Tsunami hazard assessment
what did we learn since 2004 and 2011?

Hélène Hébert
CEA DAM DIF/DASE/LDG
Bruyères le Châtel
helene.hebert@cea.fr
with contributions by François Schindelé, Anthony Sladen, Jean Roger, Sébastien Allgeyer, Audrey Gailler

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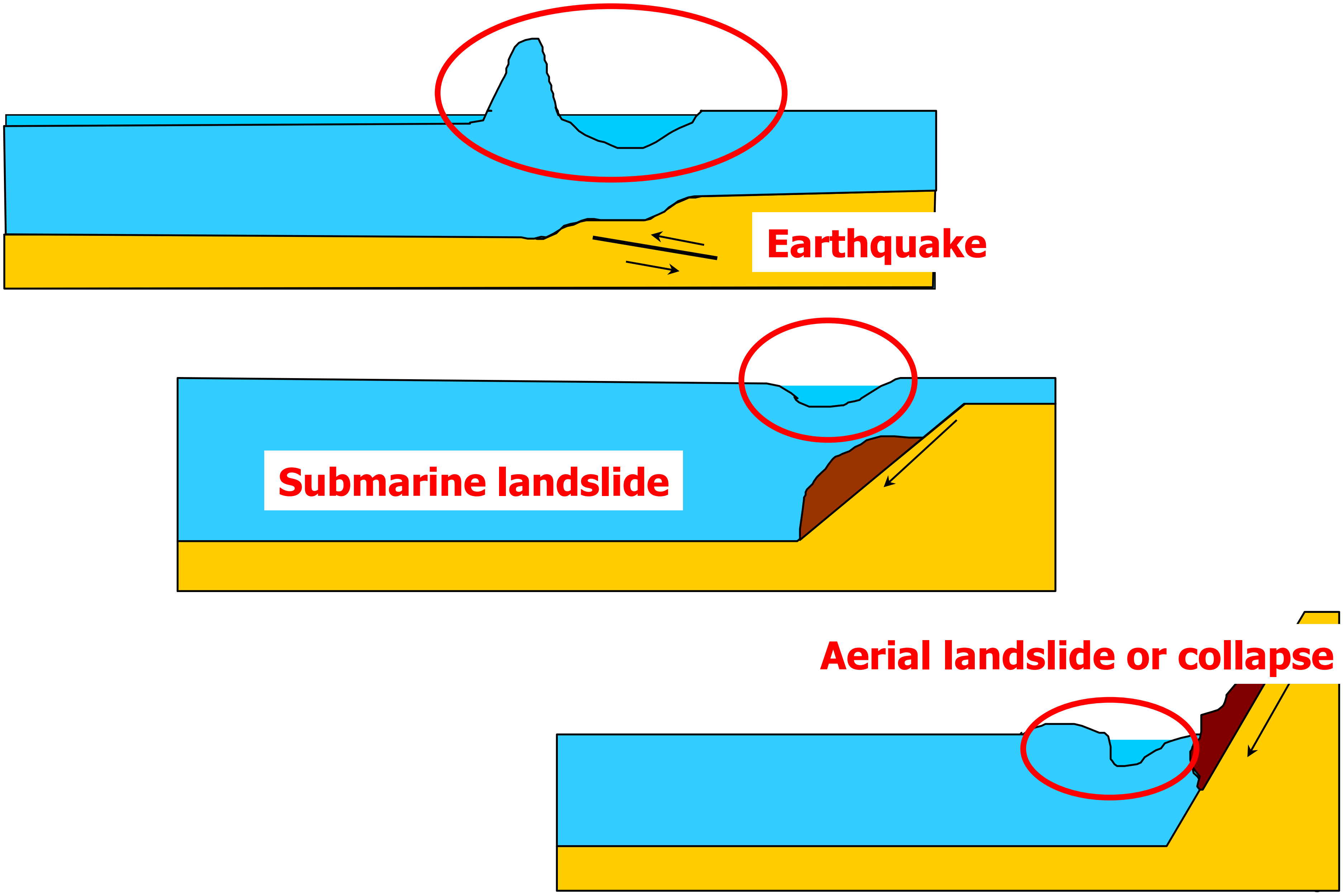
EGU Vienna

- **Tsunami hazard is more and more studied**
  - since the 1940-1960's in the Pacific Ocean, when and where the most damaging tsunamis of the 20th century occurred
  - since 2005, in any oceanic basin exposed
- **Very few extreme tsunamis during about 40 years (1964-2004)**
  - but frequent important tsunamis in the Pacific
  - several unexpected tsunamis since 2004
  - building up warning systems (IOC – Unesco)
- **The risk society...**
  - in a growing coastal vulnerability

Outline

- **Some generalities**
  - About tsunamis
  - How do we assess hazard: data and numerical methods
- **Examples of tsunami studies**
  - What we did know before 2004: lessons from French Polynesia
  - 2004: from Sumatra to the Indian Ocean
  - Back to the Euromediterranean area
    - historical cases and probable scenarios
- **Tsunami warning**
  - Example of the French tsunami warning center

What is a tsunami?



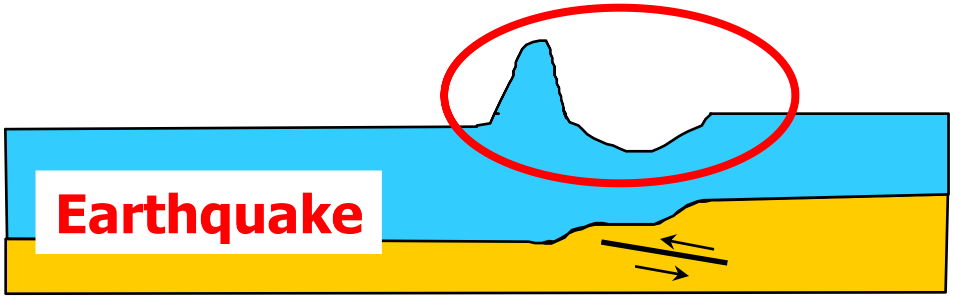
Initial deformation of the sea surface

- **In any tsunami initiation**
  - the sea surface is vertically deformed, causing a perturbation of the gravity potential energy

- **Back to equilibrium: restoring *gravity* forces**
  - uplifts tend to go down
  - depressions are filled
    - propagation of gravity waves, producing the tsunami

- **A tsunami is triggered by any "geologic" or "geophysical" cause that initially disturbs the sea surface equilibrium**

Different kinds of tsunamis



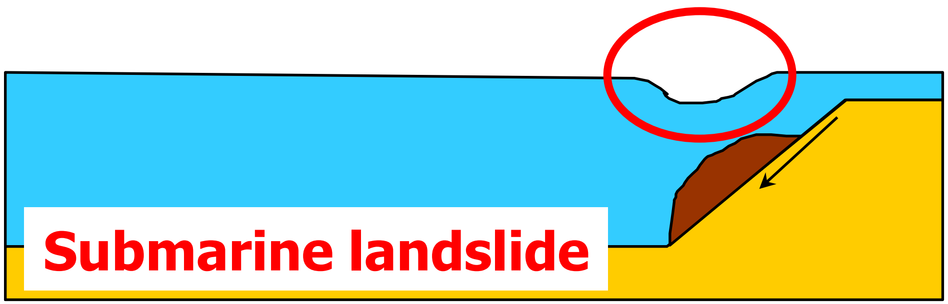
Earthquake magnitude > 7 to 7.5

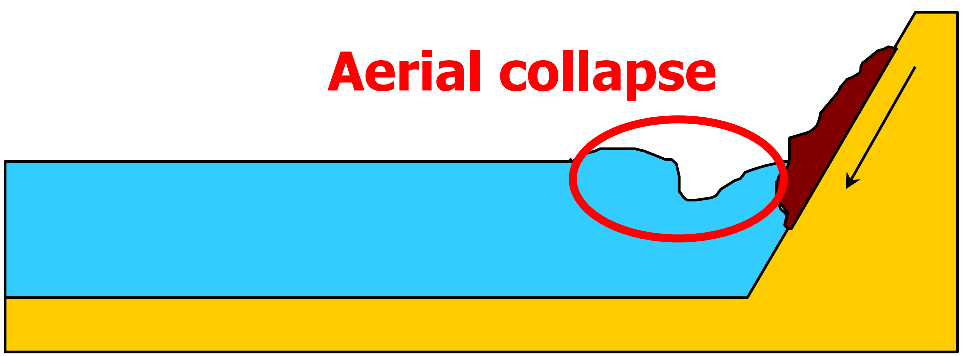
Source dimension ~ 100-800 km

Periods 15 to 40 minutes

The long wave energy is well propagated far away from the source

- considerable damage possible in far field





Landslide source

Source dimension ~ 5-30 km

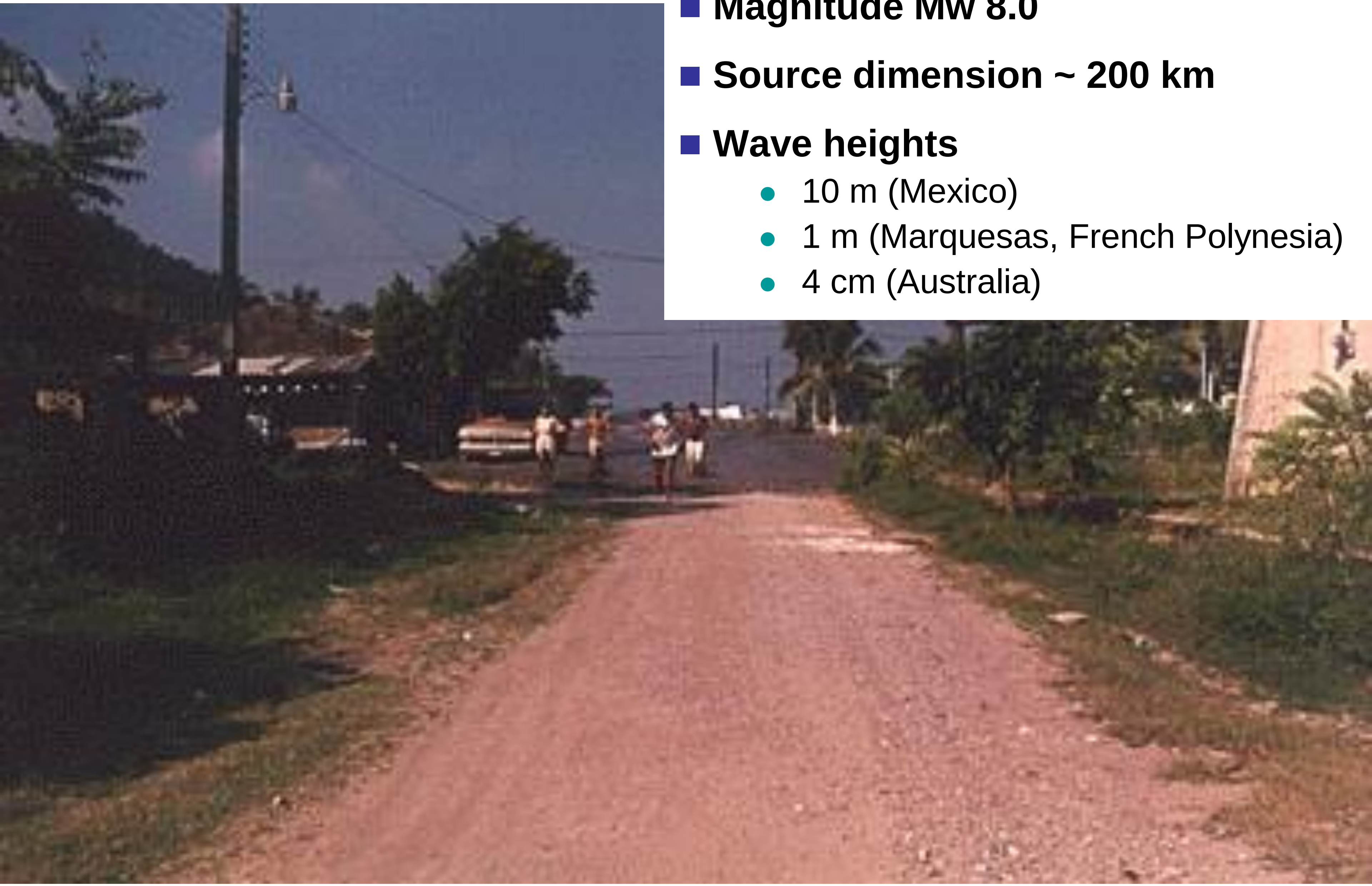
Periods 5 to 20 minutes

The tsunami energy is more attenuated

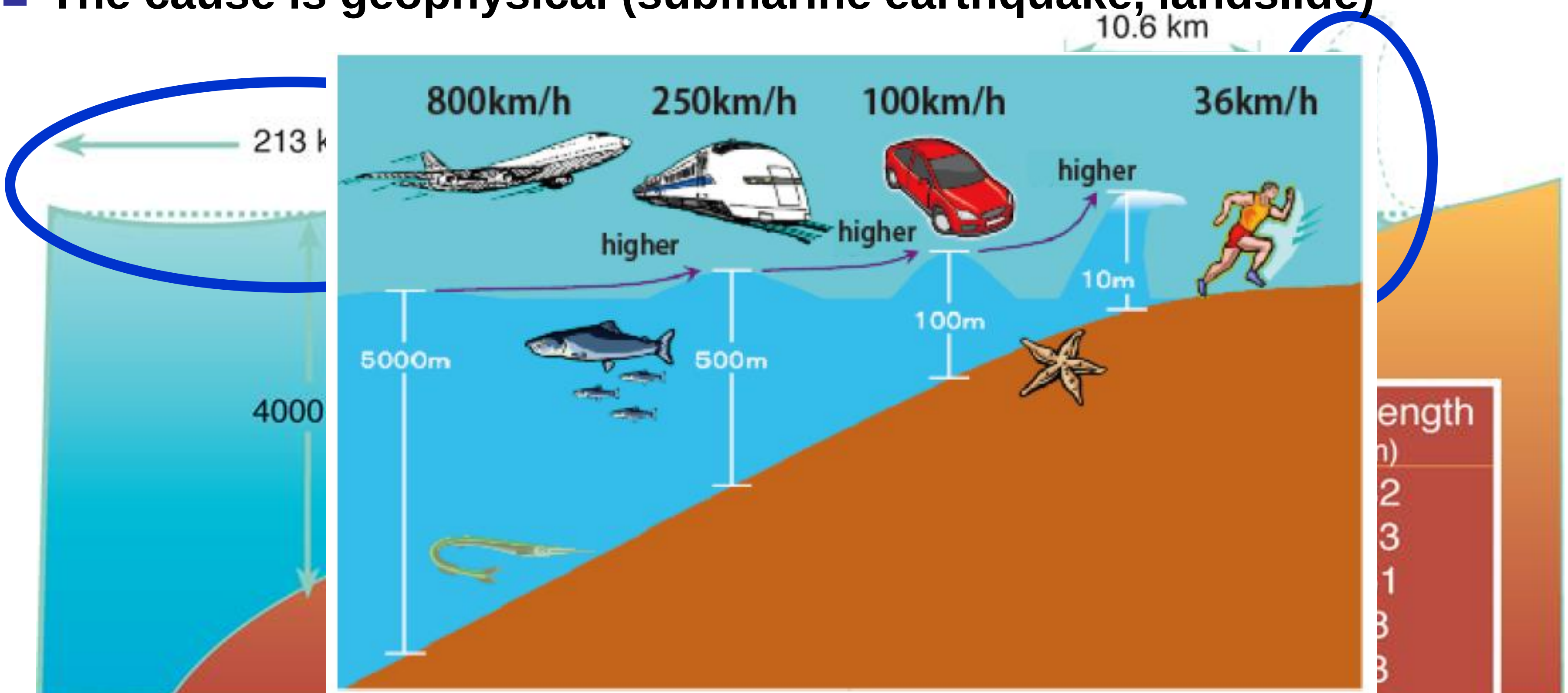
- huge damage but more locally

Manzanillo (Mexico) 1995

- **Magnitude Mw 8.0**
- **Source dimension ~ 200 km**
- **Wave heights**
  - 10 m (Mexico)
  - 1 m (Marquesas, French Polynesia)
  - 4 cm (Australia)



- **A tsunami is an <u>amplification</u>, at the <u>shore</u>, of a <u>gravity wave</u> that has propagated across the ocean**
  - small offshore amplitude (1-100 cm)
  - large wavelength (10-500 km)
  - large offshore celerity, $c = \sqrt{gh}$
  - periods 5 – 30 min
- **The cause is geophysical (submarine earthquake, landslide)**



(source Japan Meteorological Agency website)

March 2011, Miyako

- **Why were the protection walls to low ?**
  - hazard assessment
- **How efficient was the warning?**
  - sensor networks and message issuing
- **How ready were the populations?**
  - education, outreach, exercises

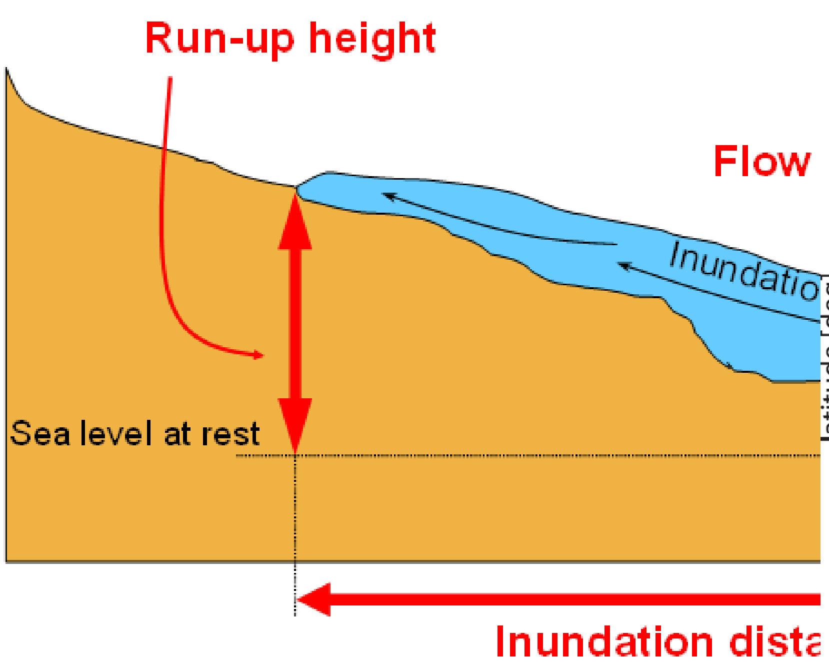
Assessment and prevention
Seismological knowledge

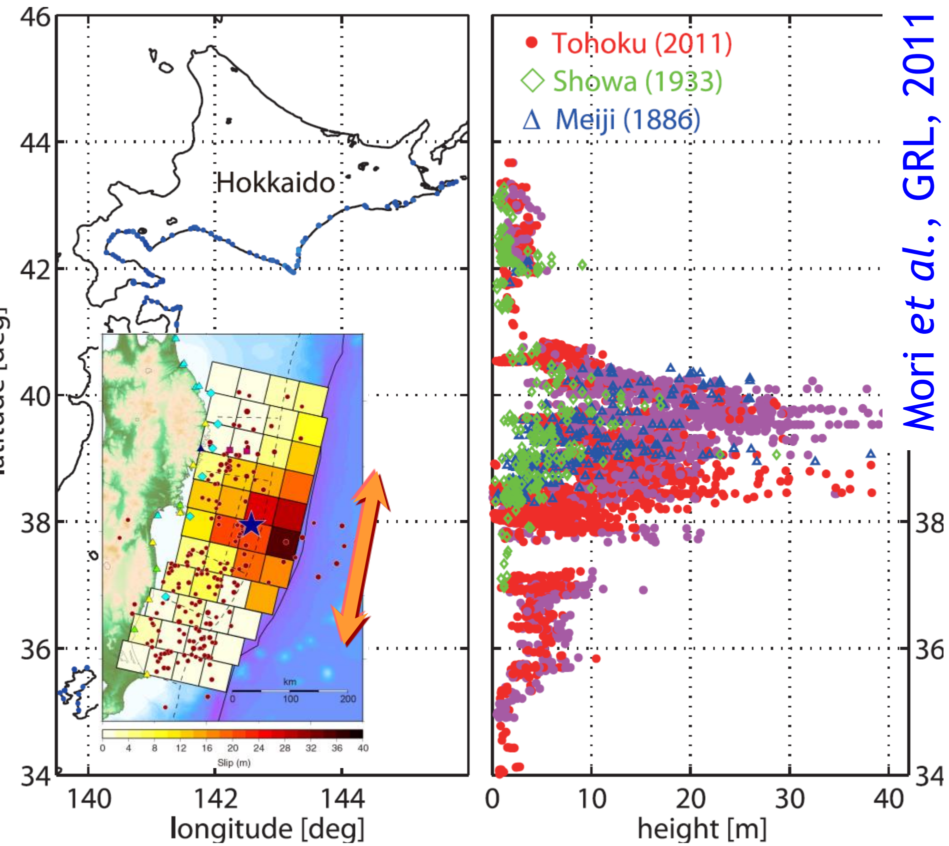
Characterizing an ongoing tsunami

Outreach, education

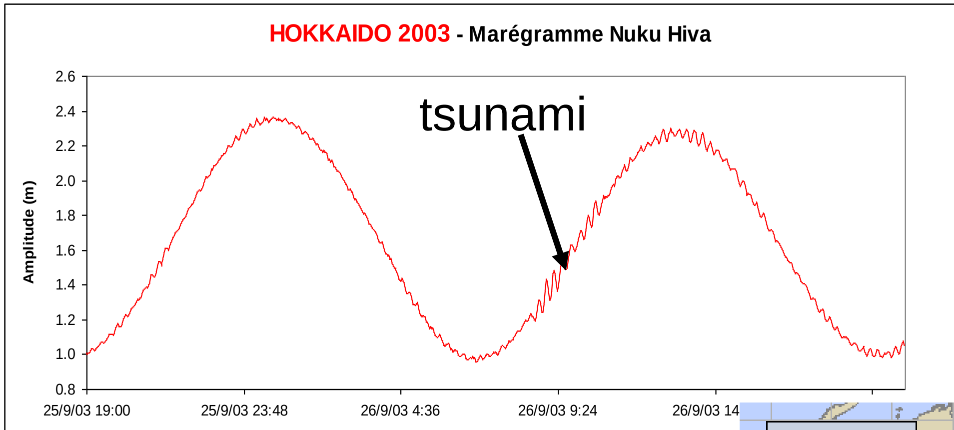
- **How can we assess tsunami hazard after 2004 and 2011?**

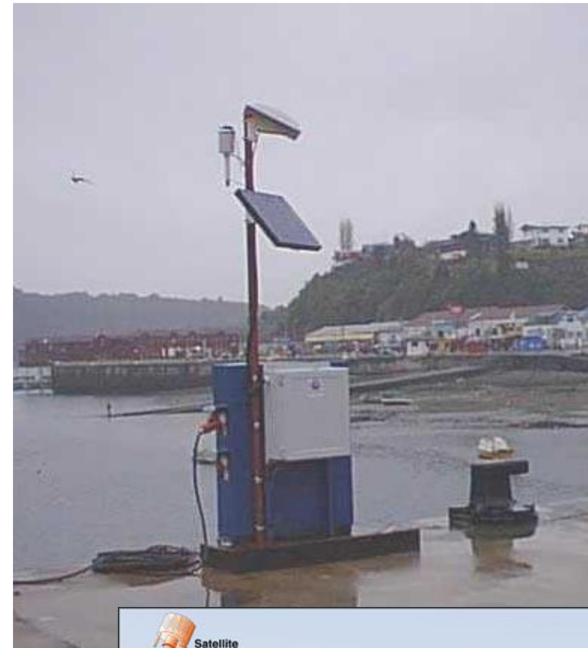
- **Field data indicating the integrated maximum effect**
  - run-up, horizontal distance, coastal tsunami height
  - few temporal indication
  - but proxy for the source extension
    - the max run-up region ←→ extension of the rupture length





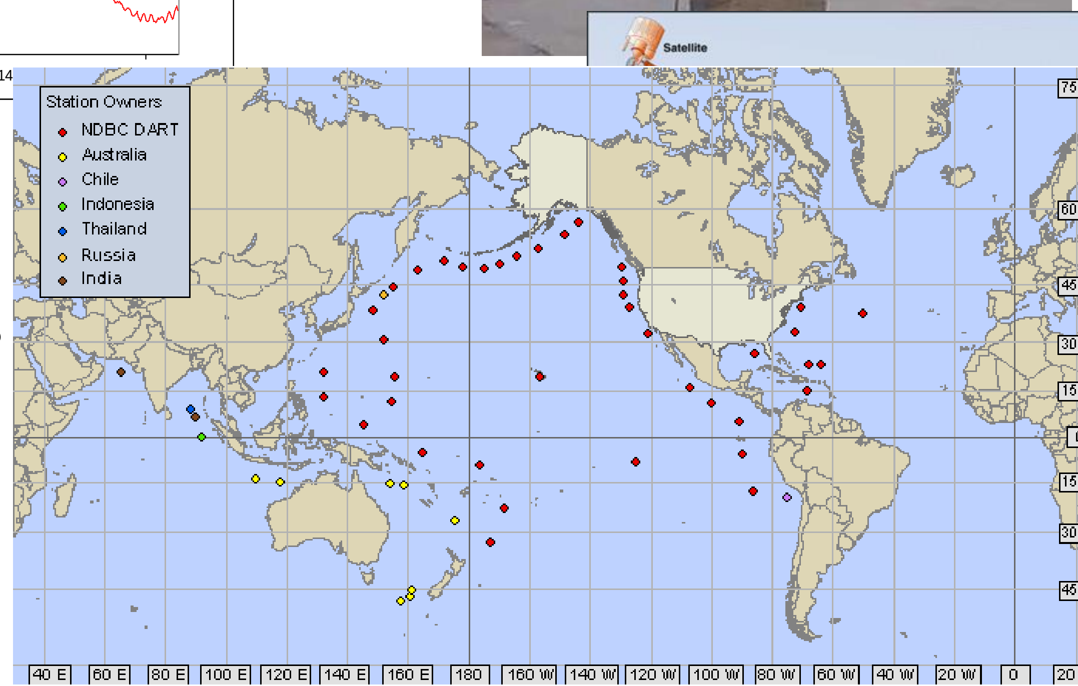
- **Temporal data : tide gauges**
  - deployed in harbours
  - devoted to the study of astronomical tides



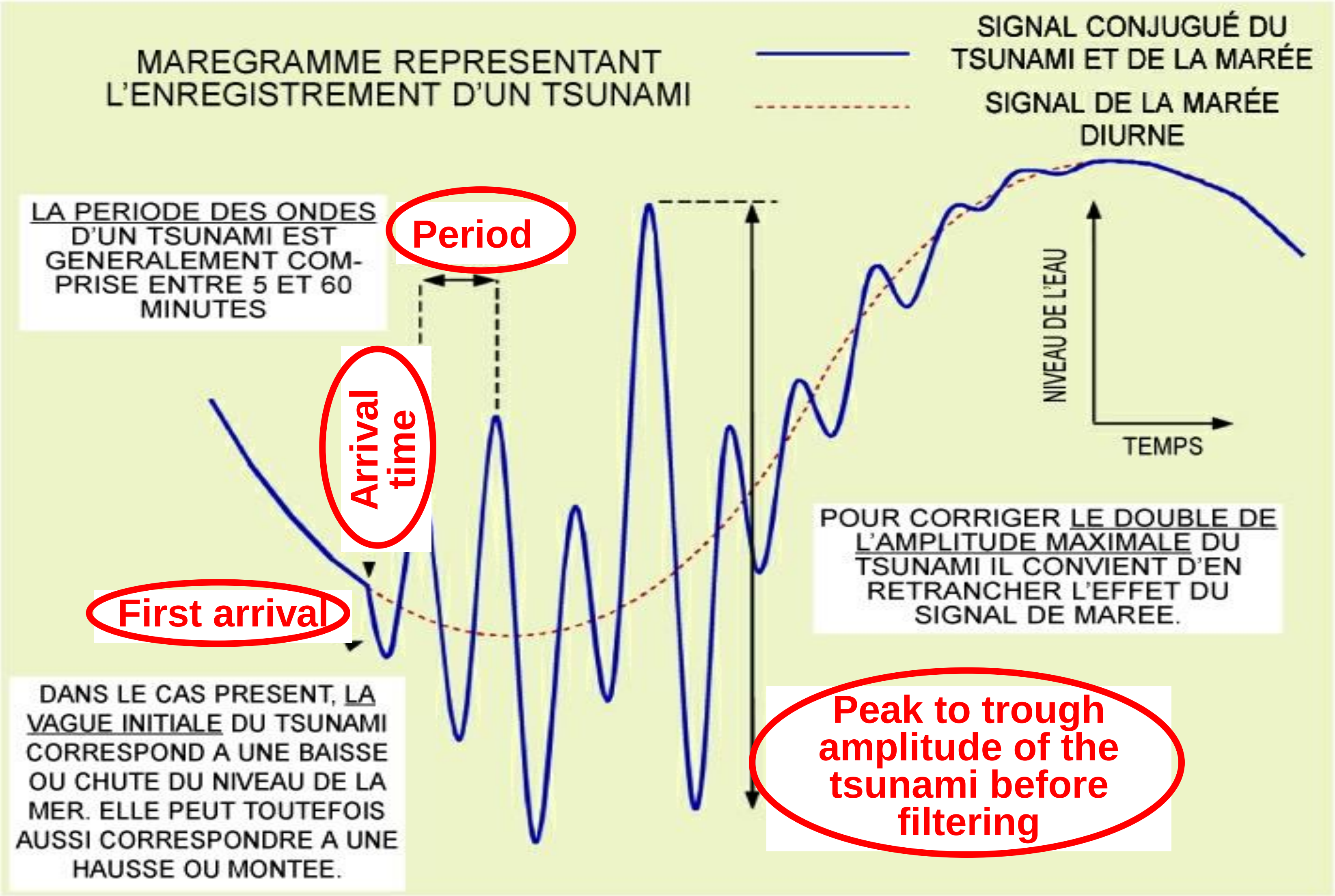


- **Sea bottom pressure gauges**
  - $\Delta P = \rho g \Delta h$: if $\Delta P \rightarrow \Delta h$

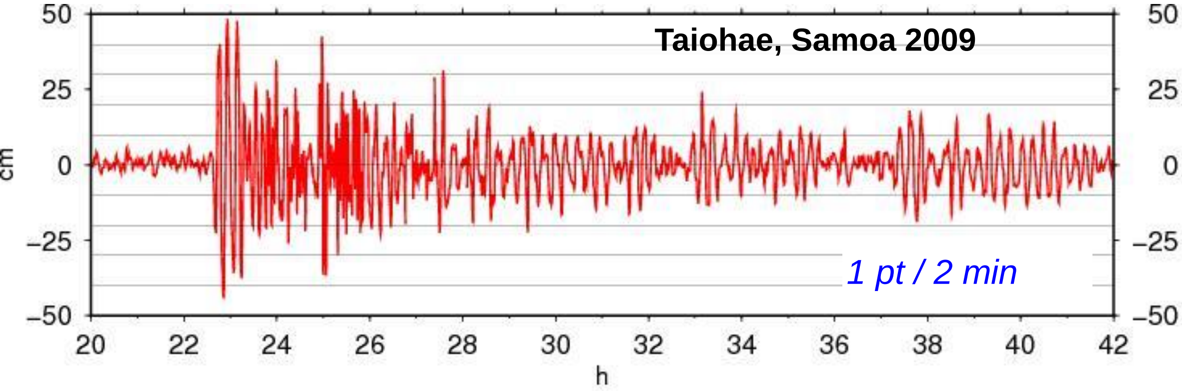
- **Satellite altimetry: rare**

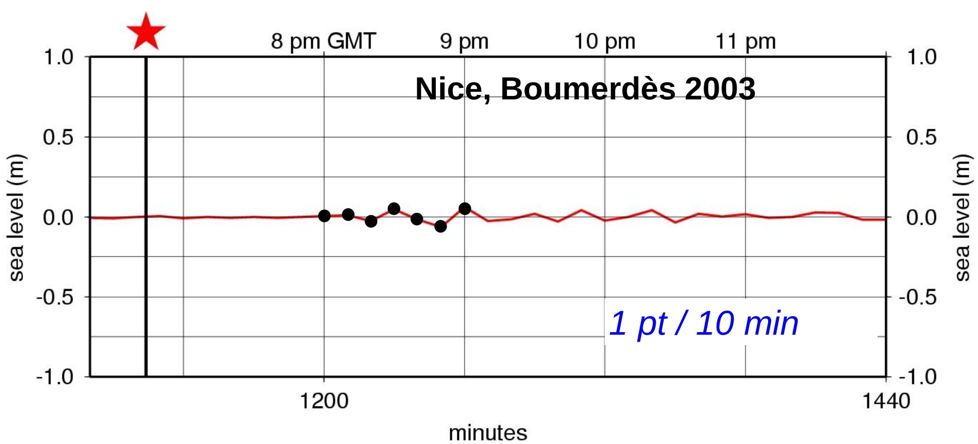


Example of a tide gauge recording a tsunami

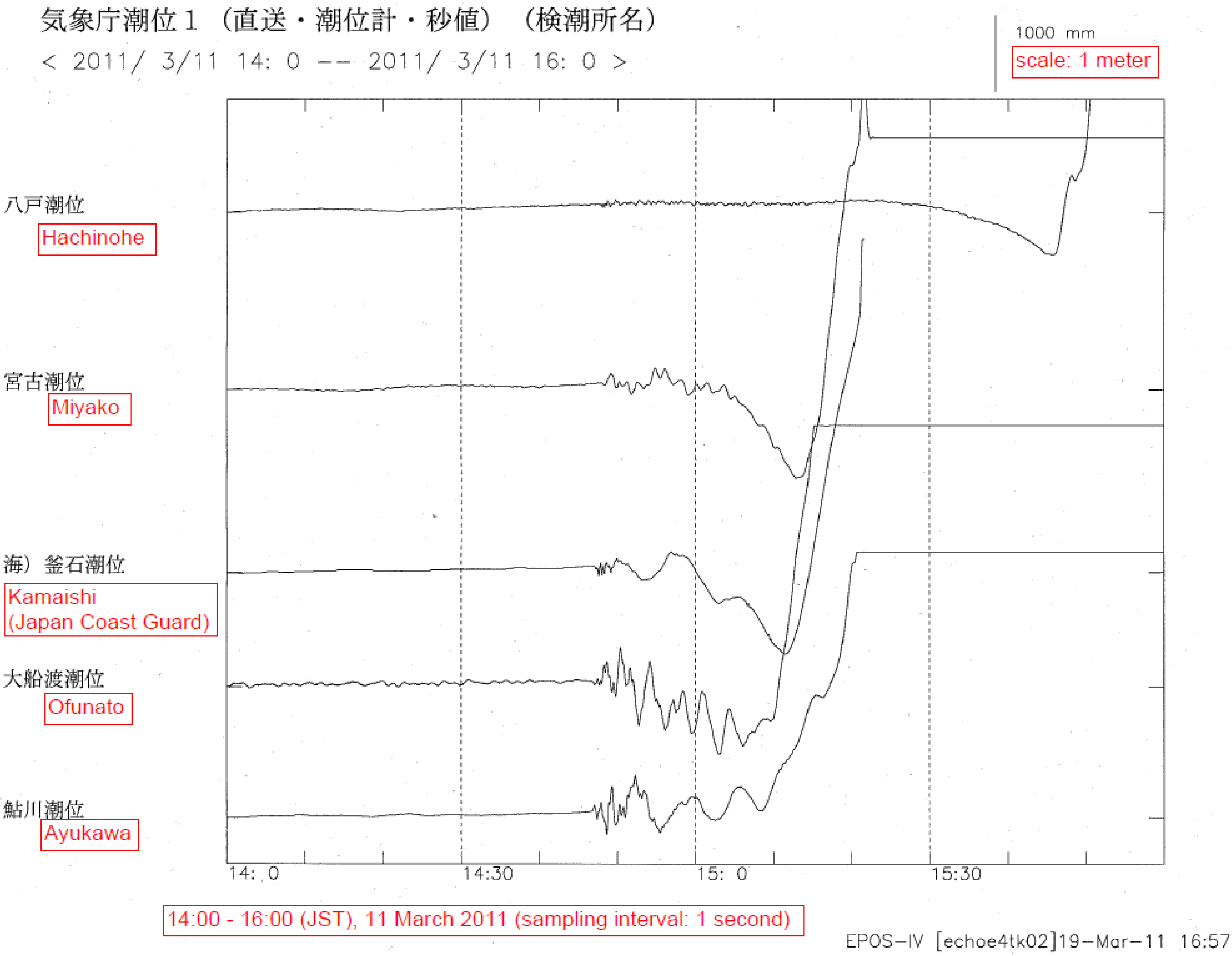


- **Tide gauge sensors were usually designed to measure oceanic tides**
  - great improvement since 2005 in the sampling rate
  - completing the operational networks

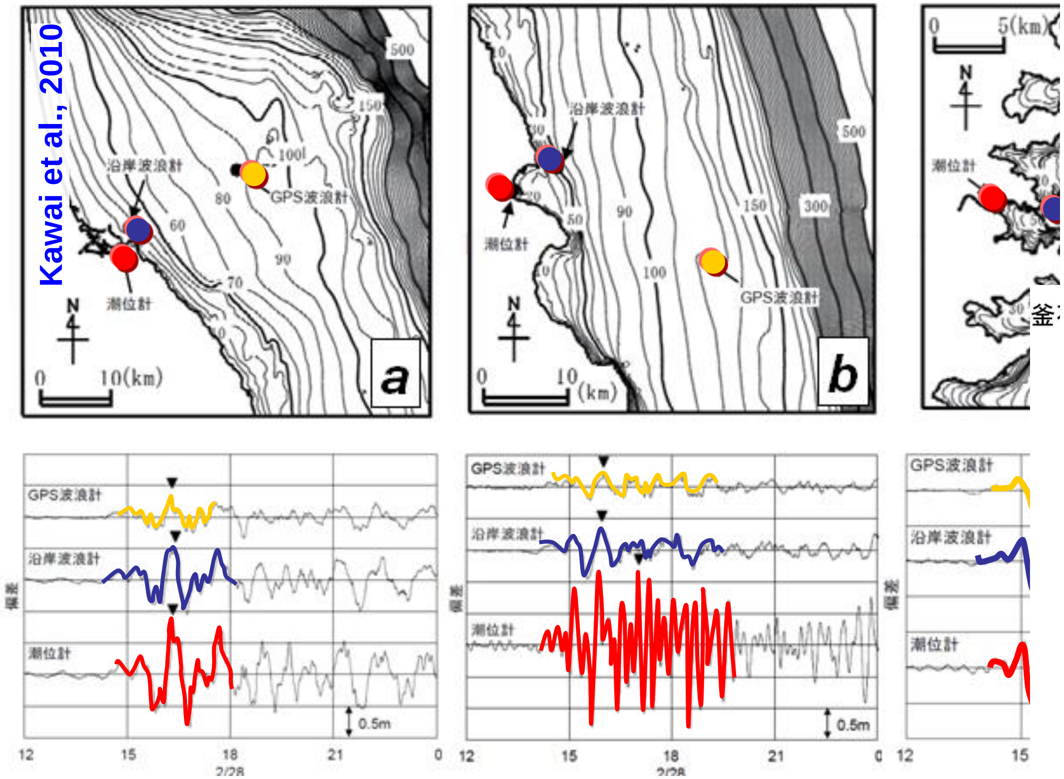




Examples in March 2011



- **Japanese technology**
  - GPS buoys and tide gauges
  - pressure sensors



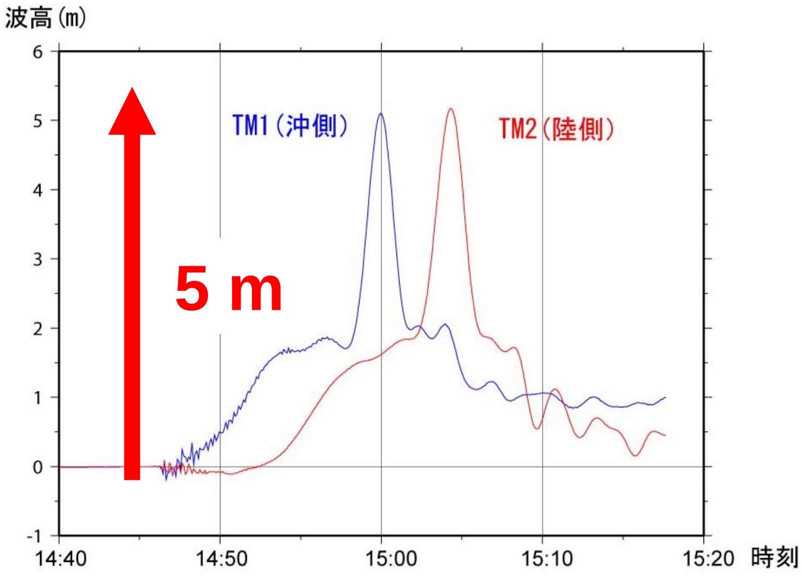


図２　海底水圧計の観測記録。14時46分頃、本震（M9.0）の振動が水圧計に伝わり、TM1（海寄り）では、その時から徐々に海面が上昇している。約２ｍ上昇し、約11分後にはさらに約3m急激に上昇し、合計約5m海面が上昇した。約30km陸寄りに設置されているTM2では、TM1から約4分遅れて同様の海面上昇を記録した。

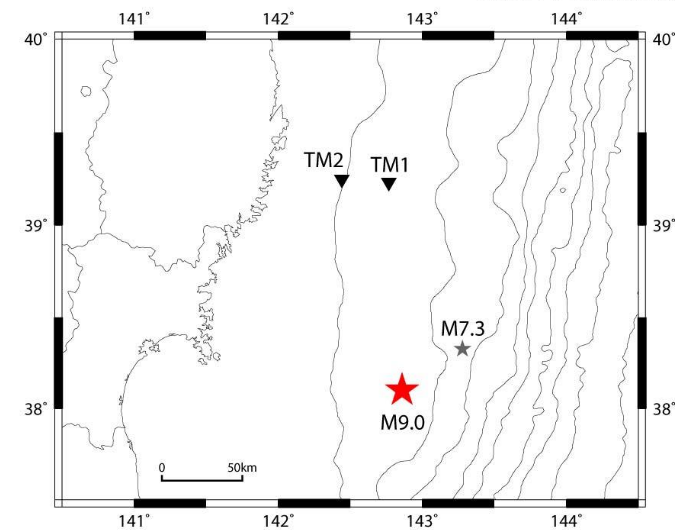
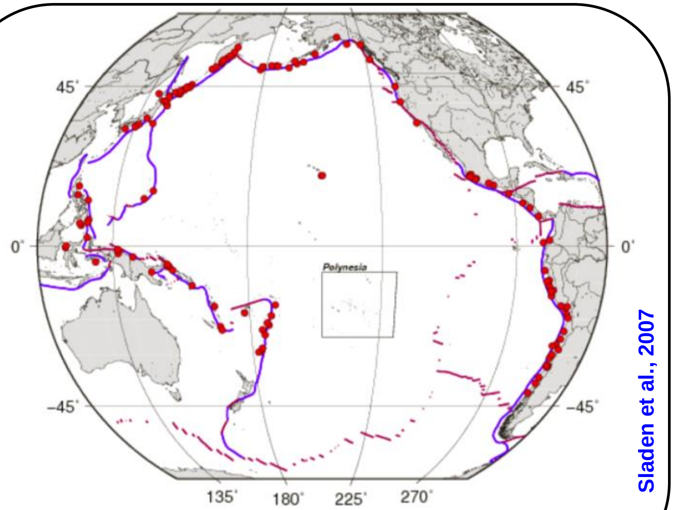
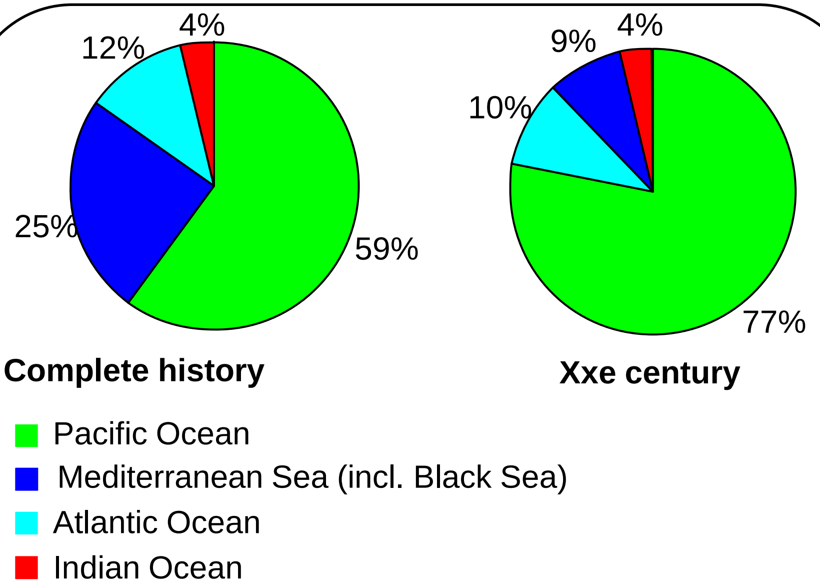


図１　釜石沖ケーブル式海底水圧計の位置

- **Historical catalogues are not complete**
  - rather complete in the Pacific (Japan, Peru..)
  - partially in the Mediterranean
  - heterogeneity in time

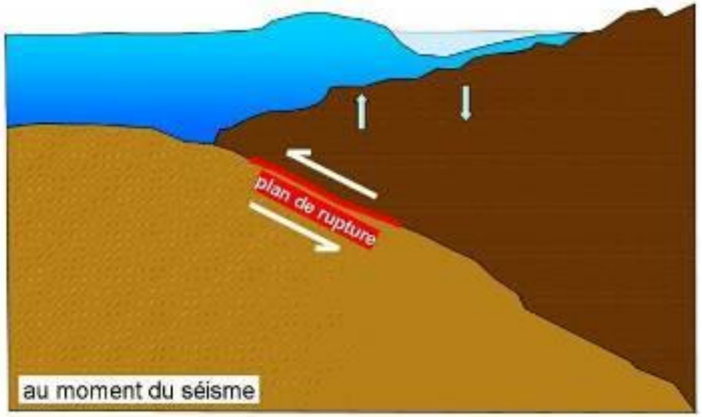


Earthquakes generating transoceanic tsunamis since 1586



- **Modeling allows**
  - assessing probable or poorly characterized scenarios
  - defining impacts expected onshore
    - hazard mapping
    - evcuation design
  - following an ongoing tsunami

- **Earthquake : elastic dislocation**
  - deformation *fully* and *instantaneously* transmitted to the sea surface



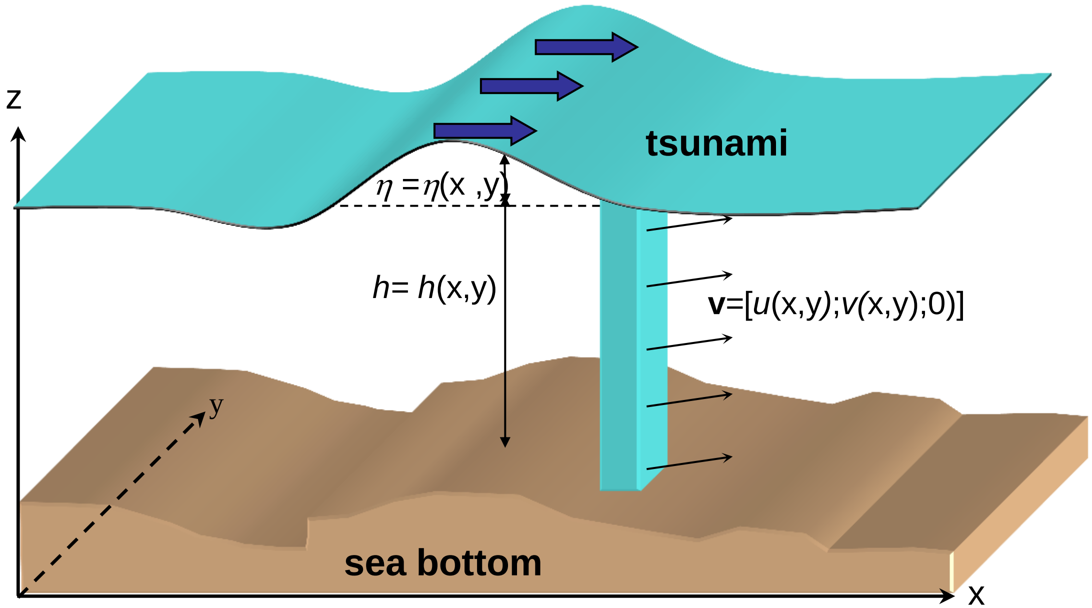
$M_0 = \mu ULW$

$M_w = 2/3 \log (M_0) - 10.73$

M_0 moment sismique
U déplacement
μ rigidité
L (W) longueur (largeur) de la faille

- **Navier Stokes equations**
  - long wave, shallow water approximation $\lambda >> h$

$$\omega^2 = gk\tanh(kh) \quad \Rightarrow \quad c = \omega/k \sim \sqrt{gh}$$



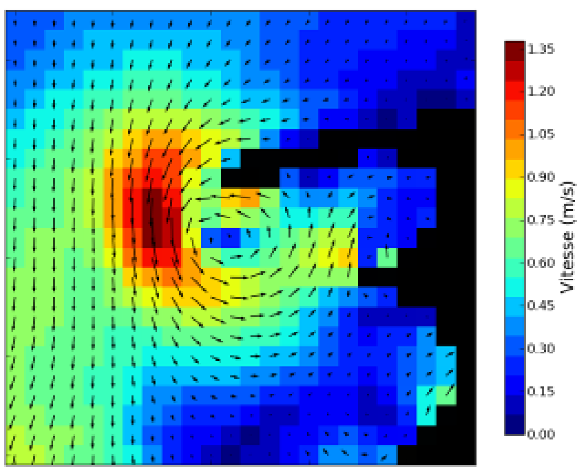
$$\frac{\partial(\eta + h)}{\partial t} + \nabla.[\mathbf{v}(\eta + h)] = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}.\nabla)\mathbf{v} = -\mathbf{g}.\nabla\eta + \sum \mathbf{f}$$

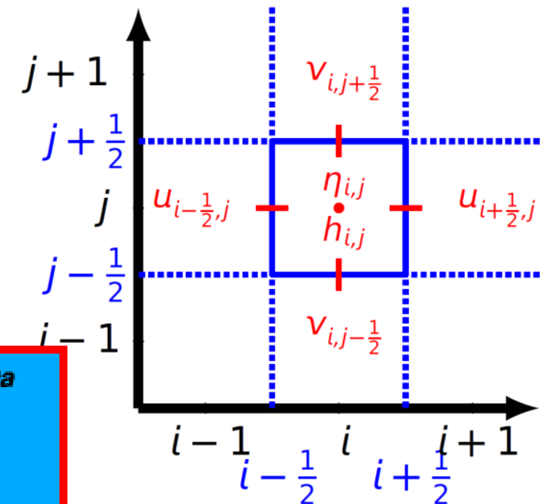
g gravity
v horizontal speed
η sea elevation

A finite difference scheme

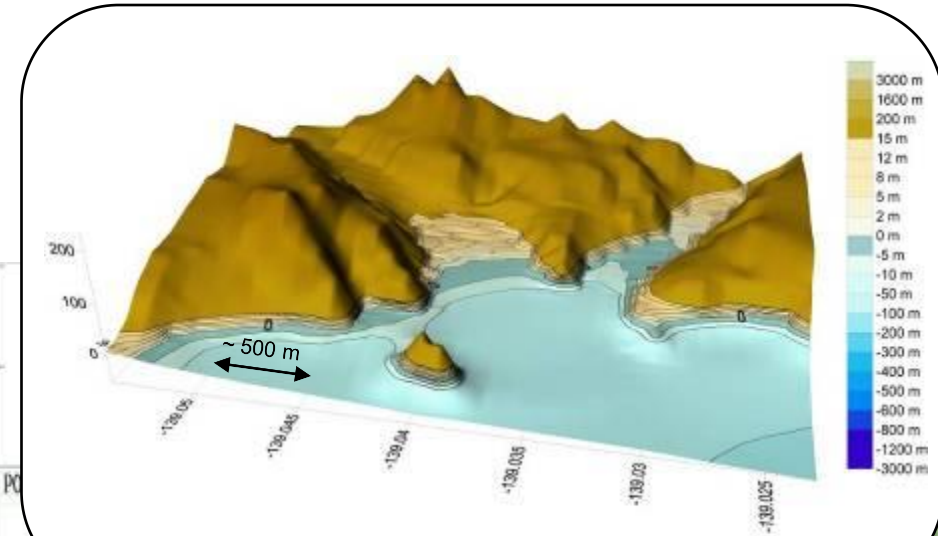
- adapted from Mader (1988 : explicit, monogrid) (Heinrich et al., 1996)
- with an iterative Crank Nicolson scheme
- multigrid : coupling of bathymetric grids with an increasing resolution
  - down to cell sizes of a few meters
- since 2010 : parallel computing allowing High Performance Computing



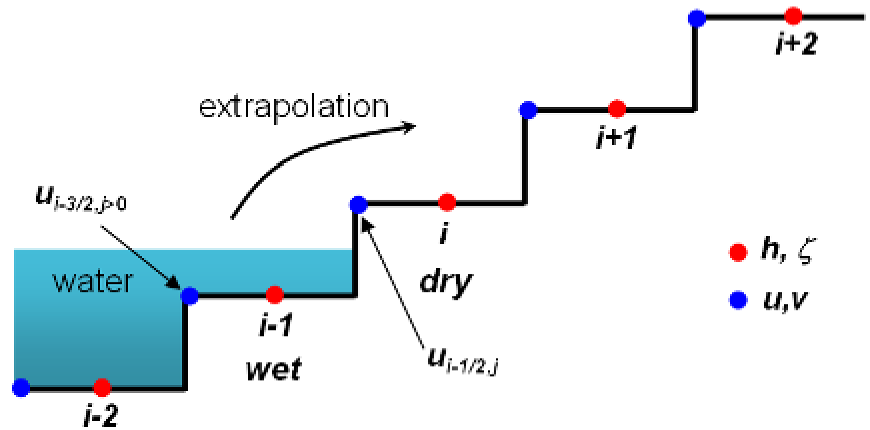
Jamelot, Allgeyer, Defief, 2010

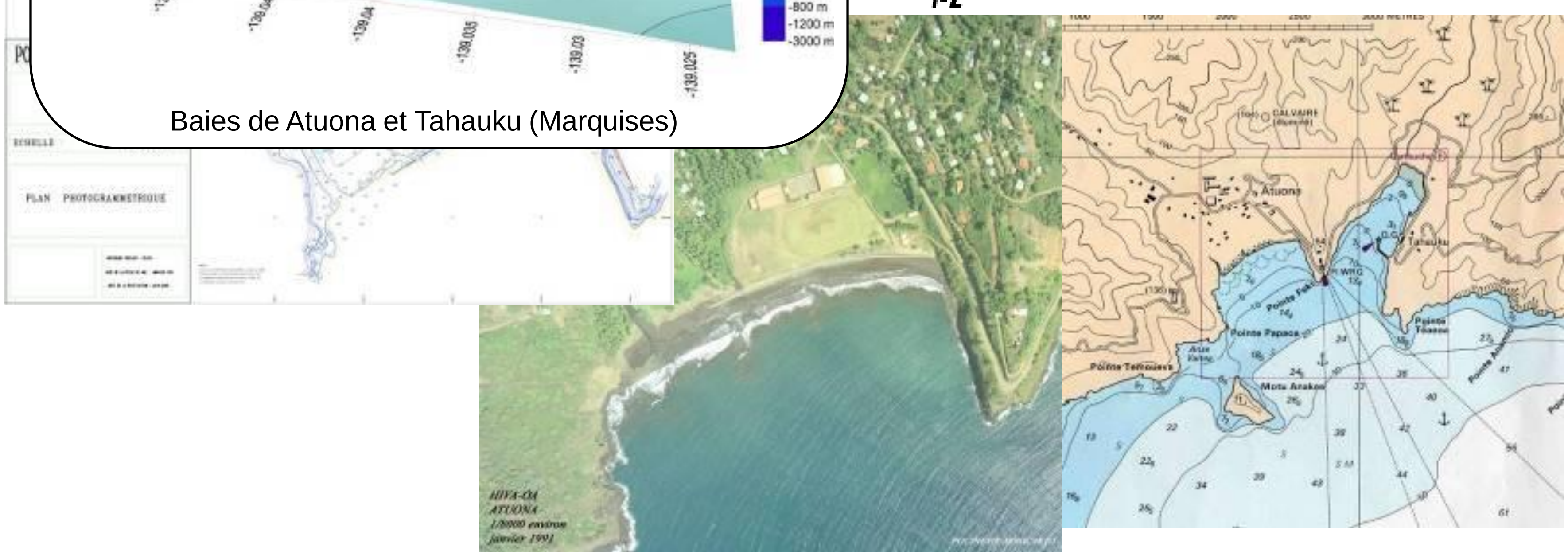


- **In order to compute run-up heights**
  - requires to merge bathymetric and topographic data at a fine scale
  - nowadays high resolution data are available (lidar data)



Baies de Atuona et Tahauku (Marquises)

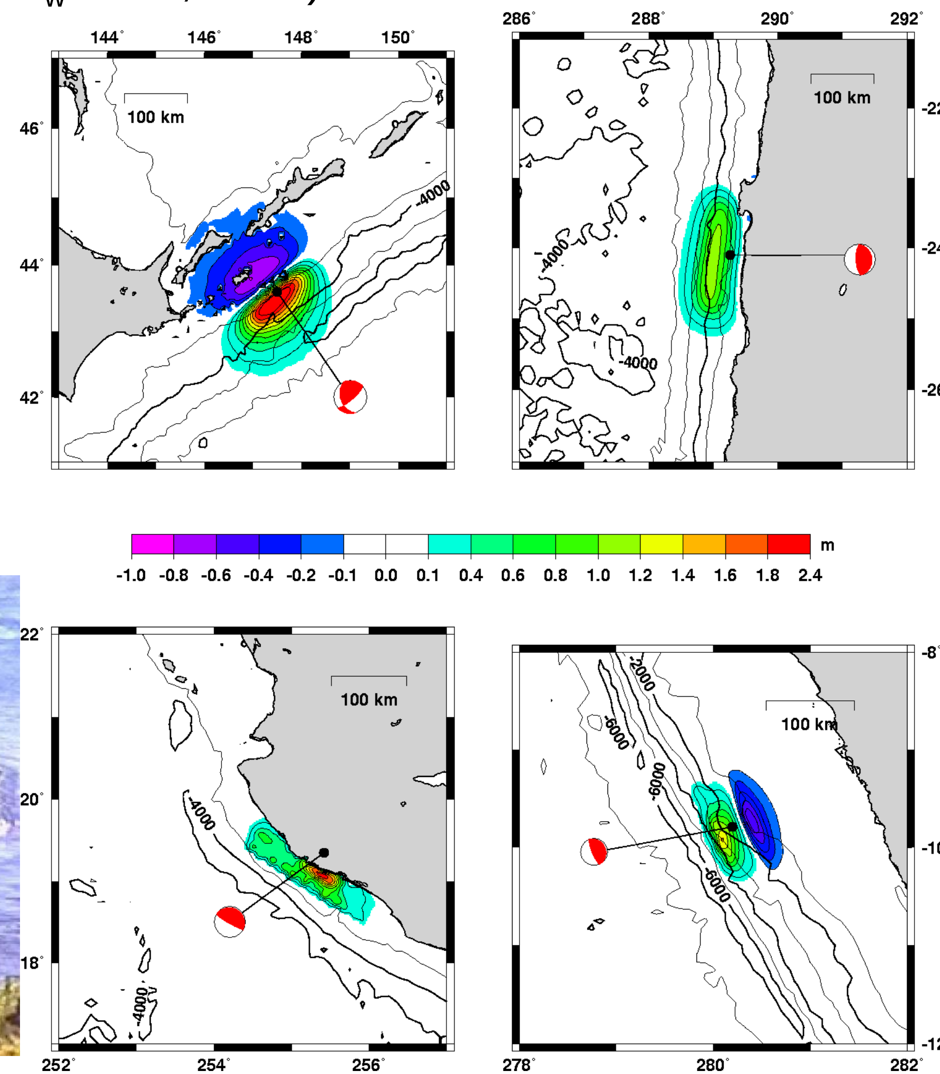




Tsunamis in French Polynesia,1994-1996

- **Between 1994 and 1996**, 4 tsunamis reached the Marquesas Isalnds, impacting with 2-3 m tsunami height (Chile, M_w = 8.1, 1995)

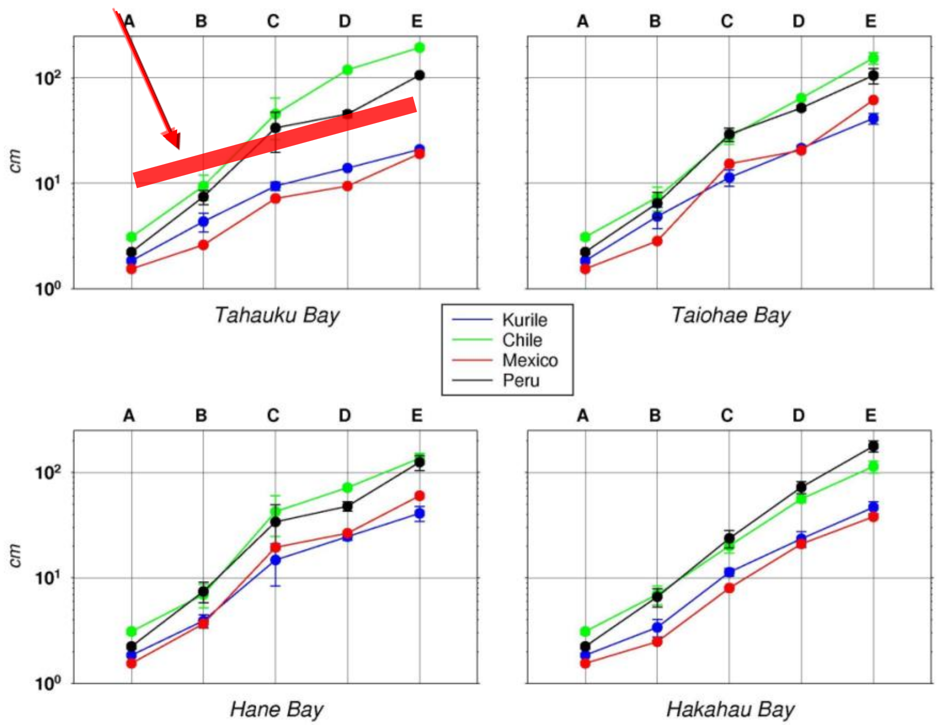
- **Observations**
  - run-up 2 to 3 m for tsunamis from **Chile** (1995, M_w = 8.1) and **Peru** (1996, M_w = 7.5)
  - almost no amplification for tsunamis from **Kurile** (1994, M_w = 8.3) and **Mexico** (1995, M_w = 8.0)

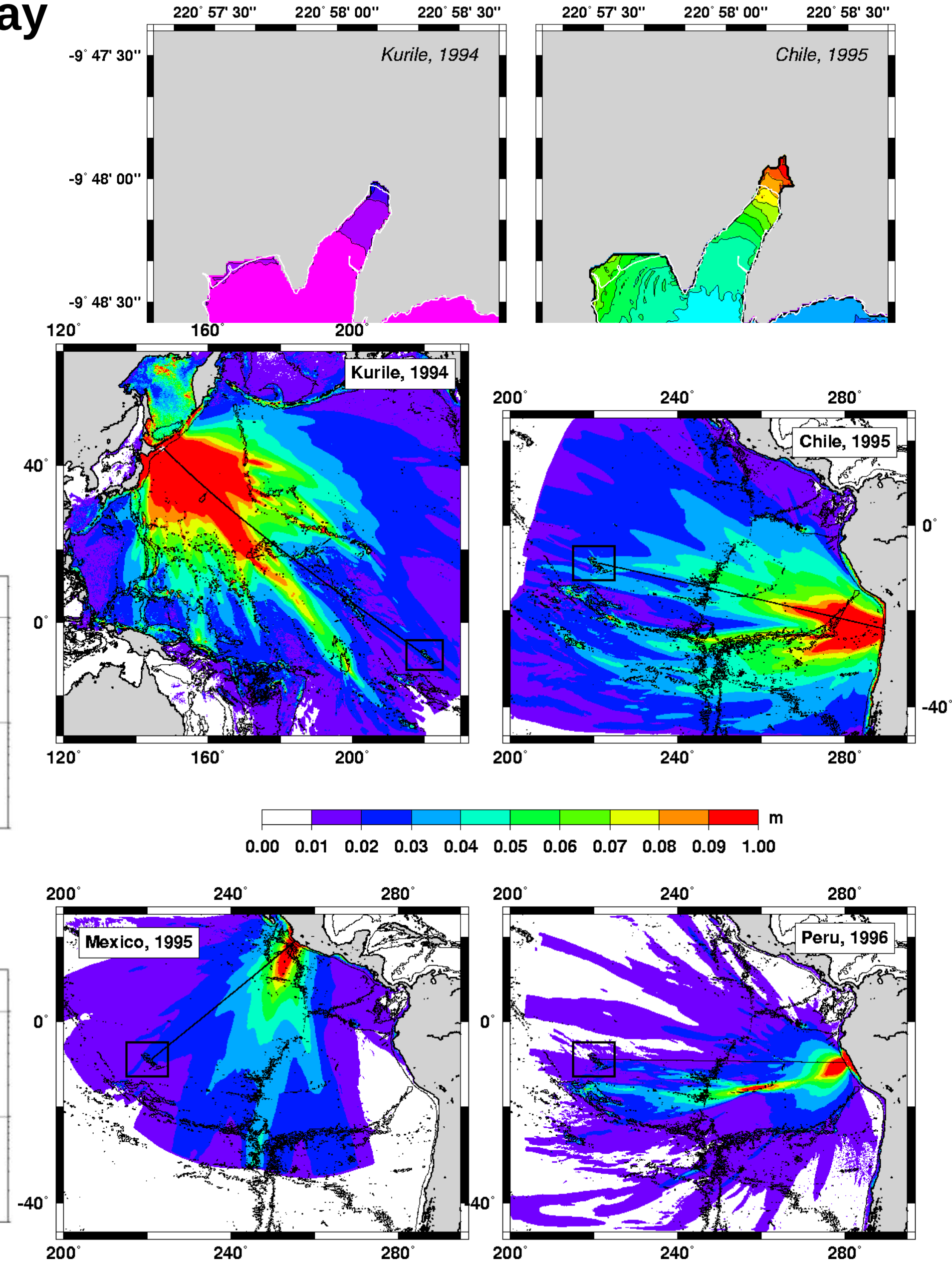


- **Maximum water heights in Tahauku Bay (Hiva Oa)**
  - in agreement with observations

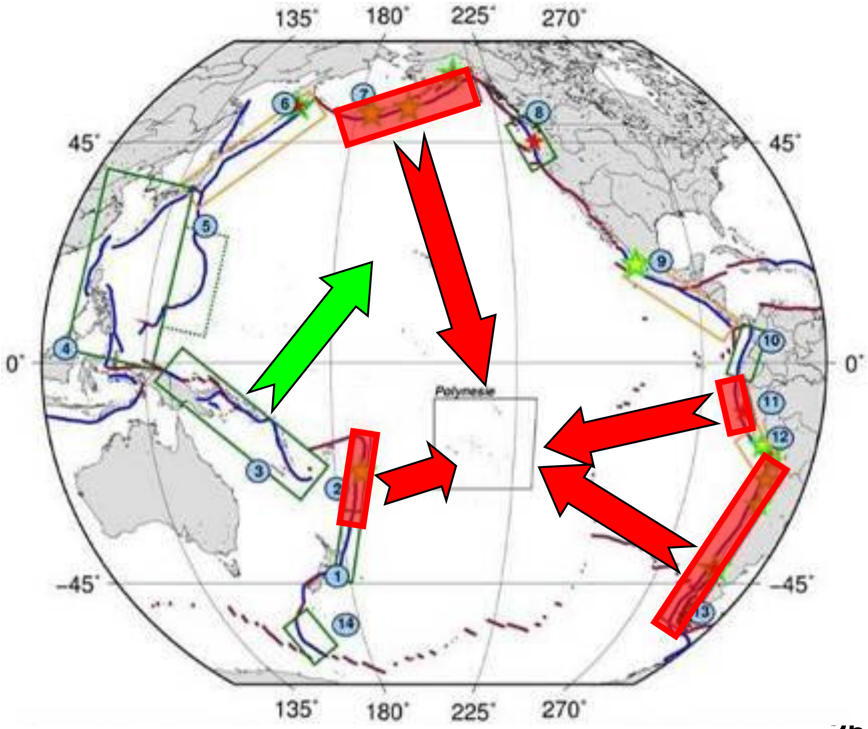
- **First order influence of**
  - submarine bathymetric features (fracture zones, volcanic ridges..)
  - fault azimuth

Green's law $H^{1/4}$

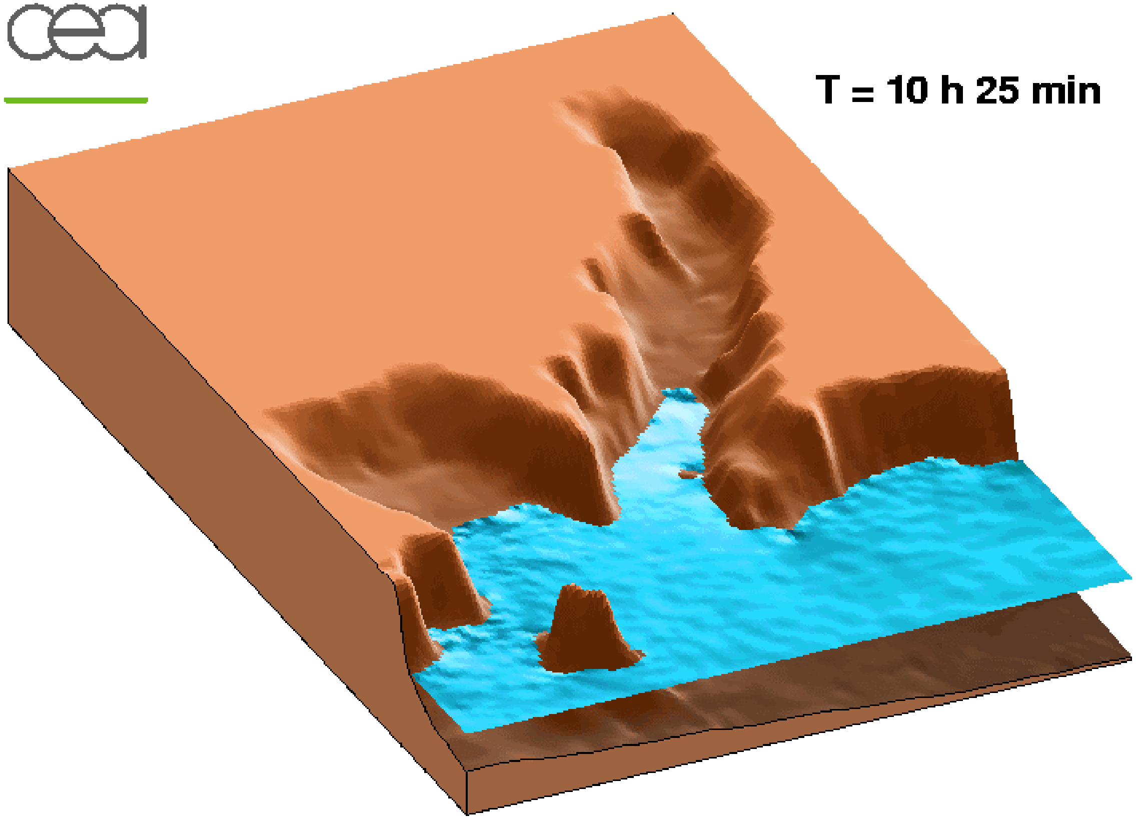


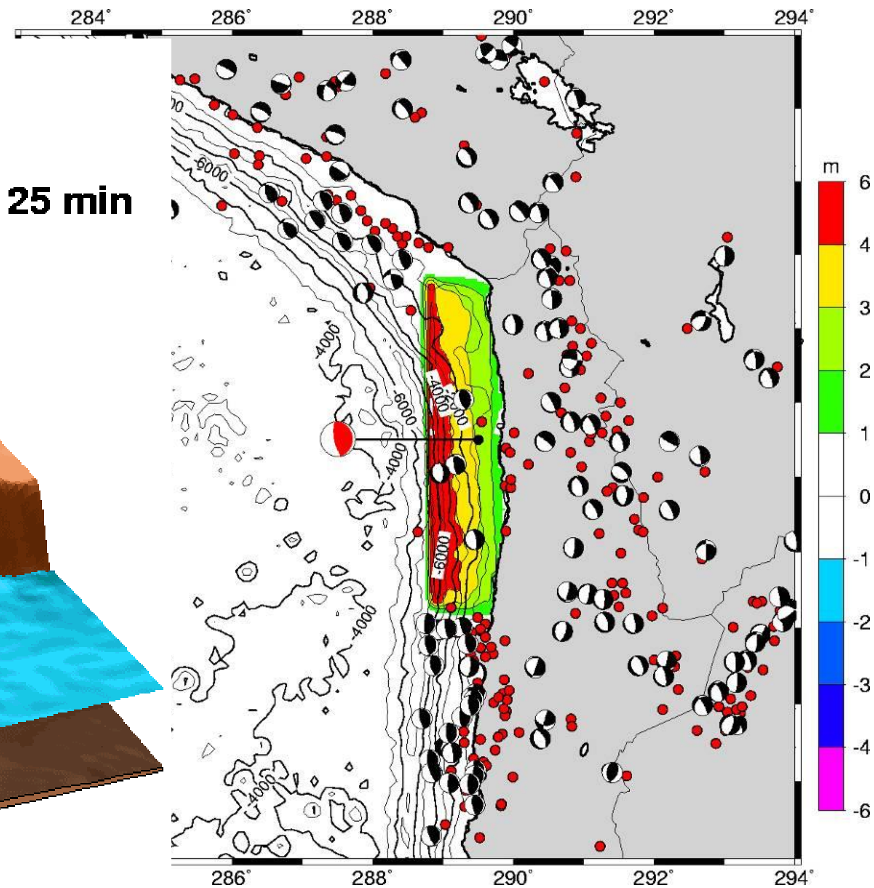


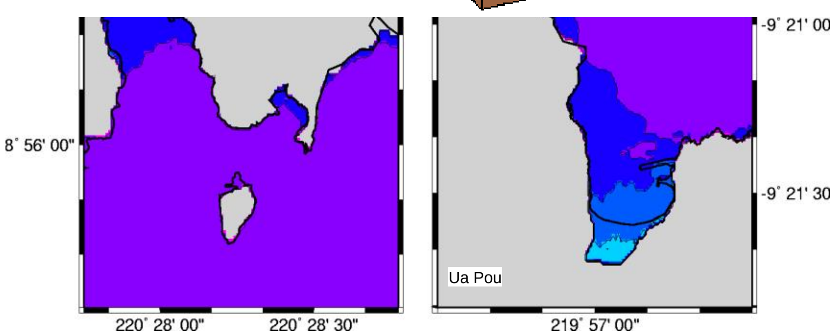
- **For a Risk Prevention Plan**
  - project **ARAI : A**léas et **R**isques naturels, **A**ménagement et **I**nformation ("protect" in Polynesian) (coord. BRGM 2005-06)
  - historical data
  - seismotectonic zoning
  - definition of threatening sources
    - deterministic methodology
- **Numerical modeling**
  - high resolution data
  - 6 coastal sites
  - 5 sources



- Earthquake expected with



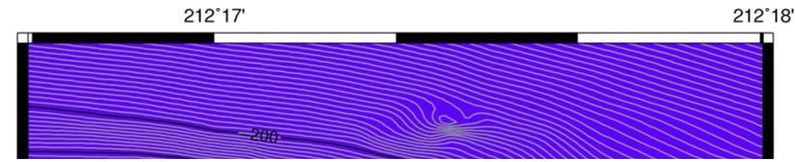


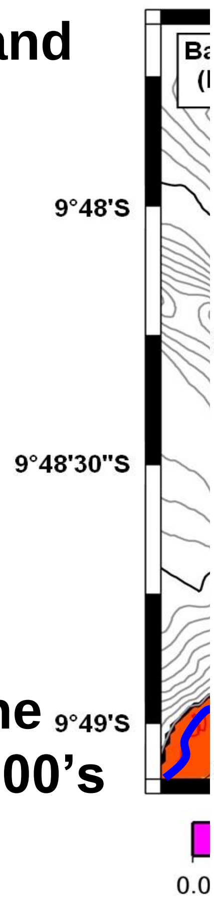


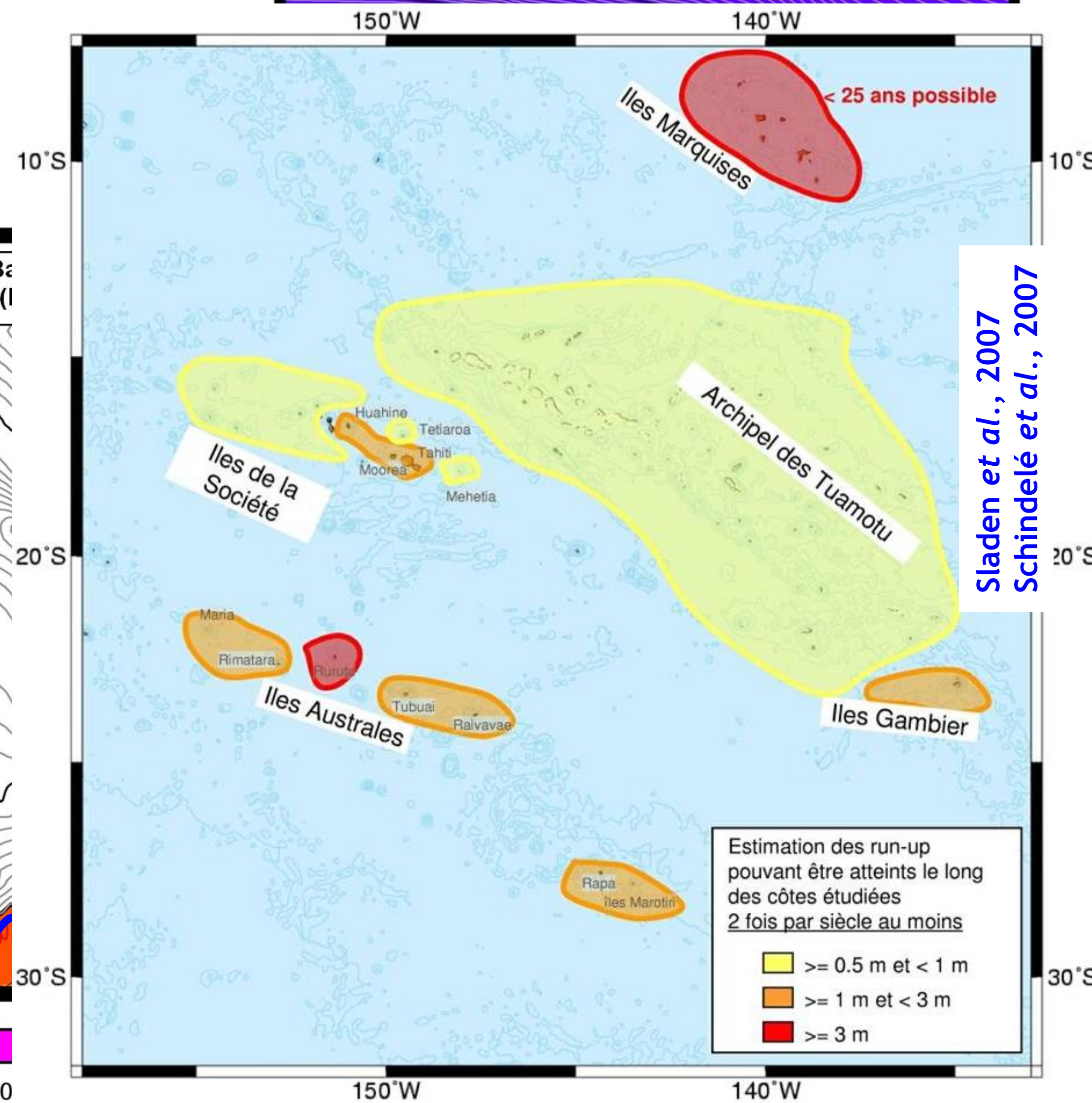
- **In the Marquesas**
  - Run-ups ➔ 11 m
  - Horizontal distance ➔ 1000 m

Integrated results for coastal sites

- **For various places and selected sources**
- **Rangiroa (Avatoru)**
  - max S Chile
  - no inundation
- **Hiva Oa (Tahauku and Atuona)**
  - max 1946
  - run-up ~ 10 m
- **Synthesis**
  - models
  - historical data
- **State of the art in the beginning of the 2000's**

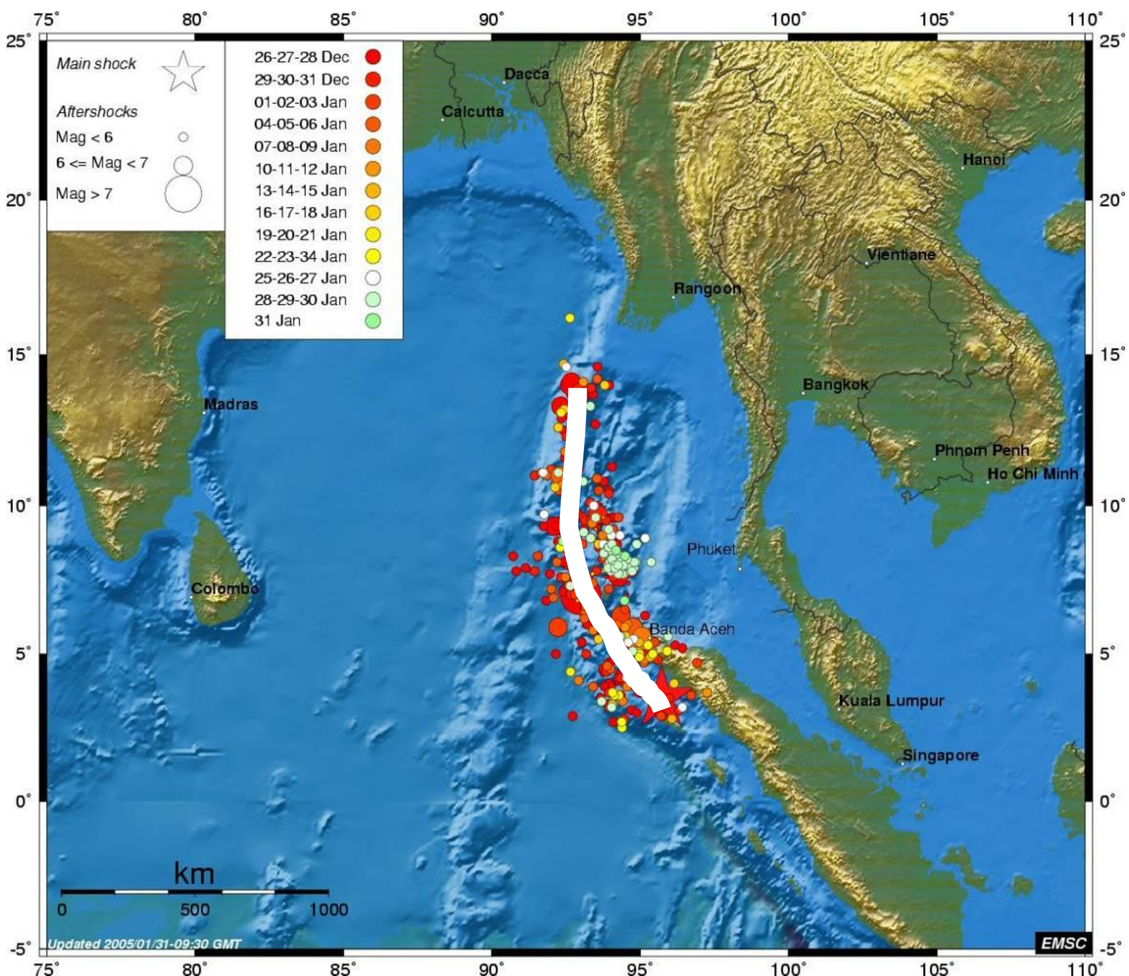


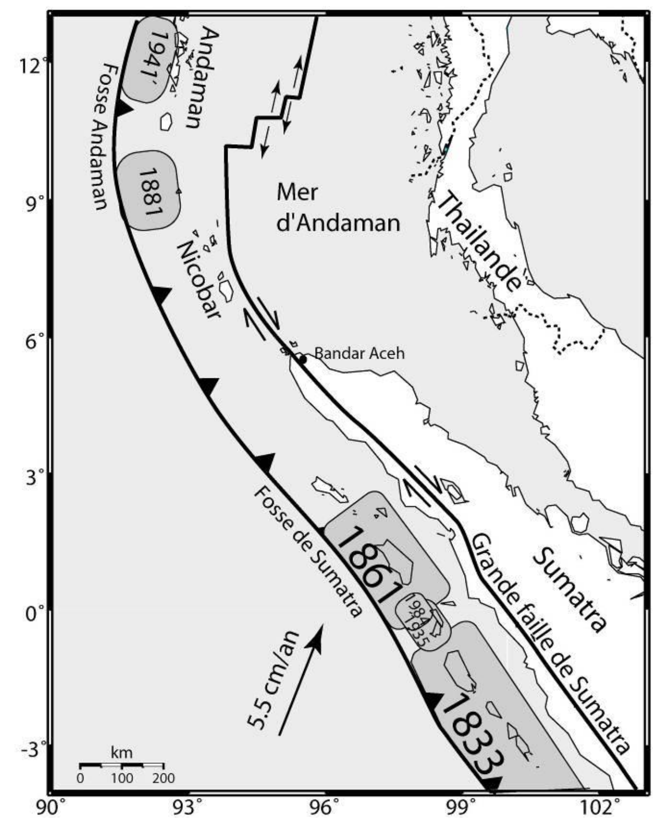




Sladen *et al.*, 2007
Schindelé *et al.*, 2007

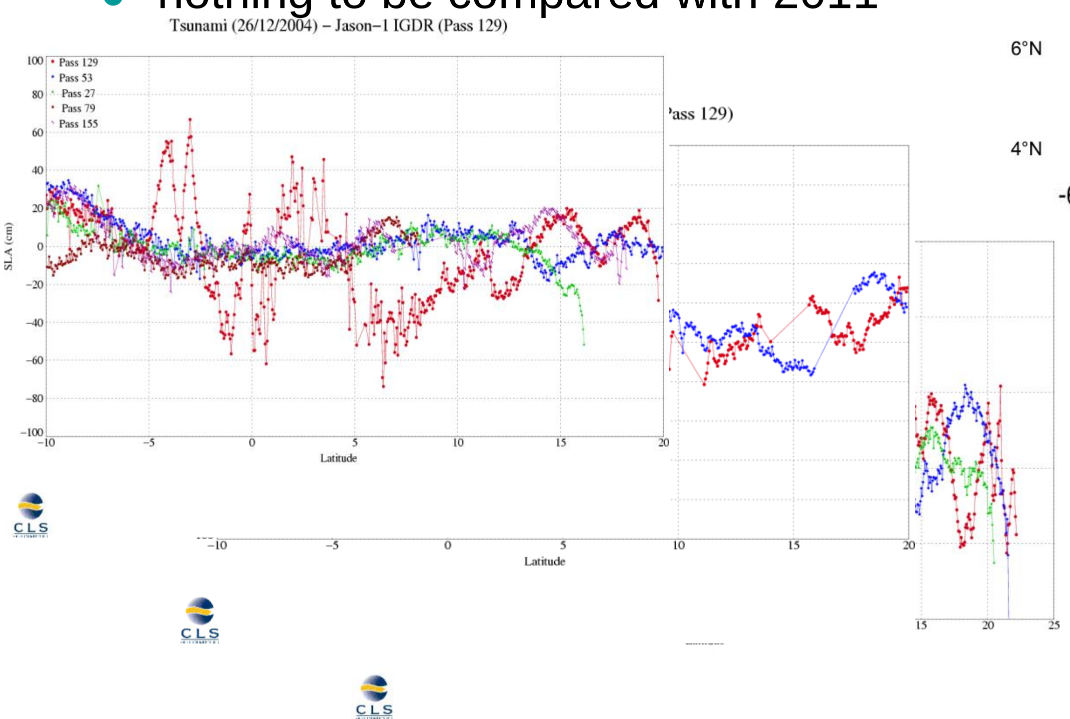
- **Major thrust earthquake (Mw ~ 9.2) ➔ major tsunami**
- **quite unexpected in the Indian Ocean**
  - high touristic vulnerability
  - many pictures, videos..

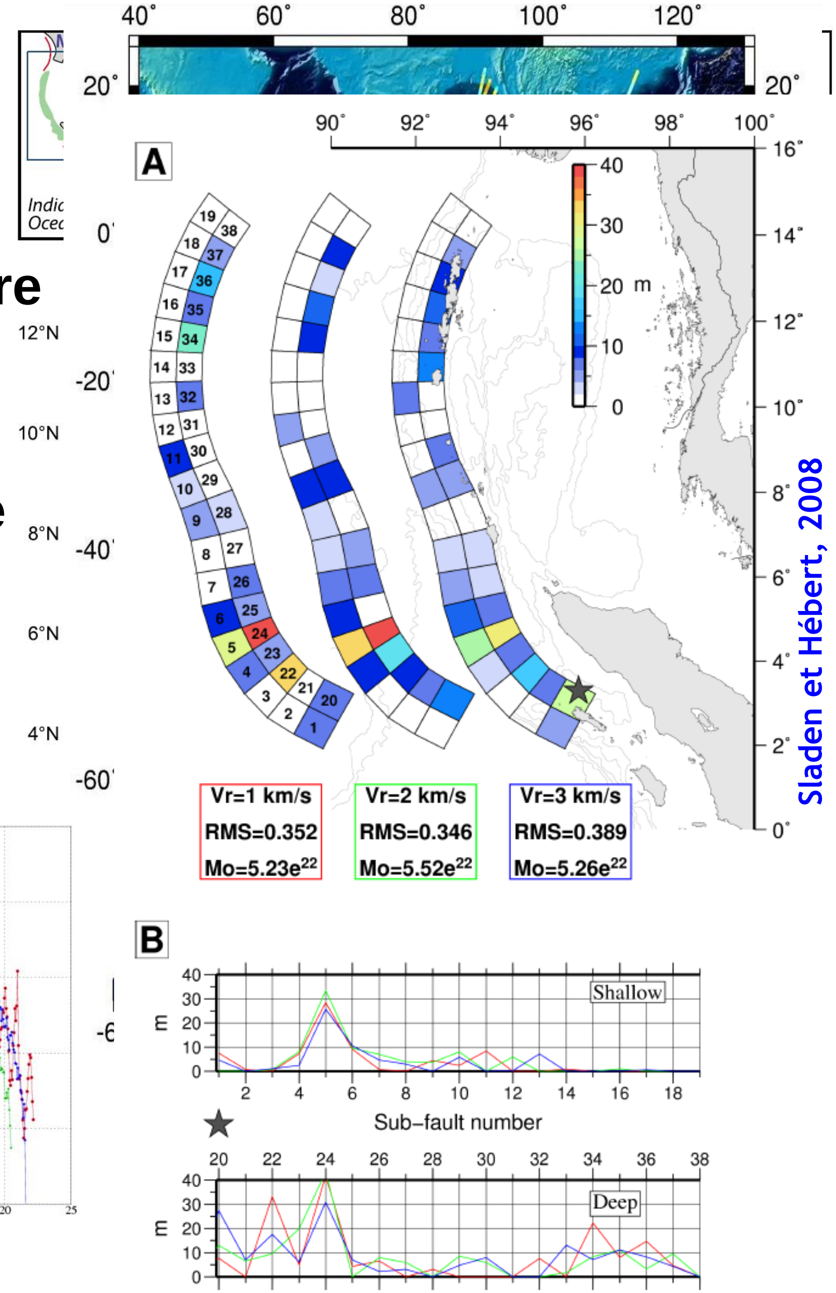




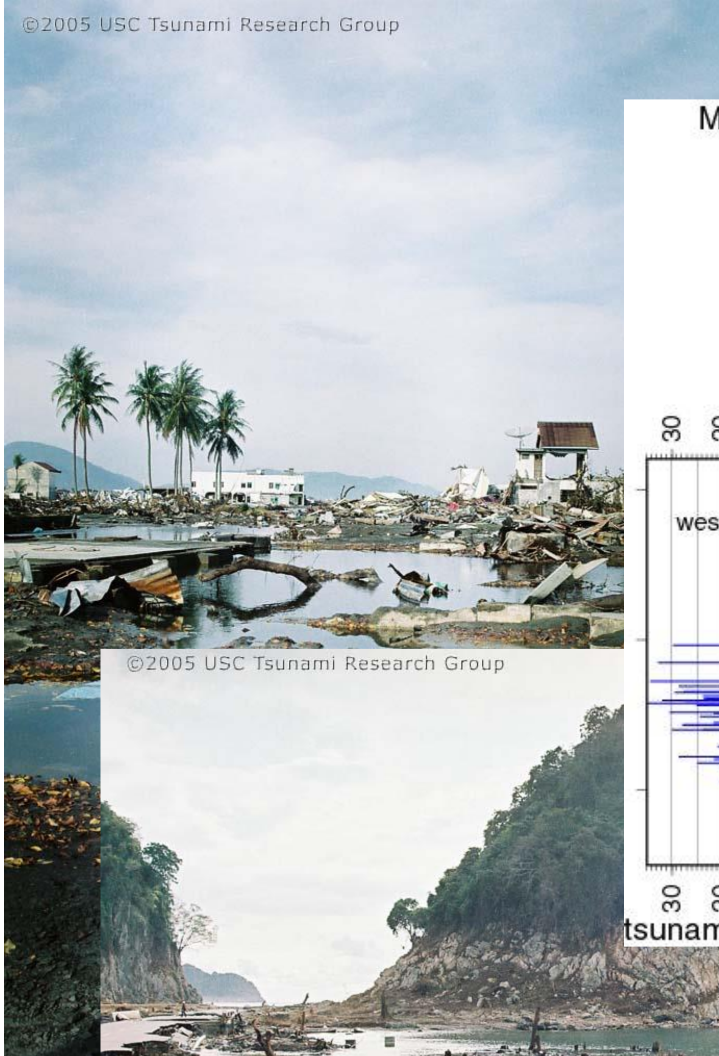
An outstanding offshore record

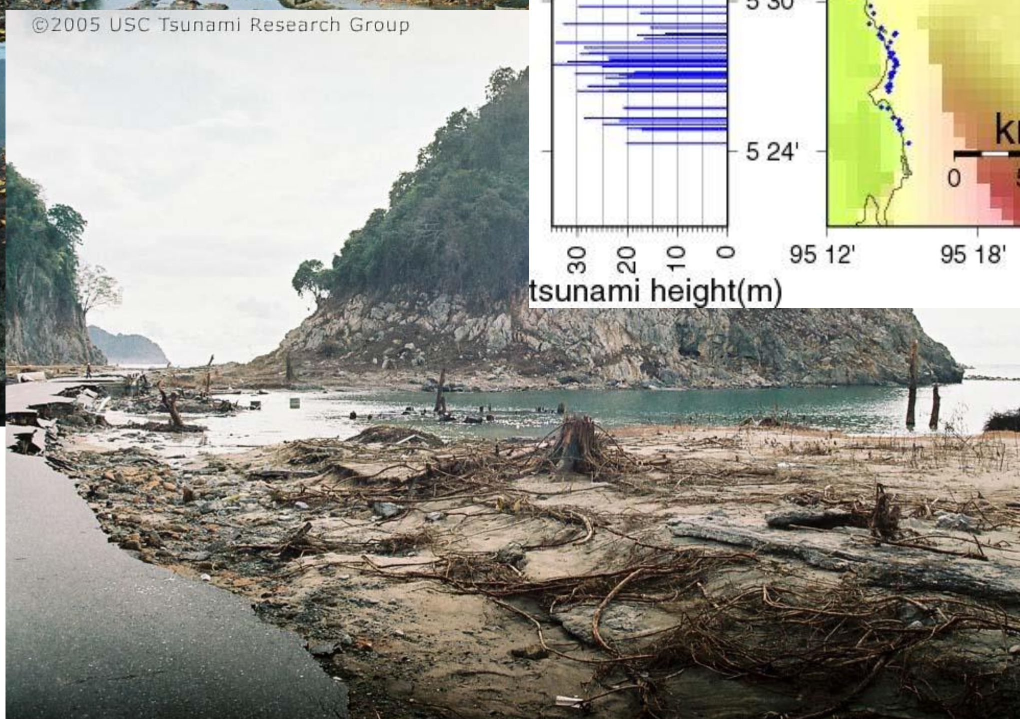
- Observation within a few hours by several altimetric satellites (Jason, Topex-Poseidon, Envisat, GFO)
- Inverting such data provides a picture of the seismic source of the earthquake
- This kind of record was quite unique
  - nothing to be compared with 2011

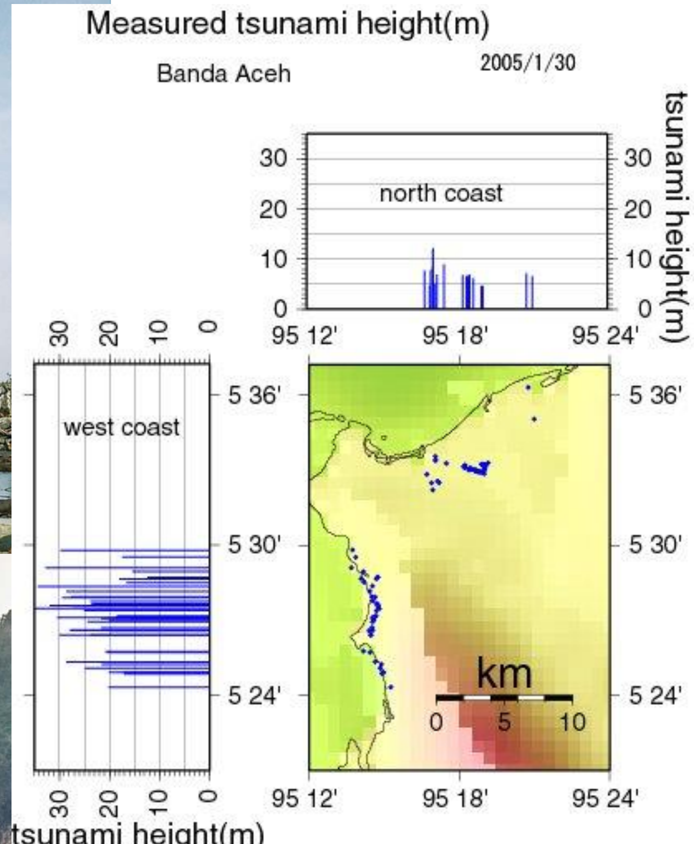


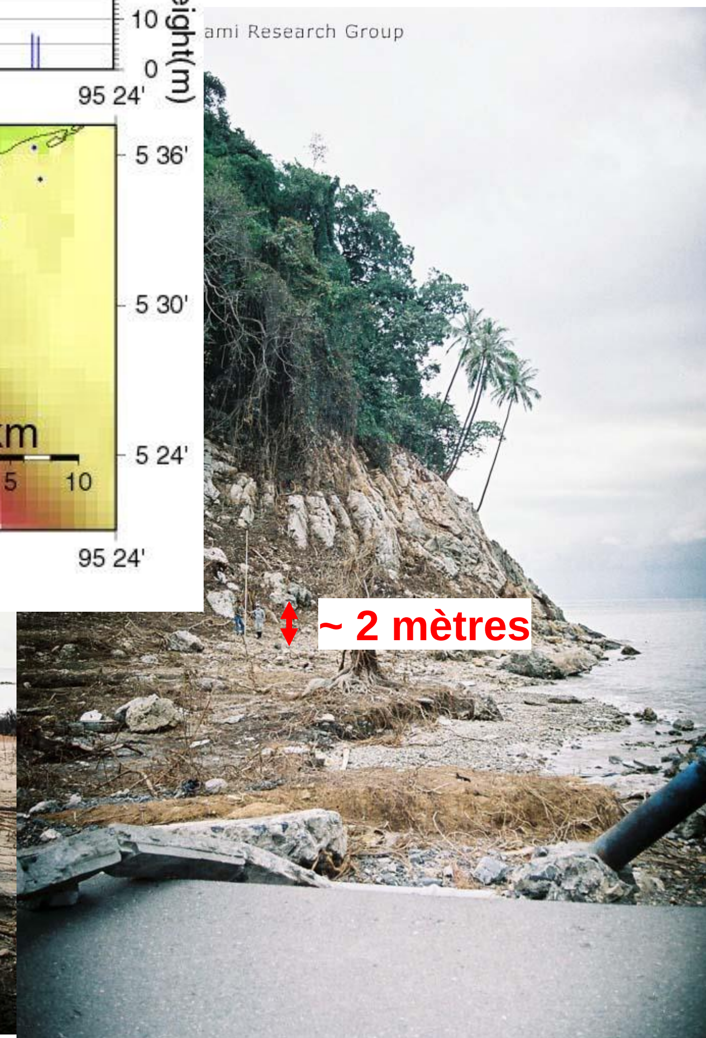


Observations in north Sumatra

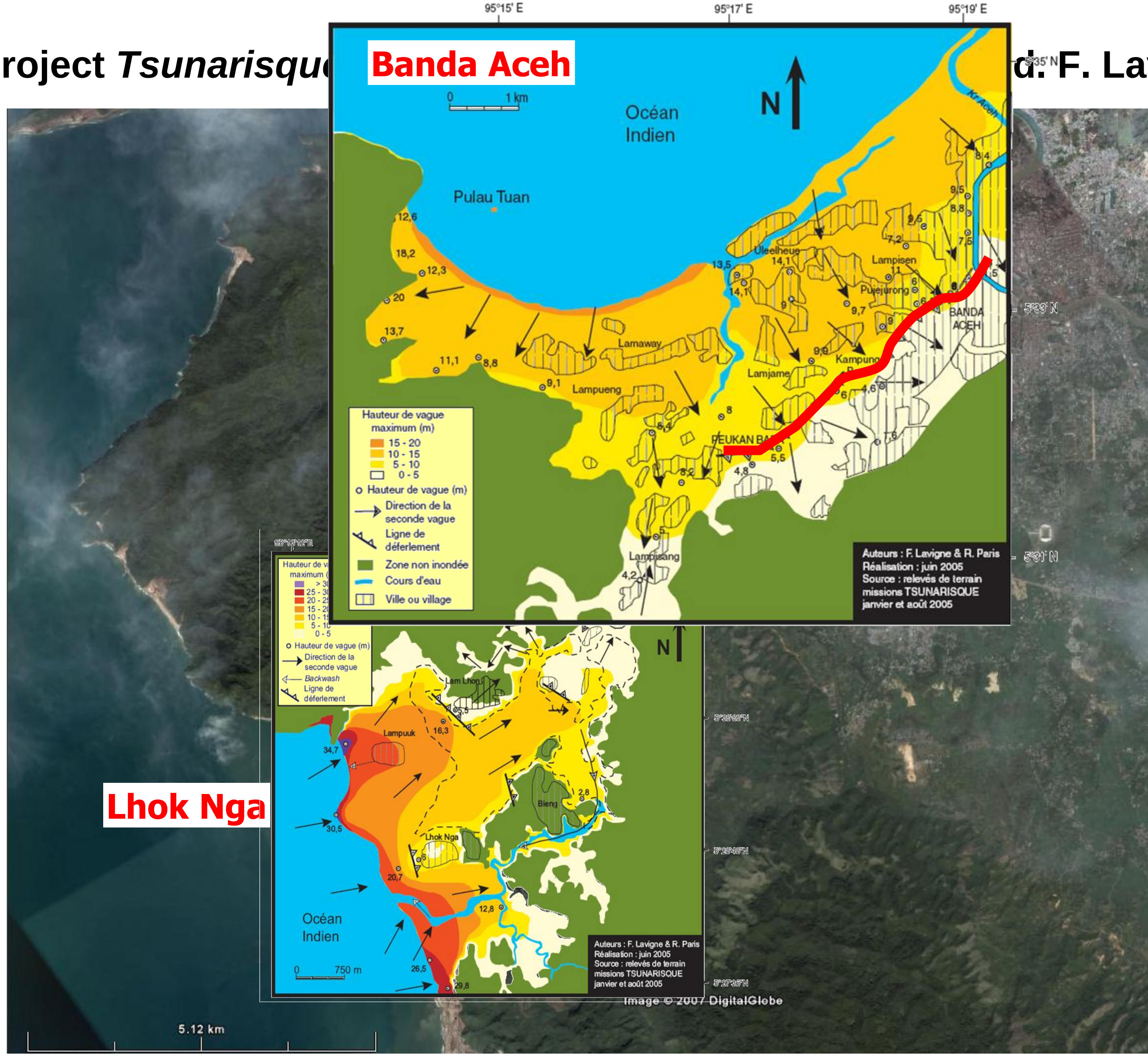




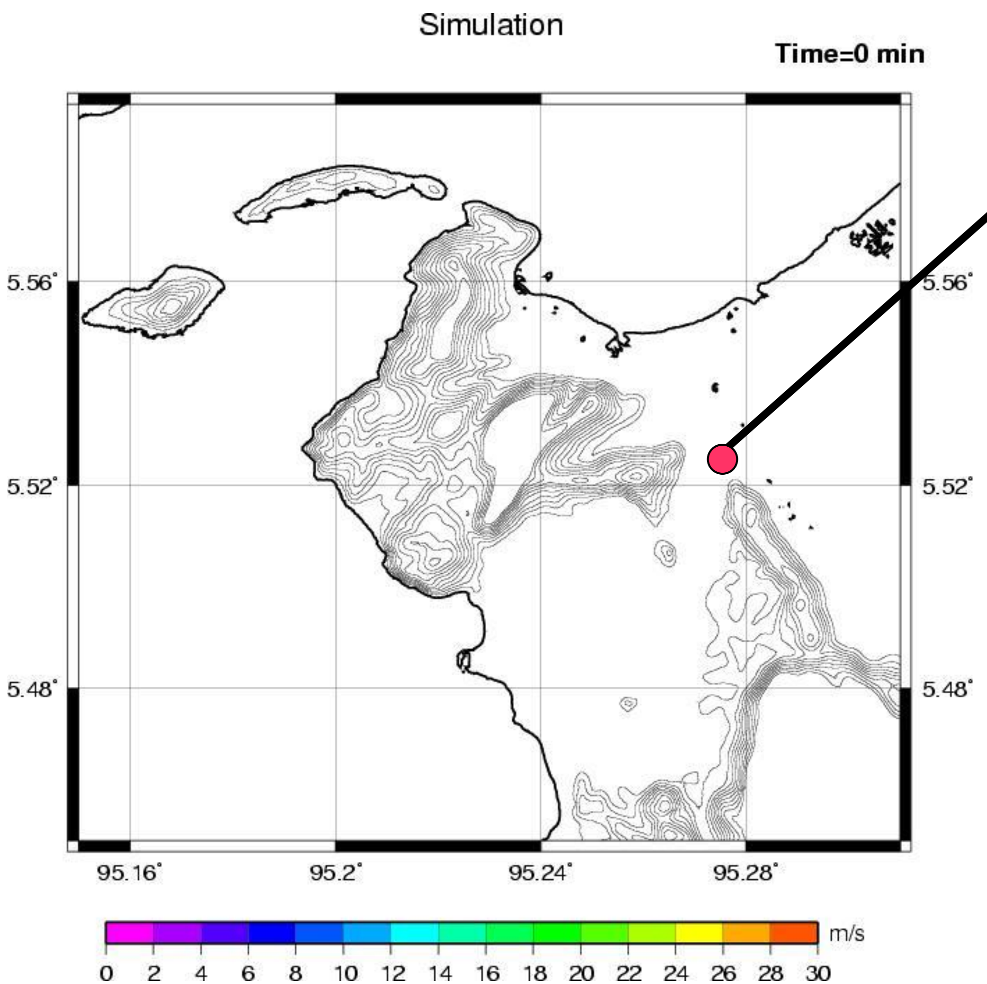




- **Project *Tsunarisqu*** … **d. F. Lavigne)**

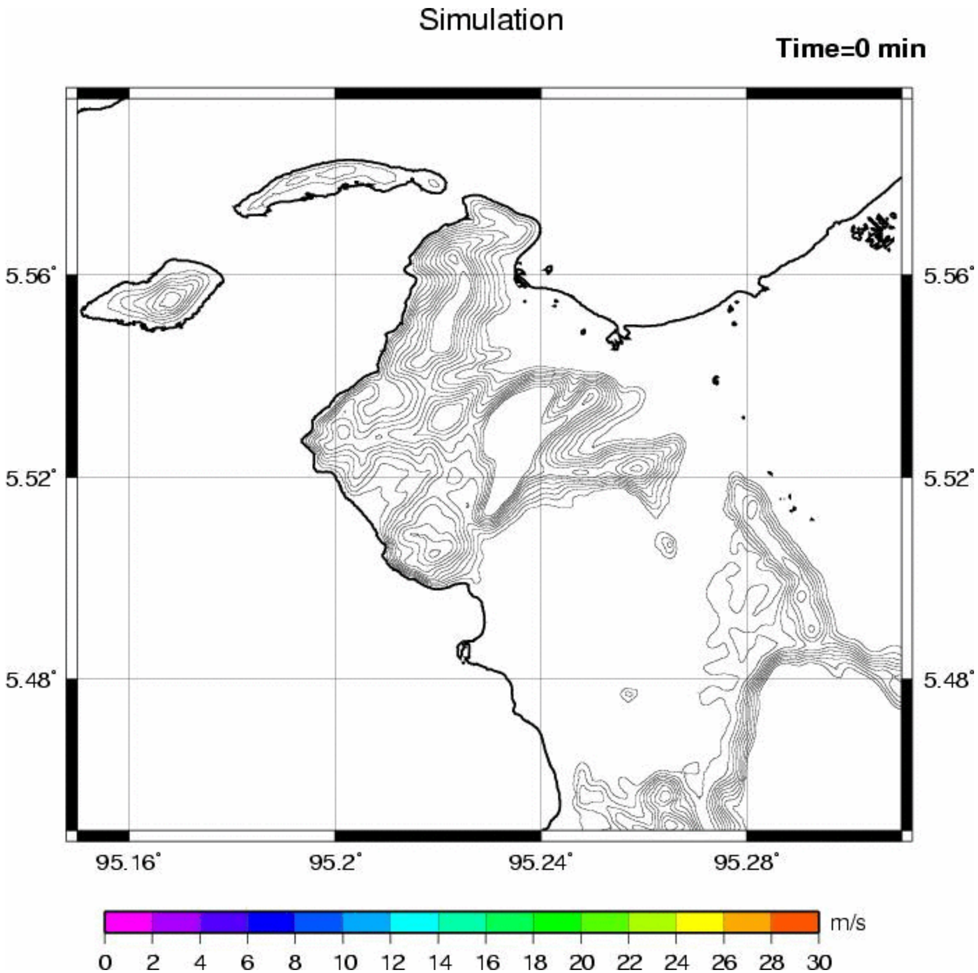


Banda Aceh / Lhok Nga

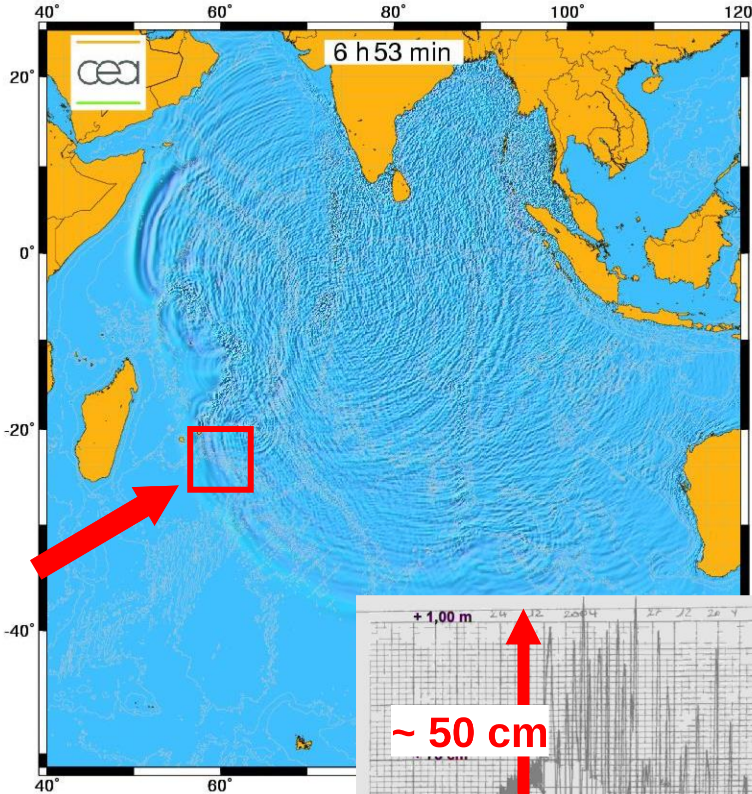


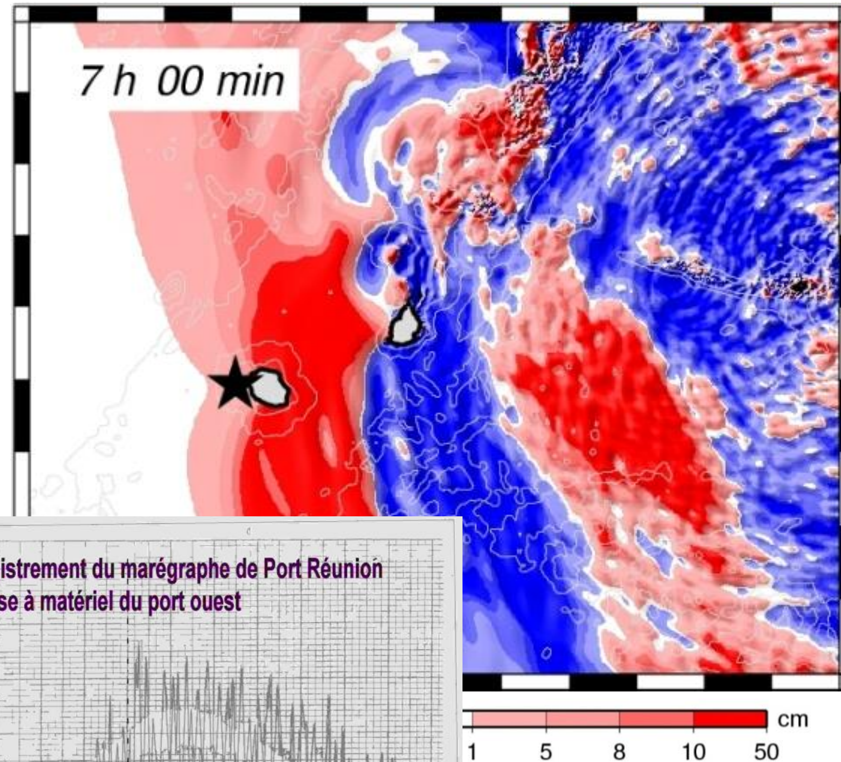
Merging of the two flows

Flow velocities from videos

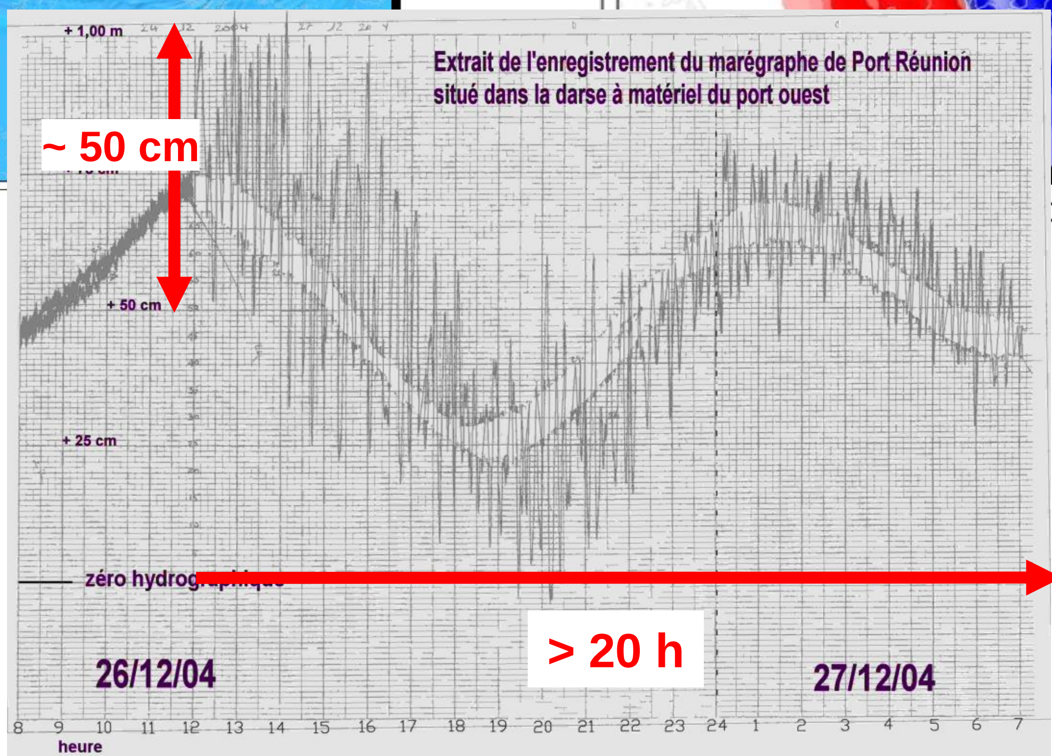

Simulation
Time=0 min
5.56˚
5.52˚
5.48˚
95.16˚
95.2˚
95.24˚
95.28˚
m/s
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30

La Réunion, 2004

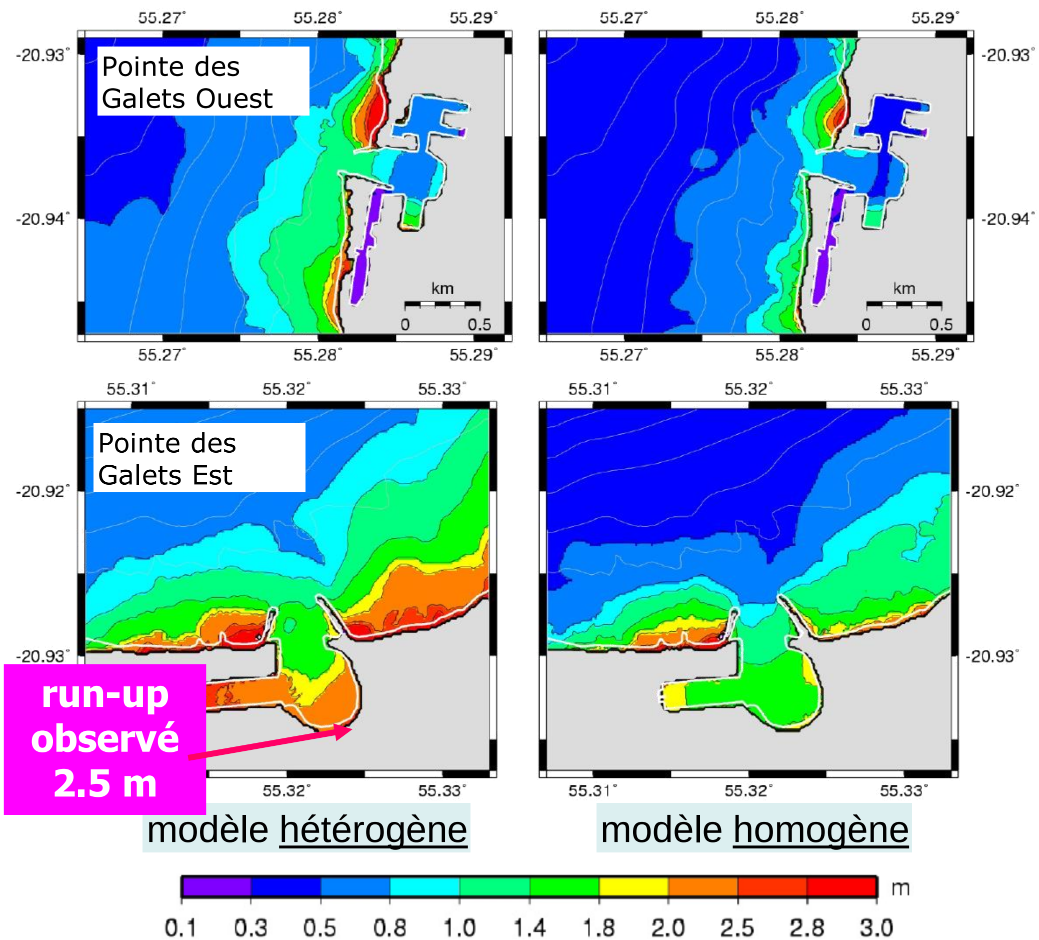


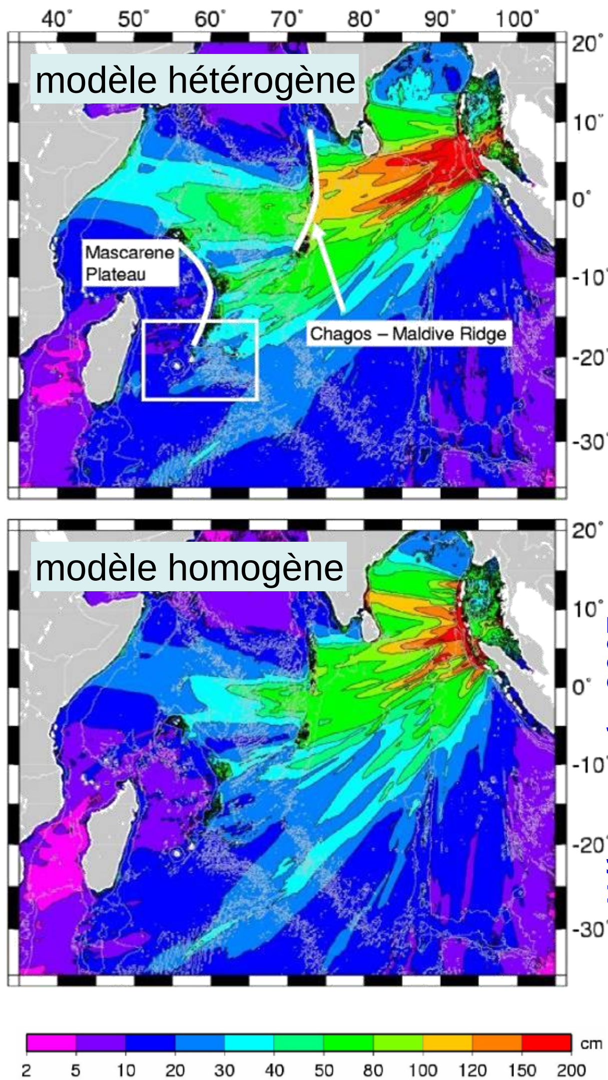


Hébert *et al.*, 2007



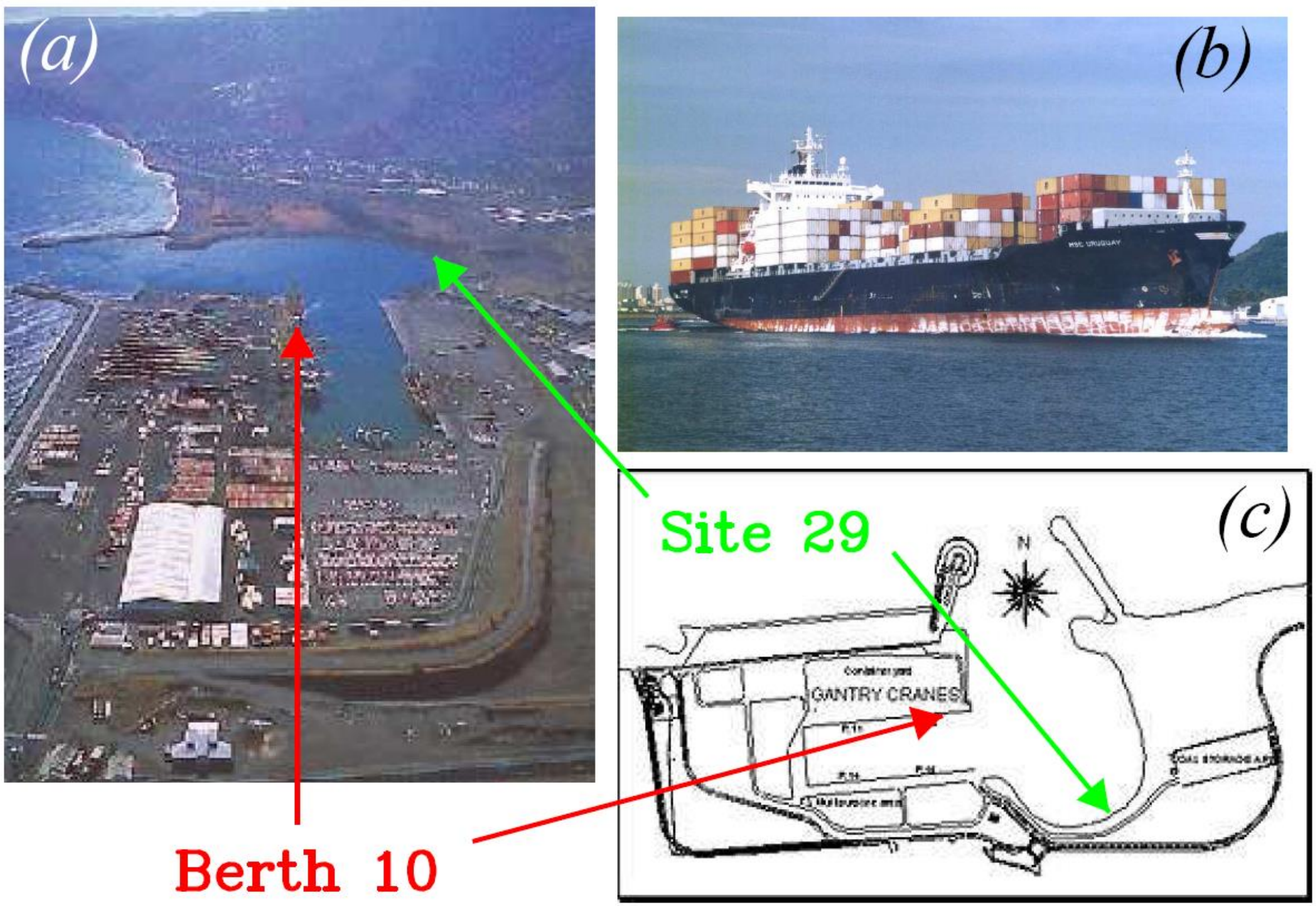
- Several very local inundations, especially in the west of the island
- Influence of the slip heterogeneities





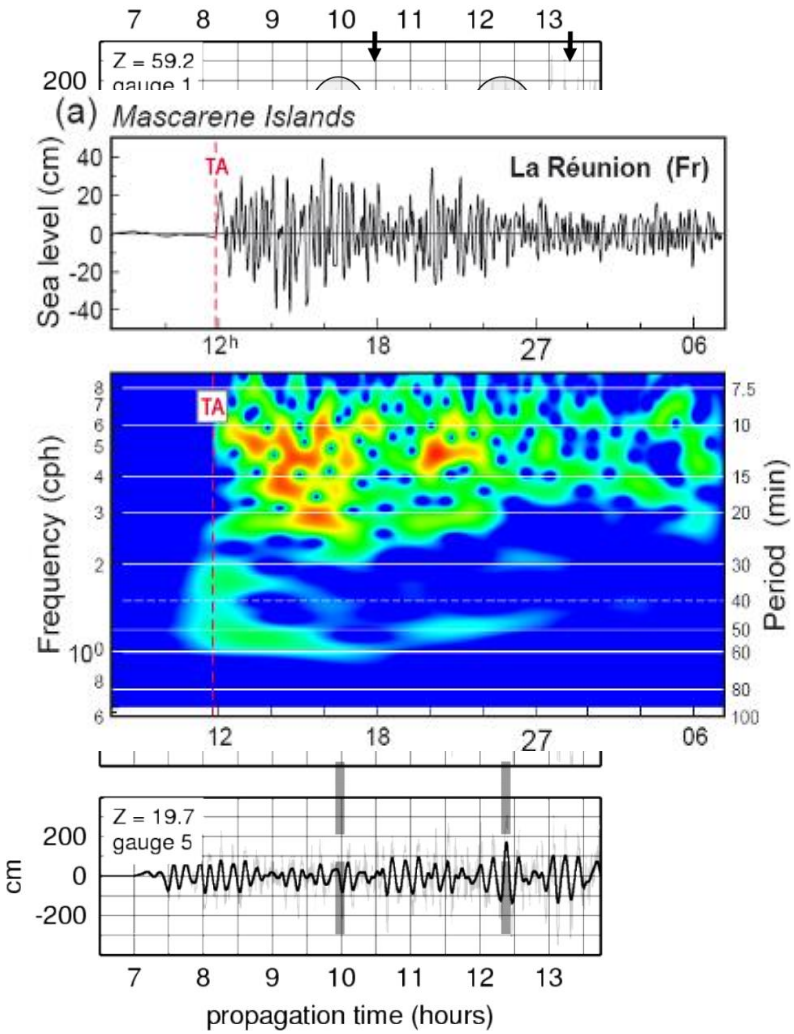
Hébert et al., 2007

- **Late tsunami arrivals**
  - moorings were broken for the *Uruguay*, twice during several hours
  - more than 4 hours after the first arrivals
  - material damage only

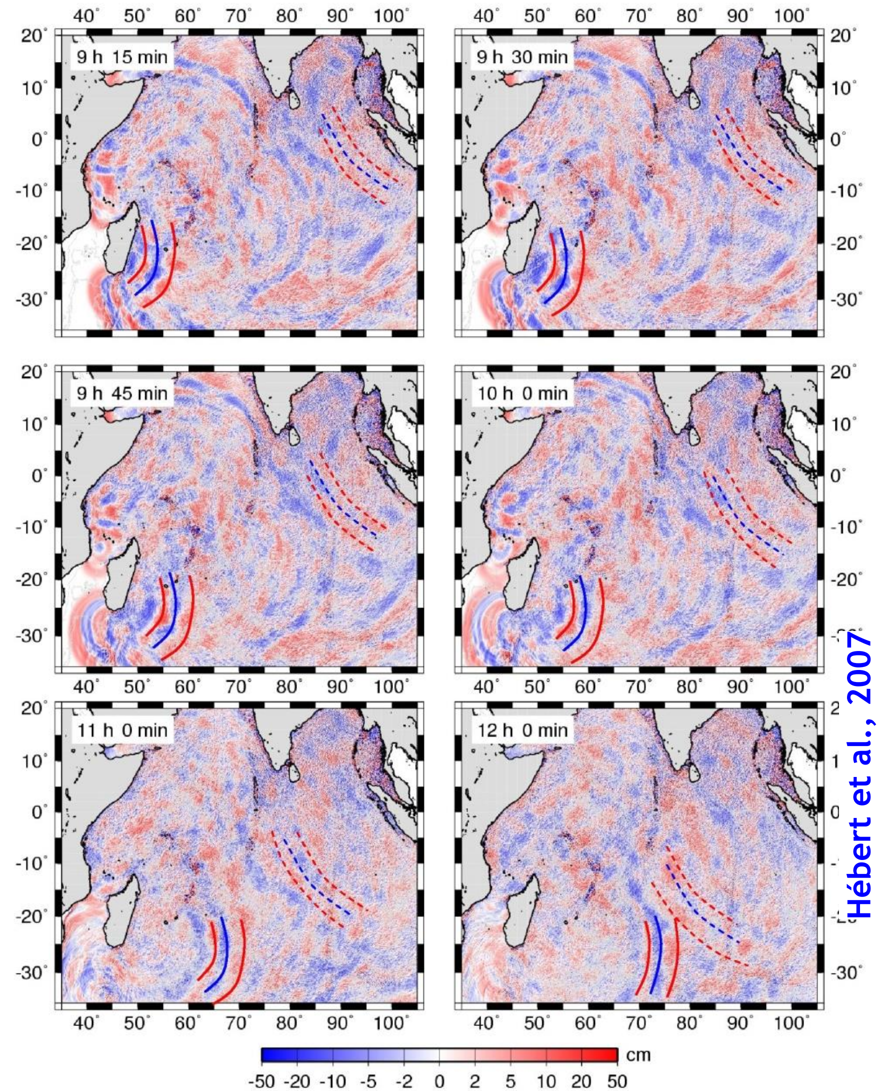


Okal et al., 2006

- **Multiple reflections?**
  - indicated by modelings mostly
  - less obvious in tide gauges



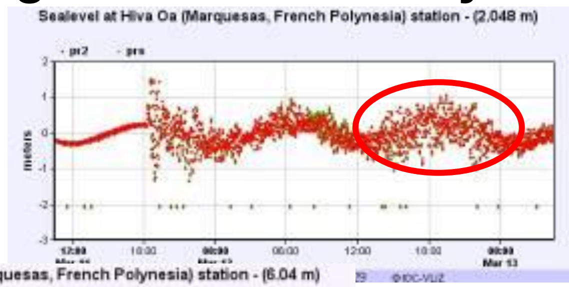
Rabinovich et Thomson, 2007

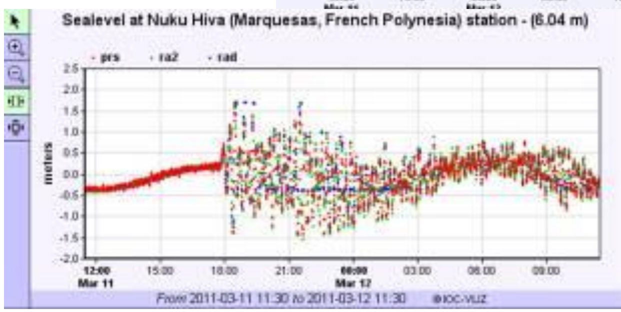


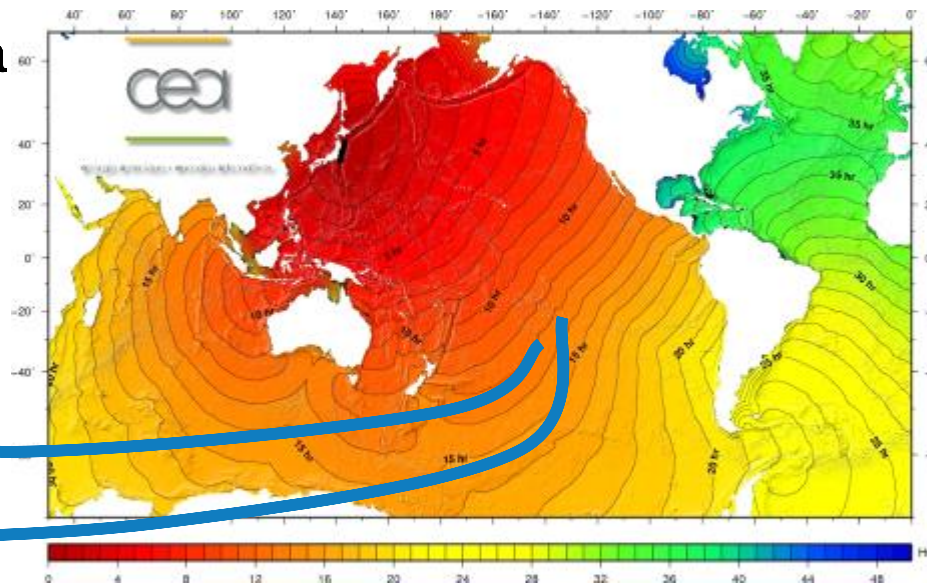
Hébert et al., 2007

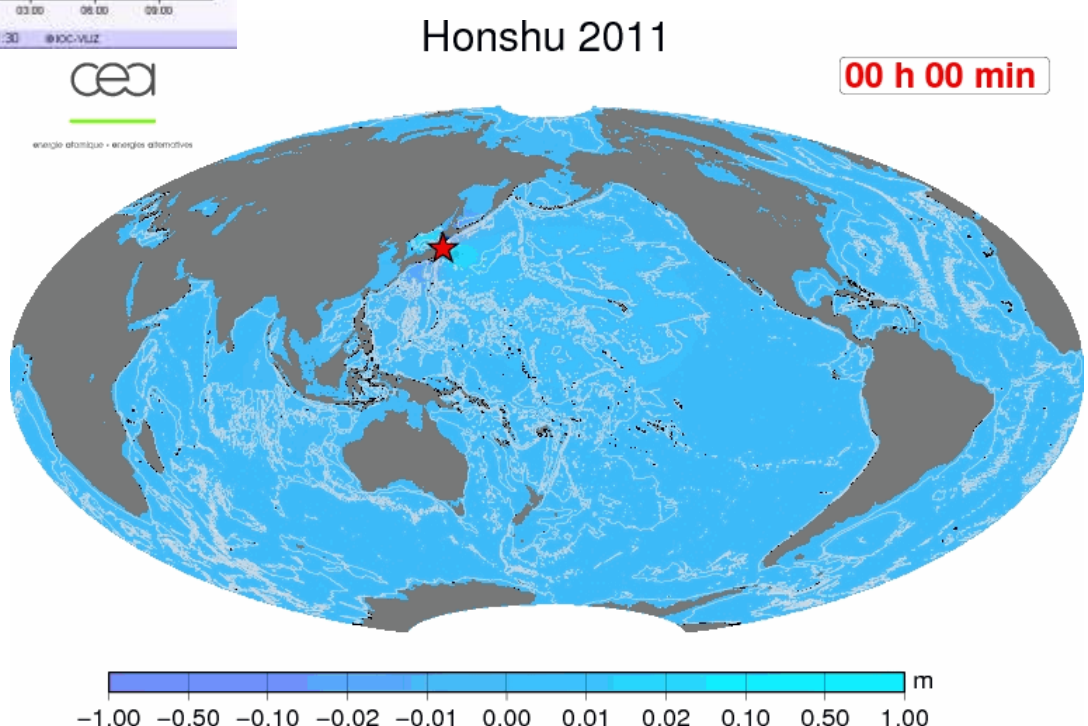
Another example of reflection in March 2011

- **Tide gauges in French Polynesia**

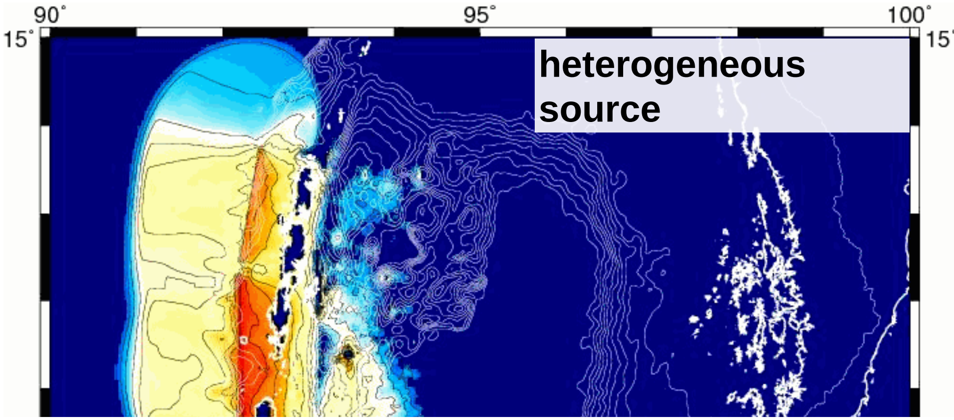




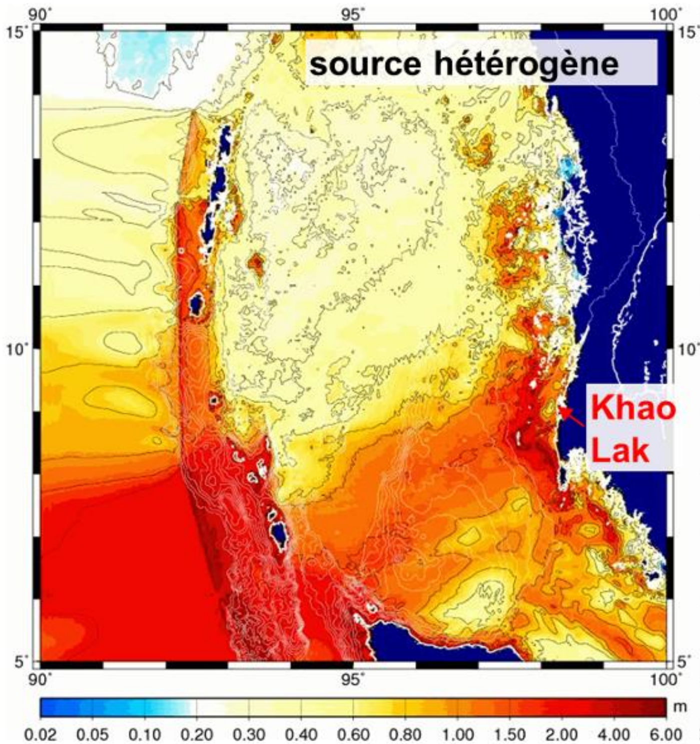


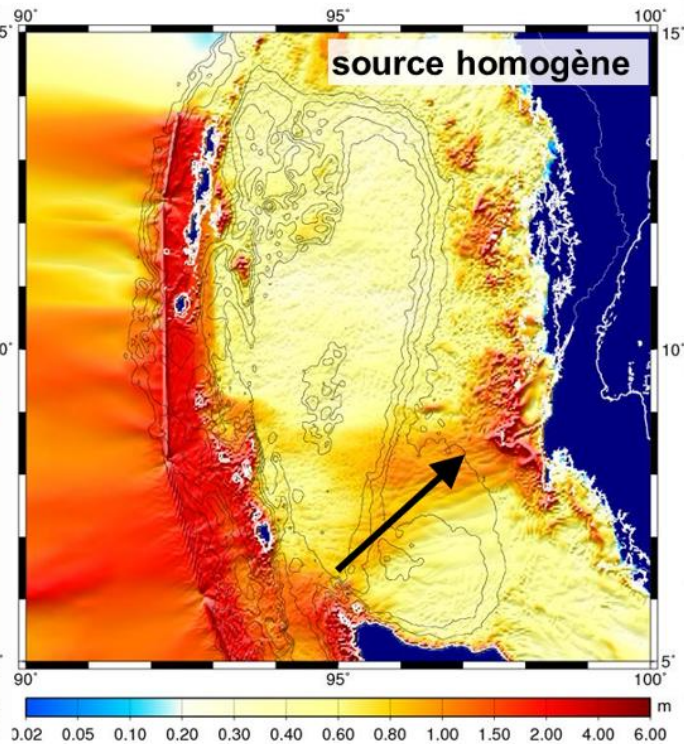


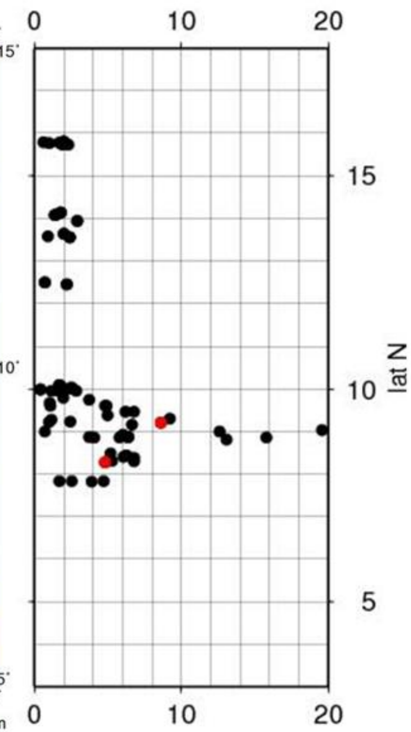
Focusing by bathymetric features



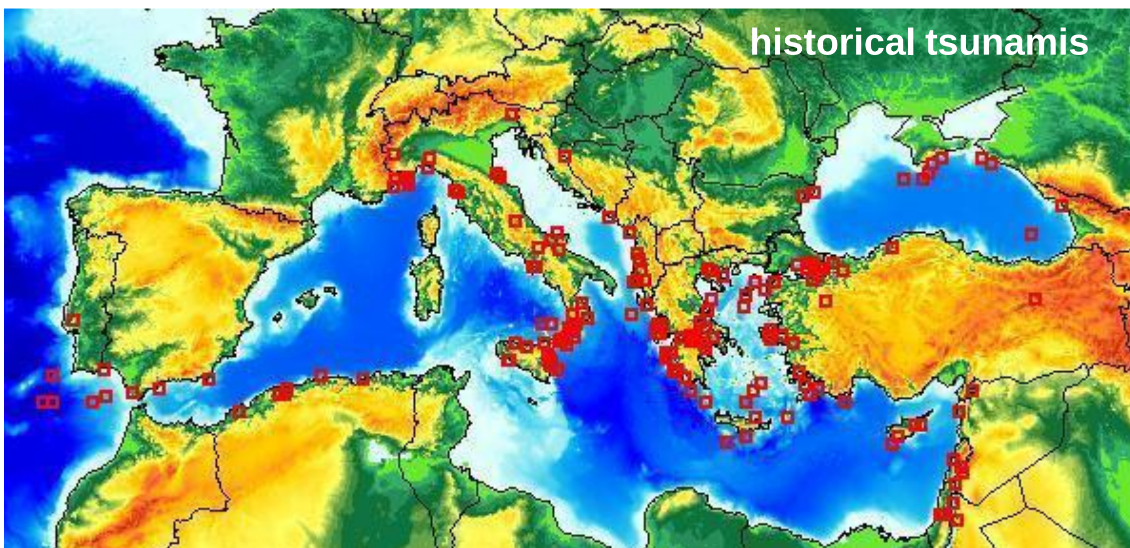
- **The area of Khao Lak – Phukhet is more exposed, due to a shallow submarine focusing feature**

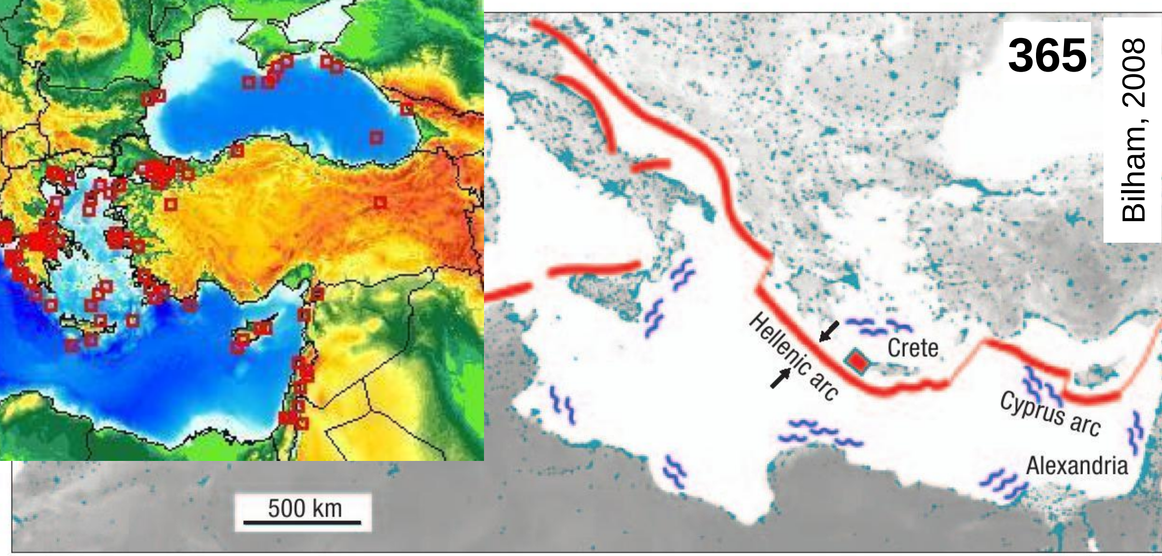






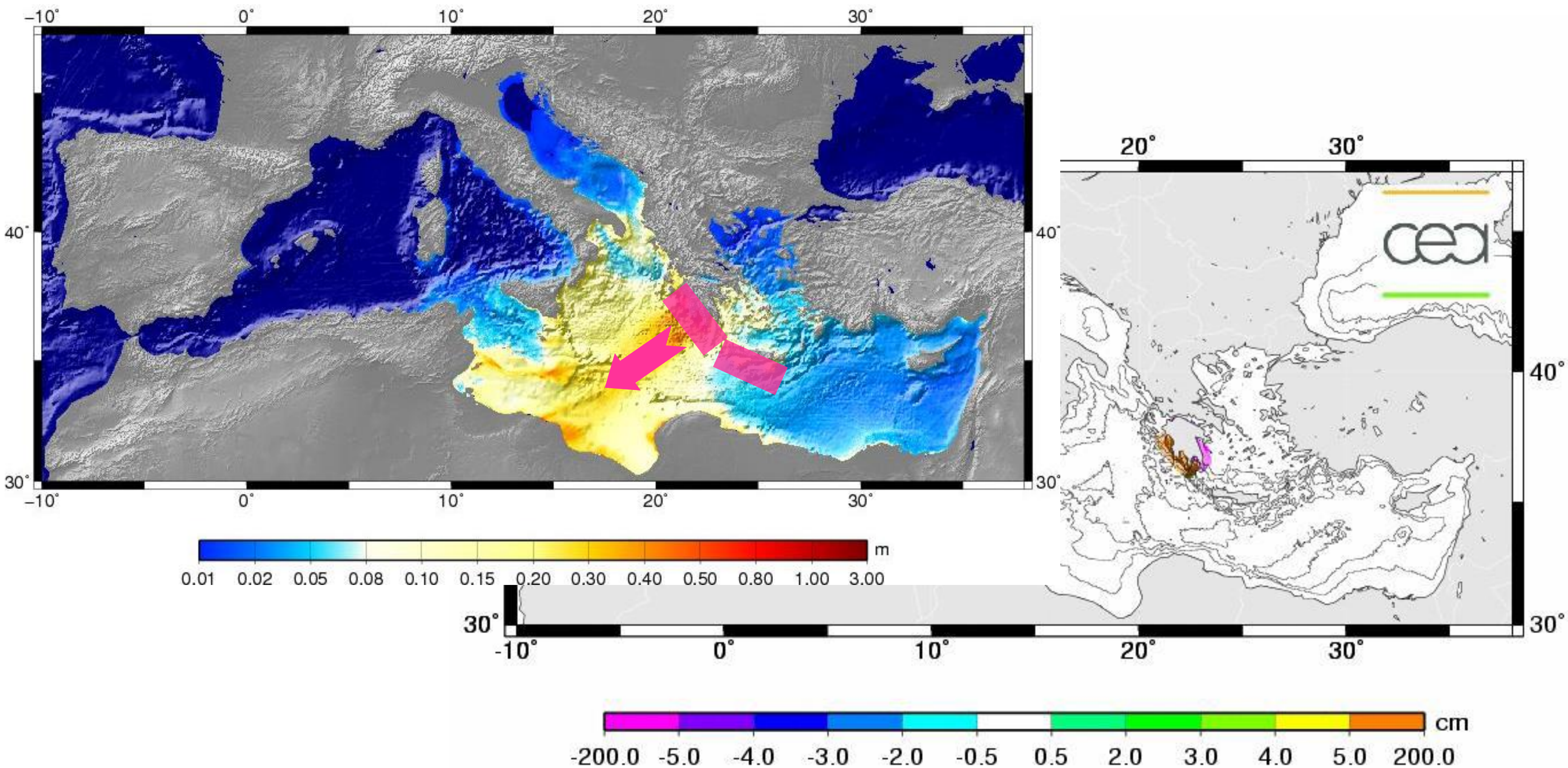
- **The Mediterranean is characterized by a complex tectonic context of convergence**
  - Aegean subduction (Crete, Greece)
  - major tsunamis already occurred in the past, but are rare
  - magnitudes above 7 and 8 possible
- **365, Crete**



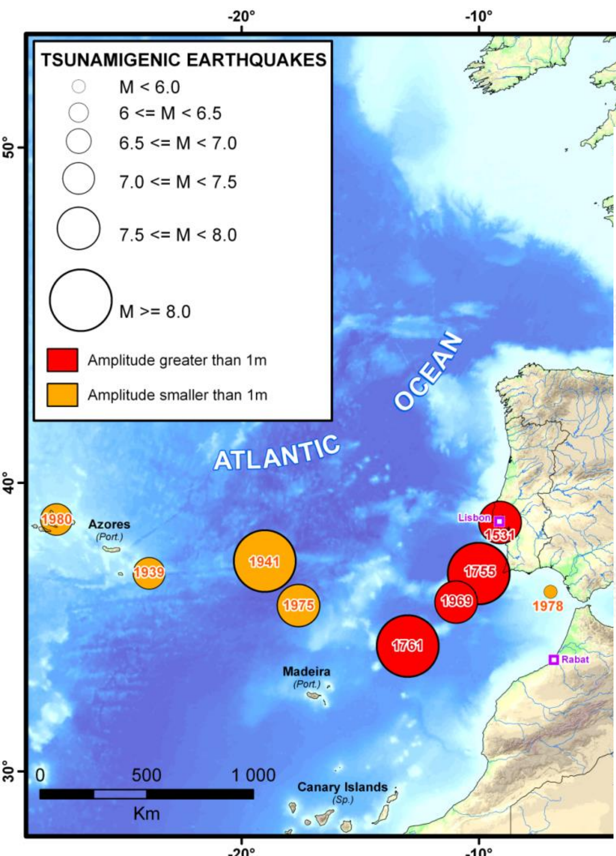


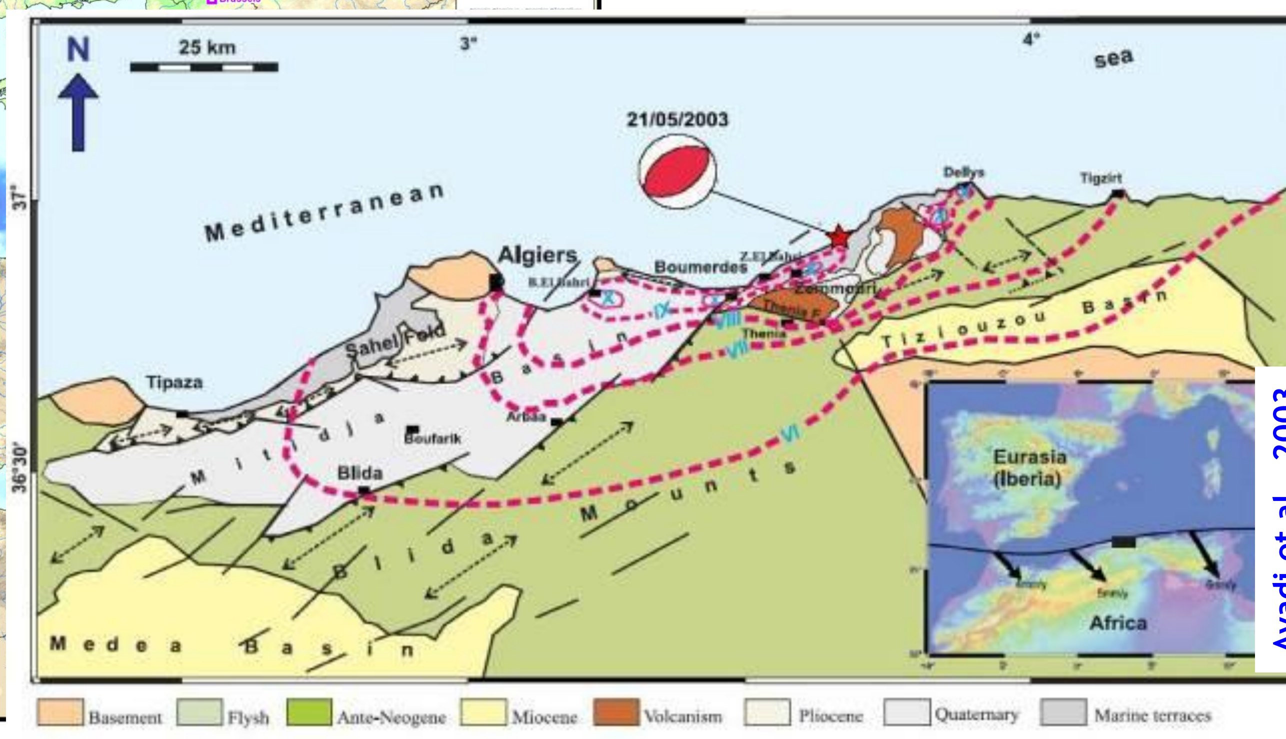
Example of a scenario in eastern Mediterranean

- **The effects are restricted to the East**
- **Example of a scenario M_w 8.0**
  - maximum impact : Greece, Lybia, Tunisia, Egypt, Turkey, Lebanon



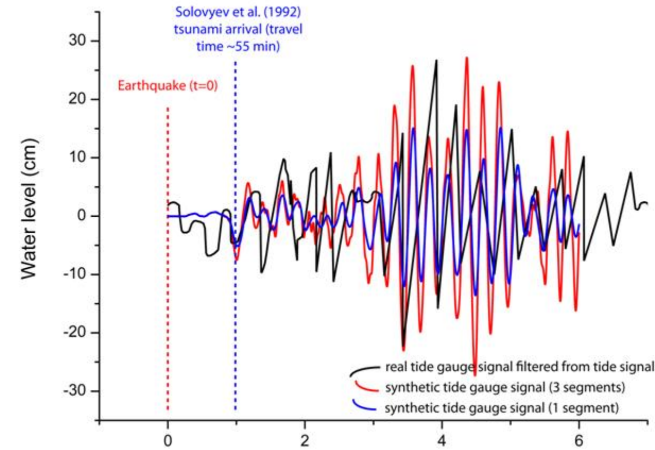
- **Seismic activity**
  - sometimes submarine epicenters
  - historical tsunamis: 1755, 1365, 1856
- **Earthquakes in Boumerdès, May 2003 (M_w = 6.9)**
  - tsunami well observed in the Balearic

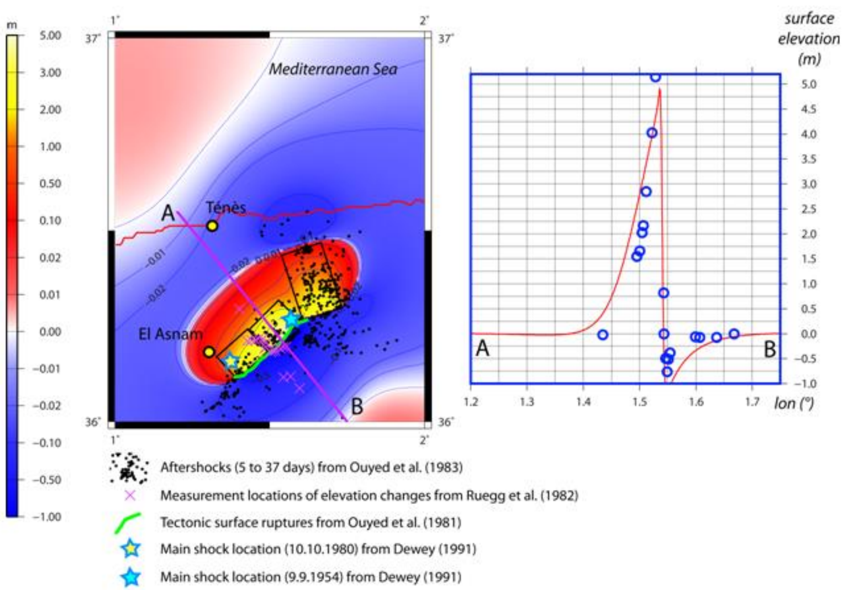




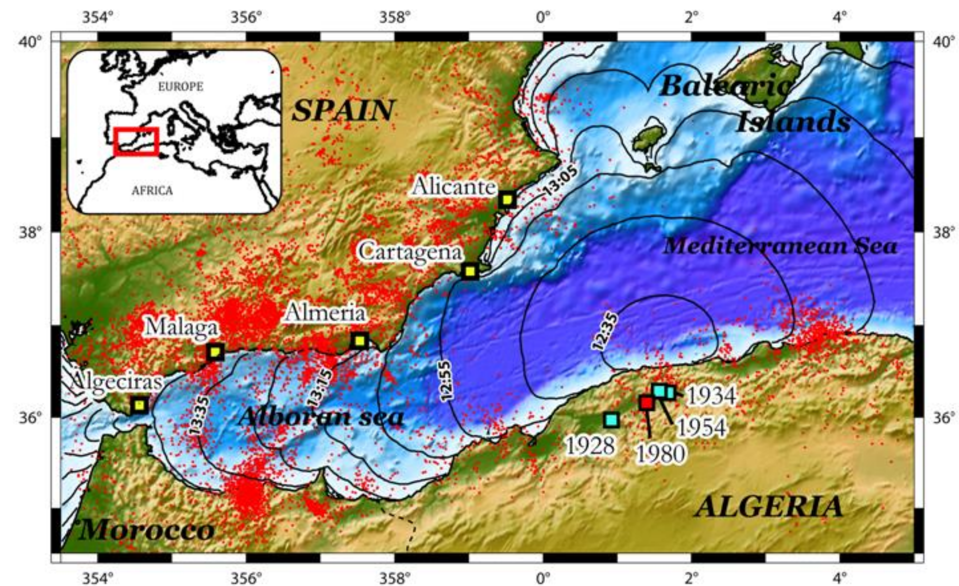
Ayadi et al., 2003

- **Modeling of tide gauges in Spain**
  - periods 15-20 min
  - results consistent with a coseismic triggering (and not turbidity flows)
- **A lesson for warning procedures**

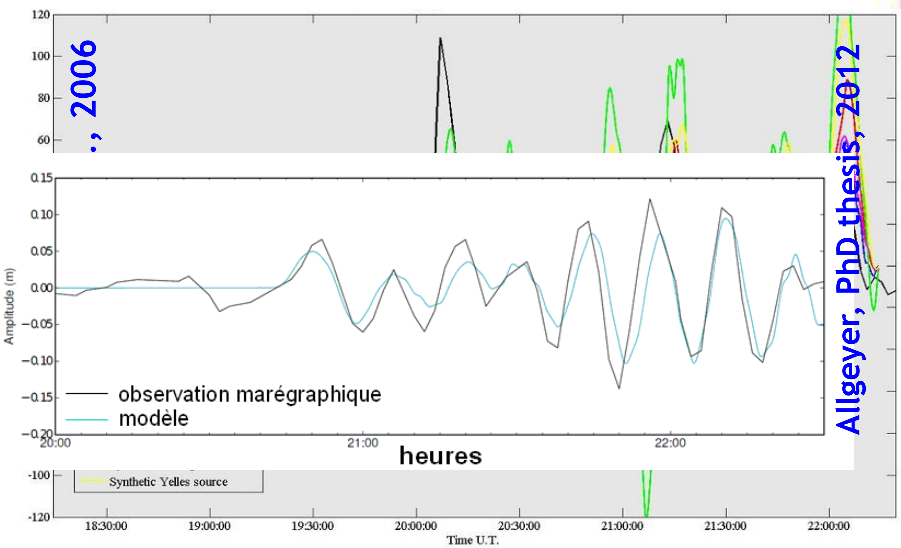


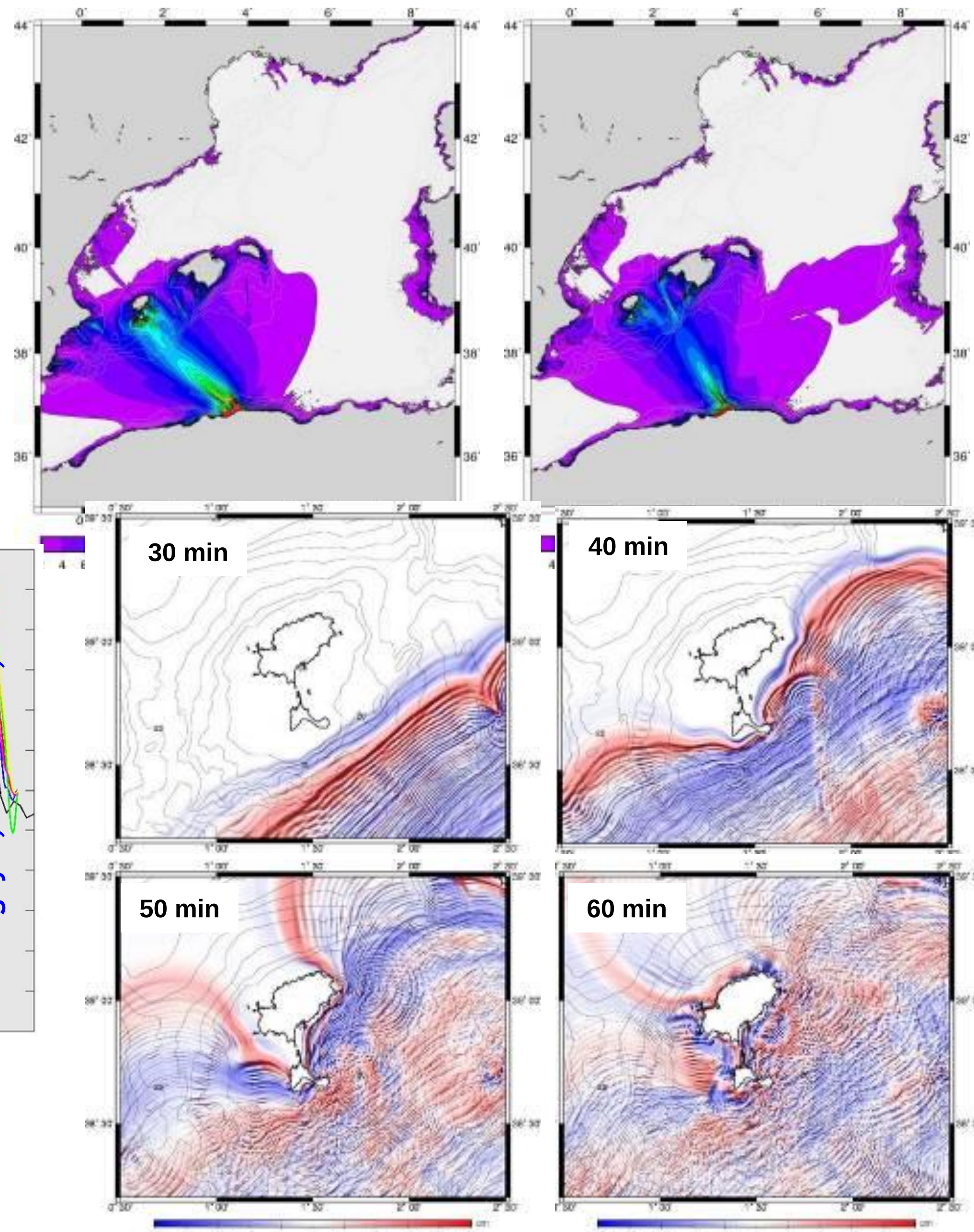


Roger *et al.*, 2011

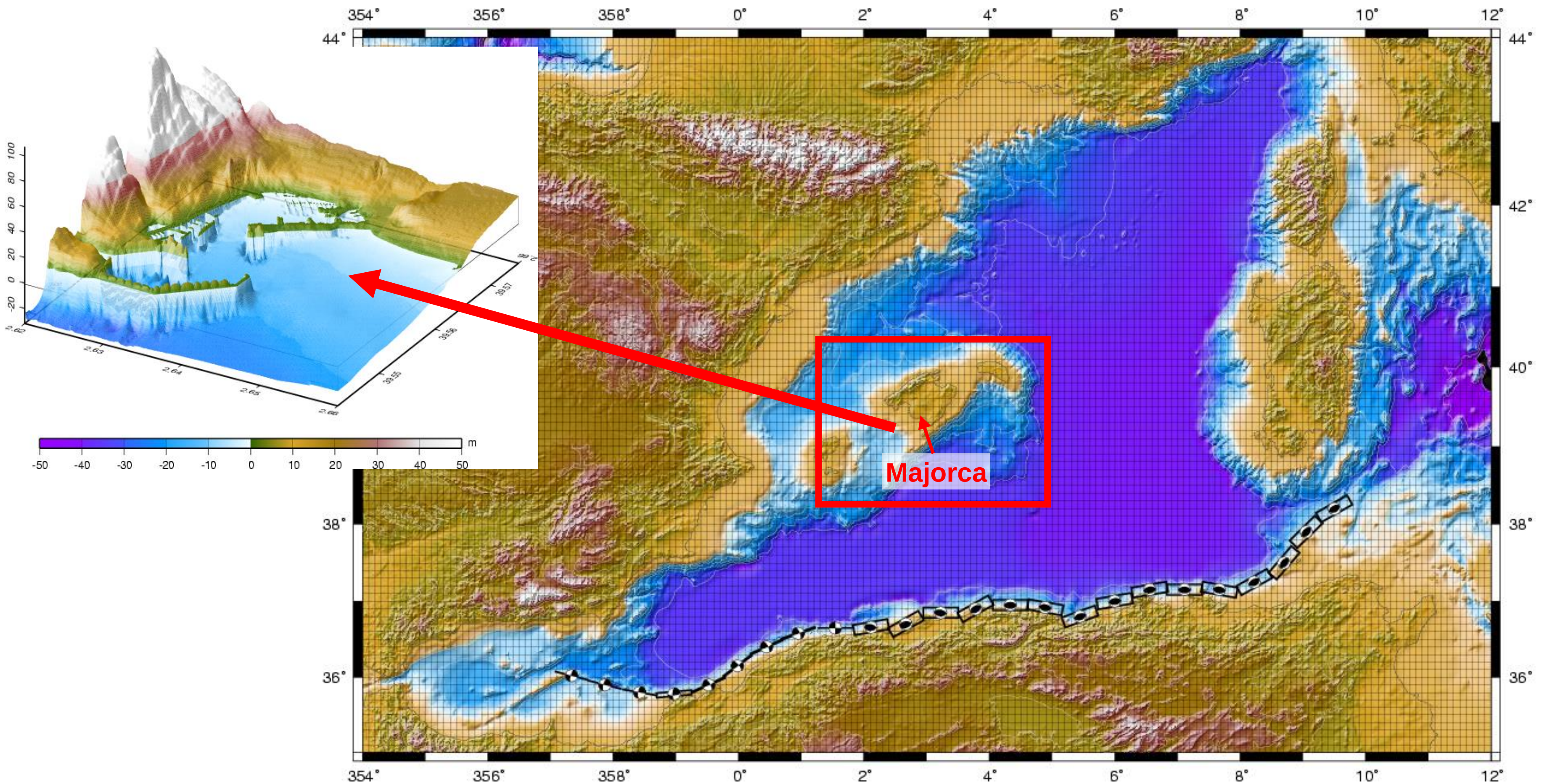


- **Main axis**
  - trapping around islands
- **Discussion on models**
  - may require a stronger source or located more offshore

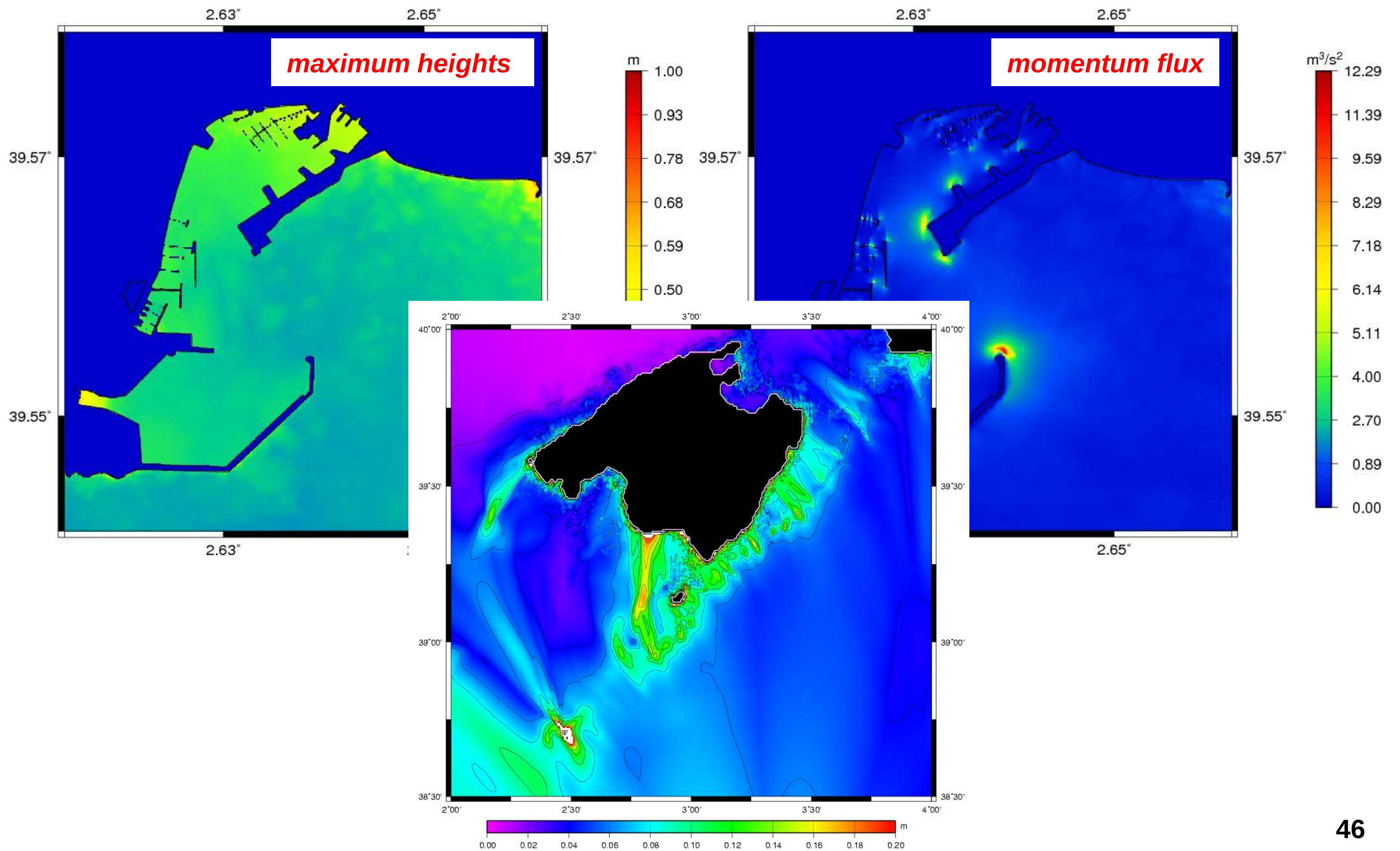




- **In the frame of the EC FP6 TRANSFER project, a hazard assessment was carried out for Palma (Majorca)**
- **24 earthquake scenarios along the Norh Africa margin**

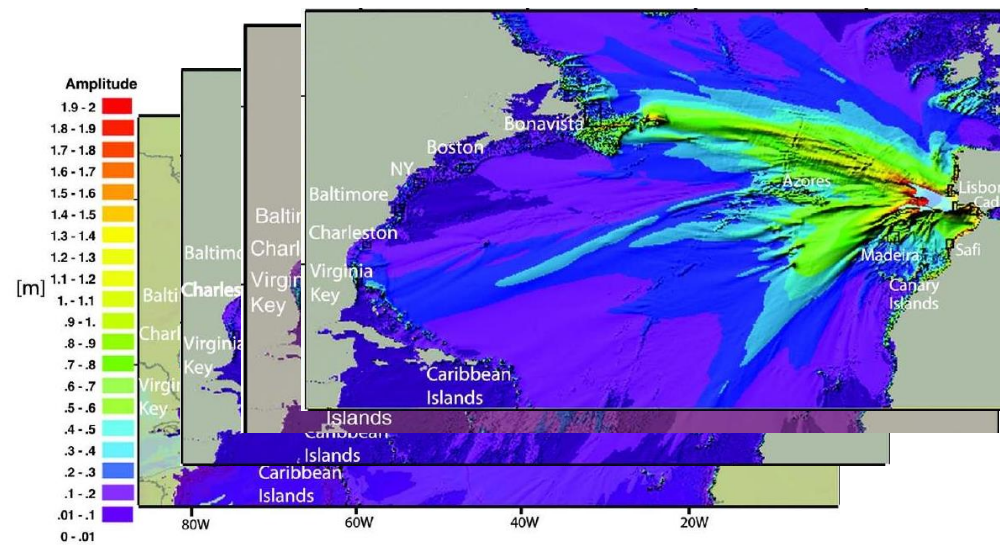


- Palma is moderately exposed to this kind of sources
  - local inundations possible
- Rather more protected than the SE coastline of Majorca

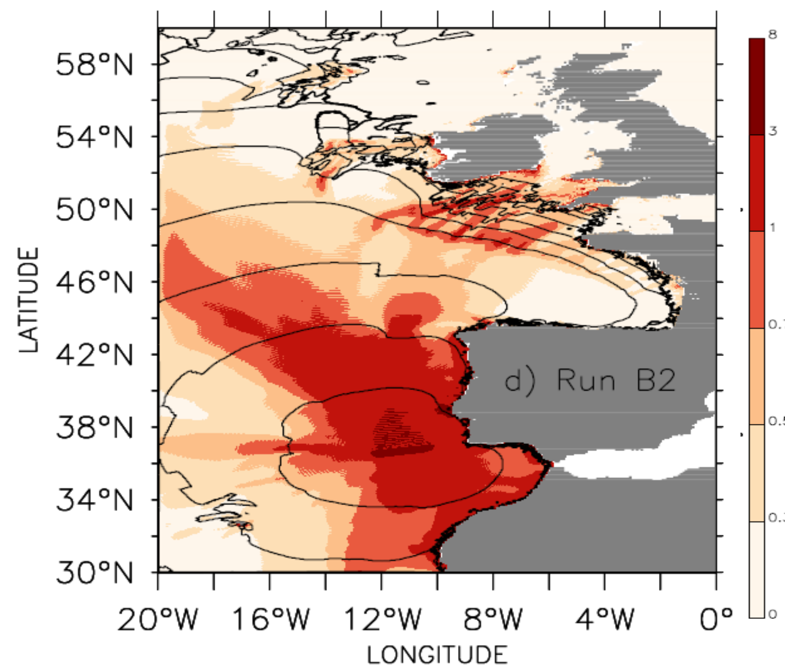


Scenarios in the Atlantic

- **1755 : a transoceanic tsunami**
  - observed in the Lesser Antilles
  - In Europe
    - Portugal, Spain, Morocco
    - Irland, Great Britain
    - France ?
- **Needs for**
  - deposits
  - complementary to fine models
- **Question**
  - How to account for a Mw 8.5 earthquak with such a small fault?

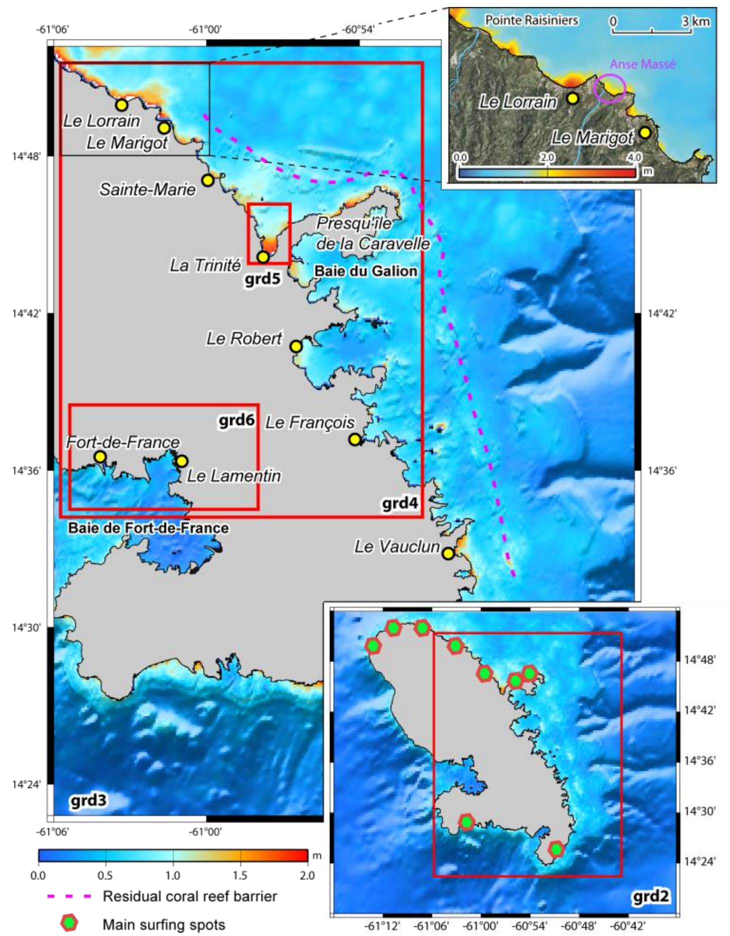


Barkan et al., 2009

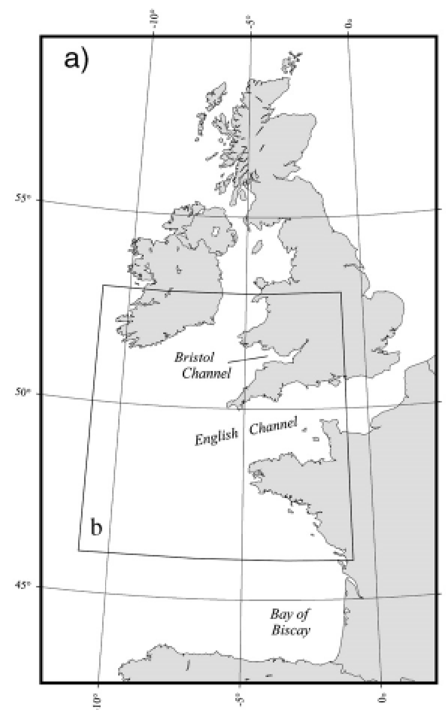


Horsburgh et al., 2008

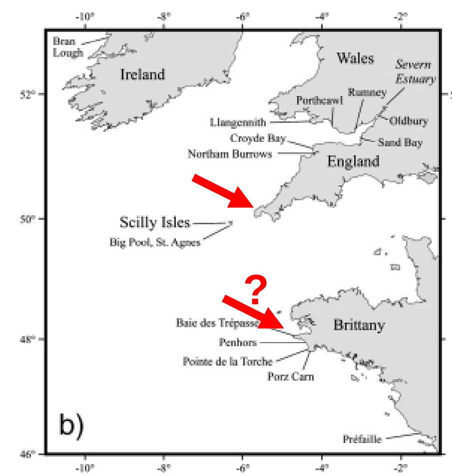
- **A key tsunamigenic area in NE Atlantic**
- **Not documented for French coastlines**
  - observations in Lesser Antilles (run-up 1 to 5 m)
  - a comprehensive historical study is necessary, with *in situ* investigations



Roger *et al.*, 2011

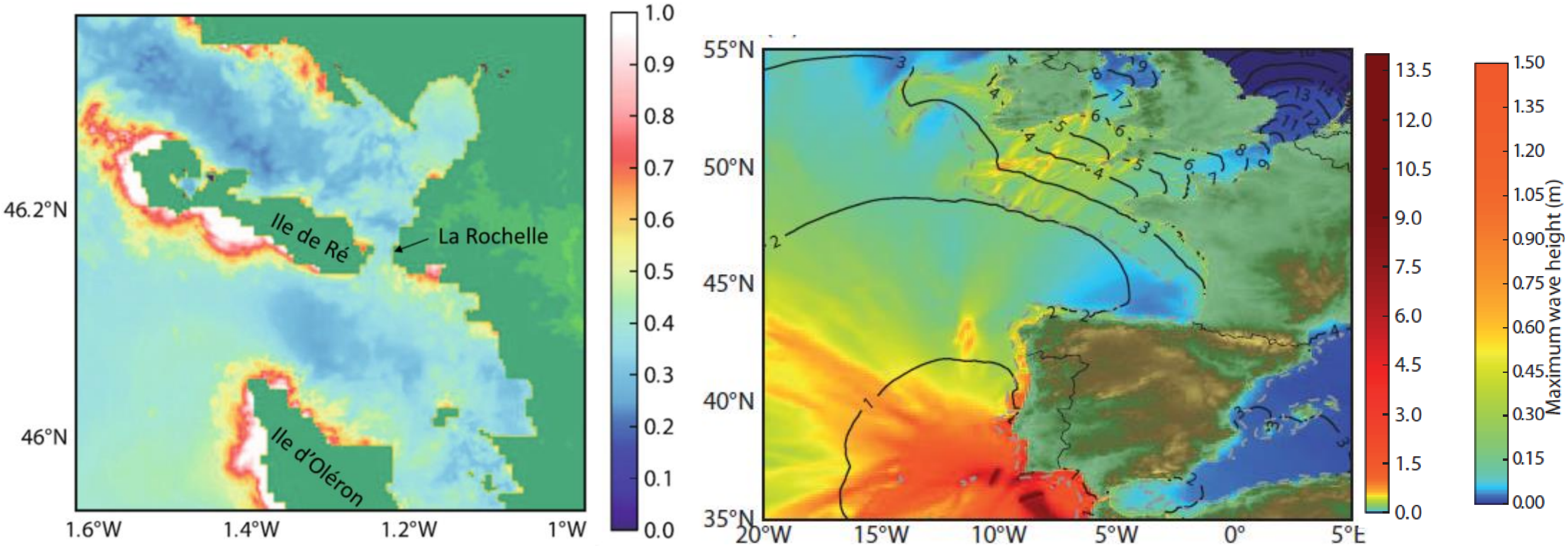


effets en France ?



Haslett et Bryant, 2007

- **Example with source parameters from Baptista (2003)**
  - focusing towards Ireland and GB
  - to a less extent towards French Brittany
- **Models towards La Rochelle**
  - protected harbour, but larger amplitudes explained to the west of the islands
    - no major flooding
    - difficult to distinguish from storm deposits



Allgeyer *et al.*, 2012

cea

SHOM

cnrs INSU Observer & comprendre

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MINISTÈRE DE L'INTÉRIEUR

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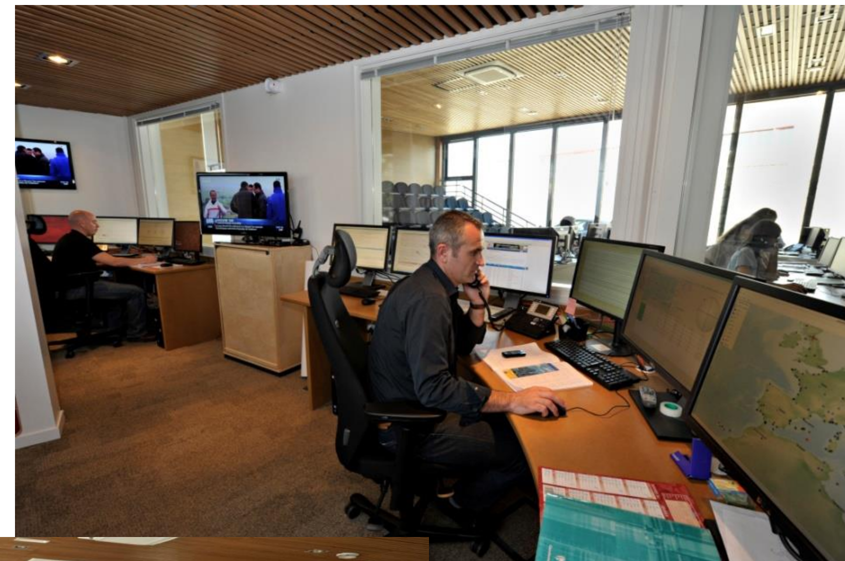
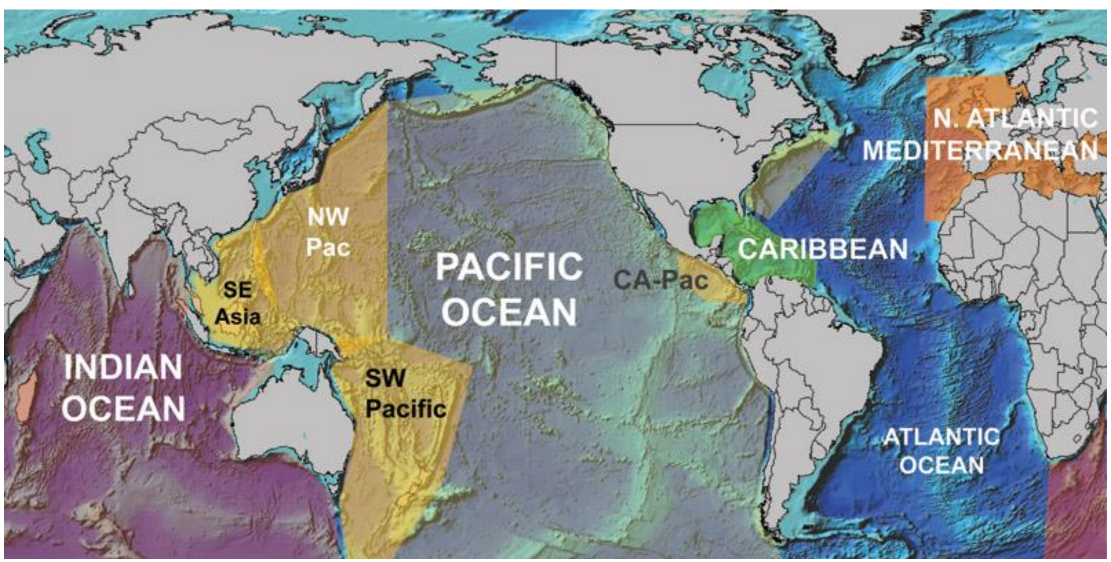
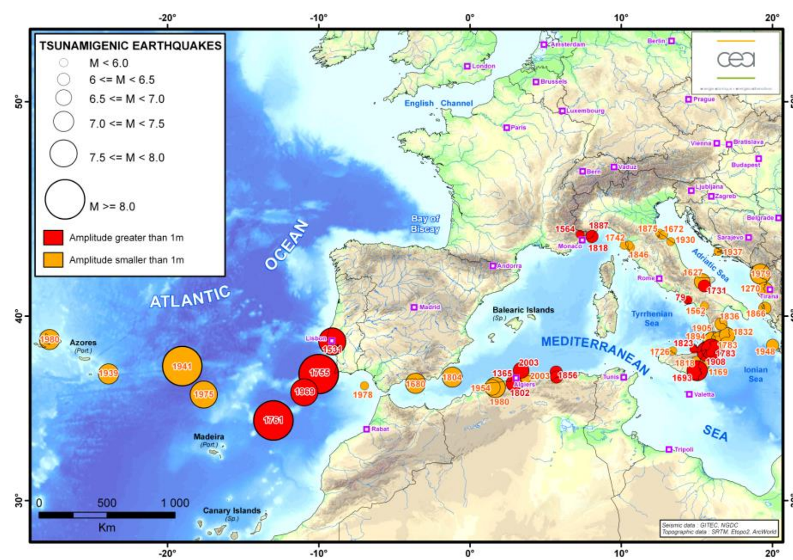
Ministère de l'Écologie, du Développement durable et de l'Énergie

The CENALT – CENtre d'ALerte aux Tsunamis



- **National context**
  - national funding
  - national consortium with relevant actors in seismology , ea level monitoring, operational infrastructure
- **Within an international frame**
  - working groups and coordination with Intergovernmental Coordination Groups set up by IOC
  - between warning centers





Tsunami Alert System – Operational Part

MONITORING

1. Earthquake Detection
   => Seismological monitoring network

2. Tsunami Detection
   => Sea level monitoring network

3. Data analysis, threat evaluation

4. Monitoring of the whole system capability

ALERT

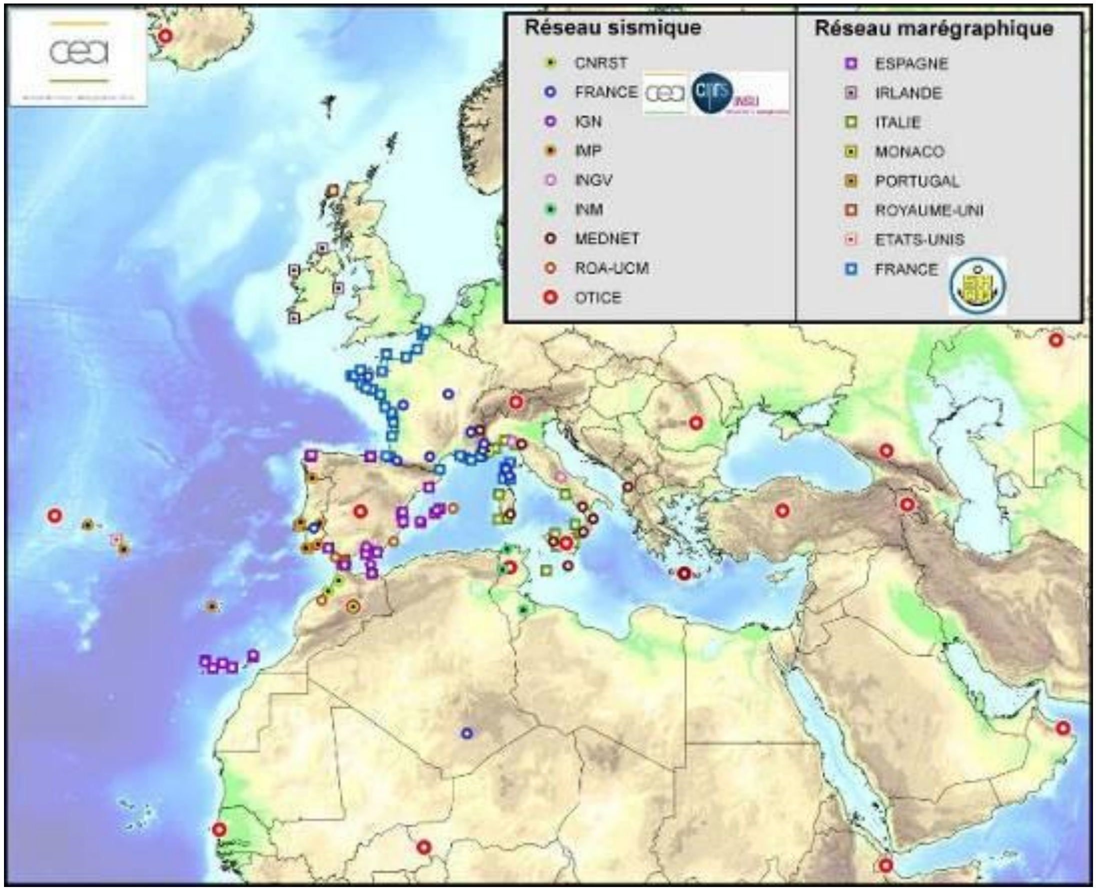
5. Elaborate and transmit alert messages
   => Alert Centre(s) – Alert, exercises and test procedures

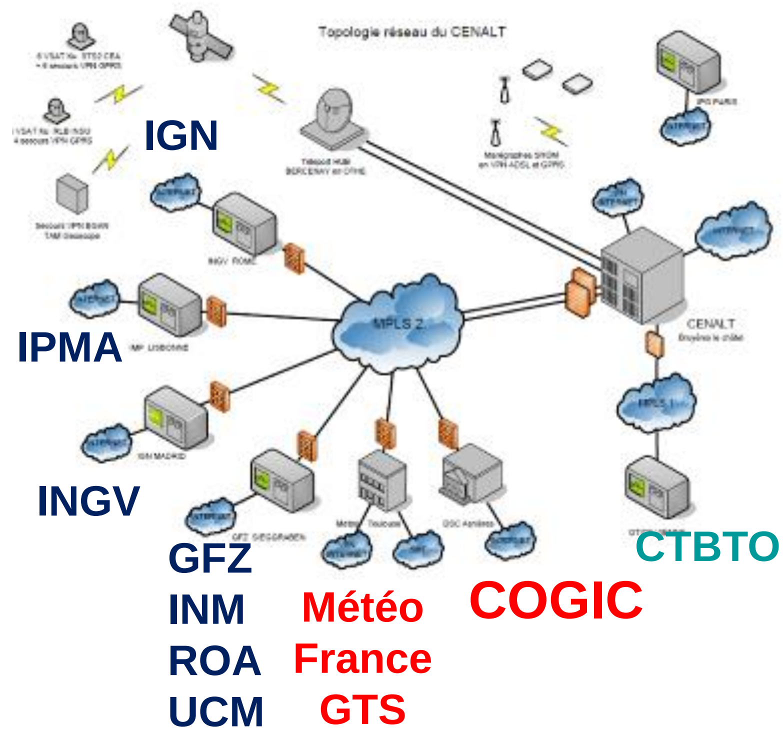
Level of warning	INTERNATIONAL	FRANCE
5,5 < Mw < 6,0		YELLOW
6,0 ≤ Mw < 6,5		YELLOW
6,5 ≤ Mw < 7,0		ORANGE
Mw ≥ 7,0		RED

Secured operational network

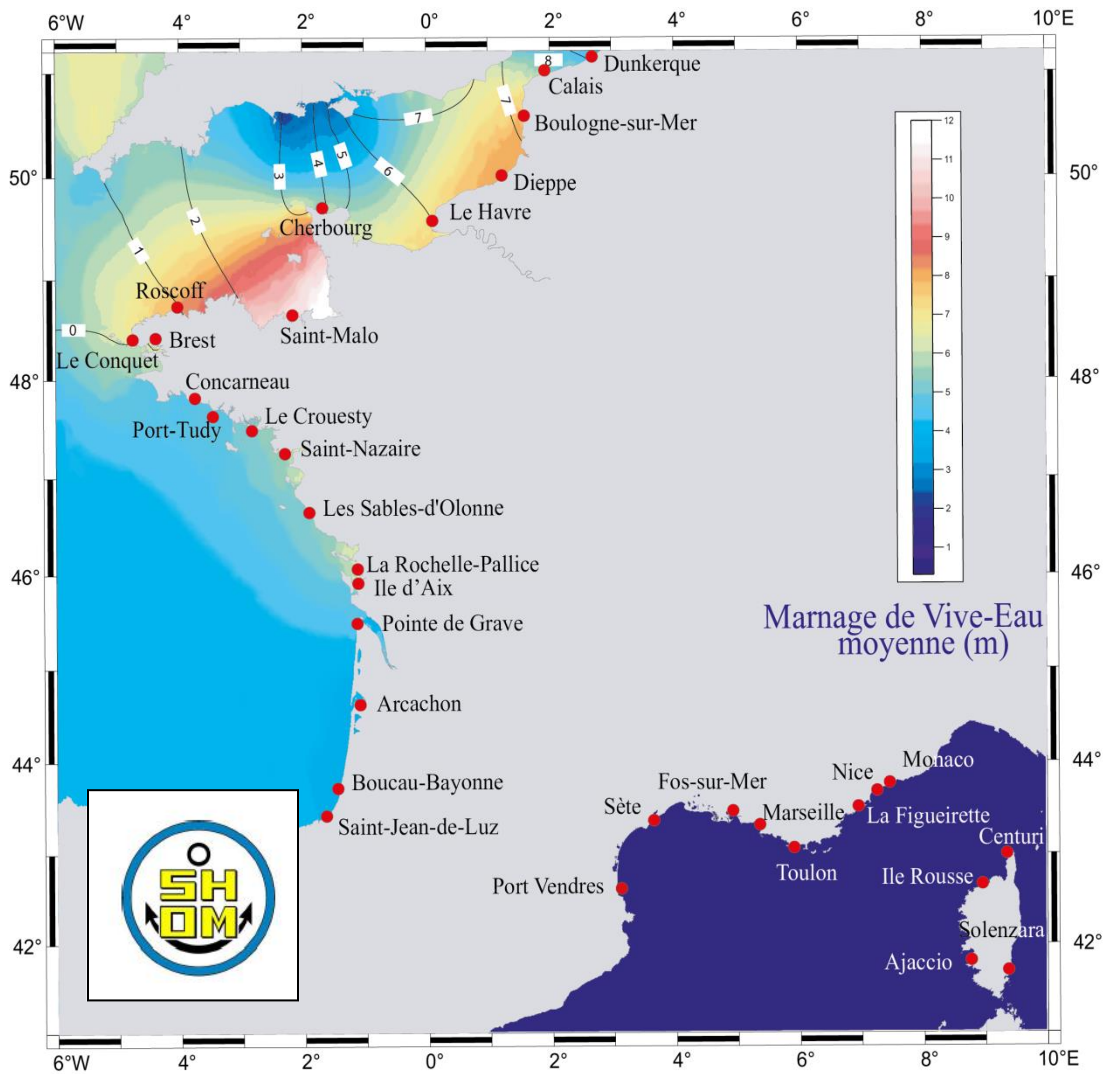
Optimal cooperation between seismic station network operators
Cooperation in progress for tide gauge network operators

Private telecommunication network for data transmission and message dissemination





Upgrade of tide gauges (SHOM)

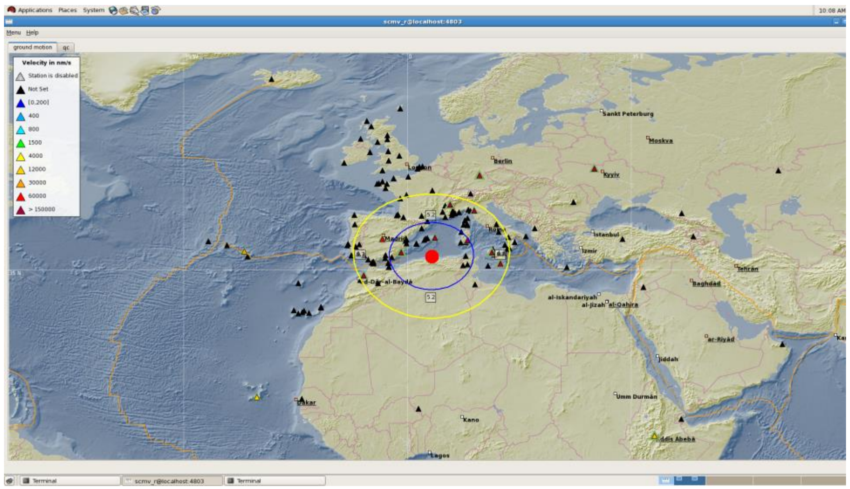


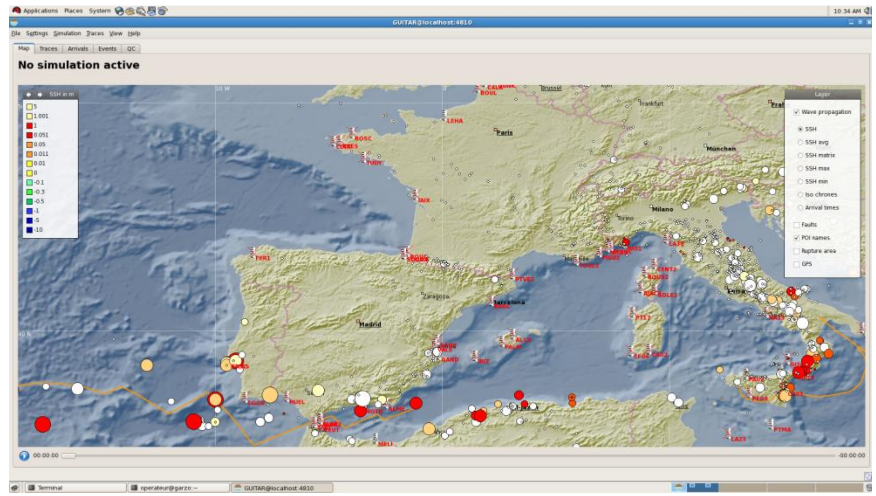
- ❑ Upgrade of 34 stations equipped with high sampling rate and real-time transmission
- ❑ Direct connection to the CENALT through VPN

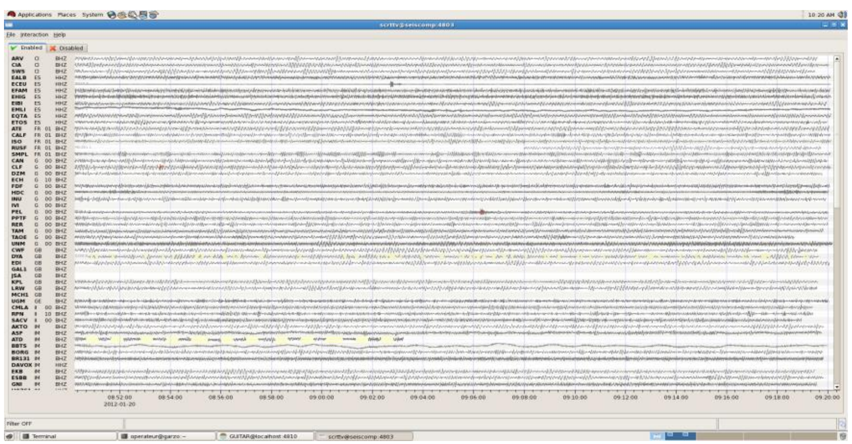
The CENALT, automatic detection and interactive processing

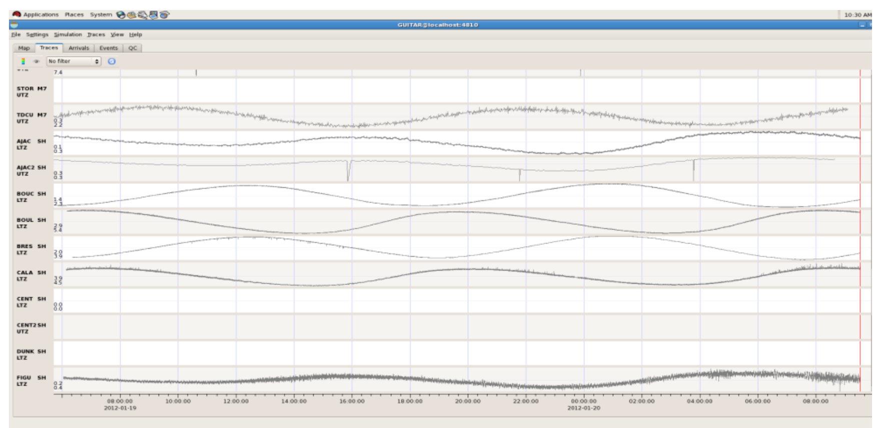
Earthquake detection in real time: time origin, association, automatic location, magnitude calculation

Continuous sea-level data reception
Historical events database









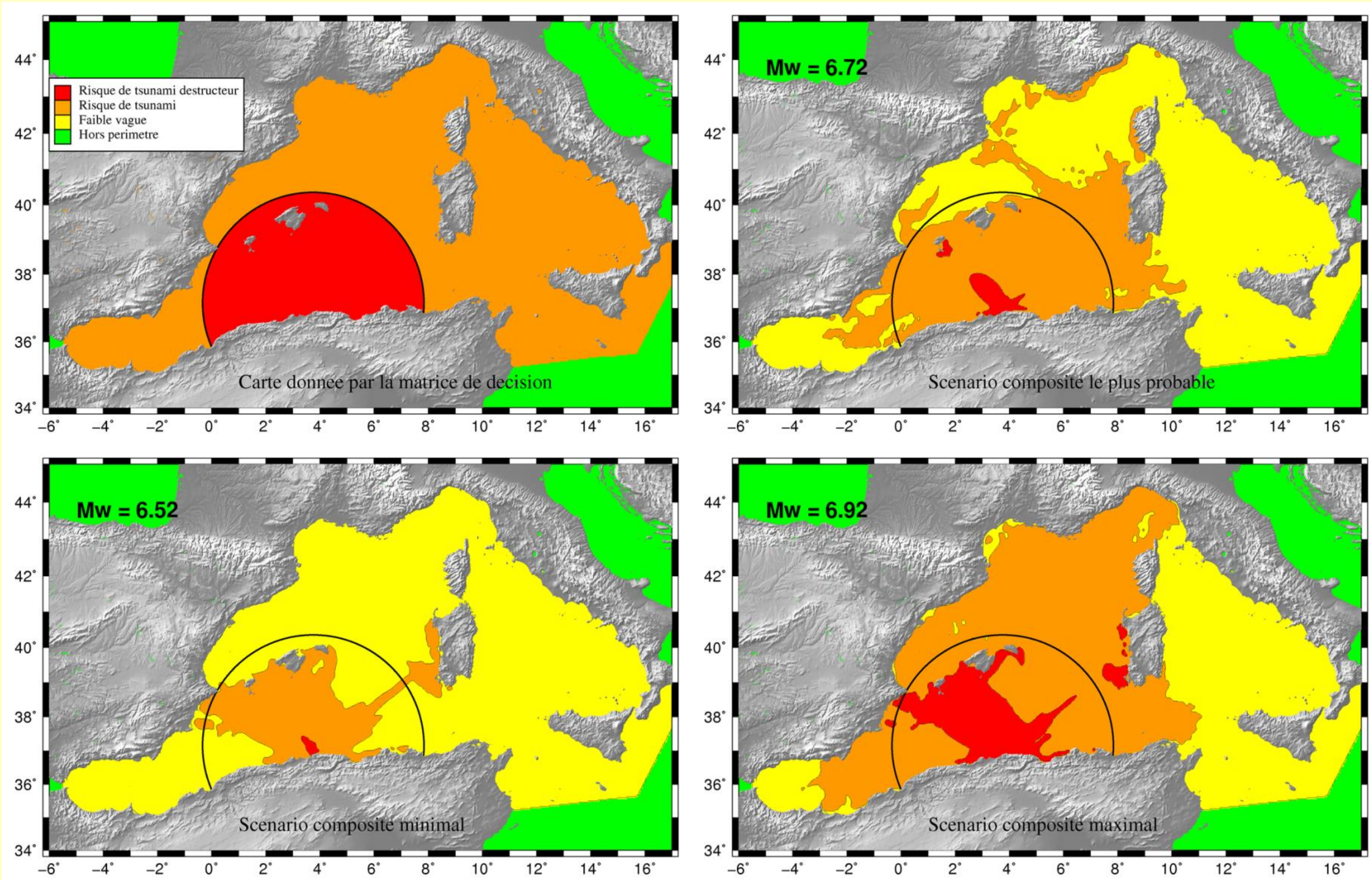
- **Data and communications flow**
- **Archiving of raw data**
- **Data format conversion**

Continuous sea-level signal reception (Atlantic ocean, Channel, Mediterranean sea)

The CENALT, real time hazard assessment and scenario database

Using the precalculated scenario database, determining min and max sea levels
Creating a map of the event

Example with the Boumerdes 2003 earthquake



The CENALT : a unique training exercise

- ❑ Need to hire a team of 7 analysts for the shifts

- ❑ Need to train them intensively over a 6-month period in :
  - Seismology, tectonics
  - Signal processing
  - Earthquake and tsunami hazard
  - Sea-level measurement
  - Use of CENALT software

- ❑ Need to evaluate the training :
  - Heavy load of hands-on exercises
  - Tests based on real events

- ❑ Three months of complete testing (April – June 2012)

- ❑ In the future, ensure continuous training although the team is taking shifts

MONITORING

1. Earthquake Detection
2. Tsunami Detection
3. Data analysis, threat evaluation
   151 events* in the NEAM region
   1147 events* at a global scale
4. Monitoring of the whole system capability

* From July 1st to October 19, 2012

CENALT is fully operating since July 2012 as National tsunami warning center (NTWC) and Candidate tsunami watch provider (CTWP).

- **Major tsunamis can occur in places where the hazard was underestimated**
  - but seismological and seismotectonic analyses help to define tsunami-prone areas (e.g. there is no subduction zone near France….)
- **Numerical modeling greatly helps to refine hazard assessment**
  - provided uncertainties are controlled
  - with accurate data at the shore
- **First order influence**
  - magnitude, mechanism, fault azimuth
  - slip heterogeneities
  - bathymetric features
- **We need**
  - more historical data for areas weakly exposed
  - improvement of high performance computing for warning
  - multidisciplinary approaches
  - more outreach and preparedness


Thank you