Contribution of HPC to the mitigation of natural risks

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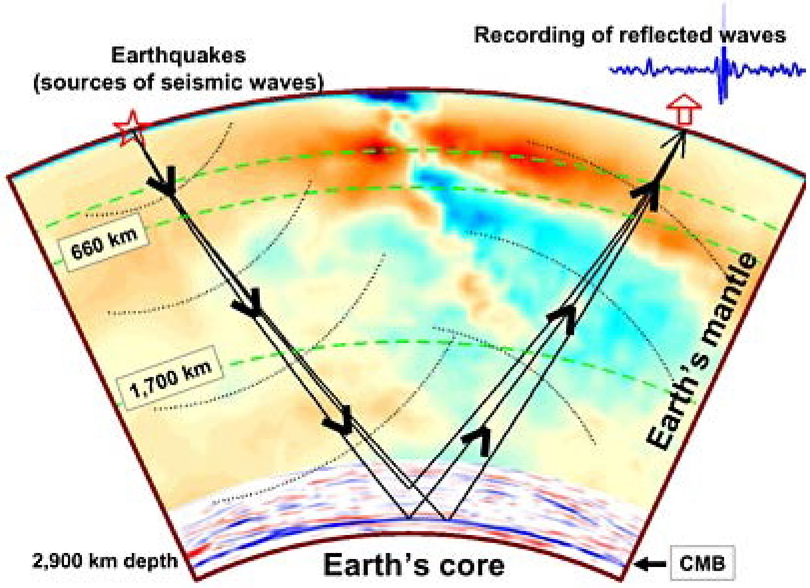
Introduction

- Over the last 40 years, the increase in computational capacities has played a decisive role in the development of earth sciences and especially the knowledge of the Earth deep interior.

- This is essentially due to the fact that we have extremely limited direct access to the body we are trying to study.

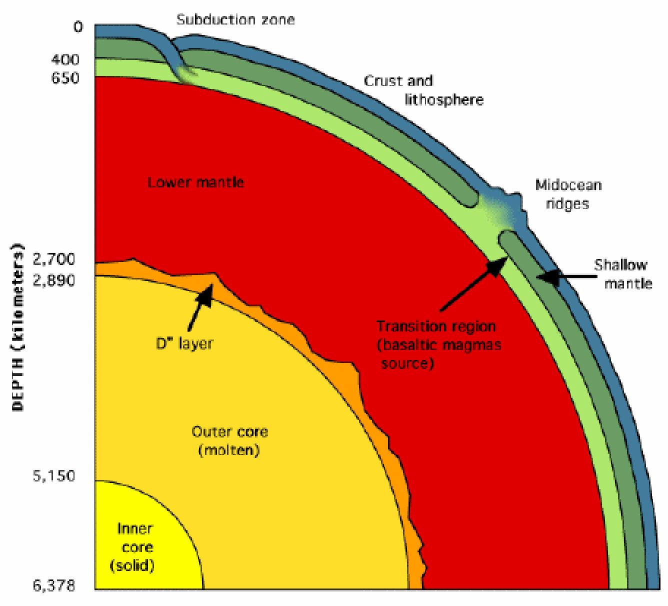
- However, earthquakes generate seismic waves that sample the earth interior. Once recorded at the surface their detailed processing allows to map the internal structure of the Earth.



(after Van der Hilst)

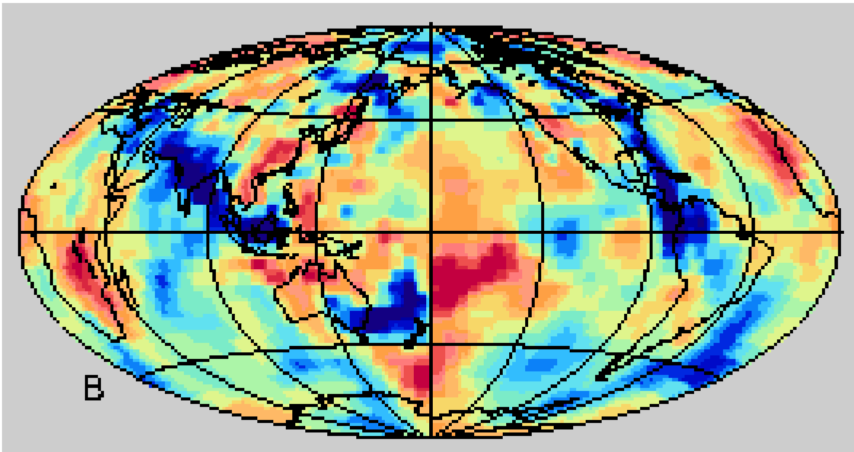
Introduction

- The use of large-scale inversion of seismological data has allowed to image the internal structure of the globe



Cross Section of the Earth

- Modern data processing schemes allow to model heterogeneities of the mantle which are necessary ro understand the dynamics of the planet

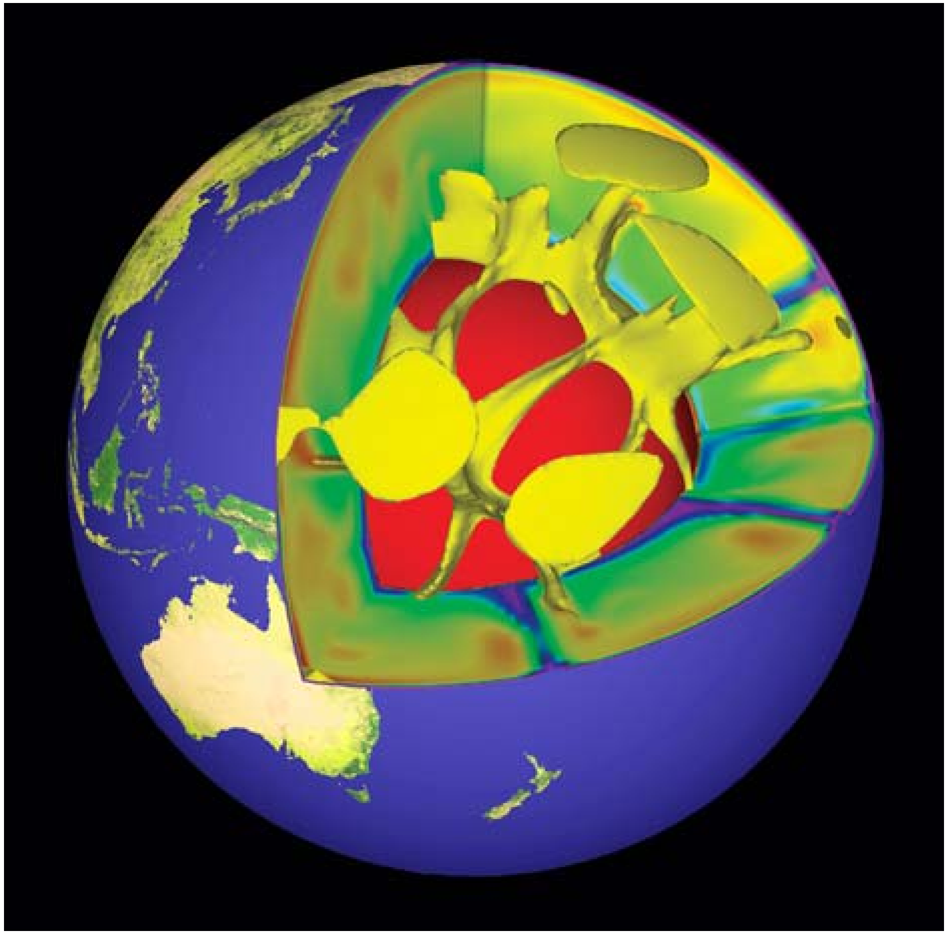


www.seismology.harvard.edu

Introduction

- Recently, the Earth Simulator initiative in Japan, a 35 Tflops massively parallel computer, aims at modelling the earth as an entire system.

- It provides an opportunity to model and understand complex phenomena such as mantle convection movements.



www.es.jamstec. go.jp

Introduction

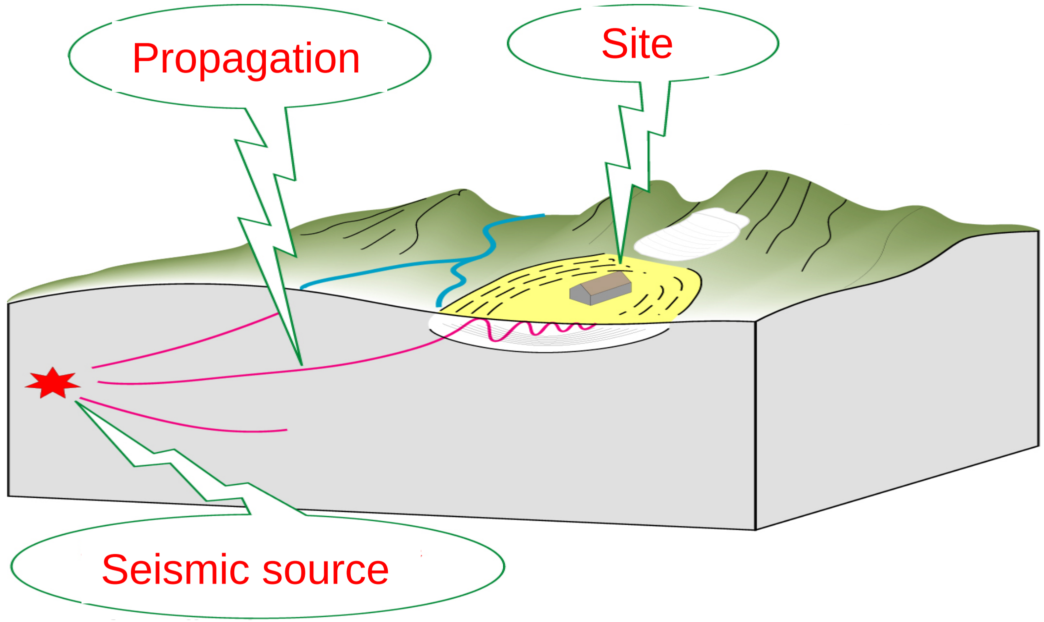
- Beside fundamental research, the increase in computing capacities has also an impact on another field of Earth Sciences that is of particular relevance for society : the mitigation of natural risks.

- Two research themes are being particularly developed at the CEA :
  - the assessment of seismic hazard;
  - the assessment of tsunami hazard.

Seismic hazard : probability for ground shaking to exceed a given value within a given time period.

Seismic hazard assessment

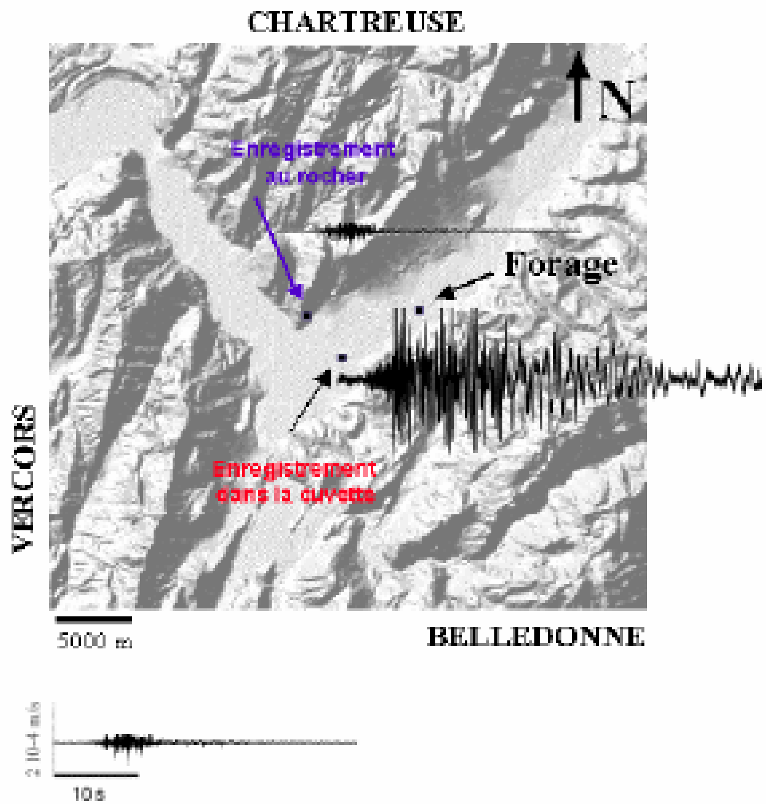
- In order to precisely evaluate seismic hazard, one must take into account 3 key parameters : the potential seismic source generating the shaking, the wave propagation in the earth, the geology of the site of interest.



- To predict the ground shaking at a site of interest, one must properly model each of the 3 key parameters.
- To date, the numerical modelling of these elements has always been performed independently. With today's HPC, a full coupling can be envisaged.

Seismic hazard assessment

- Predicting ground motion is of particular interest in geologically complex areas because a large amplification of seismic waves occur in specific areas.



(*Bard, 2002*)

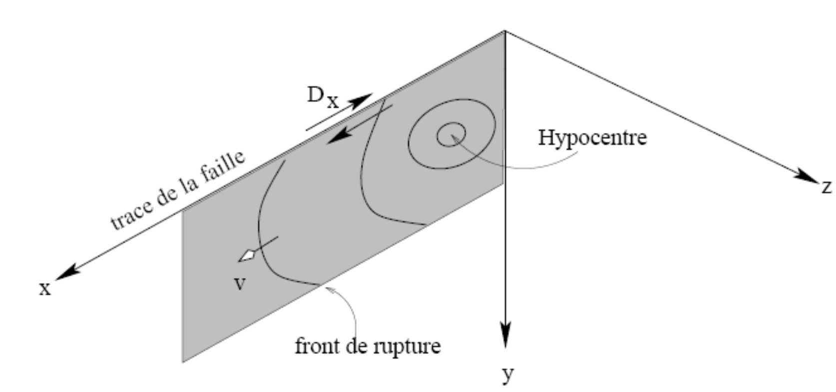
Recordings obtained in and around Grenoble after a moderate earthquake in the Alps (Laffrey, 1999).

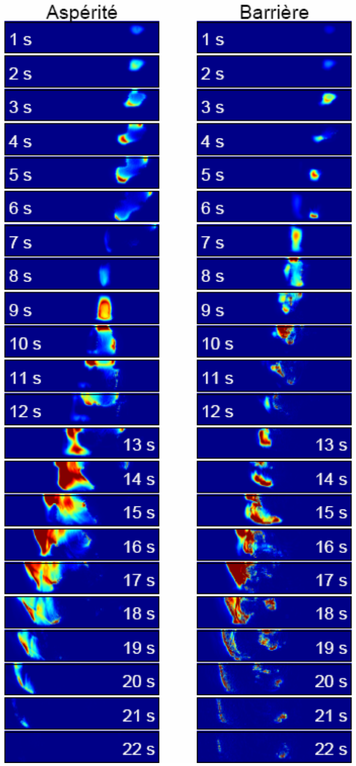
Large differences in amplitude and duration can be observed between sites located in the sedimentary basin and outside

Until recently, modelling capabilities was limited to low frequencies (few Hz)

Seismic hazard assessment : source modelling

- During an earthquake, asperities located on the fault are being fractured allowing for a rapid slip (several km/s) of the two sides of the fault and the radiation of heat and seismic waves.





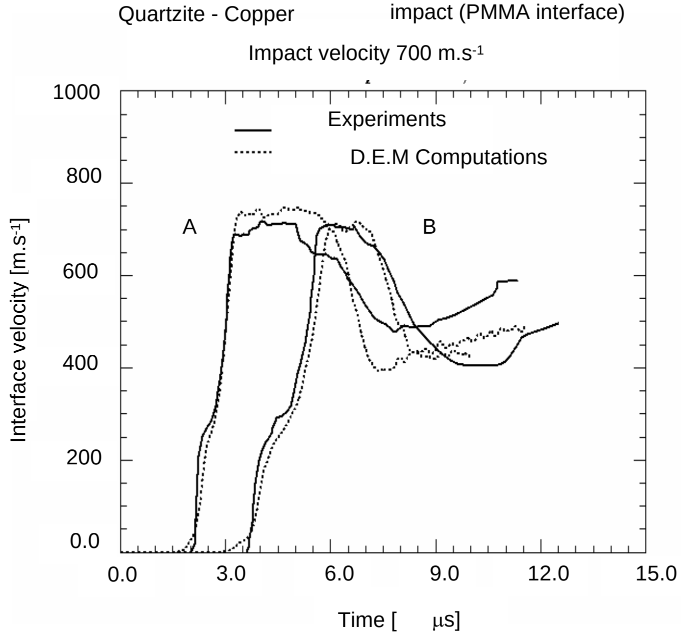
- The modelling of the rupture consists of characterizing in space and time the propagation of the rupture on the fault plane.

Landers earthquake, June 28, 1992
(Madariaga et al., 2001)

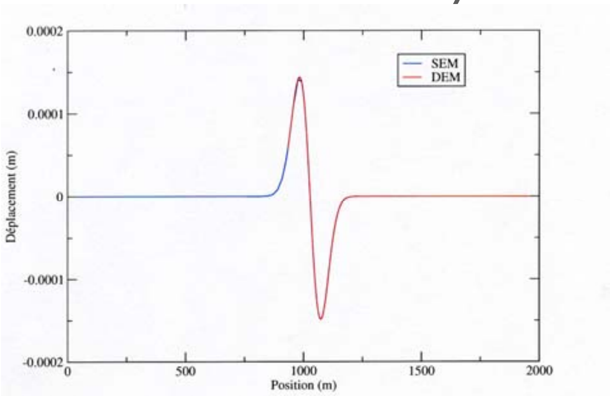
Seismic hazard assessment : propagation modelling

- In order to model the propagation of waves in a complex medium several methods exist. A new Discrete Element method has been recently developed, which can easily be scaled to size of interest.

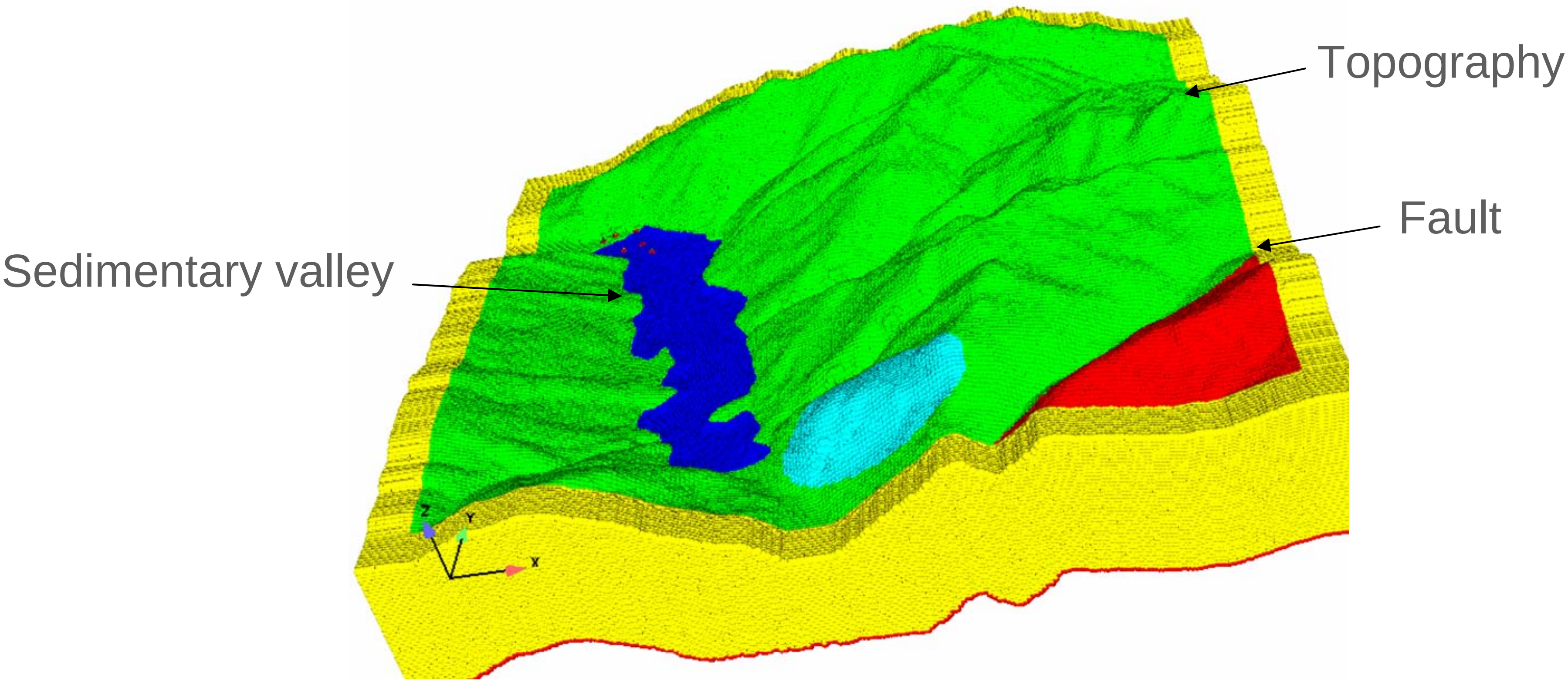
- It allows to take into account the mechanical relations between particles, down to the size of rock grains and to reproduce the behaviour of rocks and soils under dynamic sollicitation



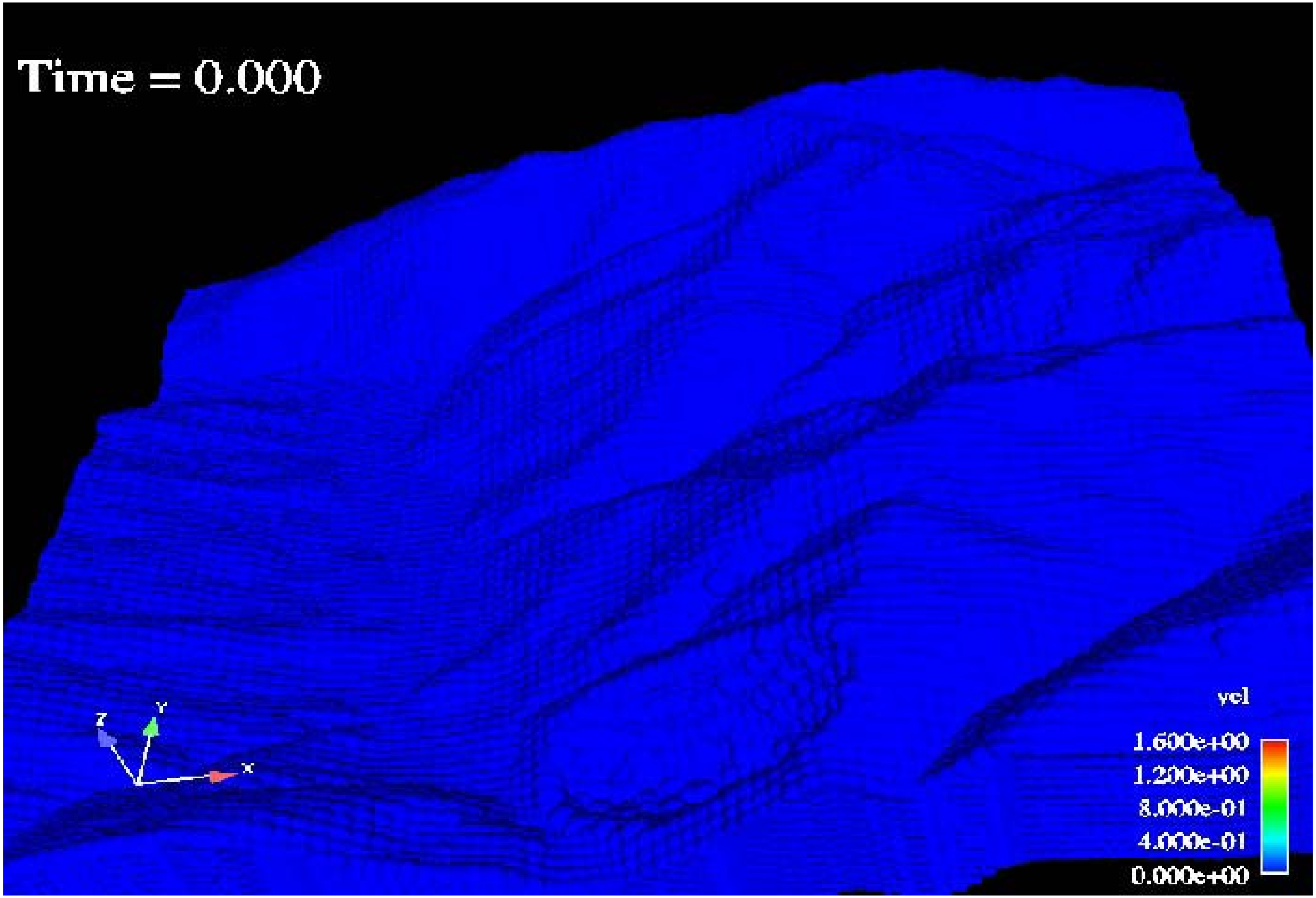
- It can be coupled with other methods (e.g. Spectral Element method) to propagate waves through large distances (tens of kilometers at several hertz)



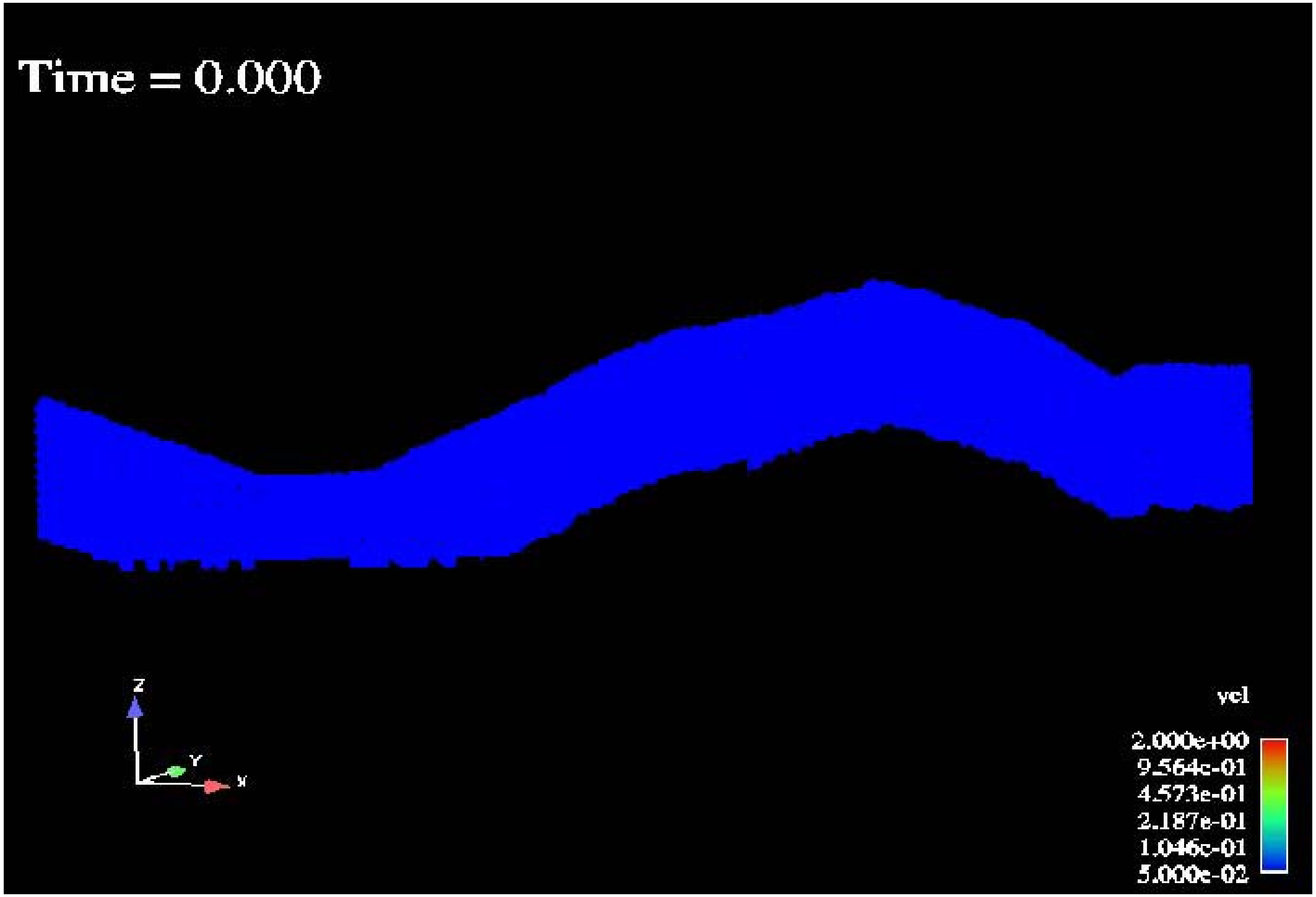
- To perform site modelling, the local geology must be known in sufficient detail. In particular, the geometry of geological interfaces will play a key role in the amplification / attenuation of seismic waves.
- Using the TERA computer, our goal is to perform full modelling from the source to the site over a 10 x 10 x 2 km region.



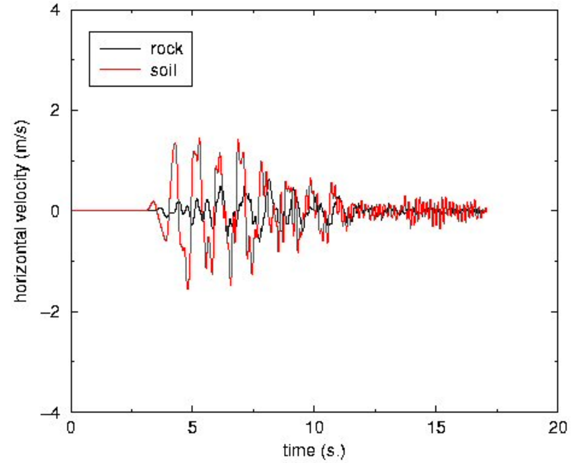
Seismic hazard assessment : full modelling

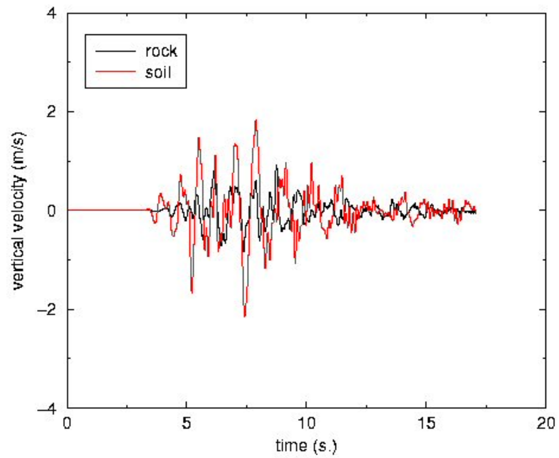


Seismic hazard assessment : full modelling



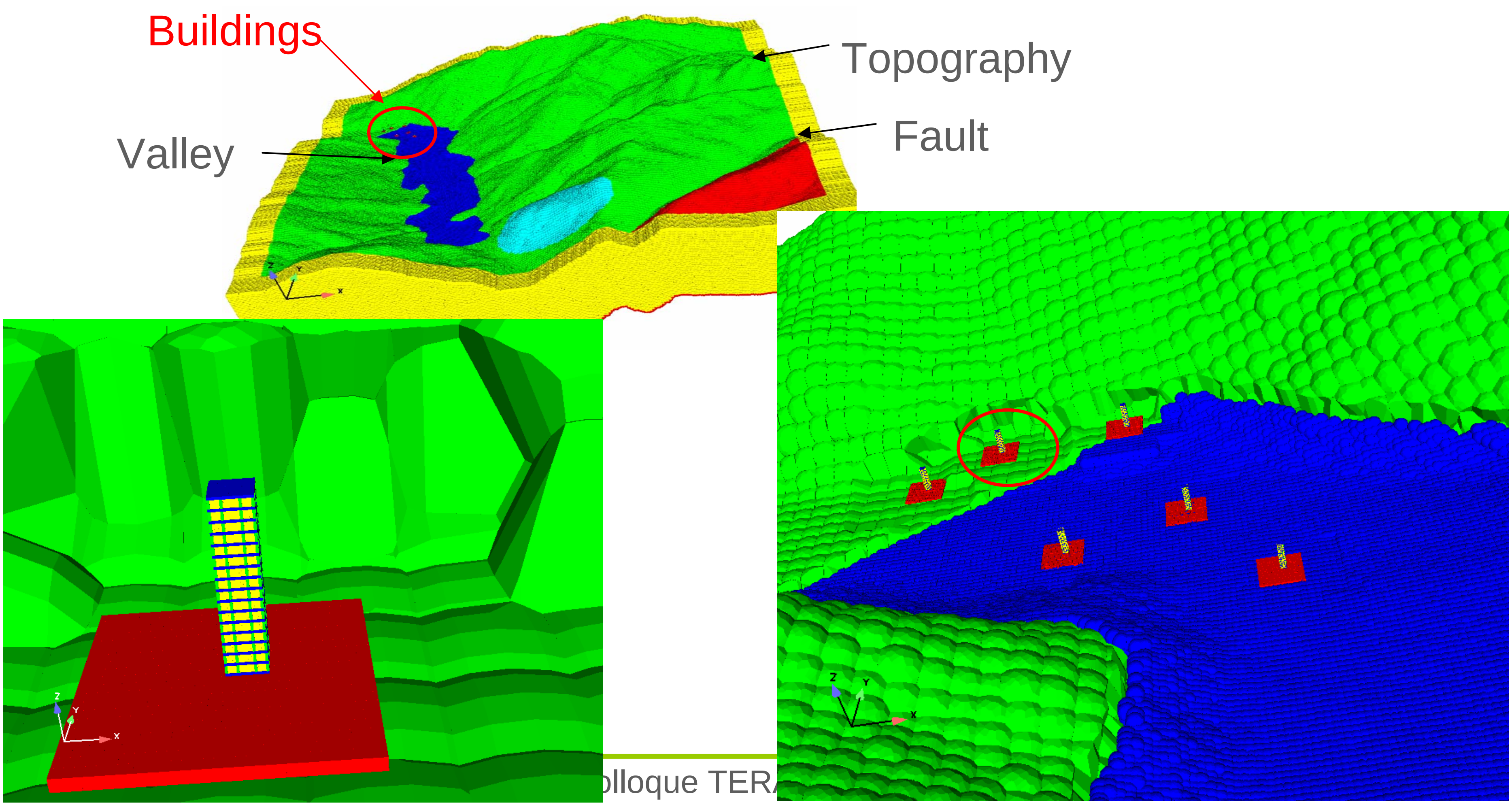
Cross-section view





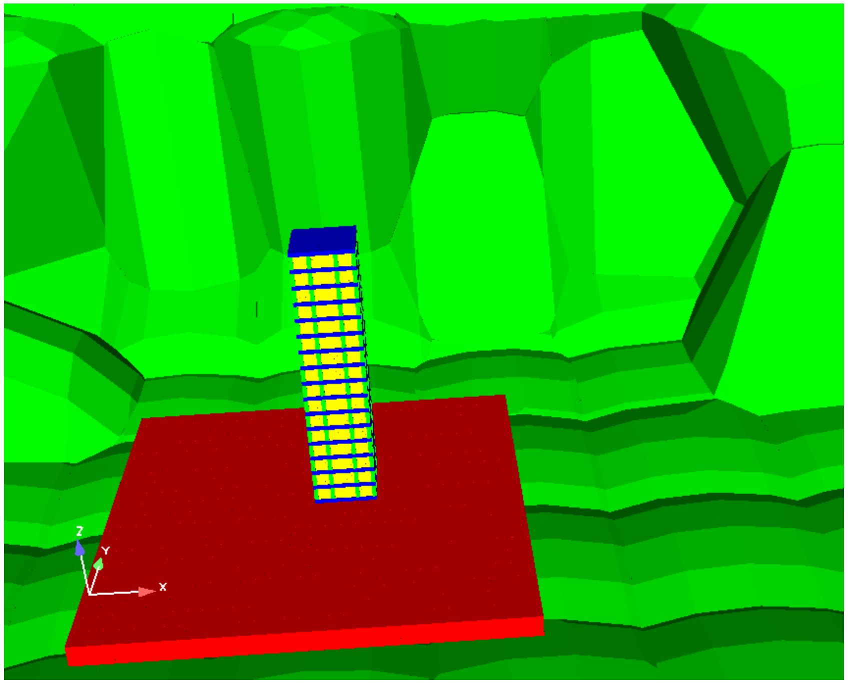
Seismic hazard assessment : full modelling

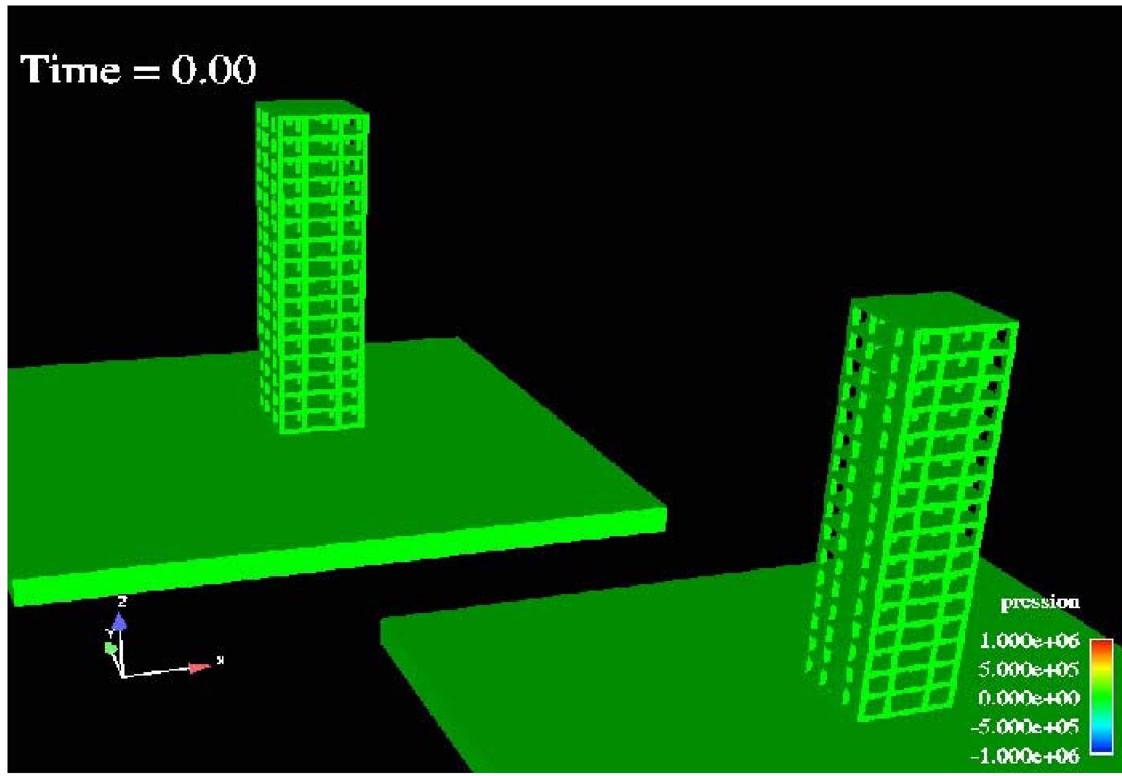
- Because of its flexibility and its intrinsic properties, the DE method allows to go one step further by modelling the response of buildings to seismic excitation.



Seismic hazard assessment : full modelling

- Because of its flexibility and its intrinsic properties, the DE method allows to go one step further by modelling the response of buildings to seismic excitation.

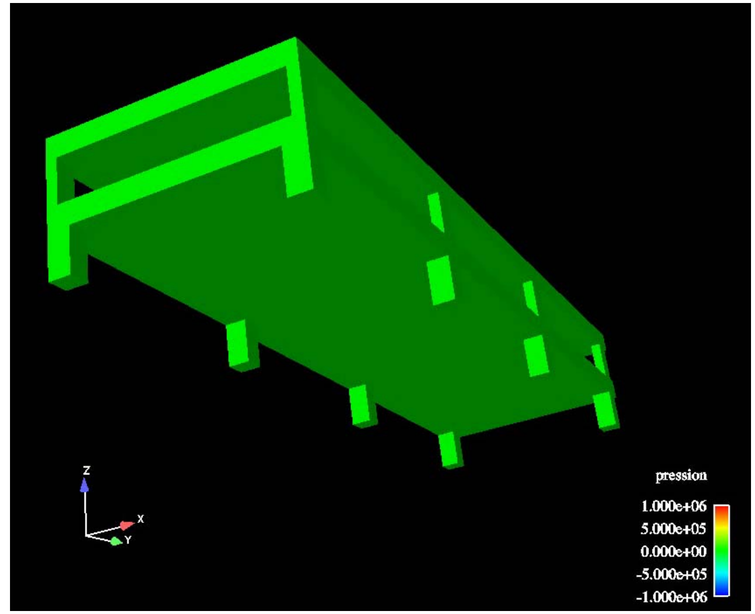


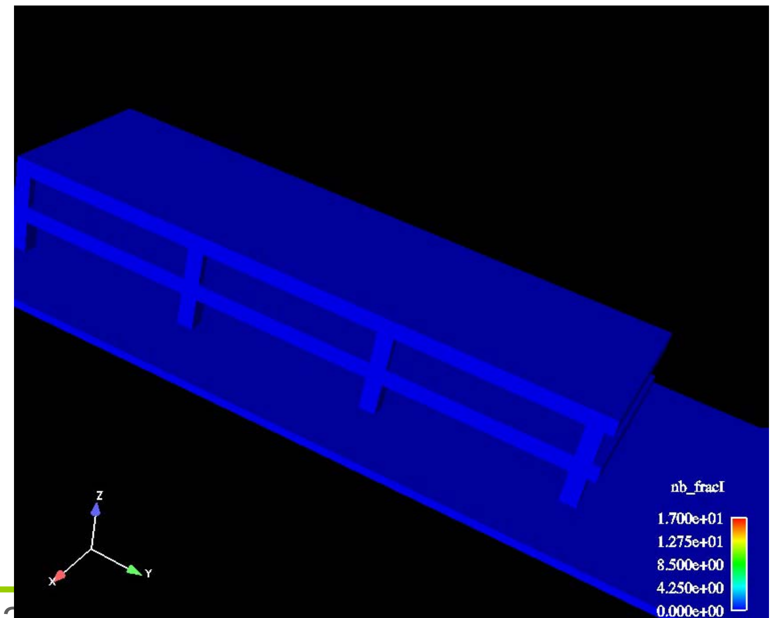


Seismic hazard assessment : full modelling

- It becomes also possible to test various scenarios of earthquake sizes and test building responses

Loma Prieta (October 17, 1989)
Case study of highway failure





Seismic hazard assessment : conclusions

- Recent developments in HPC offer new opportunities for seismic hazard assessment. Fully integrated approaches by modelling the seismic signal from the source to the site of interest at high frequencies (up to 10 Hz) over large areas (up to tens of kilometers) can now be investigated. This should contribute significantly to better understand the seismic response of complex (3D) media.

- Developments carried out using the Discrete Element method should also allow the coupling of building responses to seismic excitation modelling.

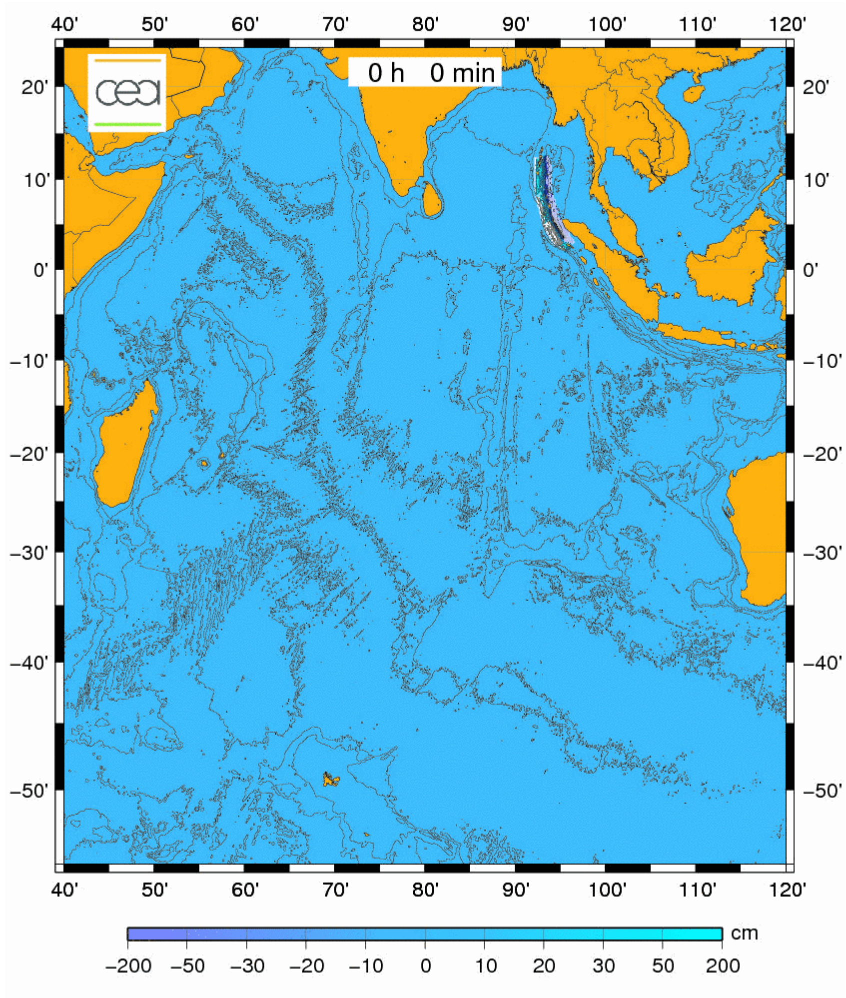
- Such numerical modelling could have application not only for seismic hazard mitigation but also for crisis management (realistic scenario of earthquake impact on infrastructures)

Tsunami hazard assessment

- In the case of tsunami hazard assessment, HPC can bring two major contributions :

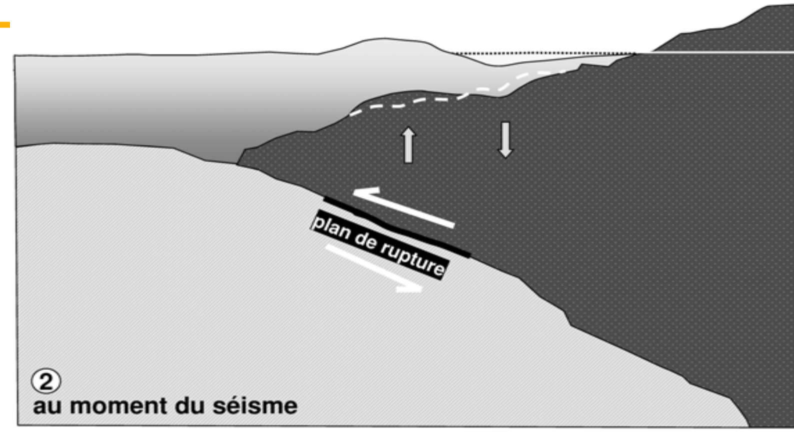
  - Assistance in evaluating the tsunami hazard. This is done by modelling the tsunami resulting from various earthquake scenarios and the response of the site of interest.

  - Assistance in triggering the alert system in case of large, tsunamigenic earthquake (medium term)



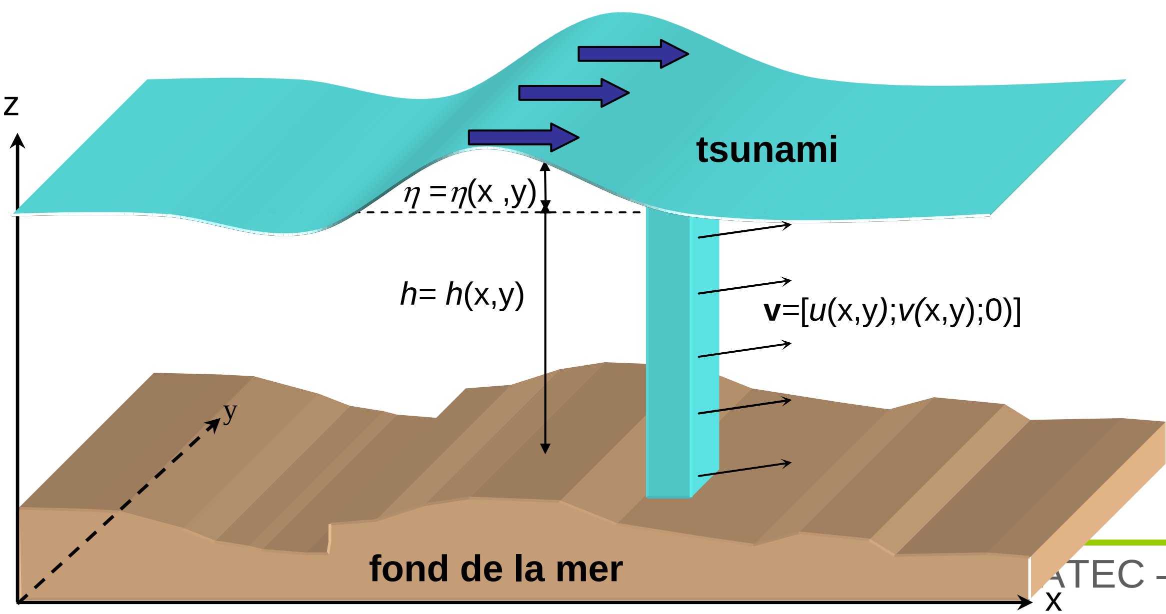
Tsunami source modelling

- Tsunami initiated by the seismic rupture
- Deformation of the water column is tranmitted completely and instantaneously at the water surface
- Propagation by resolution of the Navier Stokes equations
  - approximation of large wavelengths $\lambda >> h$
  - no dispersion



$M_0 = \mu U L W$

M_0 seismic moment
U displacement
μ rigidity
L (W) fault length



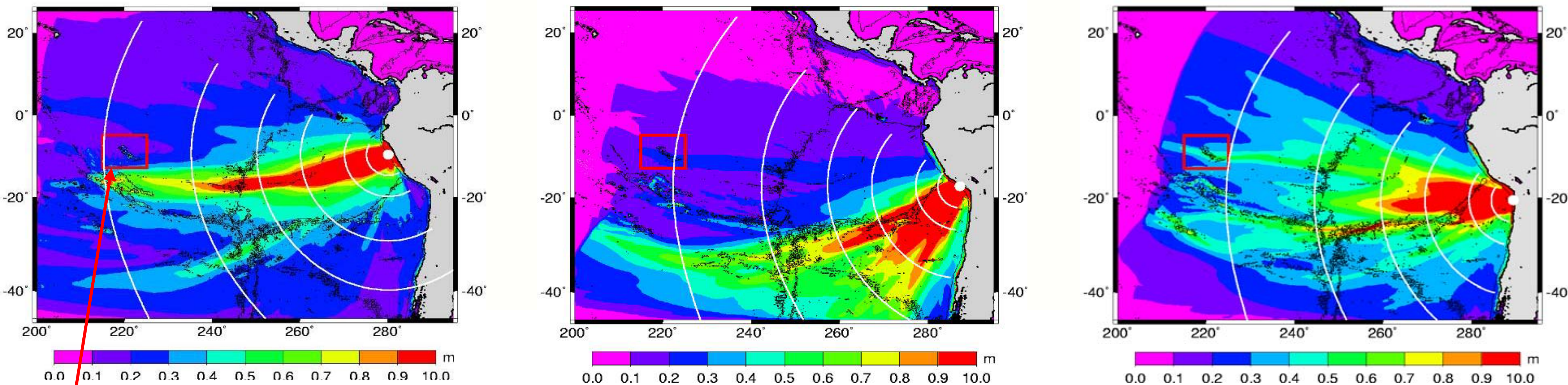
$$\frac{\partial(\eta + h)}{\partial t} + \nabla.\left[\mathbf{v}(\eta + h)\right] = 0$$

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

g gravity
v horizontal velocity
η water surface

Propagation in deep ocean

- Very variable depending on fault orientation
- Decisive to identify exposed areas



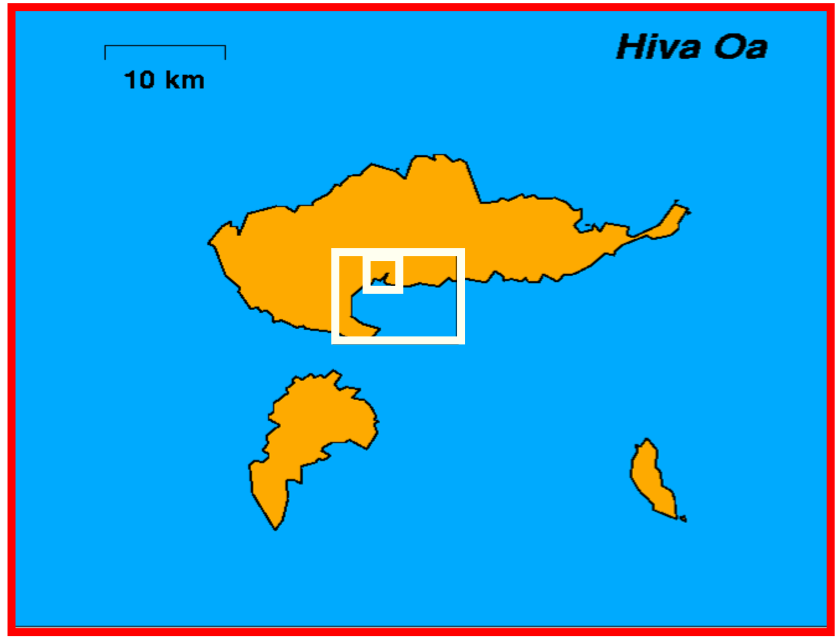
French Polynesia

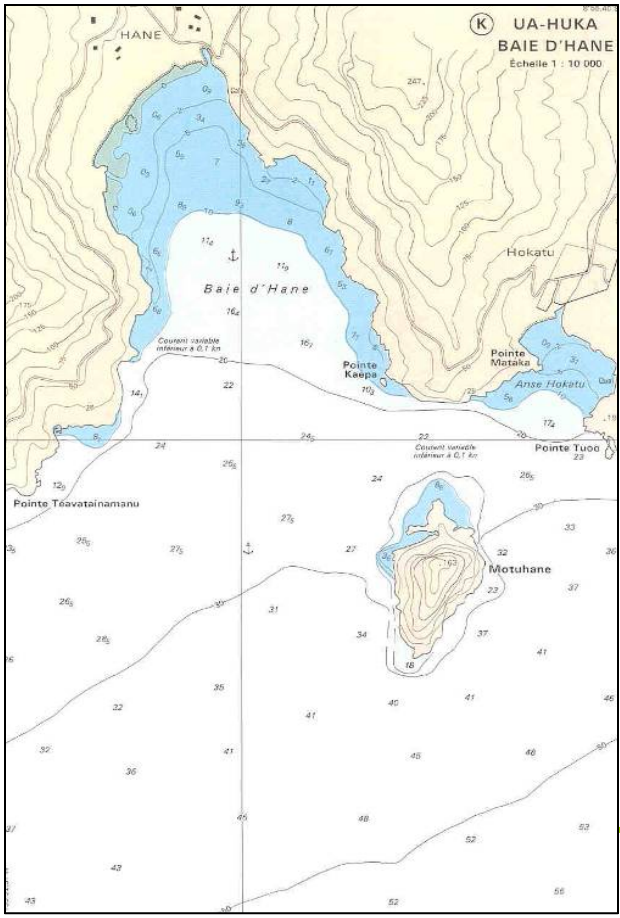
3 scenarios of potential earthquake sources in South America and their respective tsunami responses in deep ocean

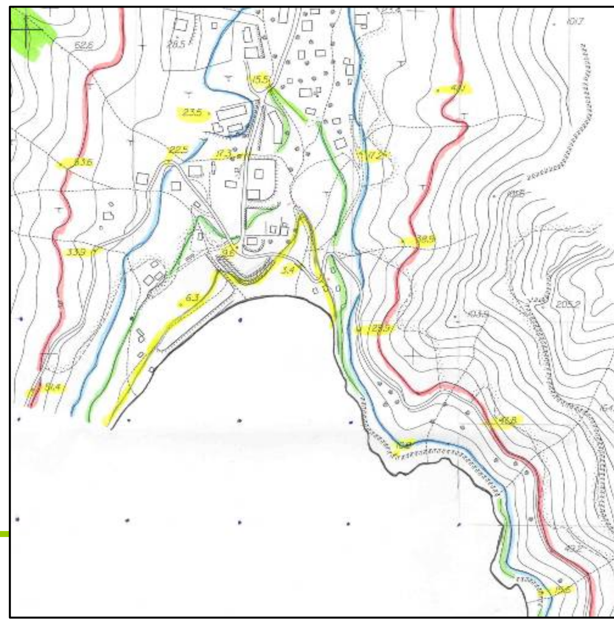
- Systematic research of all potential sources (location and magnitude) is necessary for tsunami hazard assessment

Propagation at shallow depth

- Finite difference modelling
  - Coupling of bathymetric grids of increasing resolution
    - 2 to 4 km in the ocean
    - down to 20 m in harbours or sites of interest



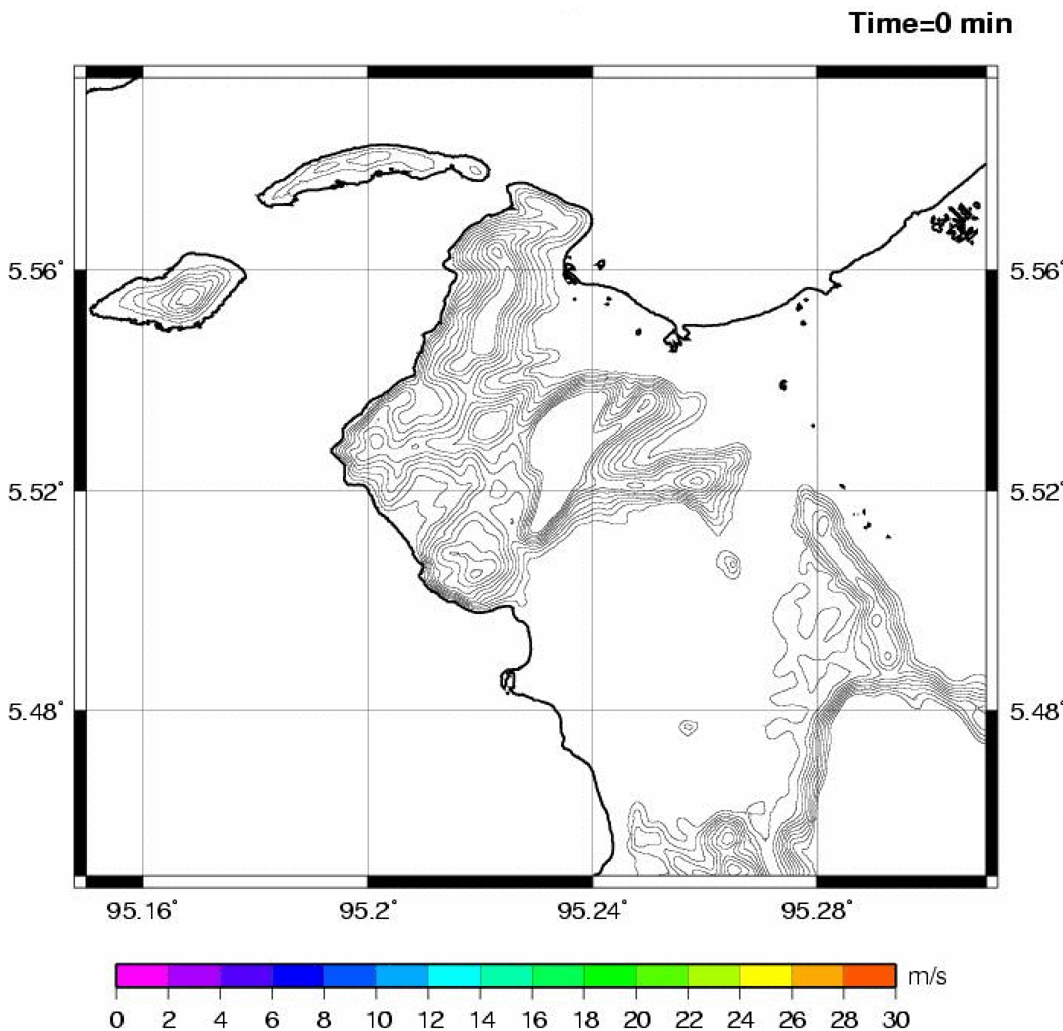


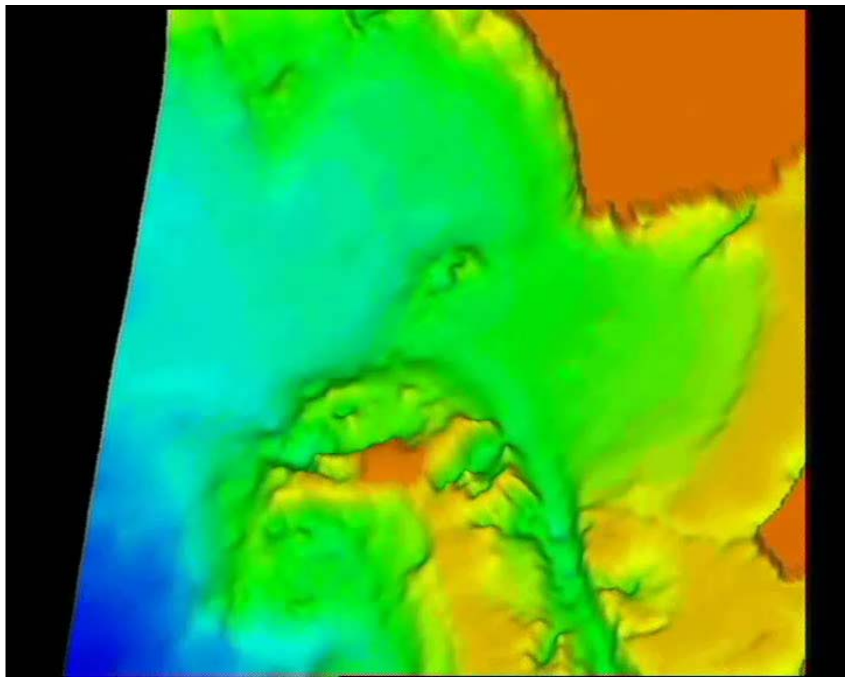


  - Coupling with high resolution coastal topographic maps to compute run-up height and inundation distance

Propagation at shallow depth

- Detailed modelling allows to accurately describe inundated areas, current velocity and temporal duration of the phenomenon



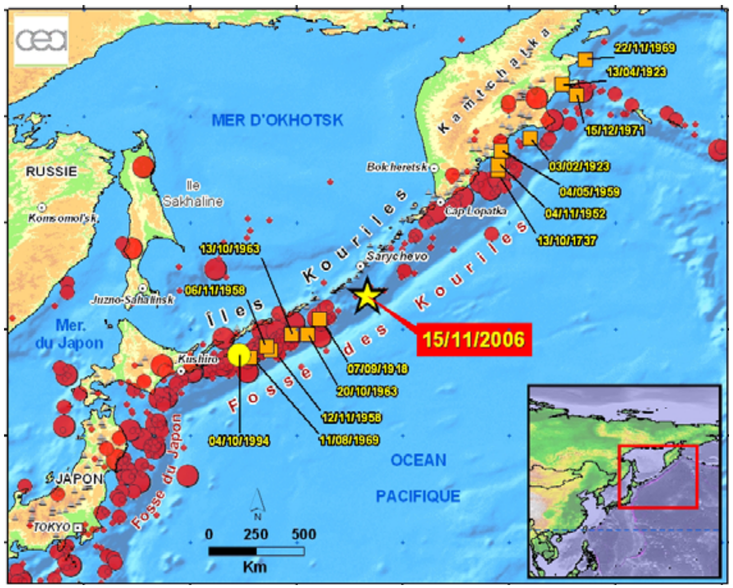


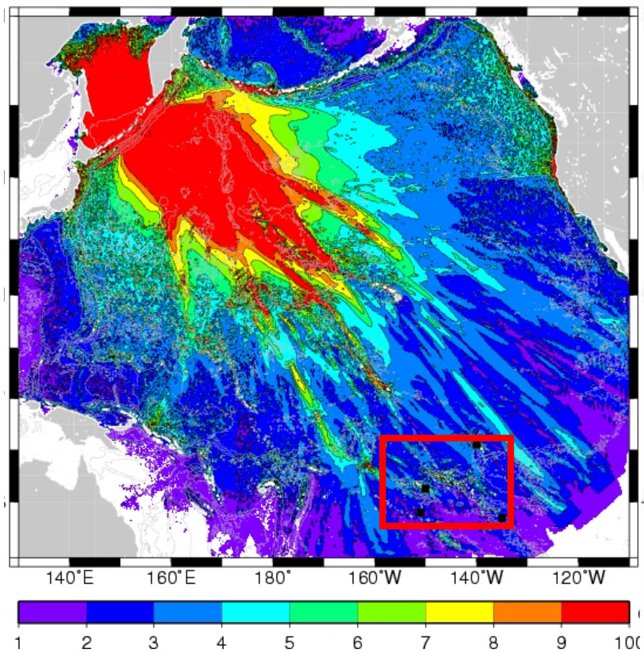
A full scenario represents several CPU hours on a regular Linux PC and several tens of scenarios have to be tested for each region

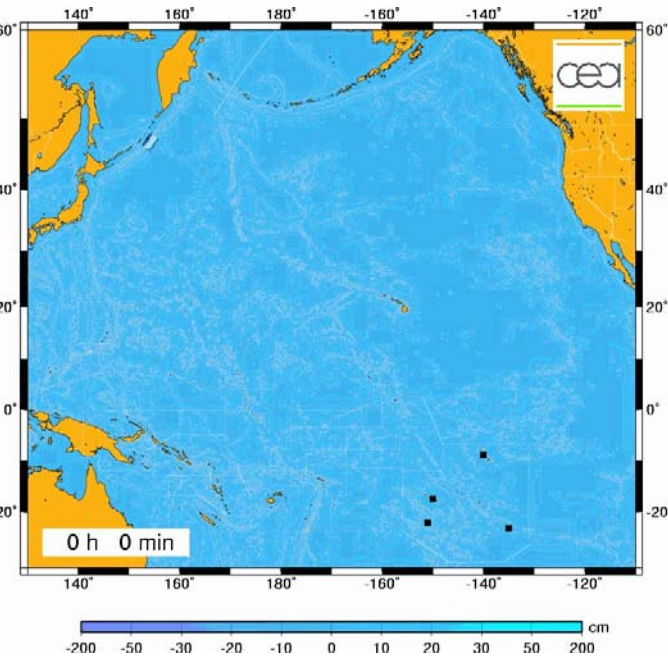
Tsunami hazard assessment

- Today, full modelling has been performed only for a few scenarios and a few sites
- The necessity of running several hundreds of cases can only be achieved through HPC

- Tomorrow, optimized algorithms could also contribute to the crisis management itself in case of tsunami propagation

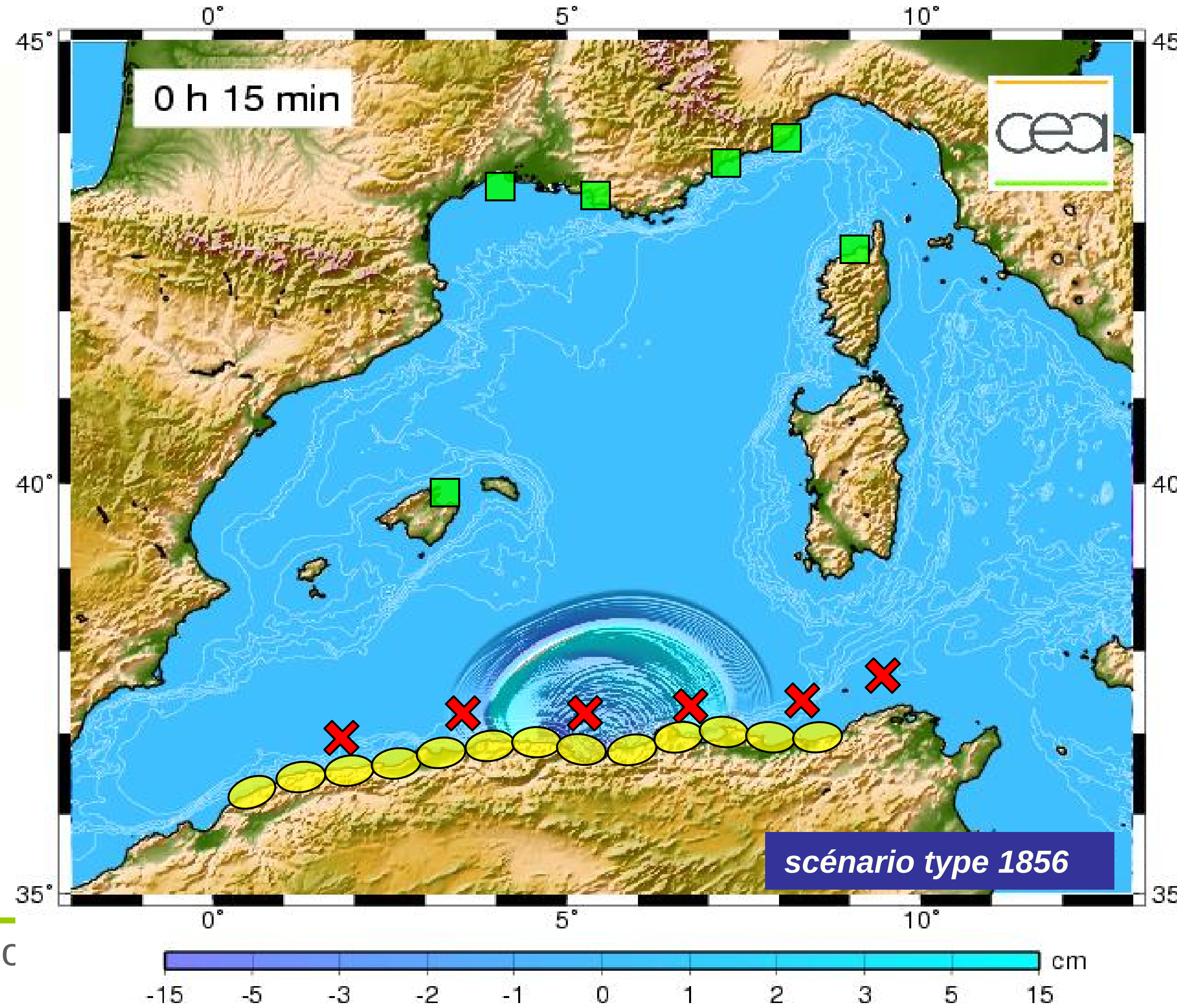






Tsunami alert systems

- Inversion of sea surface data ✖ within 10 minutes
- Evaluation of the seismic source and adjustment of pre-run scenarios ⬭ for which impact at sites has been pre-calculated
- Re-evaluation of impact at sites of interest ■
- Iterate with new data (in particular harbour measurements) as soon as they become available



Tsunami hazard assessment : conclusions

- New HPC developments can play a significant role in addressing tsunami hazard extensively in a region of interest. Due to the multiplicity of cases to be simulated, this is out of reach of conventional CPU means.

- Real-time tsunami modelling could also contribute significantly to efficient alert triggering. Optimization of algorithms will be required for small-size oceanic basins.

- Massively parallel computing open new avenues for research in Earth Sciences in general. Specific application to natural hazard assessment through numerical modelling will bring direct benefit to society.