delta \sin\lambda \cos^2\phi)$$

$$M_{yz} = -M_0(\cos\delta \cos\lambda \sin\phi - \cos 2\delta \sin\lambda \cos\phi)$$

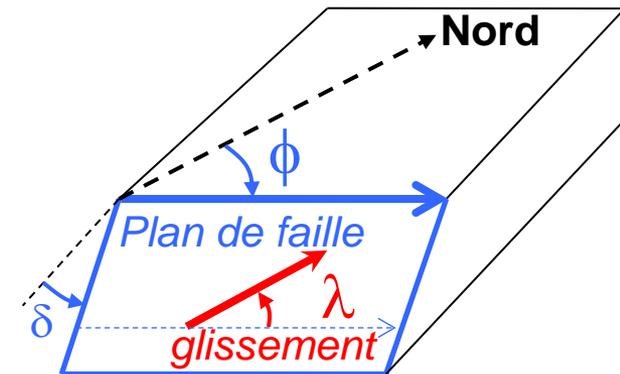
$$M_{zz} = M_0 \sin 2\delta \sin\lambda$$

$\delta$  : Pendage (**dip**)

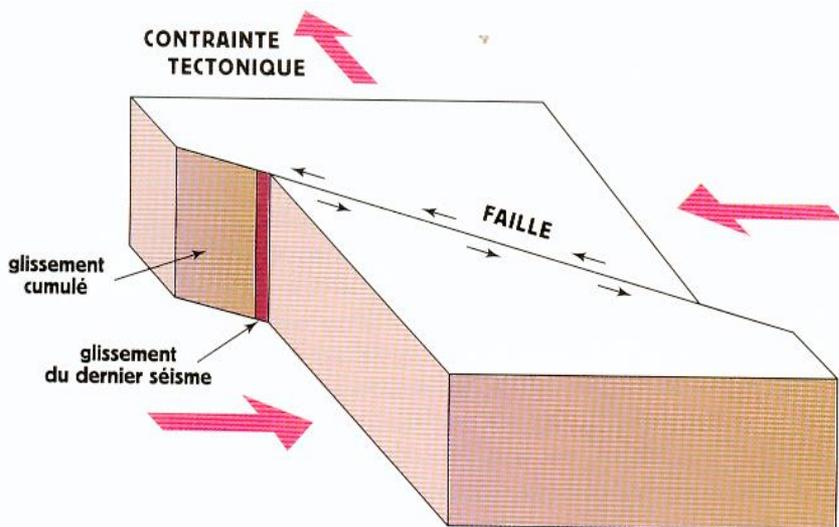
$\phi$  : Azimut (**strike**)

$\lambda$  : Glissement dans le plan de faille (**rake**)

$M_0$  : Moment sismique



## Faille décrochante

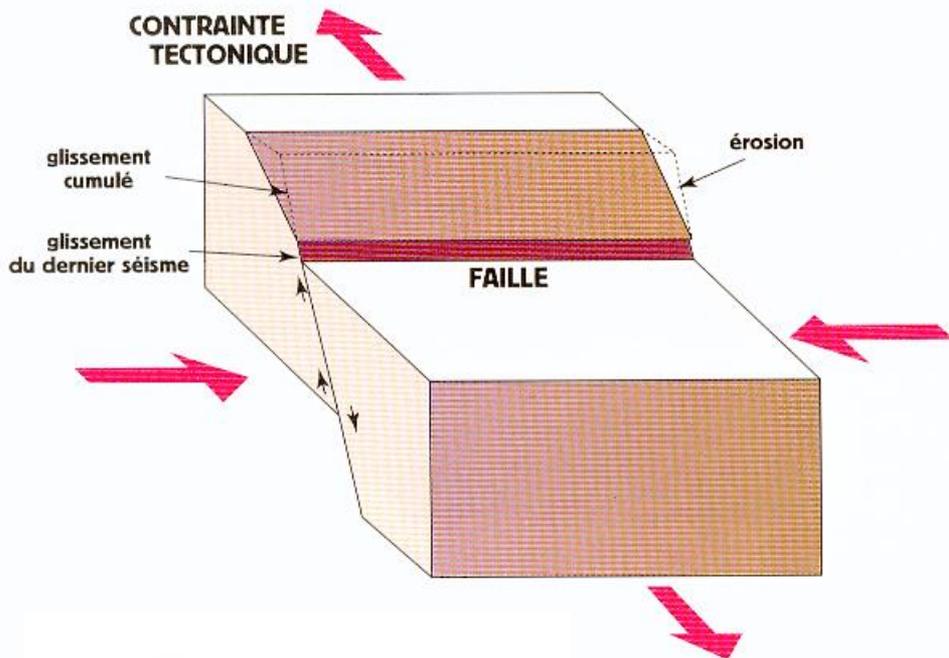


Strike Slip



# Faïlle normale

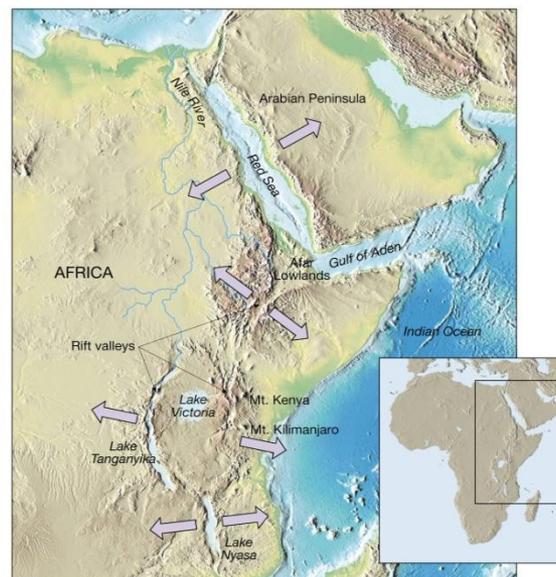
# Normal fault



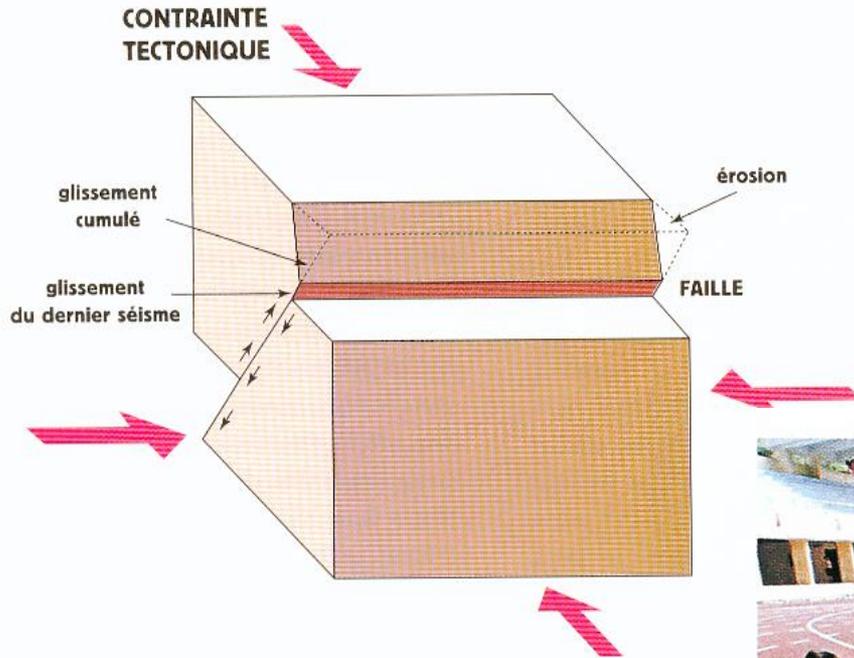
Normal



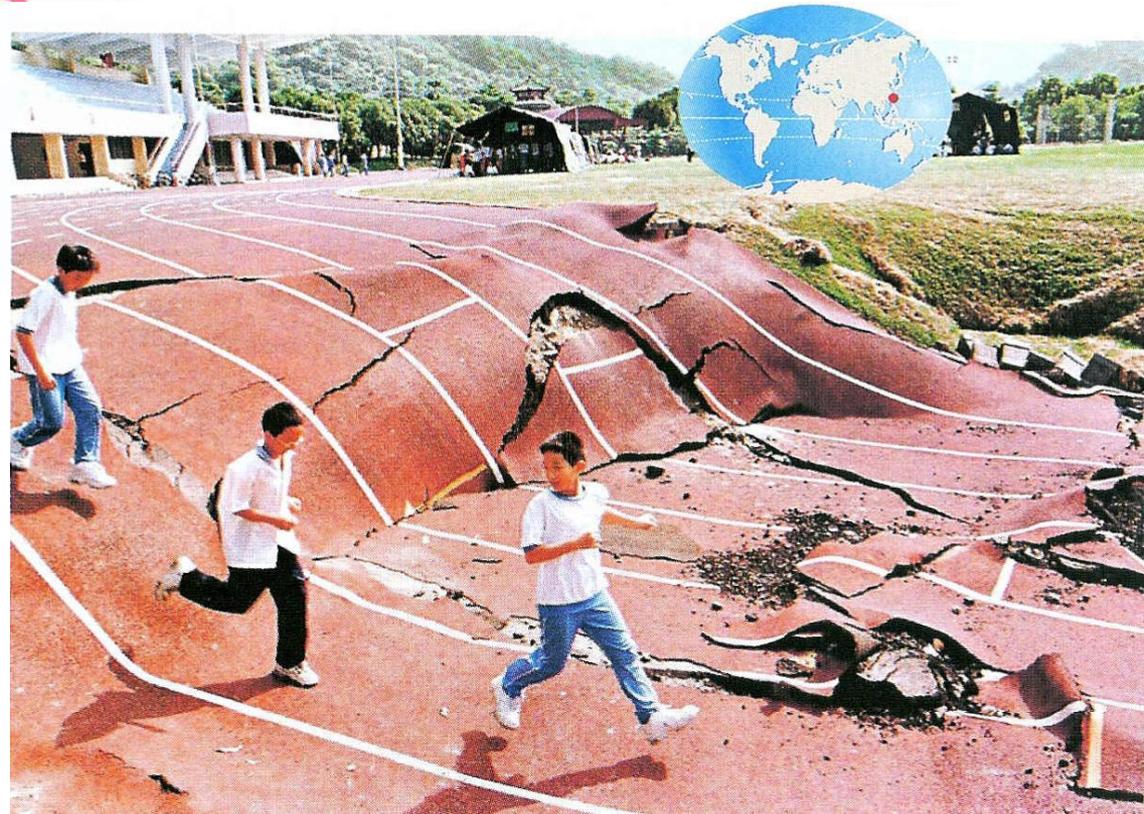
Rift est-africain



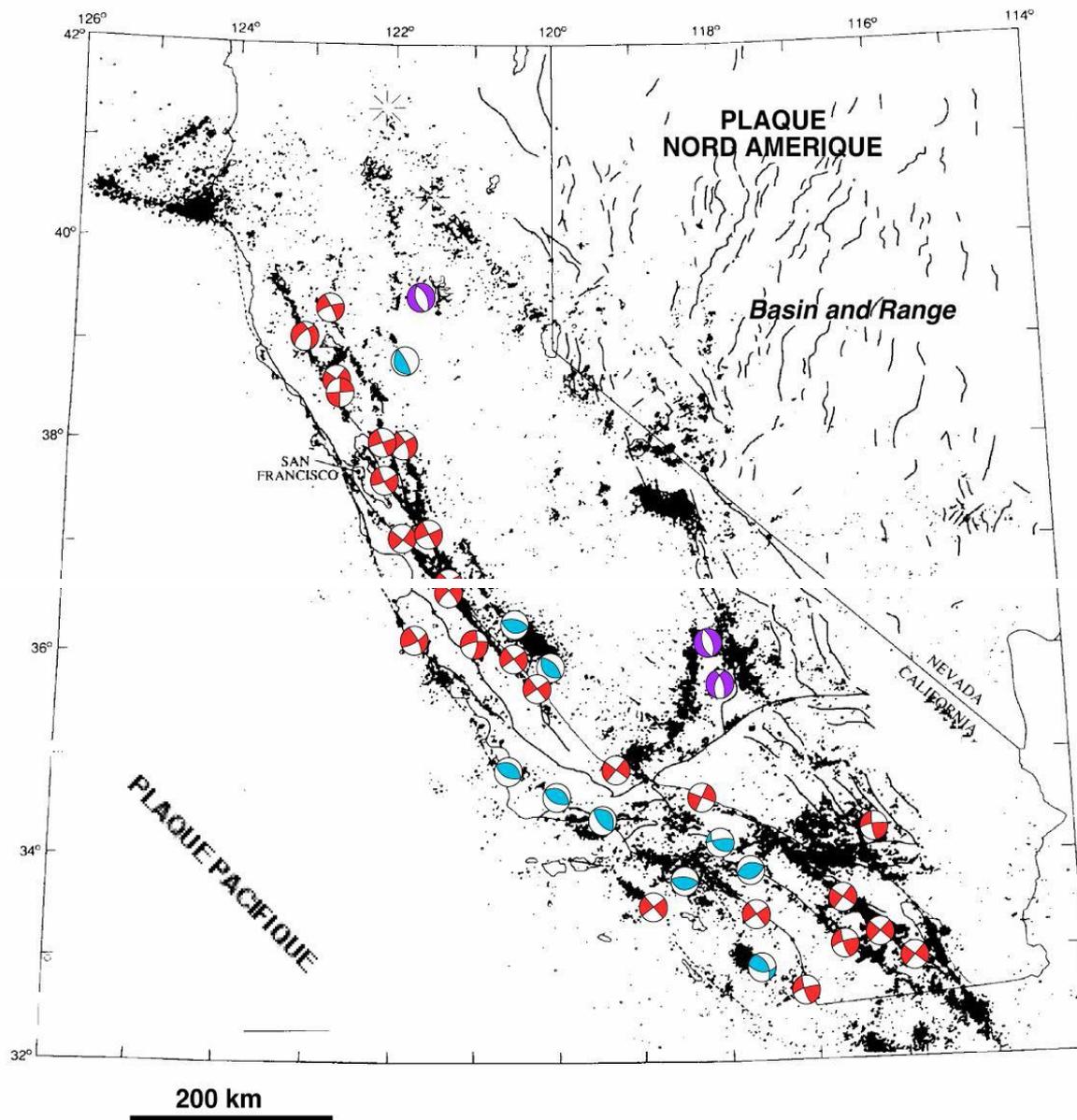
## Faille inverse



Reverse



# Décrochement dextre



# Sumatra

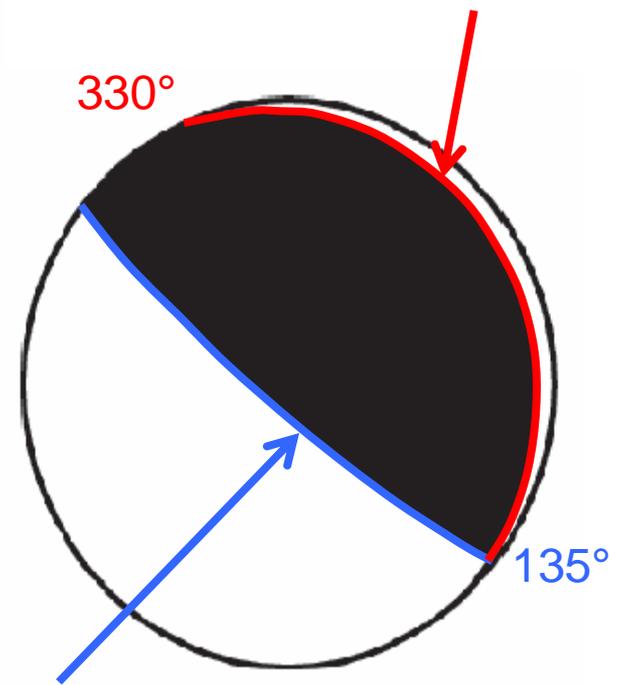
# Reverse fault



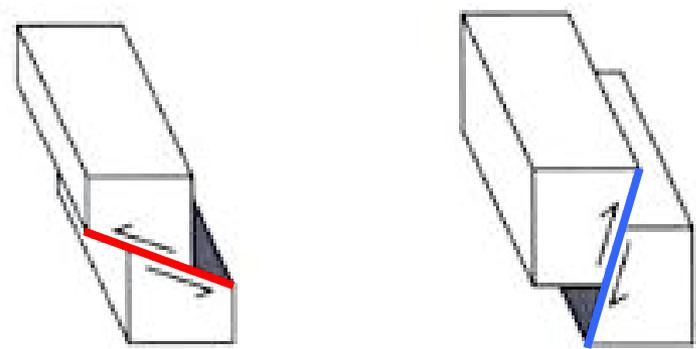
**LEGENDE**

- Séisme du 26 décembre 2004
- Répliques M ≥ 4
- Frontières de plaque
- Volcans

Plan nodal 1: 330° 10°

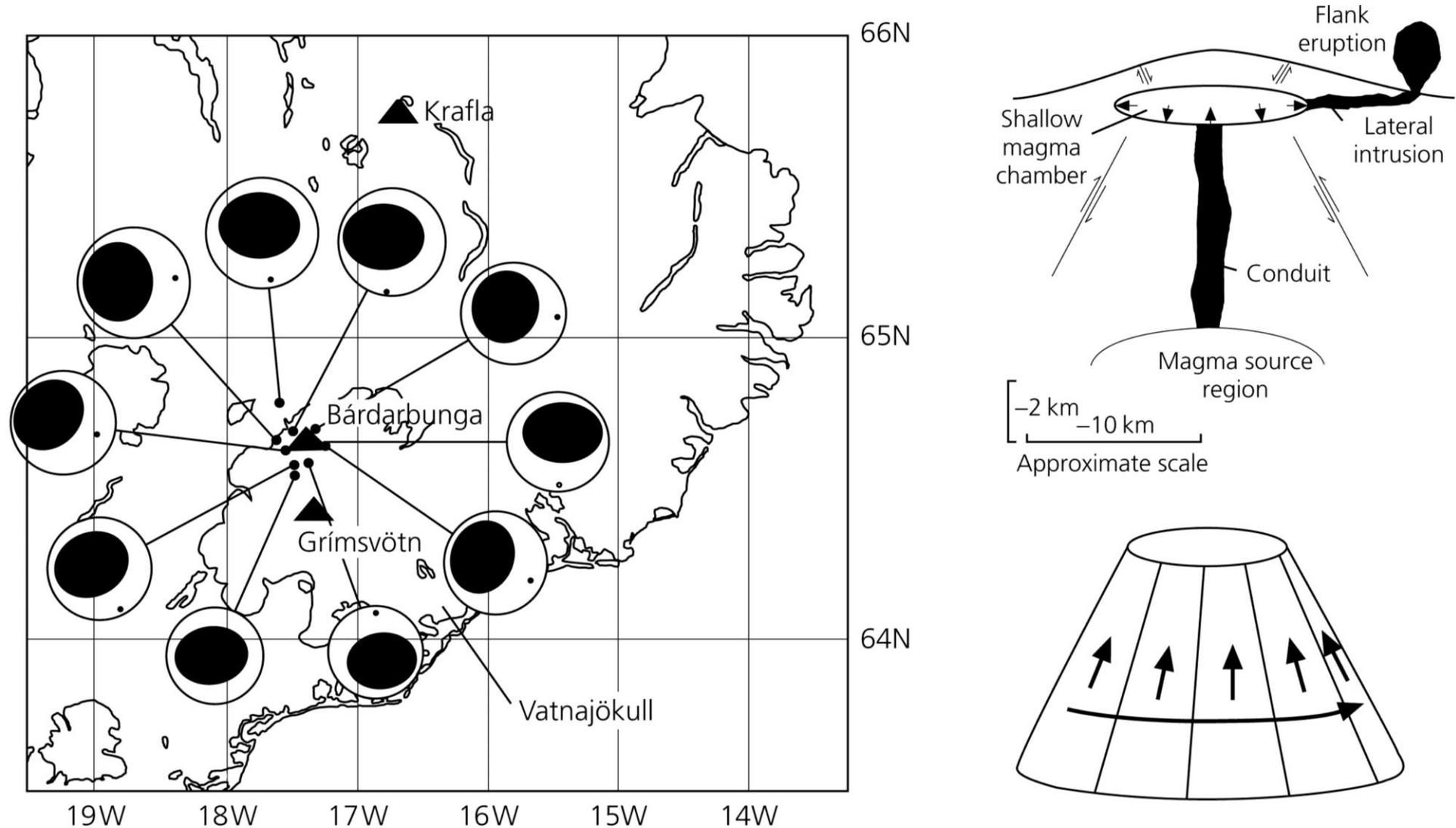


Plan nodal 2: 135° 85°

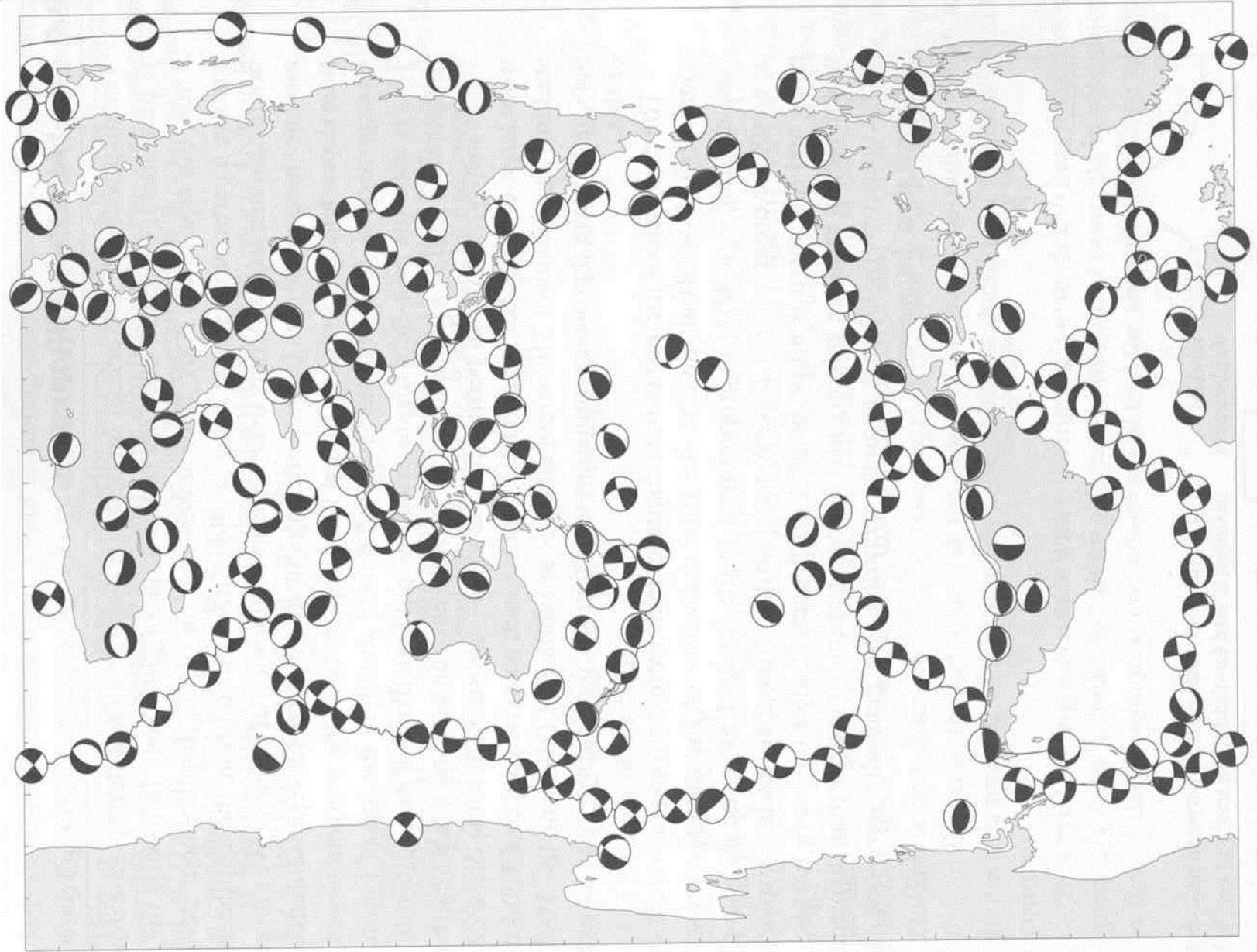


# CLVD-type focal mechanism

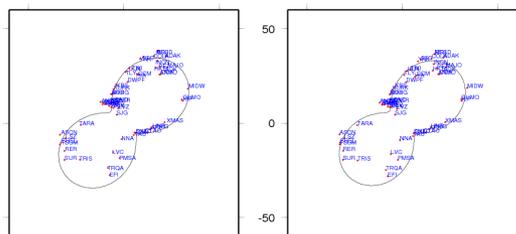
## Exemple de mécanisme de type CLVD



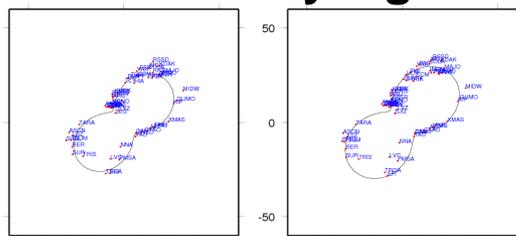
## Séismes mondiaux - sphères focales



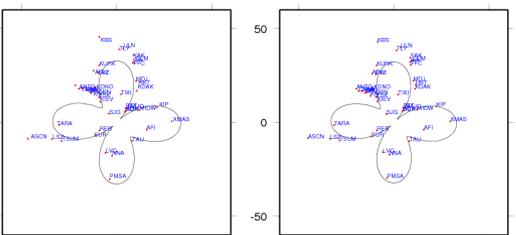
## Séisme de Sumatra du 12 septembre 2007 Mw 8,4



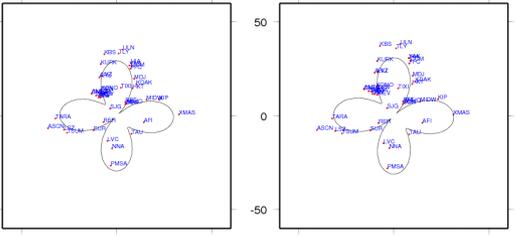
205 220  
**Ondes de Rayleigh**



293 256



205 220  
**Ondes de Love**



293 256

**BENGKULU**  
12 septembre 2007

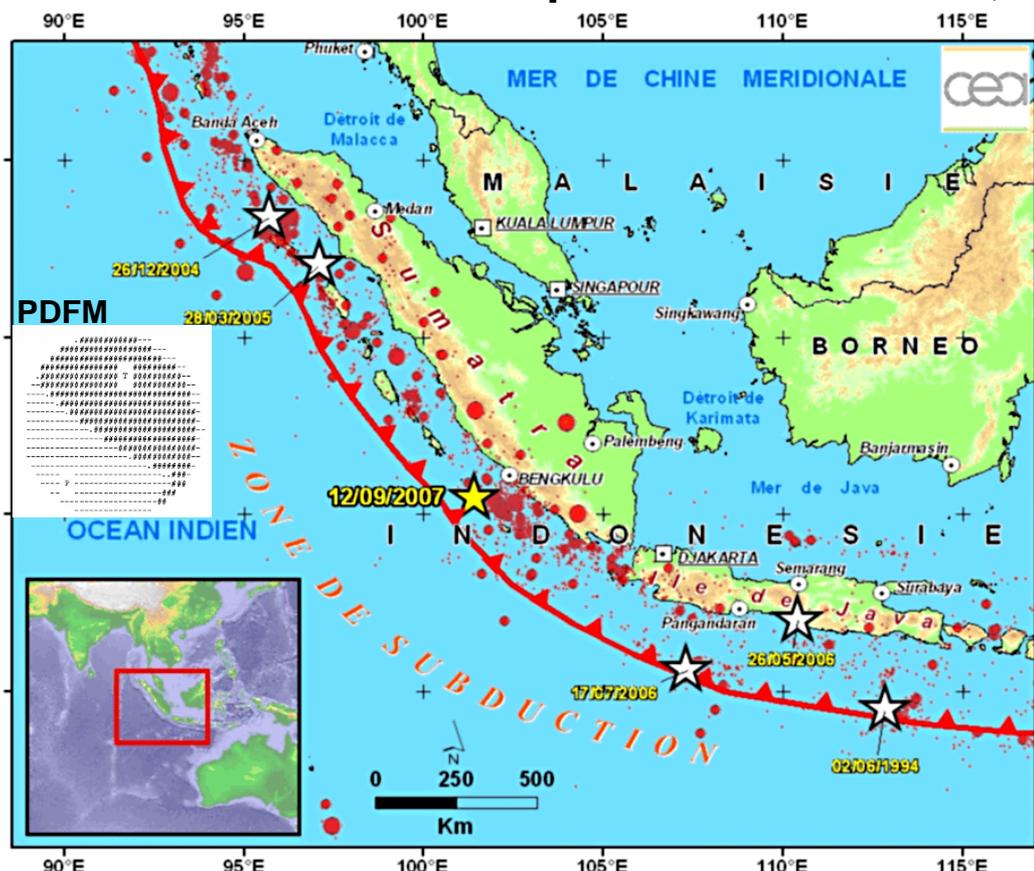
Sismicité (1973 - 2007)

- 5 < mb < 6
- 6 < mb < 7
- mb >= 7

Altitude

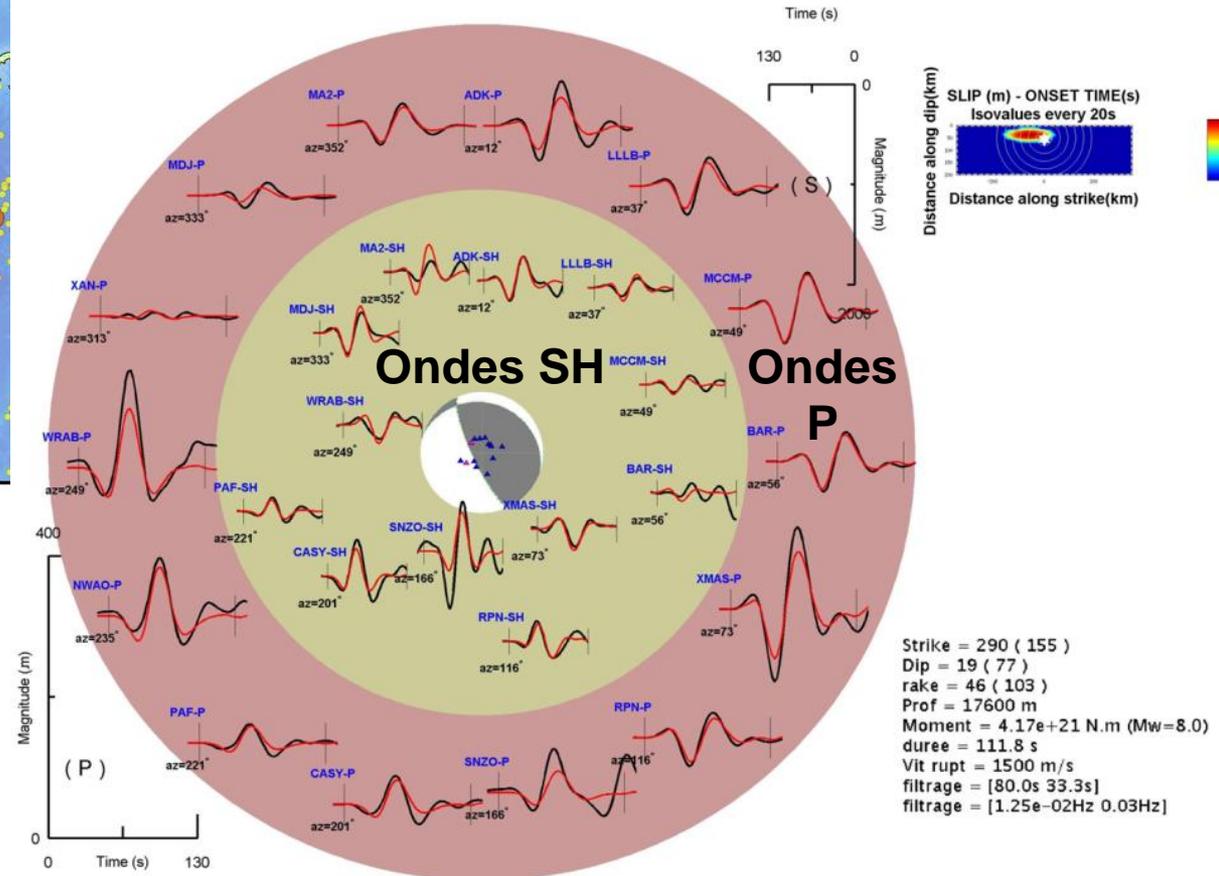
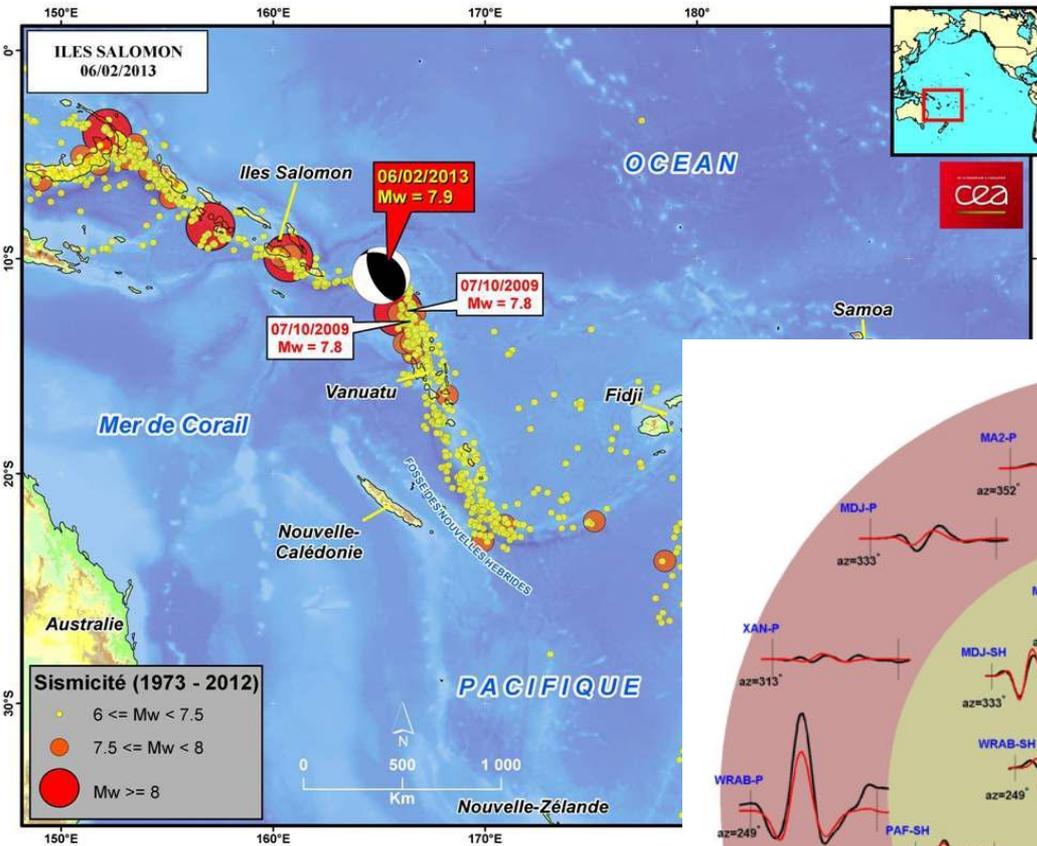
- 100 mètres
- 200
- 300
- 400
- 500
- 1000
- 2000
- 3000
- 4000
- 4500
- 5600
- > 5600

SOURCES :  
Données topographiques :  
- ICGEM (2000), SRTM, NASA (2003)  
Données sismiques :  
- USGS (1973 - 2007)



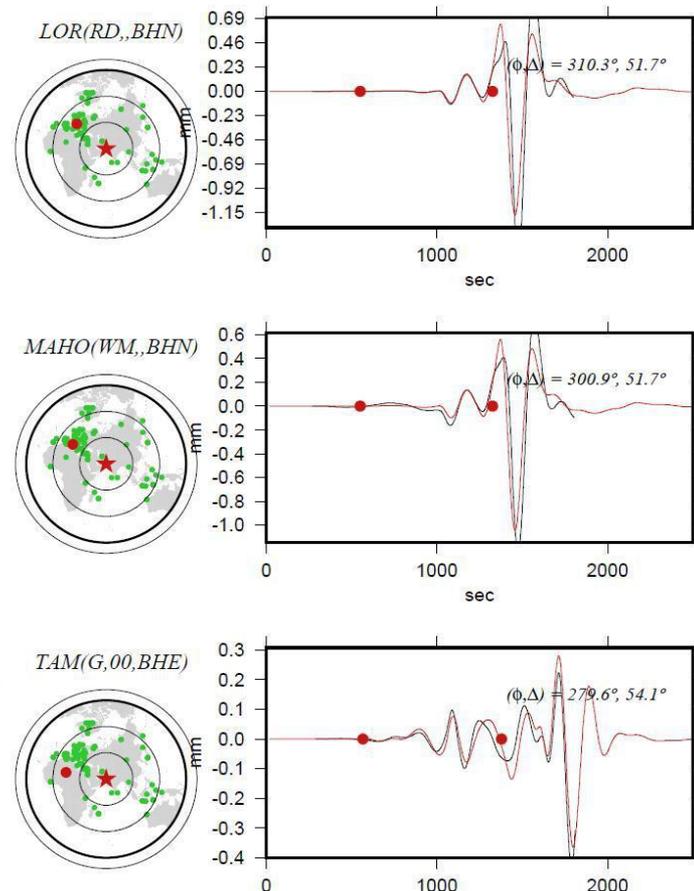
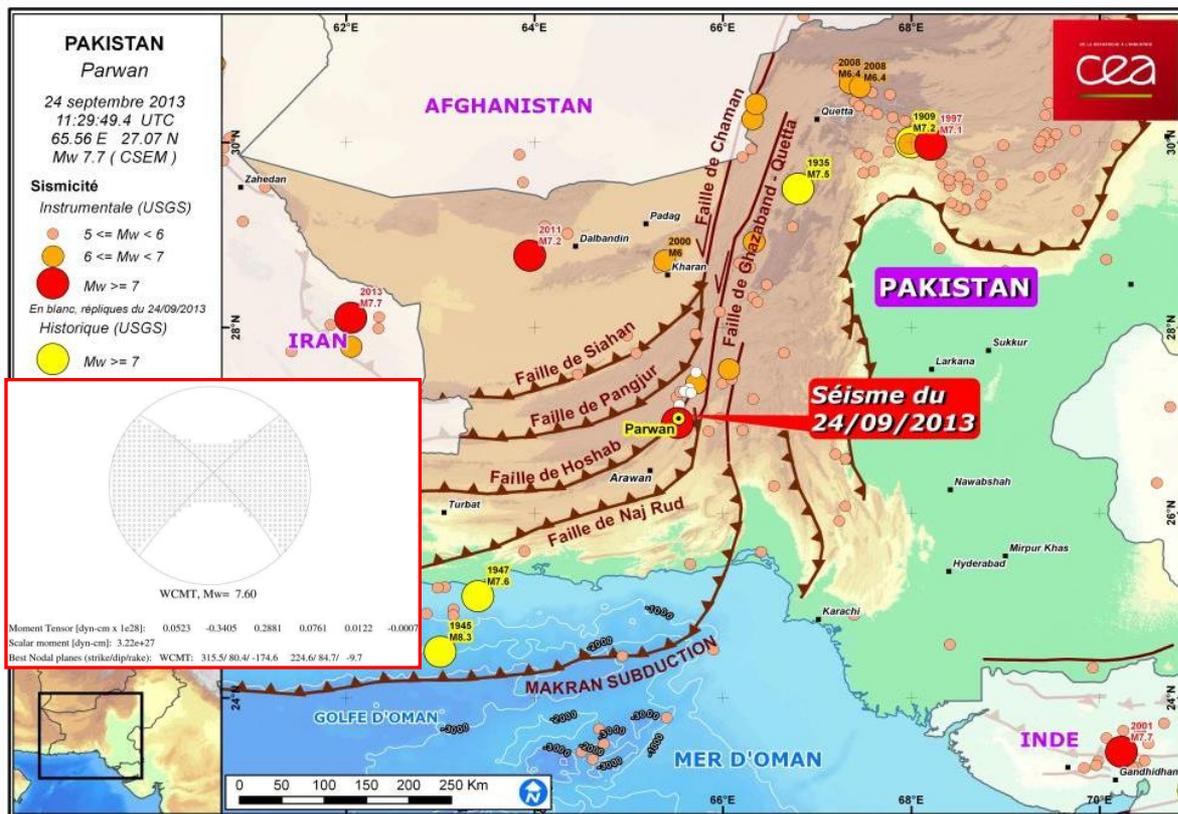
**Diagrammes de rayonnement des ondes de Rayleigh**  
(en haut) et de **Love** (en bas) à diverses périodes.

- Traits continus (modèle de source - solution PDFM).
- Points (modules spectraux observé aux stations).



# Détermination du CMT par inversion de la phase W

Inversion de la phase W (phase longue période au début du signal – typiquement 100s-1000s) à distance télé-sismique.

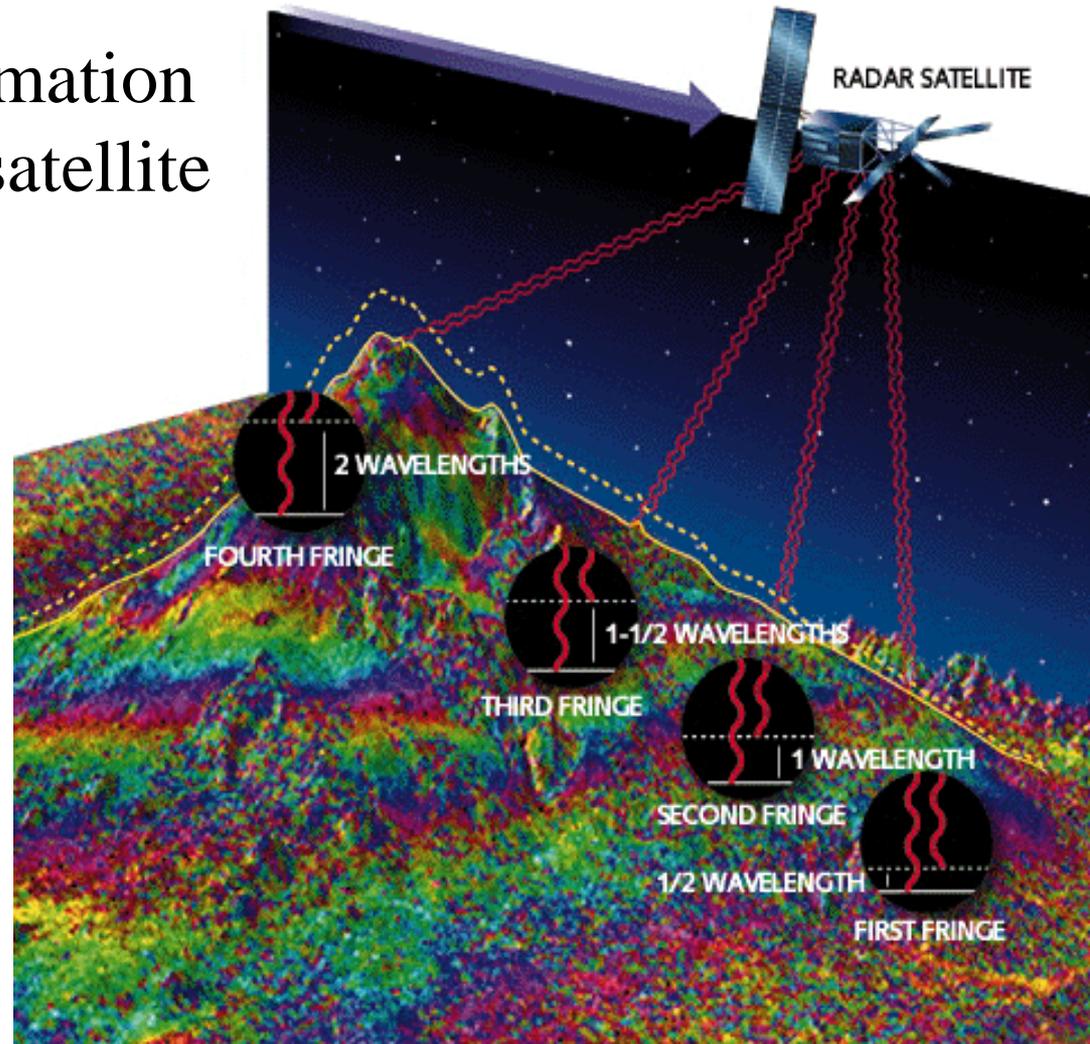


Par sa nature longue période et parce qu'elle précède les ondes de surface, la phase W permet d'obtenir une solution rapide du CMT d'un événement important alors que d'autres méthodes demandent plusieurs heures pour déterminer les paramètres de source d'un très grand séisme ( $M_w > 8.5$ ) même dans une région très bien instrumentée.

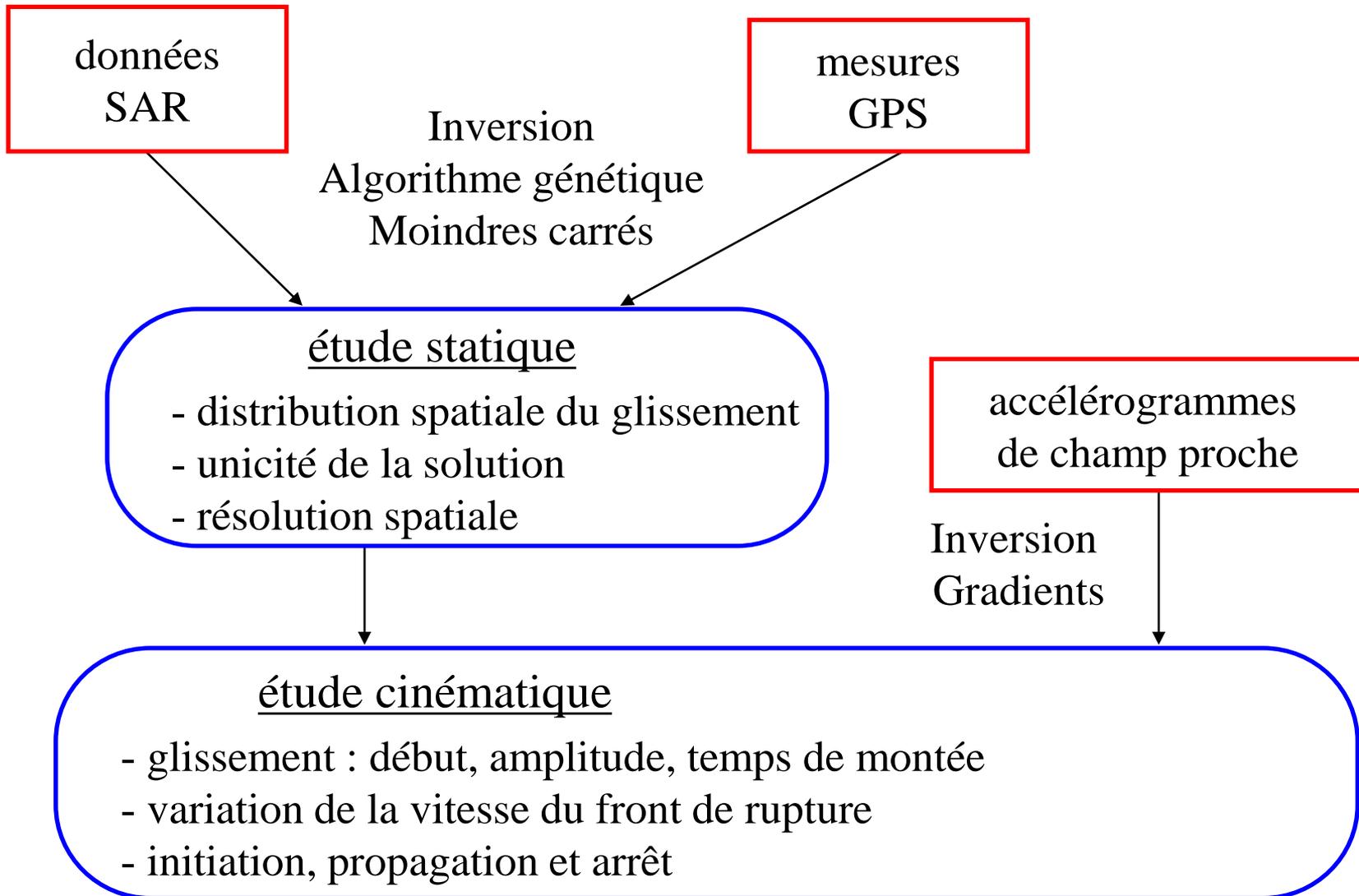
## Qu'apportent les données SAR ?

Mesure du champ de déformation  
cosismique dans l'axe sol-satellite

- Localisation
- Géométrie
- Distribution du glissement
- Libération de la vitesse de rupture



## Imagerie de la source sismique en deux étapes



## Milieu élastique à couches planes

Calcul des fonctions de Green dans un demi espace à stratification horizontale par la méthode des nombre d'ondes discrets

*Bouchon, 1981*  
*Kennett, 1983*  
*Coutant, 1989*

Profondeur, km	Vp km s <sup>-1</sup>	Vs km s <sup>-1</sup>	Density kg cm <sup>-3</sup>	Qp	Qs
0	4,1	2,3	2,5	300	300
2	5,5	3,2	2,8	500	500
4					
	6,3	3,65	2,9	500	500
26					
	6,8	3,9	3,1	500	500
32					
	8,2	4,7	3,2	500	500

## Géométrie et discrétisation de la source

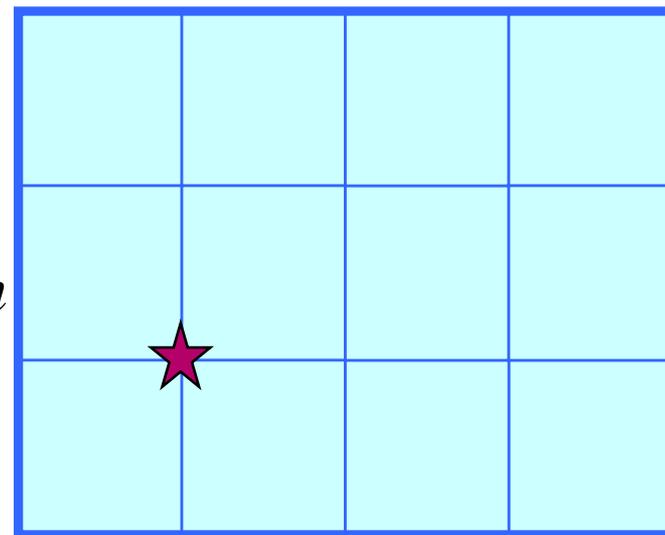
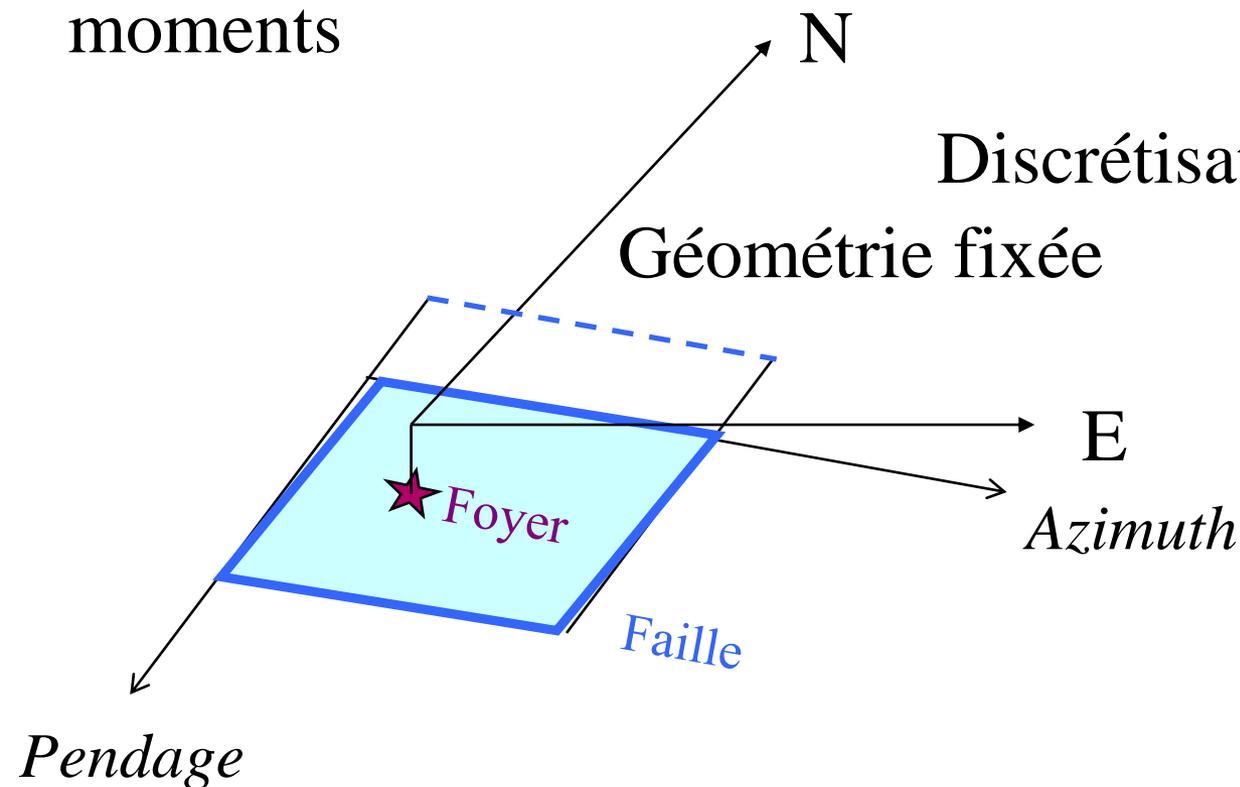
Localisation de l'hypocentre

Distribution des répliques

Solutions du tenseur des moments

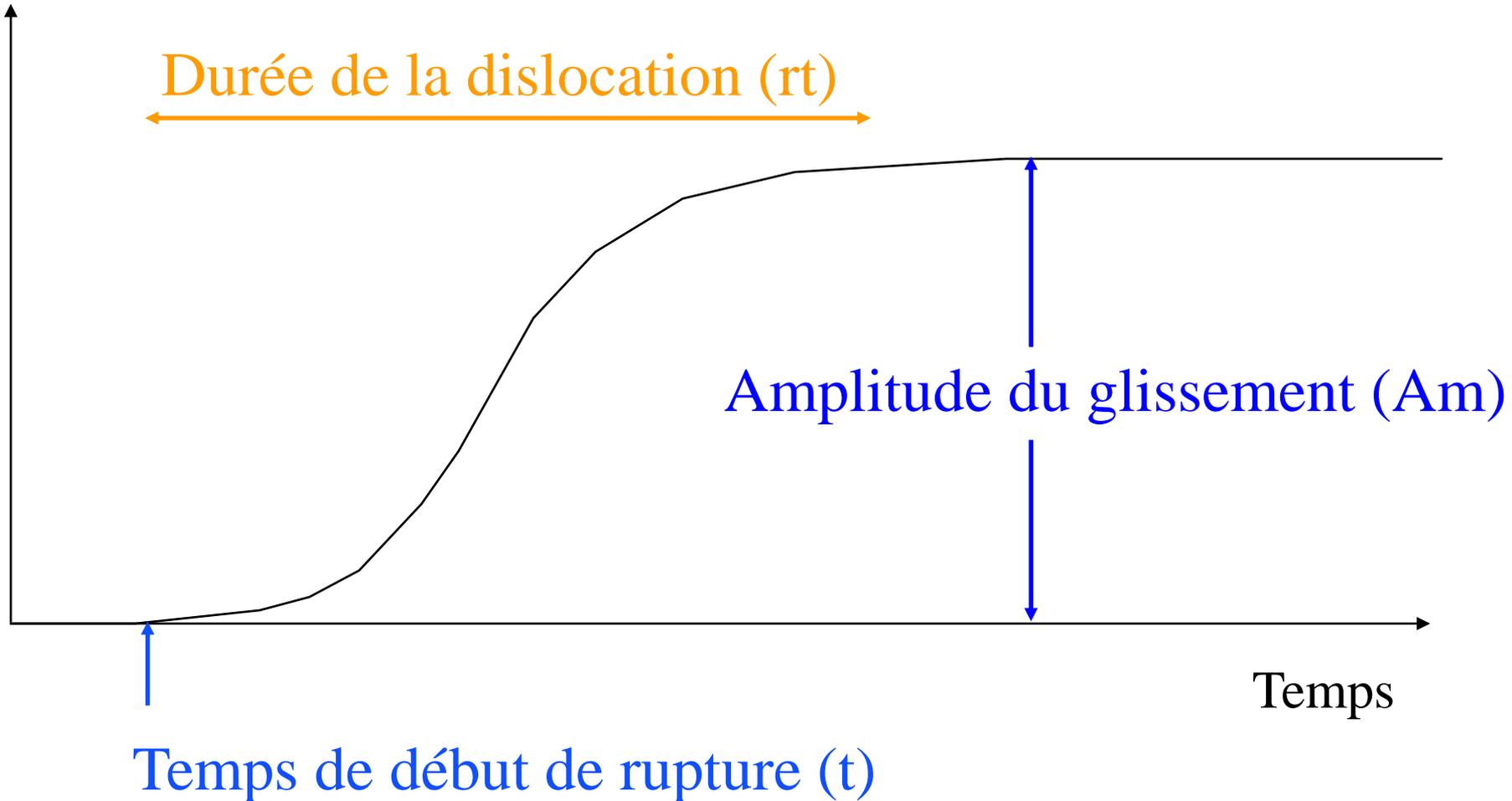
Discretisation en sous-failles

Géométrie fixée



## Fonction source associée à chaque sous-faïlle

## Glissement



## Formulation directe

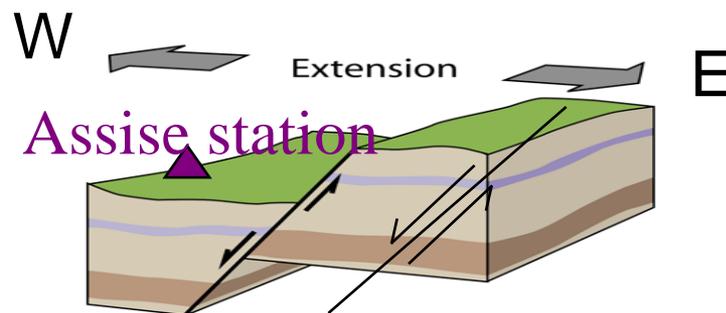
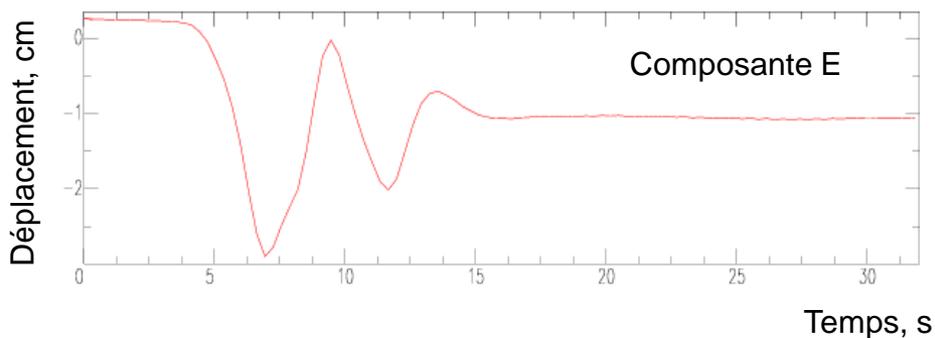
### Déformation géodésique

$$V_i(\omega = 0) = \sum_{k=1}^N Am_k \cdot u_{ki}(\omega = 0)$$

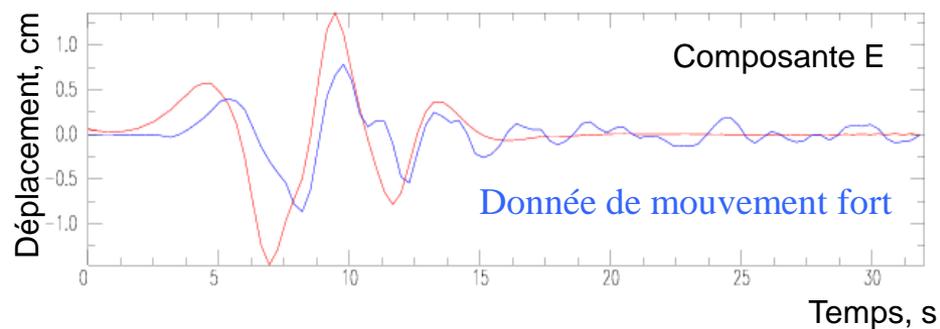
### Mouvement sismique

$$V_i(\omega) = \sum_{k=1}^N \left( Am_k \cdot S(rt_k, \omega) \cdot e^{-i\omega t_k} \right) u_{ki}(\omega)$$

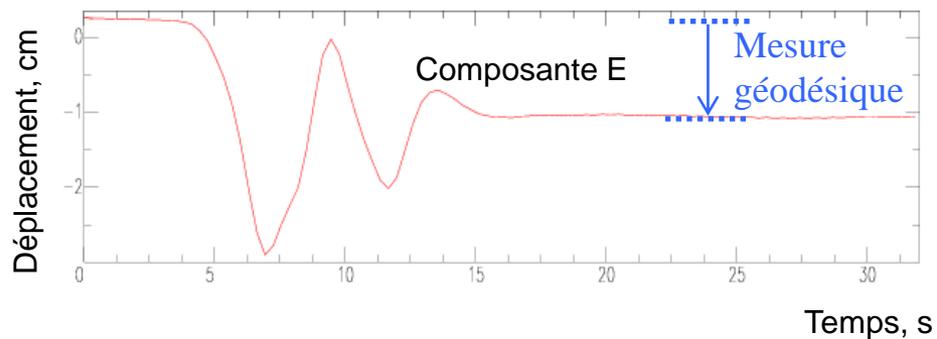
## Synthétiques [0 ; 1,5] Hz



## Mouvement sismique ([0,1 ; 1,5] Hz)

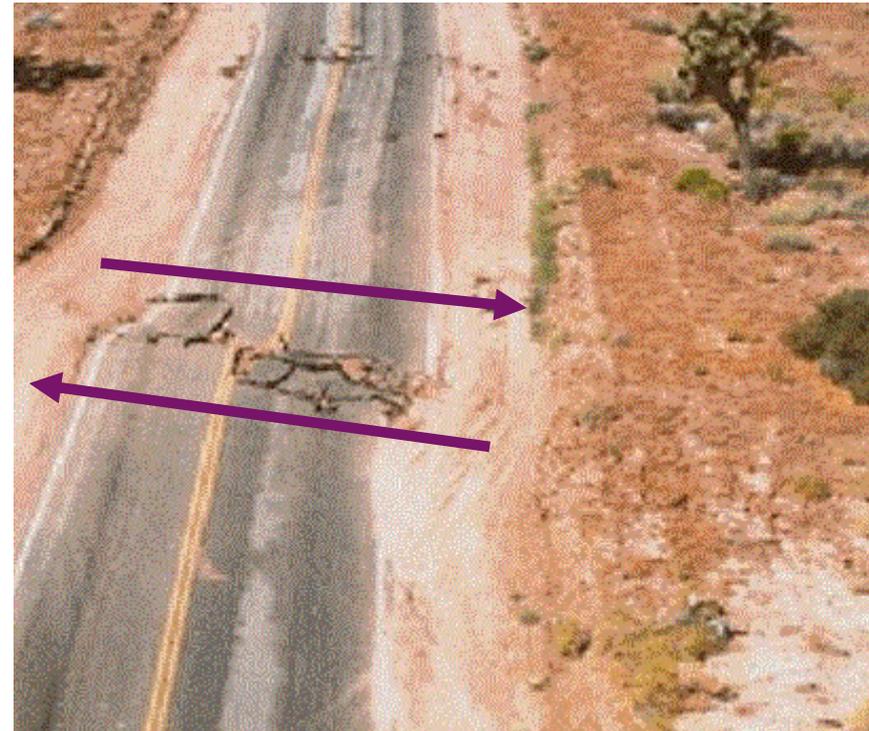
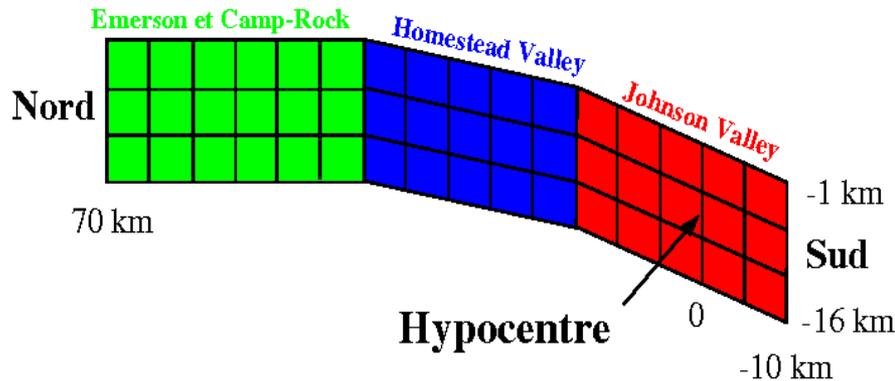
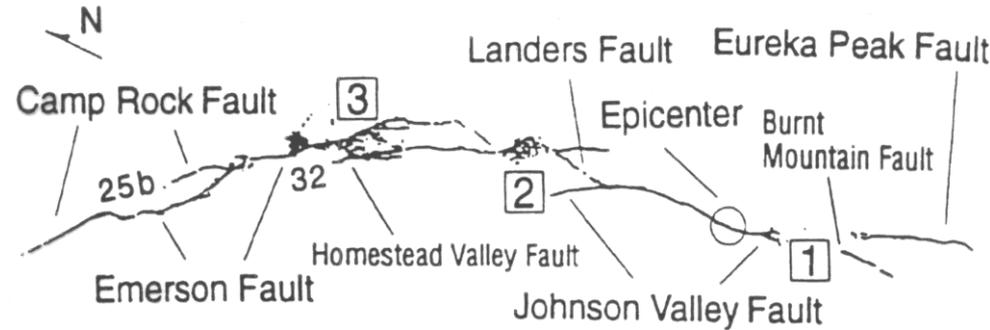
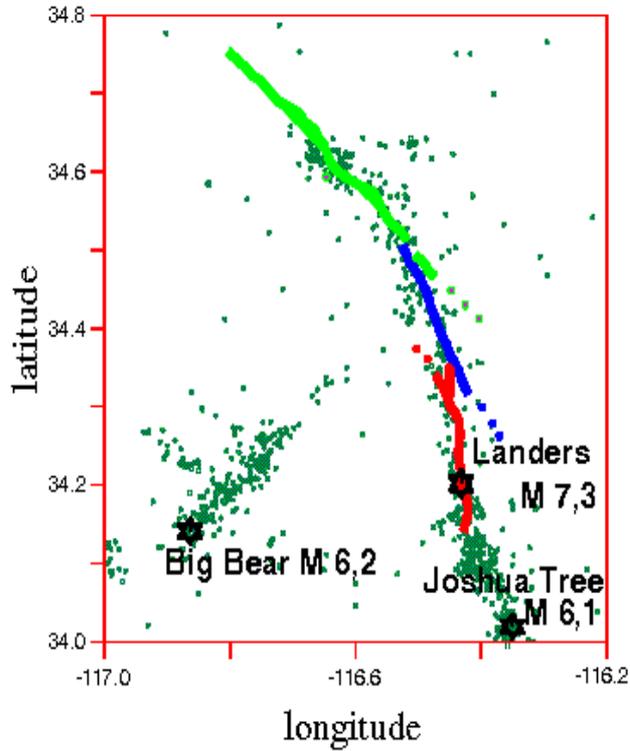


## Déformation géodésique (f # 0 Hz)

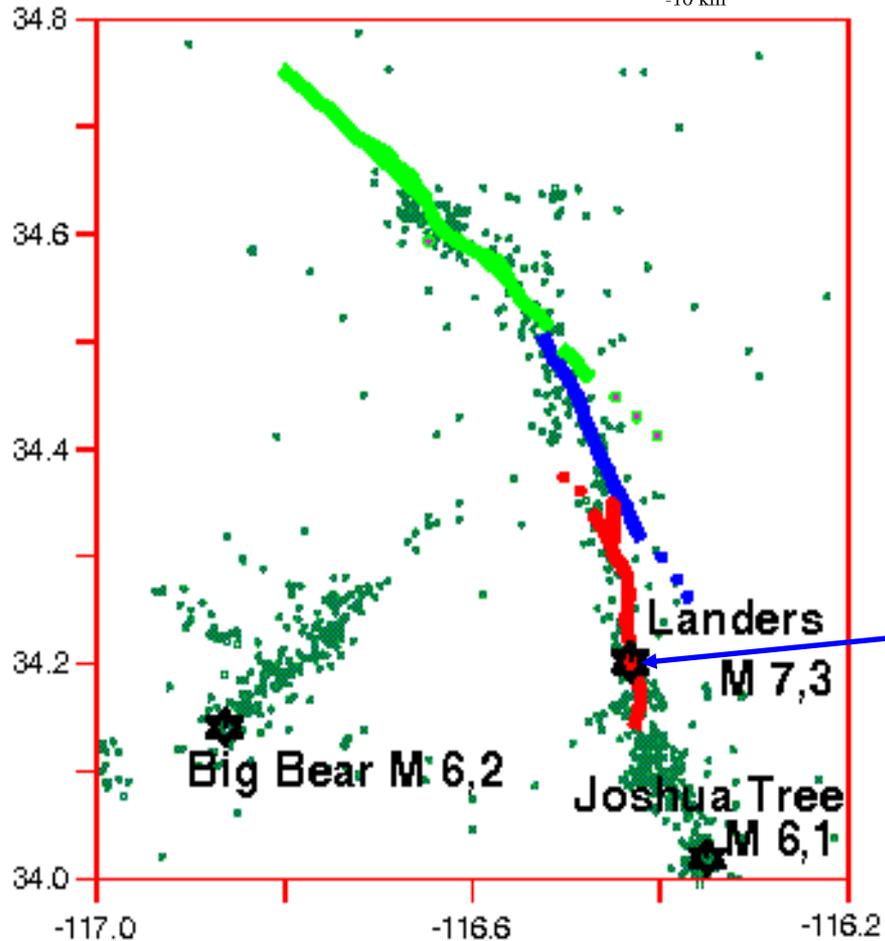
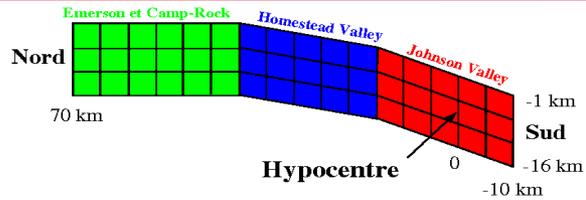


# Source inversion : an example

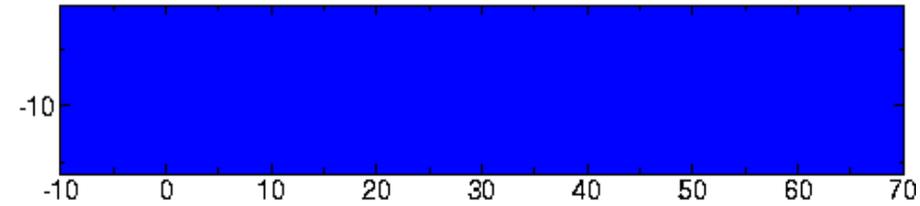
Séisme de Landers (Californie, 1992, Mw=7,3)



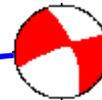
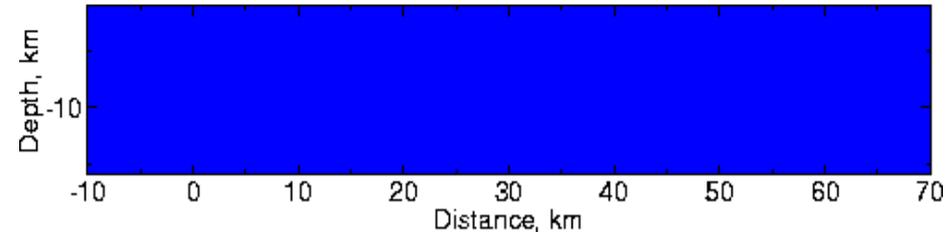
## Propagation de la rupture sismique



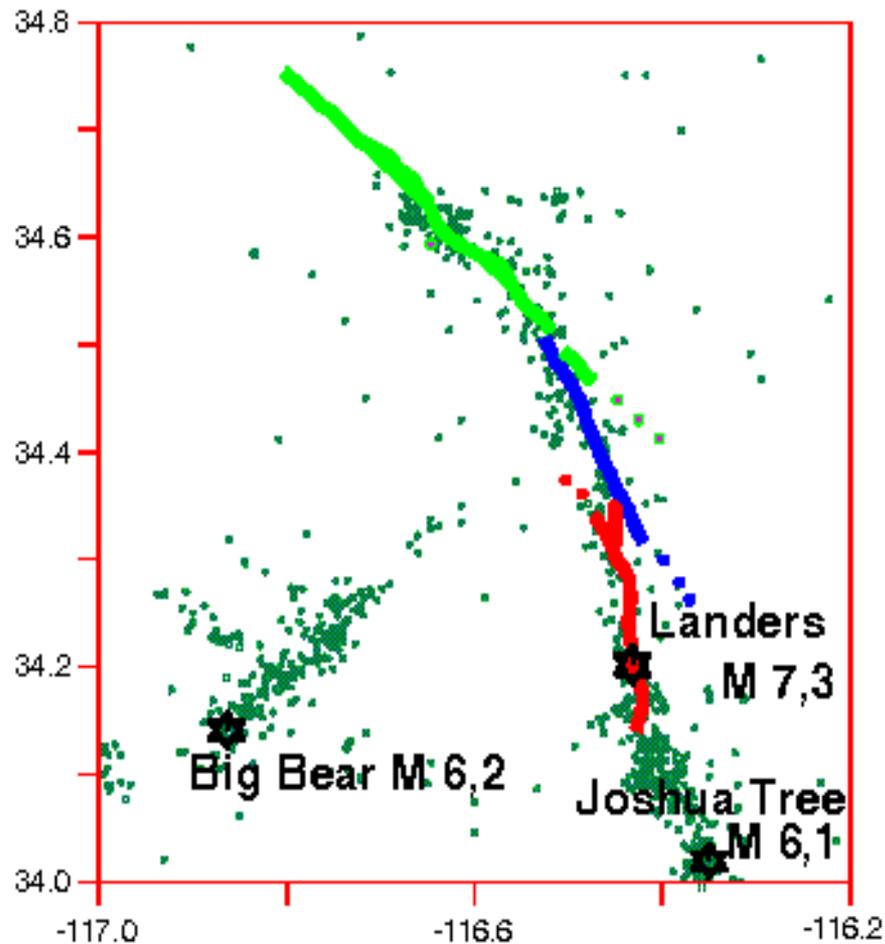
Landers earthquake



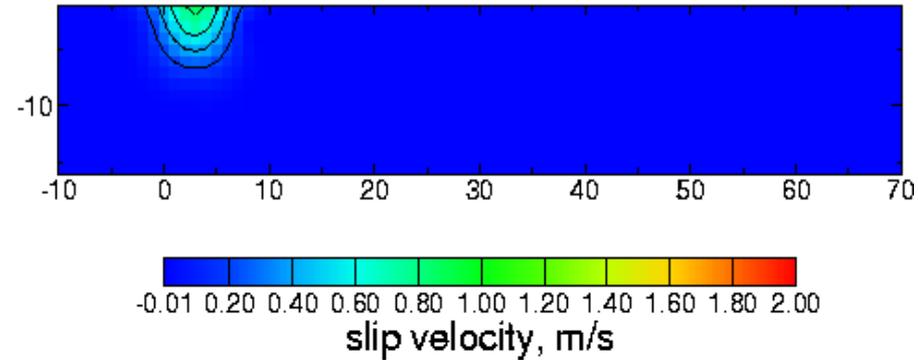
Sud Nord  
-1 s



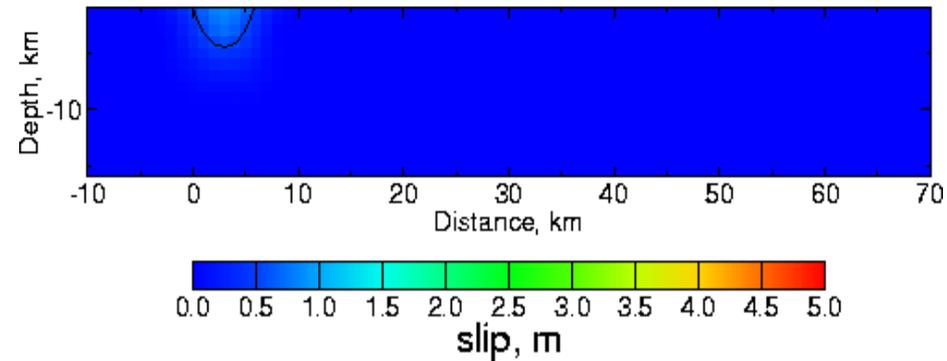
## Propagation de la rupture sismique



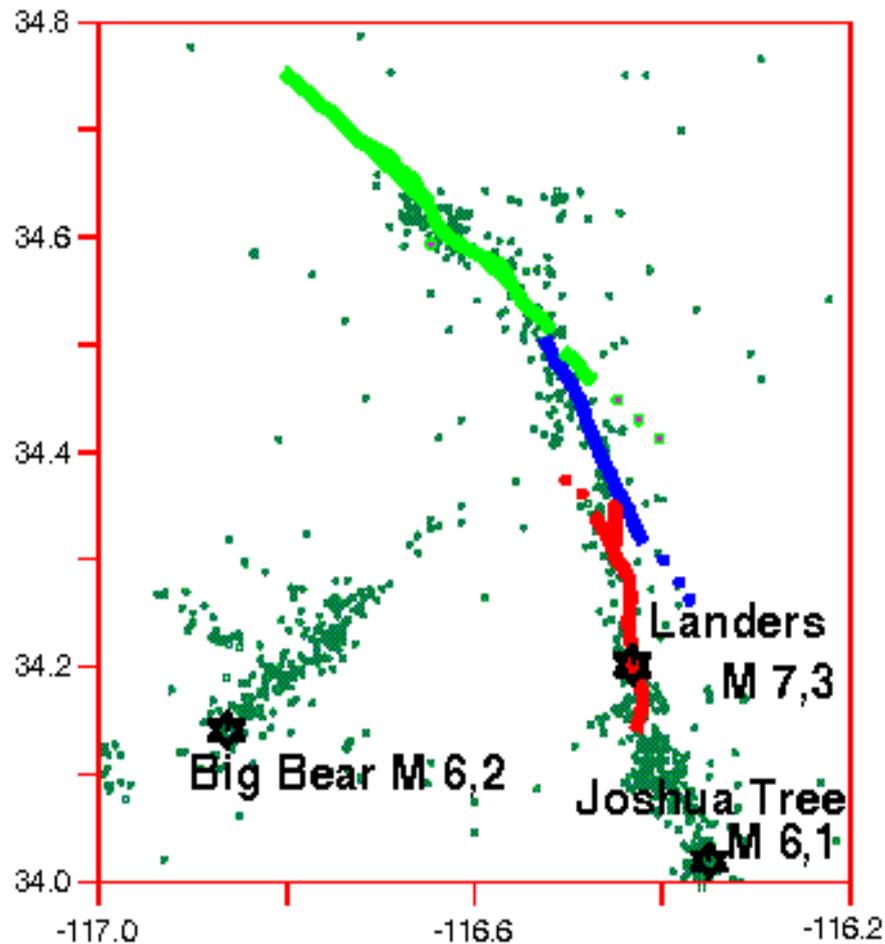
Landers earthquake



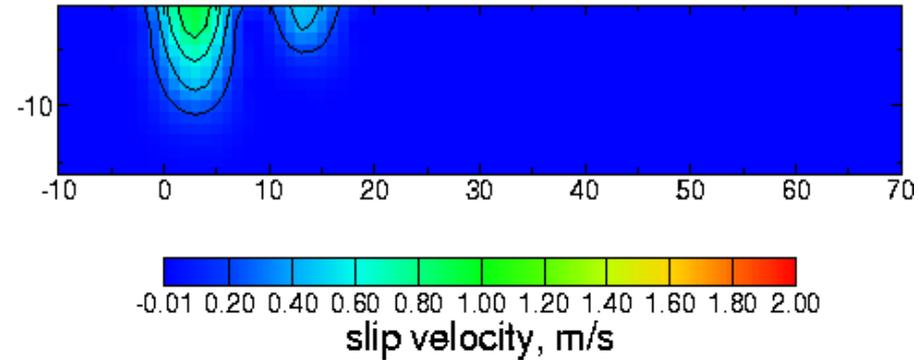
Sud 0 s Nord



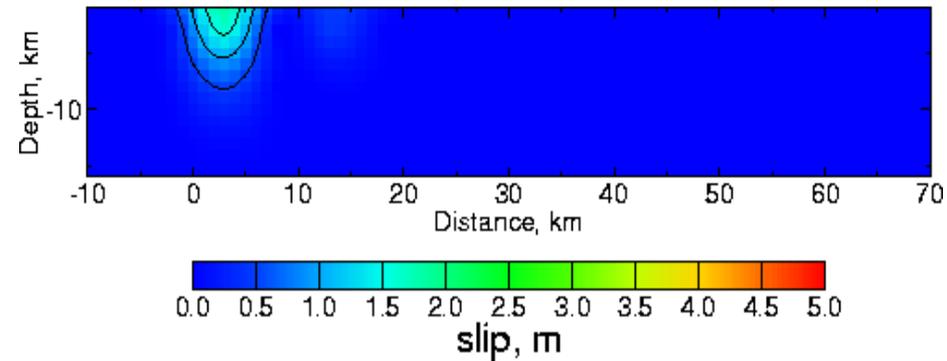
## Propagation de la rupture sismique



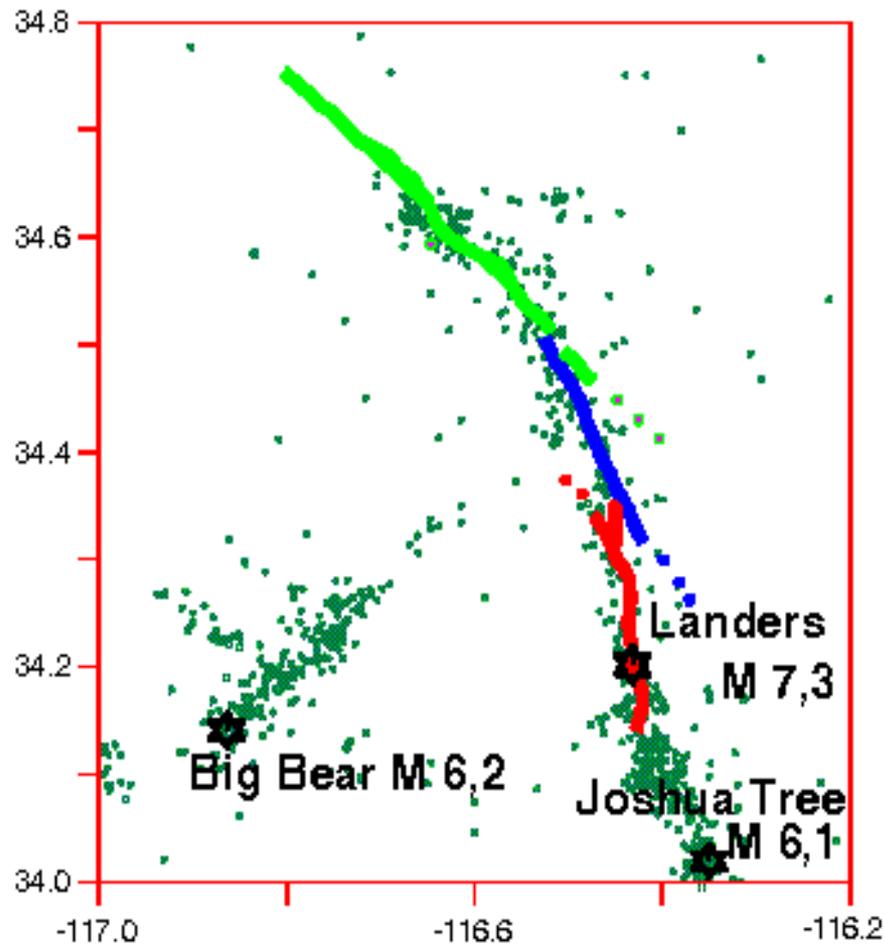
Landers earthquake



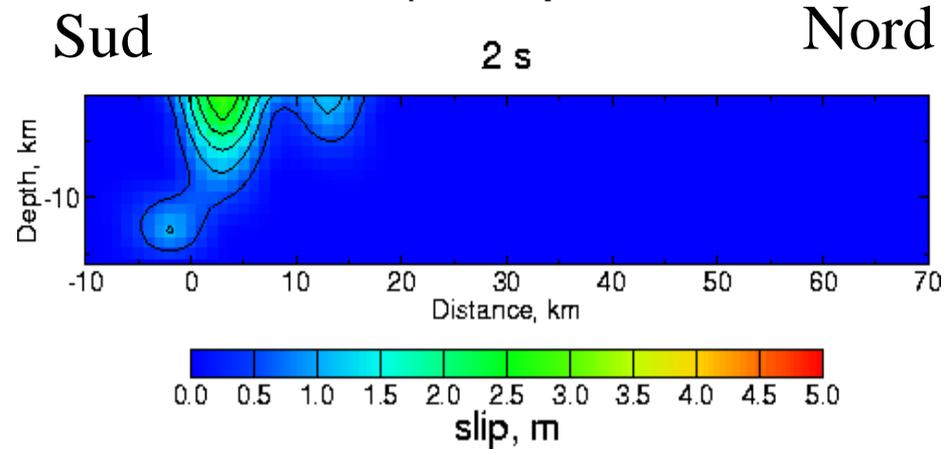
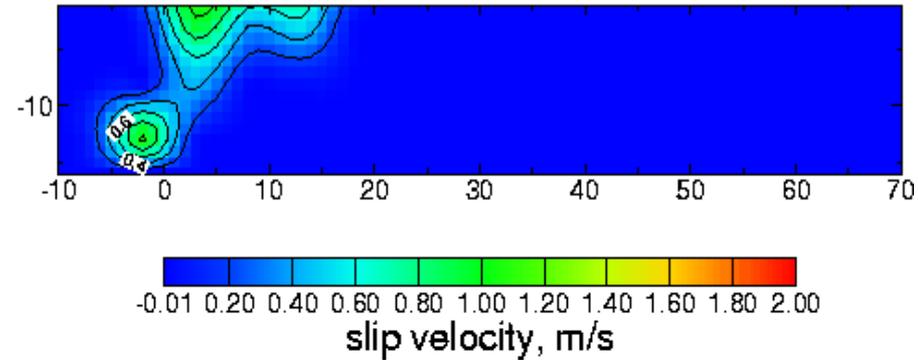
Sud 1 s Nord



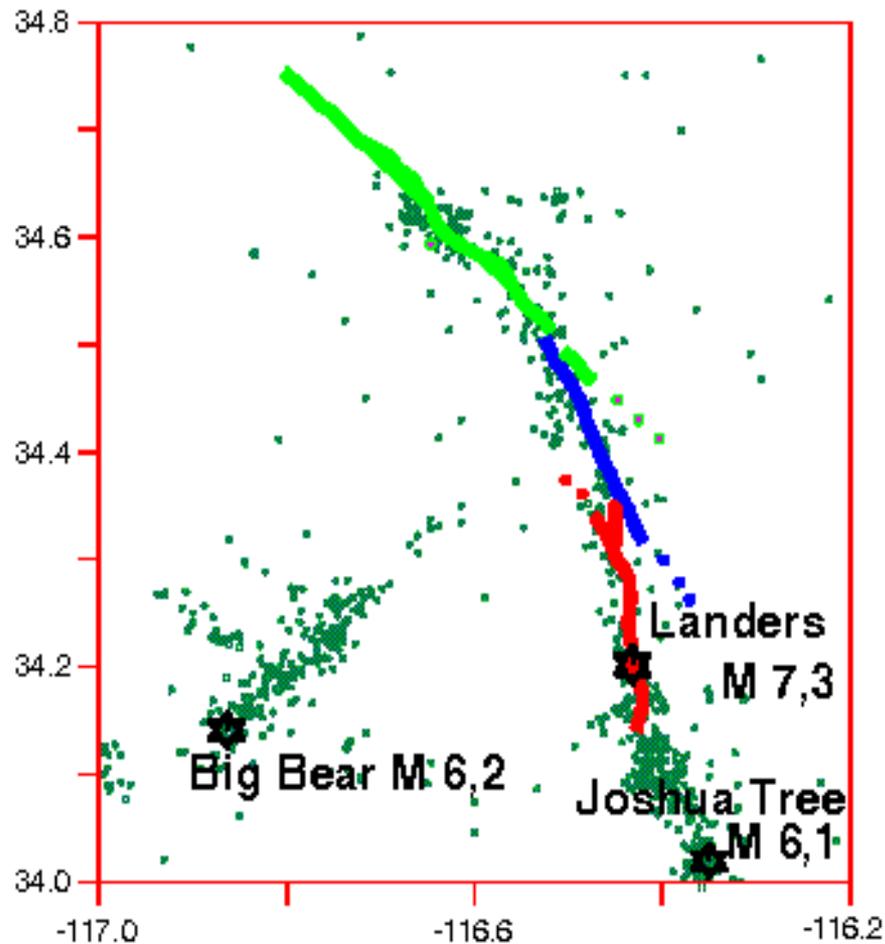
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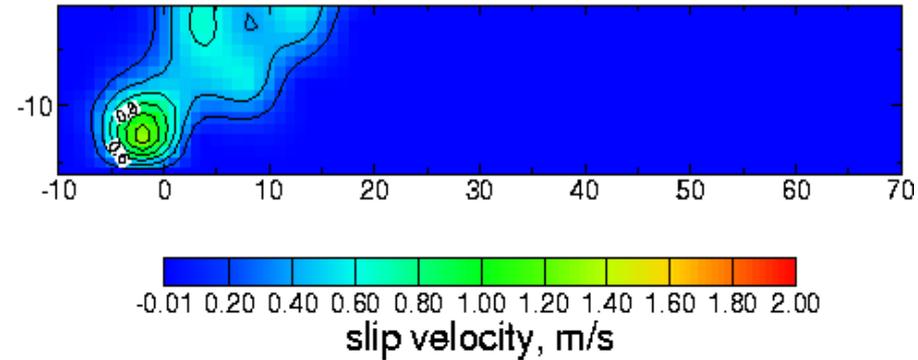
Landers earthquake



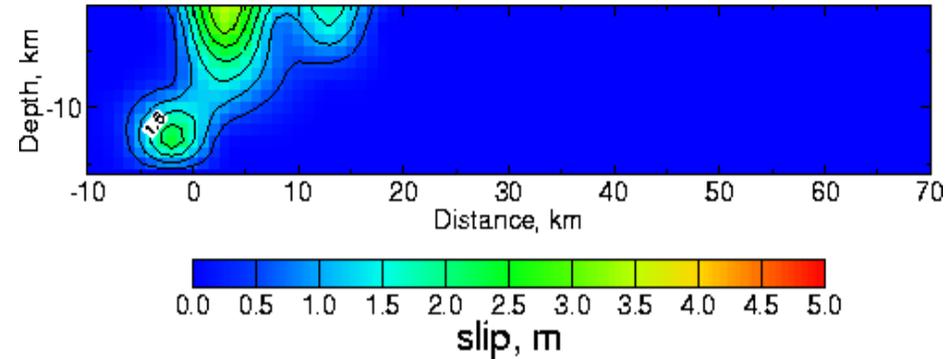
## Propagation de la rupture sismique



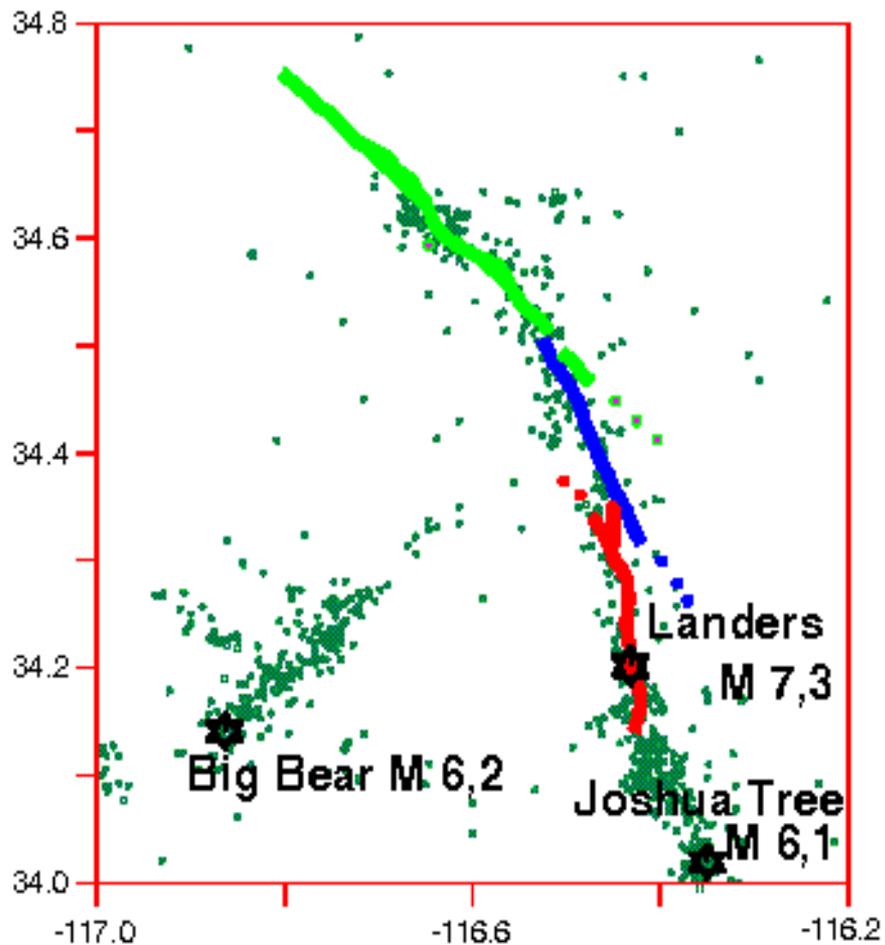
Landers earthquake



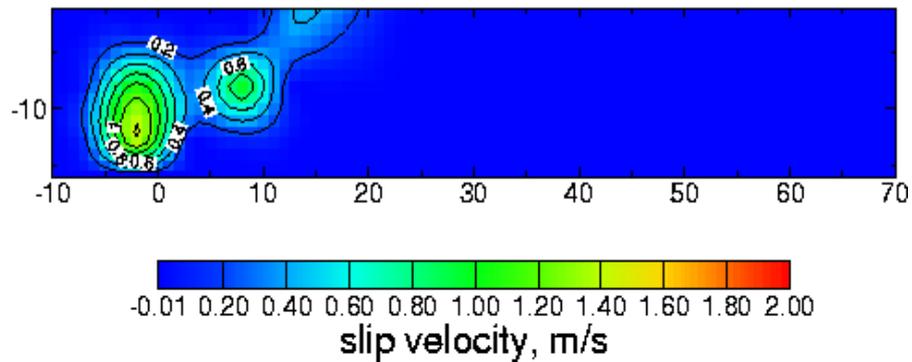
Sud Nord  
3 s



## Propagation de la rupture sismique



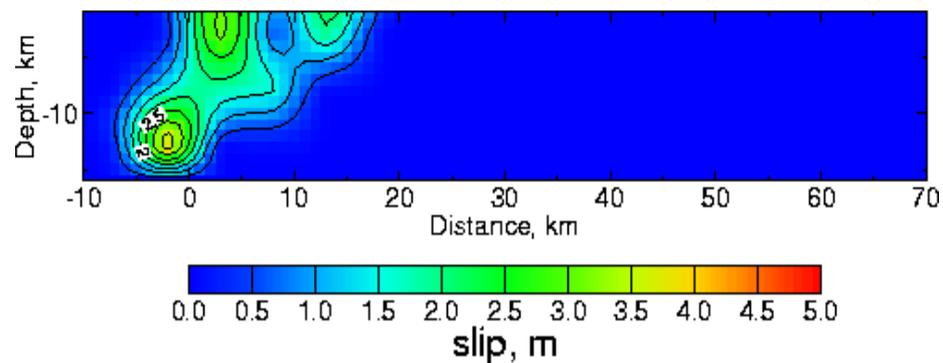
Landers earthquake



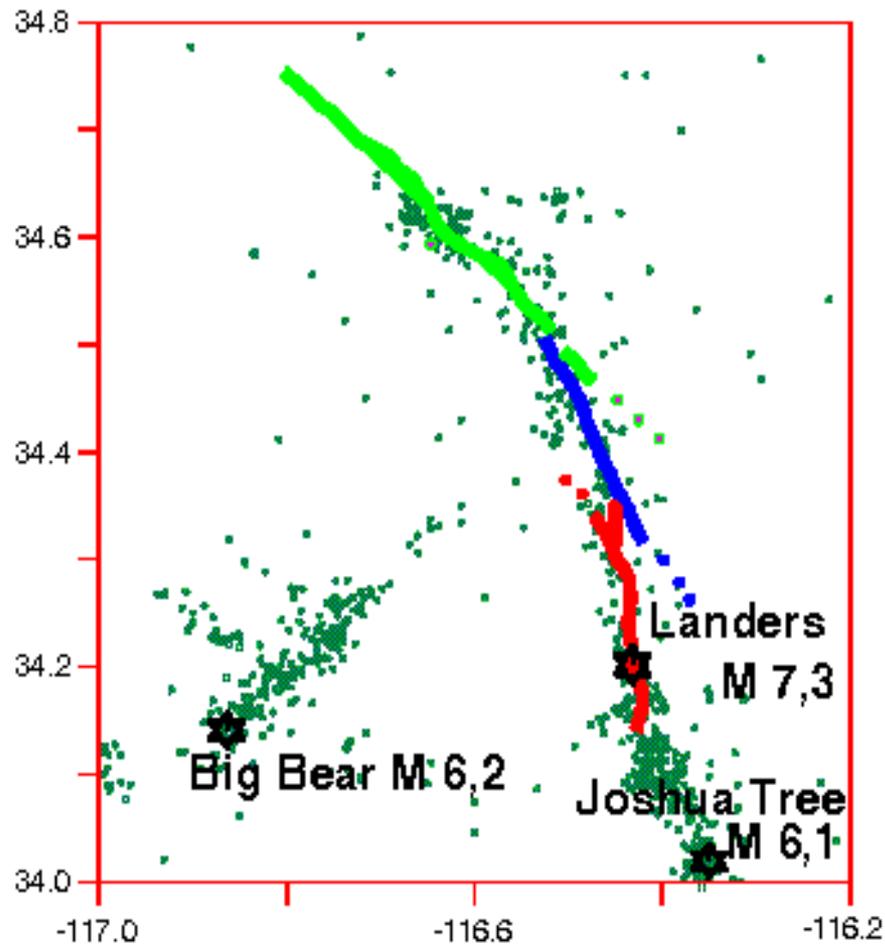
Sud

4 s

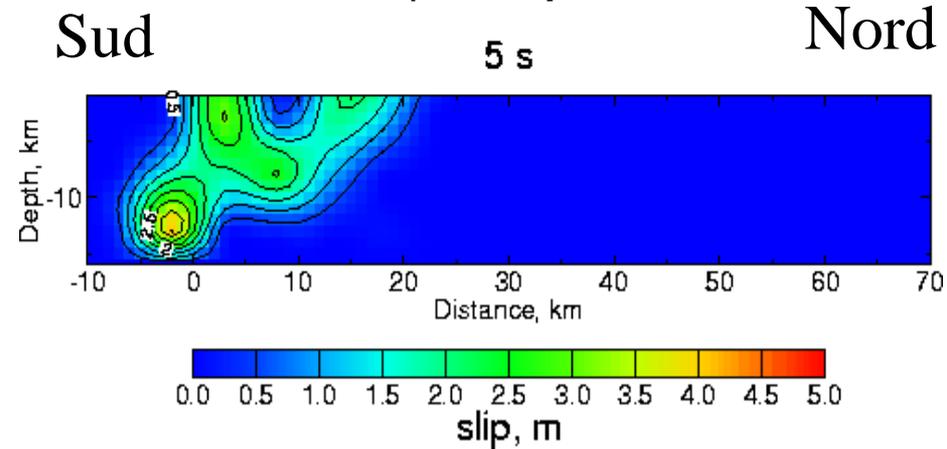
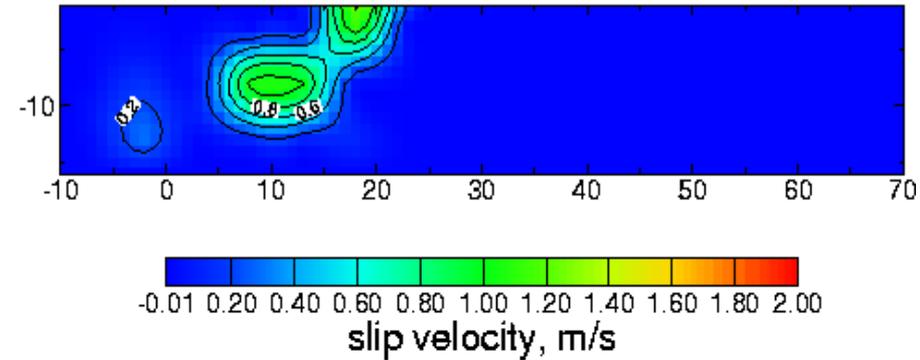
Nord



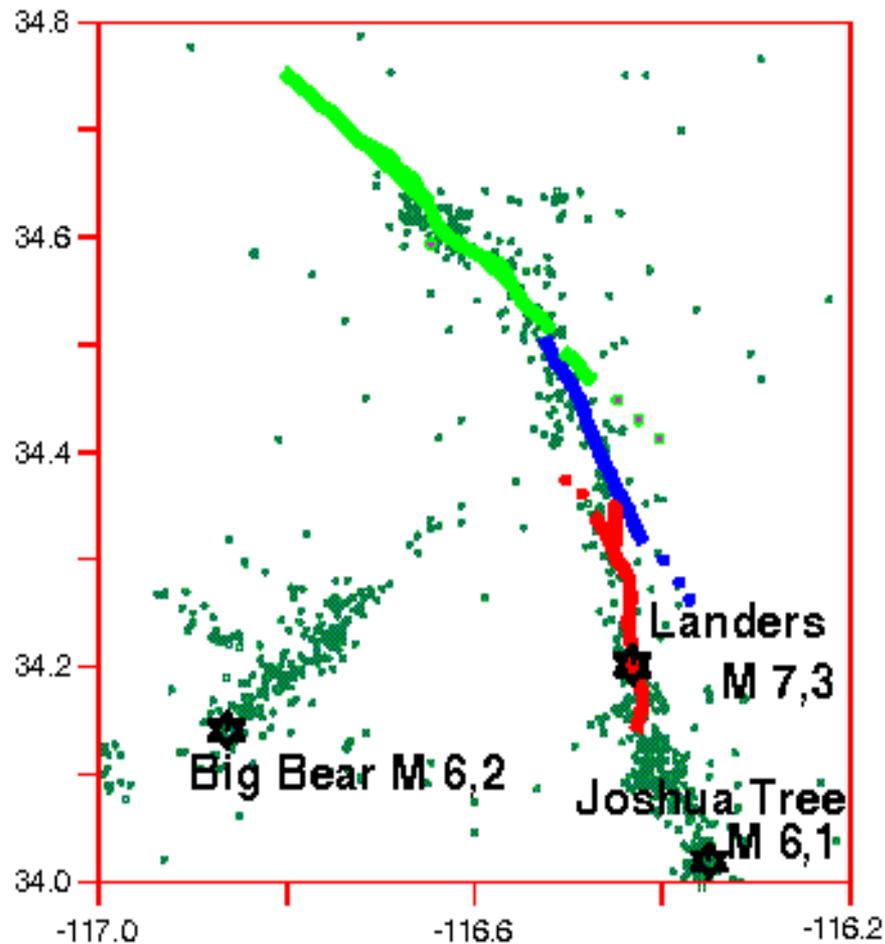
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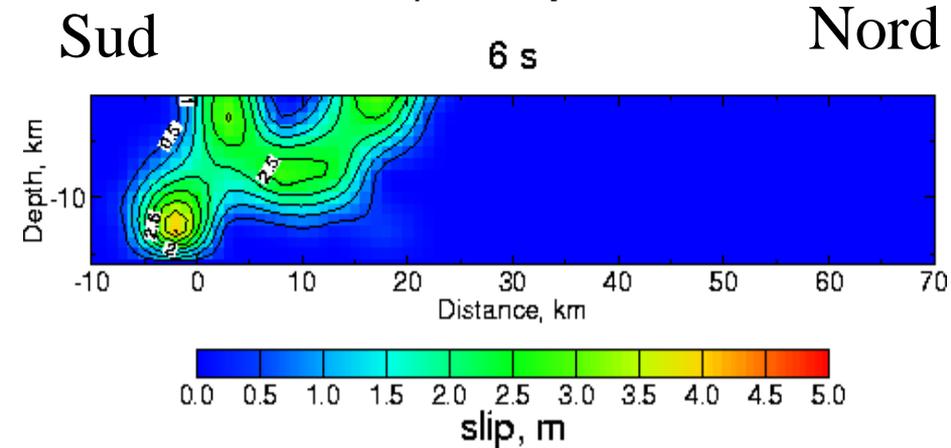
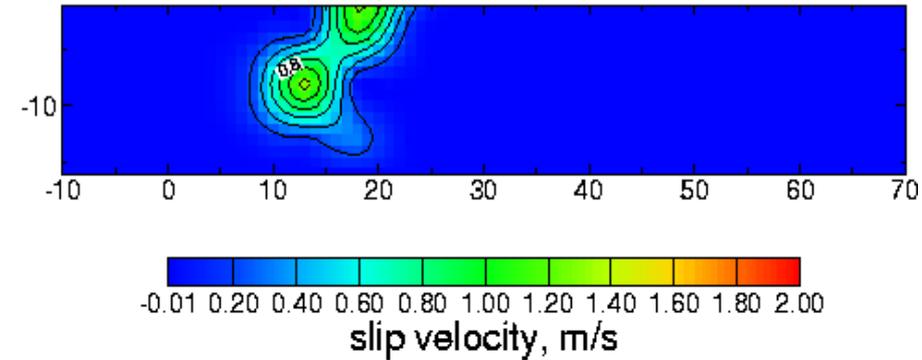
Landers earthquake



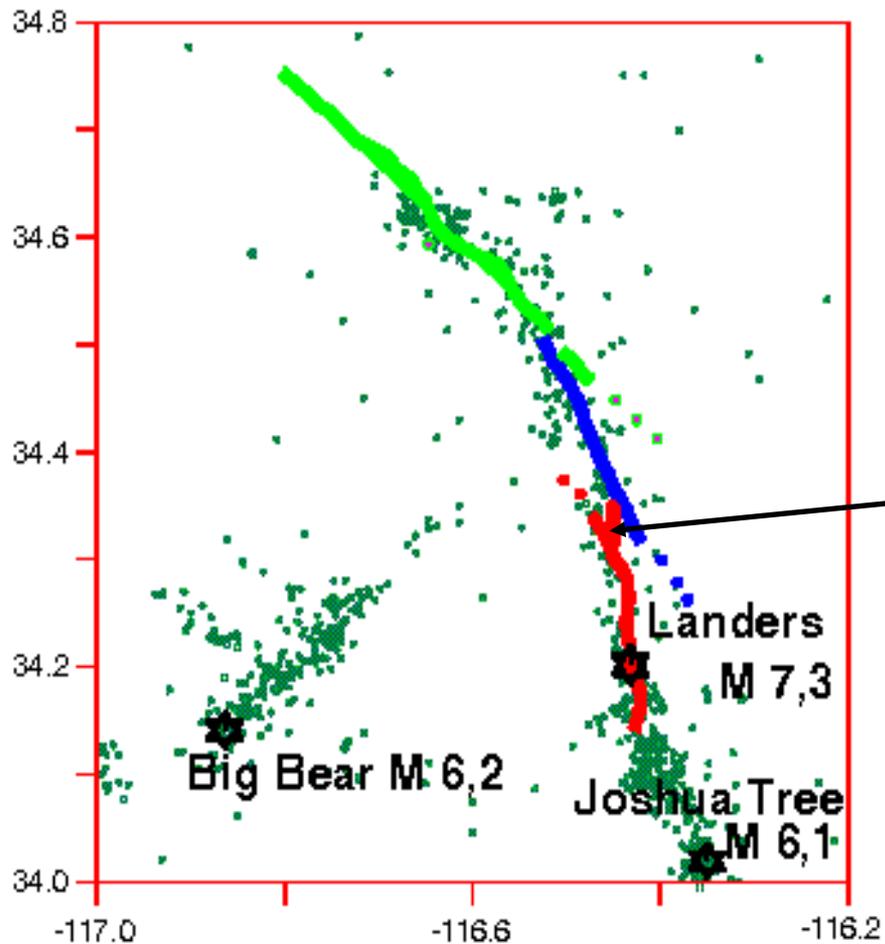
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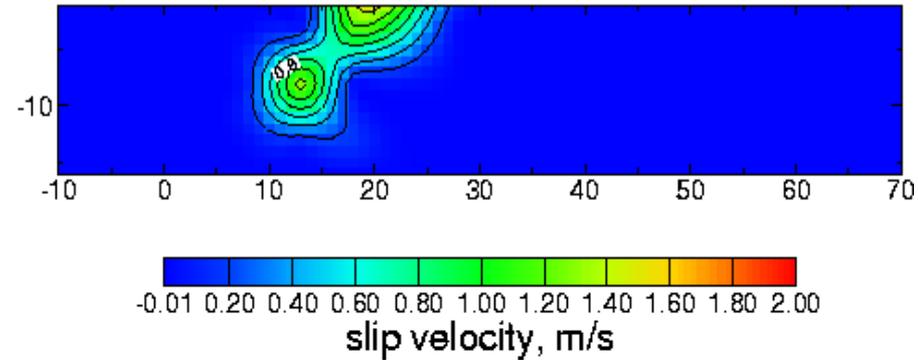
Landers earthquake



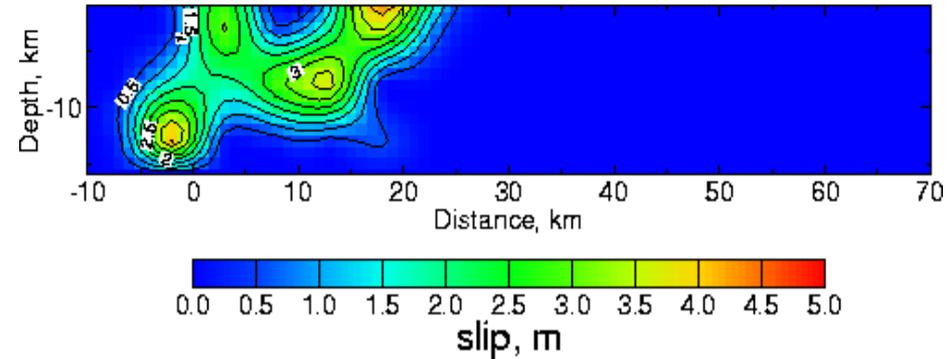
## Propagation de la rupture sismique



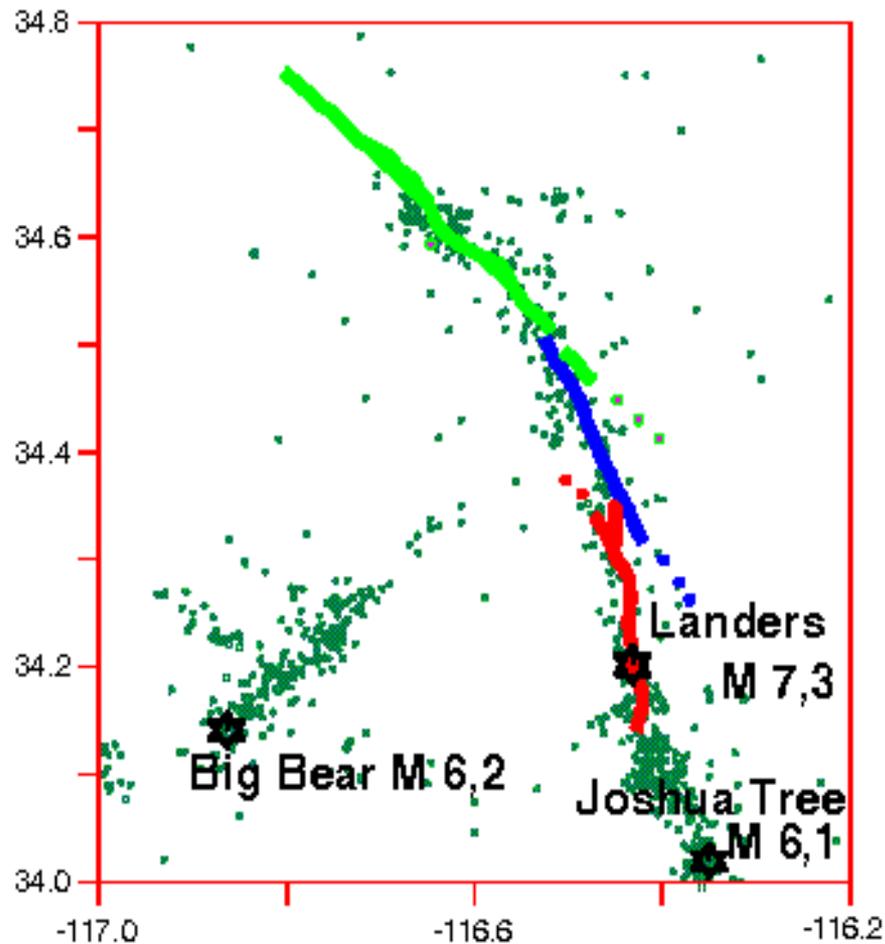
Landers earthquake



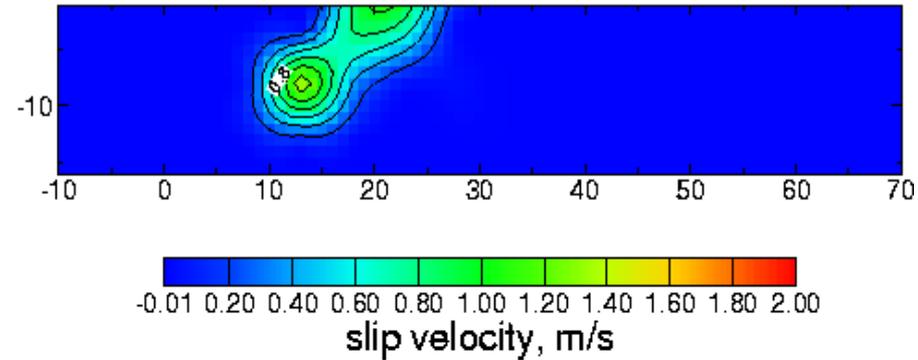
Sud Nord  
7 s



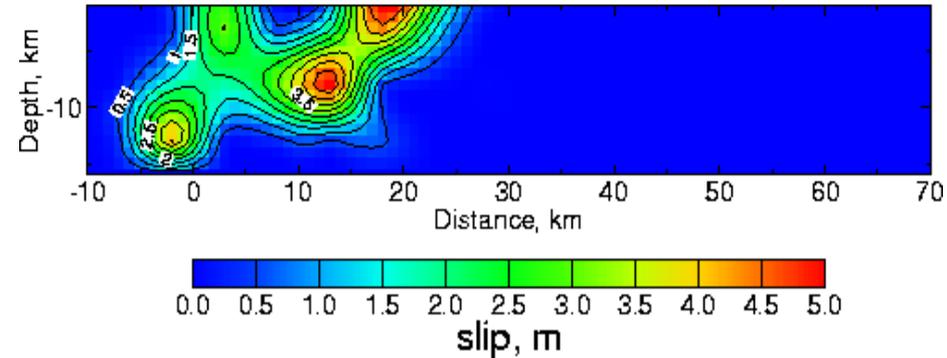
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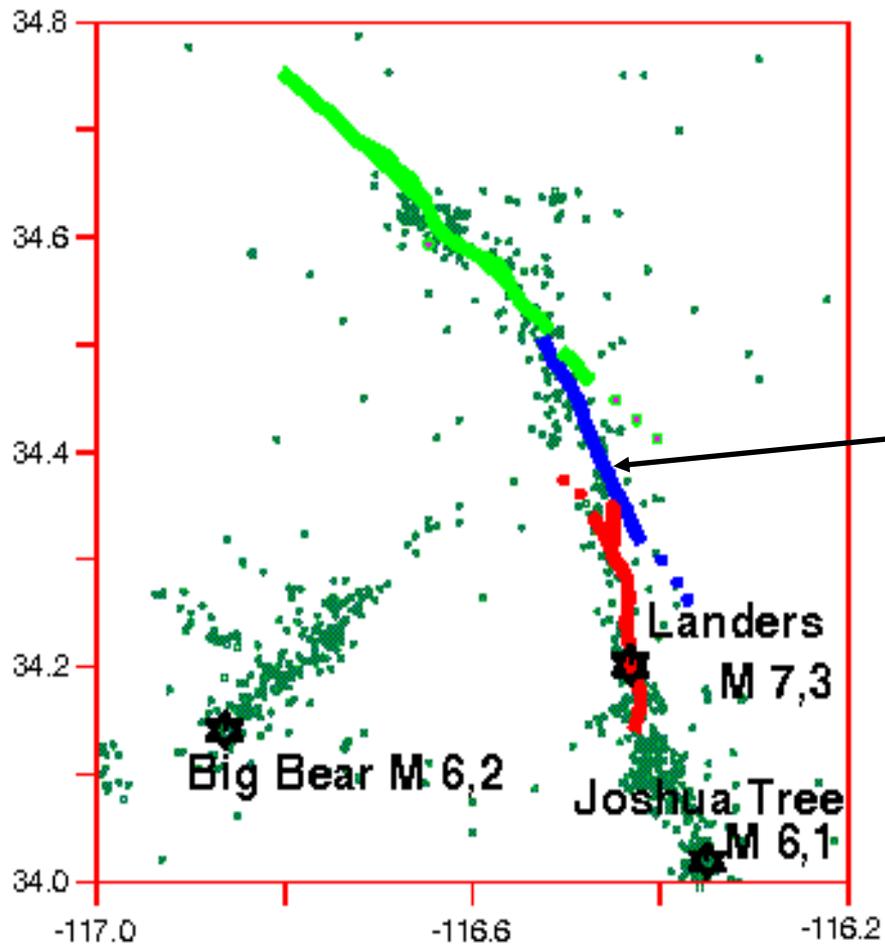
Landers earthquake



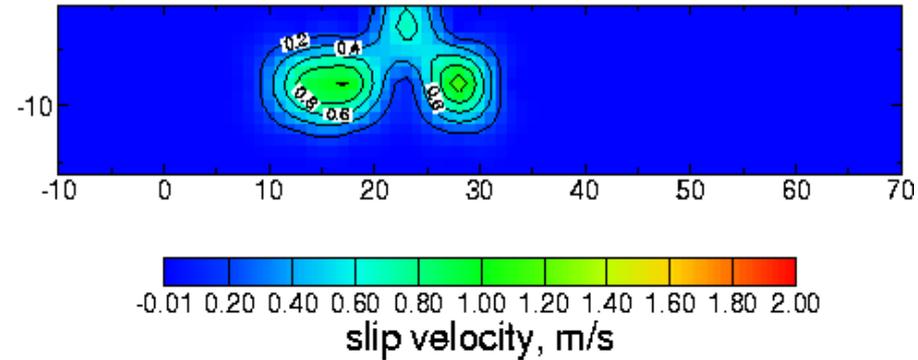
Sud 8 s Nord



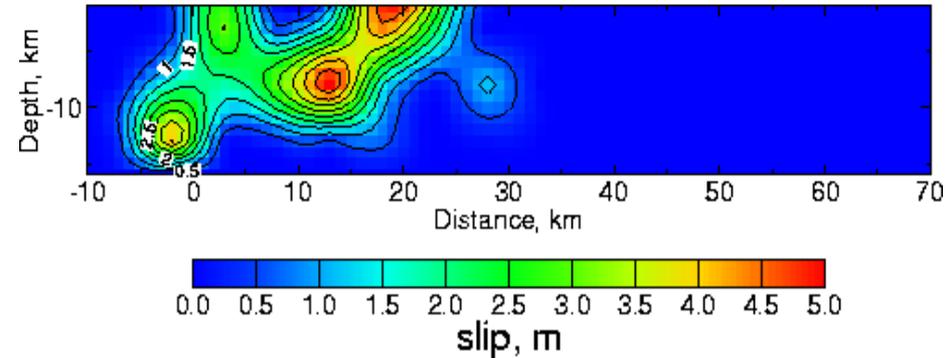
## Propagation de la rupture sismique



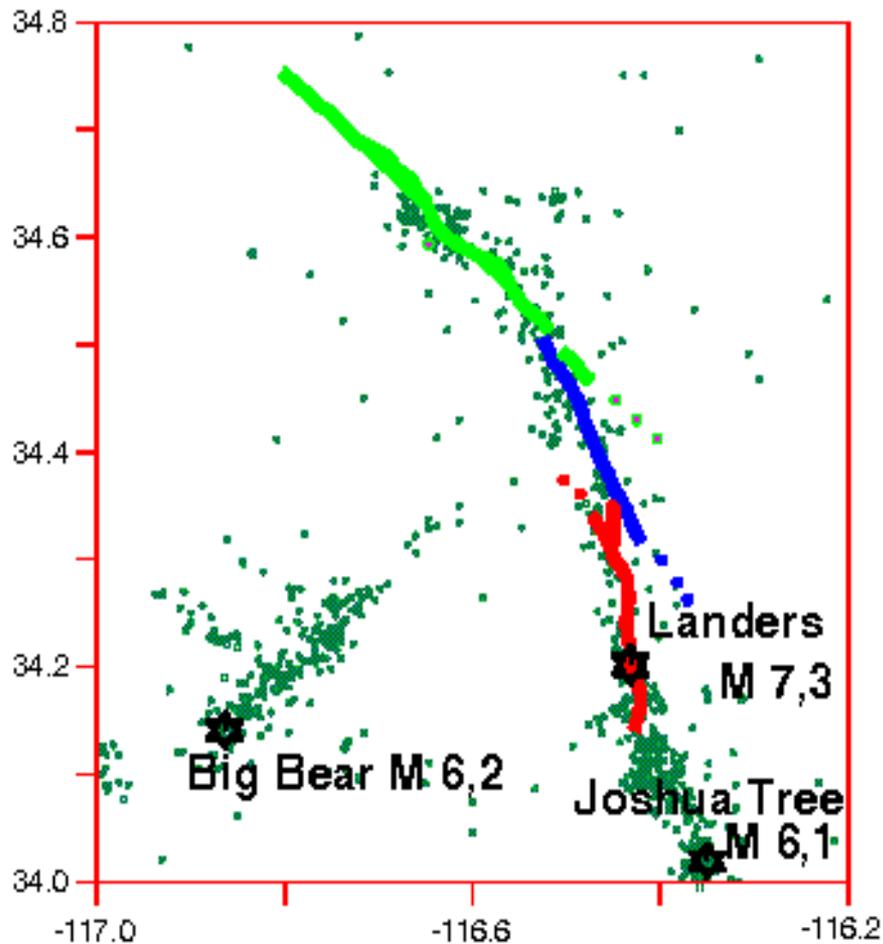
Landers earthquake



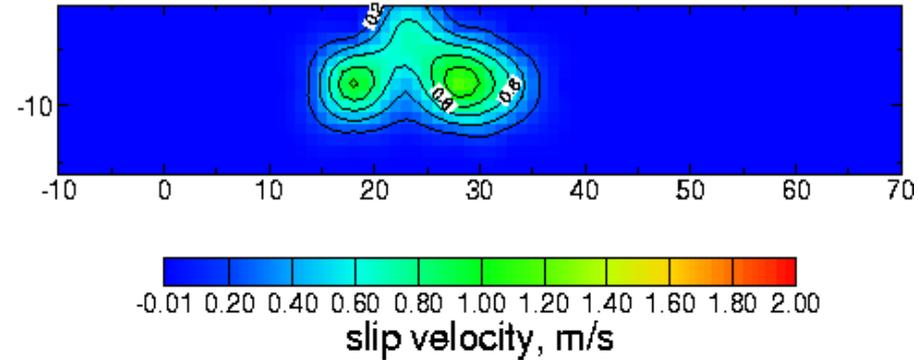
Sud Nord  
9 s



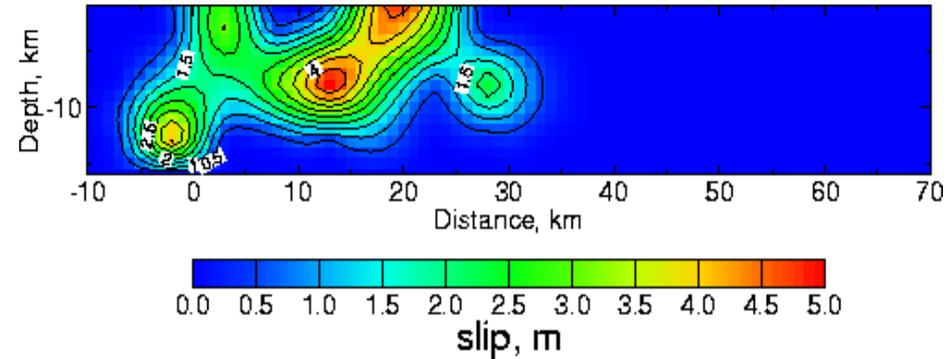
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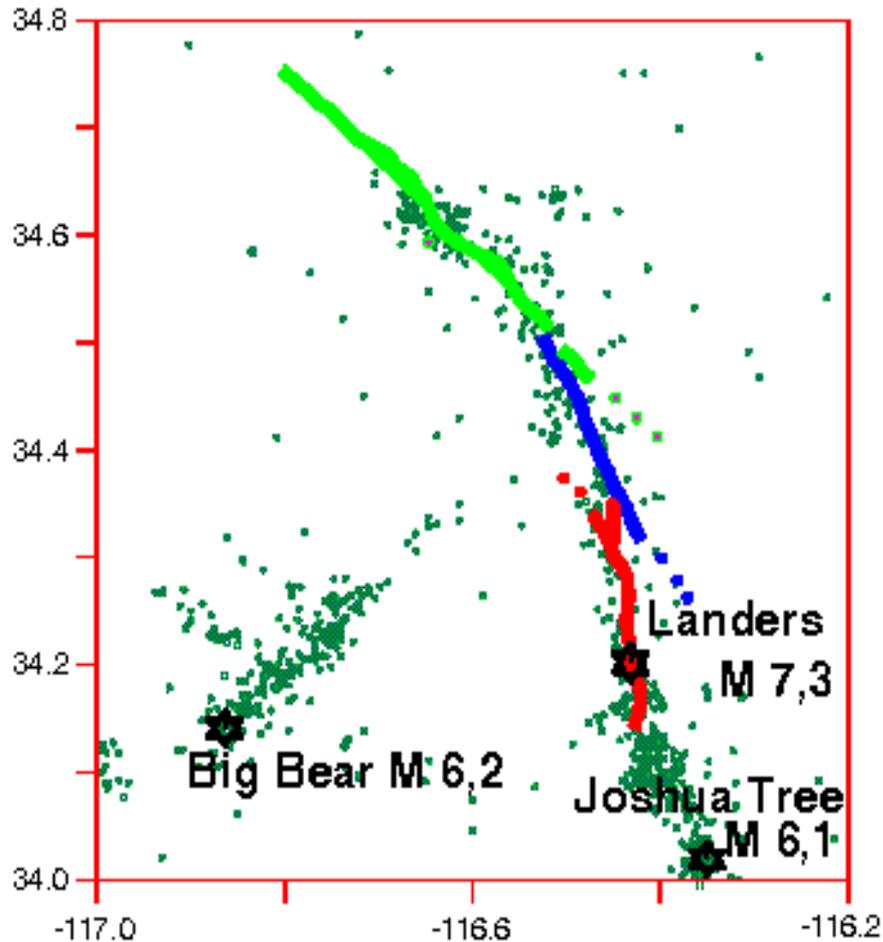
Landers earthquake



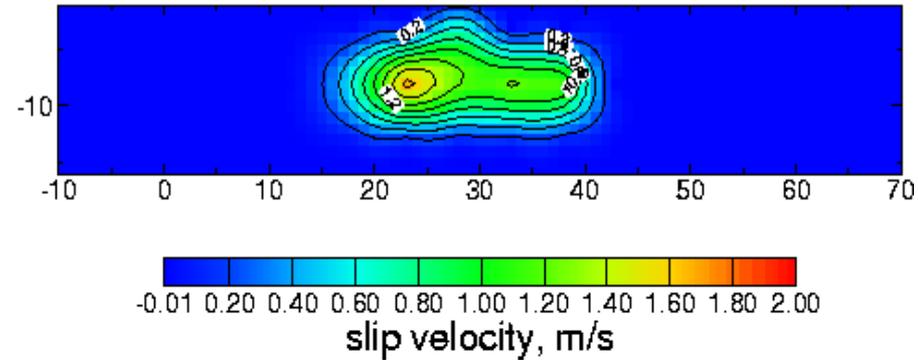
Sud 10 s Nord



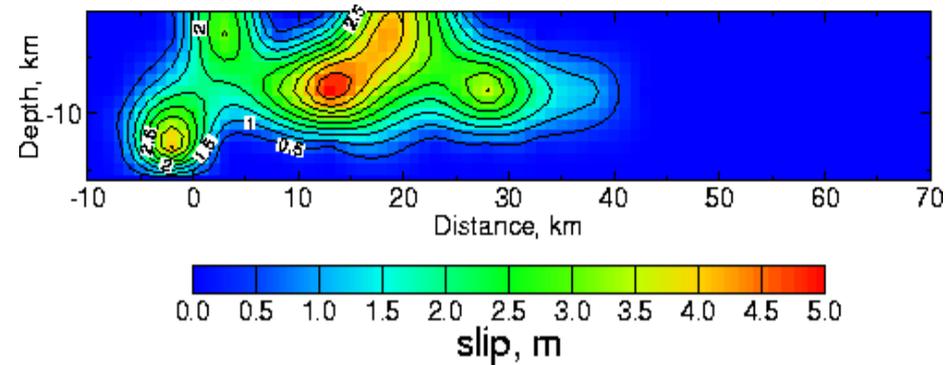
## Propagation de la rupture sismique



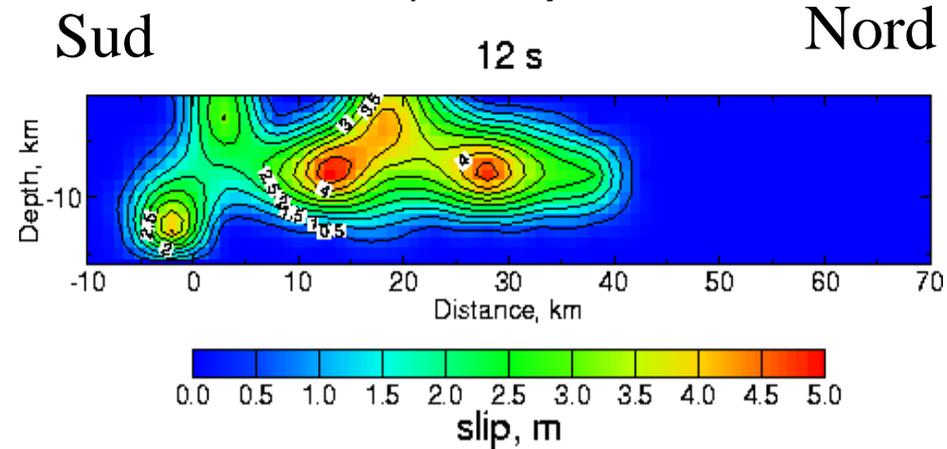
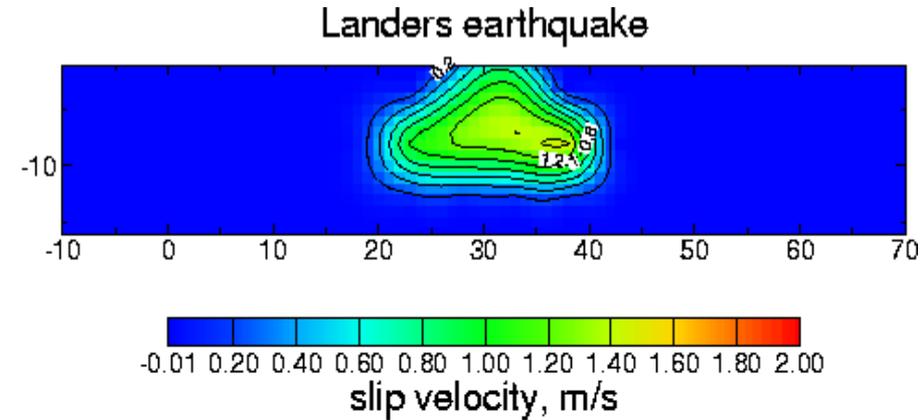
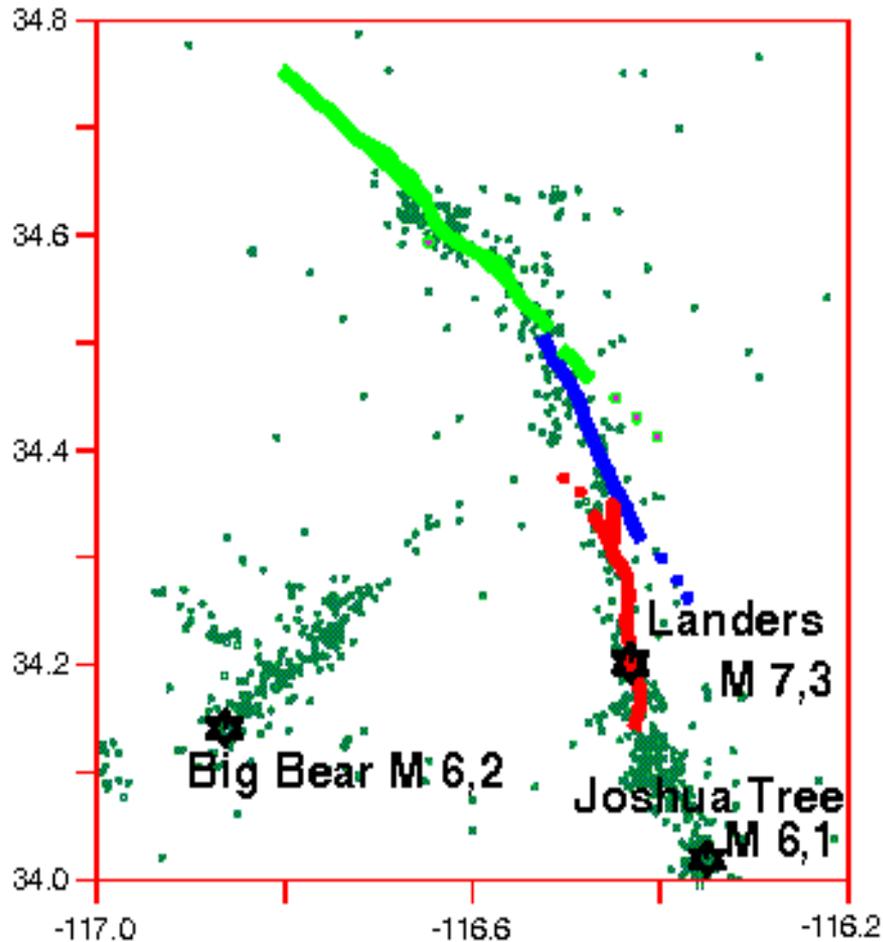
Landers earthquake



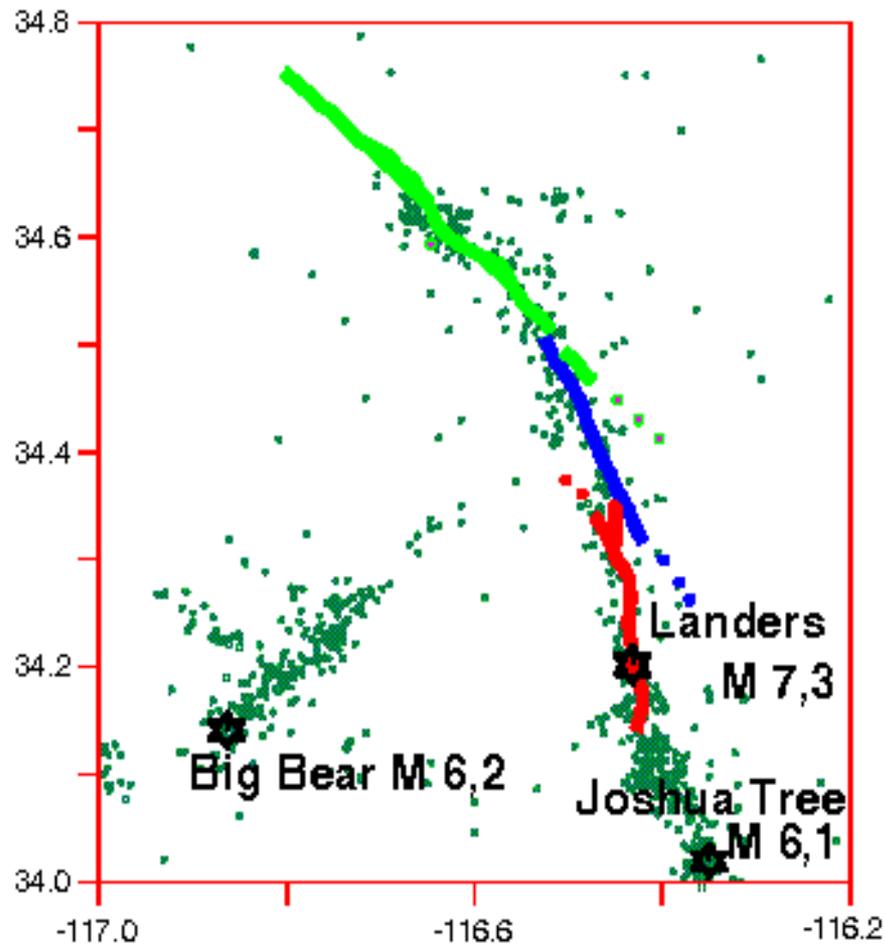
Sud 11 s Nord



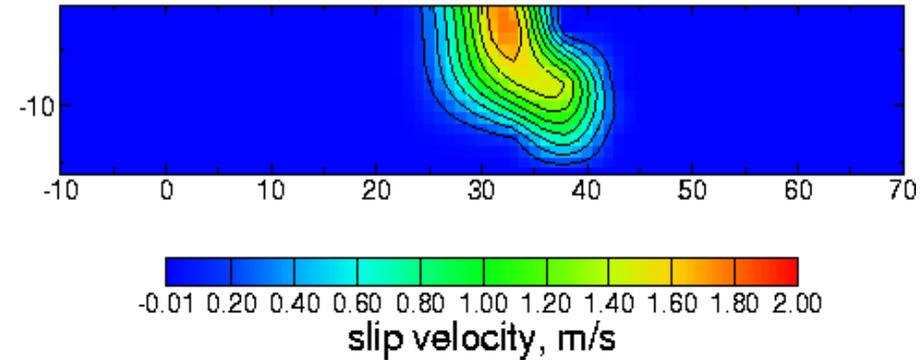
## Propagation de la rupture sismique



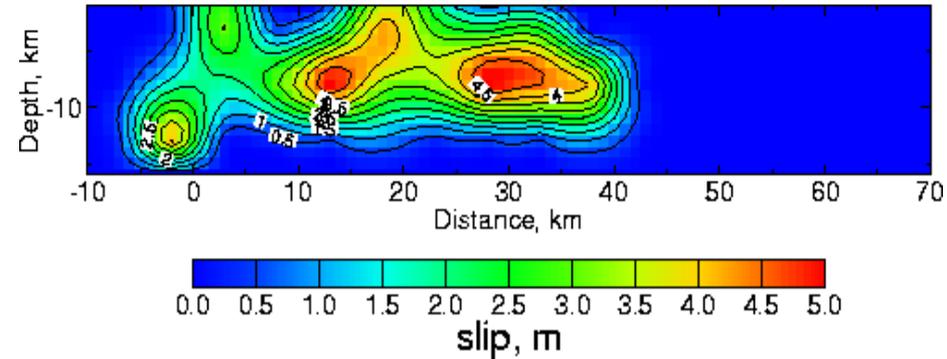
## Propagation de la rupture sismique



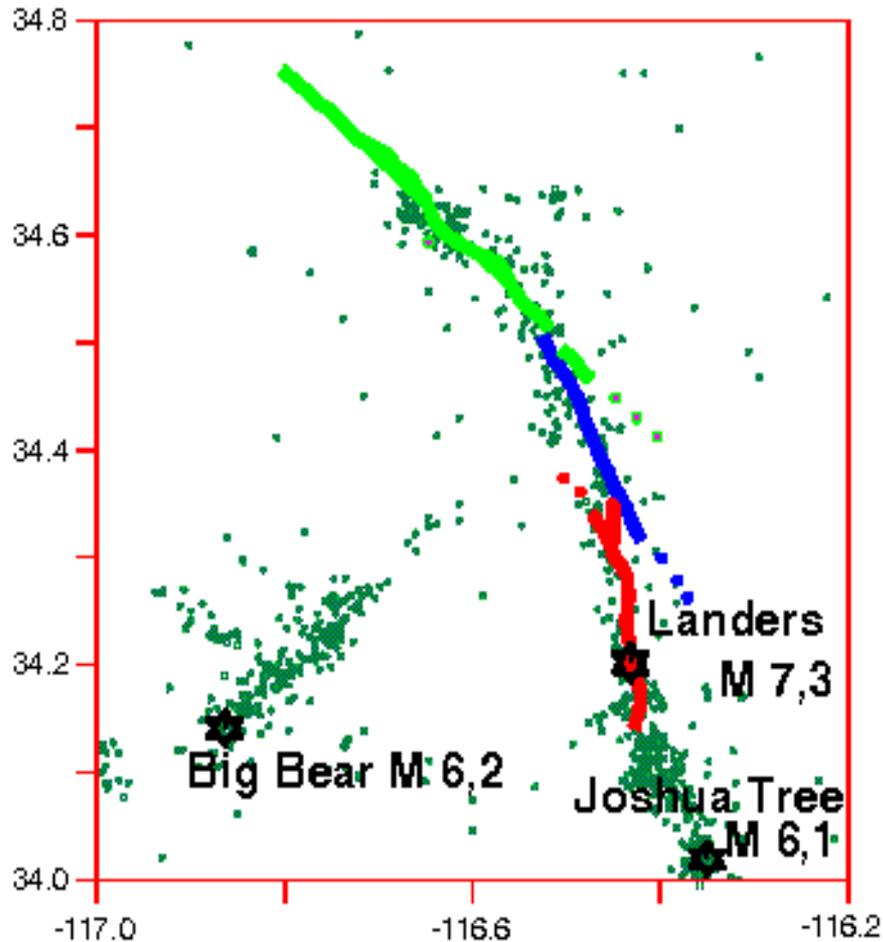
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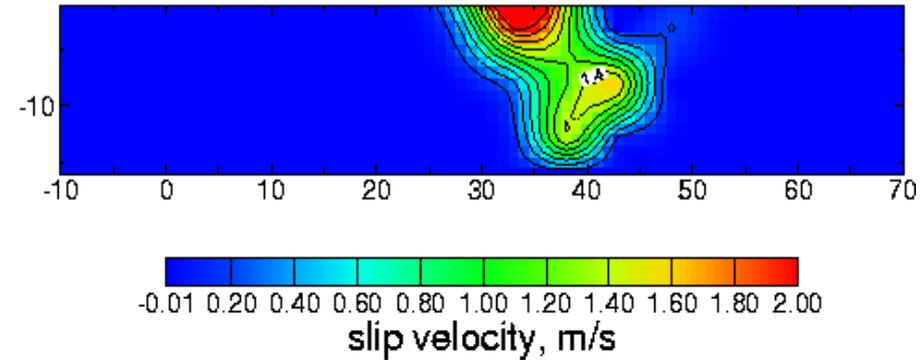
Sud 13 s Nord



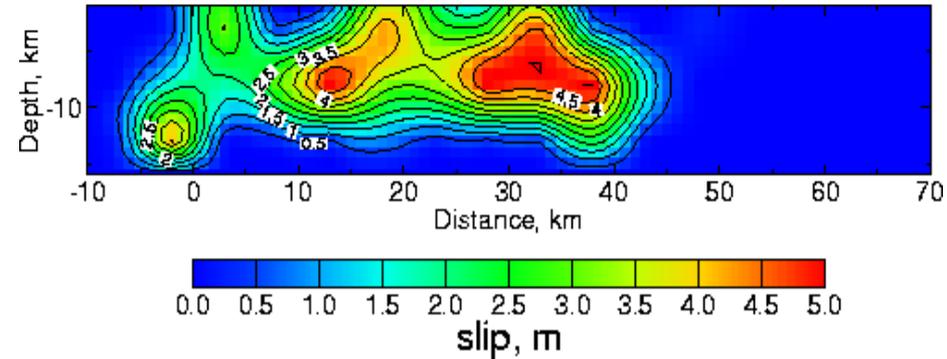
## Propagation de la rupture sismique



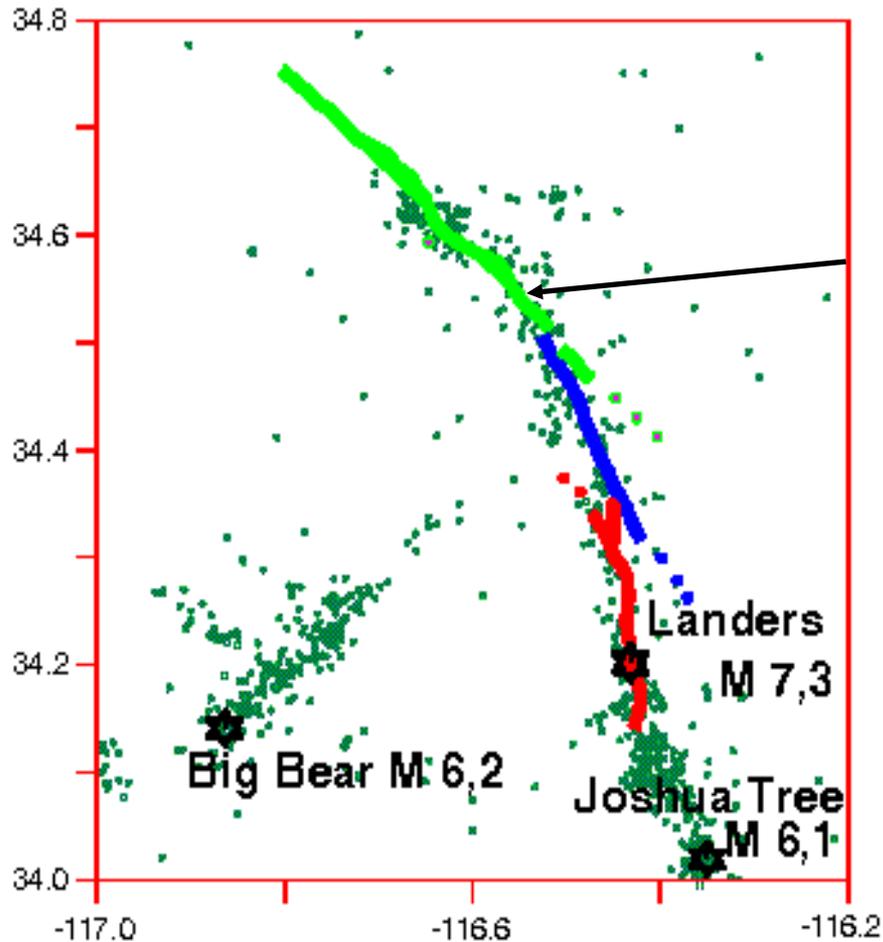
Landers earthquake



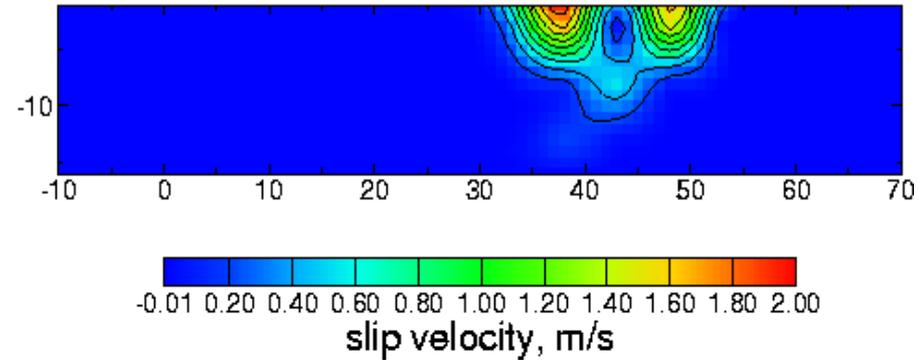
Sud 14 s Nord



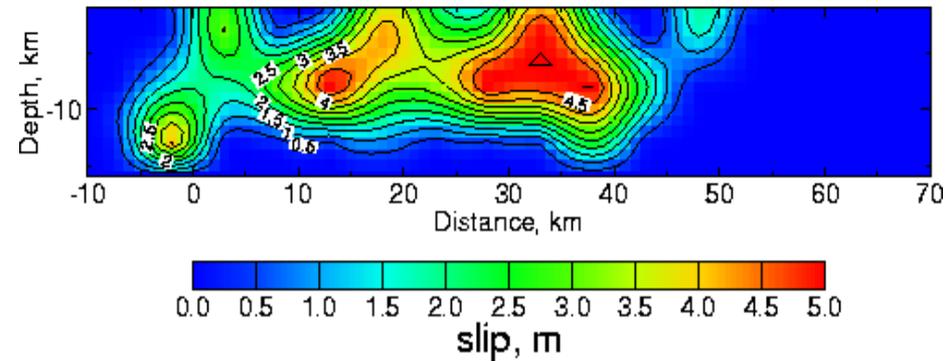
## Propagation de la rupture sismique



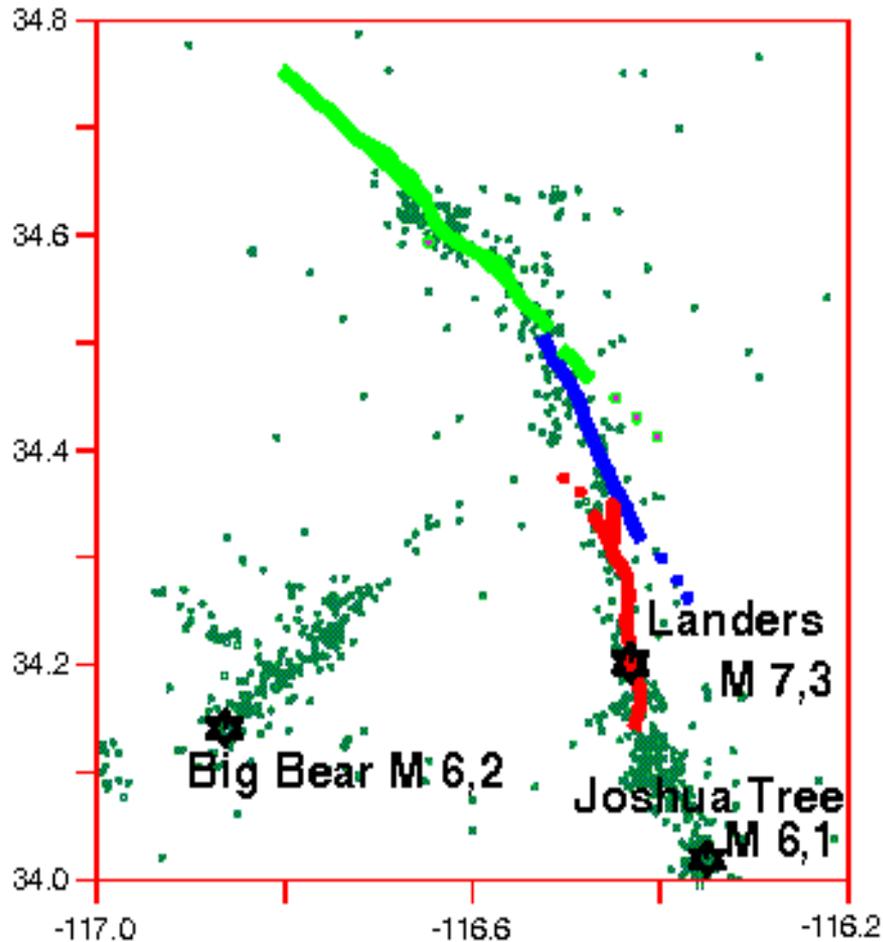
Landers earthquake



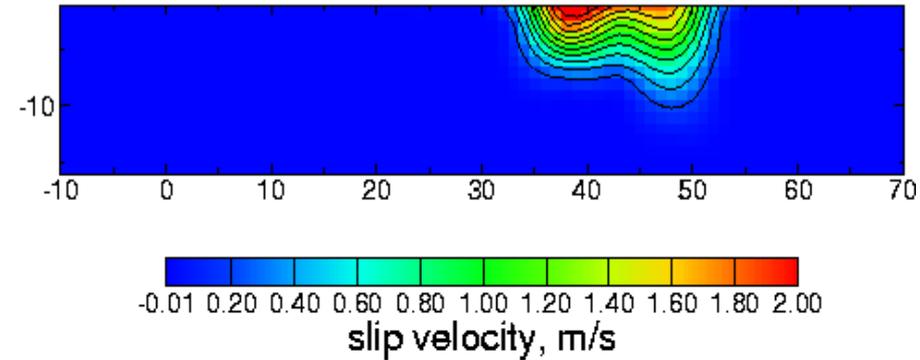
Sud Nord



## Propagation de la rupture sismique

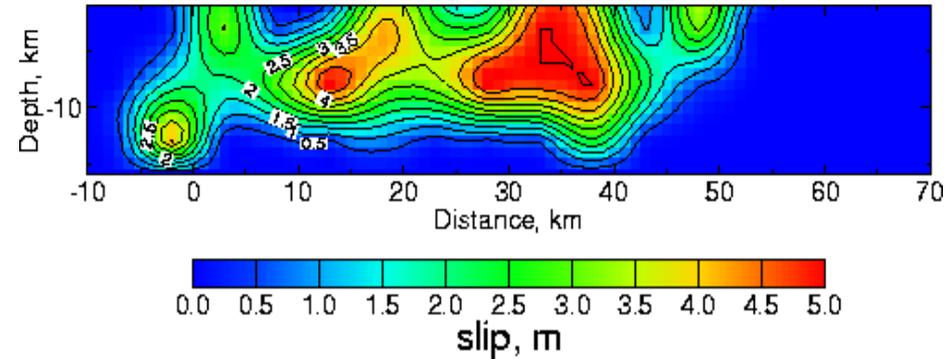


Landers earthquake

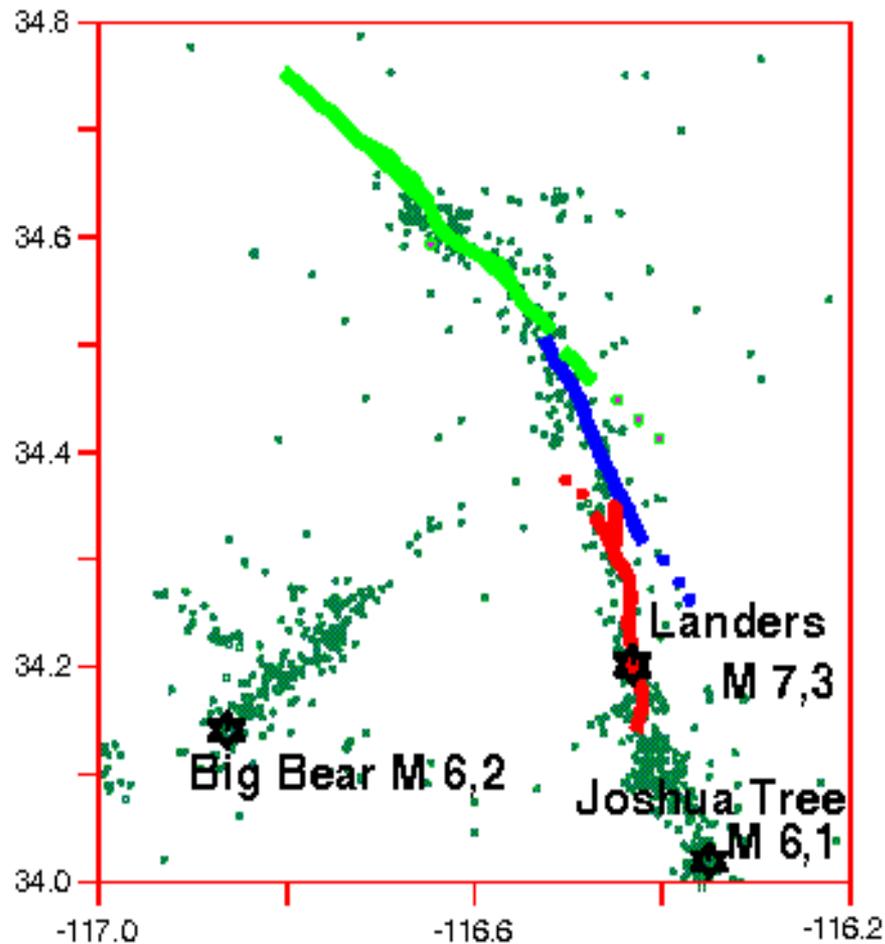


Sud Nord

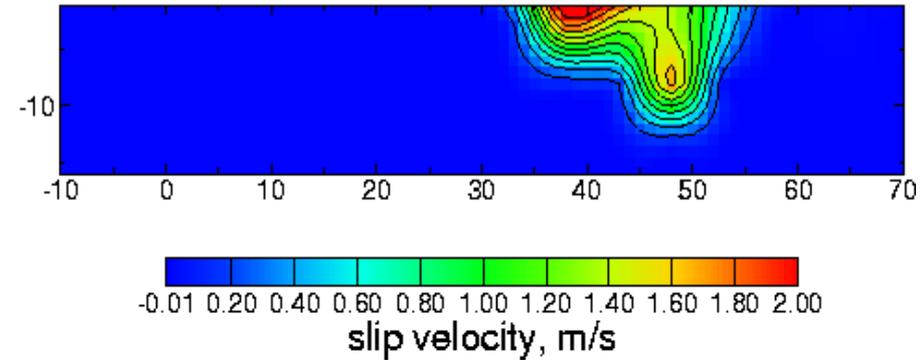
16 s



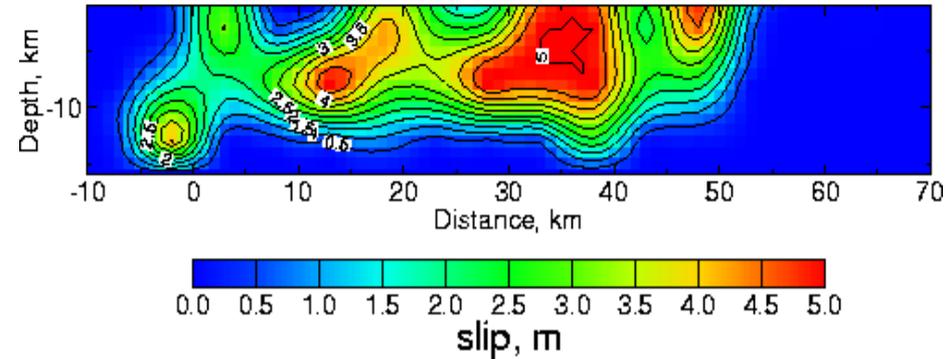
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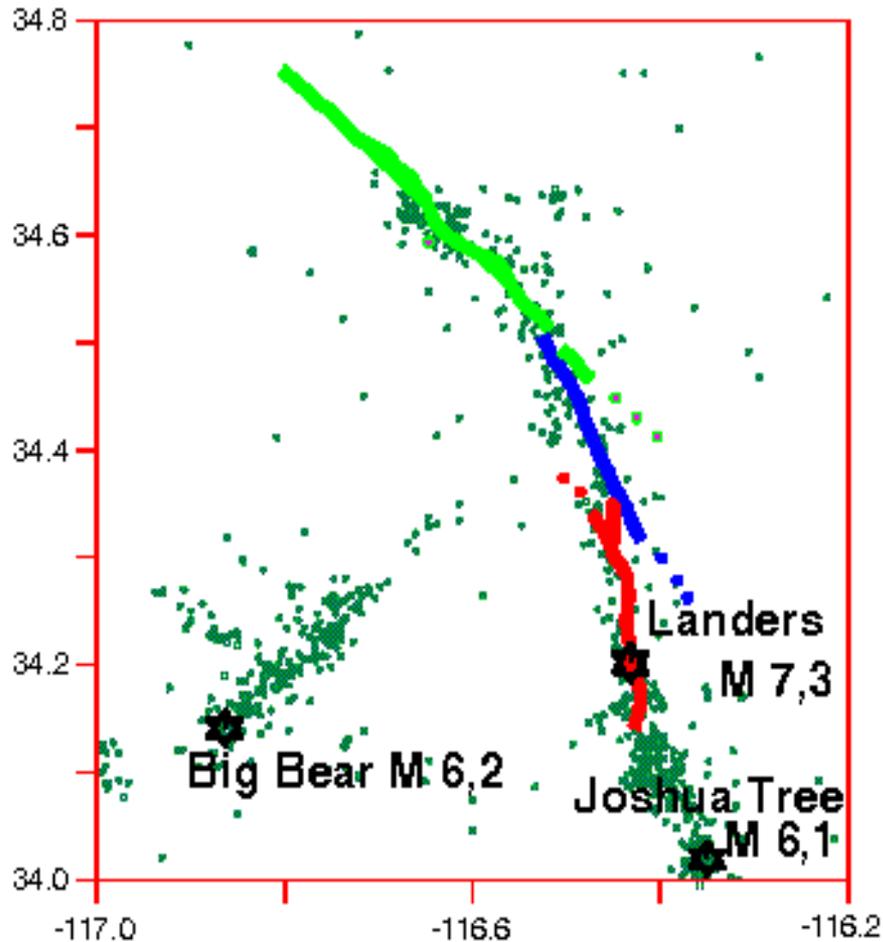
Landers earthquake



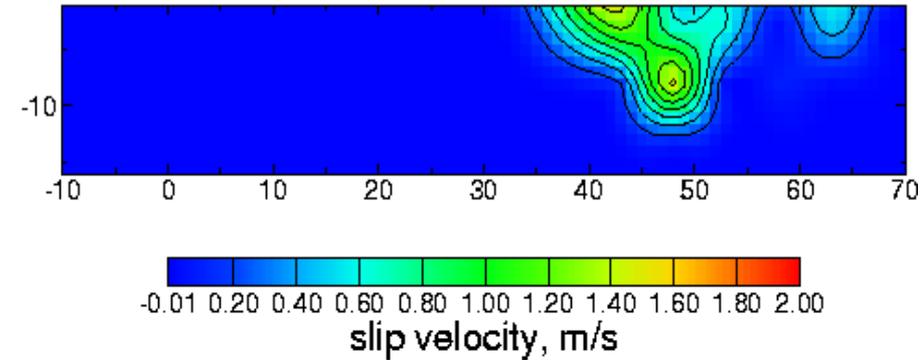
Sud 17 s Nord



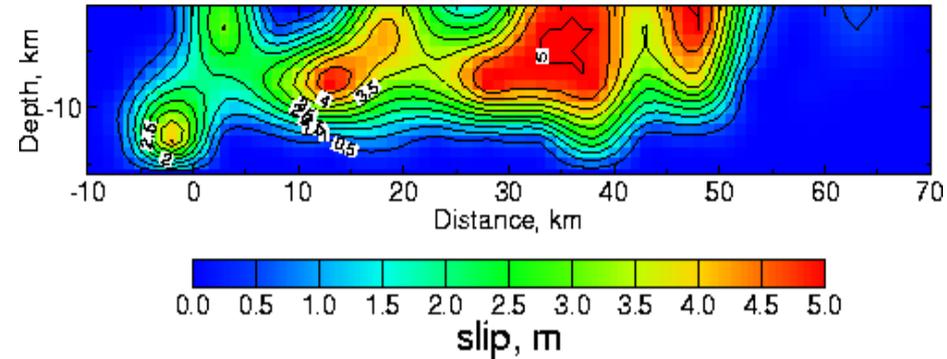
## Propagation de la rupture sismique



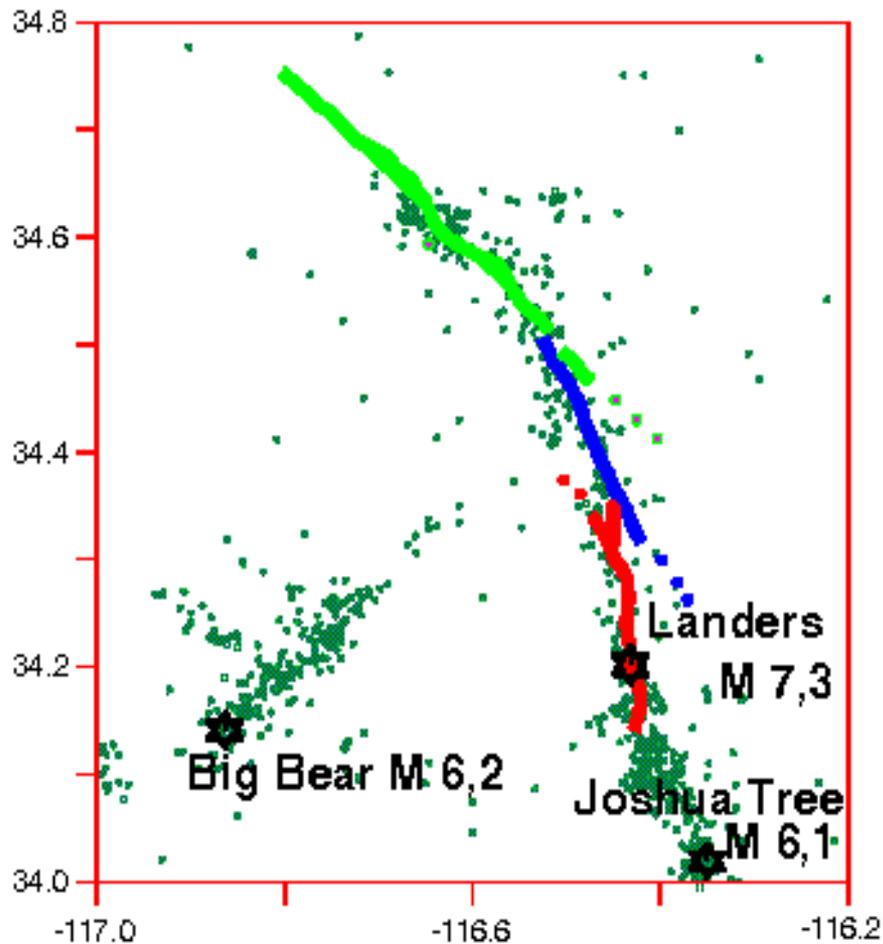
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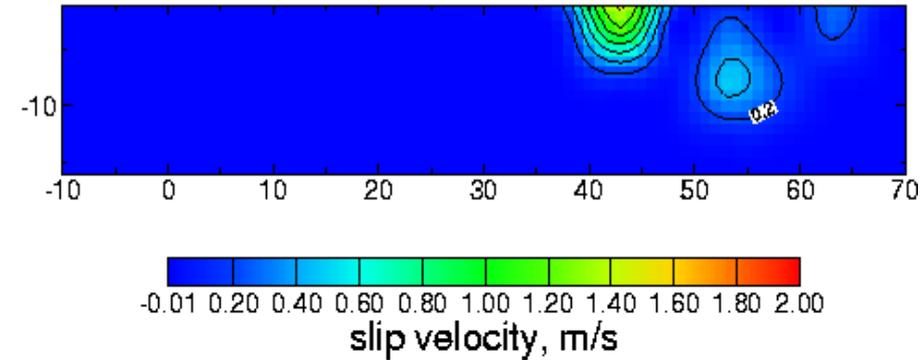
Sud 18 s Nord



## Propagation de la rupture sismique

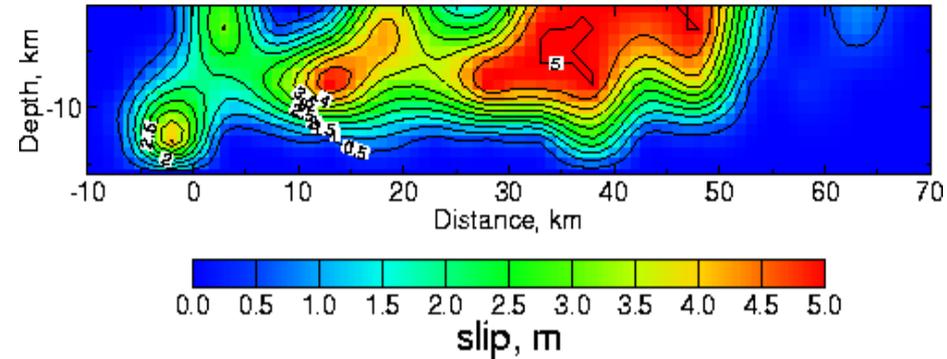


Landers earthquake

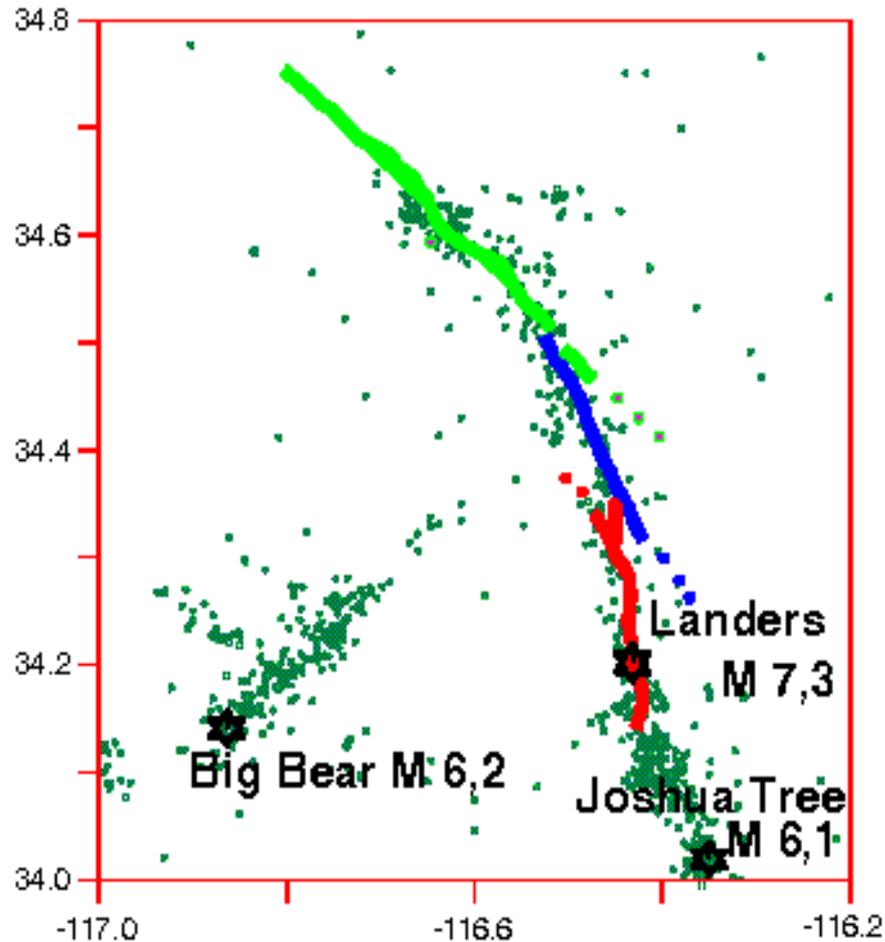


Sud Nord

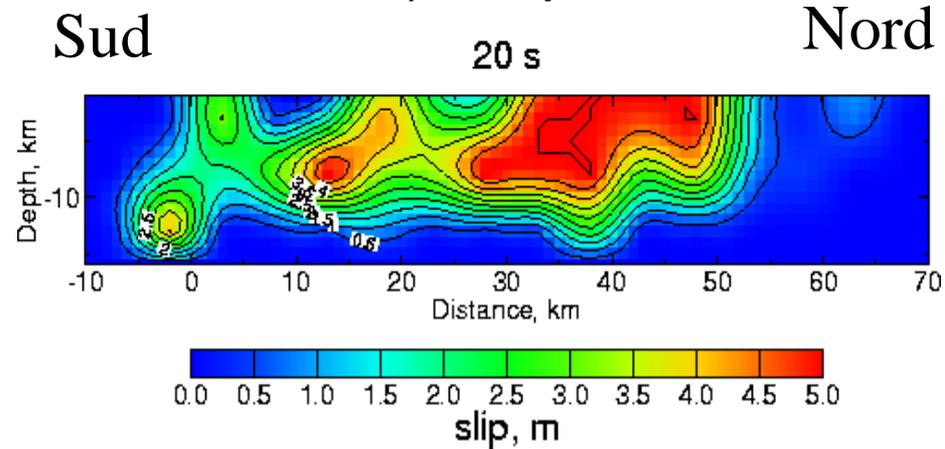
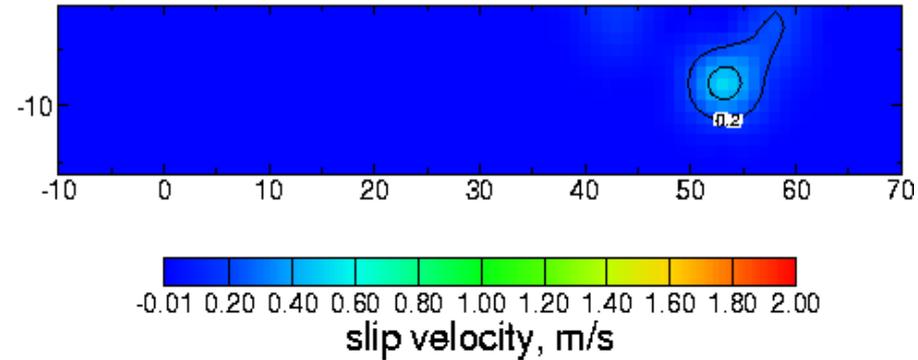
19 s



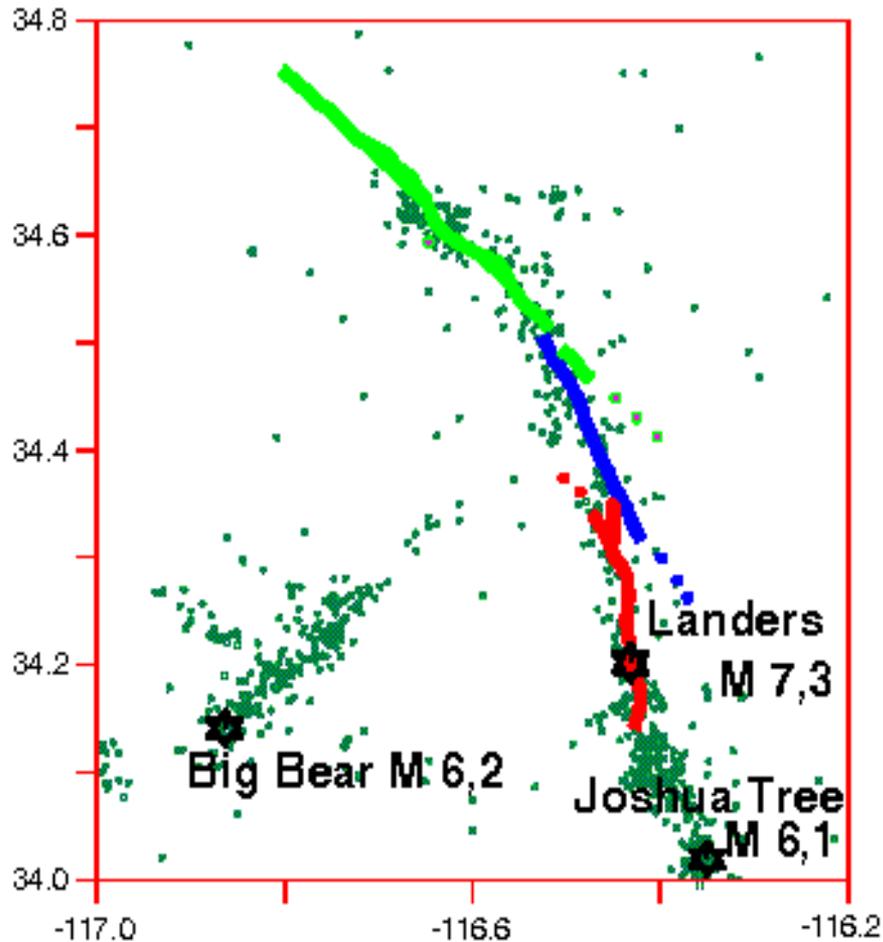
## Propagation de la rupture sismique



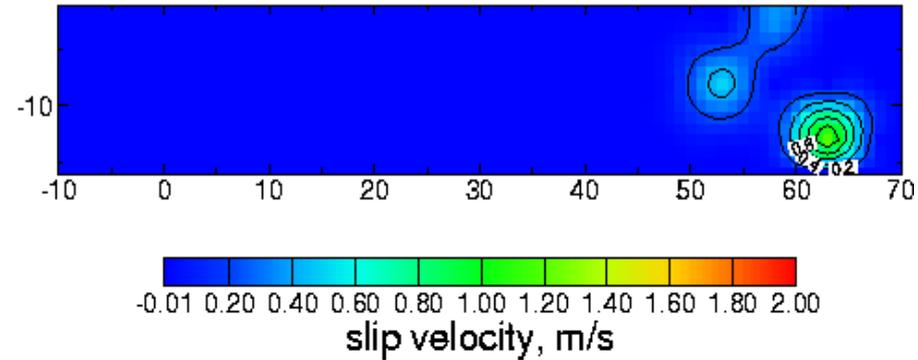
Landers earthquake



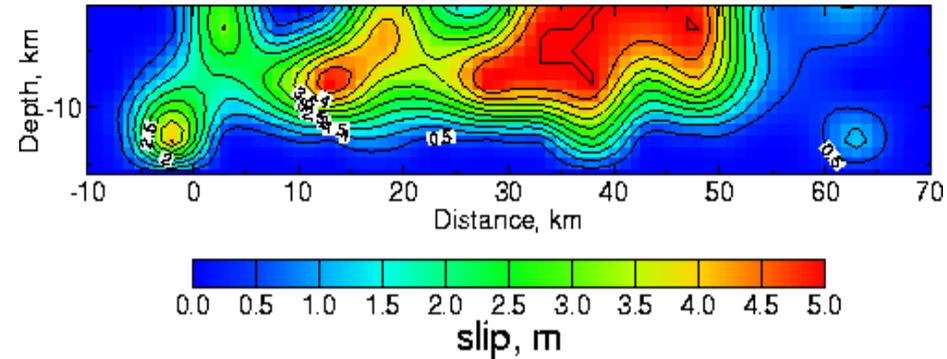
## Propagation de la rupture sismique



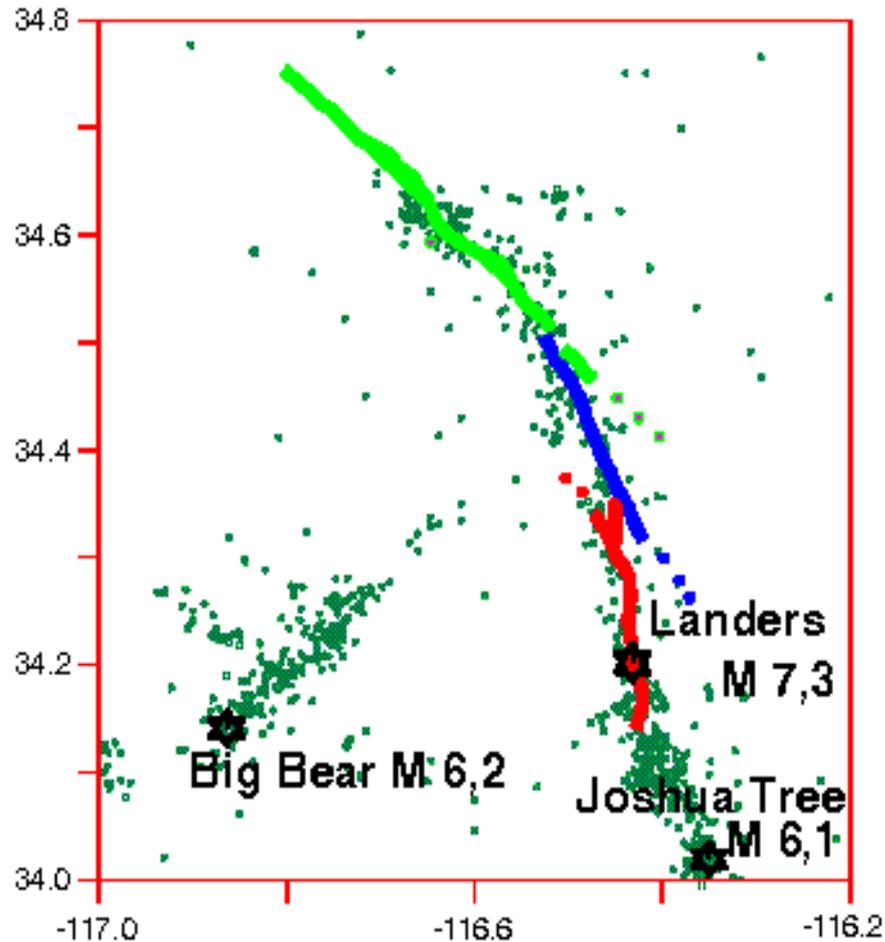
Landers earthquake



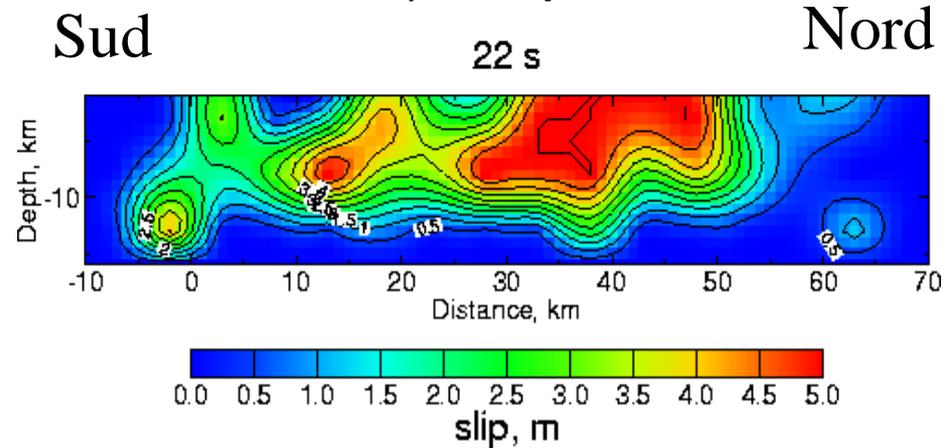
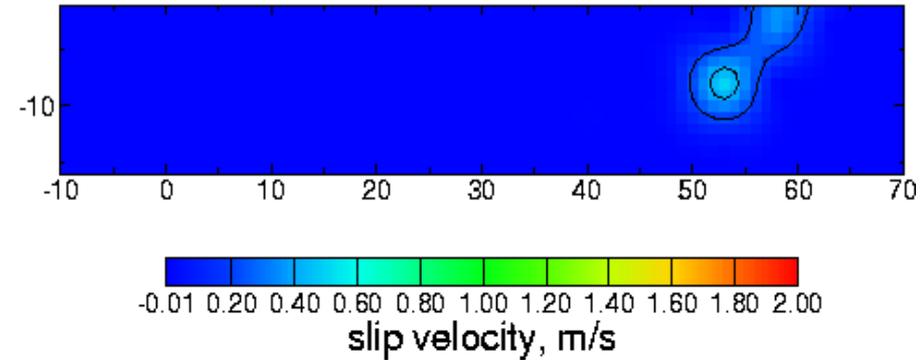
Sud 21 s Nord



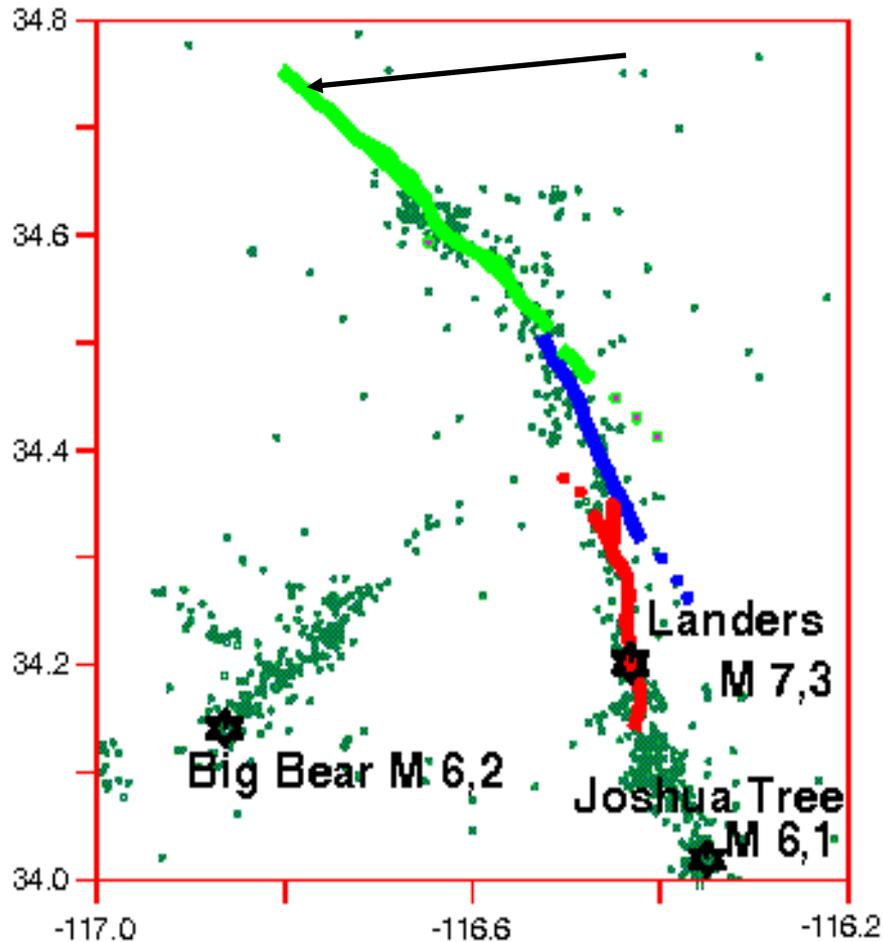
## Propagation de la rupture sismique



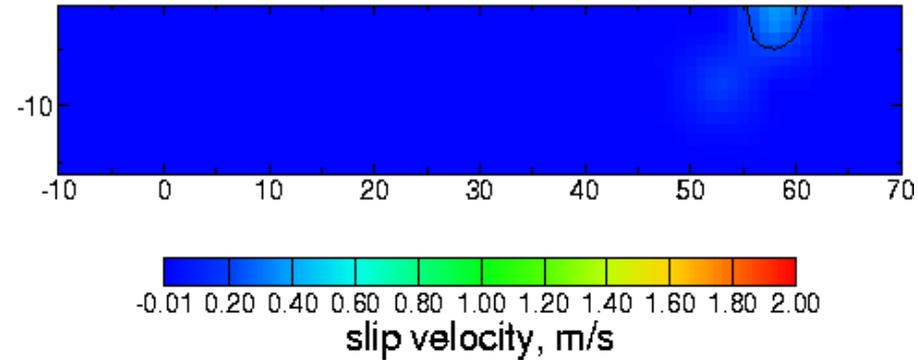
Landers earthquake



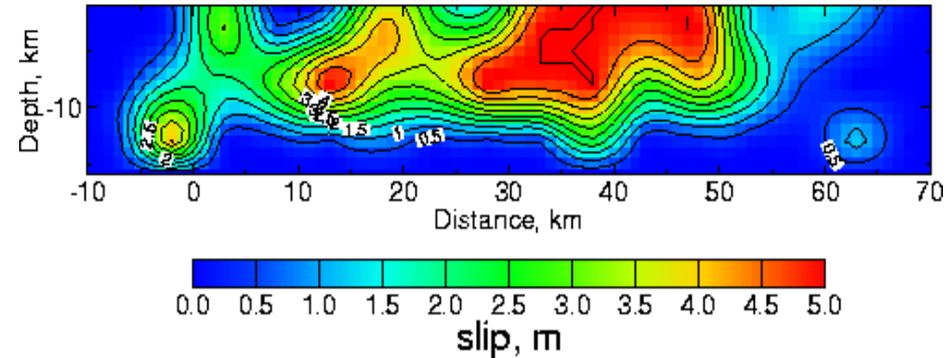
## Propagation de la rupture sismique



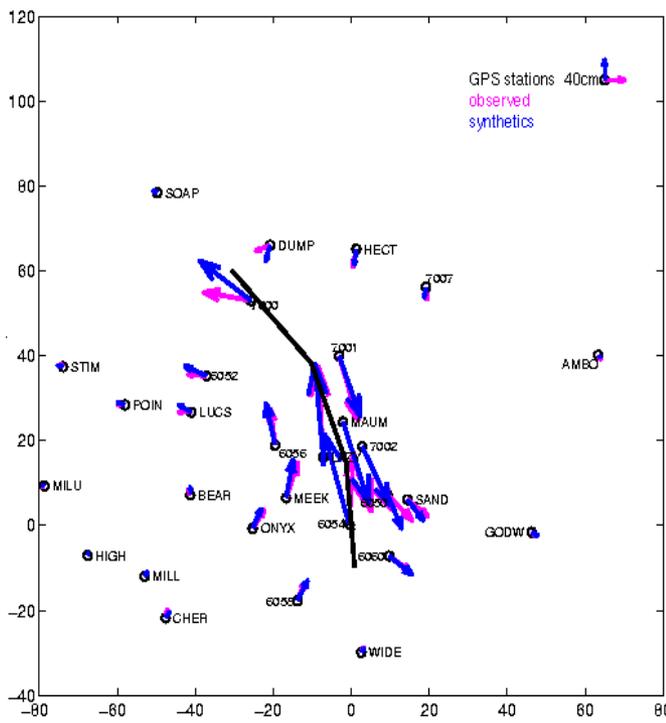
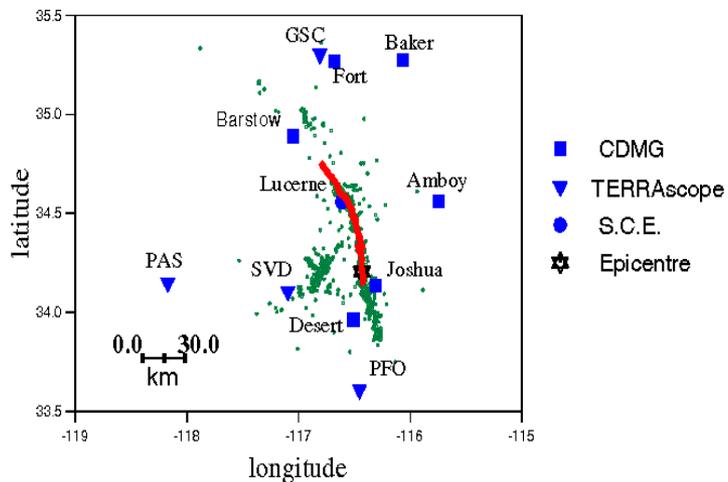
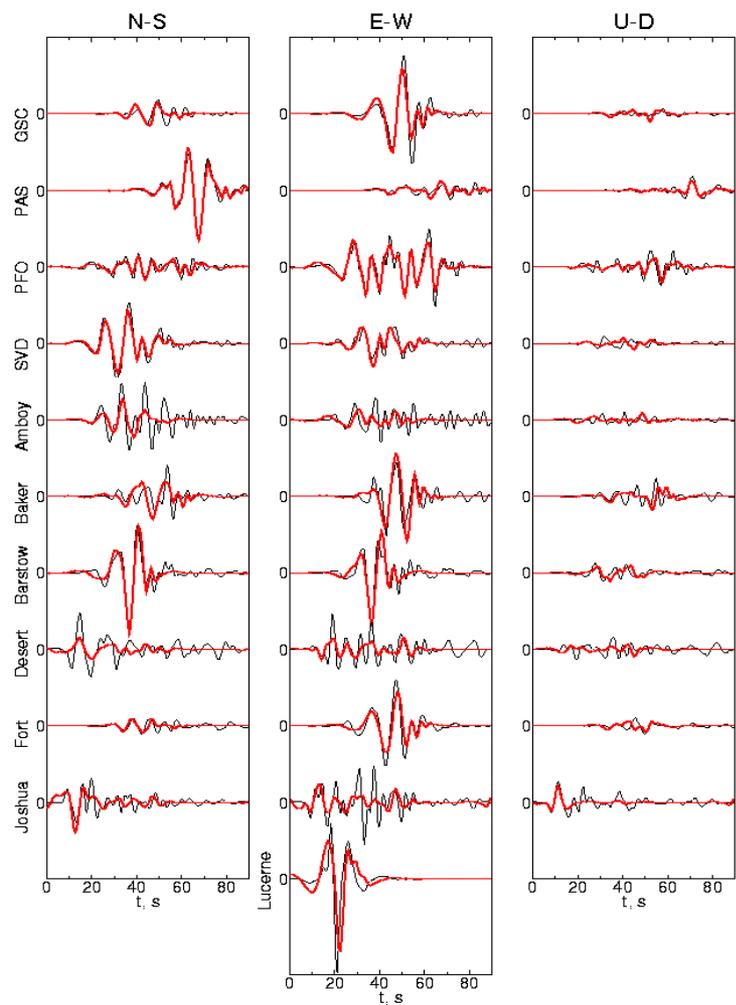
Landers earthquake

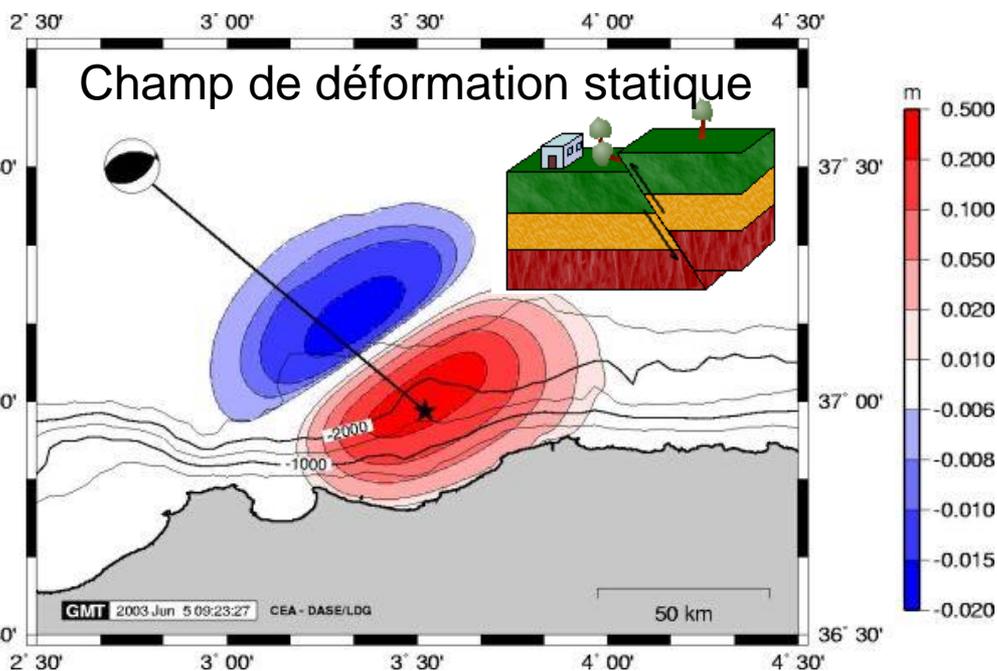


Sud 23 s Nord



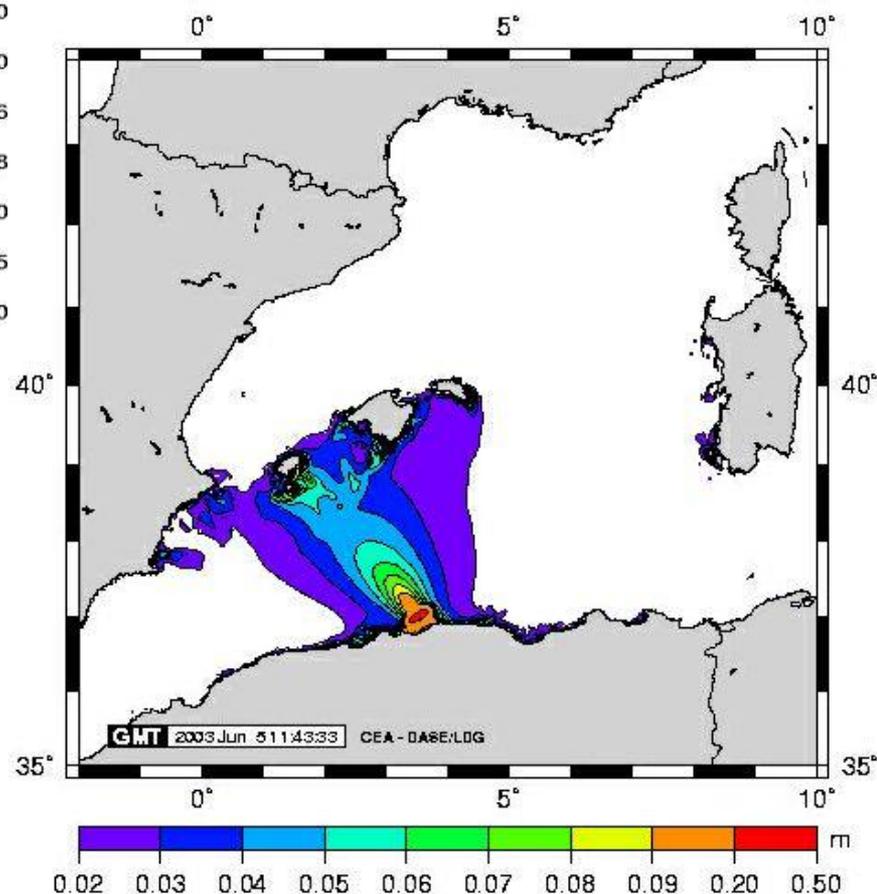
# Propagation de la rupture sismique





### Tsunami du 21 mai 2003

Simulation des hauteurs d'eau maximales atteintes après 1h30 min de propagation



Dimensions de la faille	40 x 20 km <sup>2</sup>
Strike, dip, rake	56°, 46°, 71°
Moment sismique	0,2x10 <sup>20</sup> Nm
Module de cisaillement	30x10 <sup>9</sup> N/m <sup>2</sup> = 30 GPa
Epicentre	3.52°E - 36.98°N
Profondeur	17 km

## Modélisation dynamique

Objectif : simuler la propagation de la rupture sismique sur une faille

### Propriétés du Milieu :

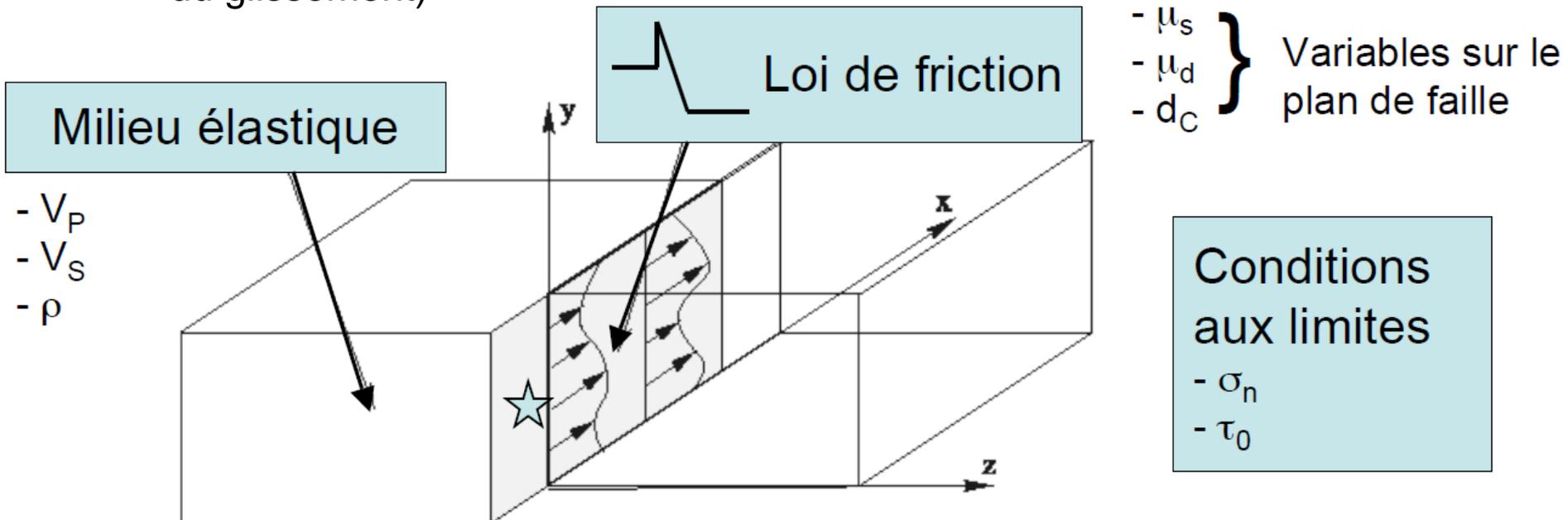
Équation de l'élastodynamique :

- loi de Hooke  $\tau_{ij} = \lambda u_{k,k} \delta_{ij} + \mu (u_{i,j} + u_{j,i})$

- loi de la dynamique  $\rho \ddot{u}_i = \tau_{ij,j} + f_i$

### Caractéristiques de l'interface :

- loi de friction (chute de la résistance au frottement de la faille en fonction du glissement)



Milieu élastique

- $V_P$
- $V_S$
- $\rho$

Loi de friction

- $\mu_s$
  - $\mu_d$
  - $d_c$
- } Variables sur le plan de faille

Conditions aux limites

- $\sigma_n$
- $\tau_0$