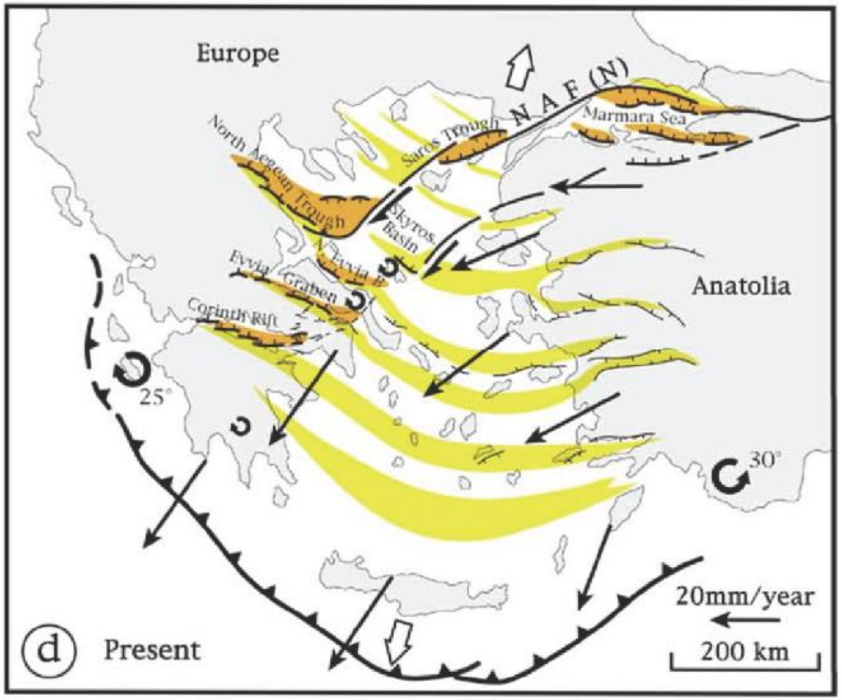
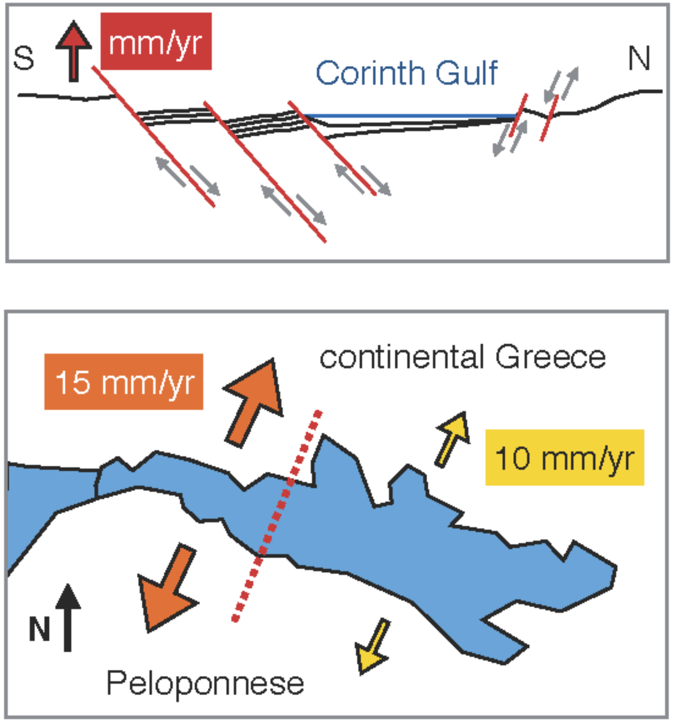
Corinth Rift : monitoring the seismicity

Anne Deschamps and CRL laboratory teams

Corinth Gulf in the Aegean tectonics



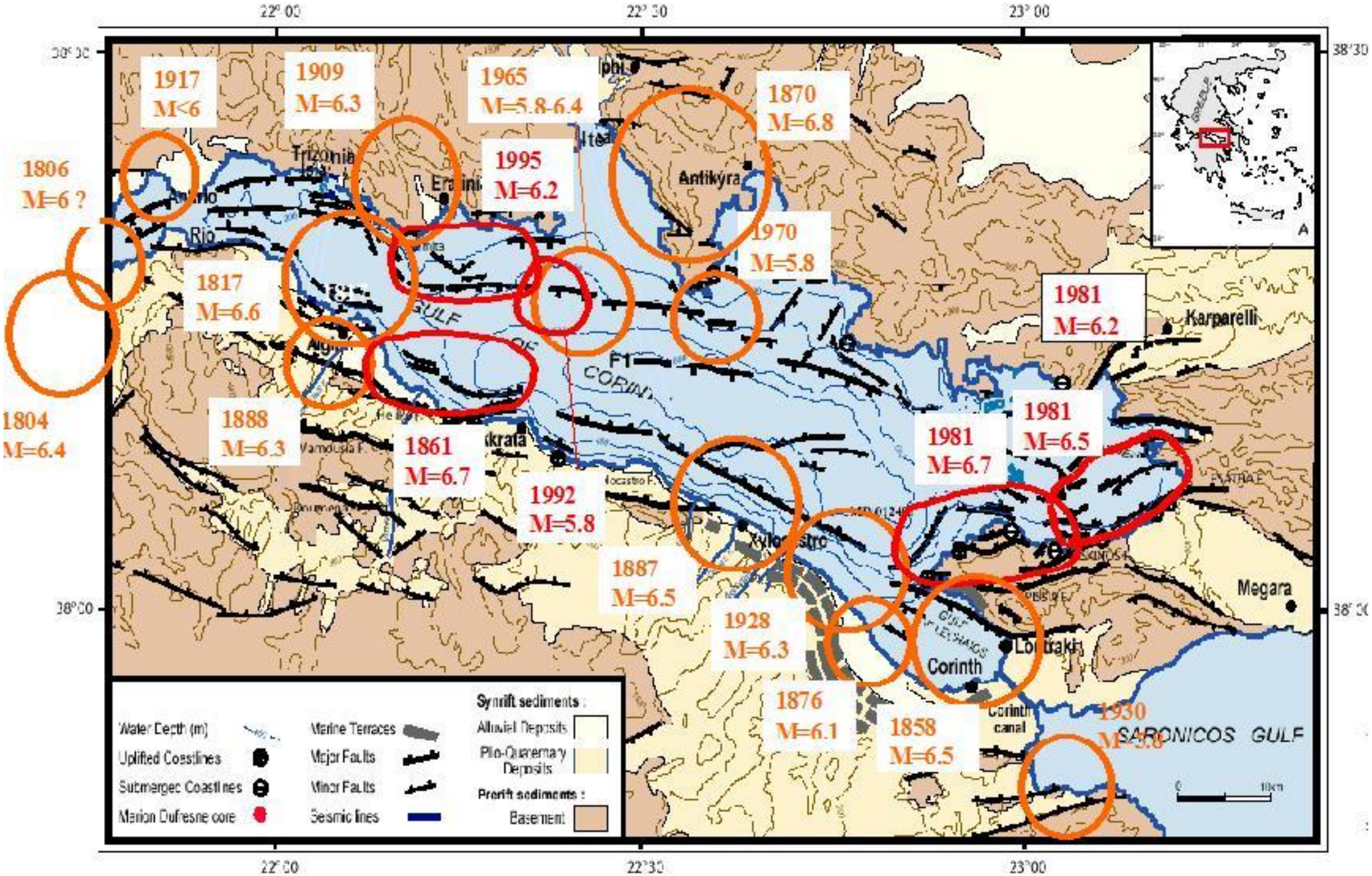
[Armijo *et al.*, 1996]



[Duverger, 2017]

Opening starts 5My ago

Historical seismicity



M> 6 in the 2 last centuries all along the Gulf

Bernard et al., using mainly Papazachos BC, 2003

Corinth Gulf is a good place to understand

- Large earthquakes occurrence in rifting conditions
- Link between large earthquakes and microseismicity
- Link between seismicity and geology
- Link between seismicity and deformation

So one of the important task was the location of the seismicity.

Corinth Rift Laboratory:

A permannt dedicated network since 2000
after Aigio 1995 and Galaxidi 1998 events

CNRS: IPGParis, ENS (Paris), Université Côte d'Azur, EOST (Strasbourg)
University of Patras
Charles University in Prague
University of Athens
National Observatory in Athens

Field work

- **Network design and implementation**
- **Maintenance**
- **Developments**

Data collecting and pre-processing

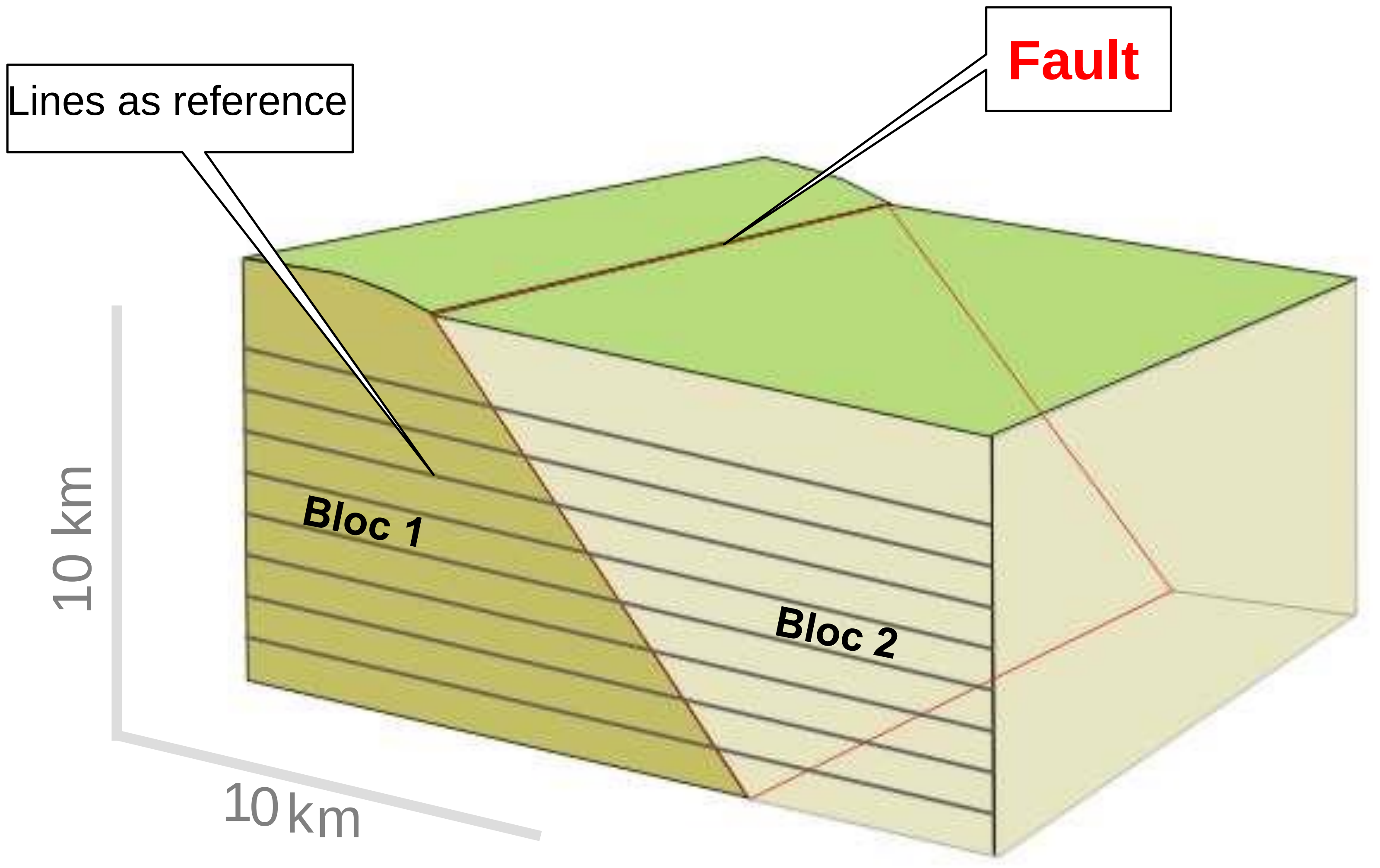
Research

- **Methodological developments**
- **Data analysis**
- **Interpretation**
- **Relation with other disciplines : geology, sedimentology, deformation…**

Was is an earthquake?

An earthquake is a fast motion on a fault which produce seismic waves. The seismic waves travel from the source into the Earth and make the surface moving.

Geological point of view

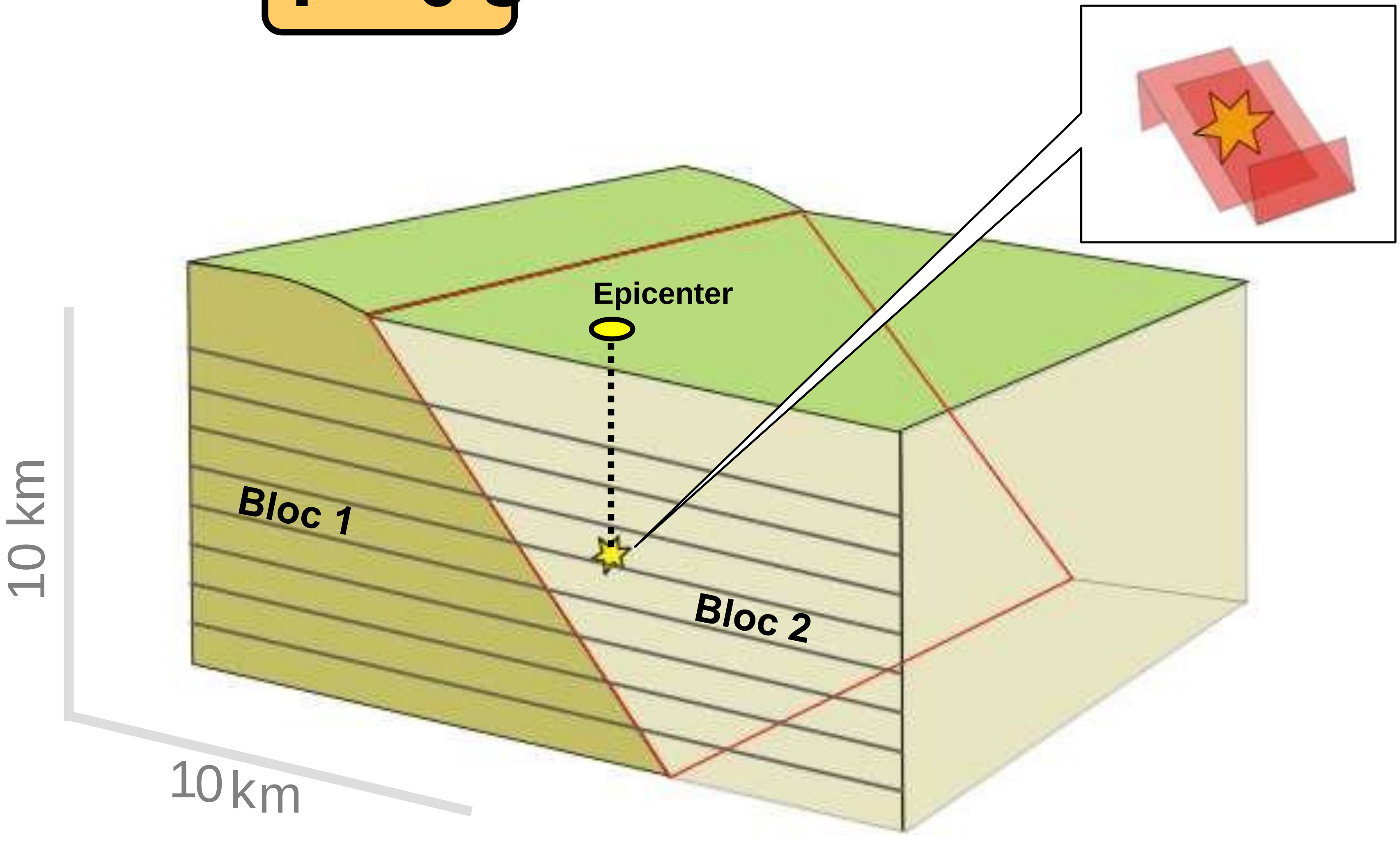


Fault
Lines as reference
Bloc 1
Bloc 2
10 km
10 km

T = 0 s

Fast shear motion

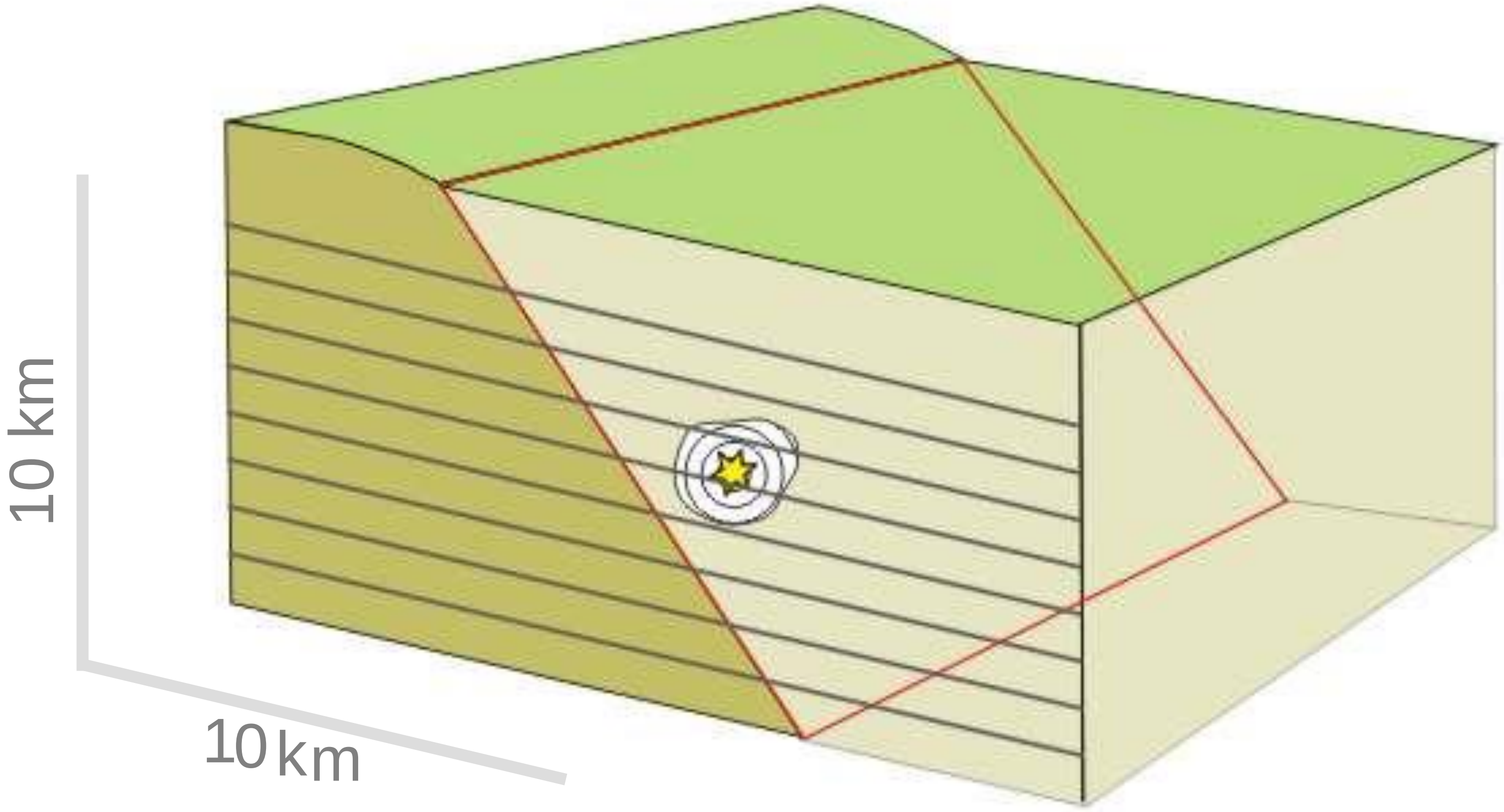
➔ the 2 blocs move one compare to the other



: hypocenter = point where the rupture starts
epicenter = vertical projection at the surface of the hypocenter

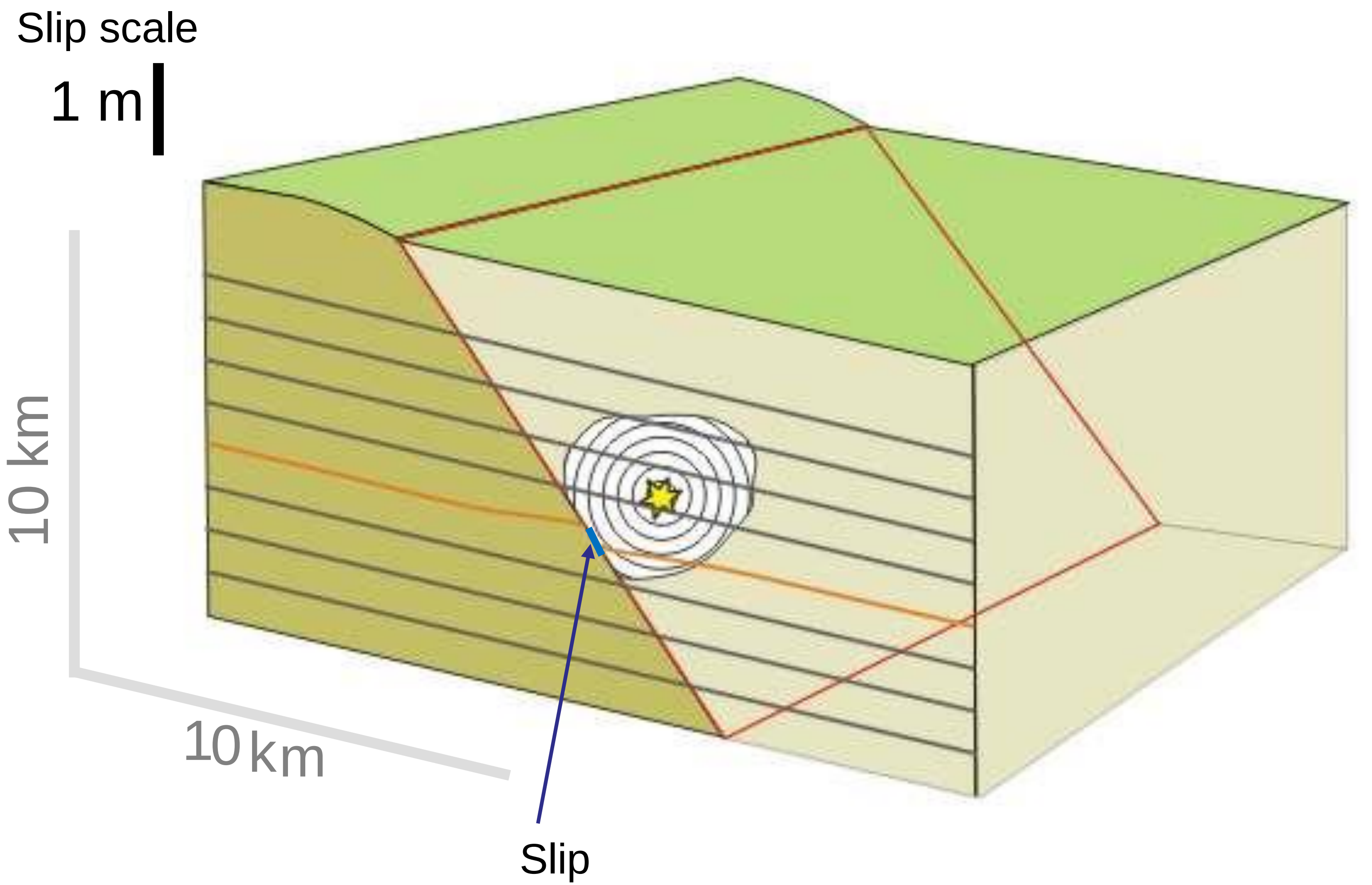
T ≃ 1 s

If the rupture stops, the magnitude of the earthquake is between 4 and 5
←→ The magnitude depends of the size of the ruptured zone and on the duration of the rupture

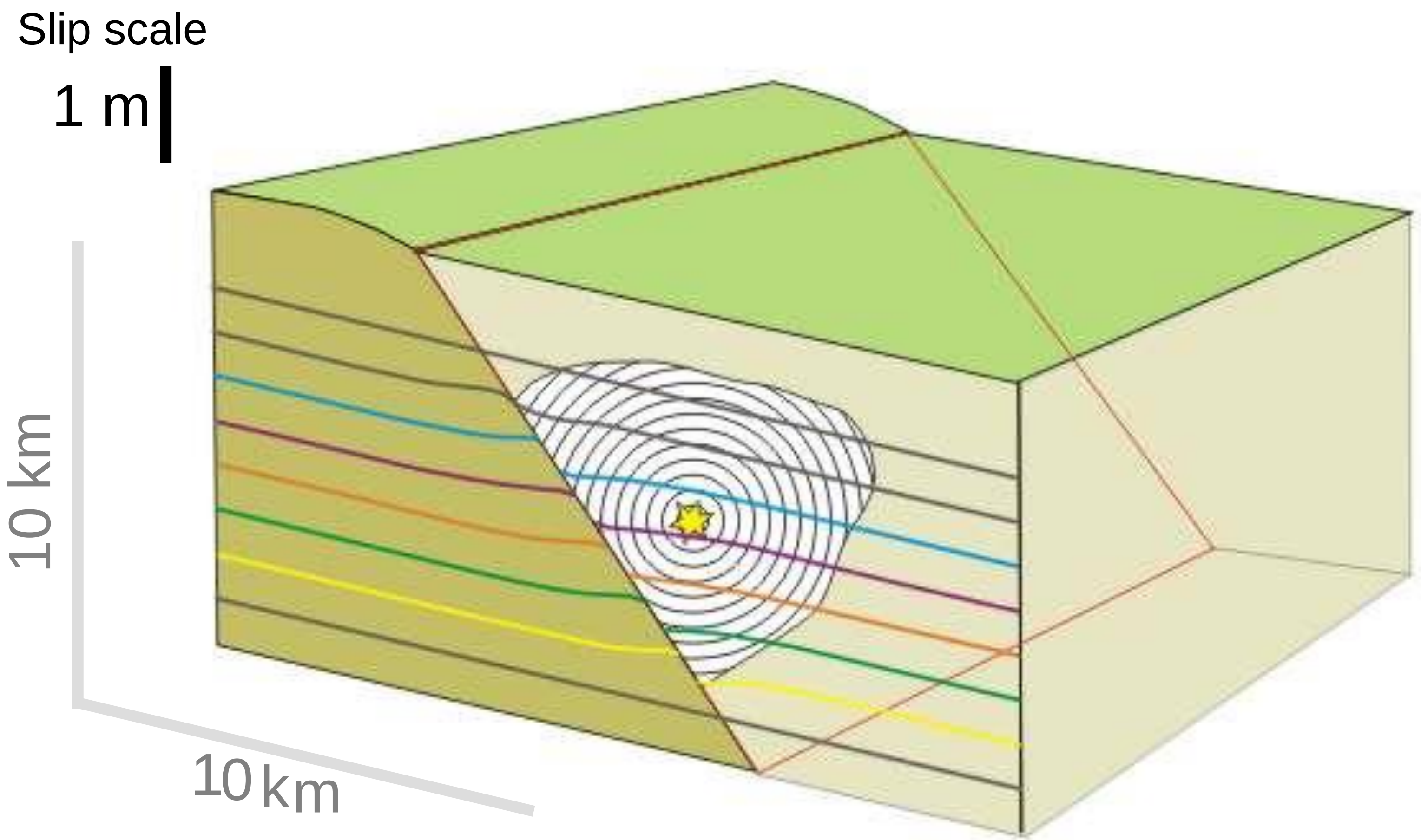


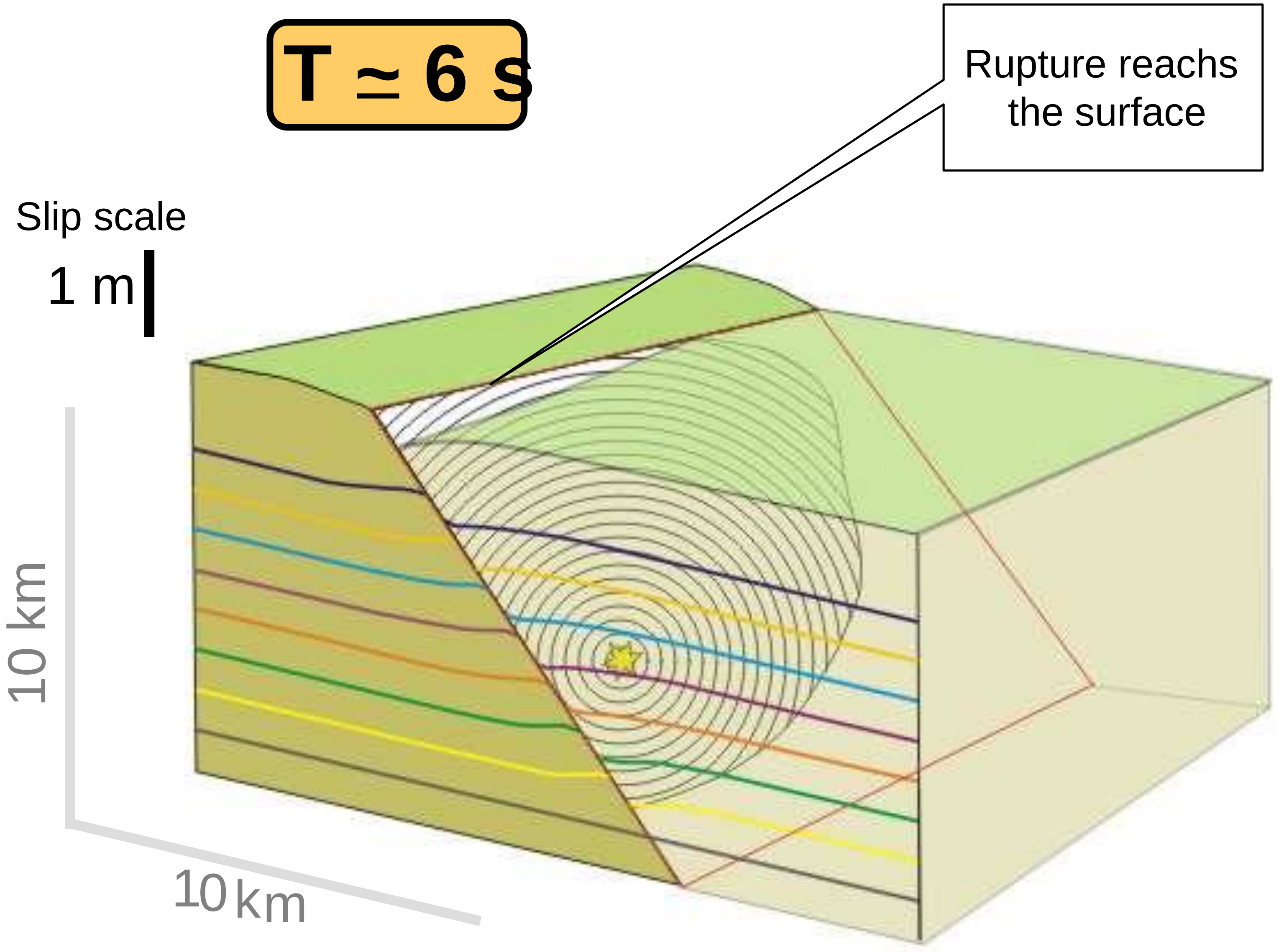
If the rupture continues, the magitude grows…

T ≃ 2 s



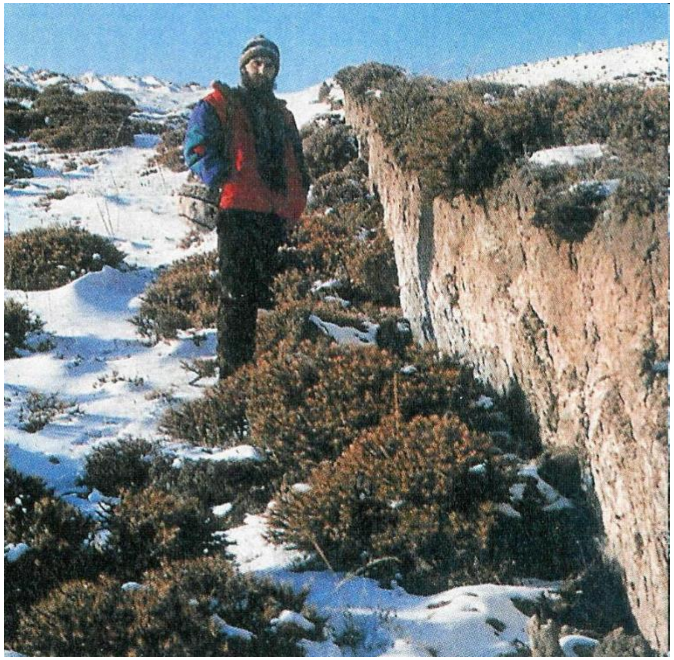
T ≃ 4 s

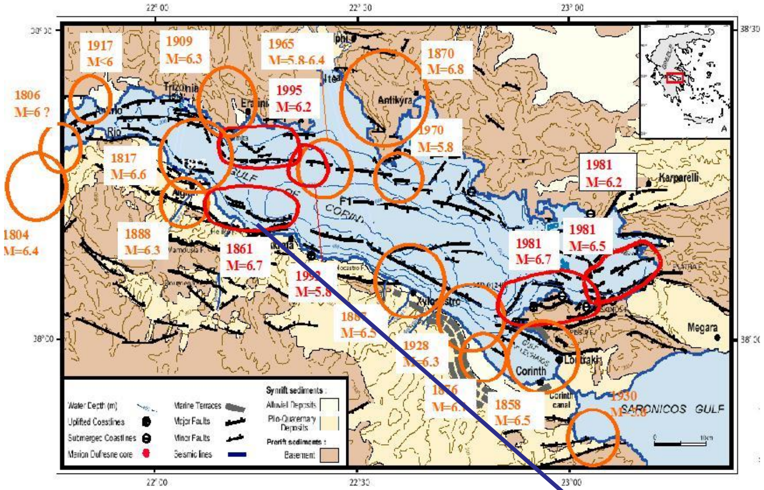




Magnitude between 6 and 6.5

Examples of some surface ruptures (M > 6.8)



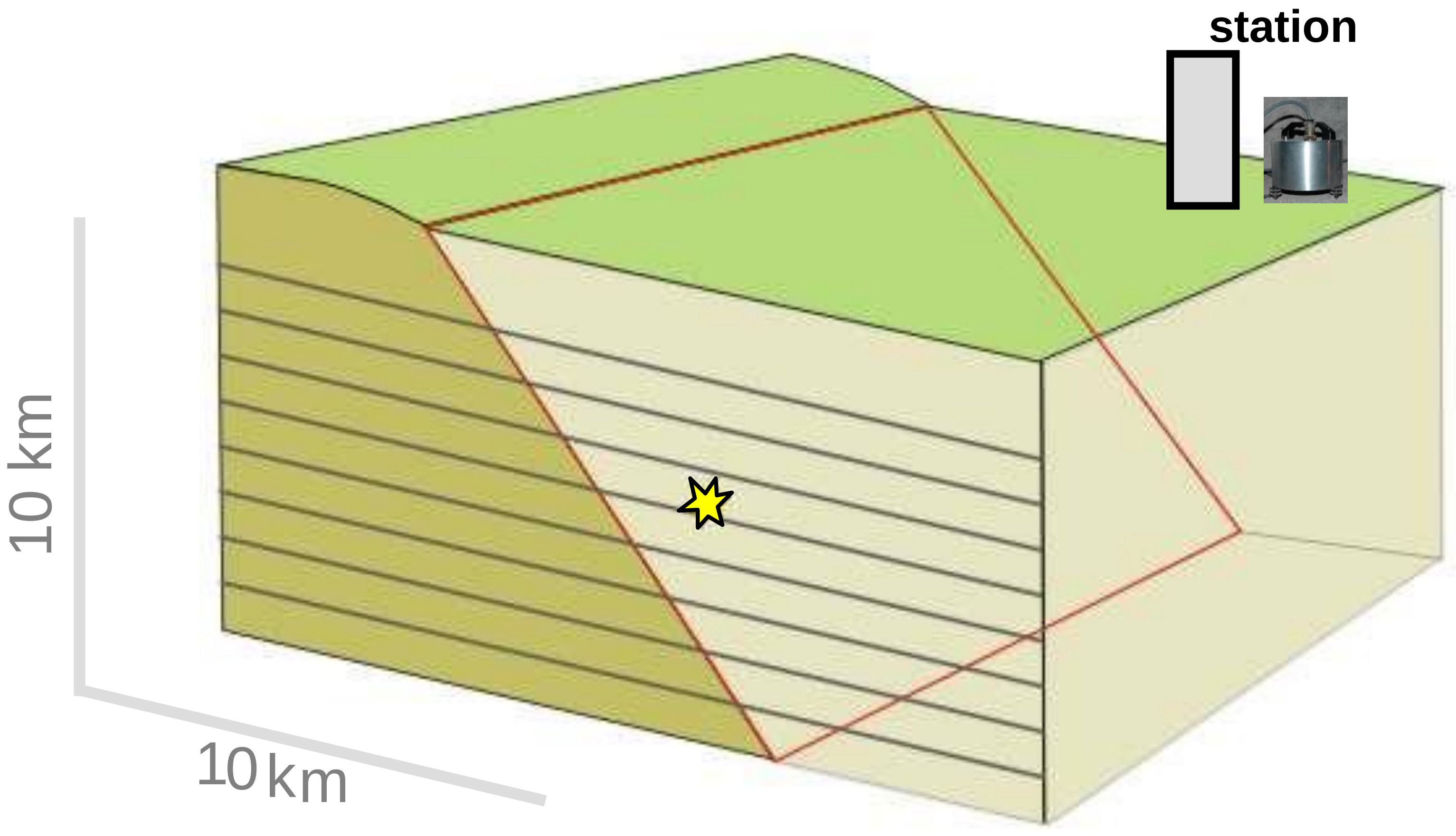


Along Corinth Gulf the best example is Heliki Fault

The seismological point of view

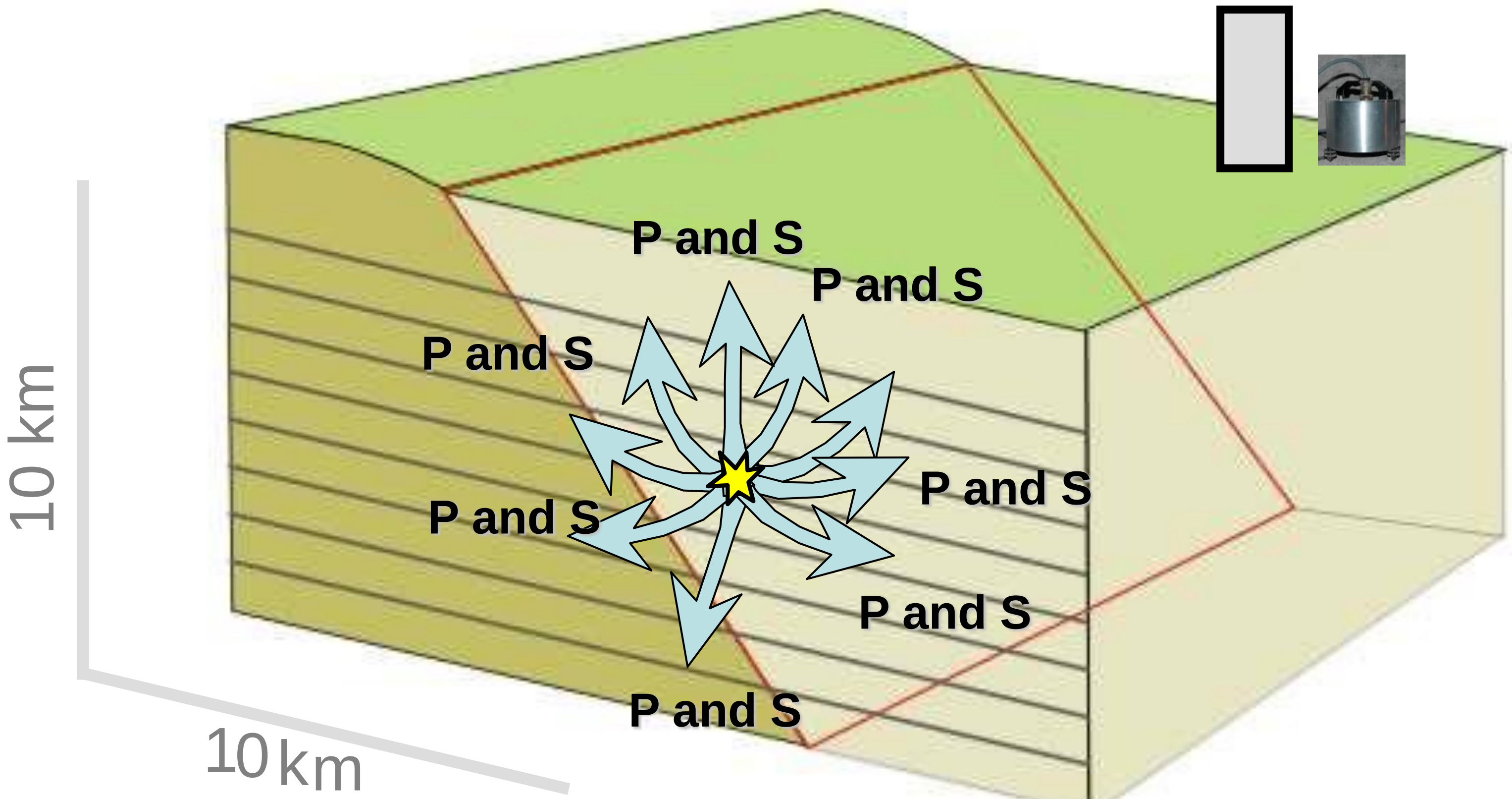
T = 0 s

Short distance



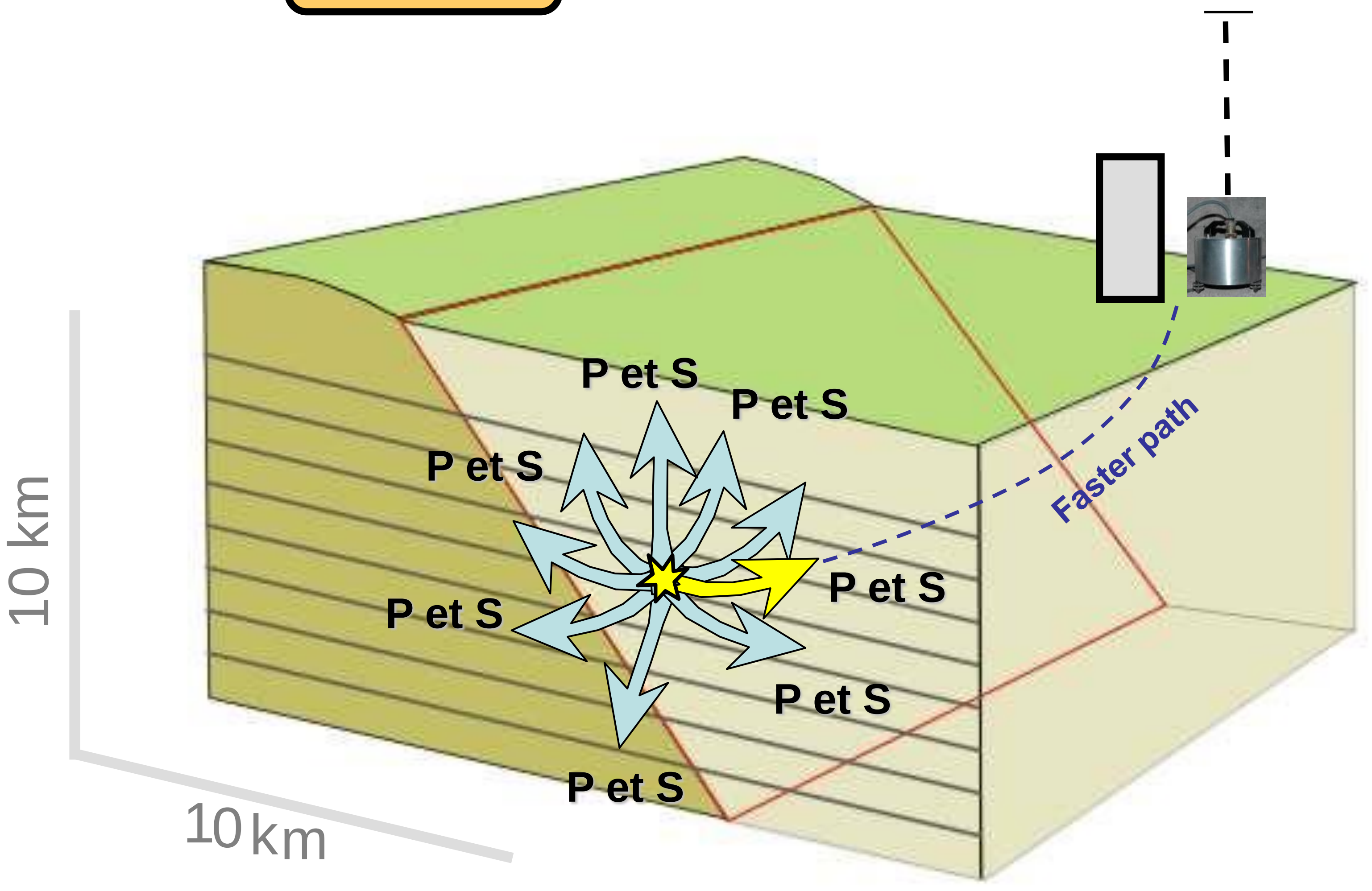
 : Hypocenter = rupture initiation point

T = 0 s

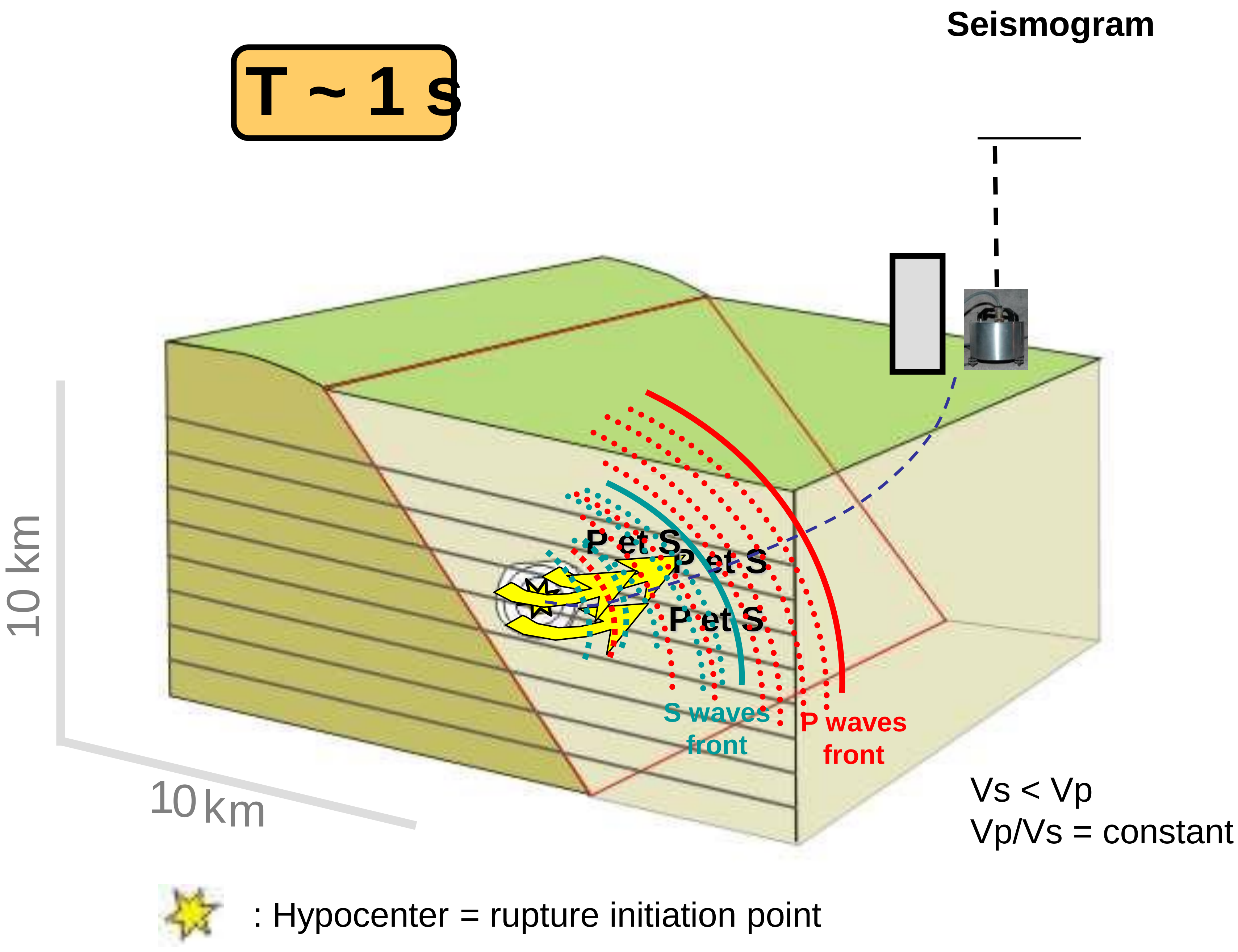


 : Hypocenter = rupture initiation point

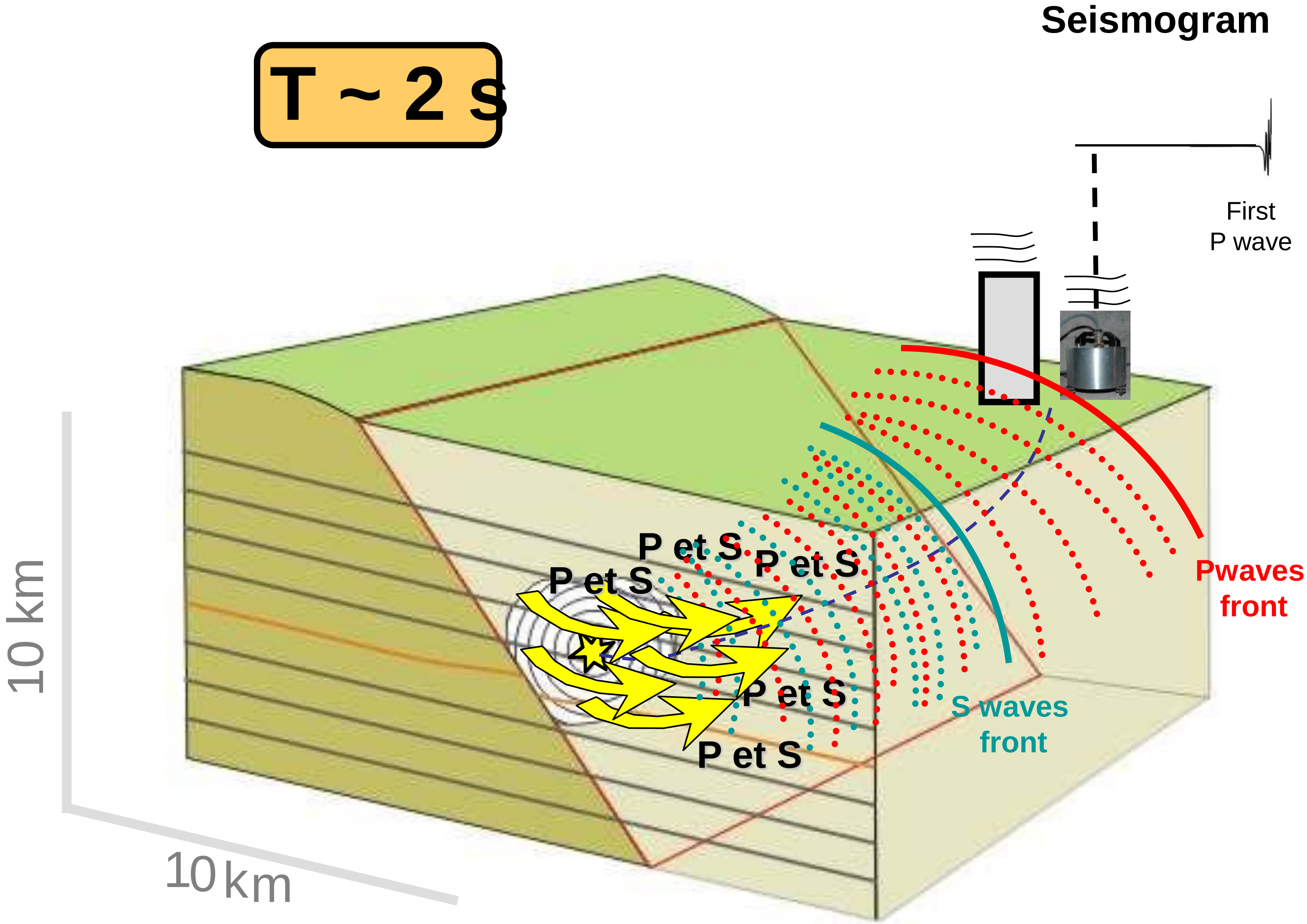
T = 0 s



 : Hypocenter = rupture initiation point



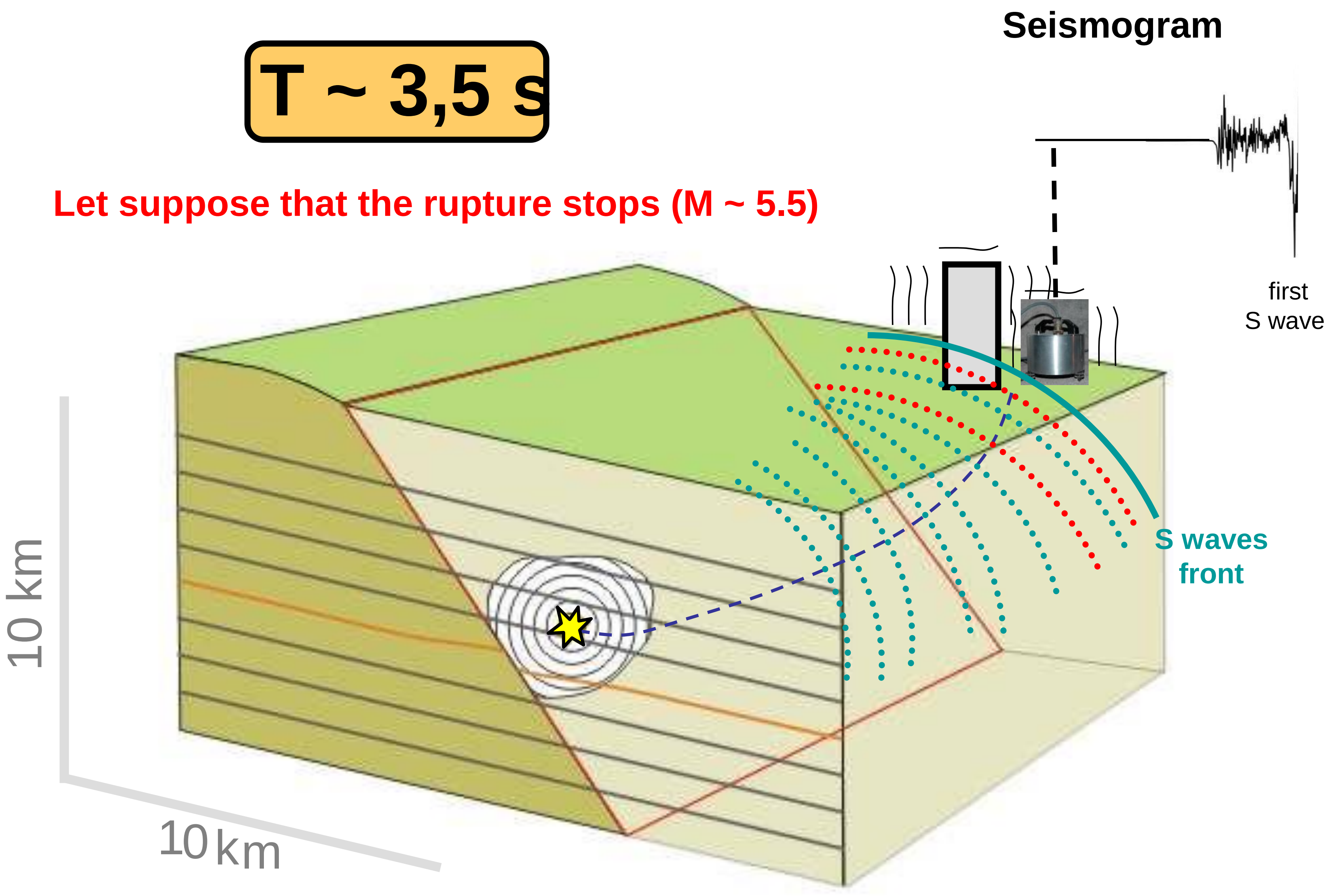
T ~ 1 s
Seismogram
10 km
10 km
P et S
P et S
P et S
S waves front
P waves front
Vs < Vp
Vp/Vs = constant
: Hypocenter = rupture initiation point



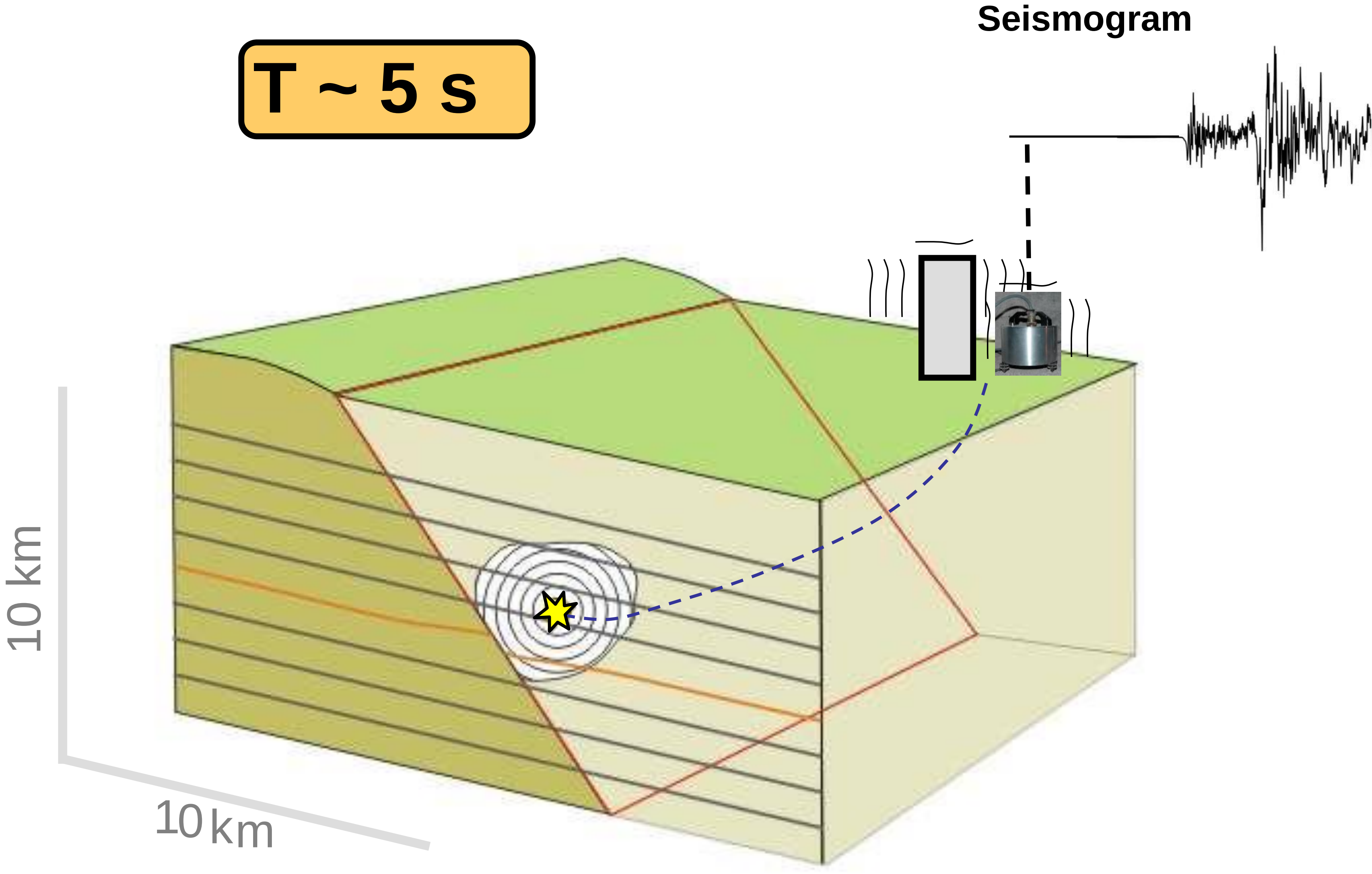
: Hypocenter = rupture initiation point

T ~ 3,5 s

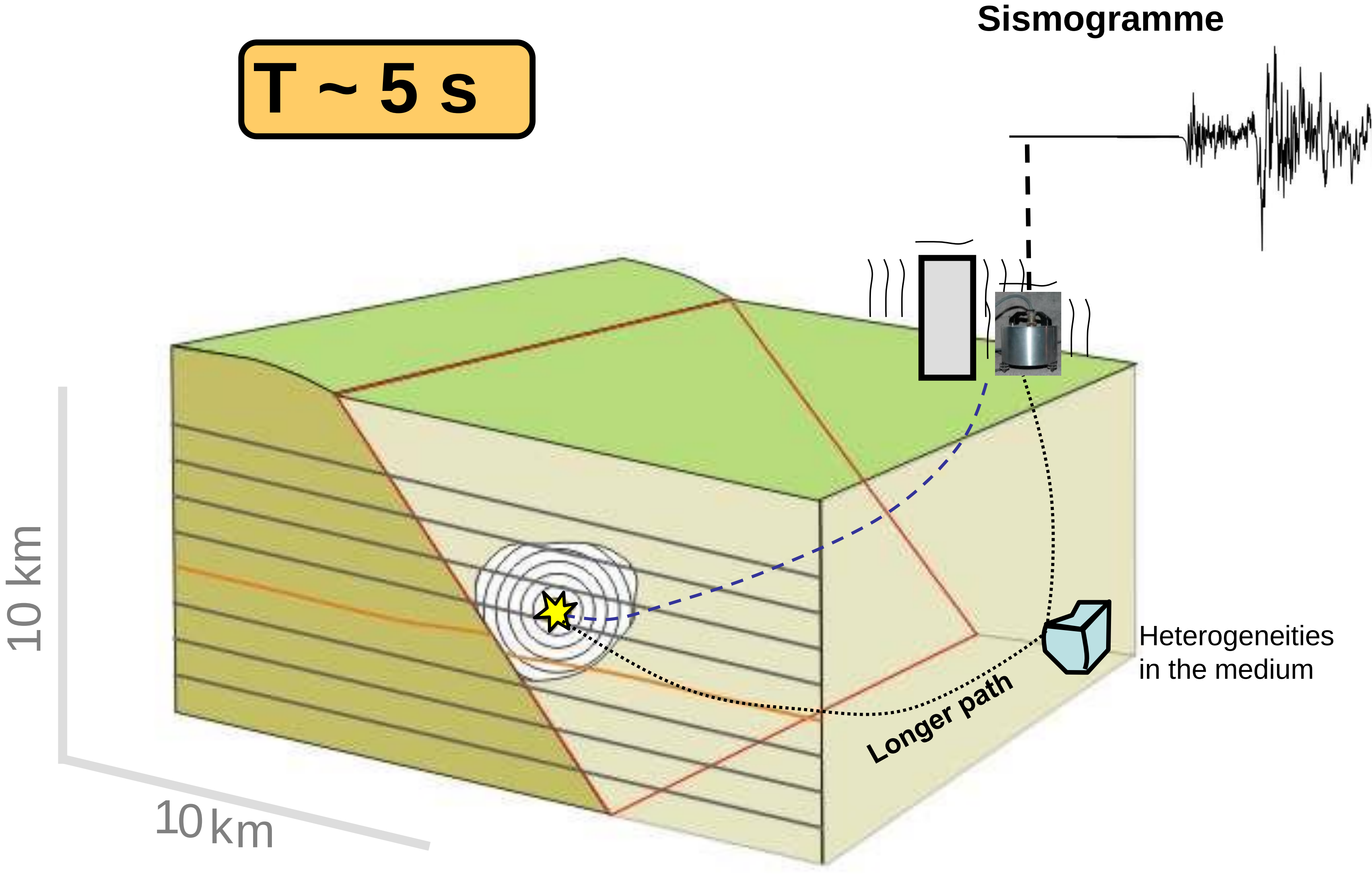
Let suppose that the rupture stops (M ~ 5.5)



: Hypocenter = rupture initiation point



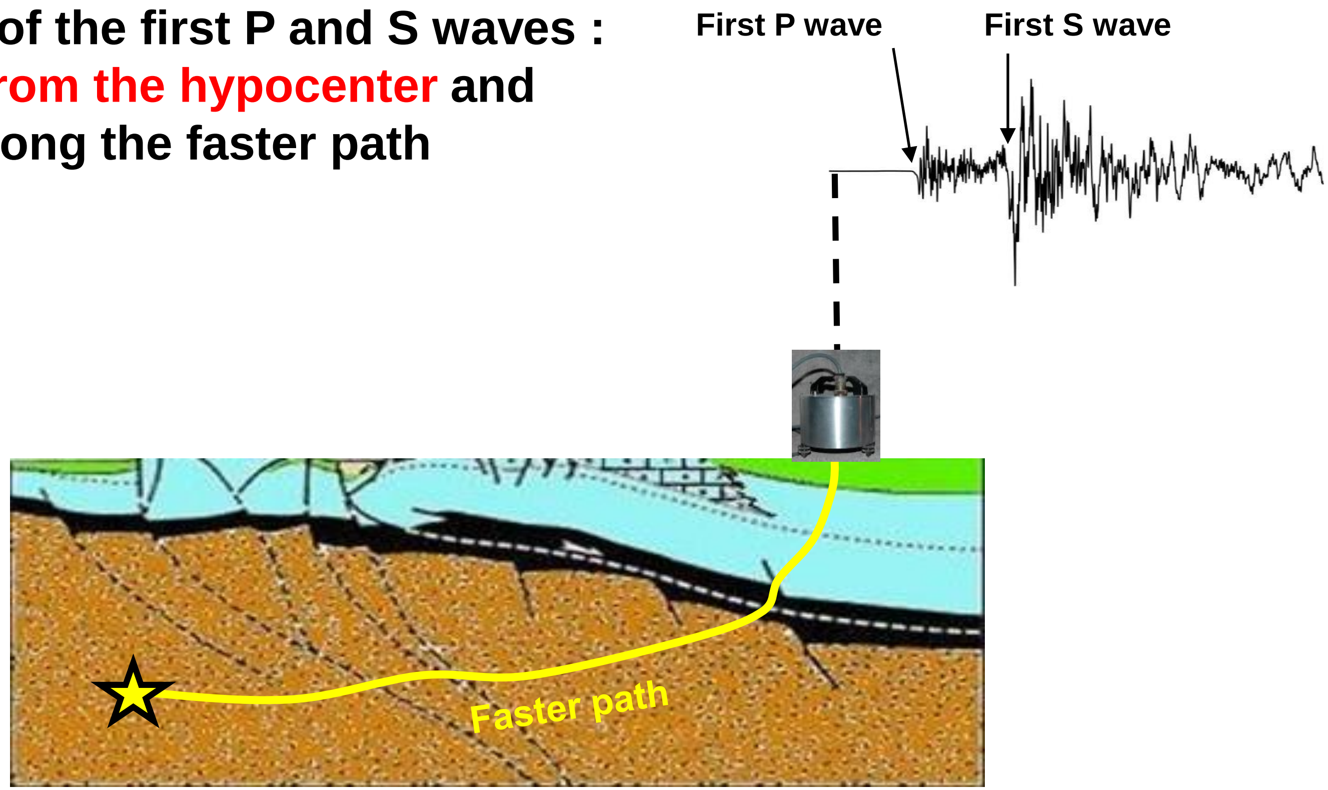
 : Hypocenter = rupture initiation point



 : Hypocenter = rupture initiation point

How we localize an earthquake?

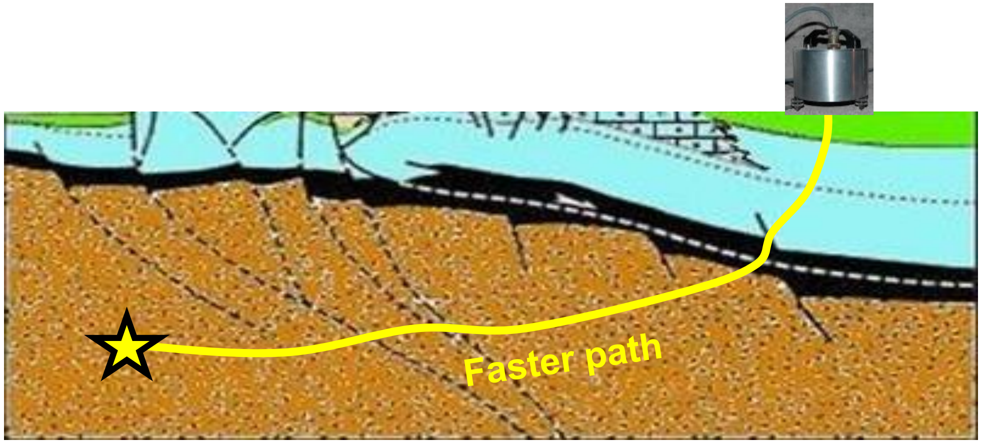
We use arrival time of the first P and S waves : the waves coming from the hypocenter and which have travel along the faster path



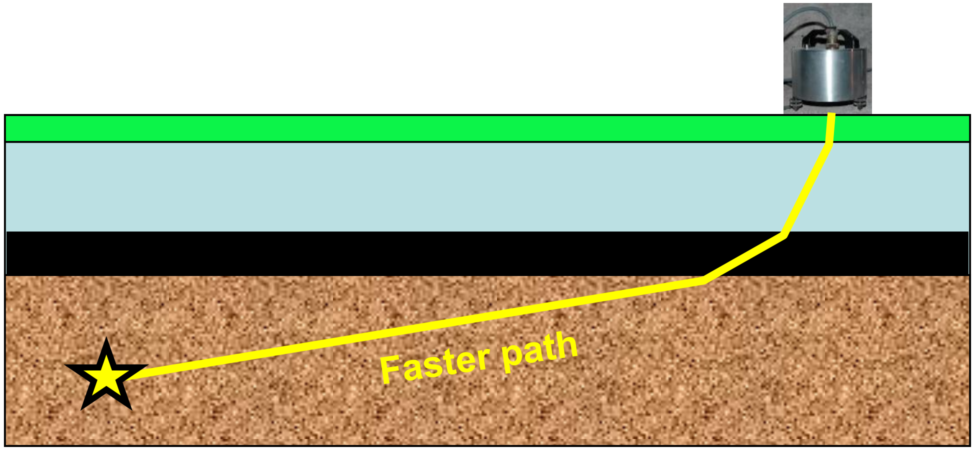
The travel time of seismic waves depends of the medium properties and the relative position of the hypocenter in this medium compare to the observation point.

Therefore, arrival time (origine time + travel time) give information to locate the hypocenter position.

Generaly we use a simplify model to represent the medium in which waves are propagating and in which we know how to calculate the travel time numerically.

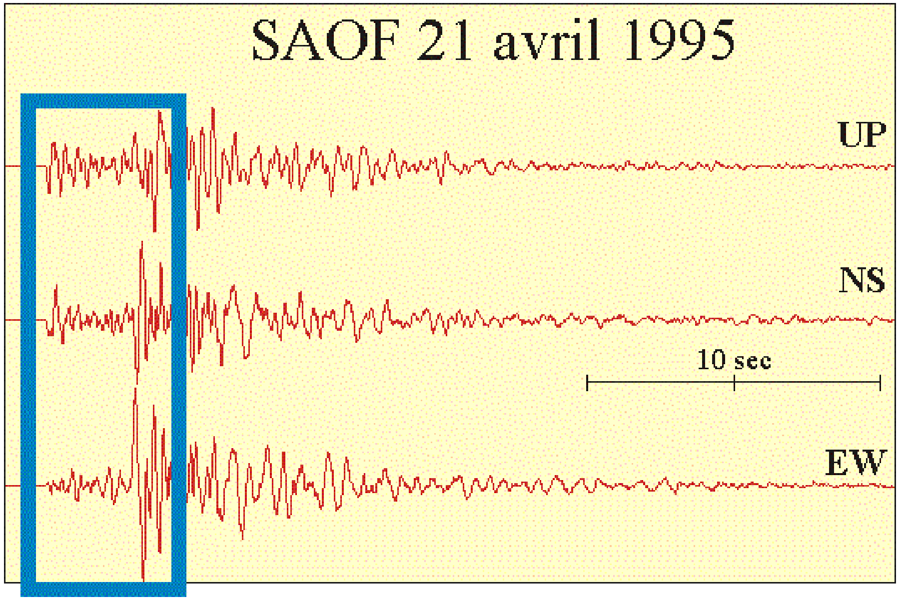


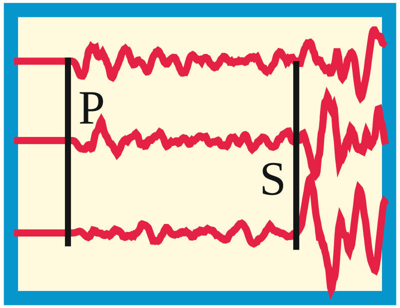
Real unknow medium



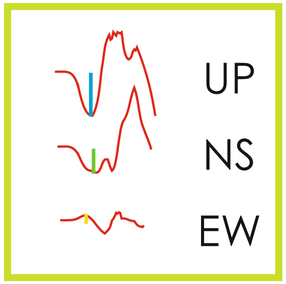
Simplified model : homogenous horizontal layers

Arrival time Picking

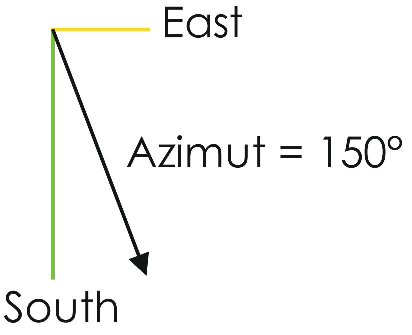




Tp, Ts

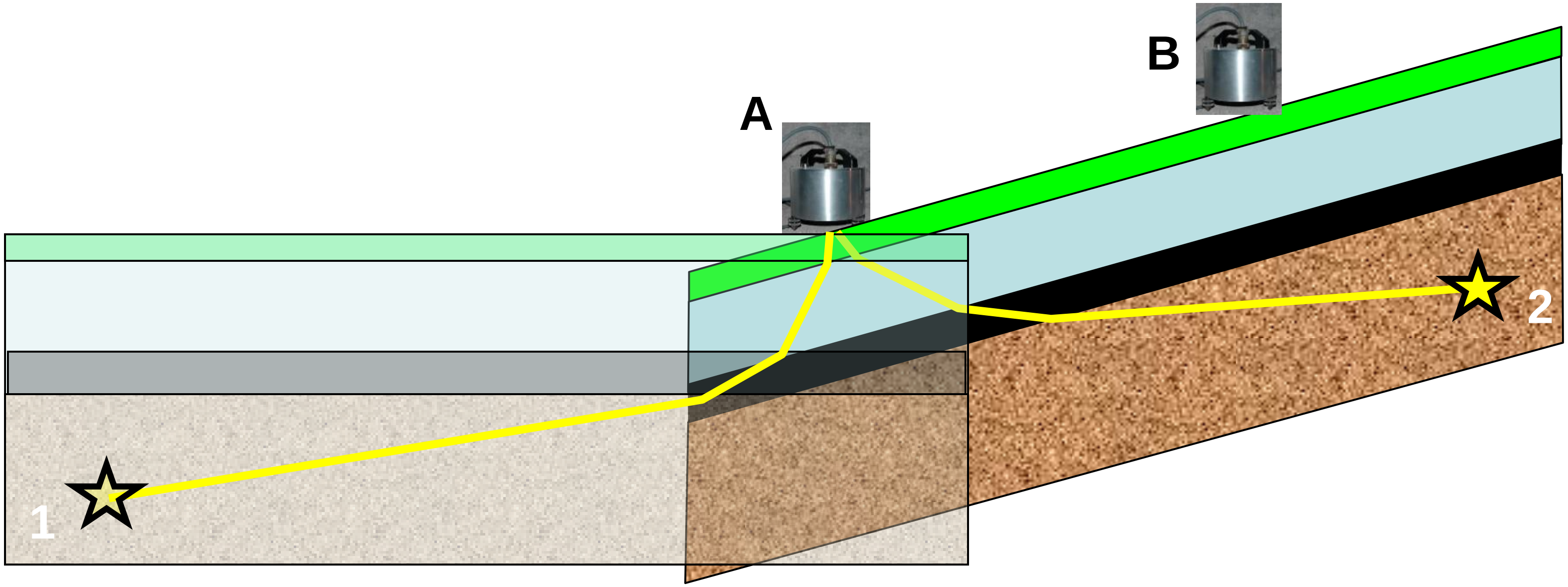


Onde P



Arrival time at one station is not enougth to locate an hypocenter.

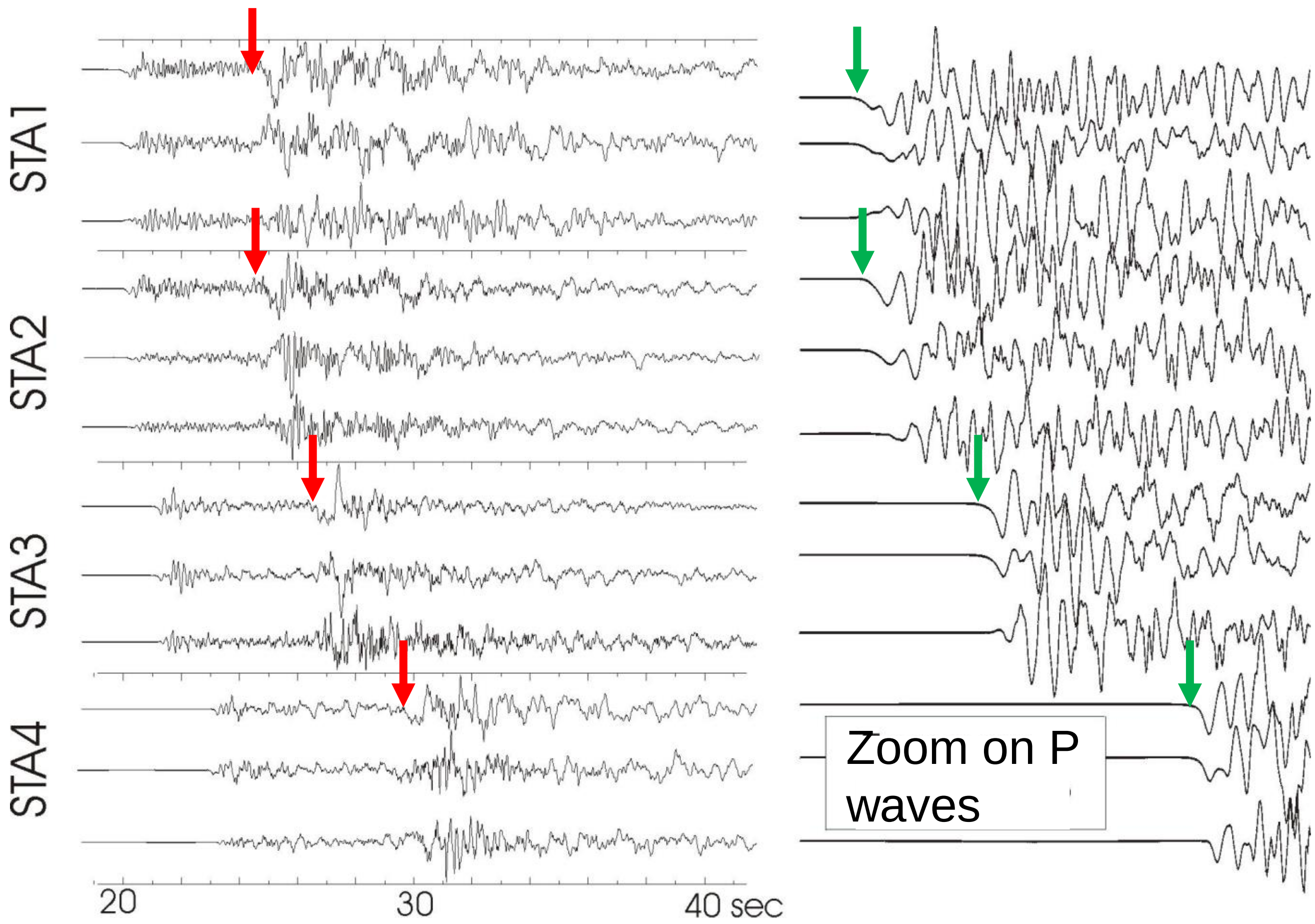
… As different hypocenters can produce P waves which will arrive at the station at identical arrival time.



Information at a second station help

If arrival time at B is earlier that at A, the hypocenter 2 is better

Pickings : good examples



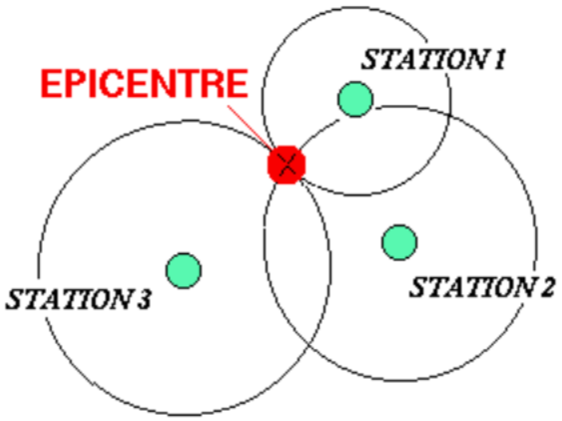
Time reference at each station should be the same: synchronized recordings

A simple approximation : circles method

- Shallow event at distance less than 200 km
- Homegeneous velocity in the superficial layer

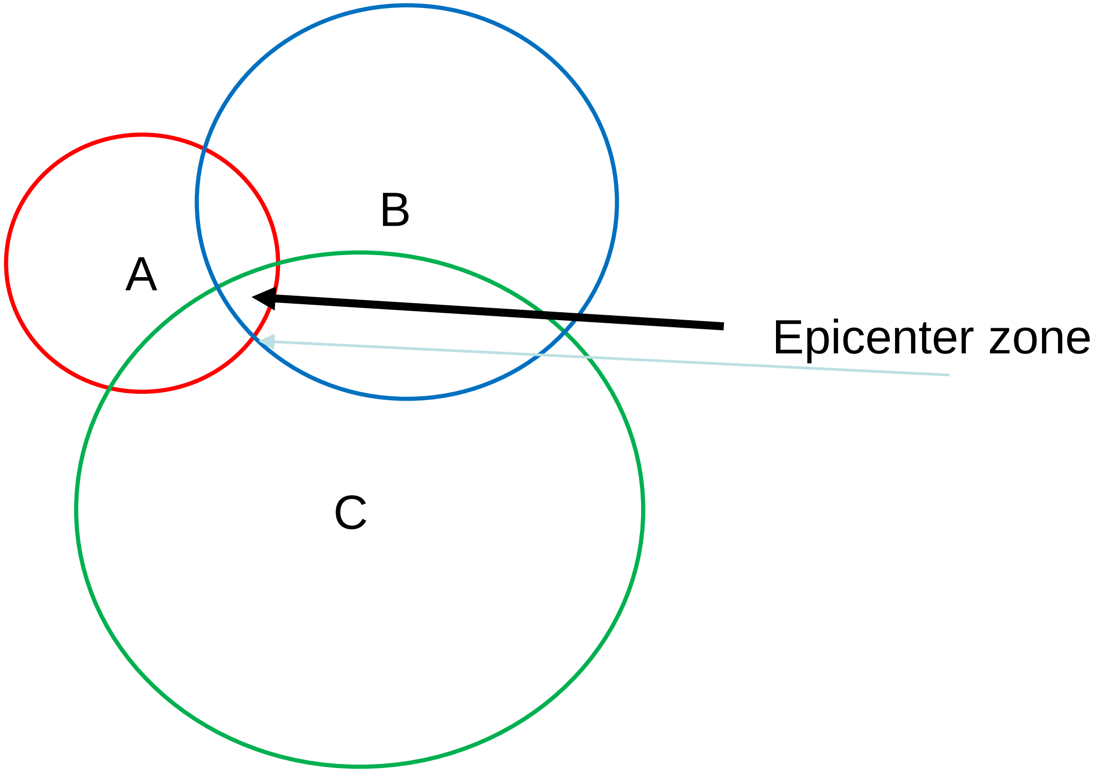
$$T_s - T_p = d \,.\, (1/V_s - 1/V_p)$$

- Pick arrival times P and S at 3 stations = 3 distances



Approximation: profondeur négligeable

In reality:



Easy, but not very usefull in practice………

Earthquake location

- A velocity model is supposed : Vp et Vs for the region and described with homogeneous layers
- Measurement of Tp et Ts on N stations
- 4 unknowns (T0, x, y, z), 2N informations

- Tp = T0 + fp(x, y, z)
- Ts = T0 + fs(x, y, z)
- Non linear relation

- Inverse problem
- Rms = $\Sigma\ \alpha_i(T_{i,obs} - T_{i,cal})^2 / N$

Earthquake location

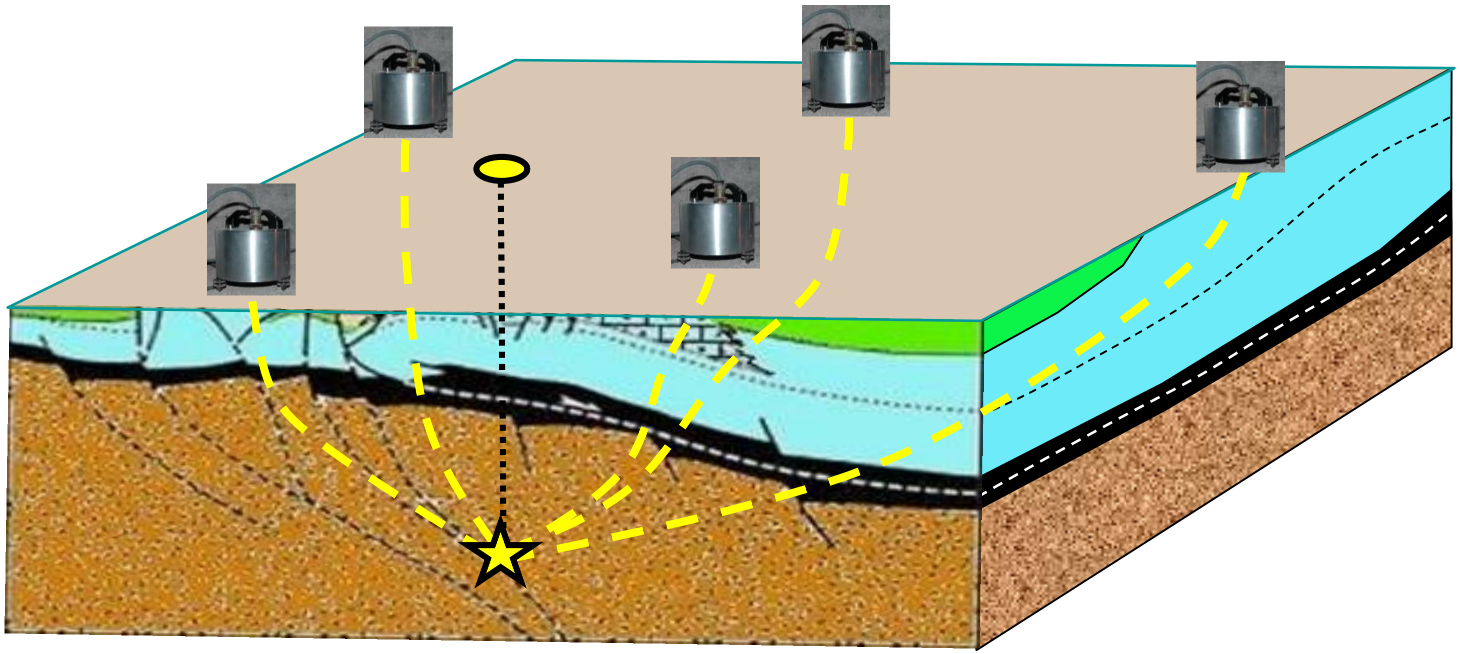
- Rms = $\Sigma\ \alpha_i (T_{i,obs} - T_{i,cal})^2 / N$
- Rms = non linear function of (T0, x,y,z)

- Solved by :

1. Linearisation around a presupposed approximate location and least mean square minimisation
2. MonteCarlo grid search or improved method for faster convergence (simulated annealing …).

- Statistical evaluation of uncertainties.

Practicaly to calculate with a good precision the position of the hypocenter we need a dense network around the epicenter.



A precise measurement of the arrival times on seismograms P and S if possible.

An error of 1 s in time corresponds to some kilometers in position.
Typical P arrival time picking error is of 0.02 s; the corresponding error in space is about 100m.

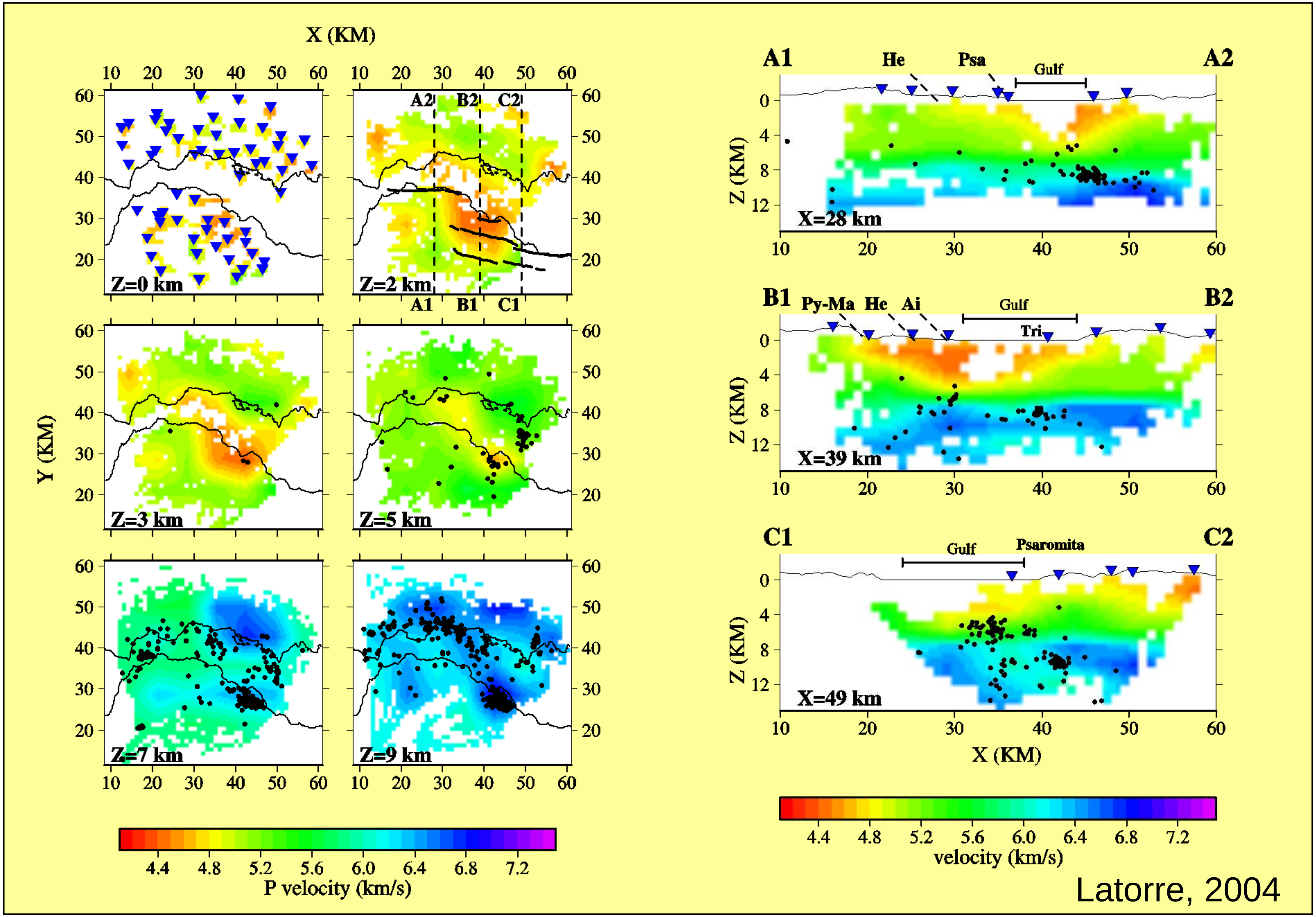
The limitation : we don't know the velocity model.

Earthquake location

- 4 parameters t0, x, y, z
- Uncertainty on the parameters
- Evaluation of the missfit

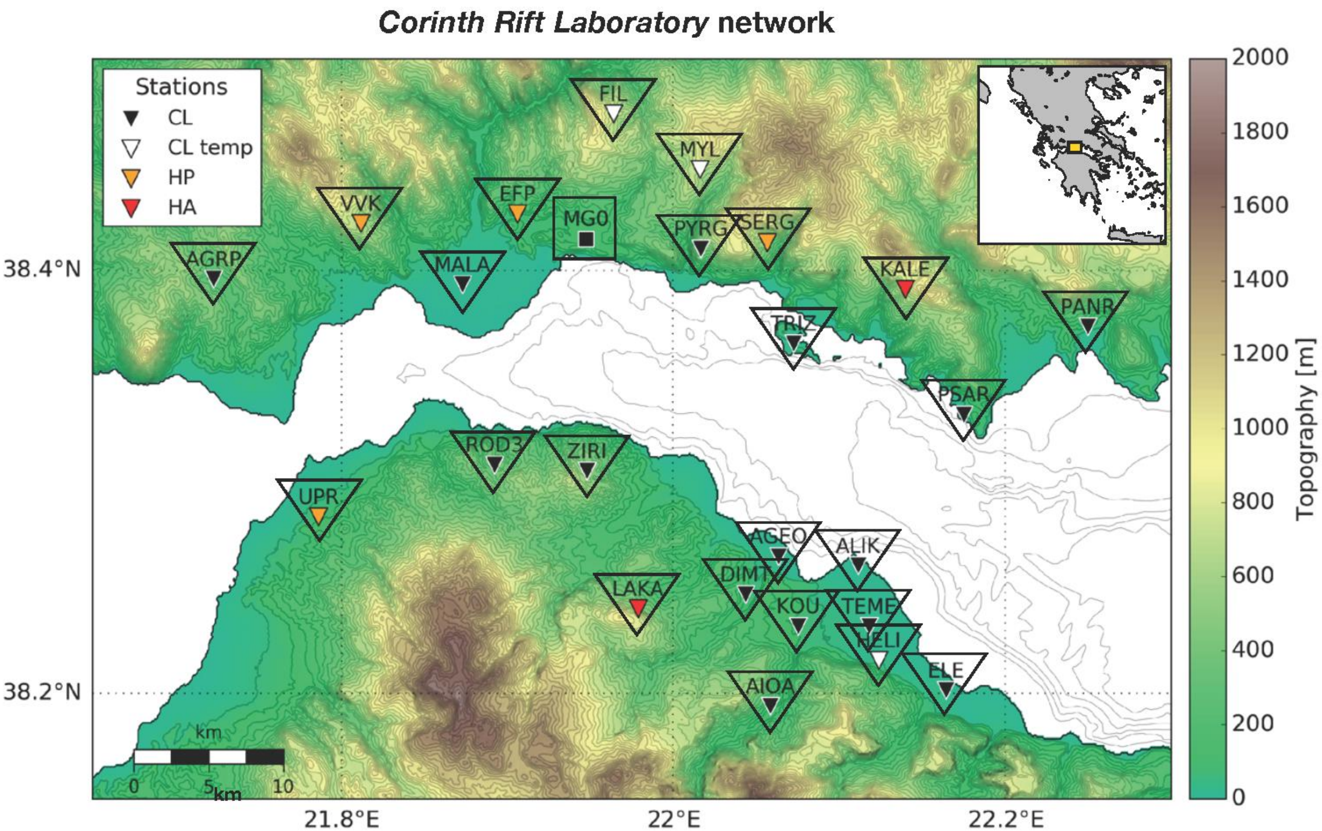
- A good location is obtained if:
  - The number of pickings is larger than 8 (P and S)
  - If the azimuthal gap is less than 180°.
  - If there is at least one station at an epicentral distance of the order of the depth of the event.
  - If the velocity model is adapted

Modèle de vitesse P



Latorre, 2004

And on Corinth Rift?



Station characteristics

2000 — 12 permanent CP stations (125 Hz)

2010 — + 4 permanent CP stations (100 Hz)

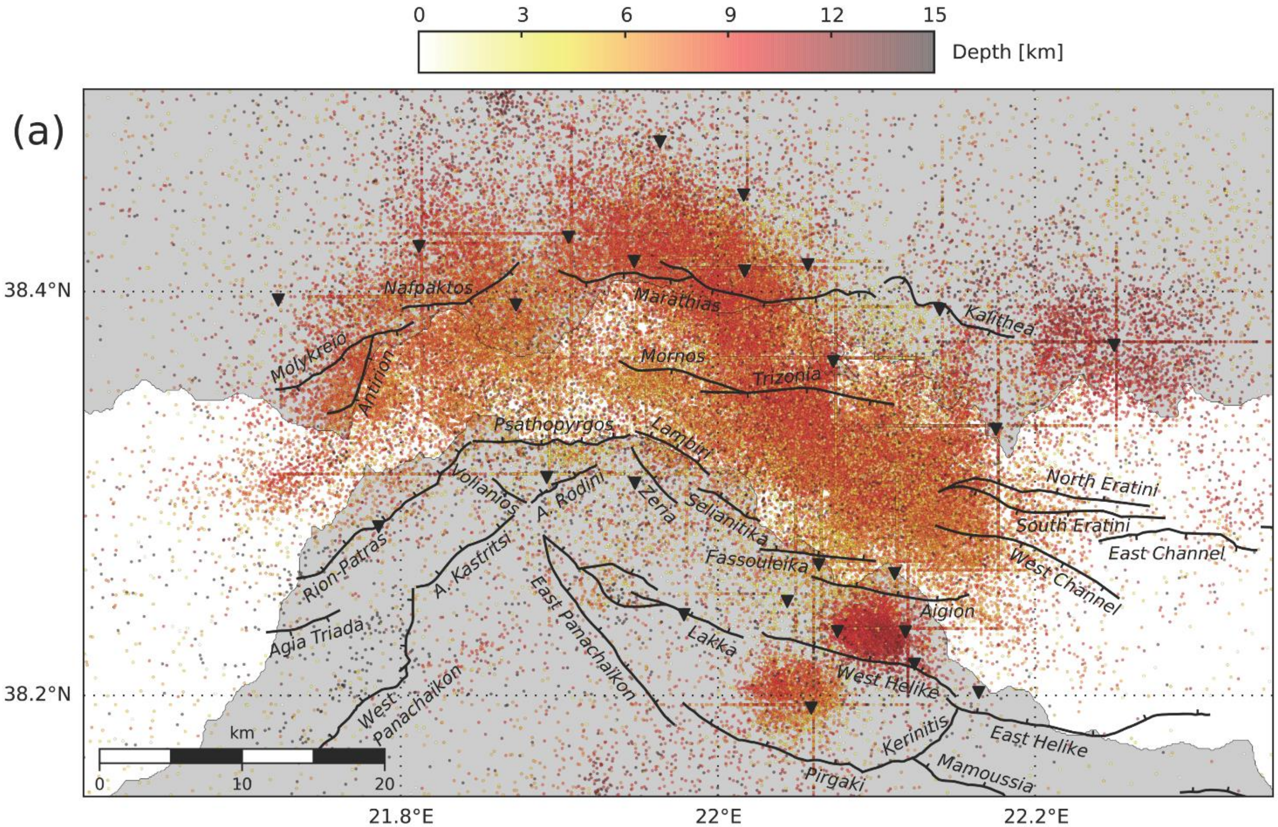
+ 7 broadband stations

+ antenna ■

2015

Duverger, 2017

Real time data flows automatically analysed



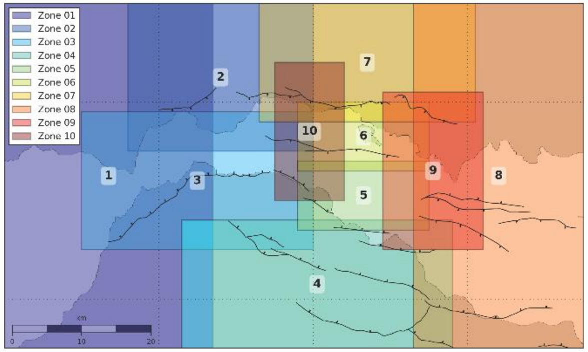
hypo71

~ 205,000 events

Manual (10%) and automatic phase picks

Velocity model 1D

[Rigo *et al.*, 1996]

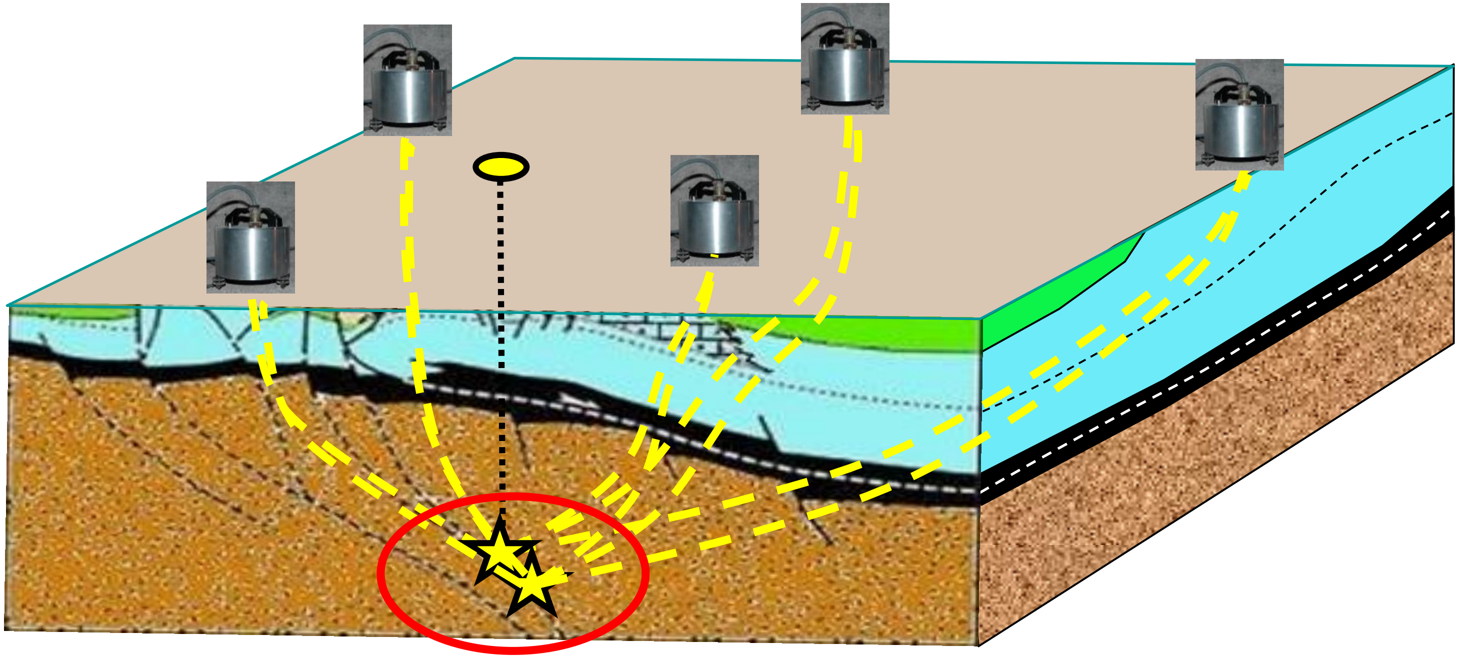


➡ relocation

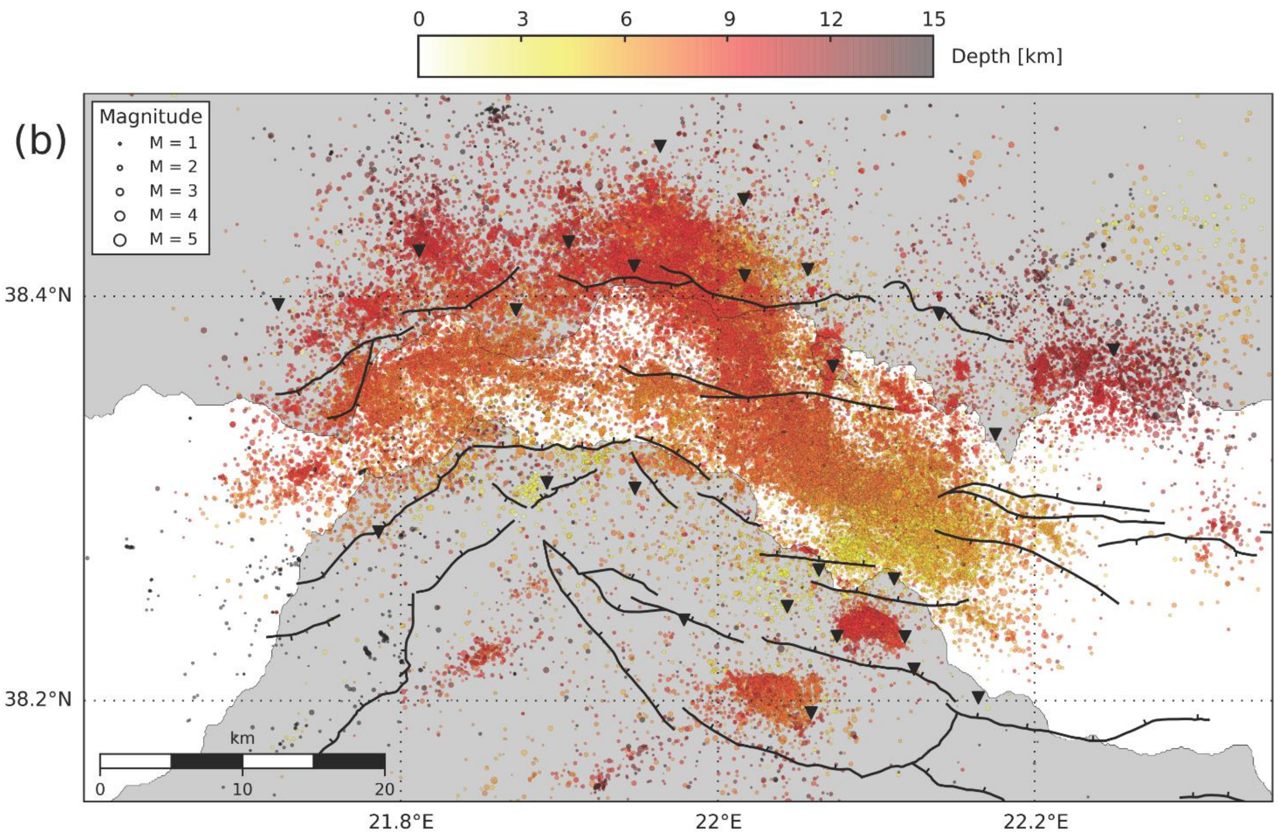
Most are automatic pickings: the image diffused due to errors in location.

Duverger, 2017

Relative location: double differences of travel time

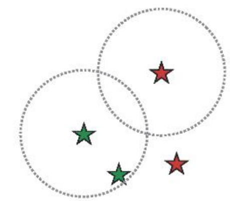


Better estimation of travel differences by cross-correlation of the signals



hypoDD

double-differences
cross-correlations



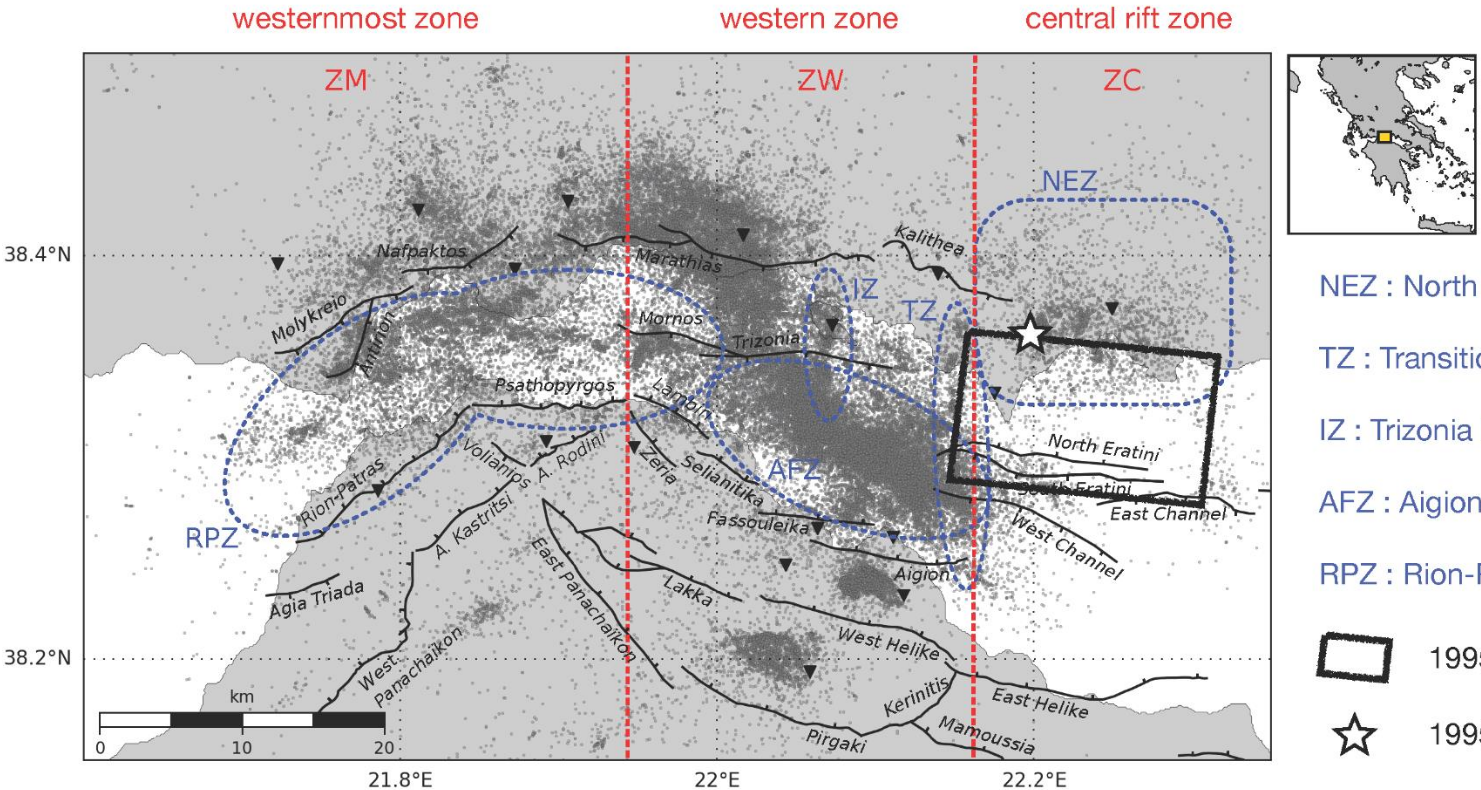
- ✓ distance < 5 km
- ✓ correlation > 0.85

~ 95,000 events

« Better image »

Duverger, 2017

Seismic zones



NEZ : North Eratini Zone

TZ : Transition Zone

IZ : Trizonia Island Zone

AFZ : Aigion-Fassouleika Fault Zone

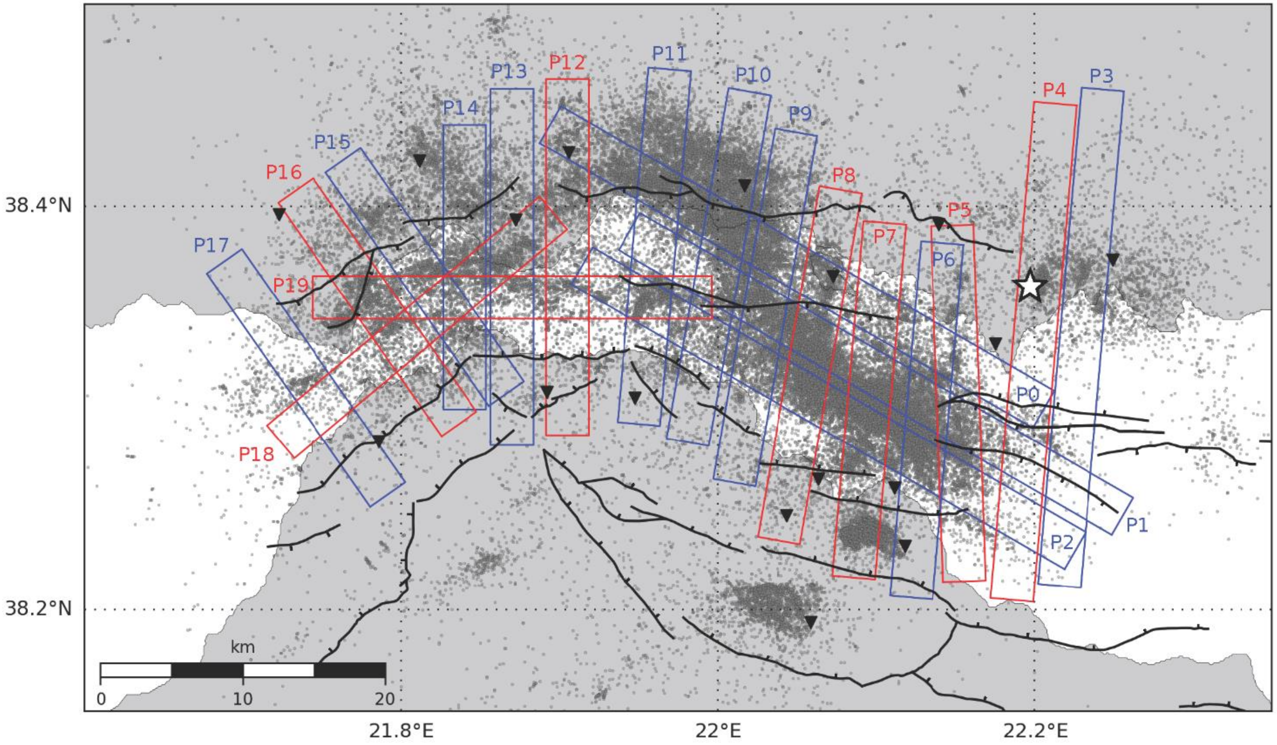
RPZ : Rion-Psathopyrgos Fault Zone

1995 rupture plane

1995 earthquake M_W 6.3

Duverger, 2017

Cross-sections

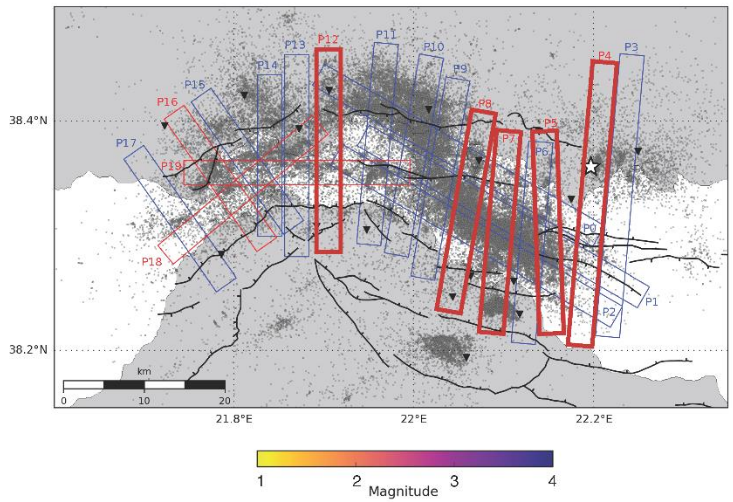


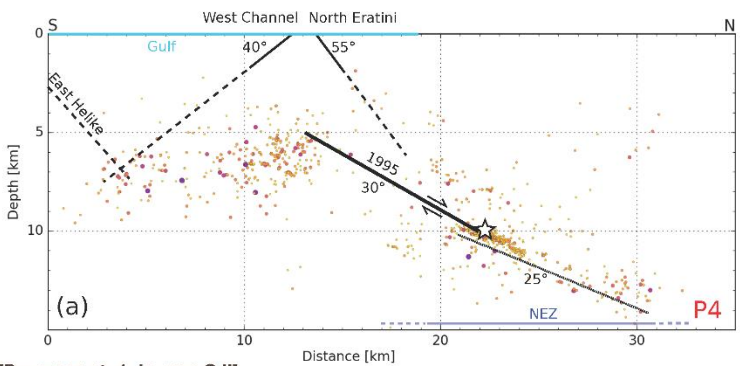
- from east to west

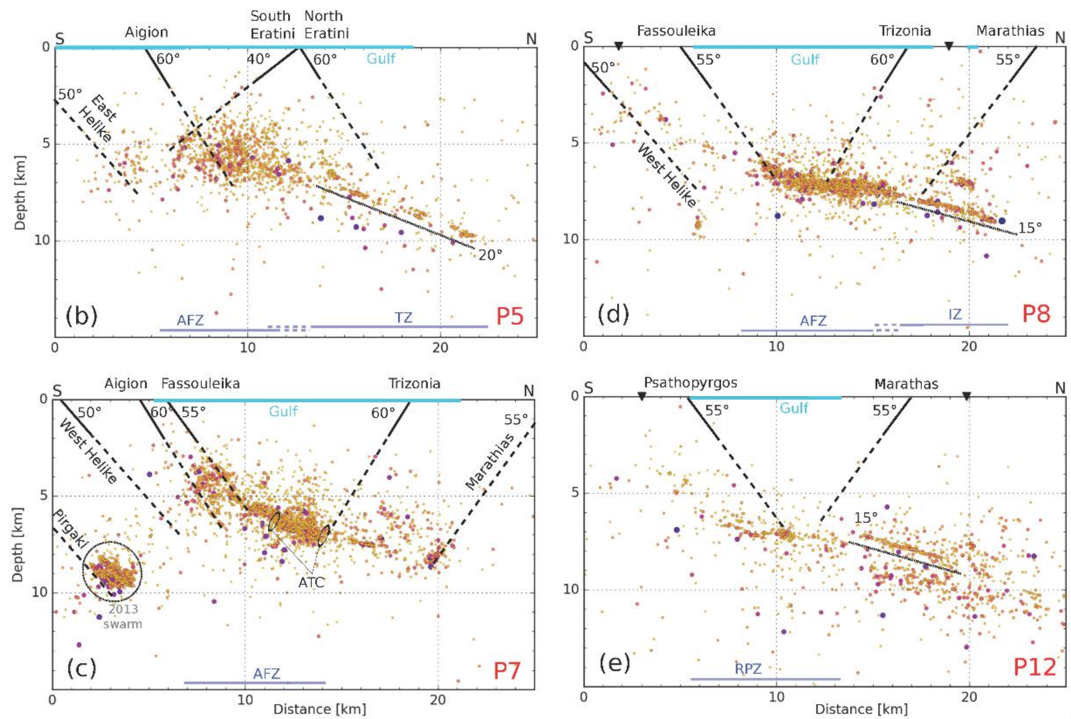
Duverger, 2017

Active fault structures - Central and western part

- continuity of the 1995 rupture plane
- seismicity at the root of faults
- thick and very thin layers



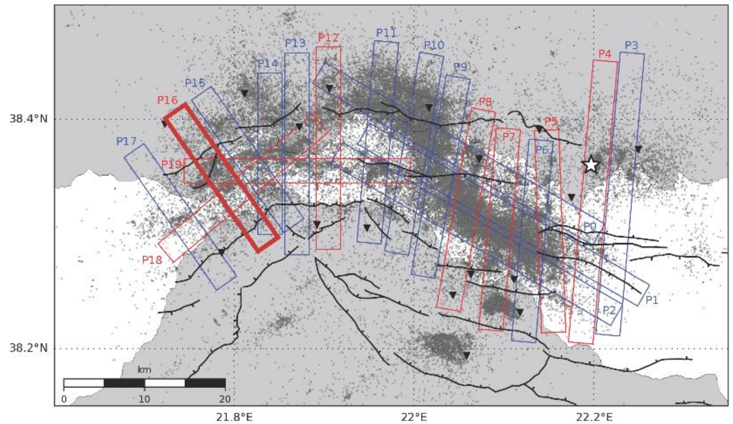


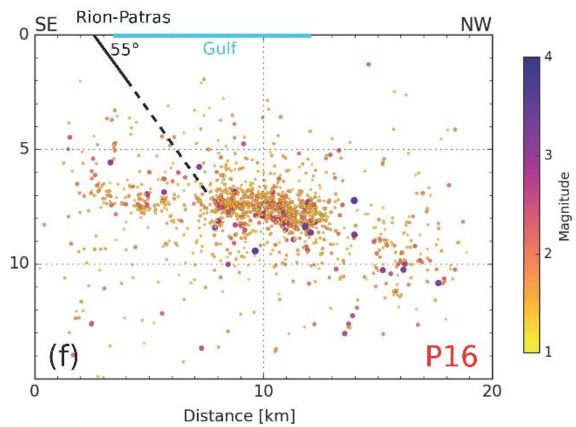


[Duverger *et al.*, in prep GJI]

Duverger, 2017

Active fault structures - Westernmost part

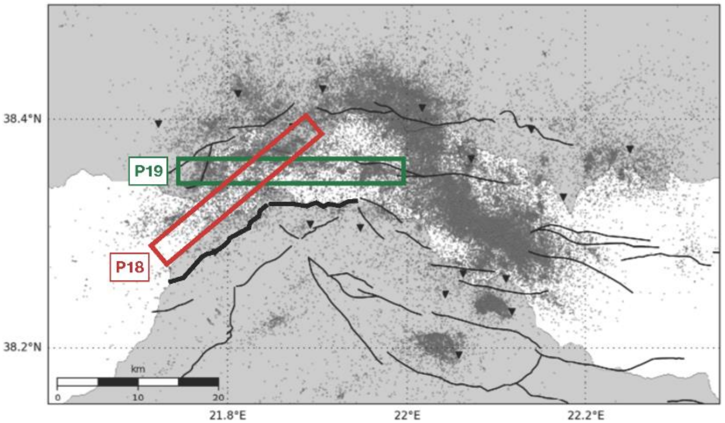




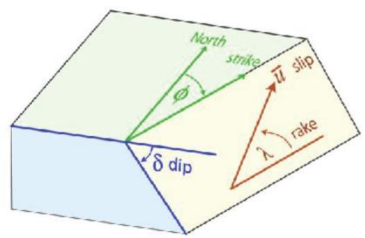
[Duverger *et al.*, in prep GJI]

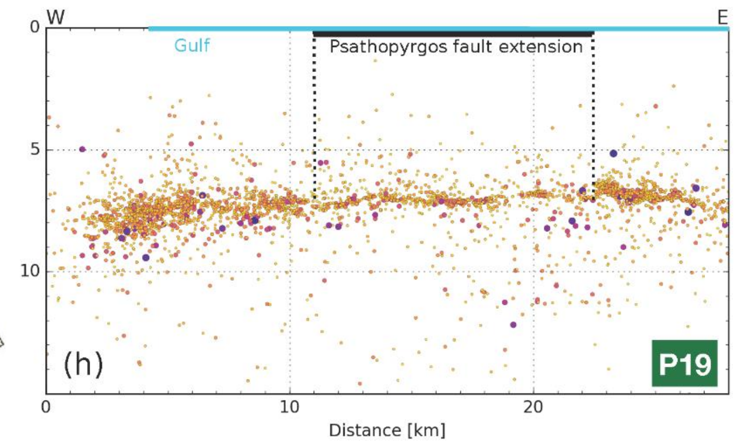
Duverger, 2017

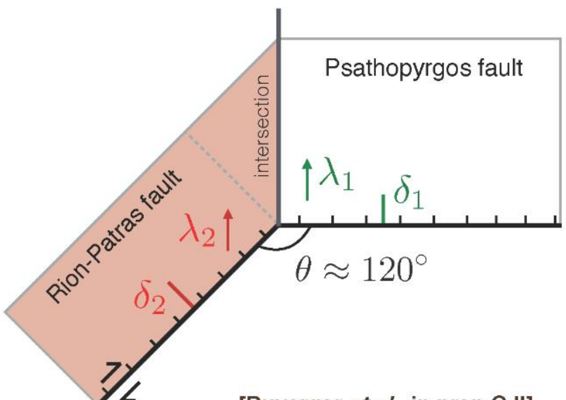
Active fault structures - Westernmost part



Angle reminder







dip $\delta_1 \approx 55^\circ$

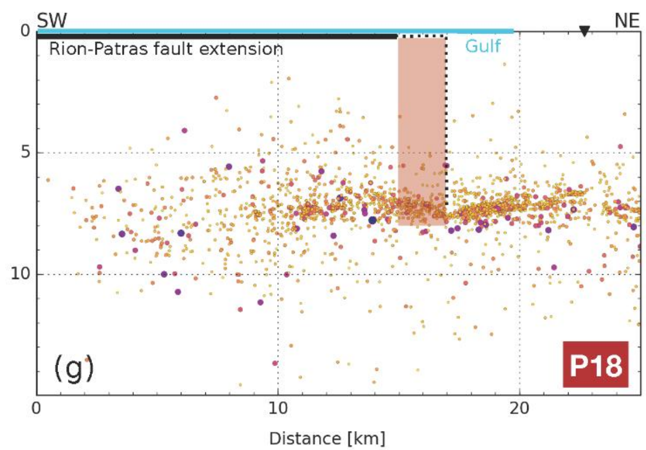
rake $\lambda_1 \approx -90^\circ$

$\delta_2 \approx 60^\circ$

$\lambda_2 \approx -115^\circ$

→ strike-slip ~ 70%
normal slip ~ 30%

[Duverger *et al.*, in prep GJI]

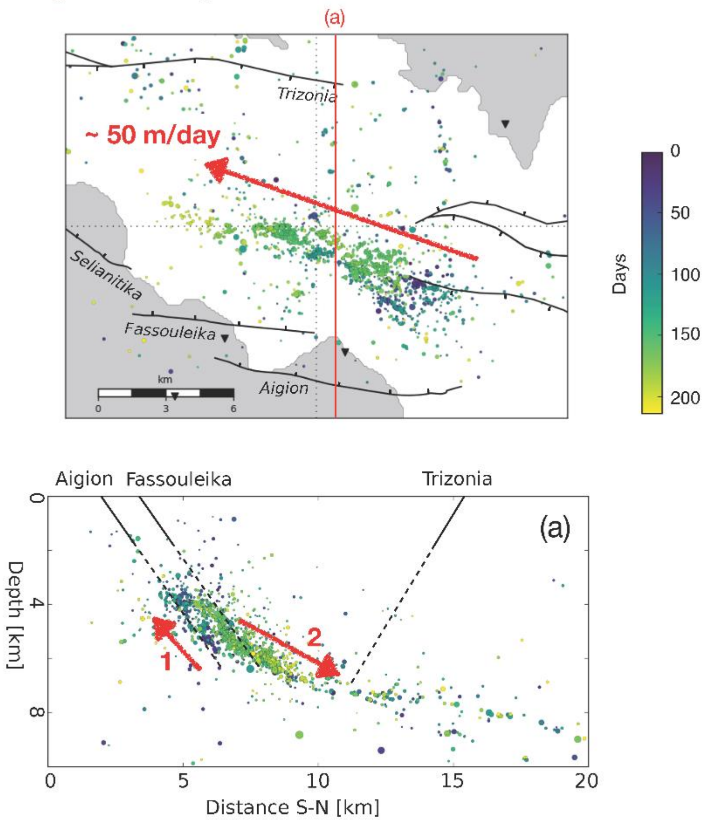


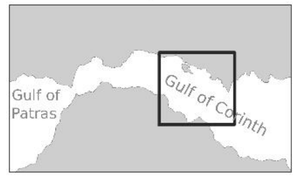
Duverger, 2017

Spatio-temporal evolution of seismic swarms

Migration 2003-2004

[Duverger *et al.*, 2015]

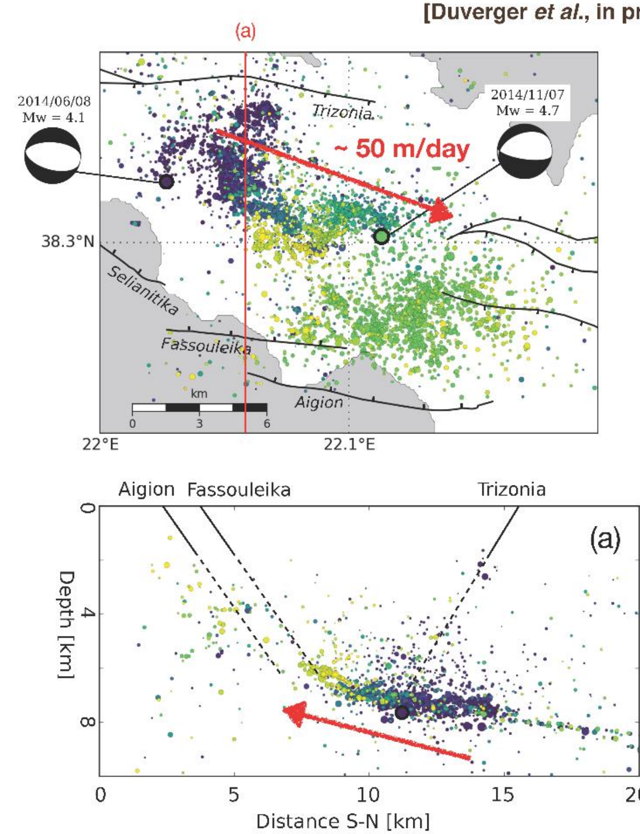




Slow large-scale migrations at typical pore pressure migration velocity

Migration 2014

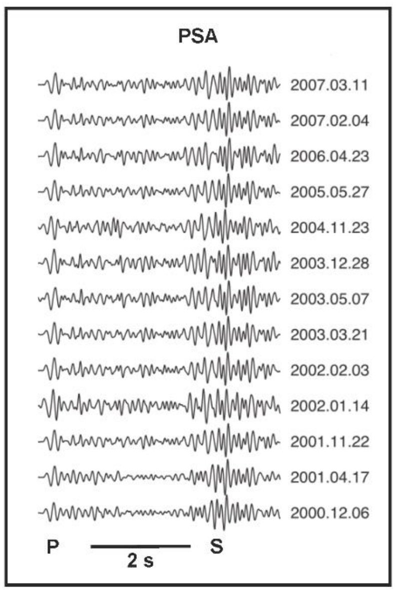
[Duverger *et al.*, in prep GJI]



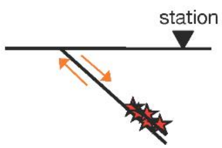
Duverger, 2017

Classification in multiplets

A multiplet is a set of earthquakes
- spatially close
- occurring on parallel fault planes
- with identical focal mechanisms
- generating similar waveforms



[Lambotte *et al.*, 2014]



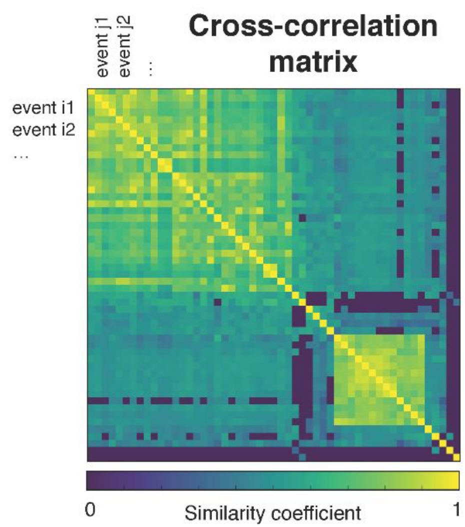
- very accurate relative location
- high resolution image of active structures
- information on fault patch mechanisms

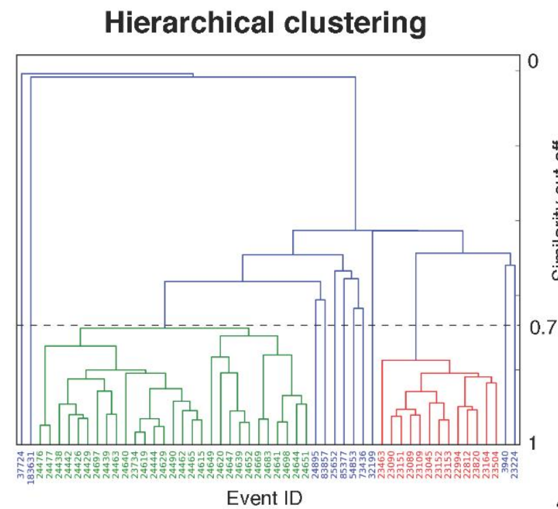
Similarity coefficient

$$Z_{ij} = \frac{\sum_k cc^P_{ijk}\, w^P_{ijk} + cc^S_{ijk}\, w^S_{ijk}}{\sum_k w^P_{ijk} + w^S_{ijk}}$$

i : event
j : event
k : station

cc : cross-correlation coefficient
w : weight associated to signal-to-noise ratio

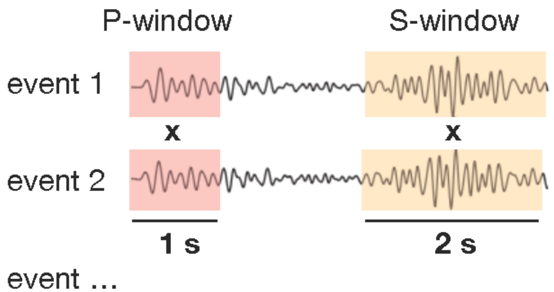




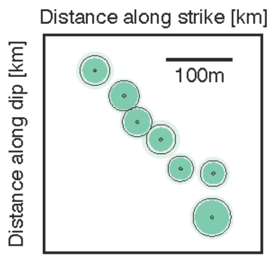
Duverger, 2017

Multiplets and repeaters

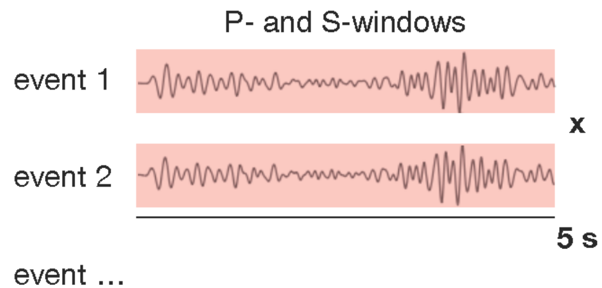
Multiplet



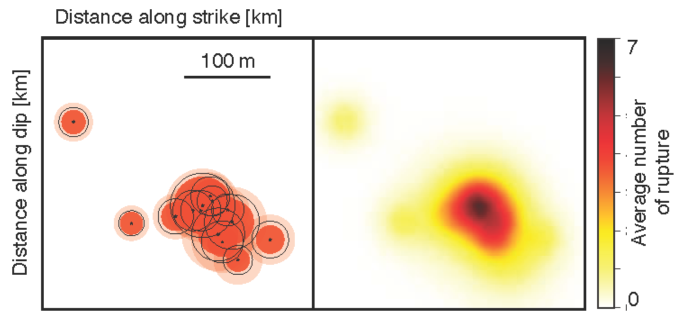
Similarity cut-off
Z > 0.8



Repeater



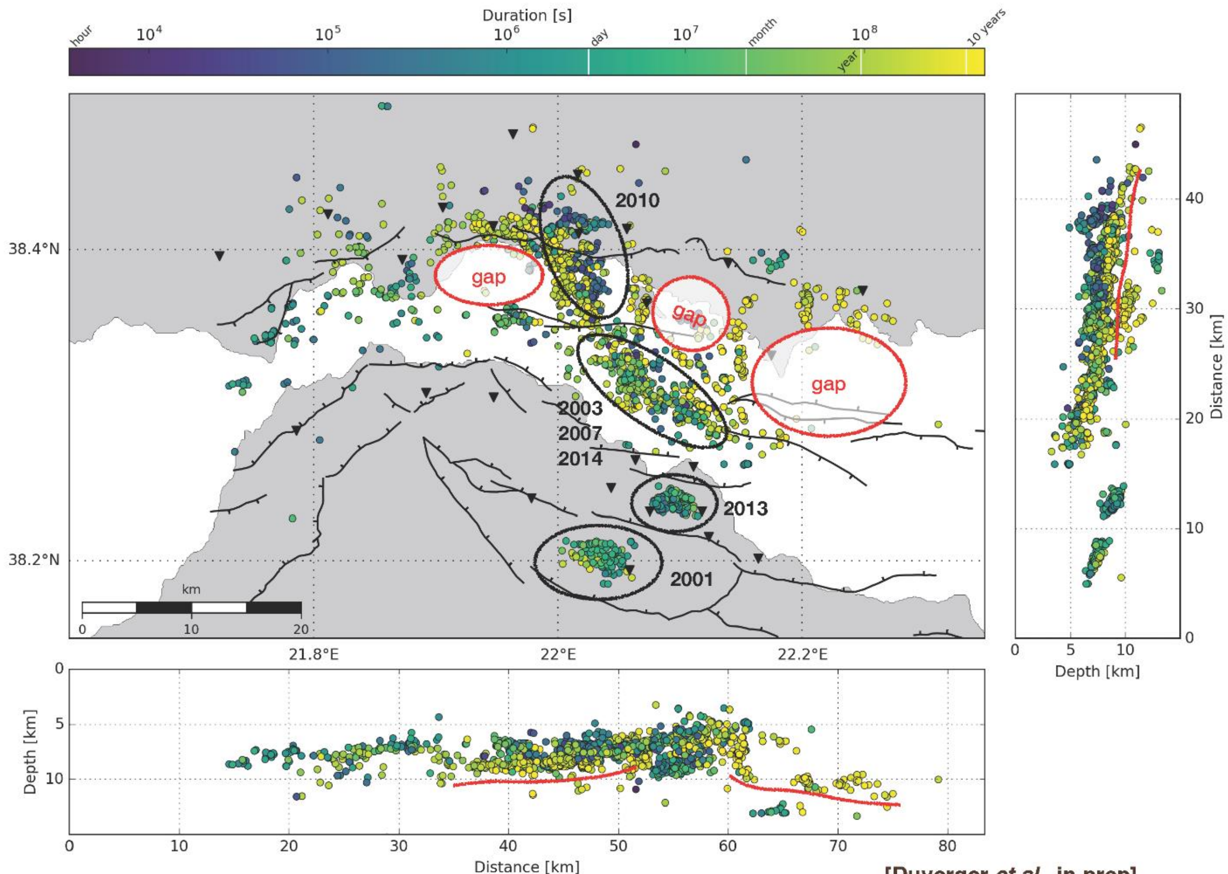
Similarity cut-off
Z > 0.9



- overlapping of the rupture asperities
- superimposed events showing an unique patch
- possible witness of aseismic slip

Duverger, 2017

Multiplets and duration



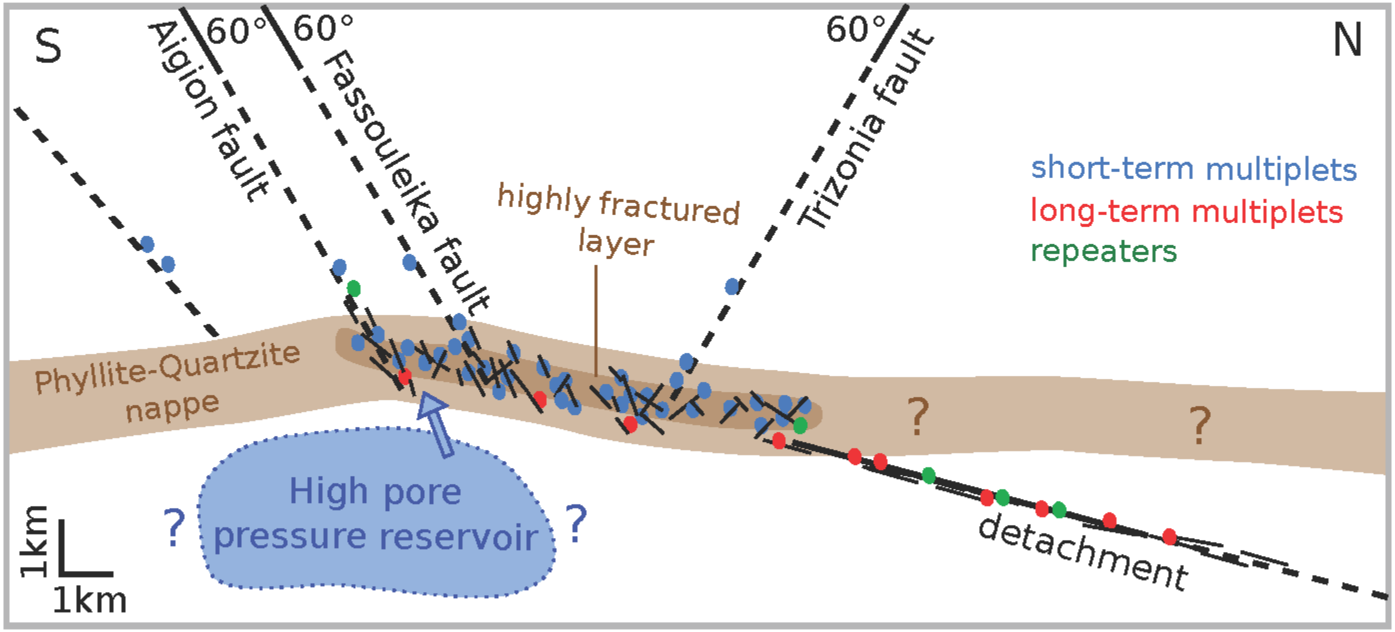
Multiplets with more than 10 events

- long-term multiplets
- short-term multiplets

- Short-term multiplets during swarms and seismic crises
- Long-term multiplets at the borders of low seismicity zones
- Long-term multiplets are generally deeper

[Duverger *et al.*, in prep]

Schematic summary of involved mechanical processes

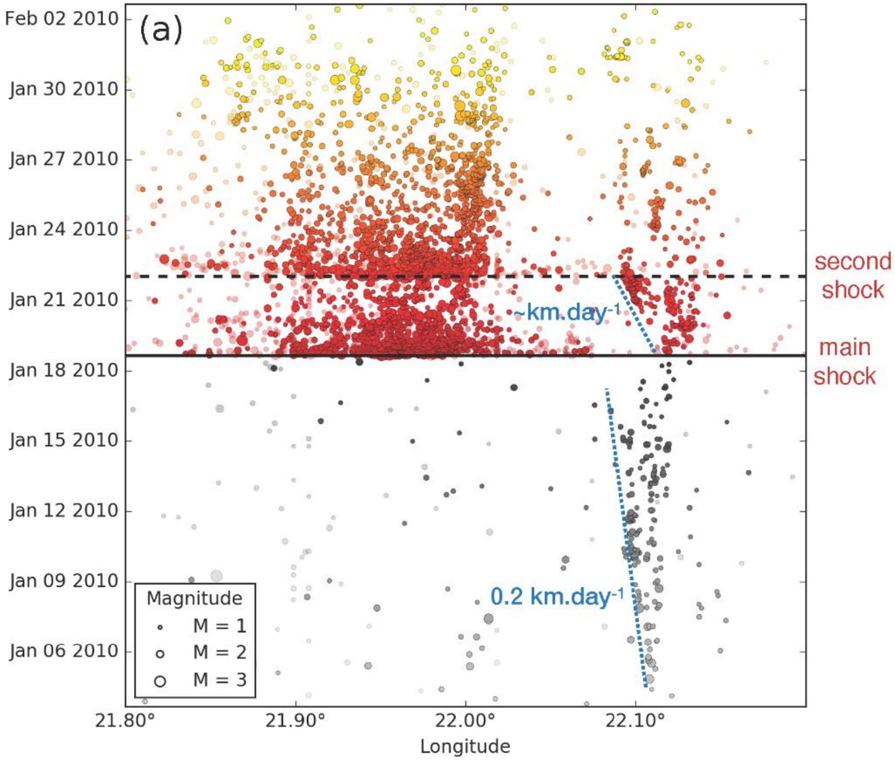


[Duverger *et al.*, in prep GJI]

Dynamic triggering: swarm reactivation and migrations

Efpalio doublet

- - - Mw 5.2, 18 January 2010 - 15:56
— Mw 5.1, 22 January 2010 - 00:46

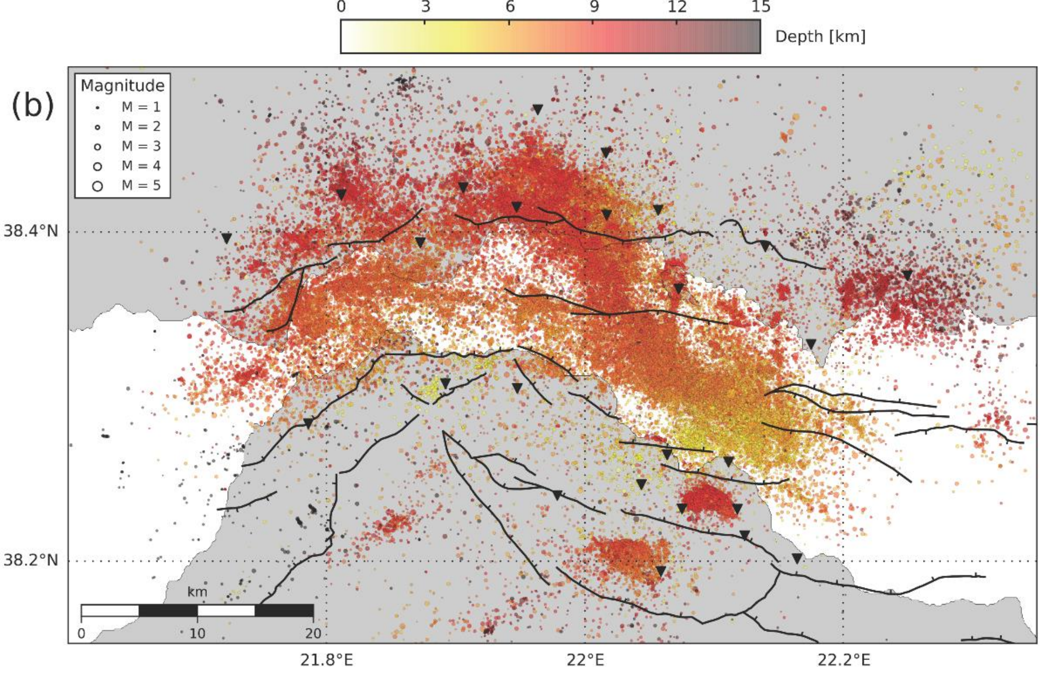


- Slow westward migration during previous swarm at typical pore pressure migration velocity
- Slow-down of the seismic activity just before the main shock
- Reactivation of the swarm with a faster migration velocity
- Back to a *normal* seismic activity

Few teleseismic and regional dynamic triggering cases

➡ Non-generalized stress state of the fault system

Duverger, 2017



- Strong background activity
- Superposed with swarm activity with main event or not.

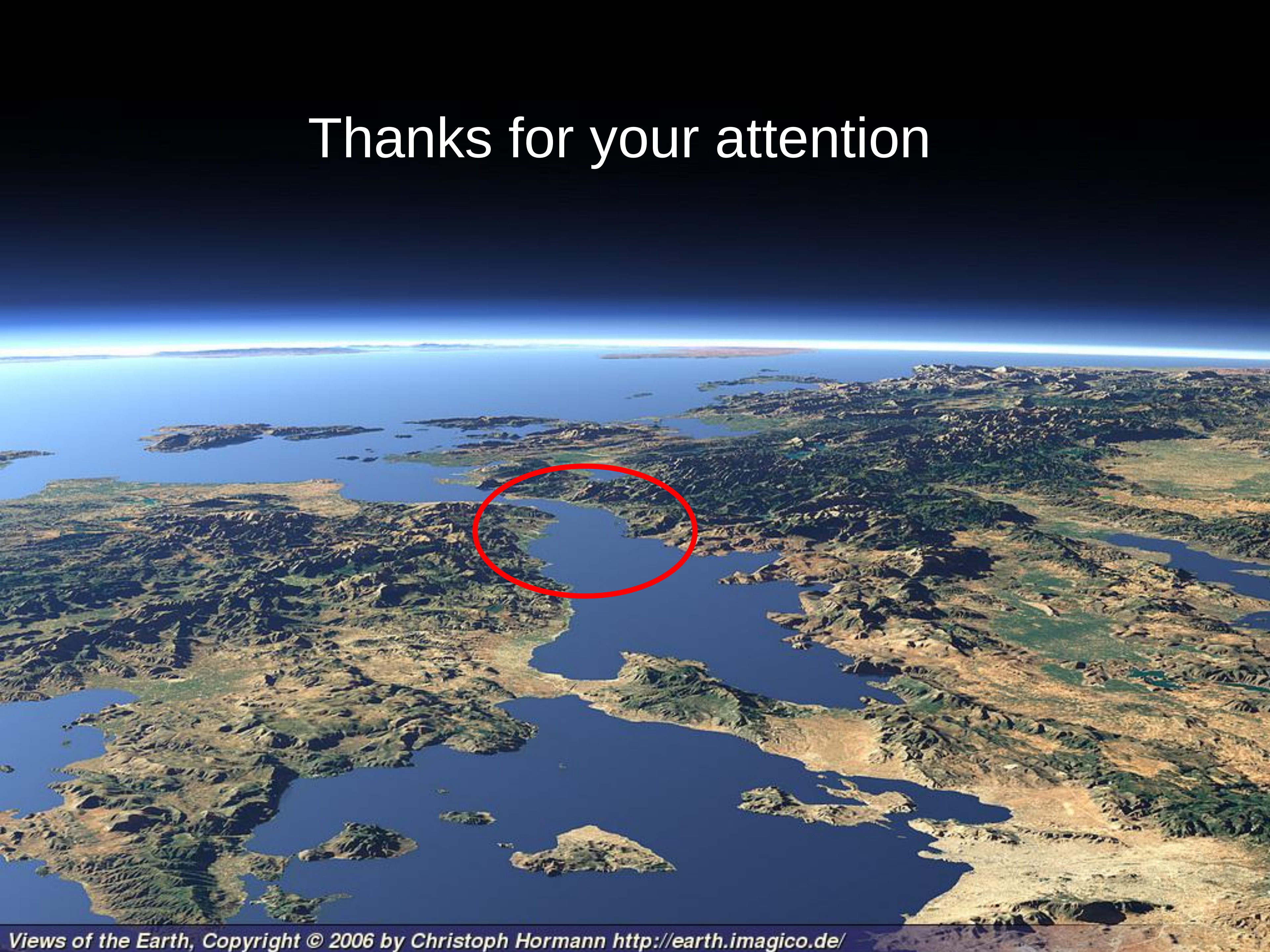
- Cannot explain the total extension: large events are necessary and observed.

A large number of small events which present some organisation in time and space.

Location and time occurrence : a possible picture of
- Geometry at depth of the faults
- State of the medium around the major faults : Aigio, Psatopyrgos …
- Fluides propagation at depth and relation with rupture initiation
- Stresses transfer

Seismic waves : possible study of the medium

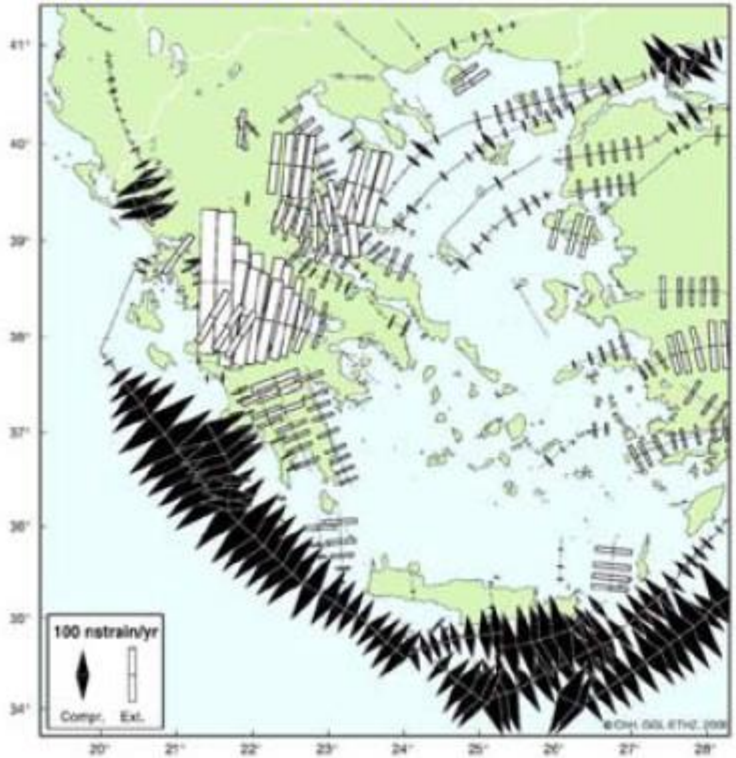
Thanks for your attention



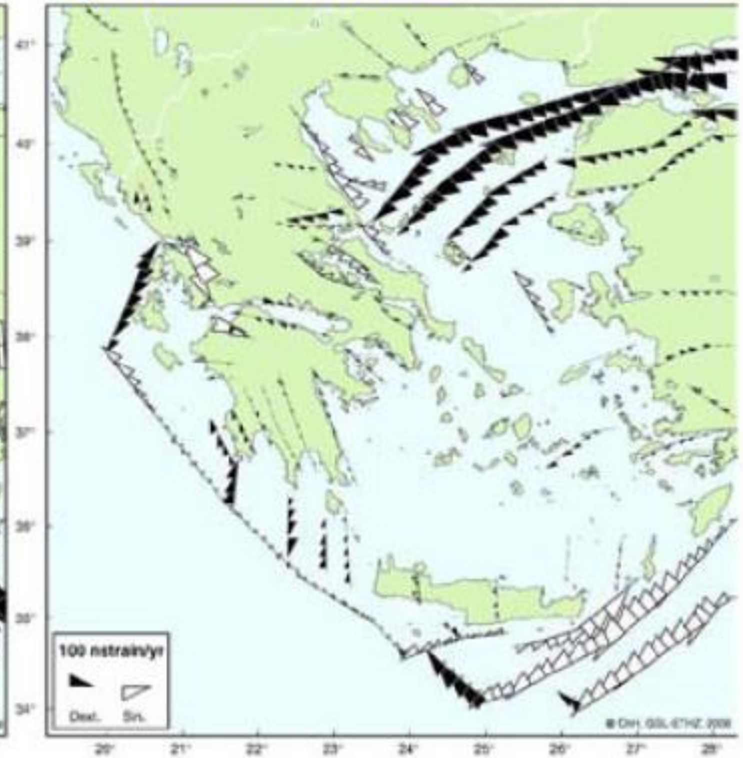
Strain distribution derived from geodetic data

Hollenstein et al 2006, 2008

Normal strain rates

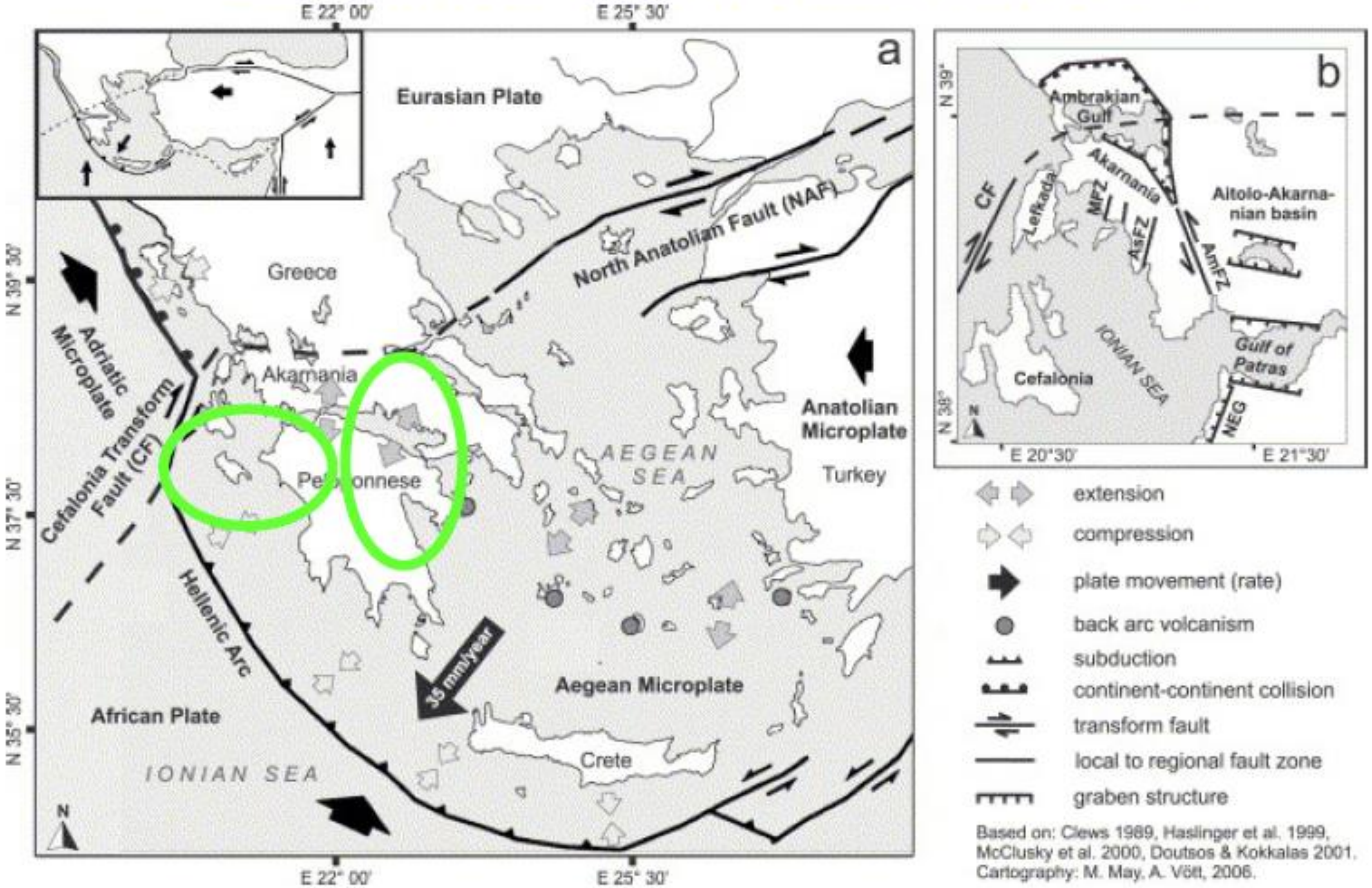


Shear strain rates



- Compressional strain normal to the East Mediterranean trench system (black arrows)
- N-S Extension across the Corinth rift
- Dextral strike slip on the North Anatolian Fault, North Aegean trench and Kefalonia Ft.

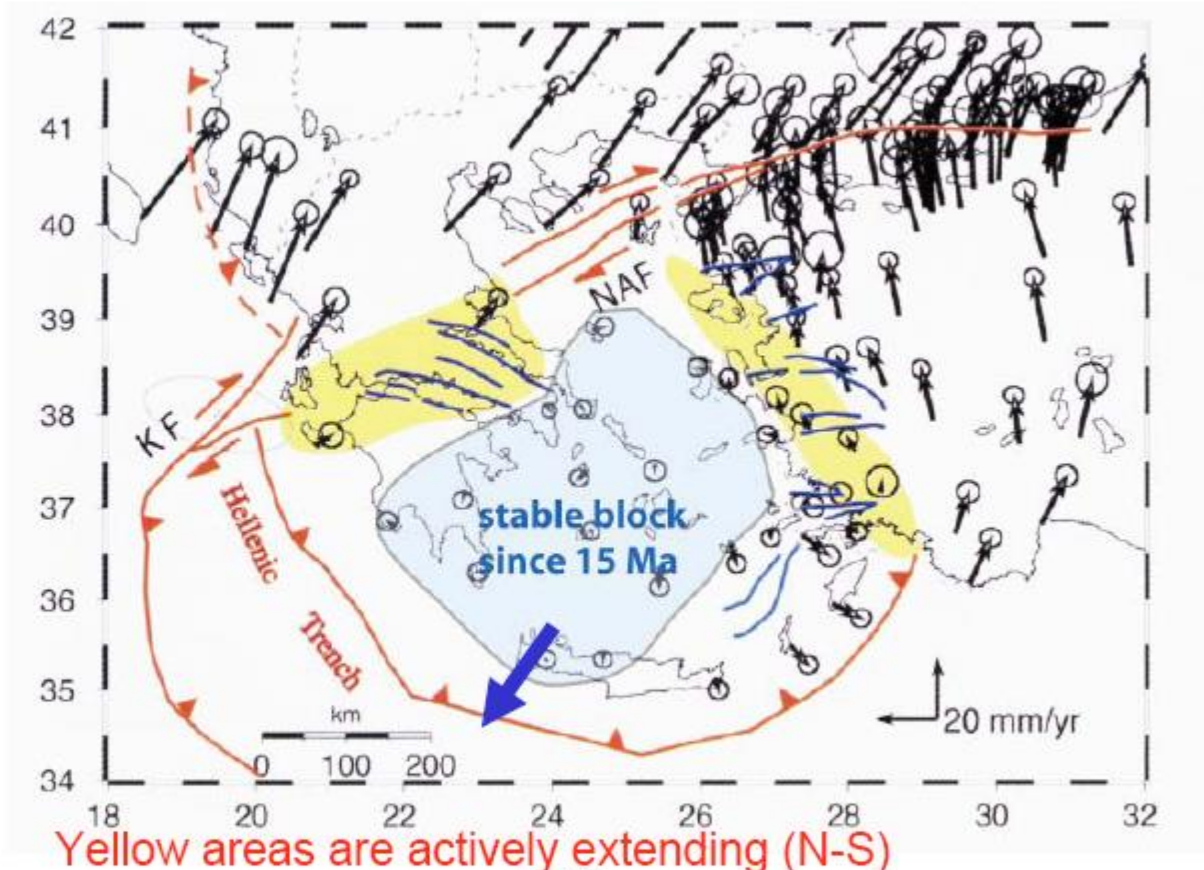
Link between Western Corinth Rift and Kefalonia fault?
Link between eastern Corinth and NAF?



Vott et al., 2006

Le rift de Corinthe est généré il y a 5Ma

Il fait partie des structures en extension qui relient 2 structures décrochantes dextres: faille Nord Anatolienne et faille de Kephalinia



Quelle est la relation en profondeur avec la lithosphère subductante?

Les unités constitutives de la croûte : les nappes hellenides

Late Cretaceous- Eocene: Subduction of Pindos ocean below Pelagonium continent

Eocene- Oligocene: Collision and Hellenide orogeny, Stacking of Hellenide nappes

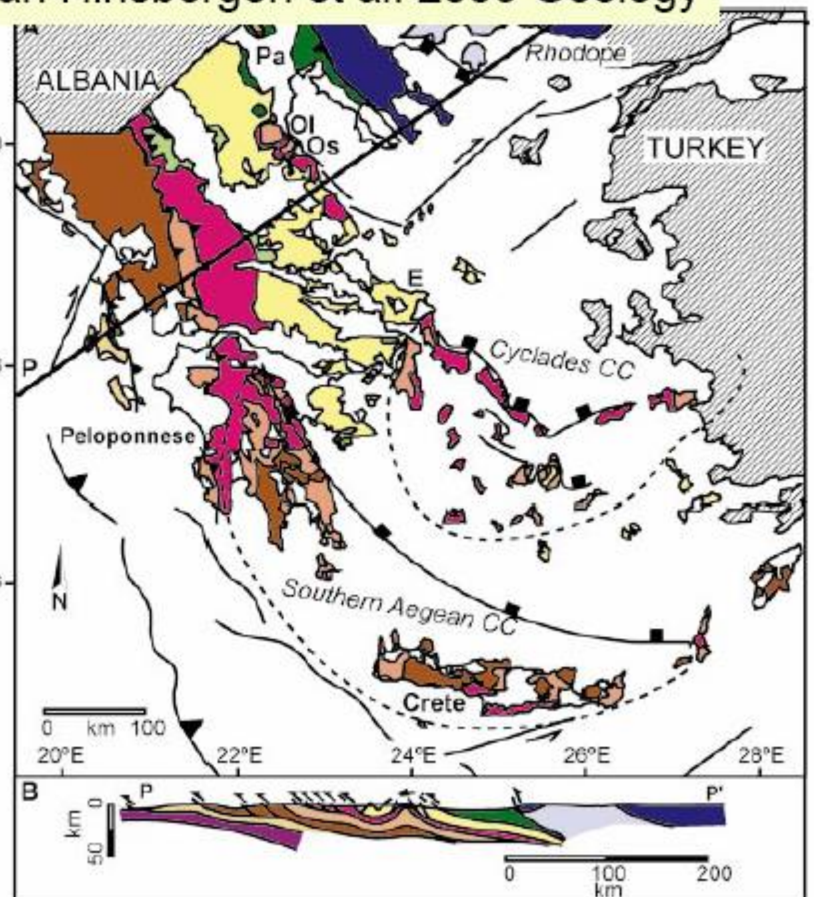
Latest Oligocene-earliest Miocene: extensional exhumation of HP rocks

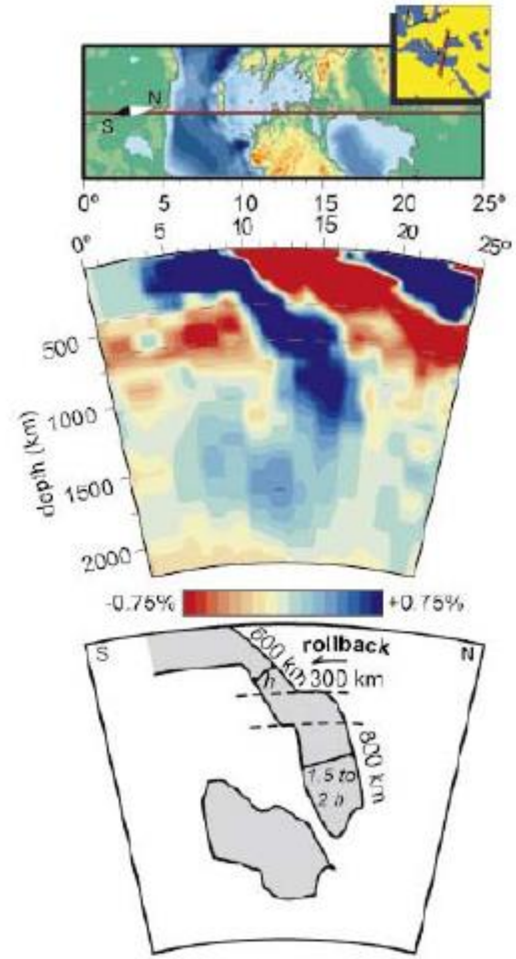
Miocene – extension and exhumation in Peloponnesos
Miocene-Pliocene : 50° CW rotation of Hellenides

Pliocene-recent : Corinth rifting

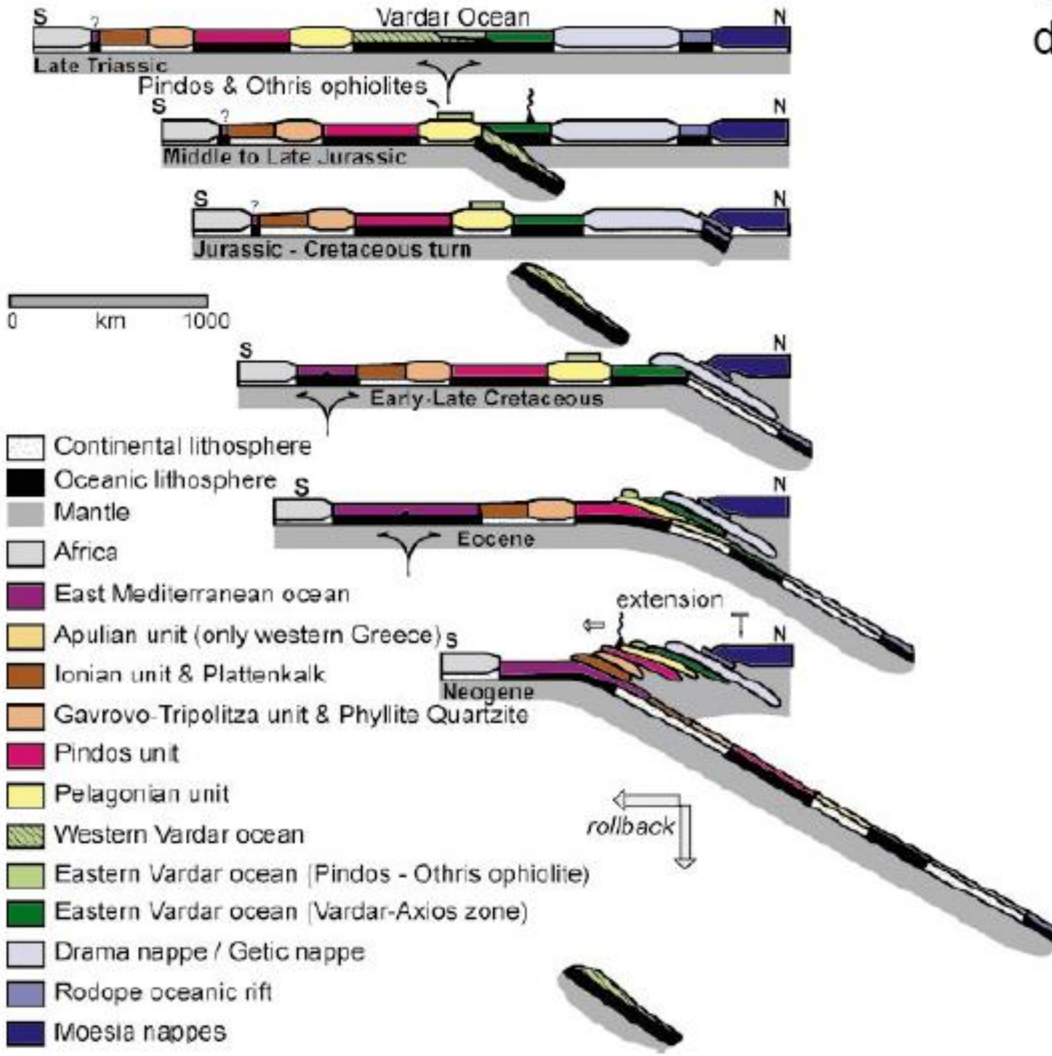
Nappe stacking and shortening in the Hellenides

Van Hinsbergen et al. 2005 Geology





Nappe stacking occurred above a single subduction zone since Early Cretaceous
At least 2400 km of sub-upper crustal lithosphere has been subducted.



Hellenide nappes have been detached from Middle crust.

2400 km of continuous subduction since Early Cretaceous

Eocene: Pindos underthrusting (Cycladic blueschists)
Original Pindos width 300 km

Oligocene : G-T and Ionian underthrusting

Miocene : Pre-Apulian