

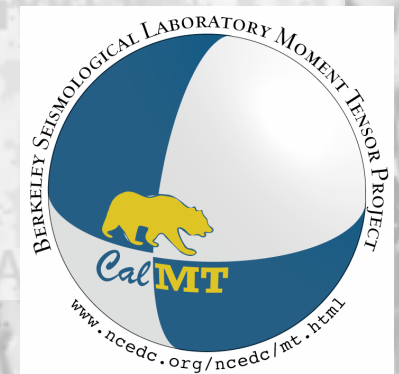
Détection de séismes en temps réel avec tenseurs des moments en Californie

Aurélie Guilhem

Collaborateurs: Doug Dreger & Bob Uhrhammer
Berkeley Seismological Laboratory - UC Berkeley

Plan

- Présentation de la région de Mendocino
- Détection avec tenseurs des moments
 - Méthode
 - Mise en place en Californie du Nord
- Premiers tests
- Applications
 - Alerte aux tsunamis
 - Recherche de séismes lents
- Conclusions

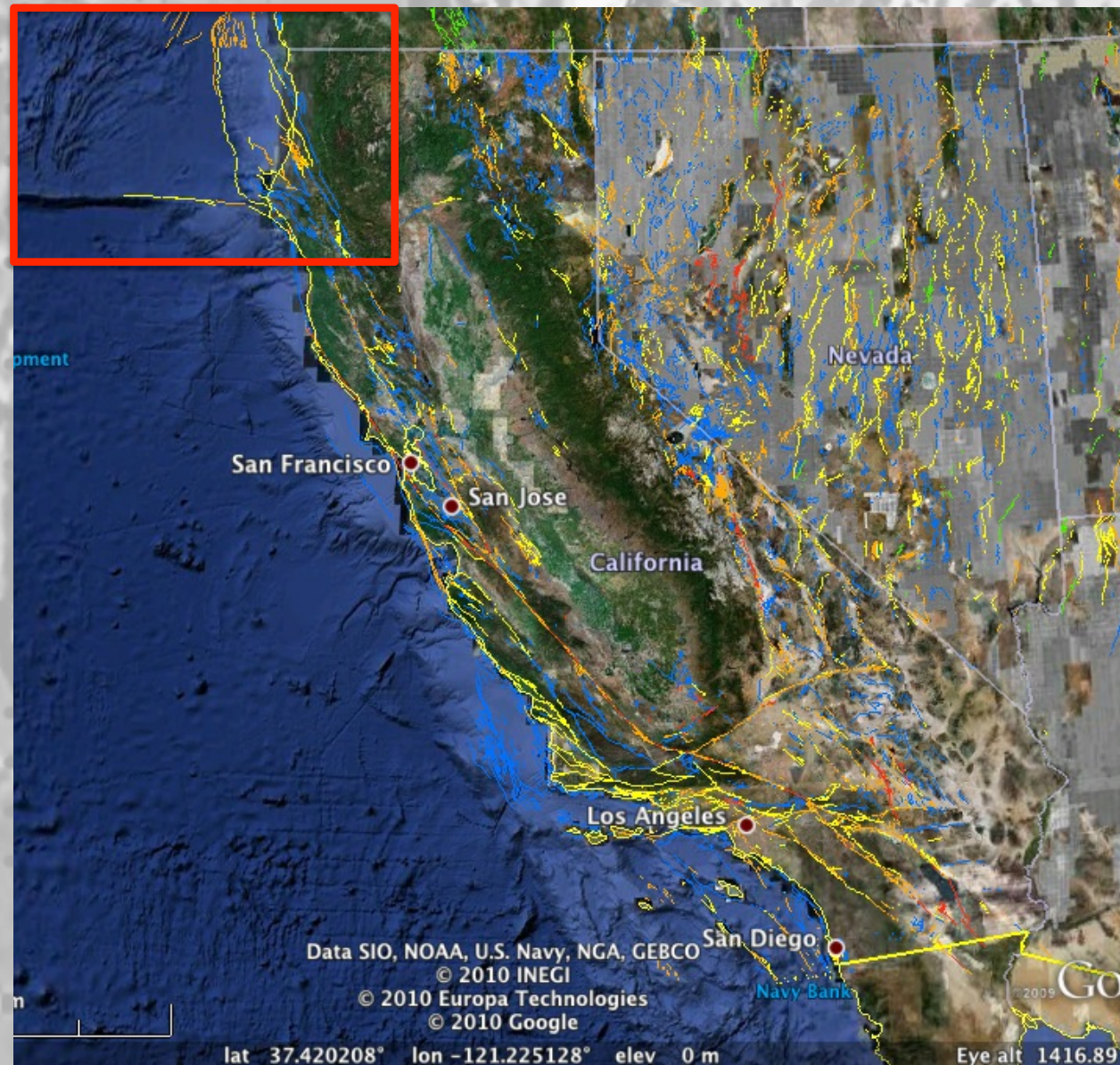


★ La région de Mendocino



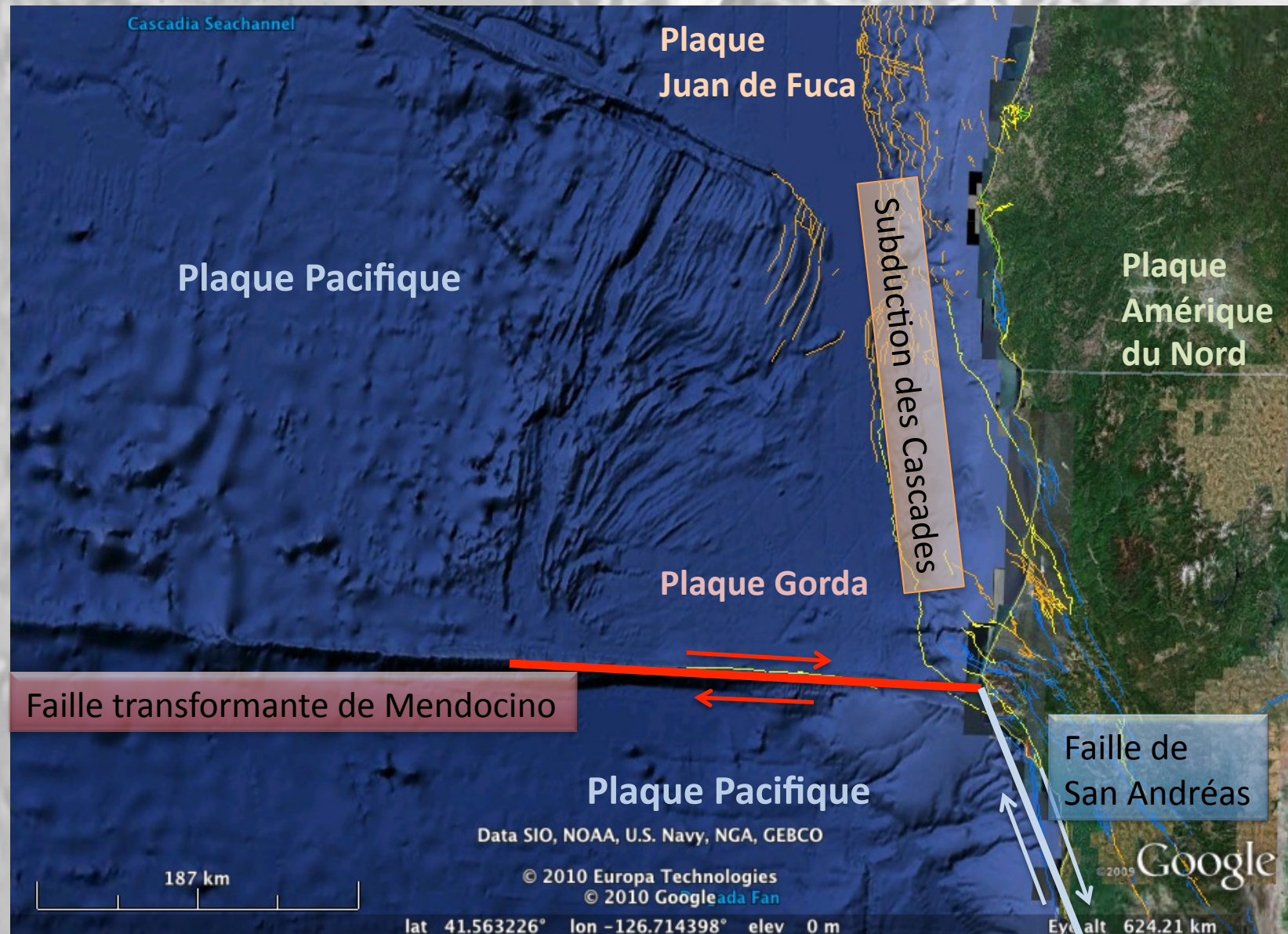
Région de Mendocino | Grille de MTs | Tests | Application: Tsunamis | Application: séismes lents

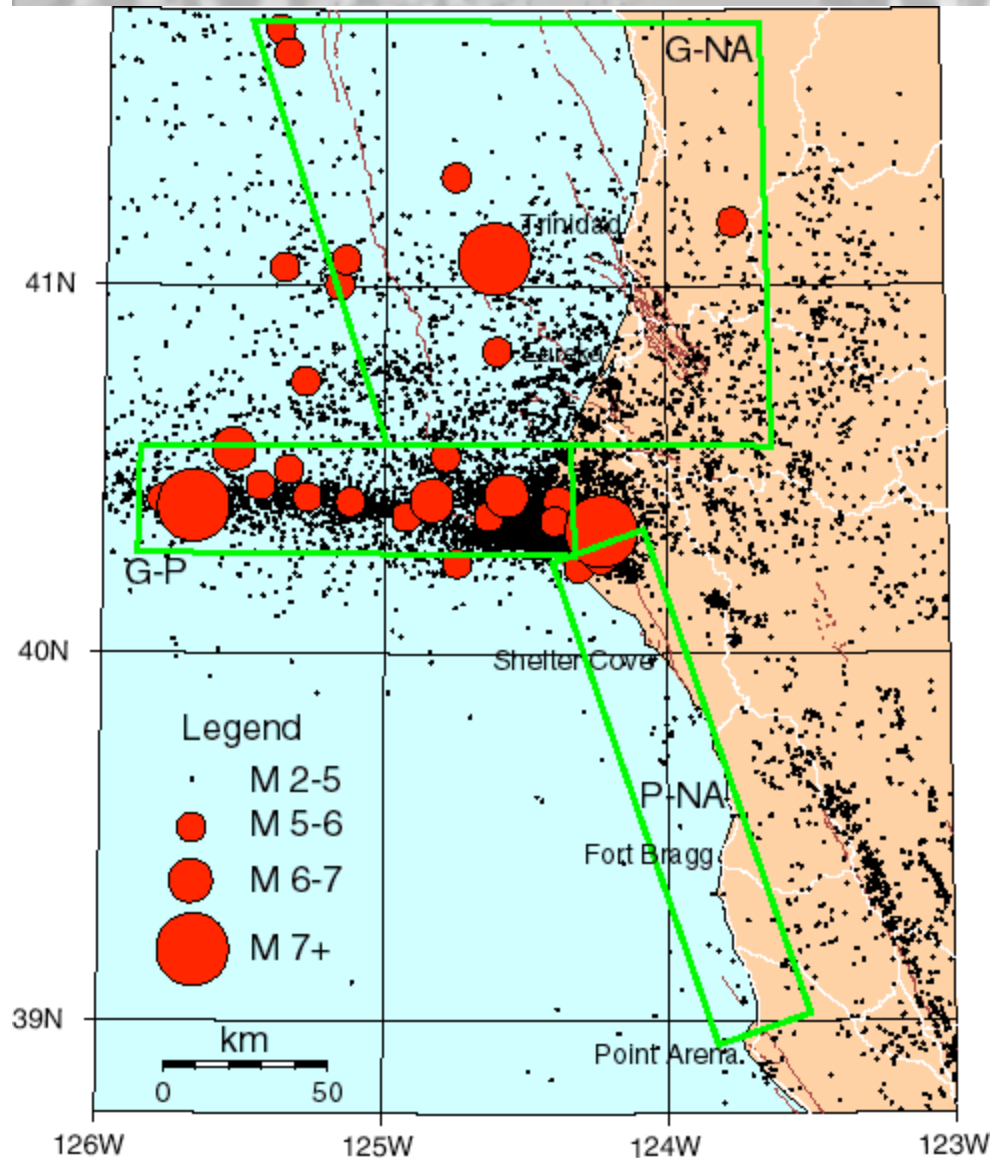
Grille de MTs | Tests | Application: Tsunamis | Application: séismes lents



Région de Mendocino

| Grille de MTs | Tests | Application: Tsunamis | Application: séismes lents





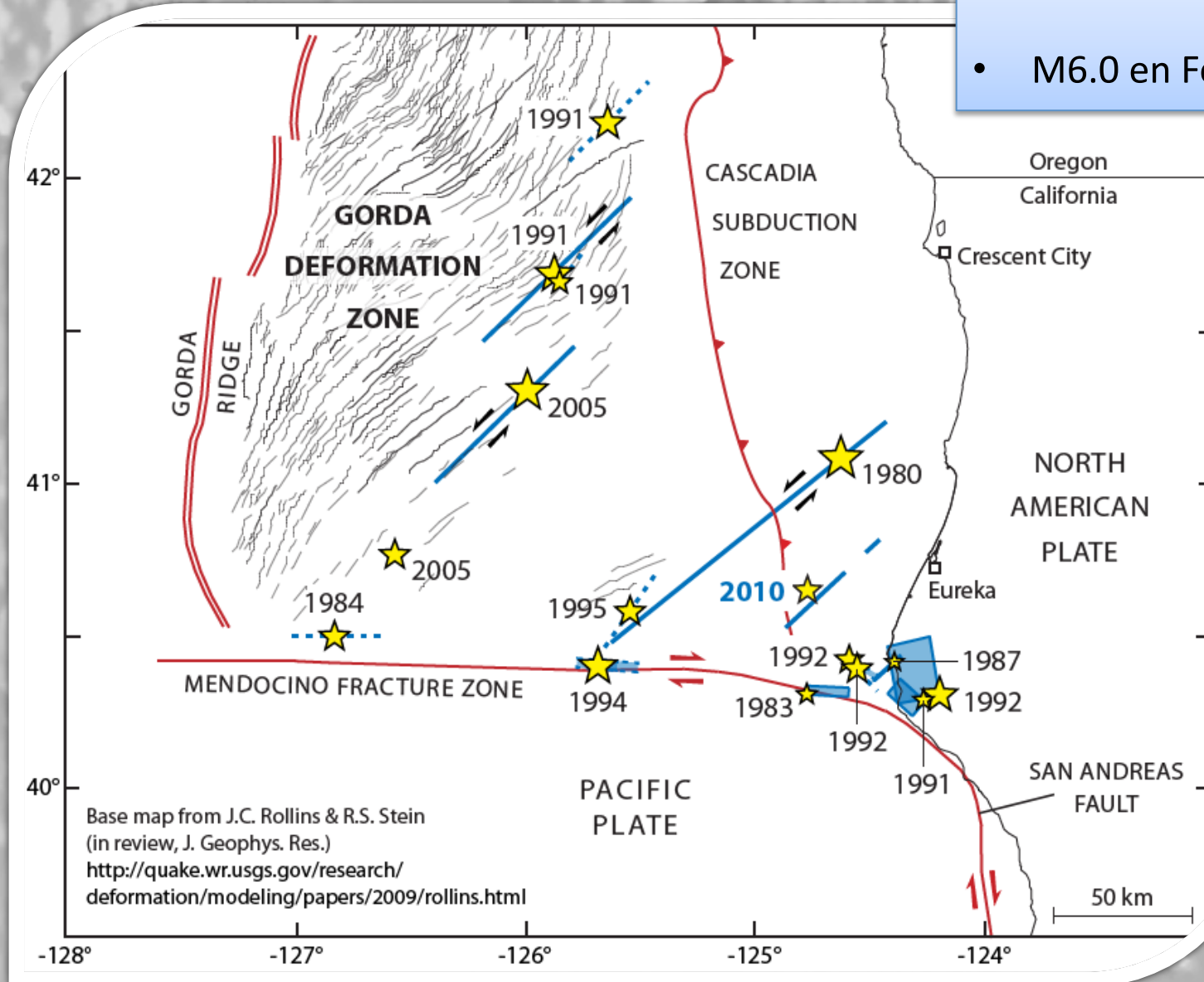
Sismicité

- La **région la plus active** de Californie du Nord
- **Intense sismicité**
 - au point triple
 - le long de la faille de Mendocino
- Environ 80 séismes avec $M > 3$ par an en moyenne
- **Divers mécanismes au foyer:**
 - Décrochant dextre
 - Décrochant sénestre
 - Normal
 - Inverse

Région de Mendocino

| Grille de MTs | Tests | Application: Tsunamis | Application: séismes lents

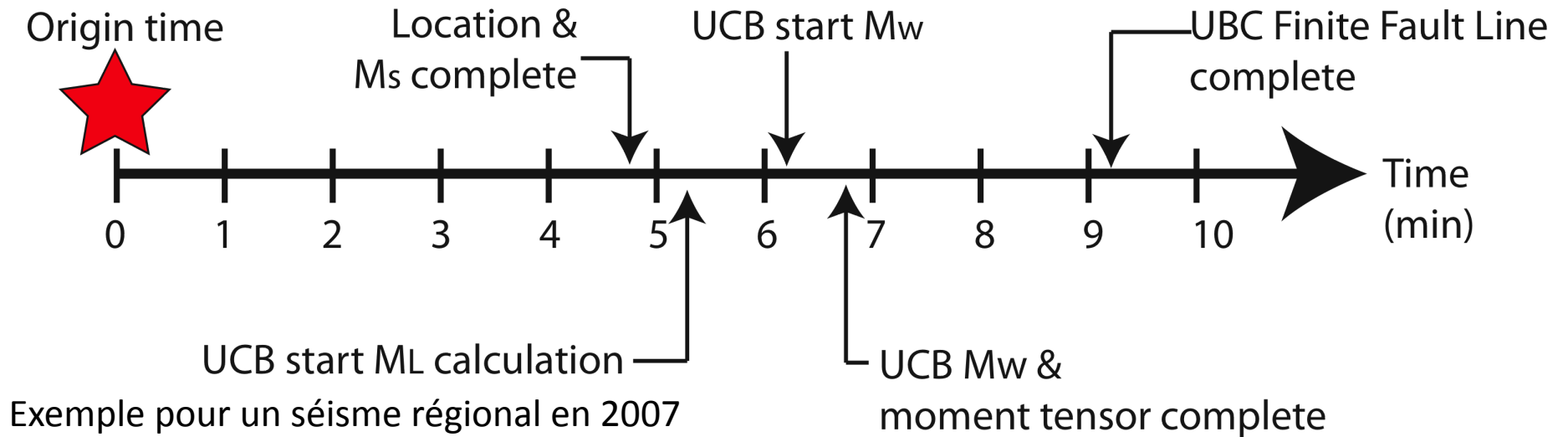
- M6.5 en Janvier 2010
- M6.0 en Février 2010



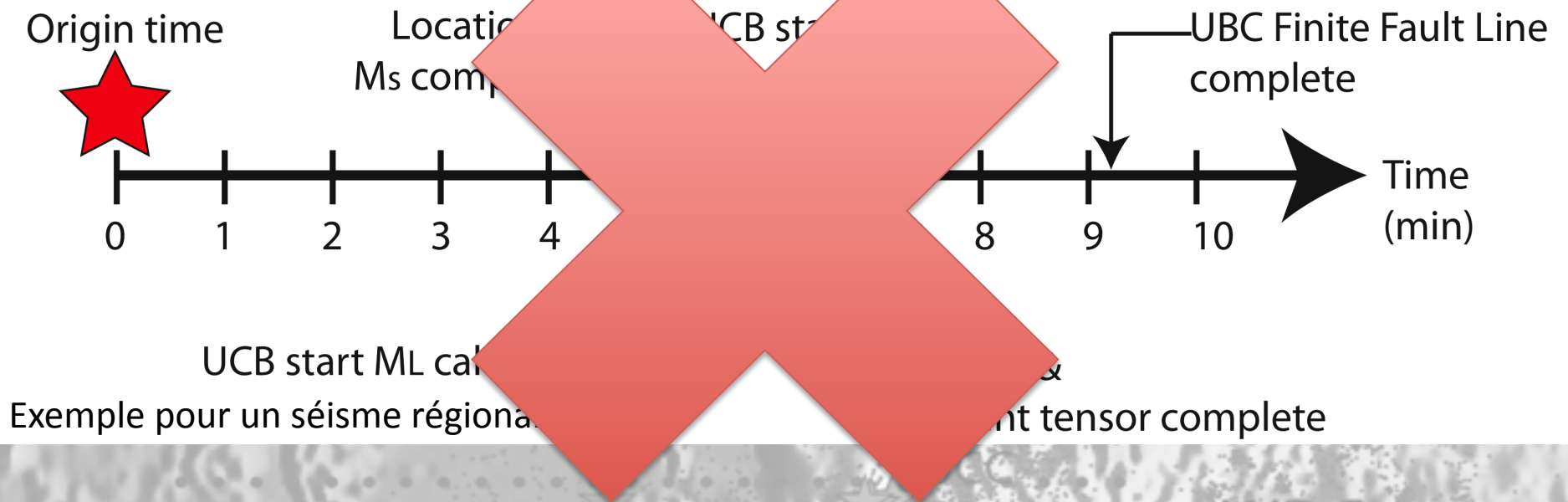
Détection de séismes: une grille de tenseurs des moments

The background of the slide is a grayscale map of the Mendocino region, showing the coastline and surrounding land. Overlaid on the map is a grid of small dots, with several stars indicating specific seismic events. Labels for various locations are visible on the map, including HUMO, YBH, WDC, GASB, ORV, and HOPS.

Une détection en cascade



Une détection en cascade



Une seule procédure pour:

- Détecter
- Localiser
- Obtenir le temps d'origine
- Obtenir le moment sismique -> magnitude du moment (M_w)
- Obtenir le mécanisme du séisme

Méthode

Adaptée de Kawakatsu, 1998:

$$\sum_i G_i^{sk}(t) m_i^s = d^k(t) \quad (1)$$

Green's functions

moment

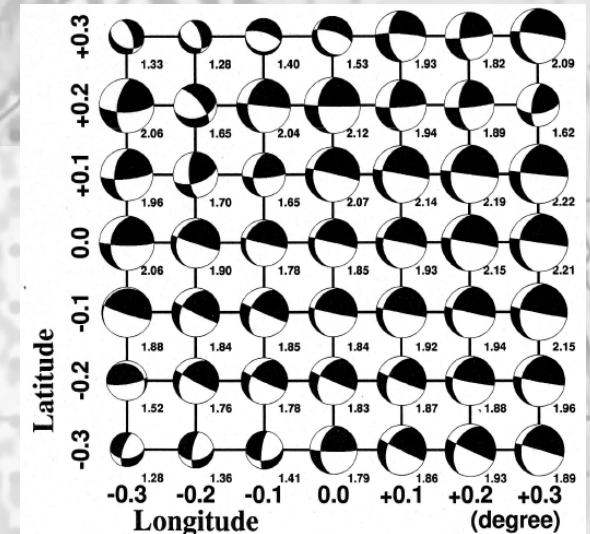
data

L'équation normalisée de (1) est :
où

$$A_{ji}^s = \sum_k A_{ji}^{sk} \quad A_{ji}^{sk} = \int G_j^{sk}(t) G_i^{sk}(t) dt$$

$$b_j^s = \sum_k b_j^{sk} \quad b_j^{sk} = \int G_j^{sk}(t) d^k(t) dt$$

$$\sum_i A_{ji}^s m_i^s = b_j^s$$



Kawakatsu, 1998

$$M = (G^T G)^{-1} (G^T d)$$

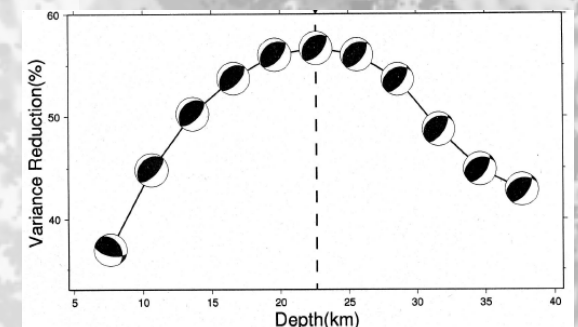
$$M = ((G^T G)^{-1} G^T) d$$

La solution aux moindres carrés est donnée par :

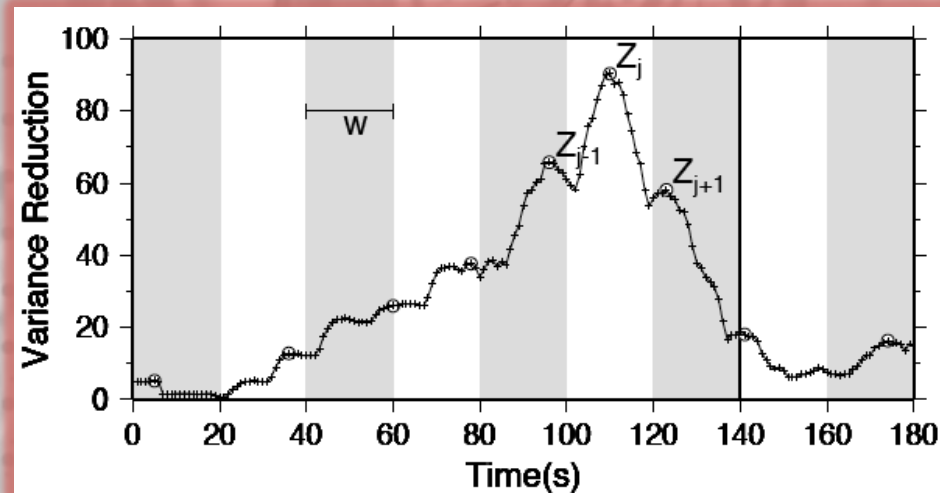
$$\hat{m} = A^{-1} b$$

Calcul de la variance réduction (VR) des tenseurs :

$$VR = \left[1 - \text{Re } s \div \sum_k \int (d^k(t))^2 dt \right] \times 100$$



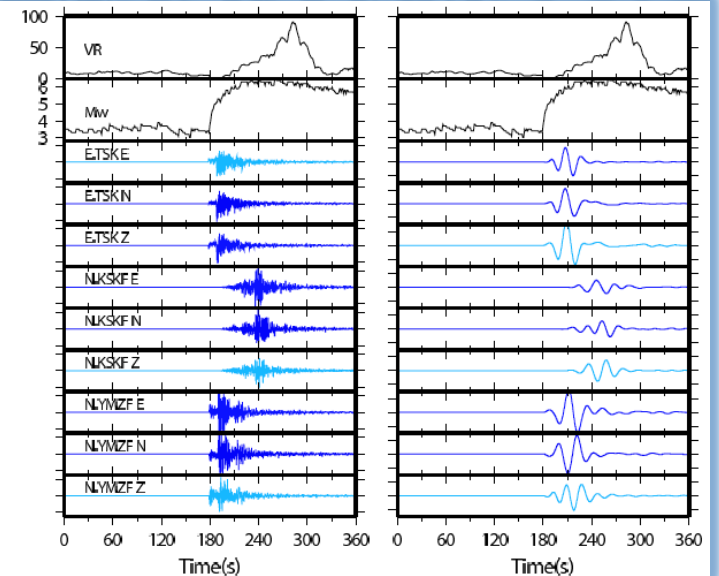
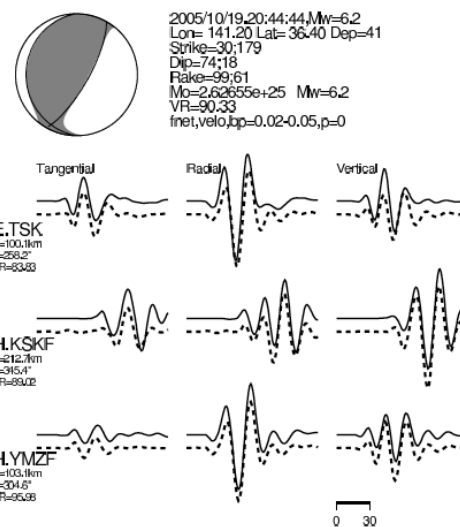
← Carte des sources virtuelles au Japon et séismes détectés avec GridMT



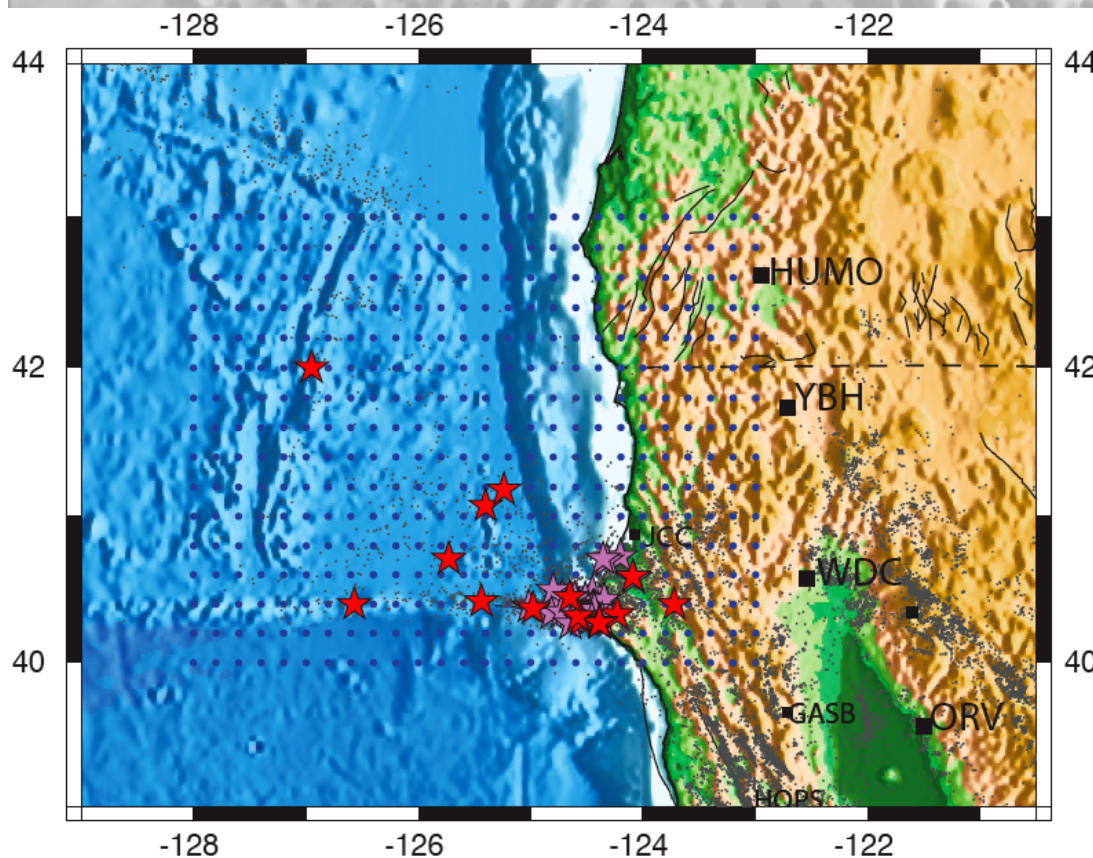
Variation temporelle du paramètre VR

Tsuruoka et al., 2009

Exemple pour un séisme (M6.2)



Application à la région de Mendocino



Grille de sources virtuelles:

- 0.2° latitude et longitude
- 3 km profondeur
- profondeurs: 5-38 km

4 stations large-bande: HUMO, ORV, WDC et YBH

1 catalogue de fonctions de Green

Données filtrées **entre 20 et 50 sec**

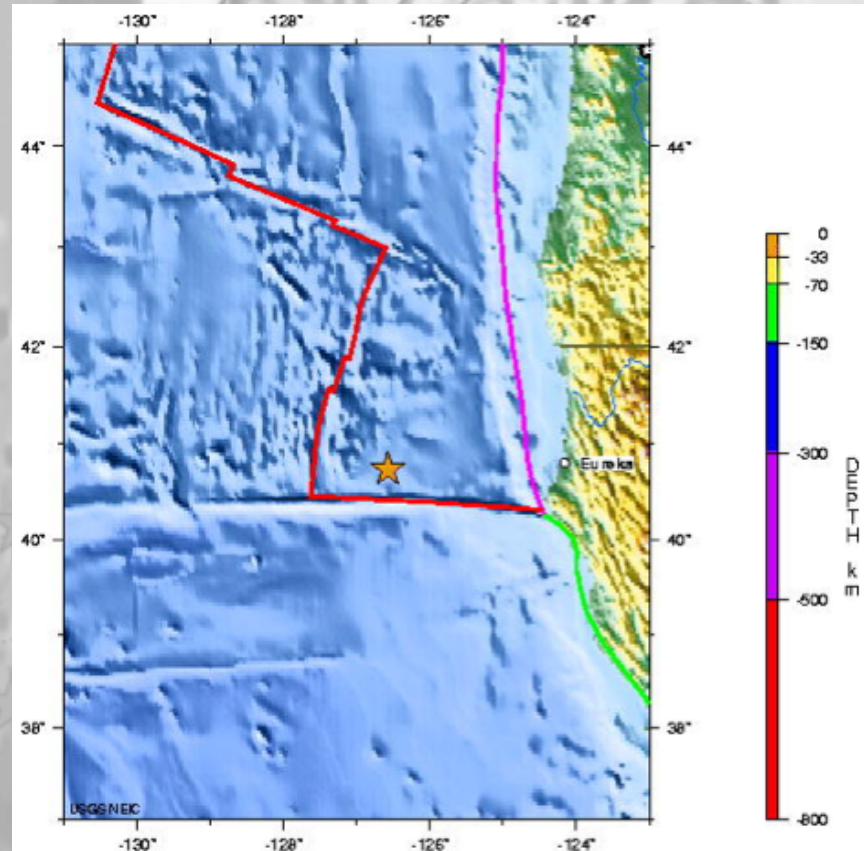
Calcul des tenseurs pour chaque point de la grille **toutes les 2 secondes (380 points)**

Premiers tests



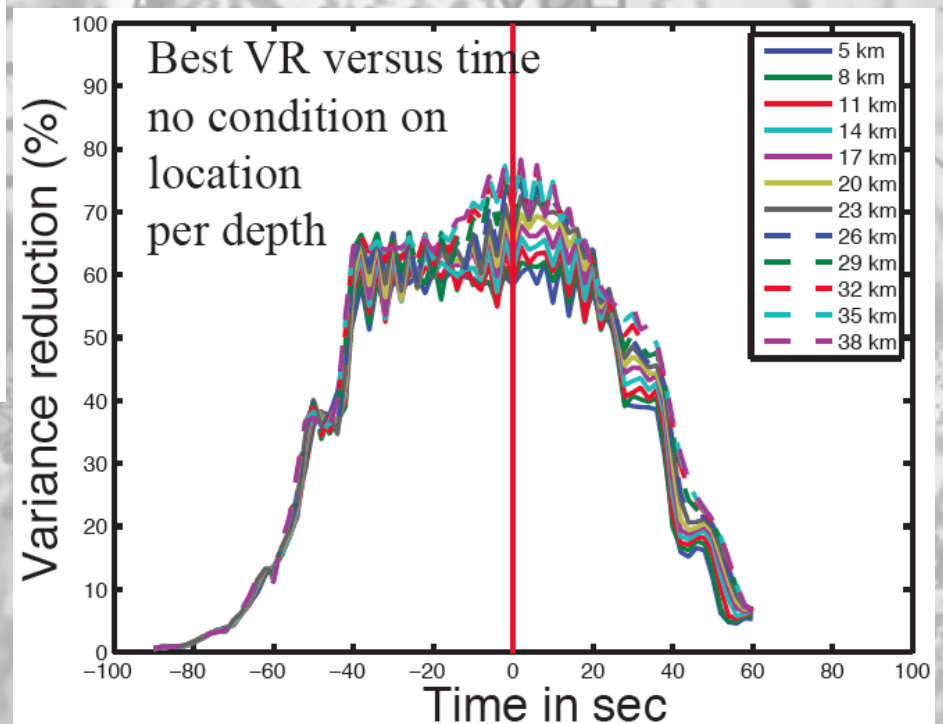
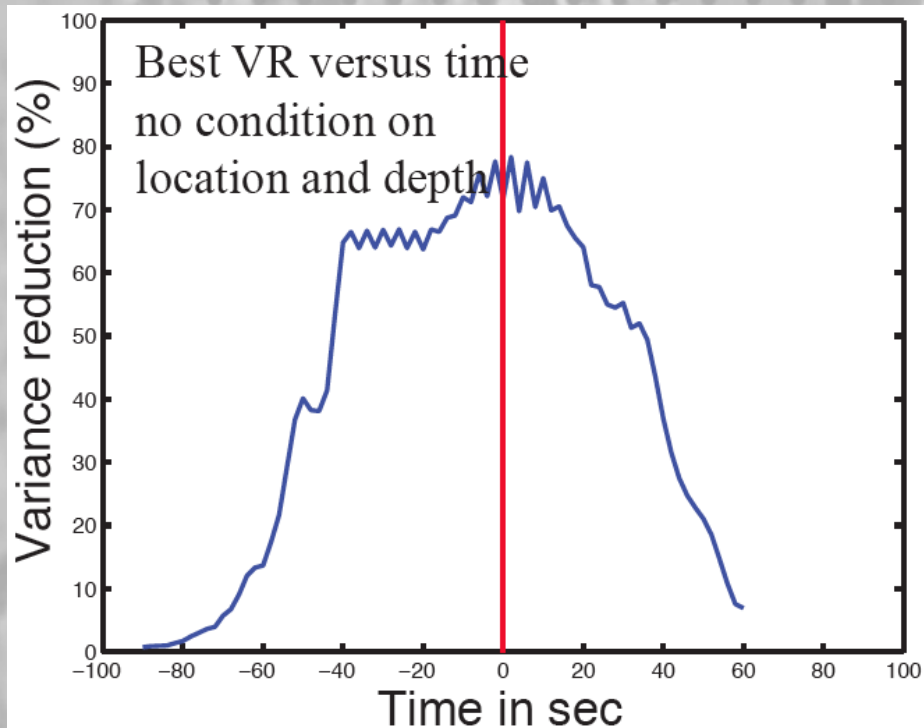
Magnitude 6.7 (18/06/2005)

Magnitude	6.7
Date-Time	Friday, June 17, 2005 at 06:21:41 UTC Thursday, June 16, 2005 at 10:21:41 PM at epicenter Time of Earthquake in other Time Zones
Location	40.758°N, 126.595°W
Depth	10 km (6.2 miles) set by location program
Region	OFF THE COAST OF NORTHERN CALIFORNIA
Distances	198 km (123 miles) W (277°) from Ferndale, CA 201 km (125 miles) W (272°) from Humboldt Hill, CA 201 km (125 miles) WNW (285°) from Petrolia, CA 205 km (127 miles) W (270°) from Eureka, CA 489 km (304 miles) NW (314°) from San Francisco City Hall, CA
Location Uncertainty	horizontal +/- 3.5 km (2.2 miles); depth fixed by location program
Parameters	NST=239, Nph=239, Dmin=241.3 km, Rmss=0.98 sec, Gp= 47°, M-type=teleseismic moment magnitude (Mw), Version=Q
Source	USGS NEIC (WDCS-D)
Event ID	uszkal

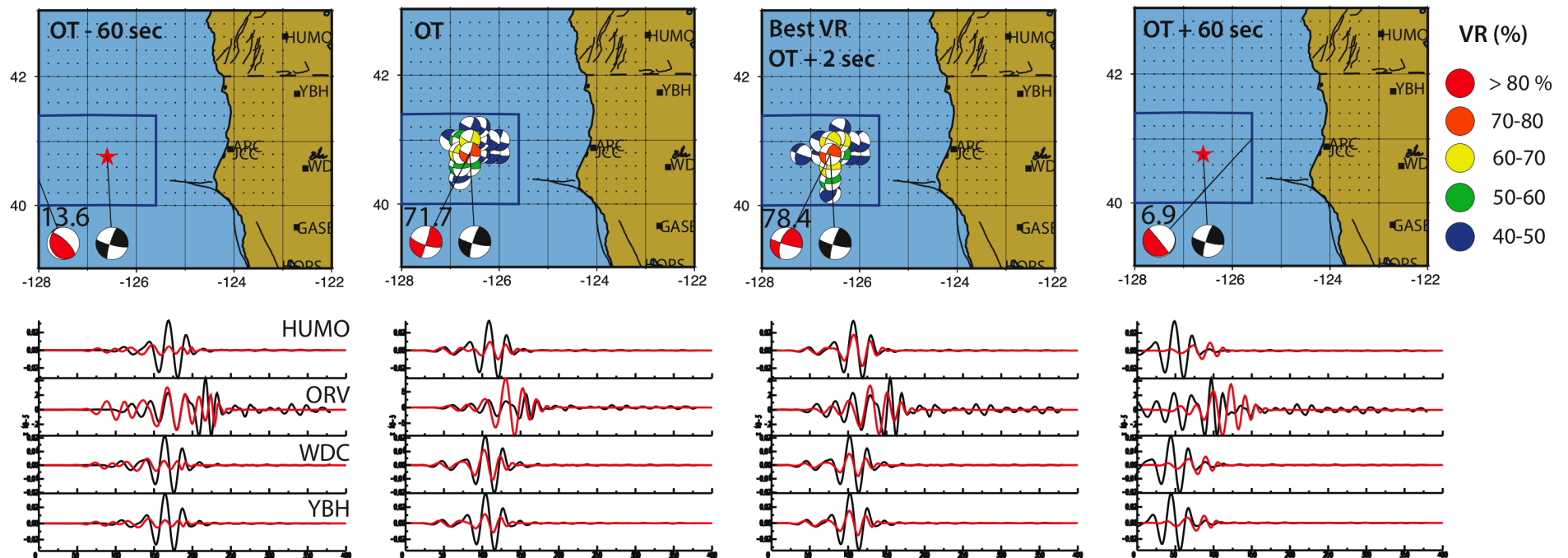


OFF THE COAST OF NORTHERN CALIFORNIA
 2005 06 17 06 21 42 UTC 40.74N 126.58W Depth: 10 km, Magnitude: 6.7
 Earthquake Location
 Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green
 USGS National Earthquake Information Center

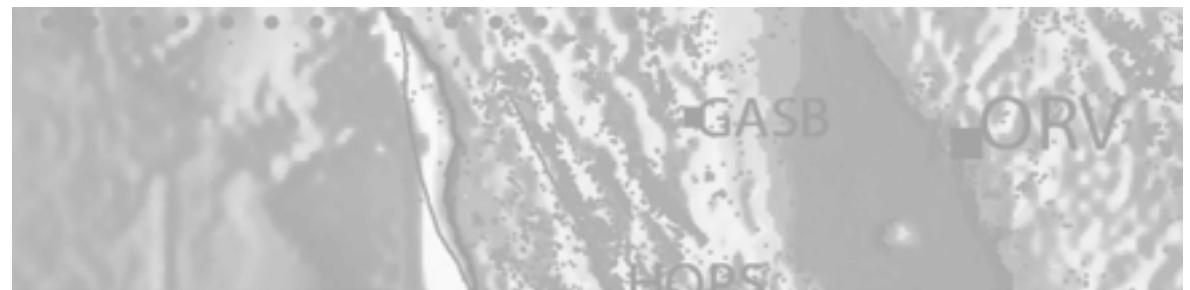
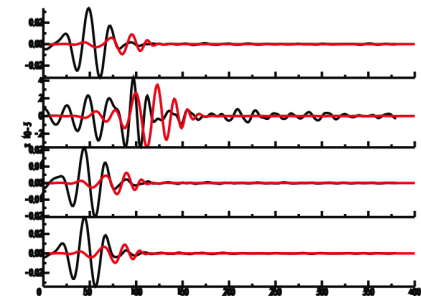
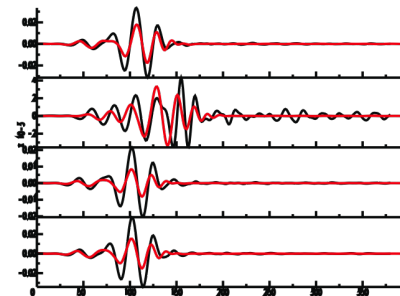
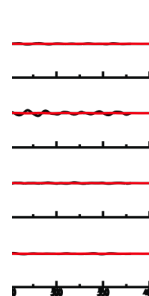
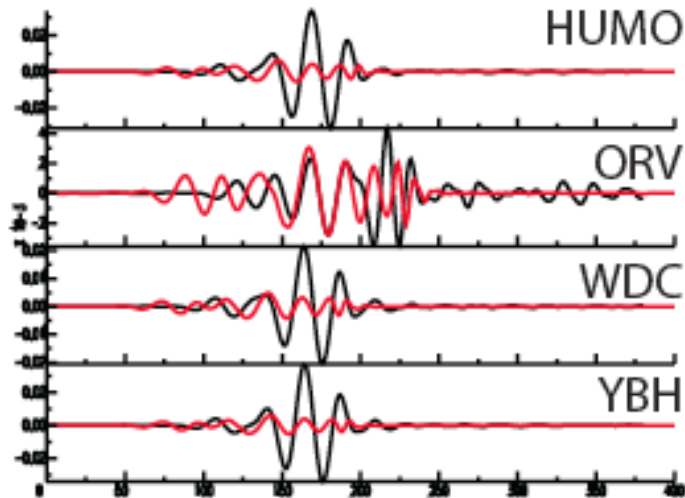
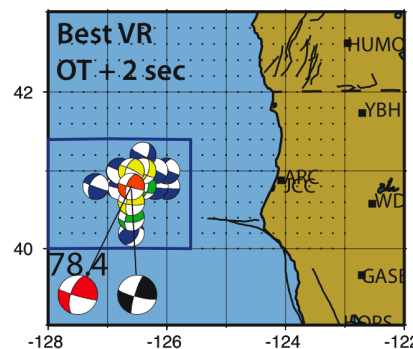
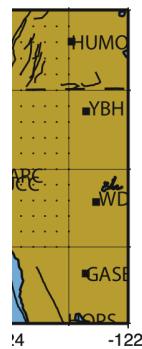
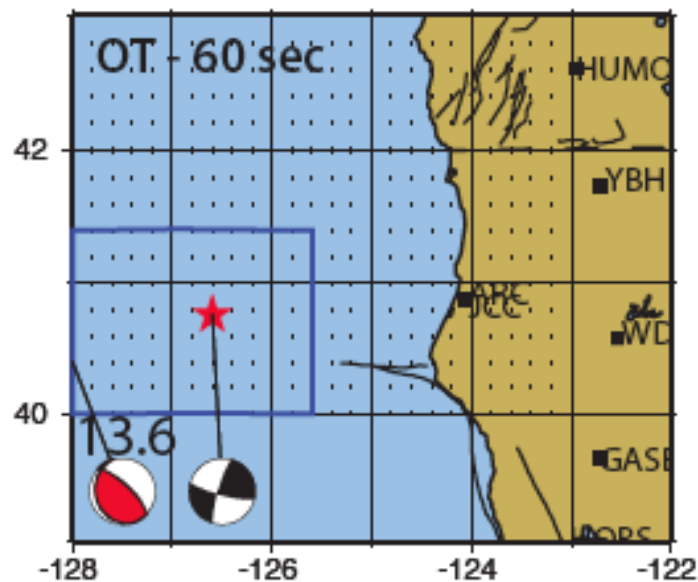
Magnitude 6.7 (18/06/2005)



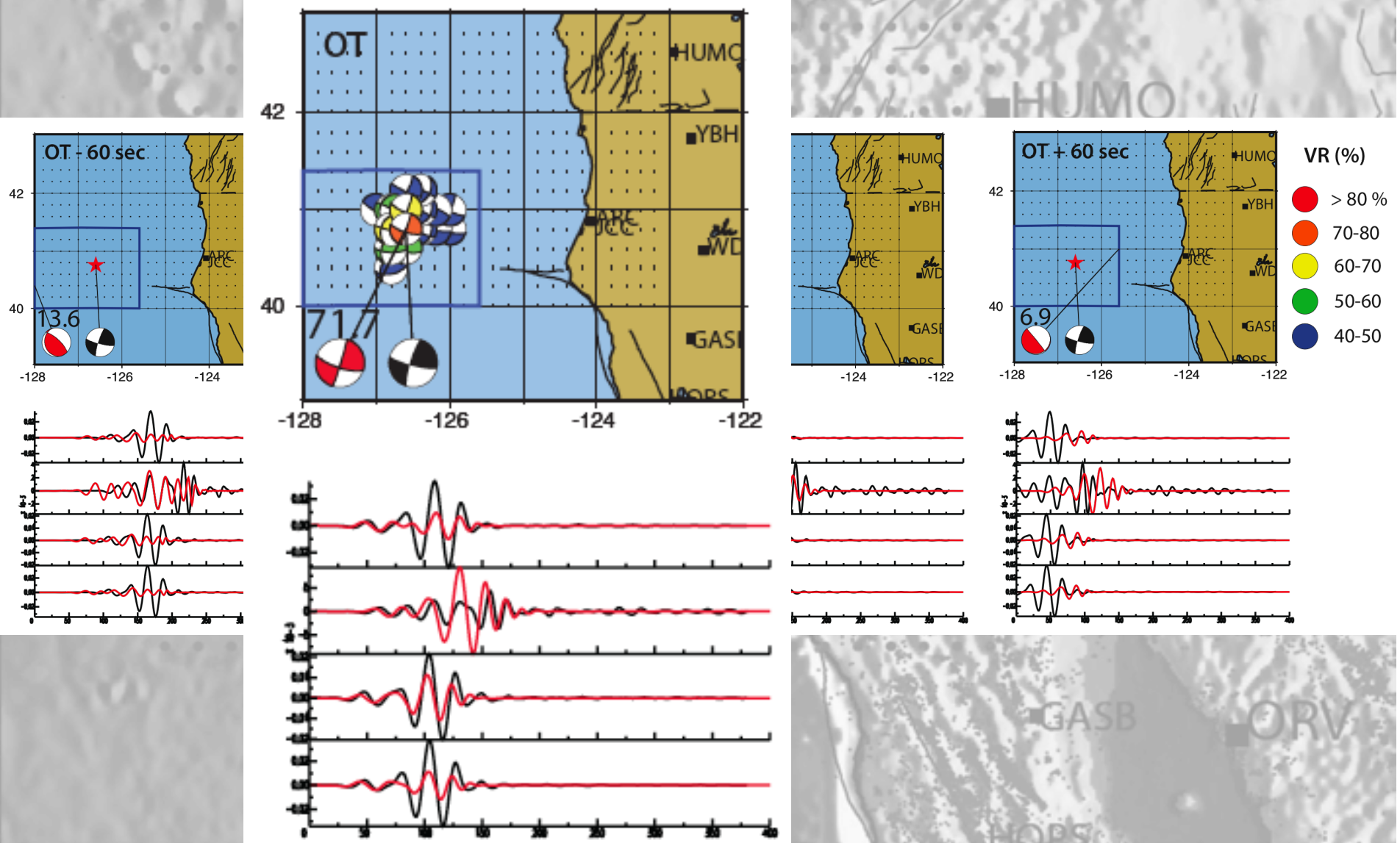
Magnitude 6.7 (18/06/2005)



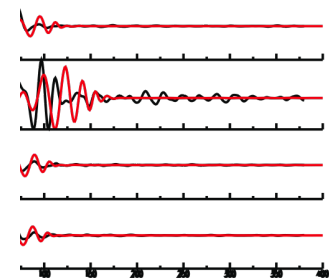
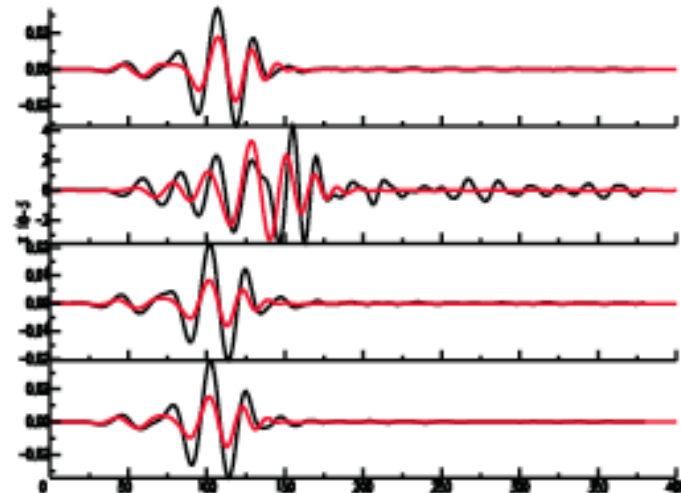
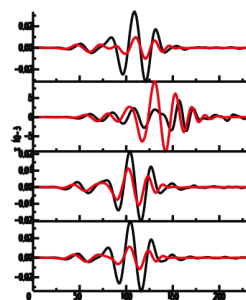
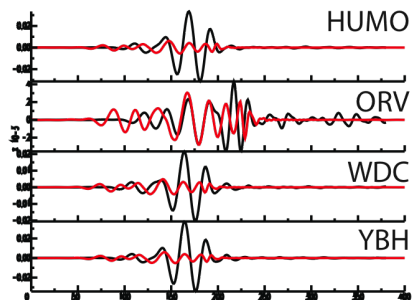
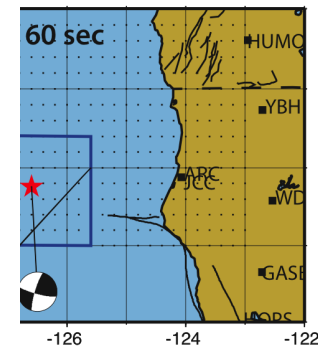
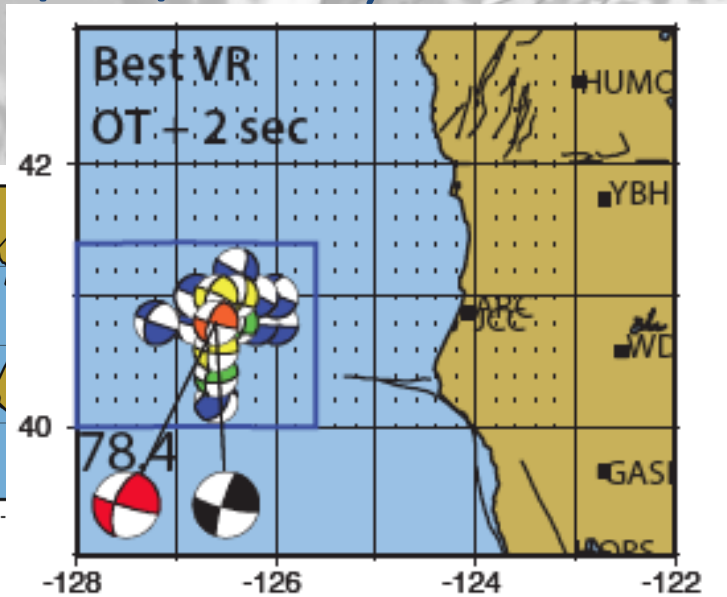
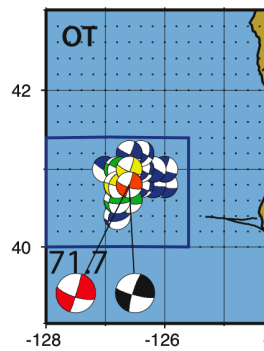
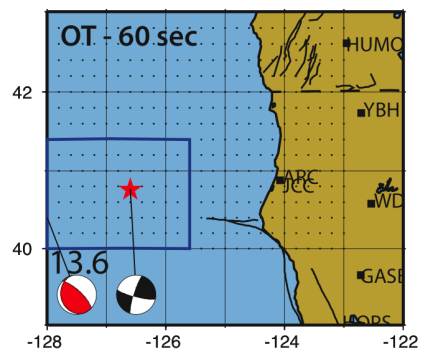
Magnitude 6.7 (18/06/2005)



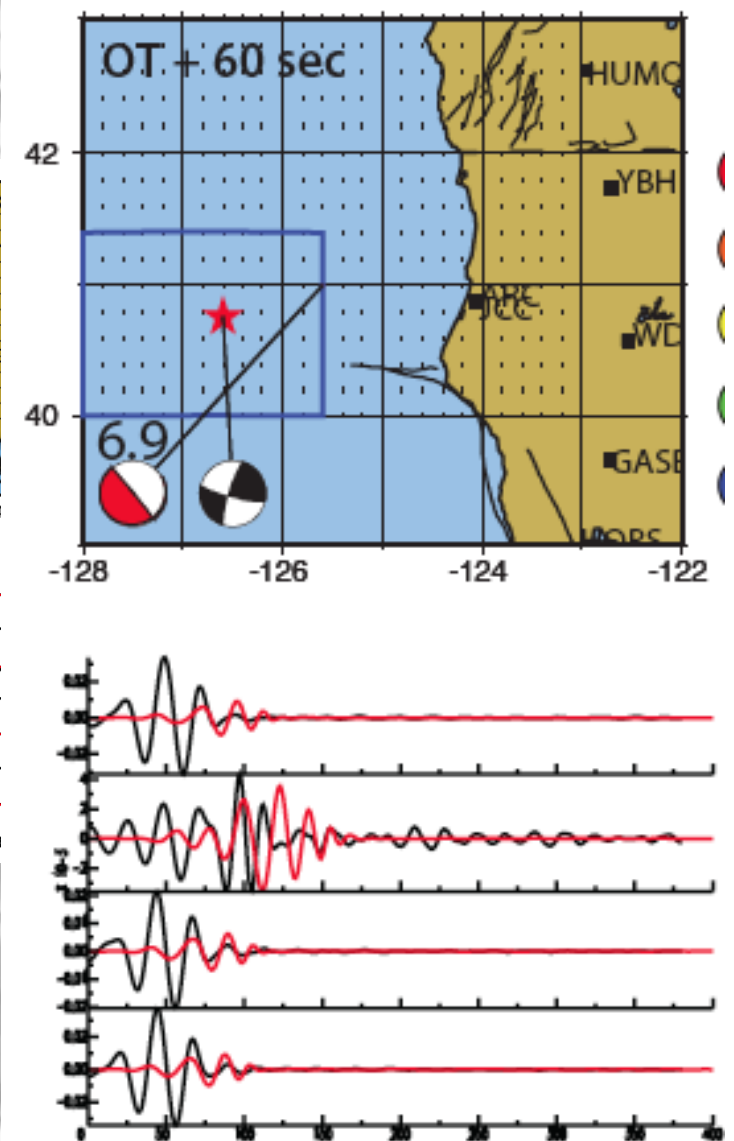
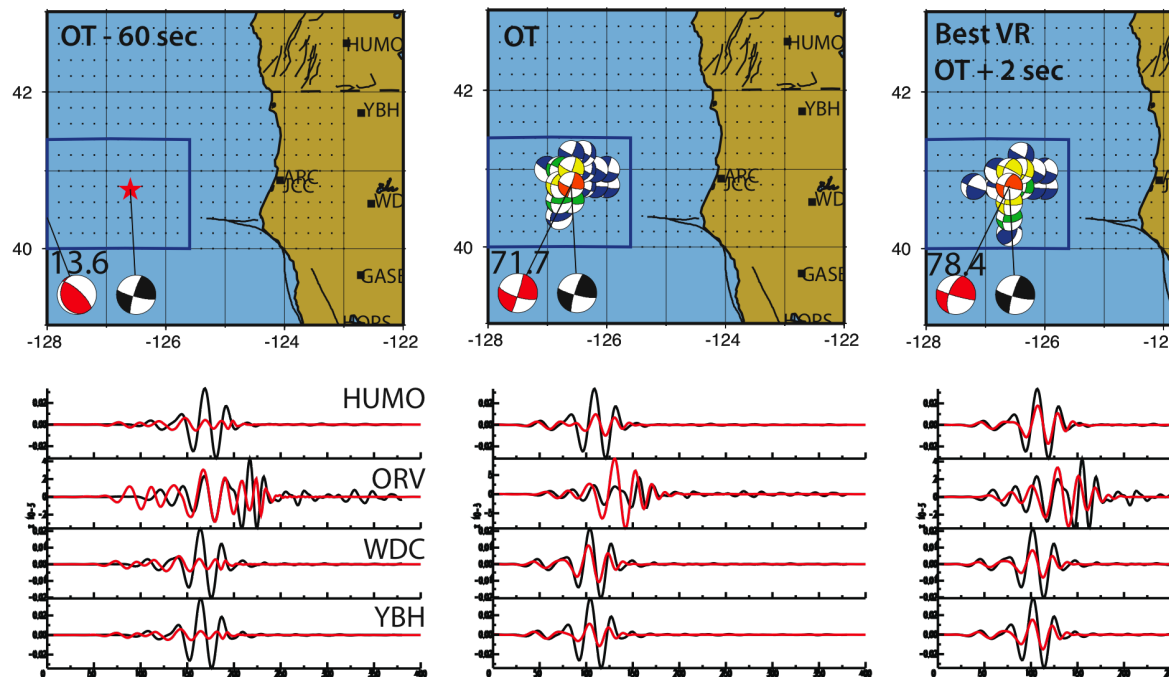
Magnitude 6.7 (18/06/2005)



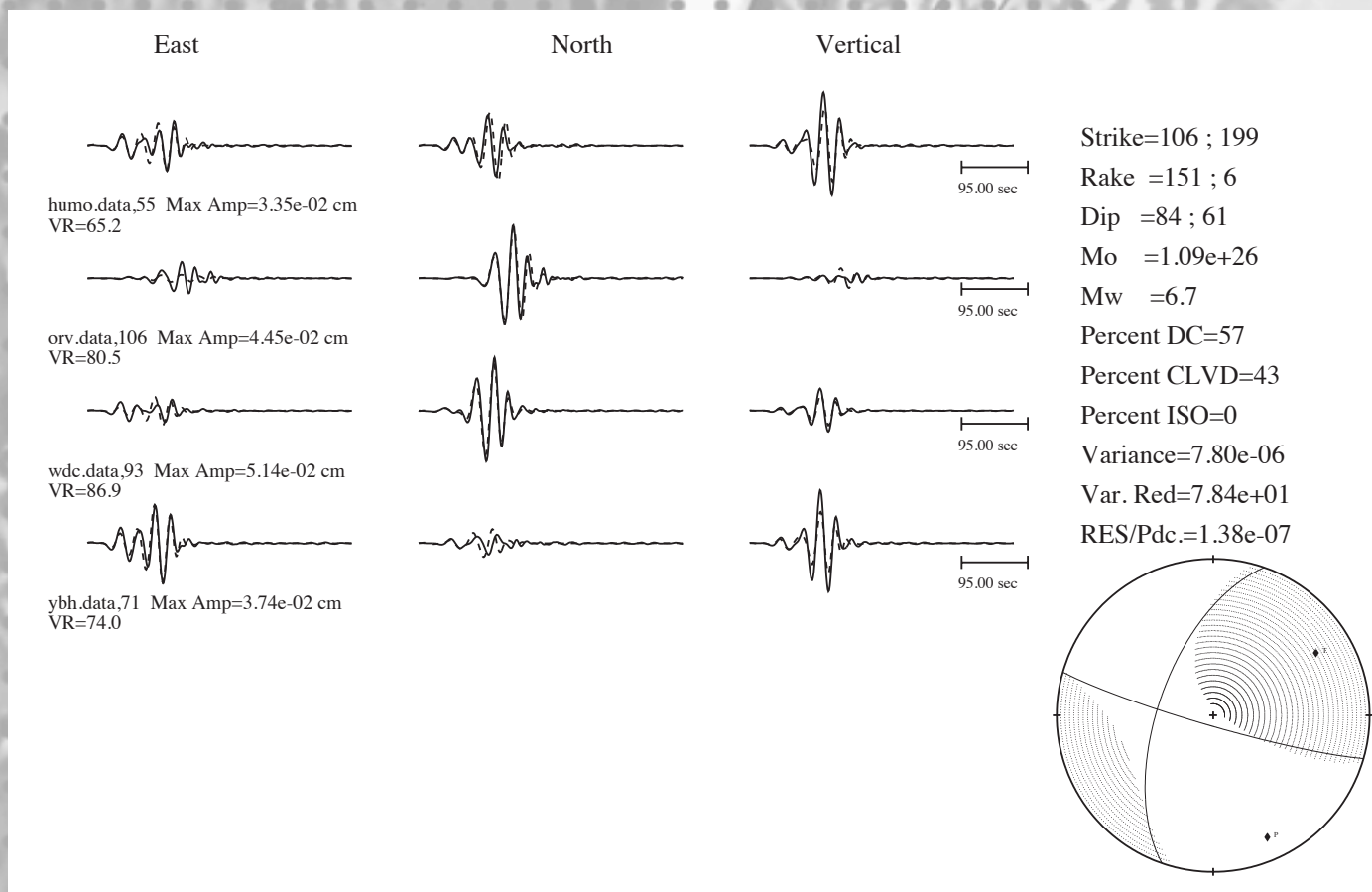
Magnitude 6.7 (18/06/2005)



Magnitude 6.7 (18/06/2005)

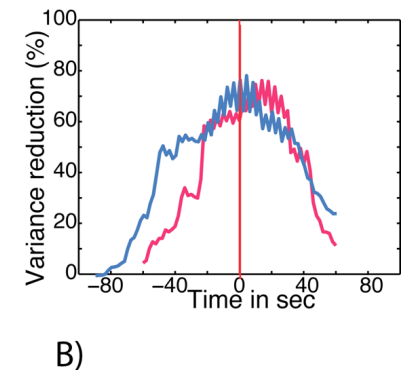
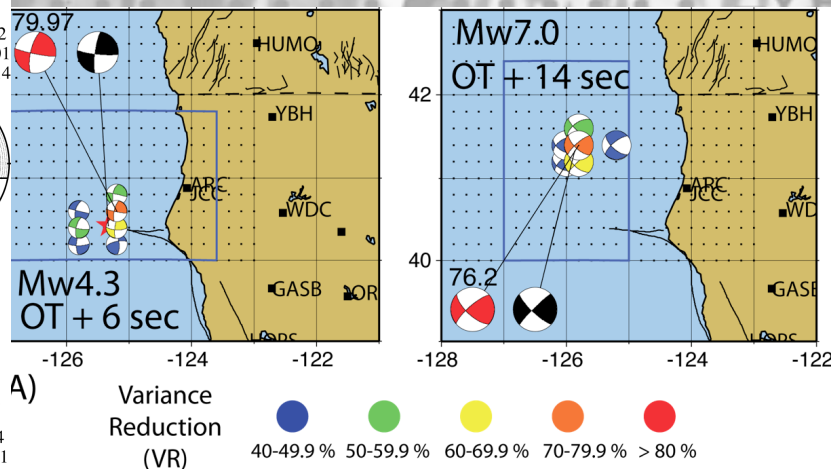
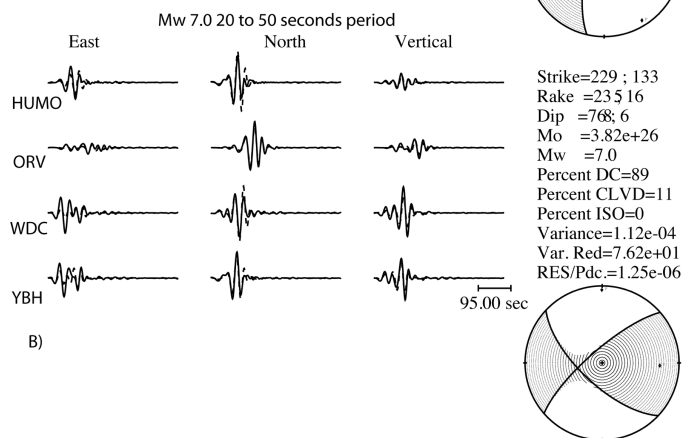
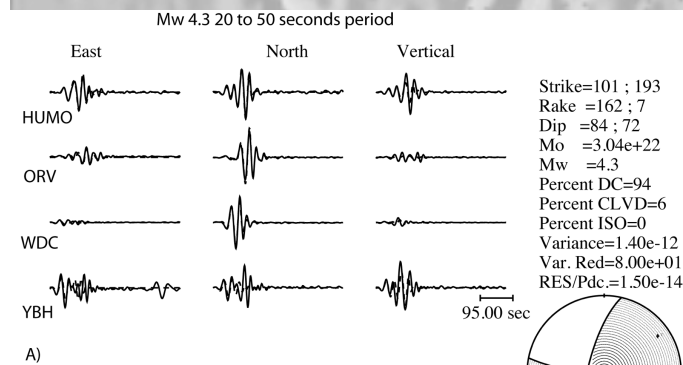


Magnitude 6.7 (18/06/2005)



	time	lat	lon	depth (km)	Mw	Strike1	Dip1	Rake1	horizontal misfit (km)	vertical misfit (km)	magnitude misfit	time misfit (s)
Berkeley MT catalog	6:21:42	40.758	-126.595	21	6.7	105	80	170				
Our solution	6:21:44	40.8	-126.6	38	6.7	106	84	151	4.7	17	0	2

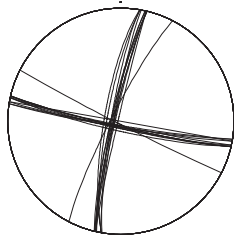
Similaires observations pour d'autres séismes de la région



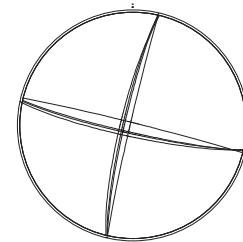
Résultats

Event	Catalog	Inversion	Magnitude difference	Horizontal difference (km)	Vertical difference (km)	Time difference (sec)	VR (%)
2008 M4.2			0	22.5	8	4	79.9
2006 M5.0			0.1	23.2	2	6	80
2008 M5.4			0.1	9.1	2	4	69.7
2005 M6.7			0	4.7	17	2	78.4
2005 M7.0			0	9.8	17	14	76.2

1 channel out



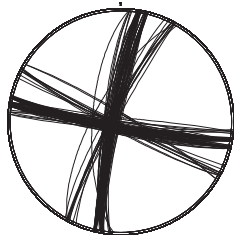
1 station out



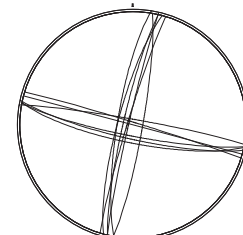
Tests of the stability of the moment tensor
when:

- up to 3 channels are out
- up to 3 stations are out

2 channels out



2 stations out

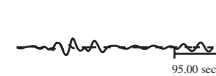
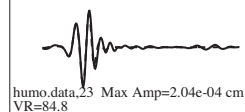


The earthquake considered is :
Mw5.0 lat=40.4 lon=-124.2 depth=32 km time=649
(07/19/2006)

East

North

Vertical



Strike=103 ; 193

Rake =174 ; 4

Dip =86 ; 84

Mo =2.95e+23

Mw =4.9

Percent DC=98

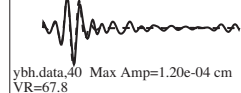
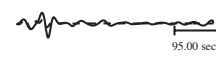
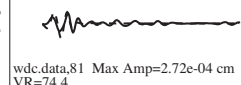
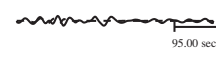
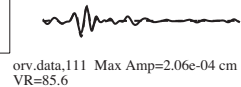
Percent CLVD=2

Percent ISO=0

Variance=1.69e-10

Var. Red=8.00e+01

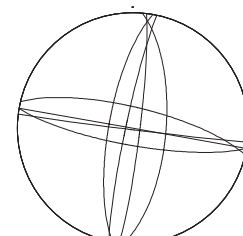
RES/Pdc.=1.72e-12



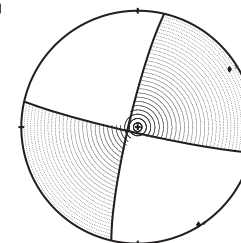
3 channels out



3 stations out

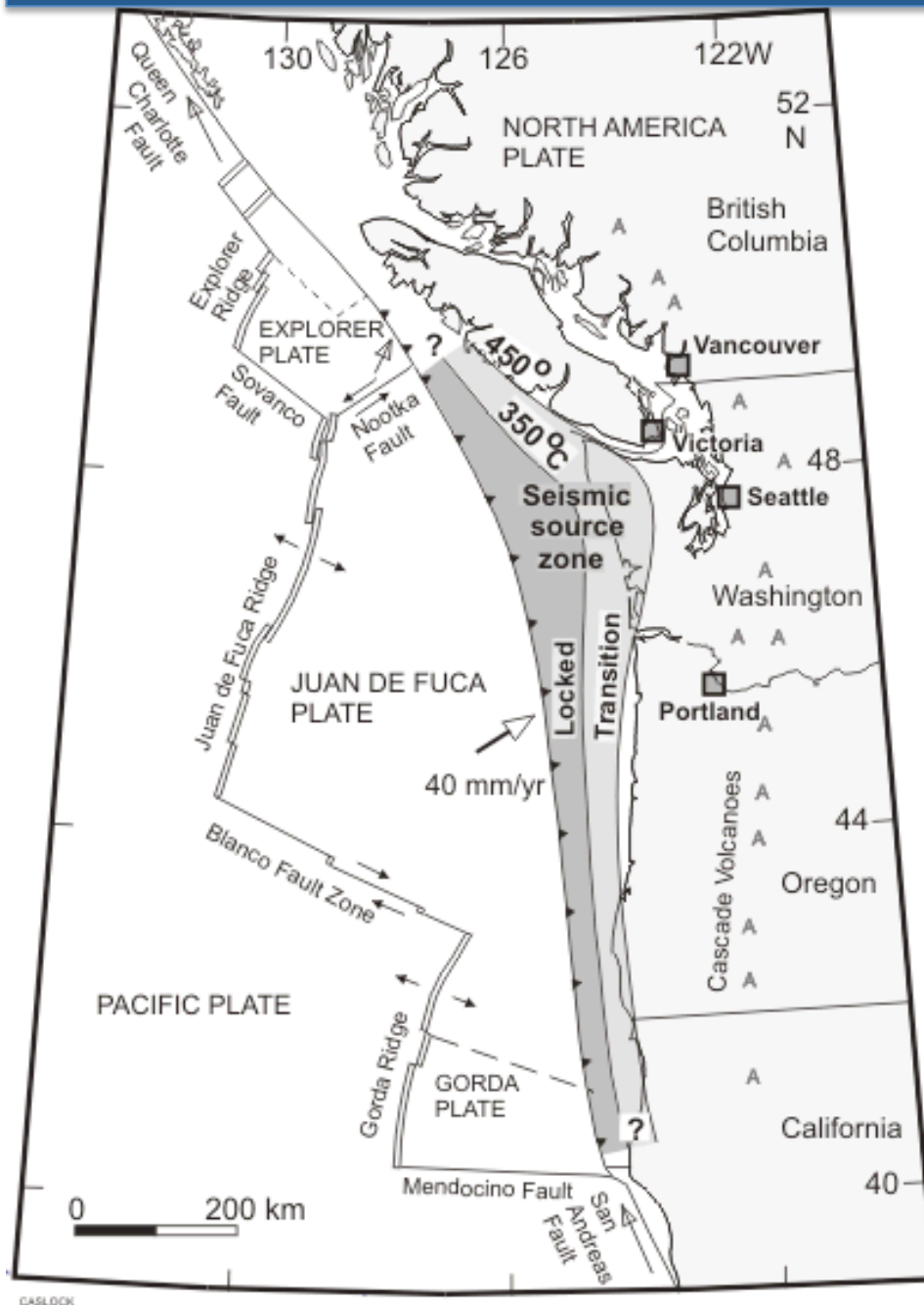


Reference moment tensor



★ Application: Alerte au tsunami

The background is a grayscale map of the Mendocino region, showing the coastline and various seismic stations marked with small squares and labeled with codes: HUMO, YBH, WDC, GASB, ORV, and HOPS. A grid of small dots is overlaid on the map, and a series of stars of varying sizes are clustered along the coast, indicating seismic activity. The title '★ Application: Alerte au tsunami' is prominently displayed in the center in a large, bold, blue serif font.



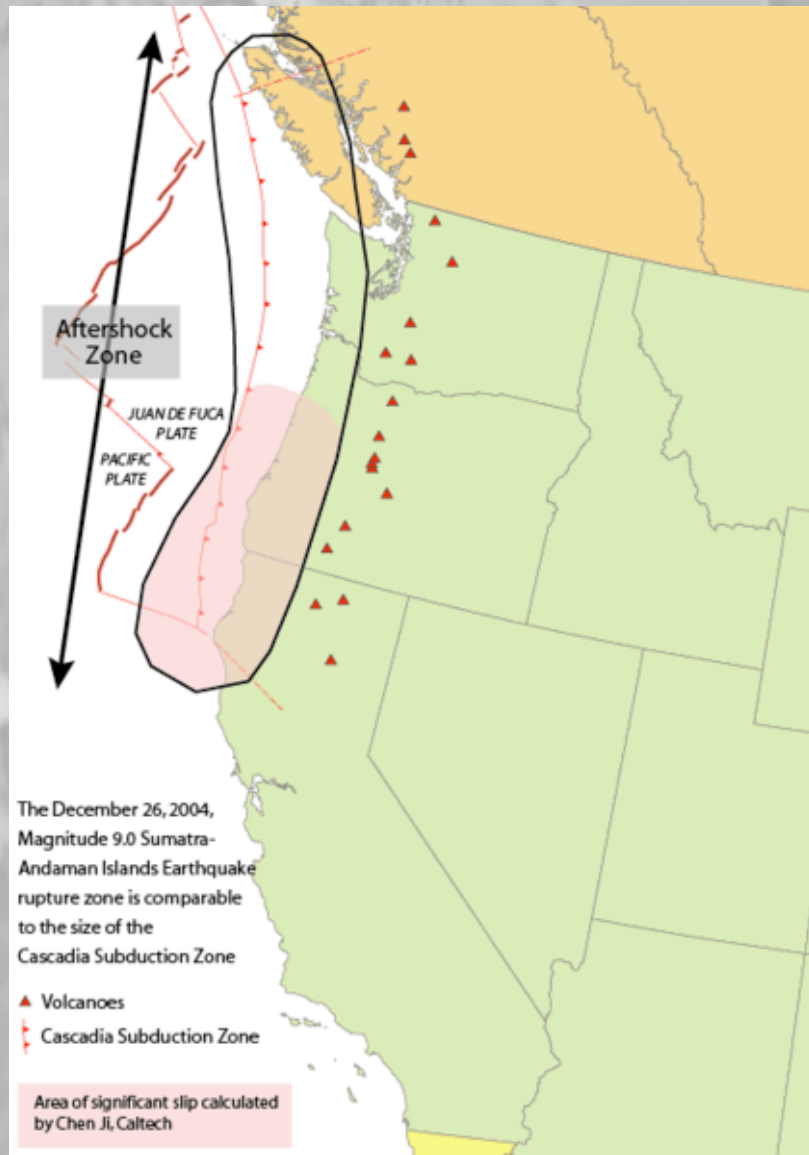
La zone de subduction des Cascades

Au nord du point triple de Mendocino

Evidences géologiques de forts séismes ($M > 7$)

- au moins 7 au cours des 1500 dernières années
- tsunamis
- Temps de récurrence varient entre 300-600 ans

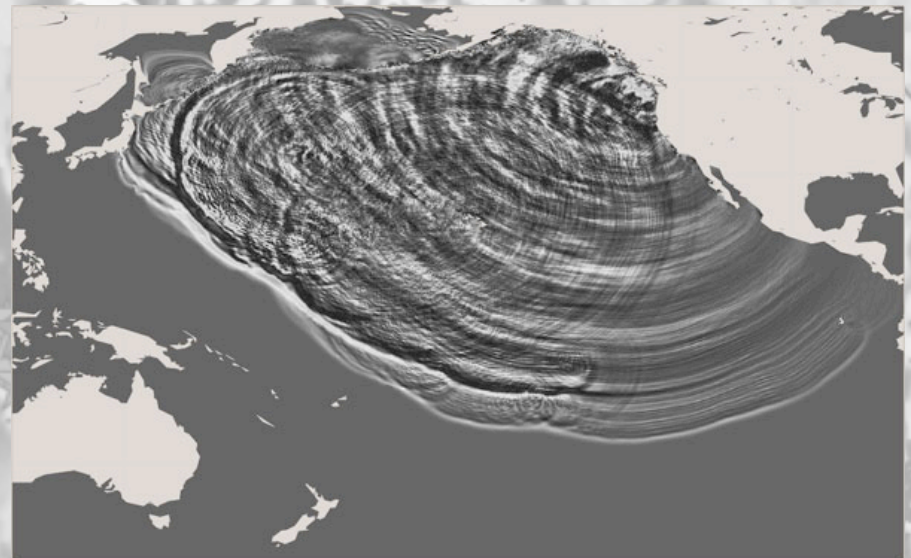
Magnitude max ~ 9



Dimensions de la zone similaires à celles de la zone de rupture de Sumatra 2004

Le plus fort séisme observé dans cette région a eu lieu en 1700

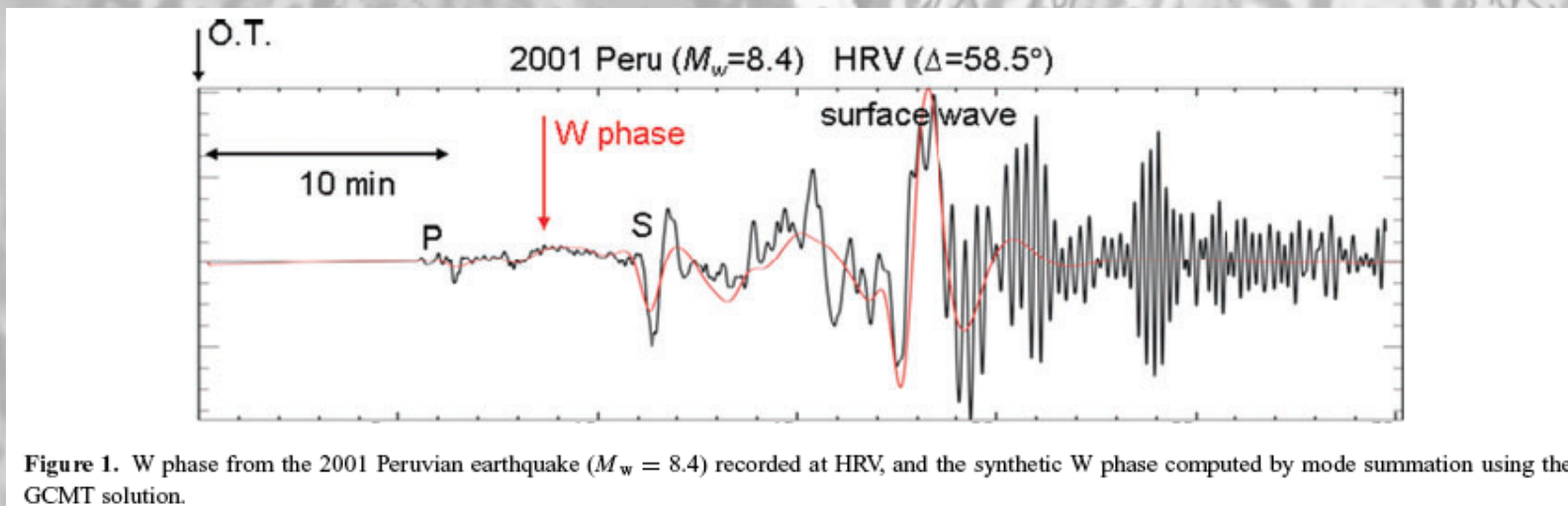
-> tsunami au Japon (10 heures après le temps d'origine)



Simulation par Kenji Satake, Japan's National Institute of Advanced Industrial Science and Technology

Alerte aux tsunamis à l'aide de la phase W

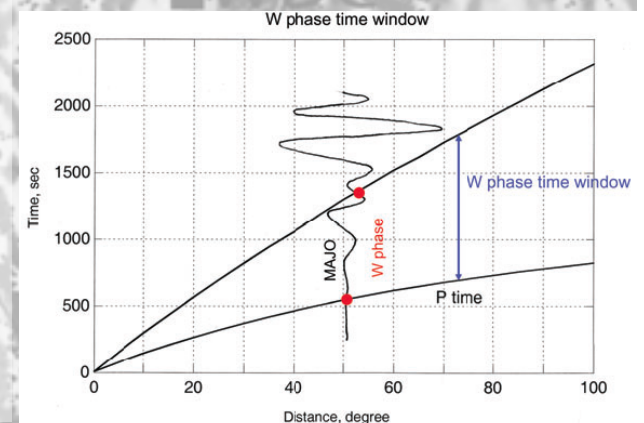
Utilisation d'observations télésismiques => Ondes de volume (P et S)
Et/ou par détection des ondes du tsunami par les bouées en mer



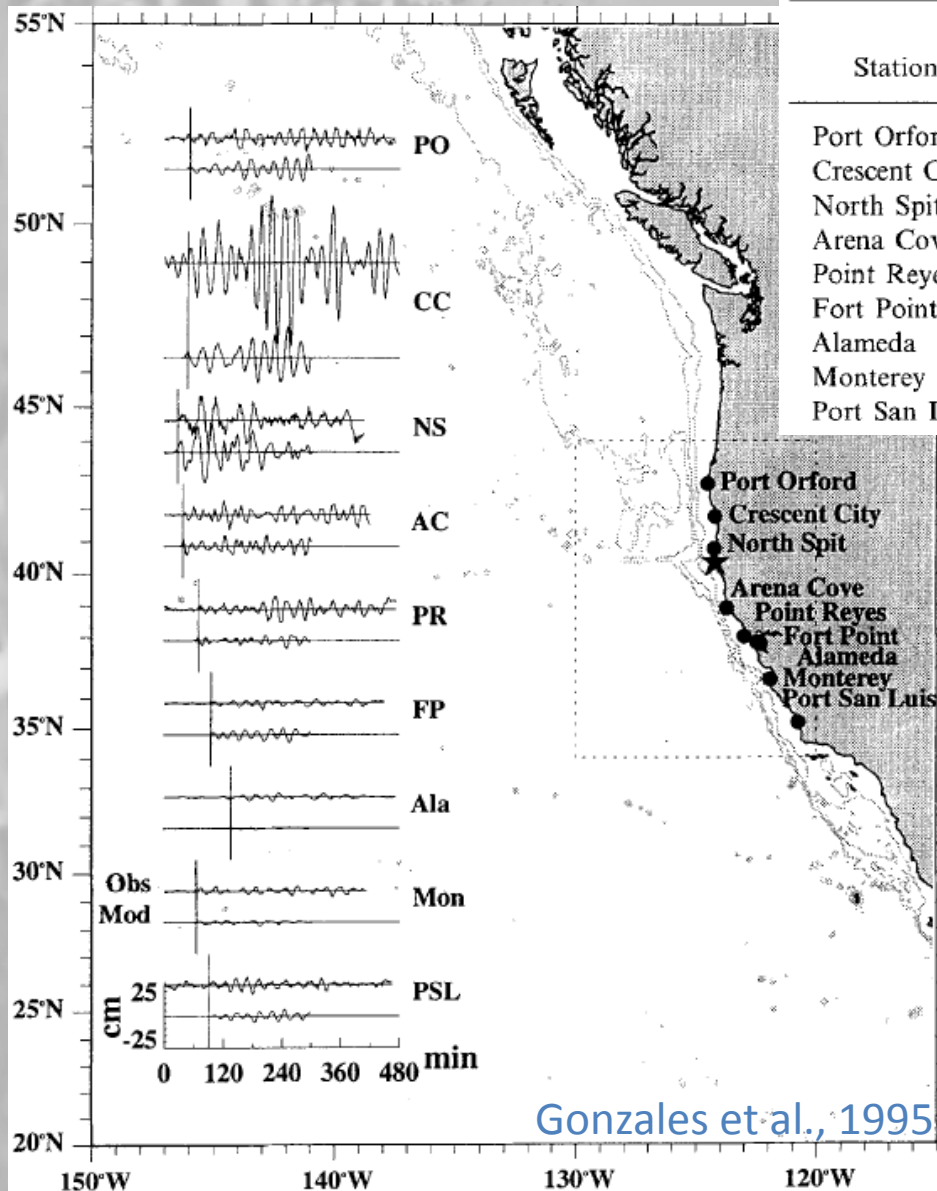
Kanamori et Rivera (2008): Utilisation des longues périodes (100 à 1000 sec) de la phase W, composée de la superposition du mode fondamental, et des 1ère, 2ième et 3ième harmoniques du mode sphéroïdal ou ondes de Rayleigh comme un moyen d'accélérer l'alerte tsunami.

$V_w = 4.5 - 9 \text{ km/sec}$

$A \sim 50^\circ \rightarrow \sim 23 \text{ minutes après le temps d'origine}$



Wave ray travel time computations,
assuming propagation speed $c_g = (gh)^{1/2}$



Besoin de développer des méthodes de détection en champ proche

Sumatra (2004):

Le tsunami a touché Banda Aceh environ 15 minutes après le séisme

Pour la région de Mendocino, le temps critique pour l'annonce d'un tel séisme/tsunami est compris entre **10 et 20 minutes.**

Tests pour un séisme de M8+

Absence de séisme de $M > 7.5$
dans le catalogue de sismicité

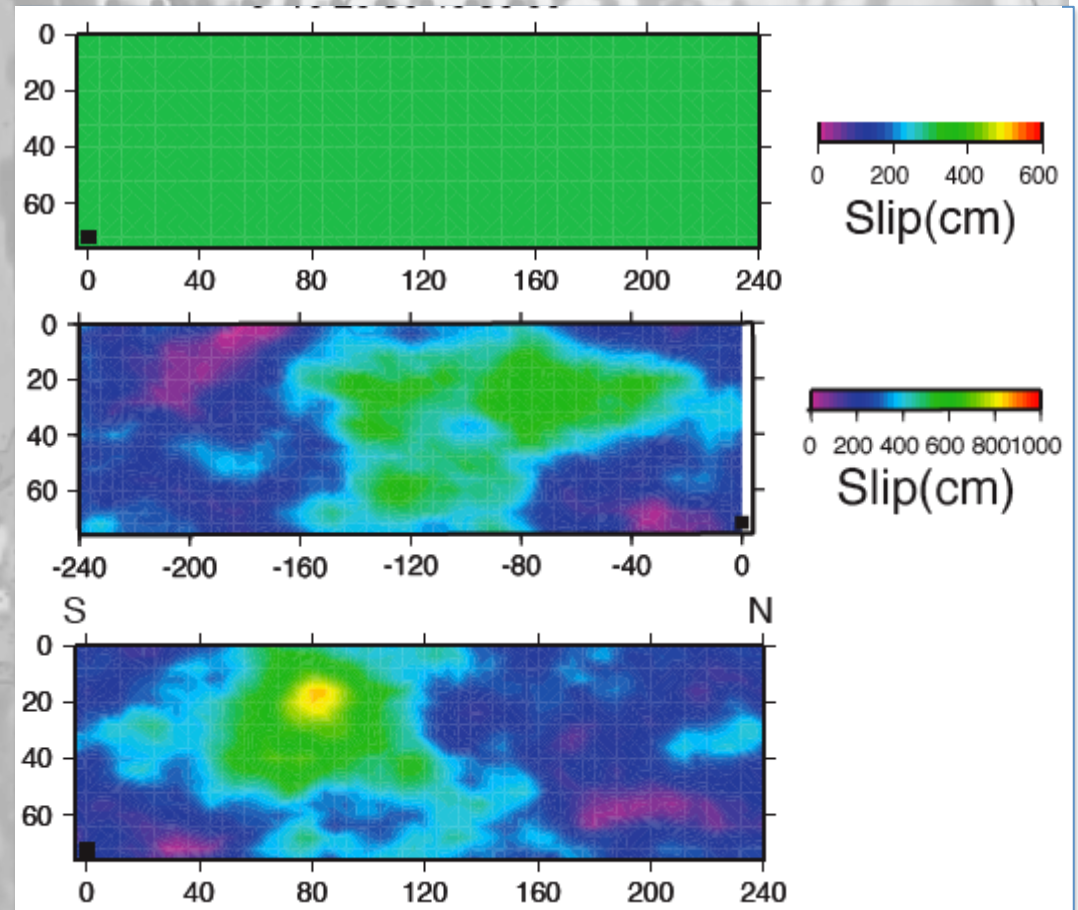
Besoin de modéliser un tel
séisme pour tester la méthode

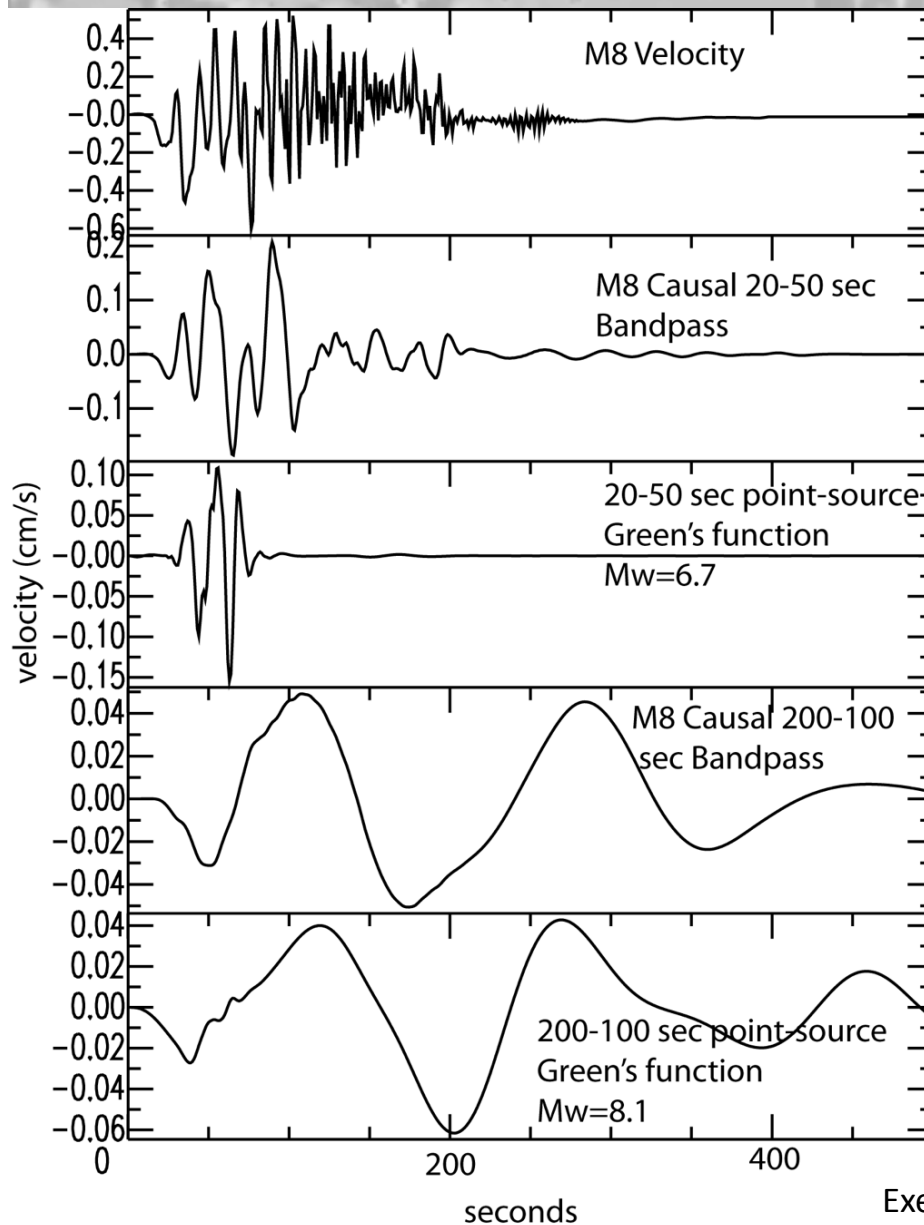
2 types de rupture:

- glissement homogène
- glissement variable

Inversion de 480 sec

Catalogue de fonctions de
Green filtrées entre 100 et 200
sec





Deux systèmes en parallèle

Pour les séismes de M4-7

- 20-50 sec
- Inversion de 380 sec

MAIS 20-50 sec: trop courtes fréquences et longueur de l'enregistrement pour de forts tremblements de terre

Pour les séismes de M>8

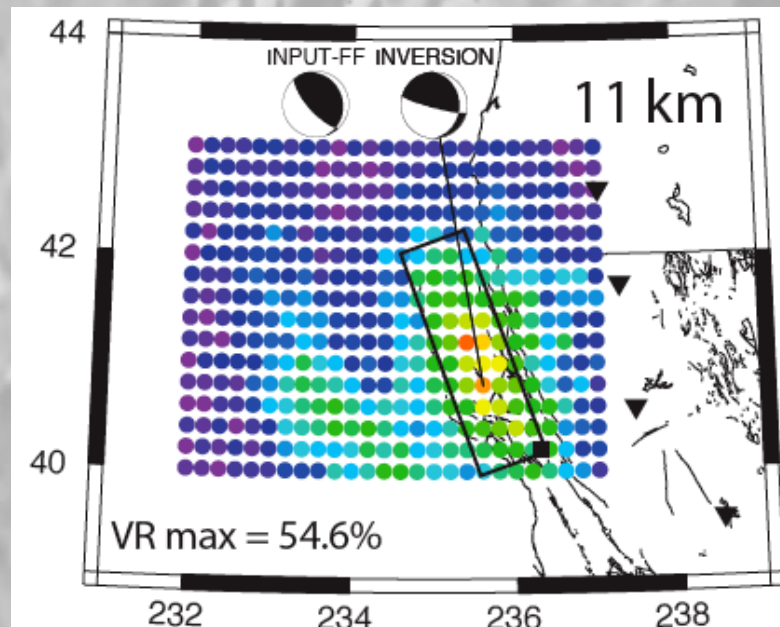
- 100-200 sec
- Inversion de 480 sec

Exemple d'une rupture de 250 km x 80 km, glissement uniforme de 3.2 m, rise time de 9 s et vitesse de rupture de 3 km/s

Rupture avec glissement homogène

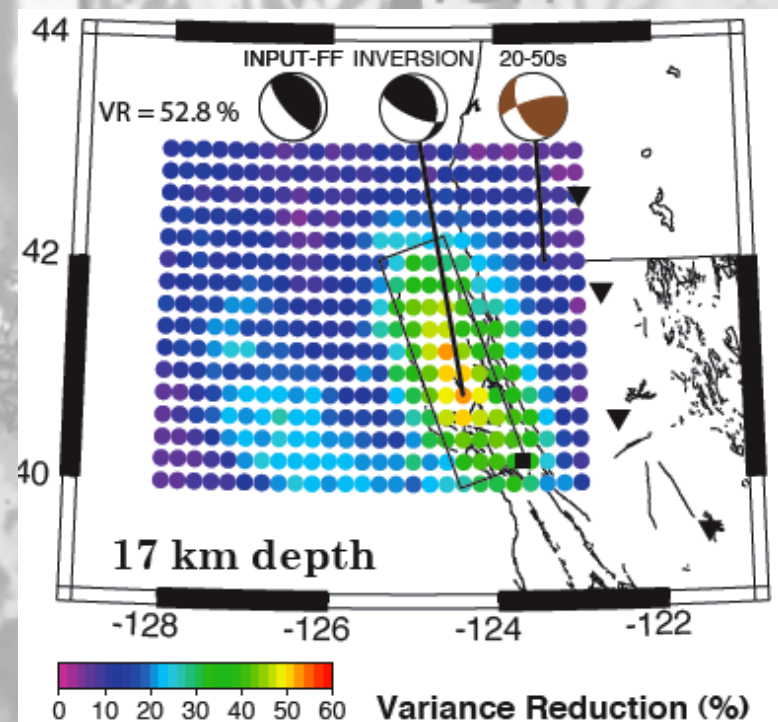
A 100-200 sec:

VR autour 50%
Localisation : dans la rupture
Temps d'origine : correct

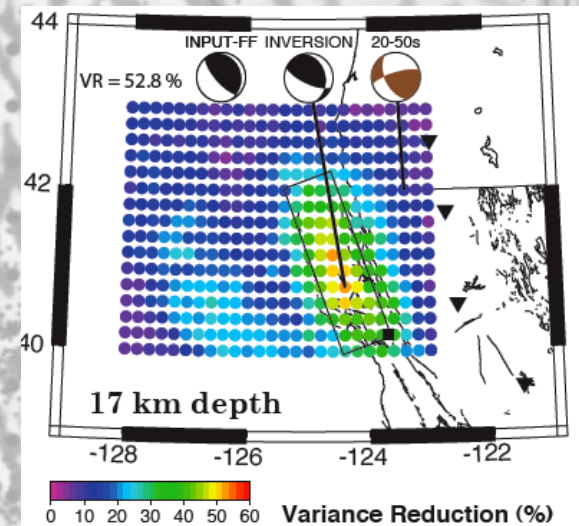
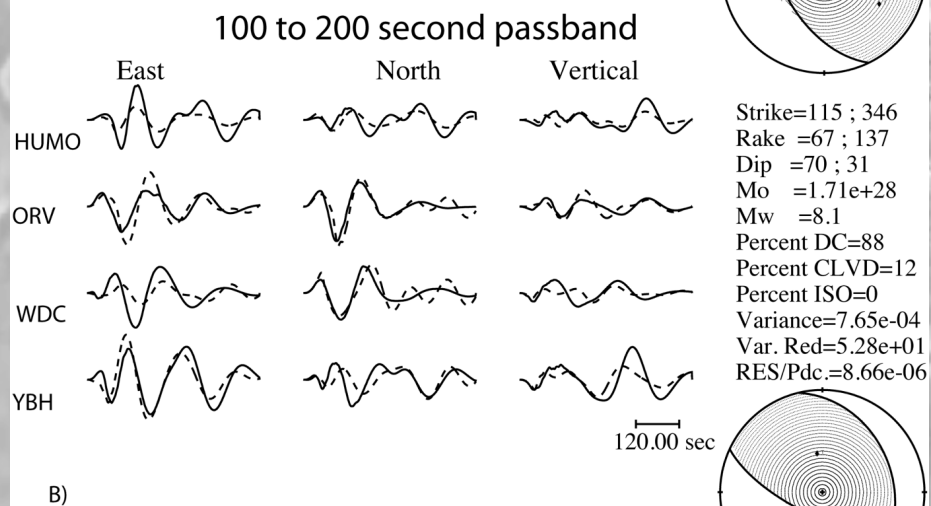
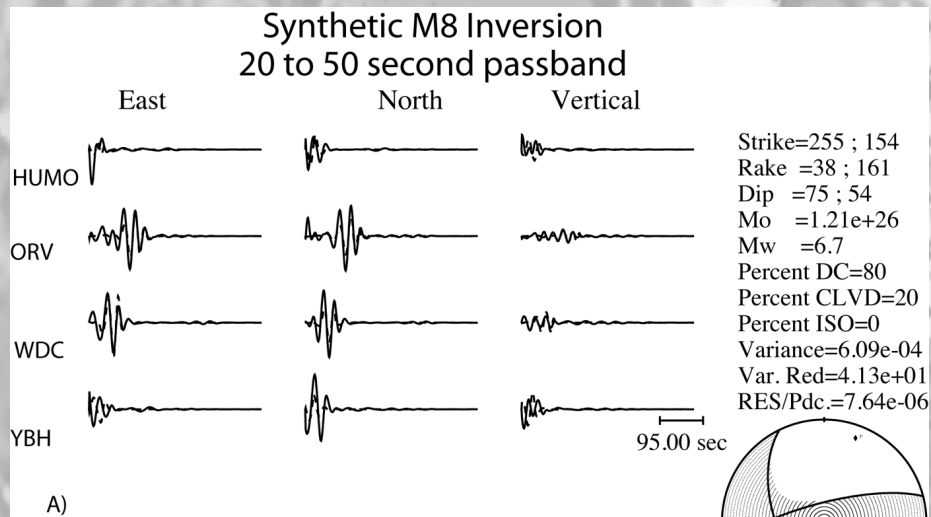


A 20-50 sec:

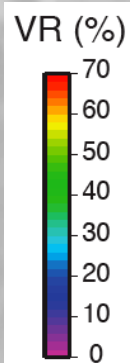
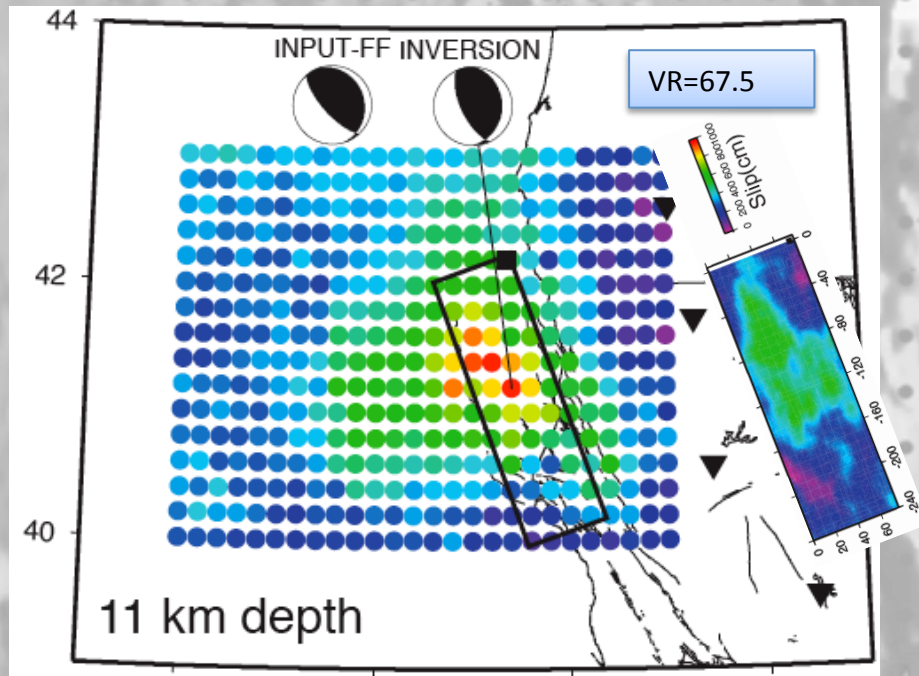
VR autour 40 %
Localisation : sur le continent
Temps d'origine: 2 min après



Rupture avec glissement homogène



Rupture avec glissement variable



A 20-50 sec

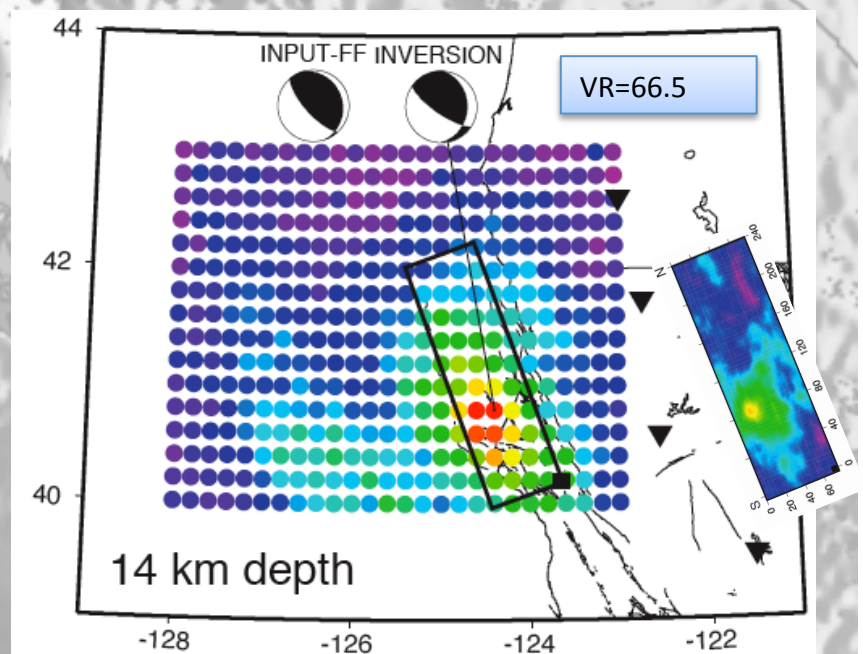
VR < 40%

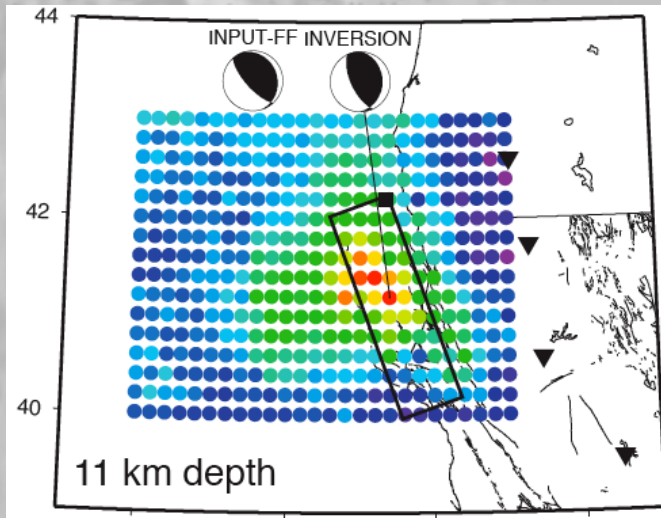


Meilleures VRs : au-dessus de 65%

Meilleures localisations : approx. au centroïde

Magnitude et mécanisme équivalents au modèle





*Wave ray travel time computations,
assuming propagation speed $c_g = (gh)^{1/2}$*

Station	Travel Time (min)
Port Orford	50
Crescent City	47
North Spit	26
Arena Cove	37
Point Reyes	69
Fort Point	94
Alameda	135
Monterey	64
Port San Luis	97

Intérêt à filtrer les données à plus longues périodes pour les forts séismes

Variance réduction au-dessus de 60% - 65%

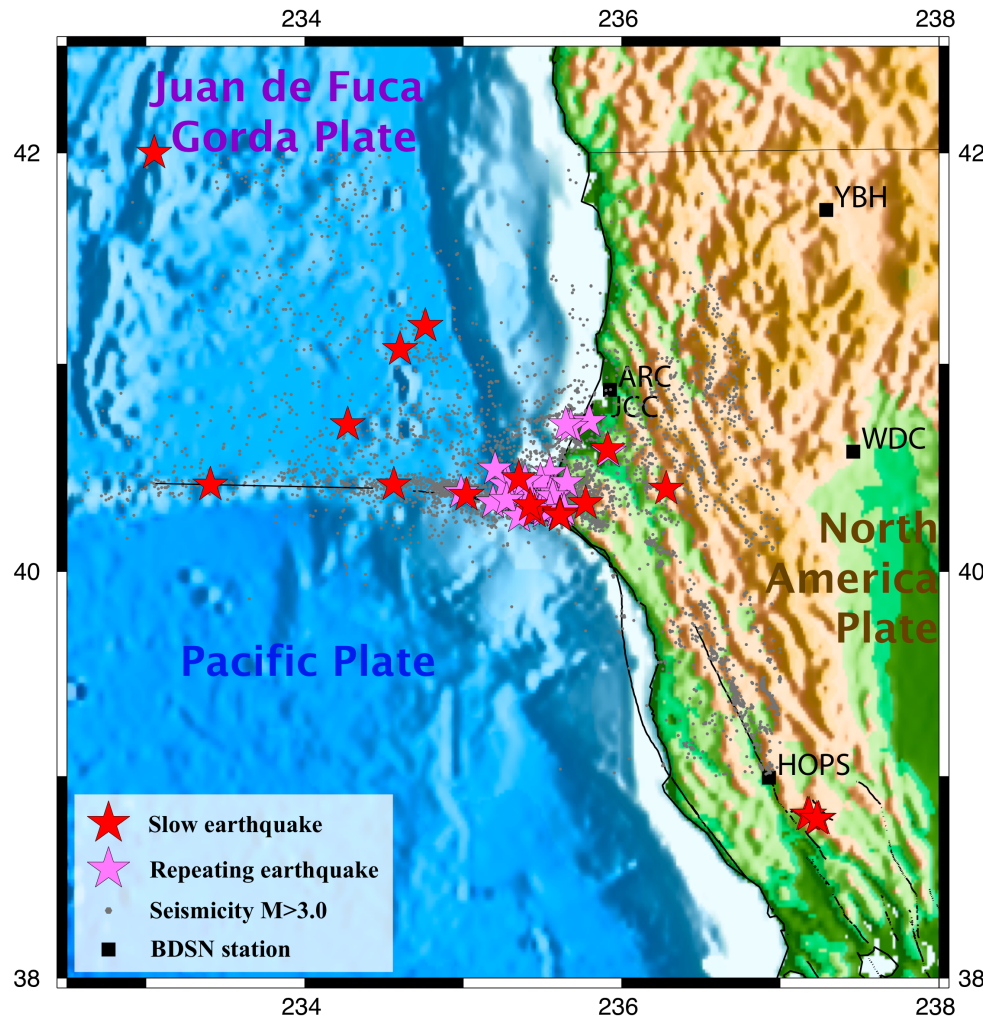
Bonne localisation des évènements

Obtention des informations complètes d'un fort séisme environ 8 minutes après l'origine

Temps de propagation des ondes tsunamiques compris entre 10 et 20+ minutes



Application: Recherche de séismes lents



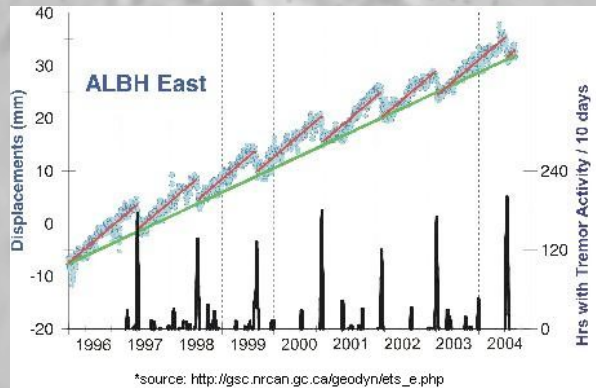
Détection de séismes lents dans la région du point triple

18 séismes lents détectés à partir du catalogue des tenseurs des moments de Berkeley

Magnitude (M_w): 4.0 à 6.8

Profondeur: 5 à 30 km

Day	Hour	Latitude	Longitude	Depth (km)	MI	Mw	Mw-MI
04/25/92	18:06	40.33	-124.23	8	6.3	6.8	0.5
06/05/92	21:46	40.29	-124.55	21	4.8	5.5	0.7
03/04/95	21:51	40.71	-125.73	18	3.5	4.6	1.1
11/11/95	20:19	40.40	-123.72	30	3.5	4.0	0.5
12/24/95	07:41	42.00	-126.95	5	4.4	5.3	0.9
01/22/97	07:17	40.27	-124.39	24	4.8	5.6	0.8
01/26/97	06:23	40.28	-124.39	21	4.0	5.2	1.2
10/06/97	12:00	41.07	-125.40	24	4.1	4.6	0.5
02/15/99	06:00	40.28	-124.39	27	3.8	4.7	0.9
12/26/99	19:41	40.27	-124.39	24	4.2	4.8	0.6
01/08/03	05:41	40.42	-125.44	8	4.2	4.7	0.5
02/18/03	14:44	41.18	-125.24	11	3.7	4.2	0.5
04/22/03	10:46	40.59	-124.09	27	3.9	4.4	0.5
06/26/03	03:39	40.40	-126.57	14	4.1	4.6	0.5
07/04/03	20:52	40.32	-124.58	21	3.7	4.3	0.6
08/26/03	02:29	40.45	-124.65	24	3.9	4.4	0.5
03/18/05	07:23	40.37	-124.98	18	4.4	5.0	0.6



Séismes lents $\neq$ séismes silencieux

Différence entre la magnitude du moment et la magnitude locale:

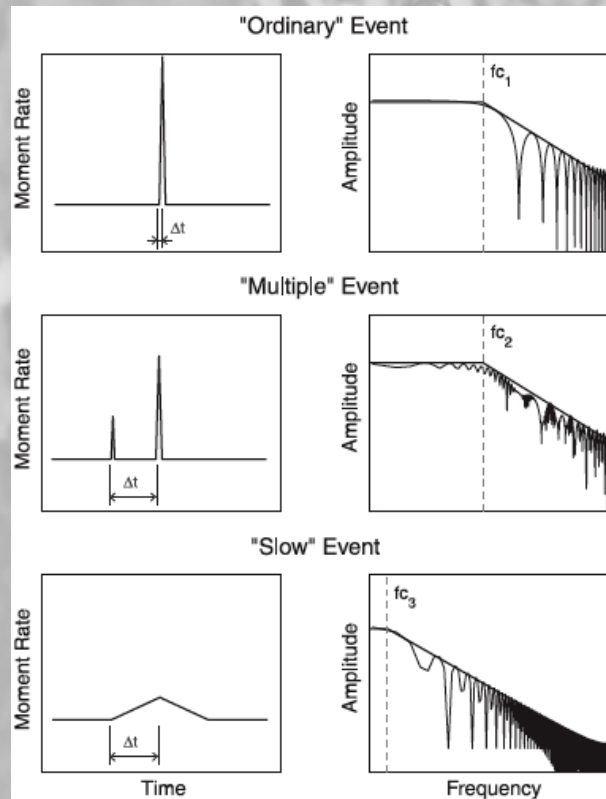
$$M_w - M_L \geq 0.5$$

Faible radiation à hautes fréquences

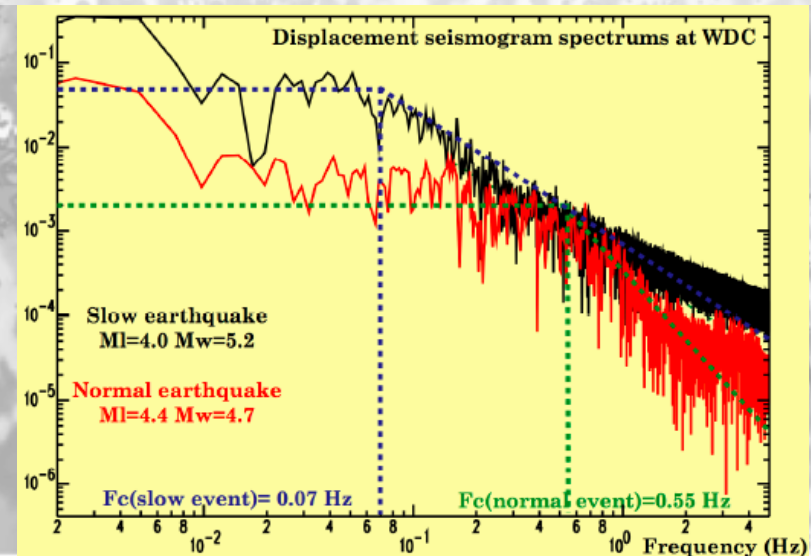
Faible chute des contraintes

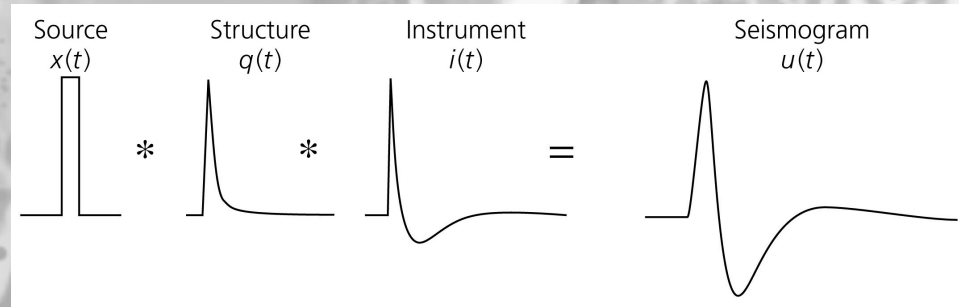
Plus courte fréquence coin qu'un séisme régulier

Fréquence coin correspondant à un séisme de magnitude supérieure



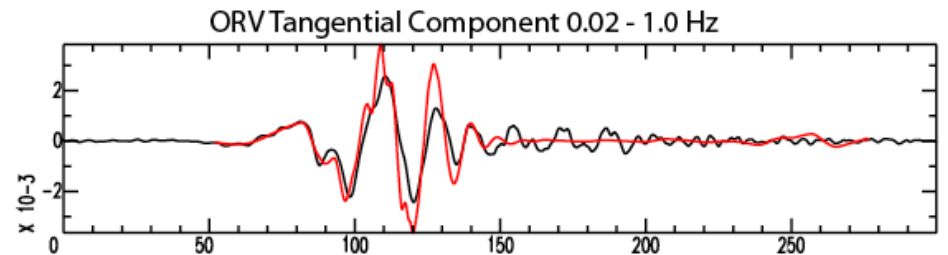
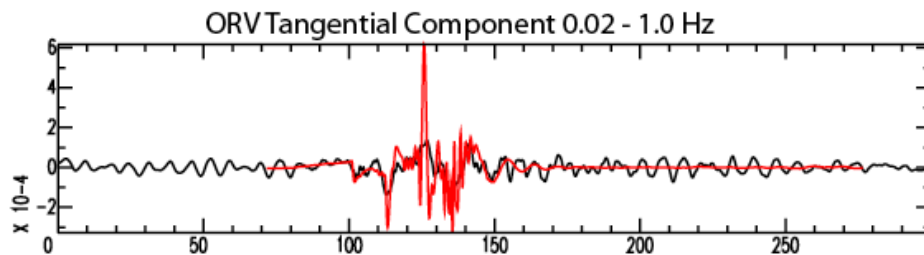
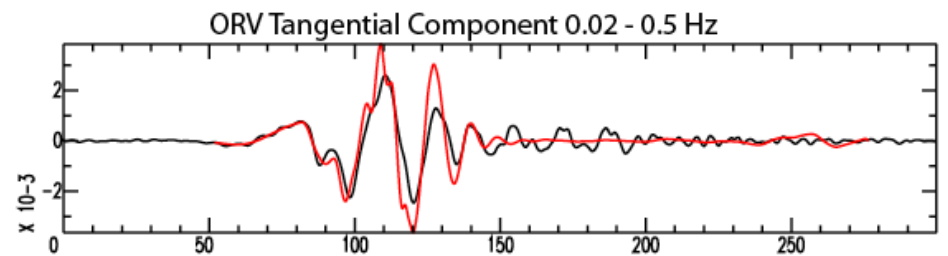
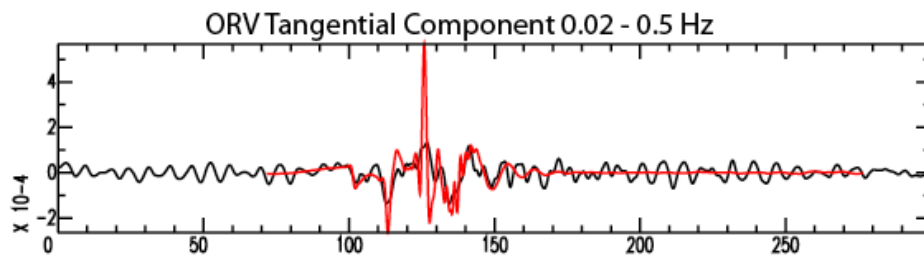
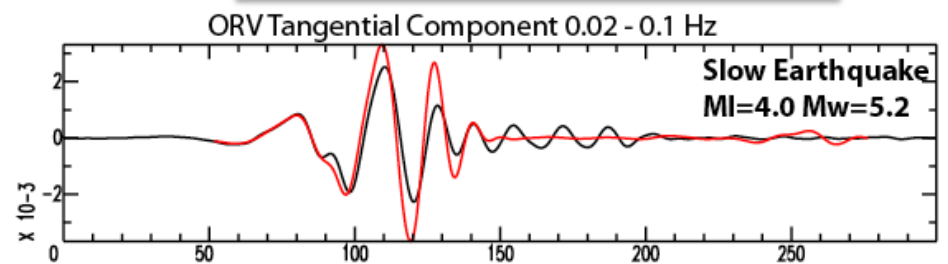
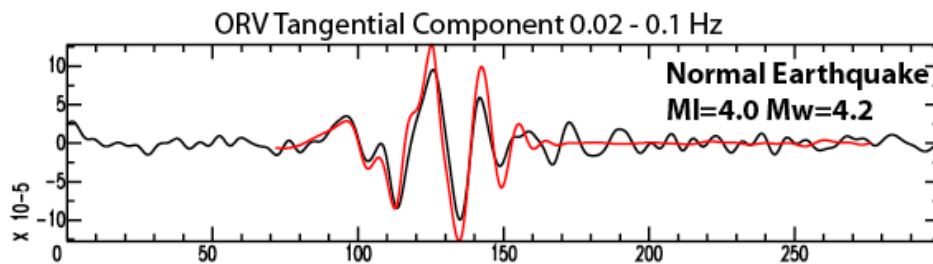
Perez-Campos et al., 2003





Uniquement la fonction de Green

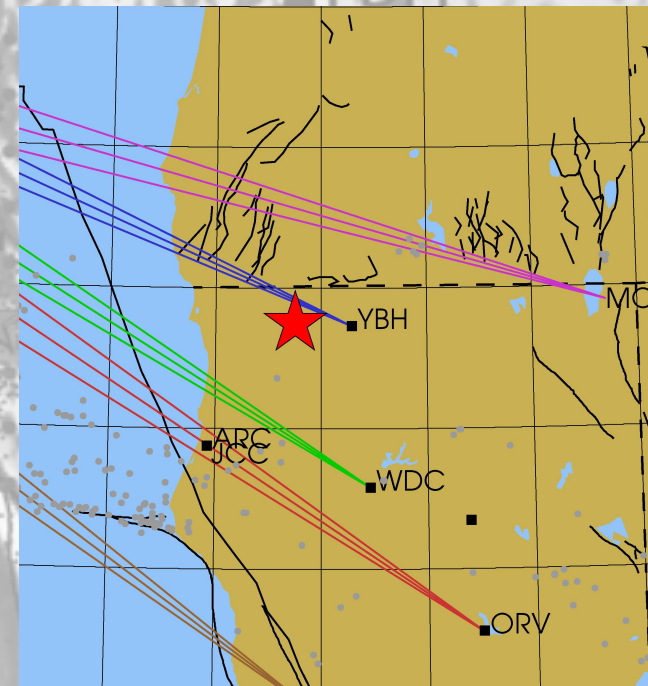
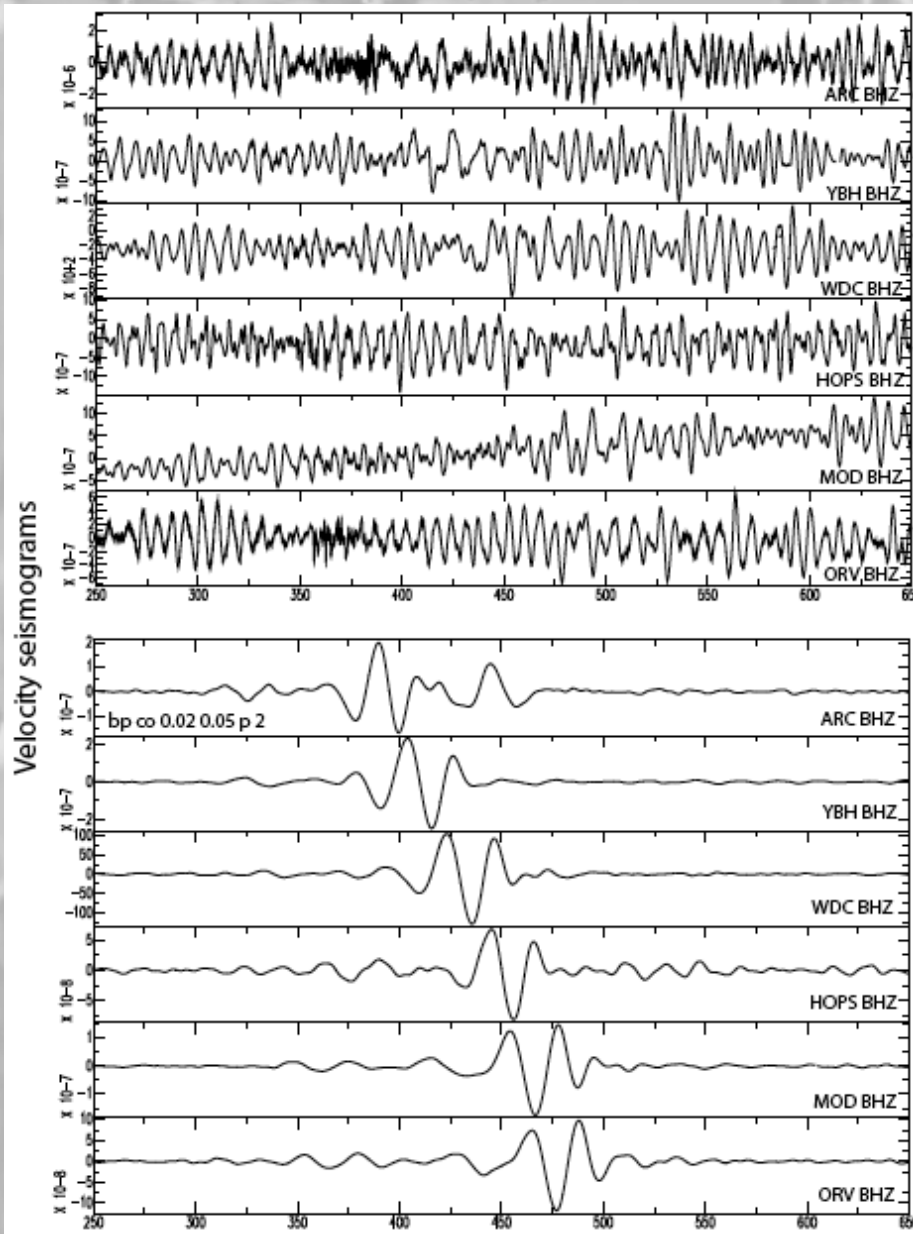
Fonction de Green
+
Fonction de temps de 10 sec



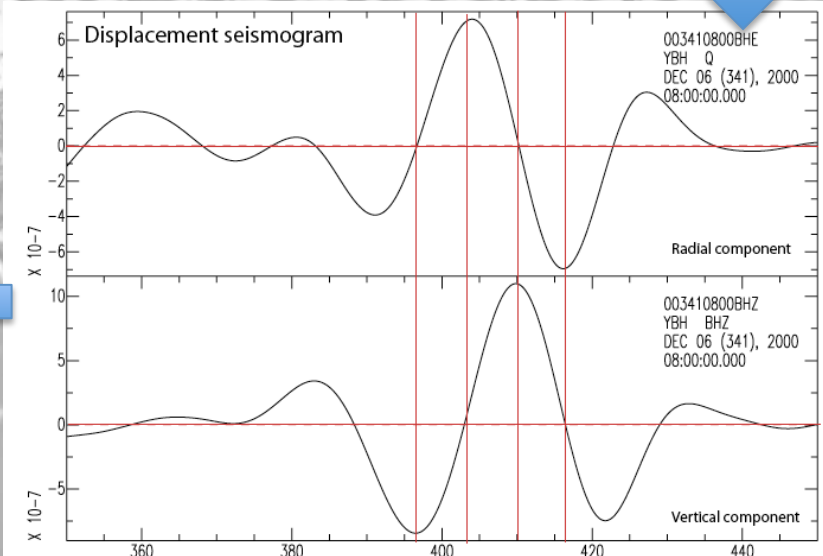
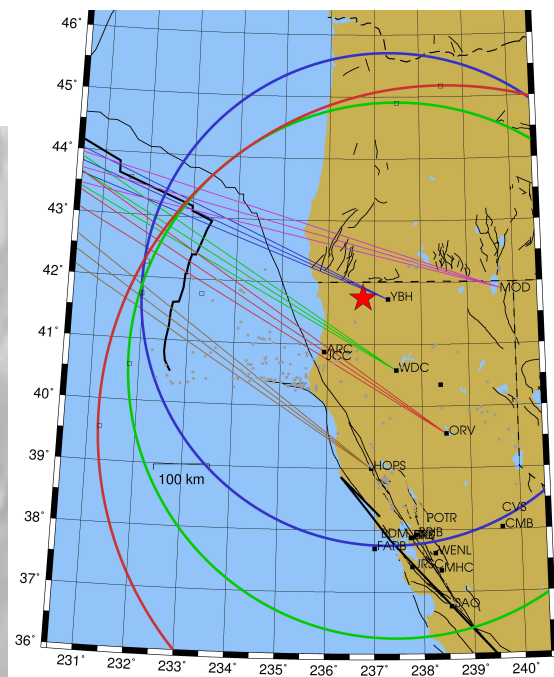
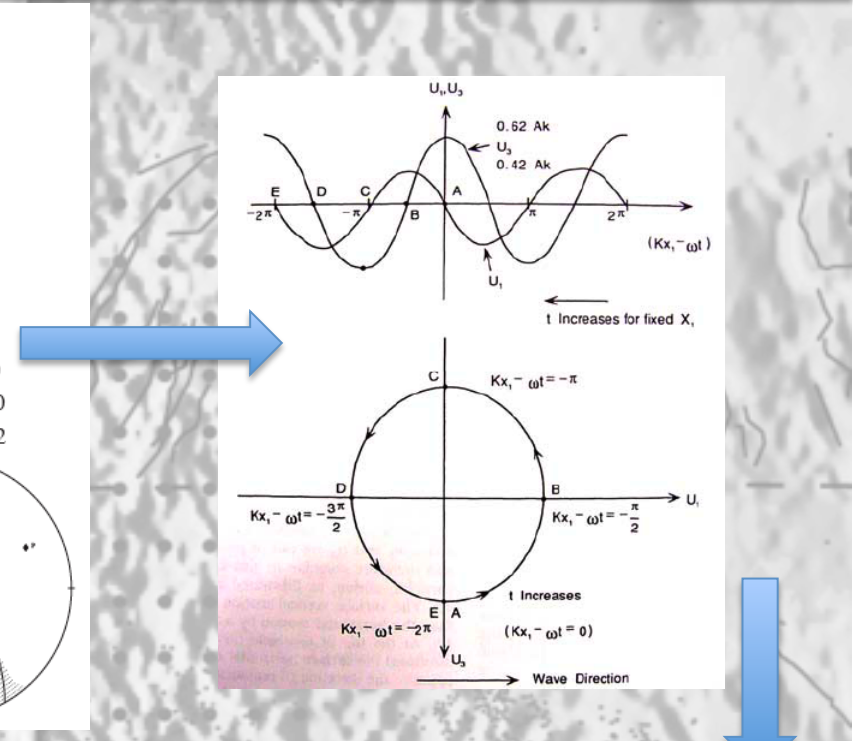
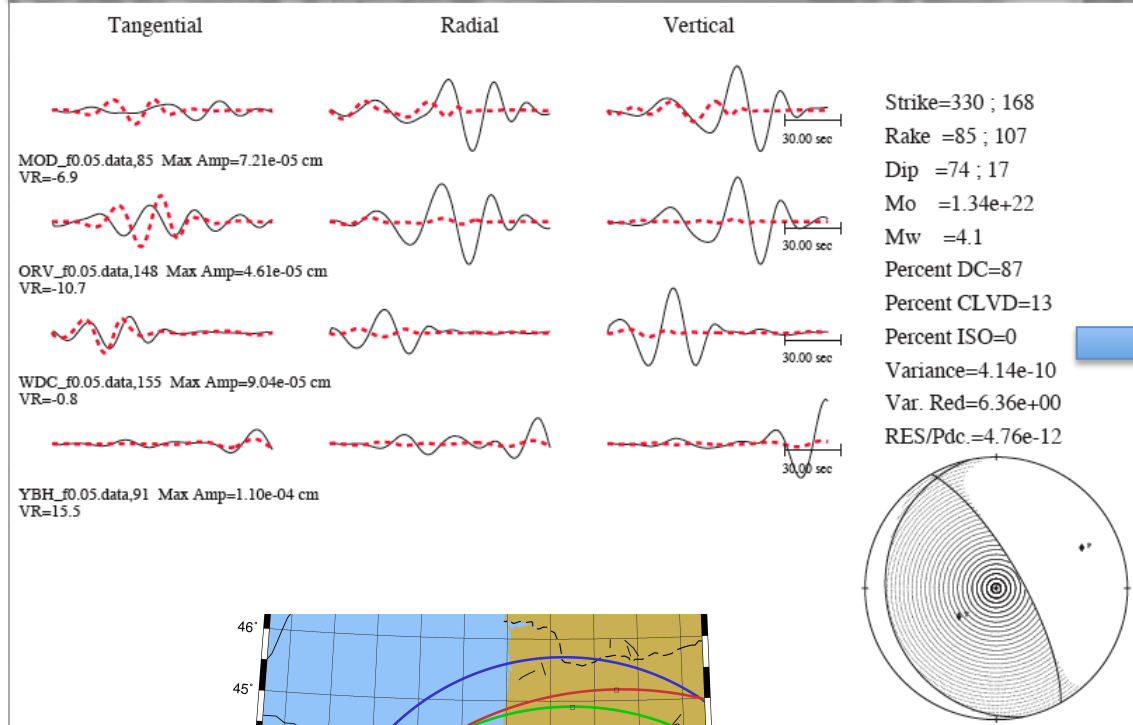
Etude d'un séisme lent

Isolé par Goran Ekstrom (Harvard):

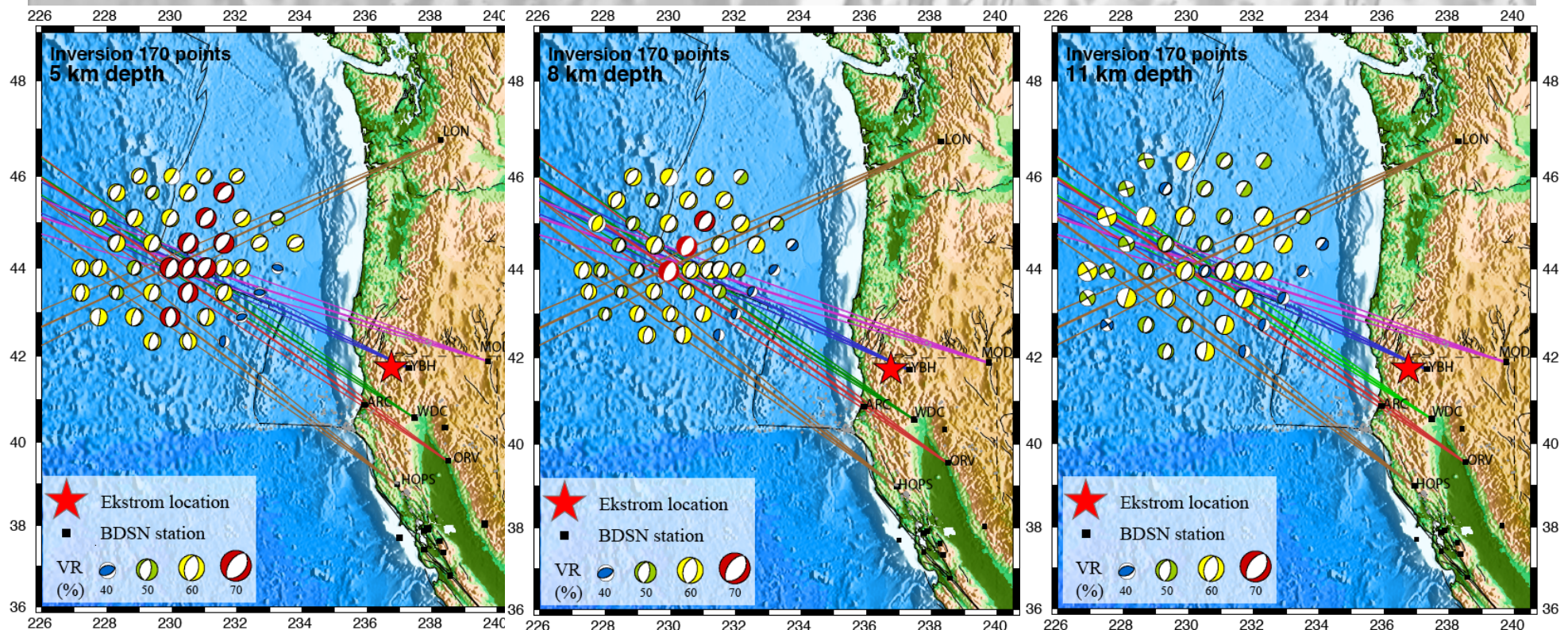
SWEC 2000 12 6 8 6 16.00 41.75
-123.25 10.0 0.0 4.8 Northern
California



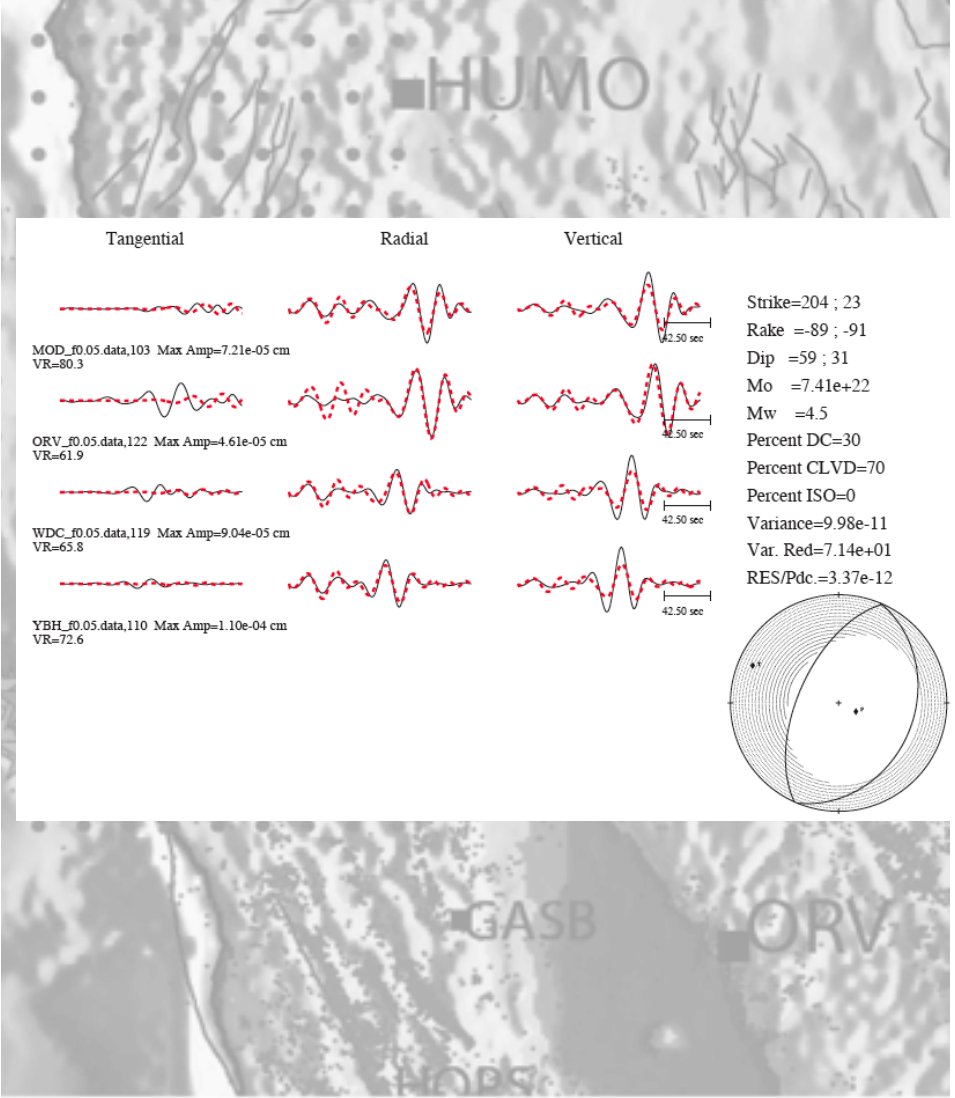
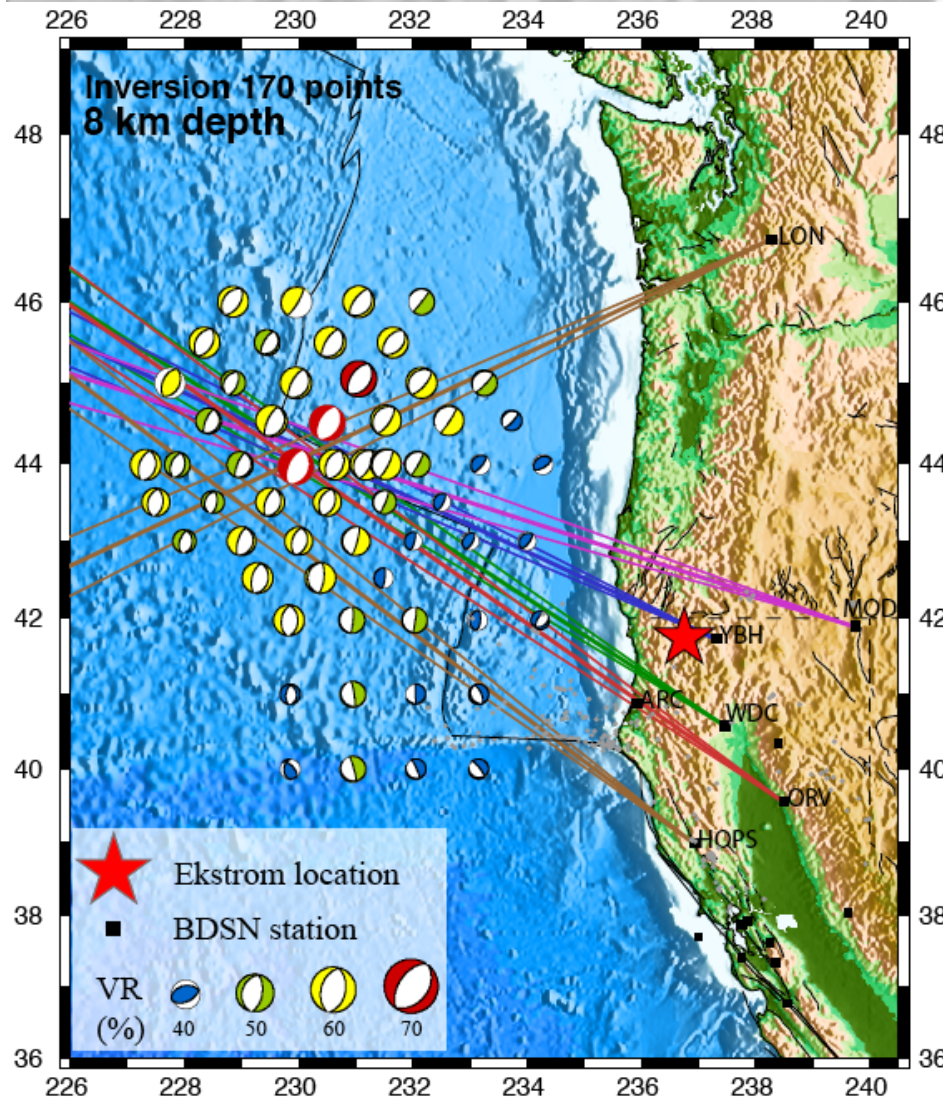
Région de Mendocino | Grille de MTs | Tests | Application: Tsunamis | **Application: Séismes lents**



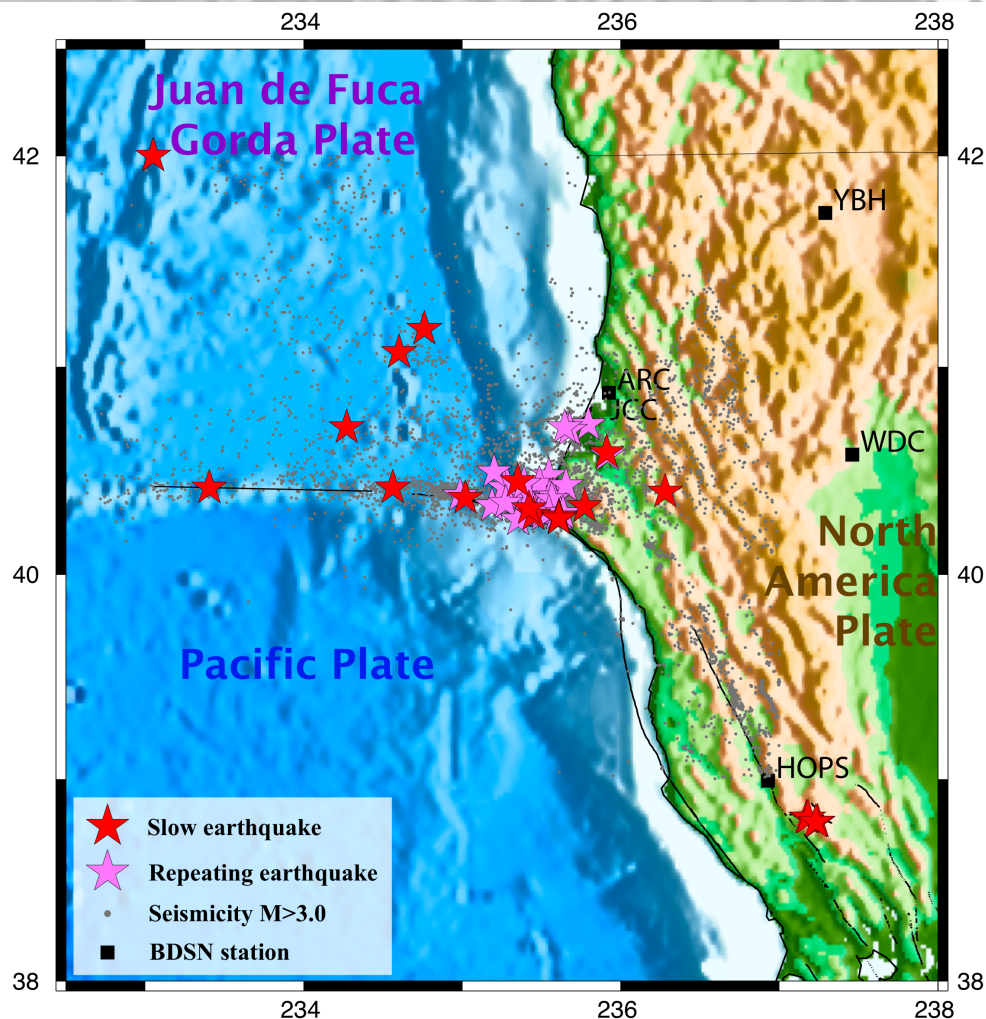
Utilisation des tenseurs des moments pour localiser ce séisme



Localisation par tenseurs des moments



Détection de séismes lents



Les tenseurs des moments de l'ensemble des séismes lents ont été calculés entre 20 et 50 sec

Mais uniquement identifiés car $M_l \geq 3.5$ pour connaître M_w

Possibilité d'identifier d'éventuels séismes lents qui auraient un $M_l < 3.5$

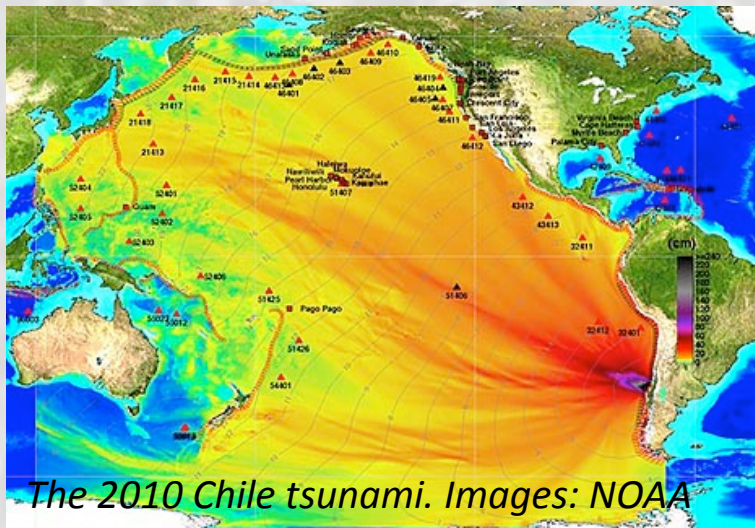
Aussi possibilité de chercher pour des séismes "plus" lents en filtrant les données entre 100 et 200 sec.

Conclusions

- Possibilité de détecter de façon continue l'ensemble de l'activité sismique de la région de Mendocino en temps réel à l'aide des tenseurs des moments
- Informations des séismes en **une seule procédure** ce qui évite les erreurs potentielles du système en cascade
- Données filtrées entre 20-50 sec pour les M4-7+ et entre 100-200 sec pour les M8+
- Possibilité de détecter les forts séismes en utilisant une méthode point-source -> centroïde

Conclusions

- Alerte au tsunami possible sur les côtes locales et régionales environ 8 minutes après le séisme -> temps d'alerte d'environ 10 minutes



AN EARTHQUAKE HAS OCCURRED WITH THESE PRELIMINARY PARAMETERS

ORIGIN TIME - 0634Z 27 FEB 2010
 COORDINATES - 36.1 SOUTH 72.6 WEST
 DEPTH - 55 KM
 LOCATION - NEAR COAST OF CENTRAL CHILE
 MAGNITUDE - 8.8

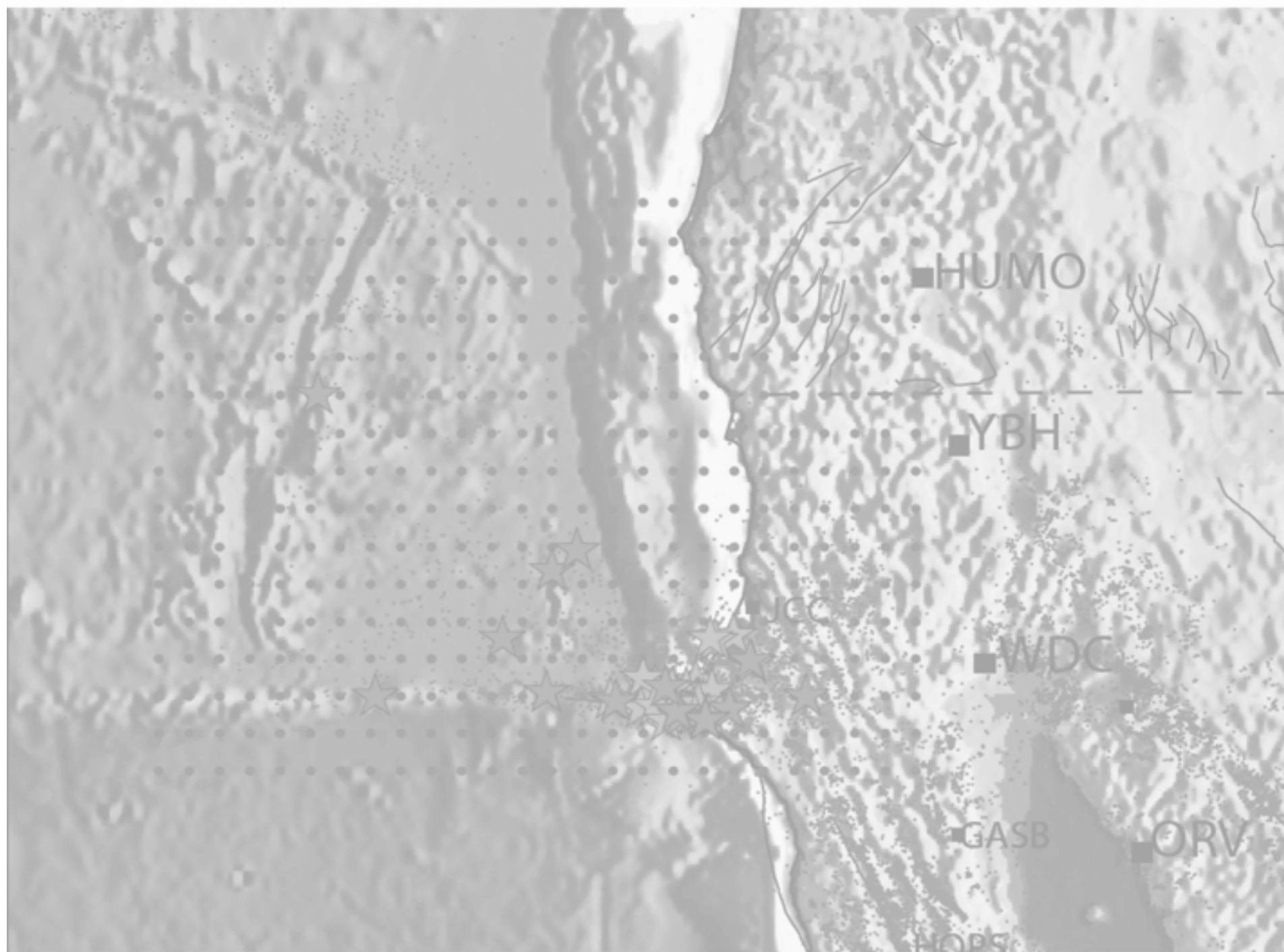
19 minutes

MEASUREMENTS OR REPORTS OF TSUNAMI WAVE ACTIVITY

GAUGE LOCATION	LAT	Lon	TIME	AMPL	PER
CALDERA CL	27.1S	70.8W	0843Z	0.45M / 1.5FT	20MIN
ANTOFAGASTA CL	23.2S	70.4W	0832Z	0.40M / 1.3FT	58MIN
TALCAHUANO CL	36.7S	73.4W	0653Z	2.34M / 7.7FT	88MIN
COQUIMBO CL	30.0S	71.3W	0852Z	1.32M / 4.3FT	30MIN
CORRAL CL	39.9S	73.4W	0739Z	0.90M / 2.9FT	16MIN
SAN FELIX CL	26.3S	80.1W	0815Z	0.53M / 1.7FT	08MIN
VALPARAISO CL	33.0S	71.6W	0708Z	1.29M / 4.2FT	20MIN

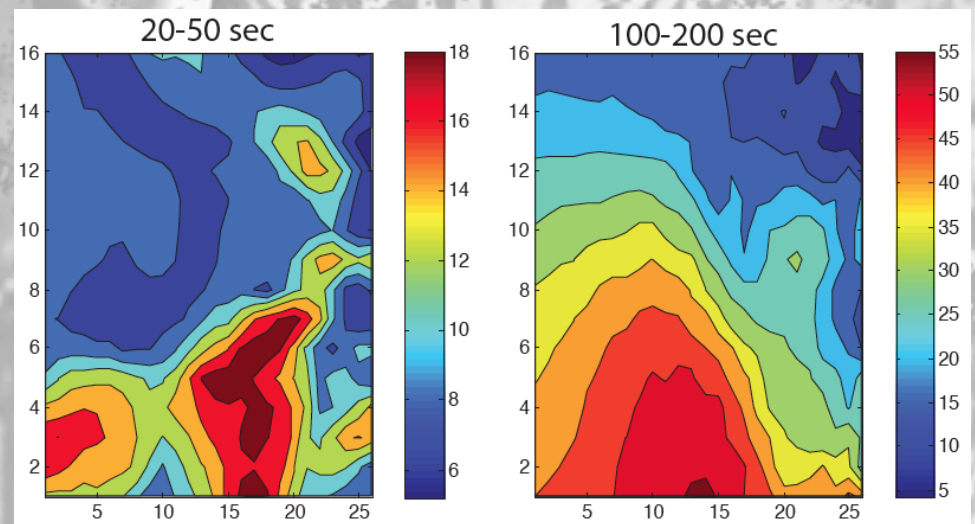
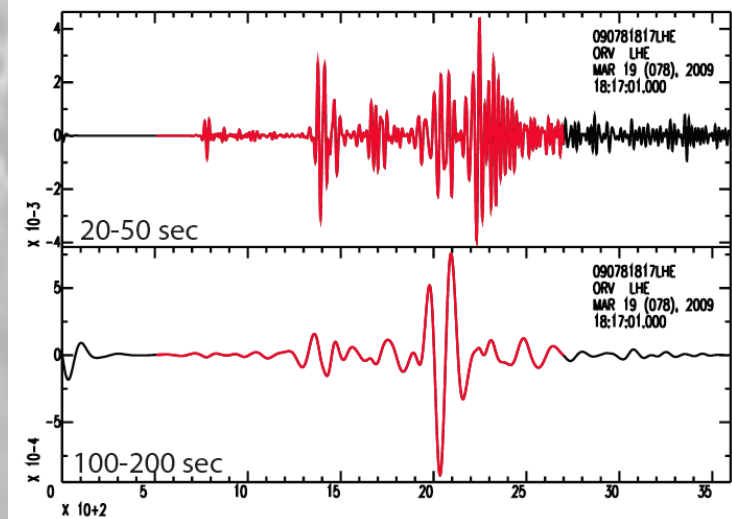
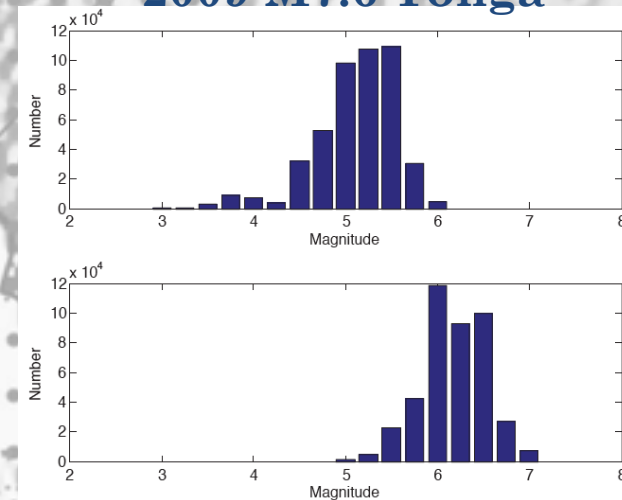
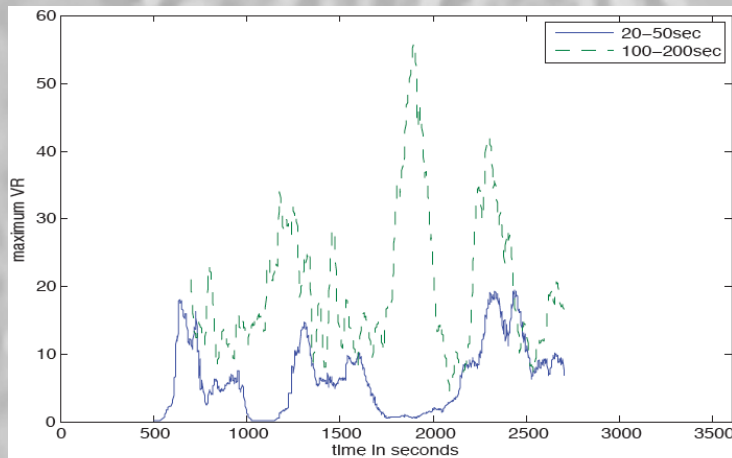
LAT - LATITUDE (N-NORTH, S-SOUTH)
 Lon - LONGITUDE (E-EAST, W-WEST)
 TIME - TIME OF THE MEASUREMENT (Z IS UTC IS GREENWICH TIME)
 AMPL - TSUNAMI AMPLITUDE MEASURED RELATIVE TO NORMAL SEA LEVEL.
 IT IS ...NOT... CREST-TO-TROUGH WAVE HEIGHT.
 VALUES ARE GIVEN IN BOTH METERS(M) AND FEET(FT).
 PER - PERIOD OF TIME IN MINUTES(MIN) FROM ONE WAVE TO THE NEXT.

- Outil intéressant pour la détection de séismes lents



Quel résultat obtient-on avec des forts séismes téléseismiques ?

2009 M7.6 Tonga



Quel résultat obtient-on avec du bruit sismique?

