Master Class Senior ISTerre

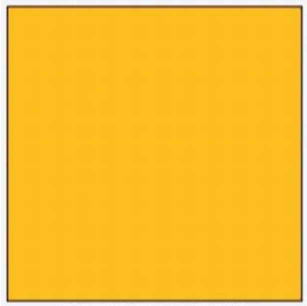
Interaction onde-structure: les enjeux de l'imagerie crustale

Une vision partielle de Jean Virieux

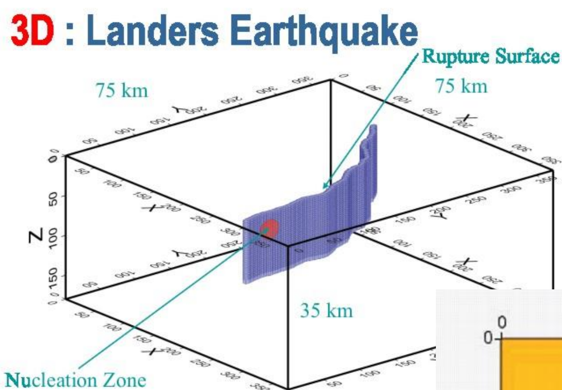
Direct contributions from
Romain Brossier (ISTERRE)
Ludovic Métivier (LJK/ISTERRE)
Stéphane Operto (GEOAZUR)
Alessandra Ribodetti (GEOAZUR)
Many other contributions from SEISCOPE's team (over 15 years)

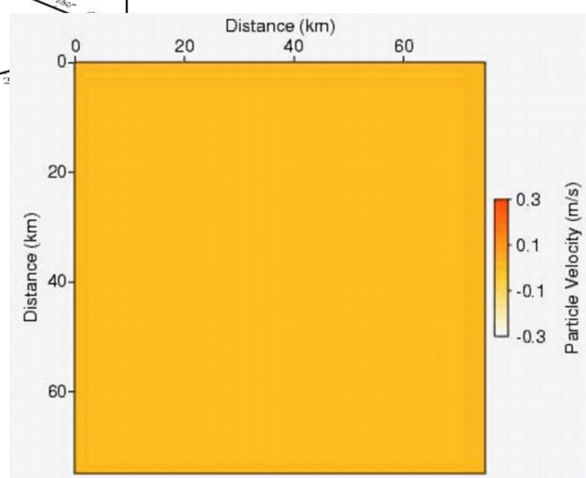
Seiscope consortium

Waves: attractive & vanishing object


Cruz-Atienza et al., 2003

Complex wave propagation





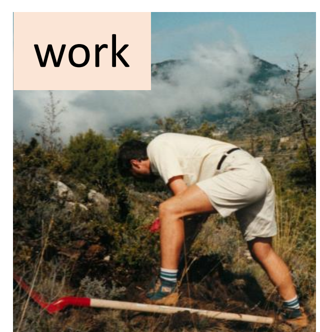
1992, 3-D Landers Earthquake Simulation

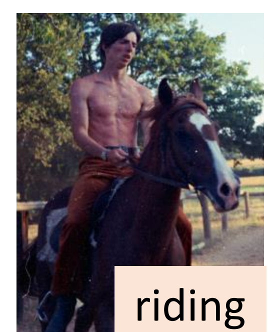
My personal scientific interest:

- Waves (optical, acoustic, elastic):
  - unique communication when away
  - unique probing of hidden objects
  - very few other left alternatives…
- Why Earth Sciences:

& challenging physics: elastic propagation with two speeds

& outdoor activities: key argument for me



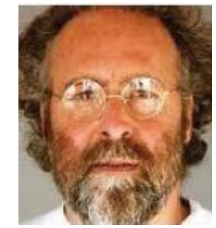


Scientific topics…

PhD topic: earthquake dynamic rupture …
theoretical investigation using numerical tools
(specifically FD wave propagation modeling)

No data!

aside output: theoretical FWI
with the consortium « GTG »



Post-PhD: travel-time tomography with many people (still on)

Data! Volcanic area (Mt Vesuvius/ Campi Flegrei
nearby Naples) & Rift zone (Gulf of Corinth)

Post-PhD: RAY+BORN imaging with many people (consortium « GRS »)

Data from Oil&Gas enterprises (Elf-Aquitaine – Oseberg field)

Long time after: real applications of FWI (consortium SEISCOPE, still on)

New generation …

Few Students at GeoAzur …

Alessandra (1994 – 1998)

Hafedh (2006-2009)

Romain (2006-2009)

Victor (2003-2006)

Vincent P. (2008-2012)

Vincent E. (2007-2011)

Guanghui (2008-2012)

Bernhard (2000-2003)

Celine (2004-2007)

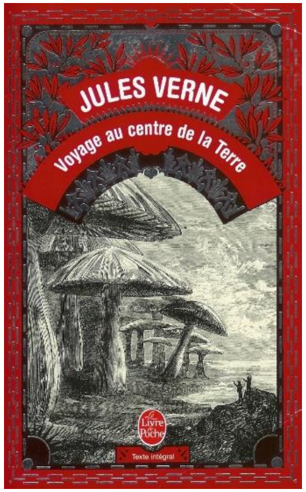
Raffaella (1996-2003)

Francoise (1991-1994)

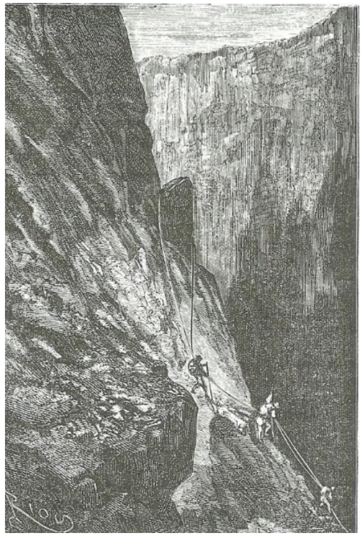
Pascal (après sa reconversion…)

And many others …

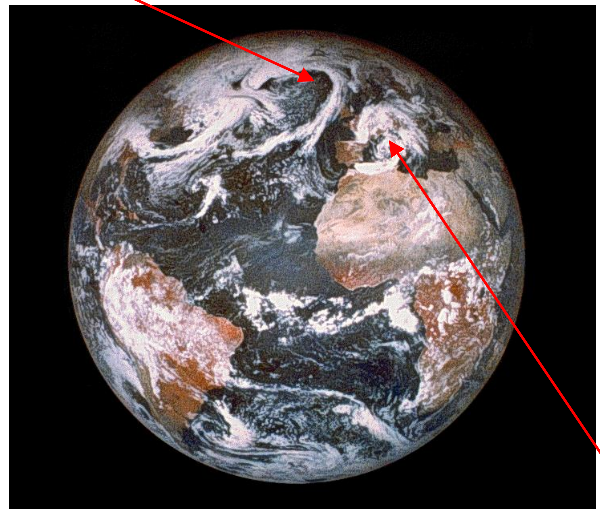
The Earth system: its mysterious interior?

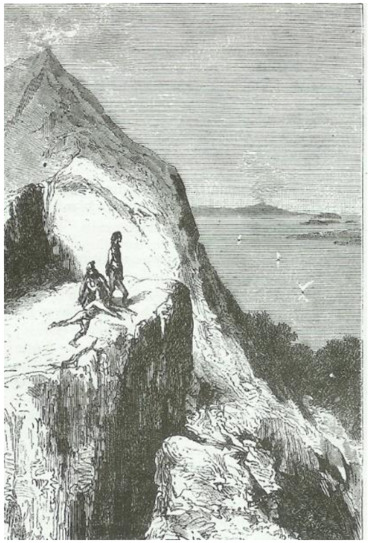


From Snaeffels



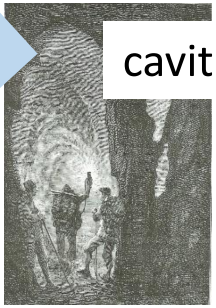
Journey inside the Earth



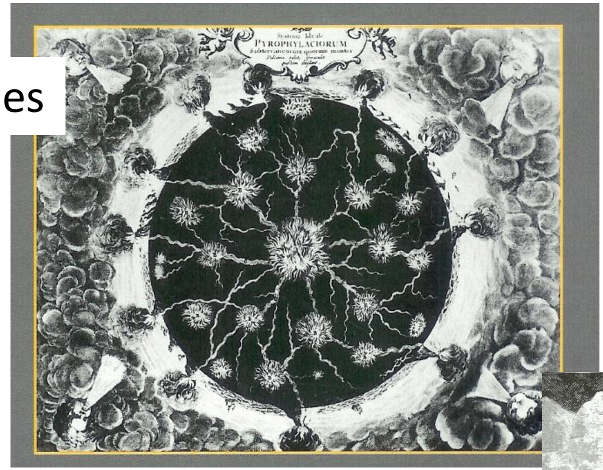


To Stromboli

WHAT DID THEY FIND?



cavities



(Kircher, 1665)

minerals

Over-pressurized water

lakes

The Earth interior?

Great discovery at the end of te XIX century
Modern seismology was born!

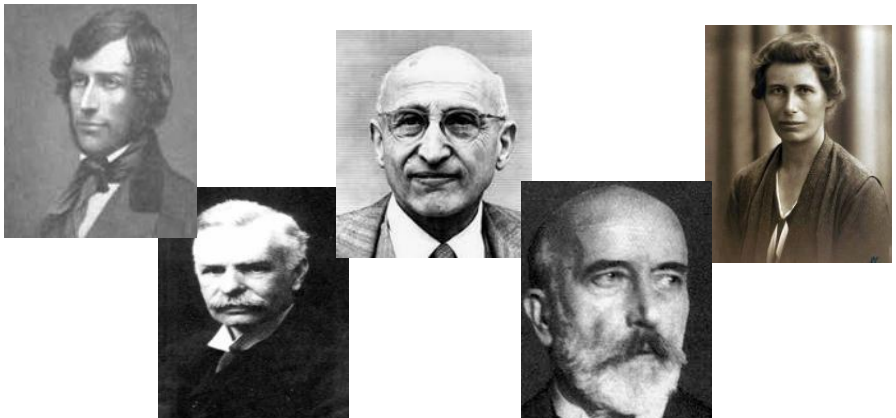
In 1889, a ground vibration in Europe was linked to a Japanese earthquake: waves can travel inside the entire Earth.

Oscillation of a pendulum at Potsdam (Germany)

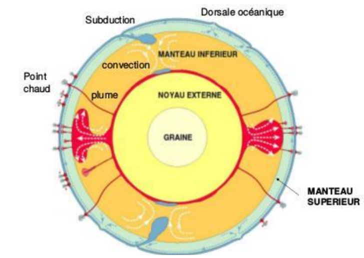
Telegraph revolution!
Correlation between two far-away objects!

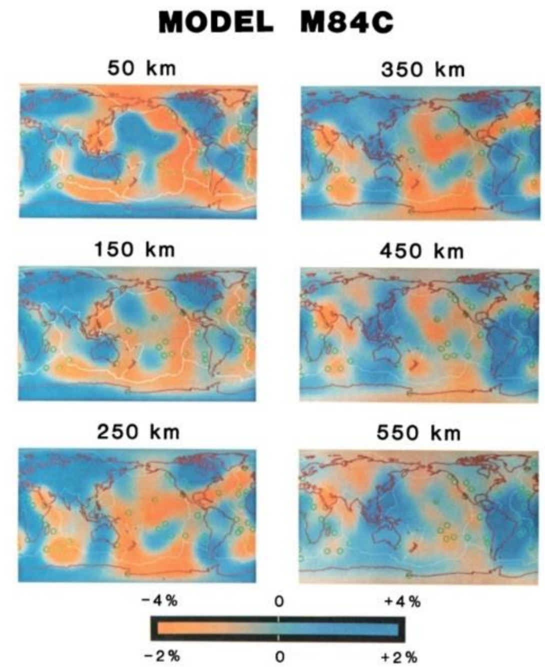
Seismology (including seismics)

Before 80's, seismic imaging was based on travel time measurements (direct and reflection signals): radial model such as the PREM model (Dziewonski, 1981)



Richard Dixon Oldham

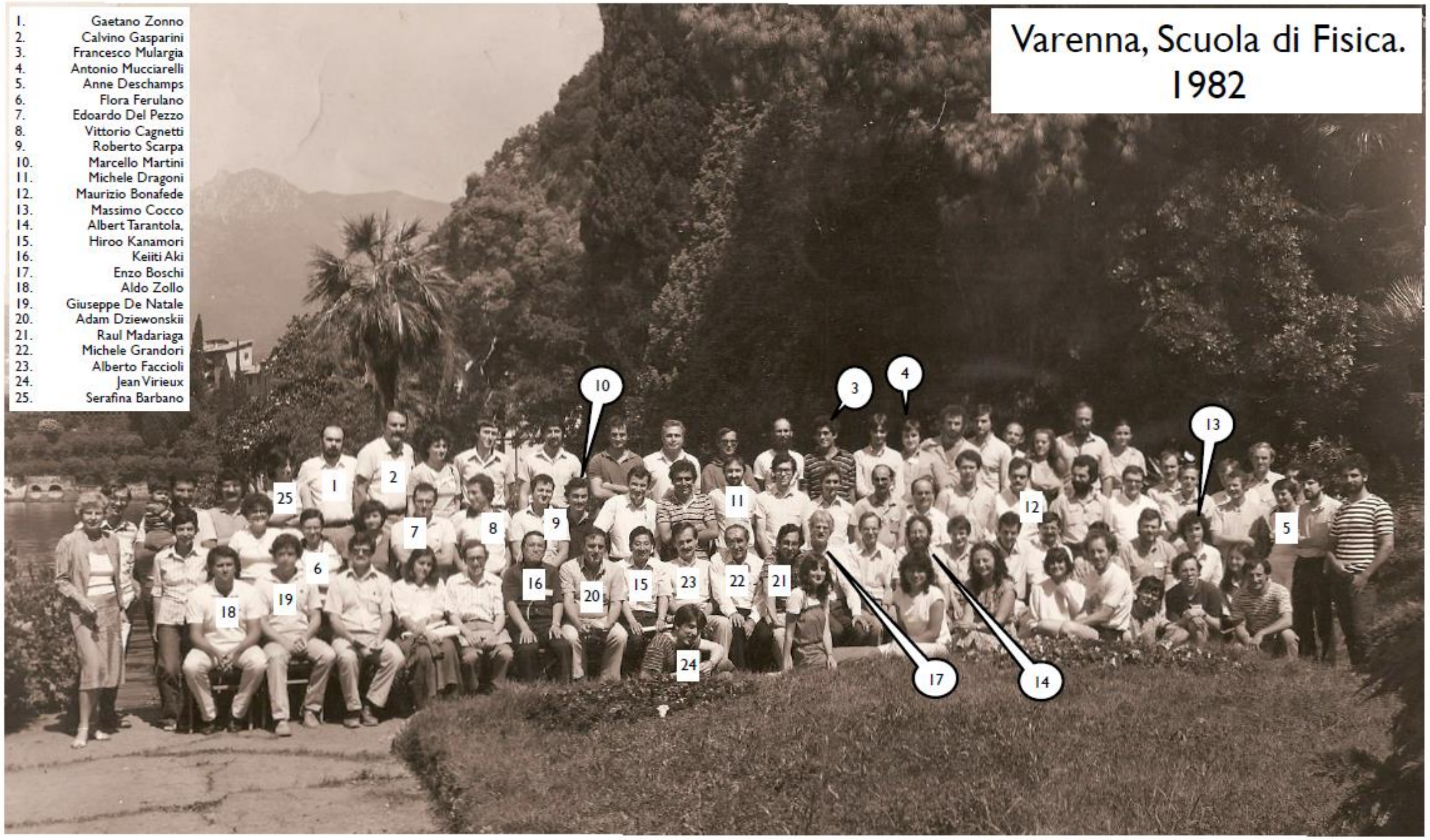




First paper using amplitude: M84C models of the Earth interior (Woodhouse & Dziewonski, 1984) competing with models based on phase/time data (Dziewonski, 1983, 1984; Dziewonski & Anderson, 1984).

Phase information plays a crucial role

Brain storming from workshops



Message of John Woodhouse

Focus your attention on **seismograms** (amplitude analysis)!

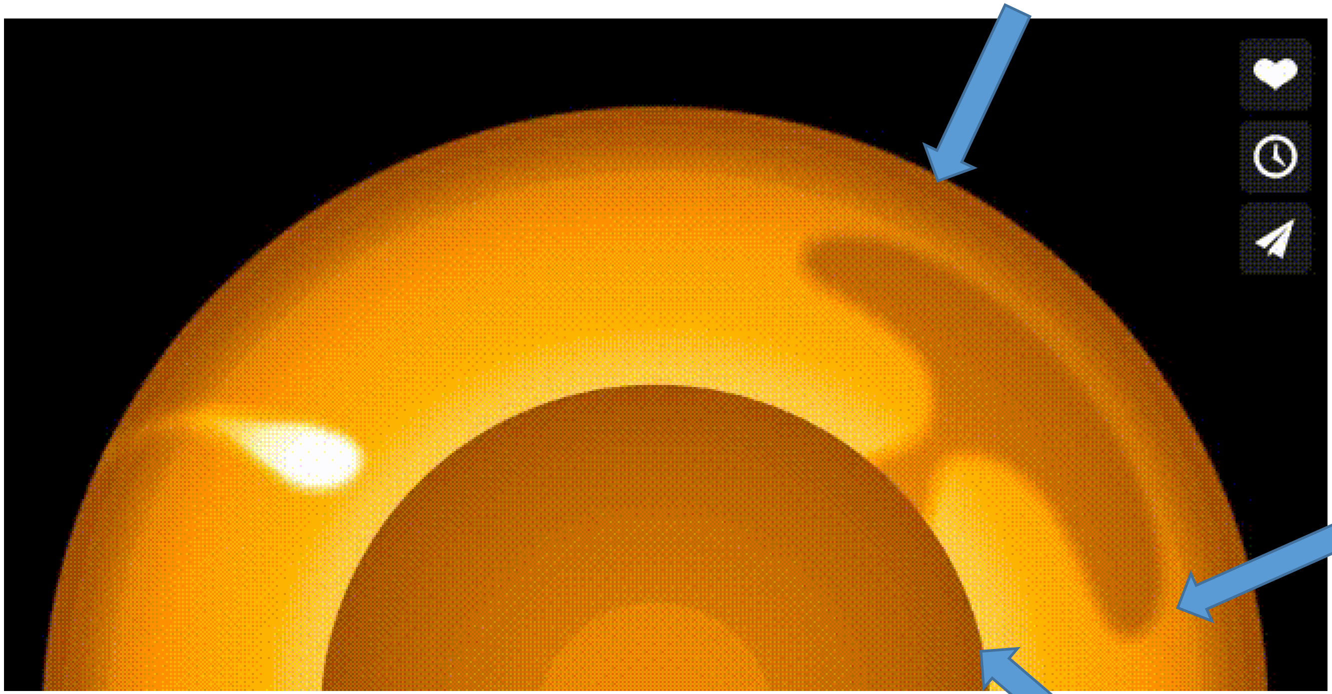
They carry a lot of information (normal modes summation)

Global Earth: big object but same physics

SEISCOPE

Focusing targets !!!

Crust: complex nearby object



Mantle: still a rather simple object!

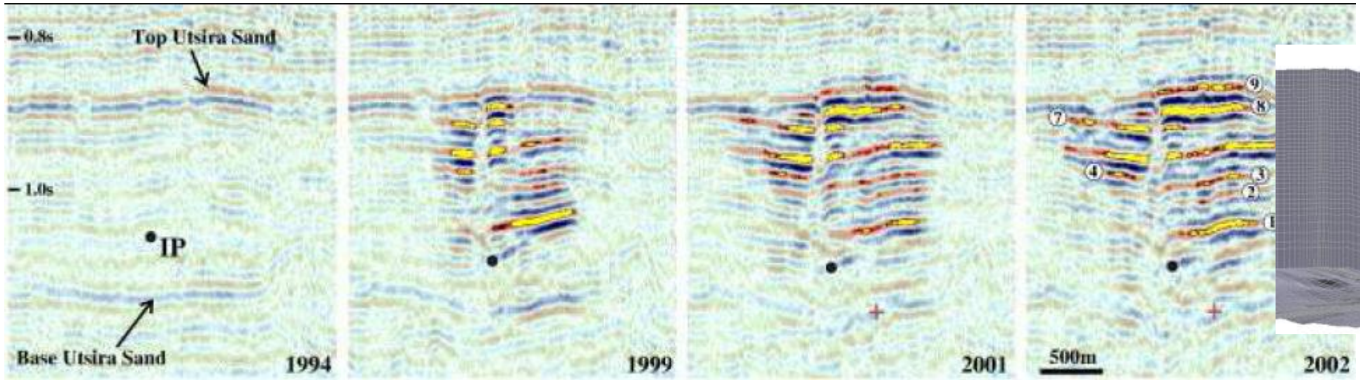
Movie from Stahler & Tarje

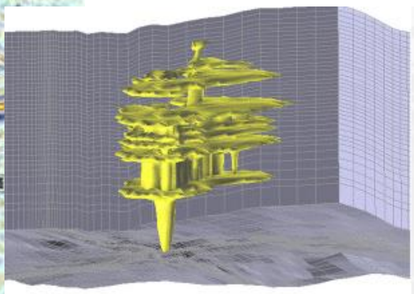
CMB: a far-away object
should be much more complex than available images …

The Earth crust: hugh storage capacity?

On the need to image, characterize and monitor the subsurface

CO2 storage: monitoring the Sleipner reservoir … Reservoir model





Geological structures for giant storage:

Ultimate storage: CO2 sequestration, chemical deposit, nuclear deposit and so

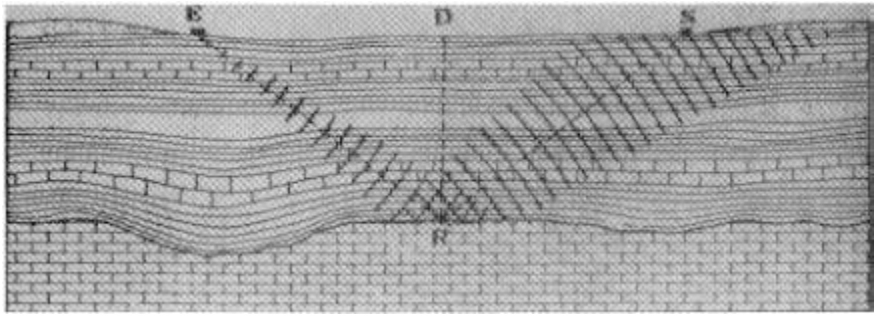
Temporary storage: heat (geothermal targets), H2, CH4, HP gas over year cycling

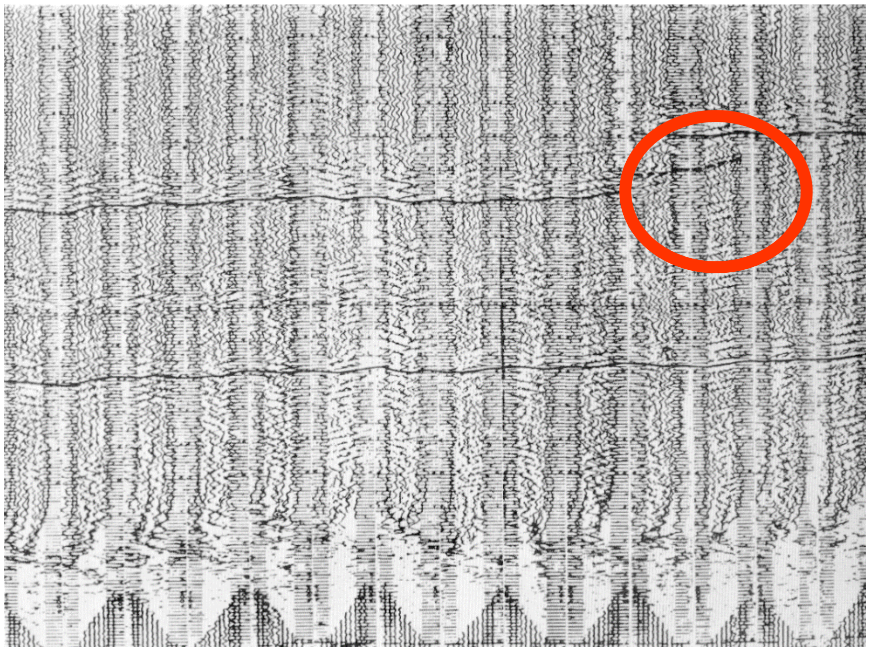
Seismic imaging: not only a crucial need for Oil & Gas primary resources, but of critical importance for energy demand.

Young generation should be trained on that topic!

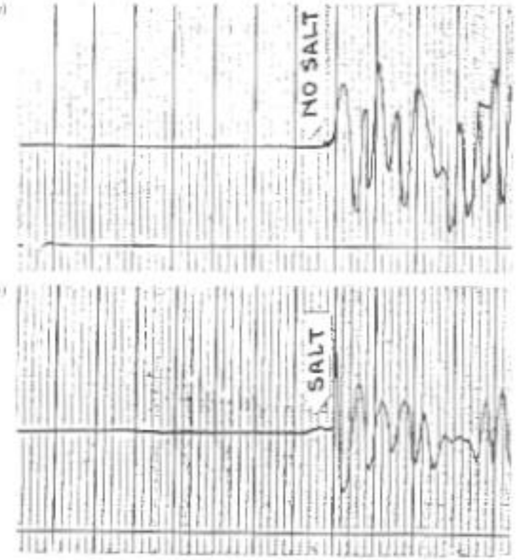
Seismic data: heroic times before 1940

Interpretation cartoon (1921)

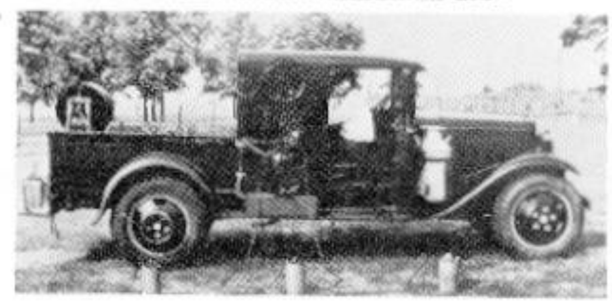




Fault detection on paper plots



Head wave:
Polarity as a
salt proxy



Three sensors and an acquisition truck!

Hard life for field seismologists

but in lovely places

Seismic wave recording … Academic world

Smooking the drum!

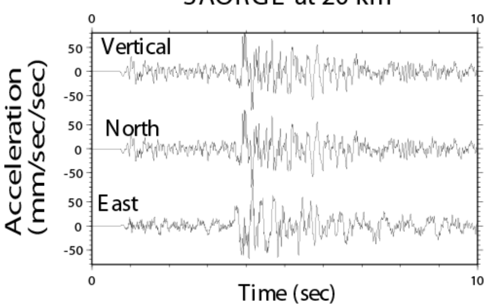
My student time

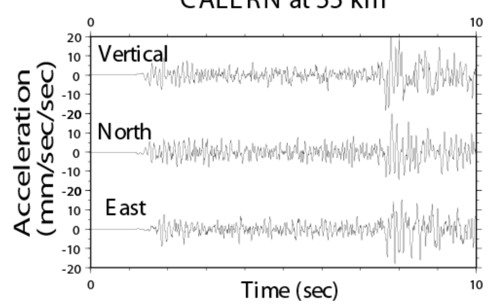
TGRS: STEF station in my family village

My research time

Radio clock (<1995)
to
GPS clock (> 1995)

True amplitude



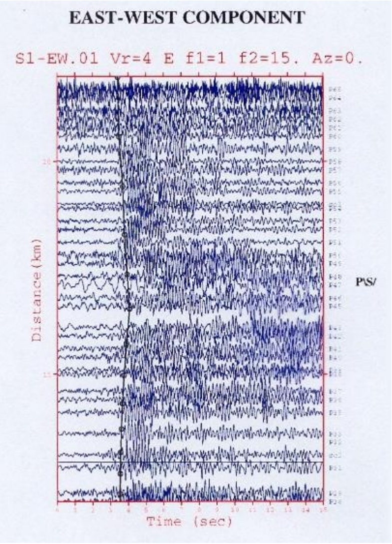


INSU/CNRS *MESR/UNSA*

Hunting for amplitude variation?
Seismic array on Vesuvius summit!

Learning field challenges
Job done but clock synchro. KO!

LALA phase!

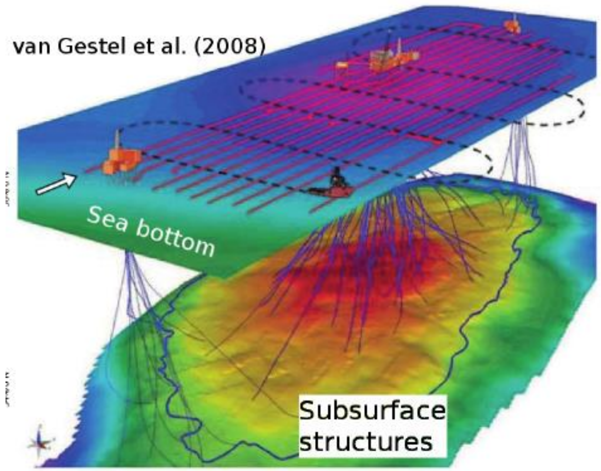


A lot of fun, but take-away lesson: professional experts needed
->
Look at industrial datasets for crust imaging

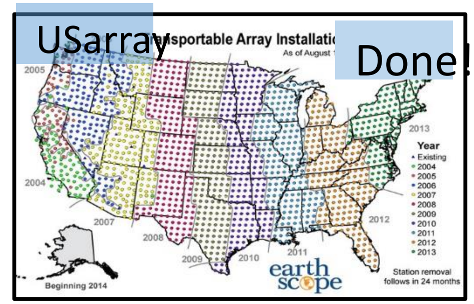
Seismic data: modern time

High-quality data with unprecedent density of stations at various scales

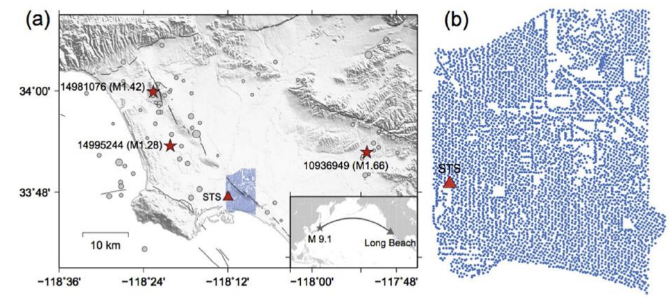
Valhall experiment:
50000 shots; 2300 receivers



New data?
New interpretation?
New methods?

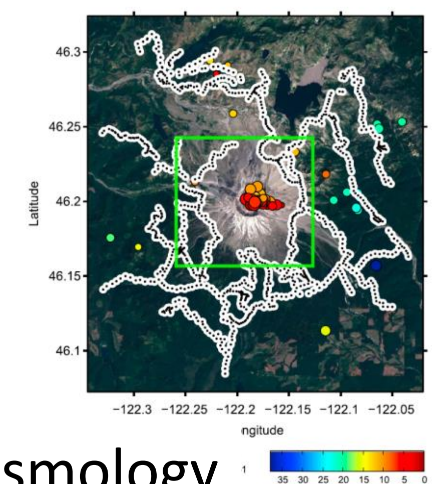


Alparray
Chinesarray

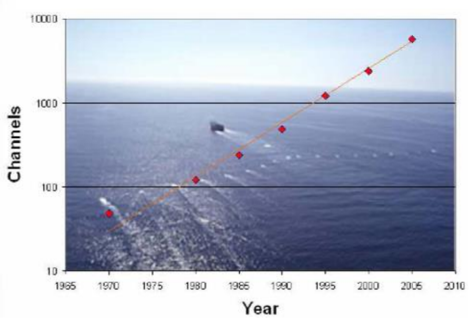


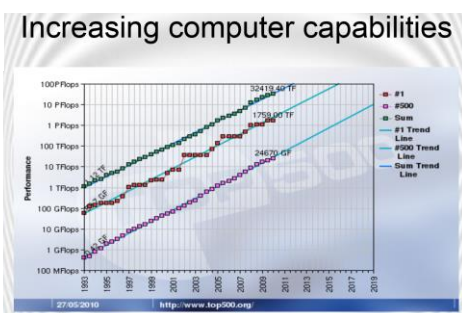
Beach nodal array (Slater & Hollis, 2012;Li et al, 2018)

Mt St Helens (Hansen & Schmandt, 2015)



Moore 's Law:
marine seismic channels





Seismics

Seismology

Nowadays

- Dense seismic data

Sophia Antipolis

- High computer capabilities

How lucky are you?

Better knowledge, better management of underground structures and resources (toward technical sustainability …)

Before (my time) few data and limited computer resources (especially in France):
supercomputer ‘80s ~ Smartphone ‘10s

Expected resolution from seismic data

Real medium

Translucent Earth

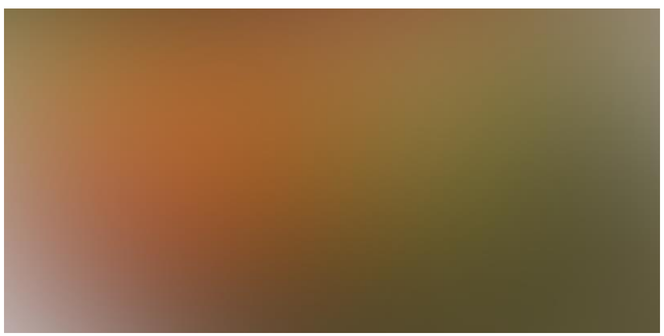
Unaccessible target?
Intrinsic remote sensing limitation
Seismic finite frequency & attenuation

Additional information?

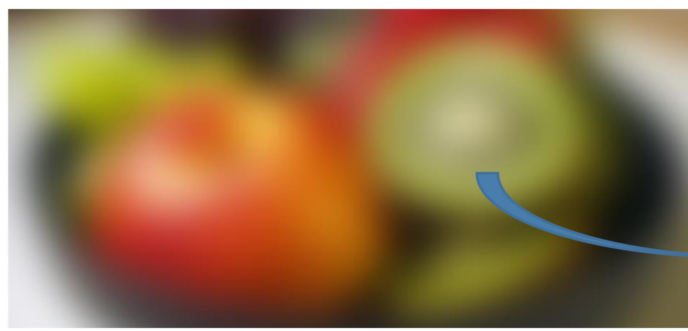
Seismic imaging

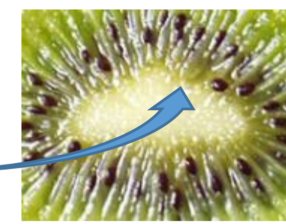
Interpretation?

Travel time information?



Waveform information?





Beyond seismic resolution: dictionary learning

How far should/could we go with seismic waves?

Inspired from Romanowicz's lecture

Seismic data: modern time

Industrial & Academic communities interact more nowadays !!!

Pending question:

Are we extracting all the information
contained in these massive high-cost datasets?

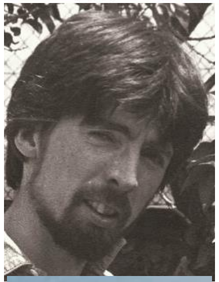
Efficiently, precisely and timely!

Upper crust: the 80's dream!

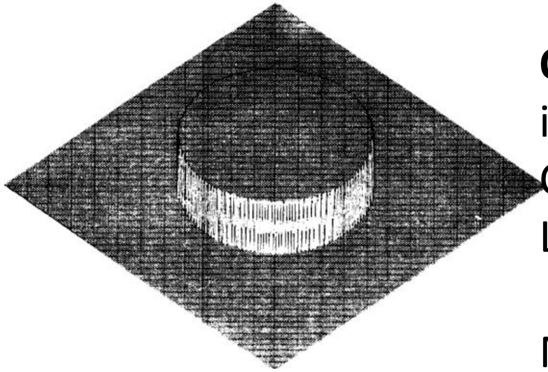
Open body (# closed body such as the global Earth: exit normal modes)

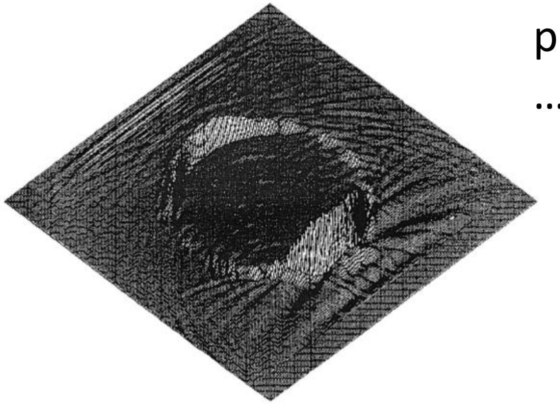
No more guitar!

Odile Gautier



Synthetic model





Reconstructed model using gradient with 5 iterations

From French Mathematical Community

Optimal control of parameters investigated by Lions (1968), Chavent (1974), Bamberger et al (1977), Lailly (1984), and finally Tarantola (1984)

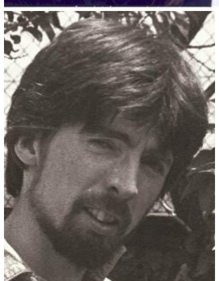
More than ten years for a slow percolation from mathematics to geology …

CRAY-1 resources:

Only acoustic case; not enough memory; a lot of I/O (my own virtual memory tool …); few iterations using gradient method …

Upper crust!

Open body (# close body such as the global Earth: exit normal modes)



No mo

Synthetic model

Reconstructed model using gradient with 5 iterations

Solution f ... al

Com

...arameters

...68), Chavent (1974),

...ger et al (1977), Lailly (1984),

...d finally Tarantola (1984)

FULL WAVEFORM INVERSION!

A dream at that time (1985)

Ten years for a slow percolation from mathematics to geology …

CRAY-1 resources:

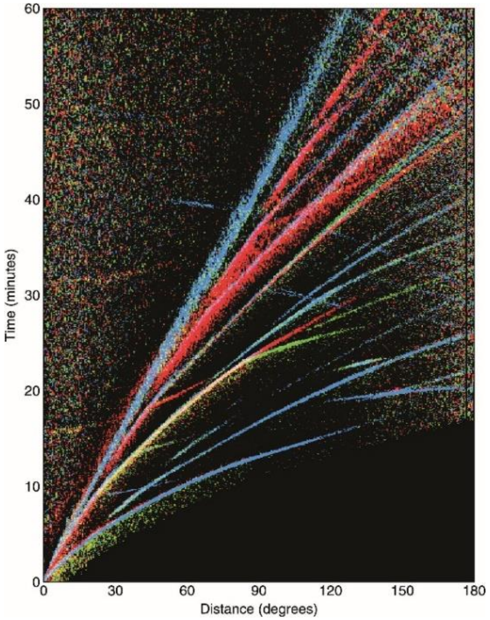
Only acoustic case; not enough memory; a lot of I/O …; few iterations using gradient method …

Back to basics!

Travel-time tomography: phase information of wave propagation

Robust observable based on clock precision (GPS) and not on instrument calibration

Half-century recording
Earth phase events



For mantle tomography

detection/association phase events OK

For crust tomography

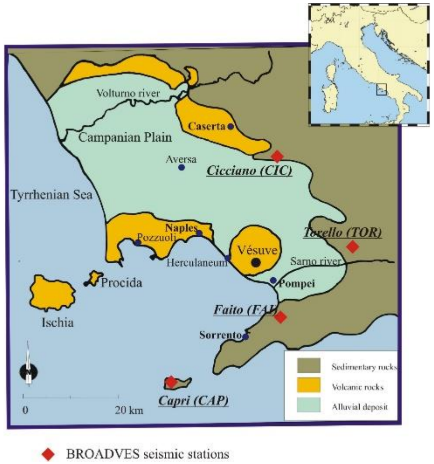
overlapping phase events ???

passive tomography (local earthquake tomography)
active tomography (upper crust tomography)

Warning

You may hear that I am using in a rather equivalent way the word « phase » and the word « traveltime ».

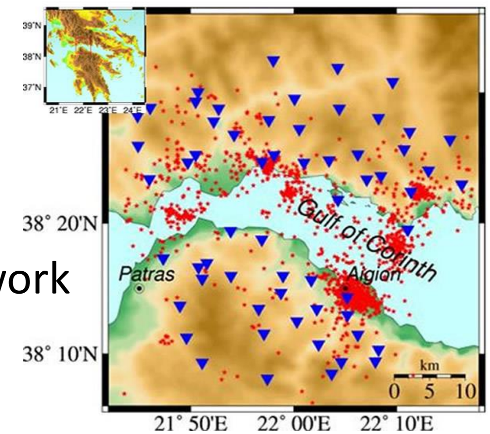
They describe different ways of propagation for dispersive waves. For balistic waves, which are almost non-dispersive, they are equivalent.



- Naples volcanic structures: Mt Vesuvius & Campi Flegrei: local earthquake tomography (LET) and active seismics.

  More than 20 years of investigation!

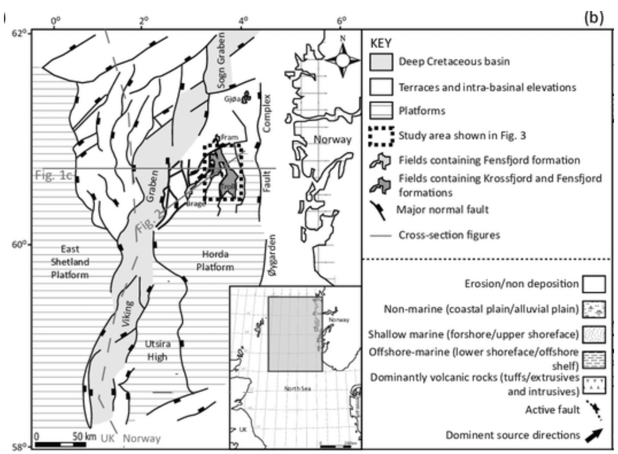
  Hunting amplitude variation (Oh LALA !!!)



- Corinth Rift:

  LET 1991 (H. L-C), 2001 (3F-Corinth F.C. & I.M.) -> CRL (P. B.)

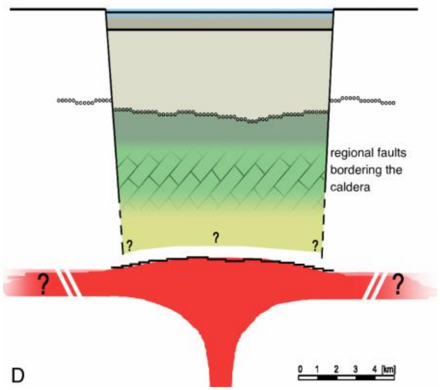
  Two seismic temporary experiments before permanent network



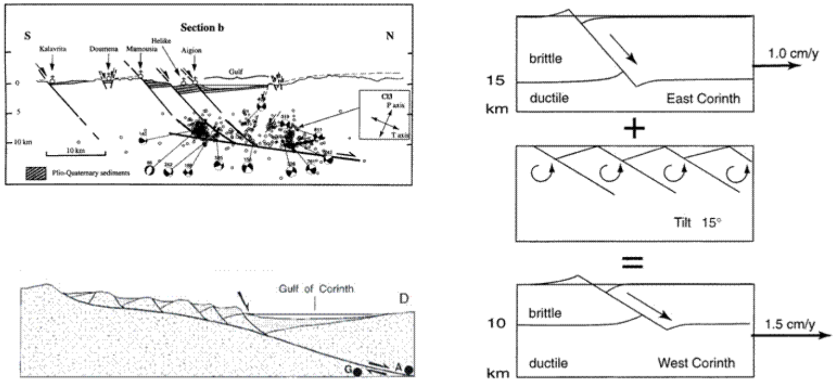
- Viking Graben (Oseberg field of Norway) : active seismics (Ray-Born Imaging) 1992 (R. Madariaga consortium GBS supported by Elf-Aquitaine and CNRS)

Simple questions and difficult answers!

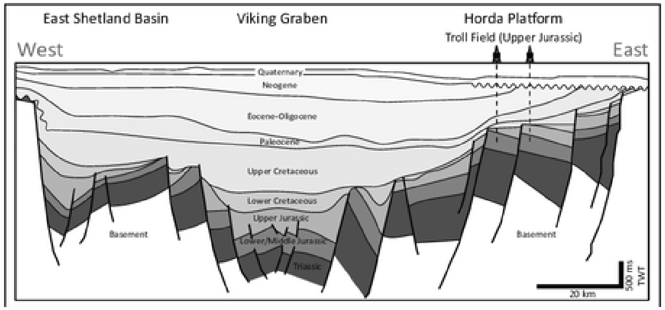
- Mt Vesuvius & Campi Flegrei: are these volcanic systems connected at depth?



- Corinth Rift: extension interpretation?



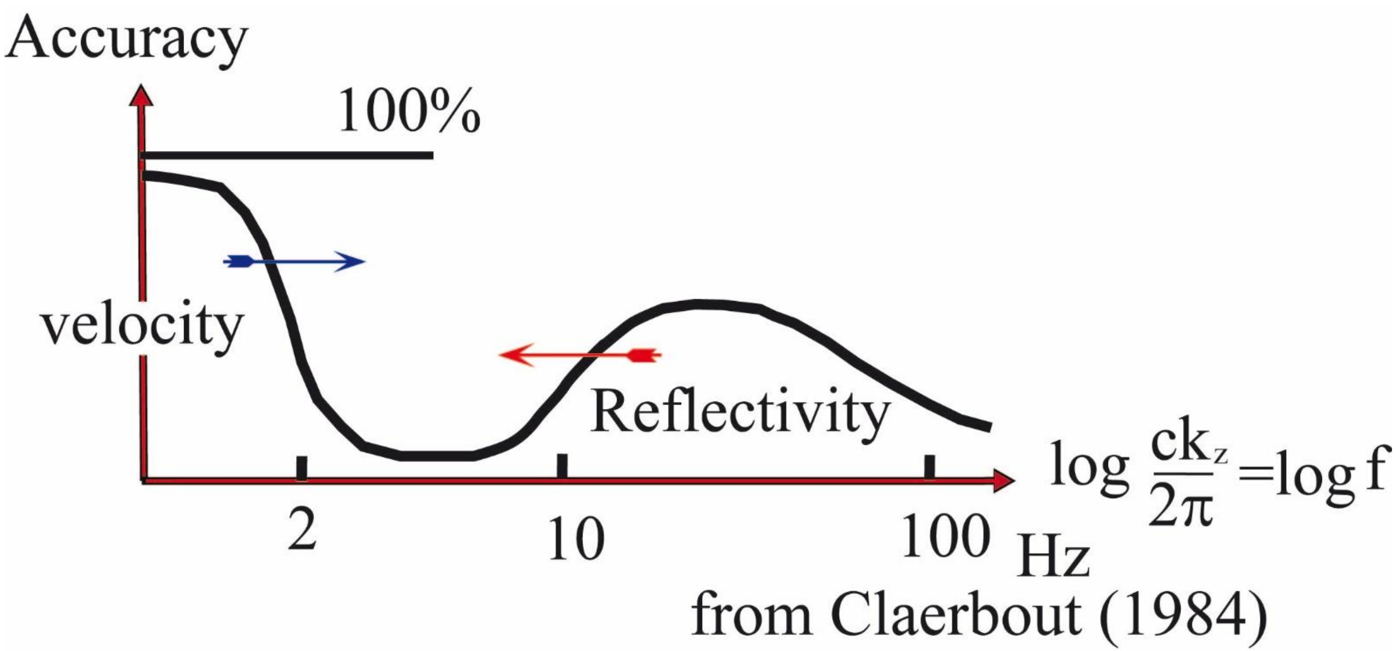
- Viking graben: fluid migration?



Seismic data and interpretation aside other geological, geochemical and geophysical data … (no black/white answer)

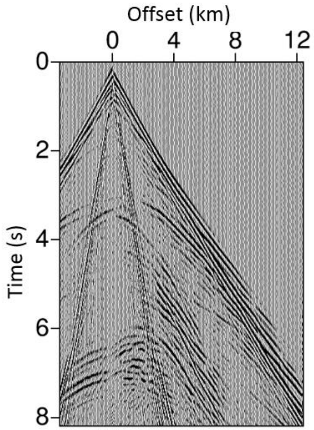
Two scales show up in the model reconstruction

Recorded seismic traces bring different information from medium properties

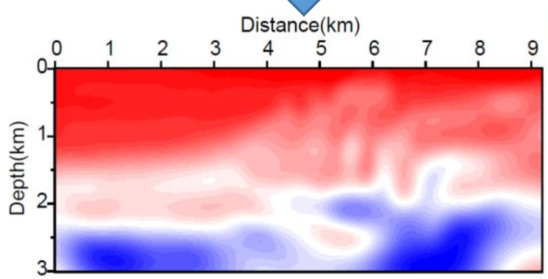


Phase (traveltime for non-dispersive wave) drives imaging

Data



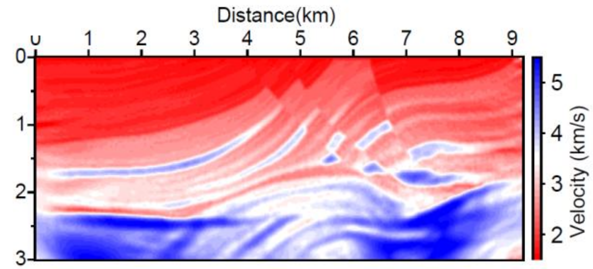
low-k



Macro-model based on velocity analysis

FWI

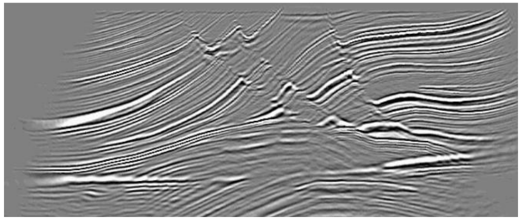
Quantitative model?
Velocity based on waveform



LSRTM

RTM
or
PDM

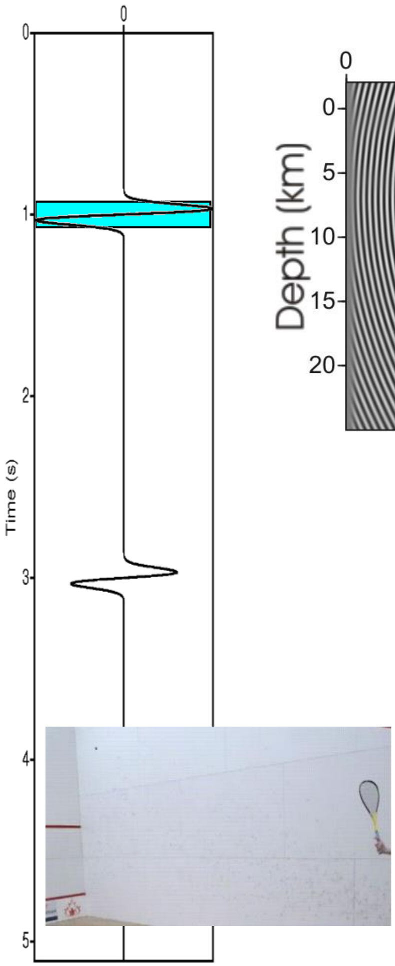
high-k

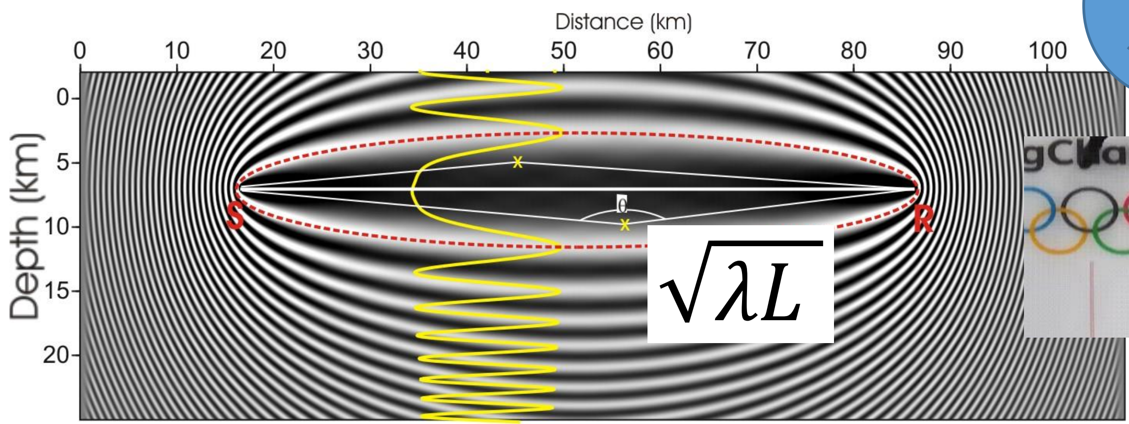


Qualitative model?
Reflectivity based on migration

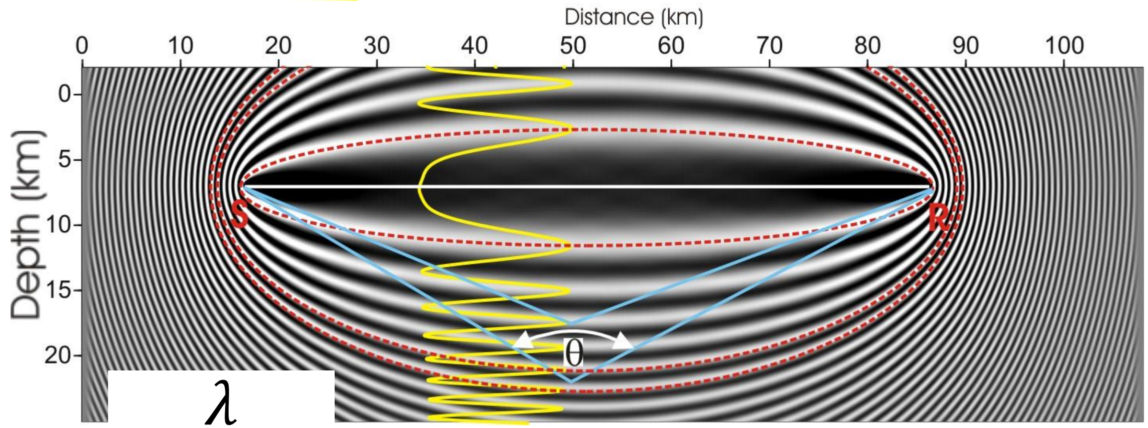
Wavepath: sensitivity kernel

From transmission information (velocity analysis) …



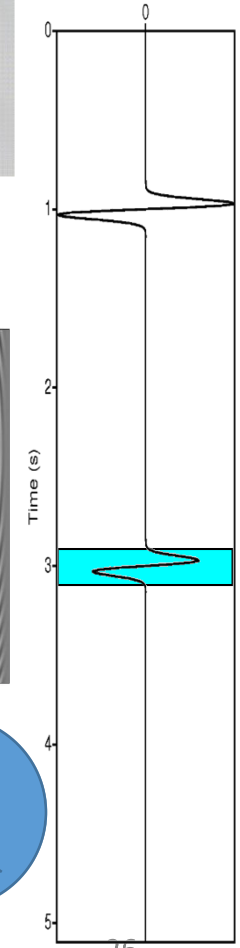


$$\sqrt{\lambda L}$$



$$\frac{\lambda}{2\cos(\frac{\theta}{2})}$$

Inverse of Kz

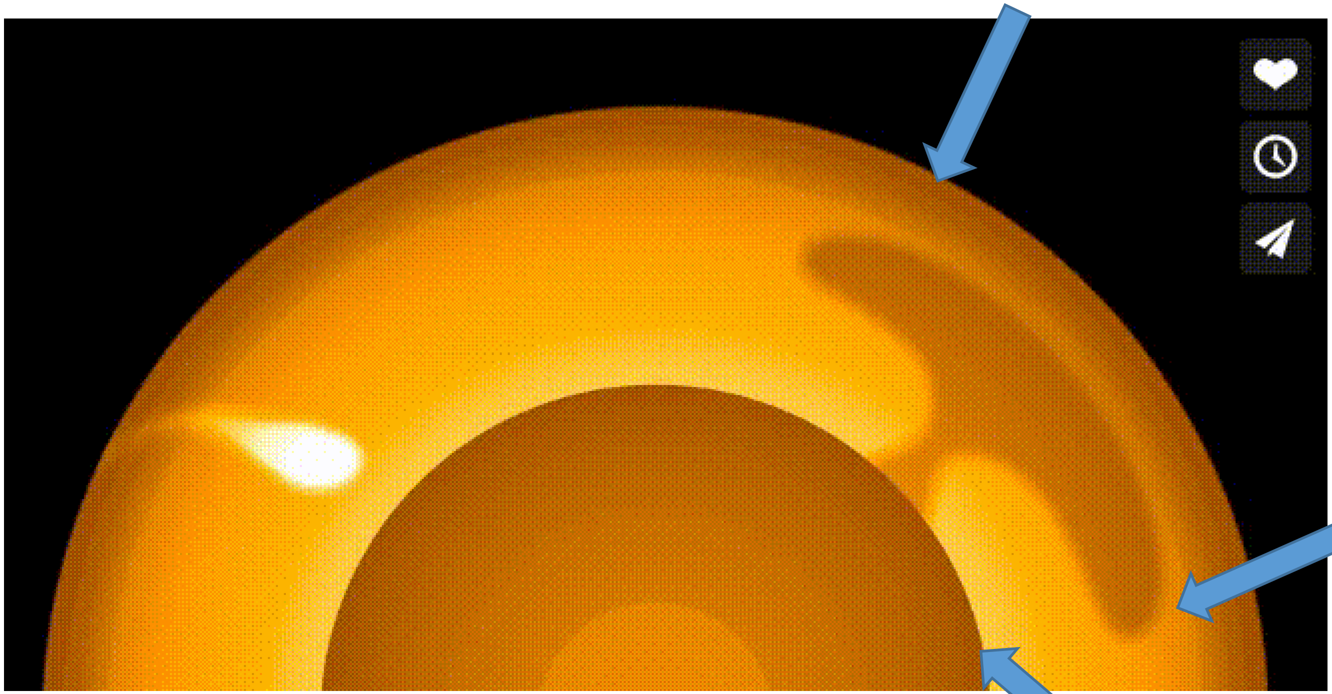


… to reflection information (migration,fwi)

Global Earth: probing # objects

Crust and Transition zone (CMB) are two expected complex targets

Crust: combined transmission and reflection regimes and all intermediate regimes



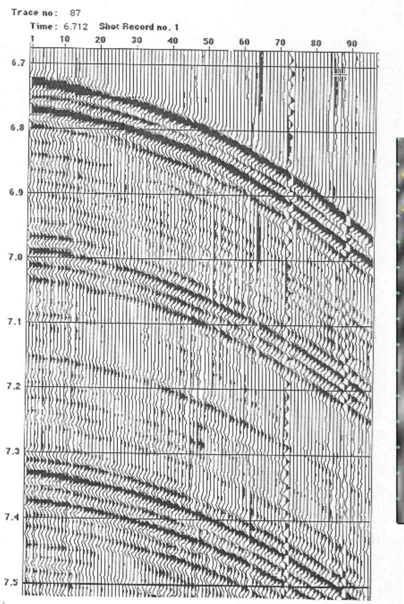
Mantle: only transmission regime for now on!

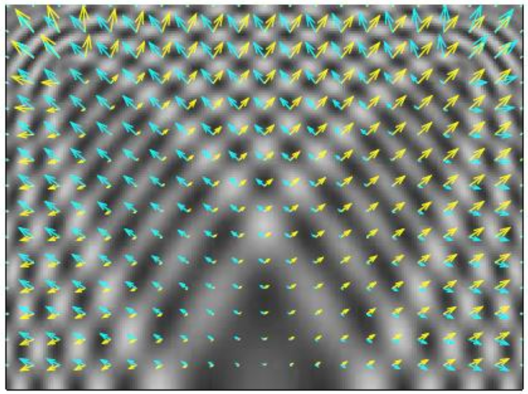
CMB: mainly probed by waves through transmission regime while expecting more complex interaction!

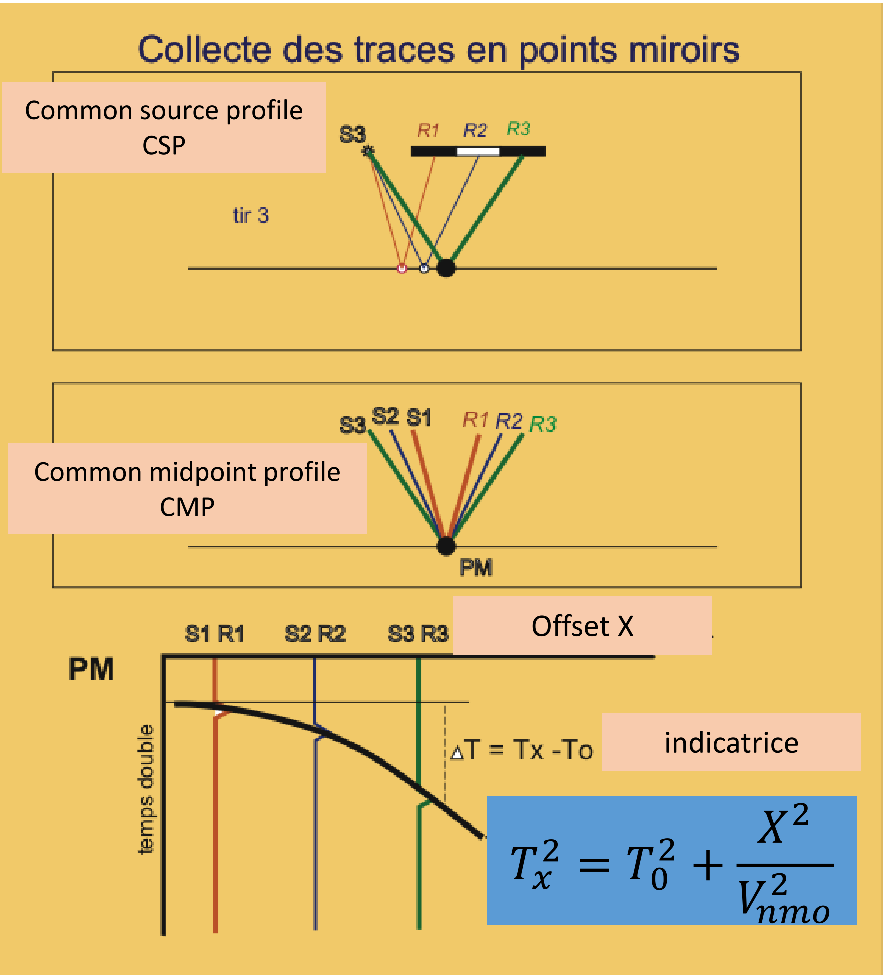
Movie from Stahler & Tarje

Macro-model reconstruction

Kinematic correction: NMO velocity







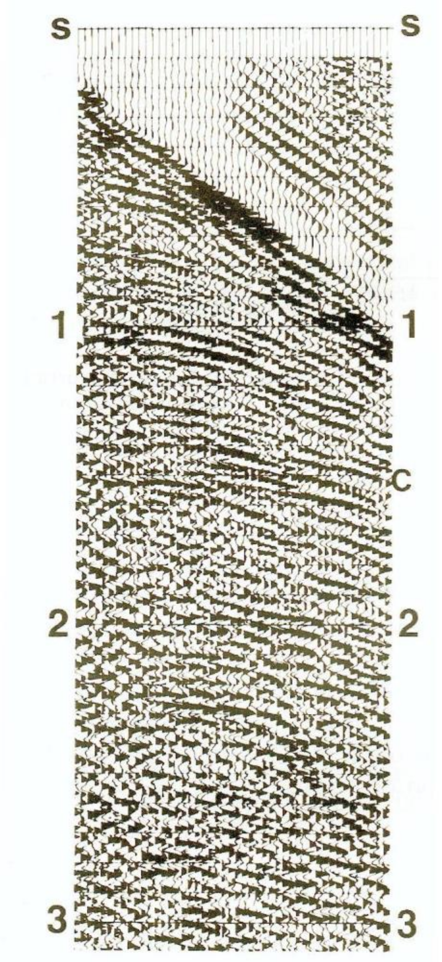
NMO velocity: estimation based on the identification of hyperbolae lines of reflections

Wave-matter interaction:
Transmission regime based on reflection events

Hierarchical structure of seismograms

In the Earth

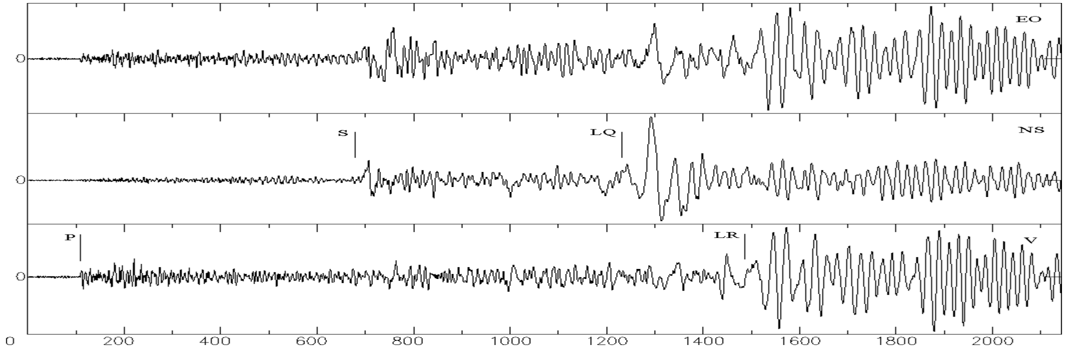
Seismics



Three time scales (for balistic waves)
Three spatial scales …

Two options:

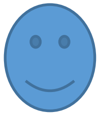
a. extracting specific observables (time/phase)
b. *using records as they are (calibrated amplitude!)*



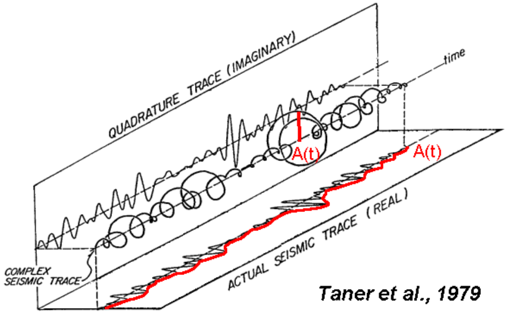
Seismology

Extracting specific observables from records

Kinematic observables (as for oceanographic and infrasonic tomographies)

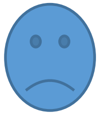


- times or (instantaneous) phases (used in seismic time tomography)
- angles (back-azimuth and slowness angle: source, receiver, diffractor)
- time curvature (example of velocity analysis)



Correct physical description of time/phase data

Tools for predicting accurately these observations



Dynamic observables (option A+)

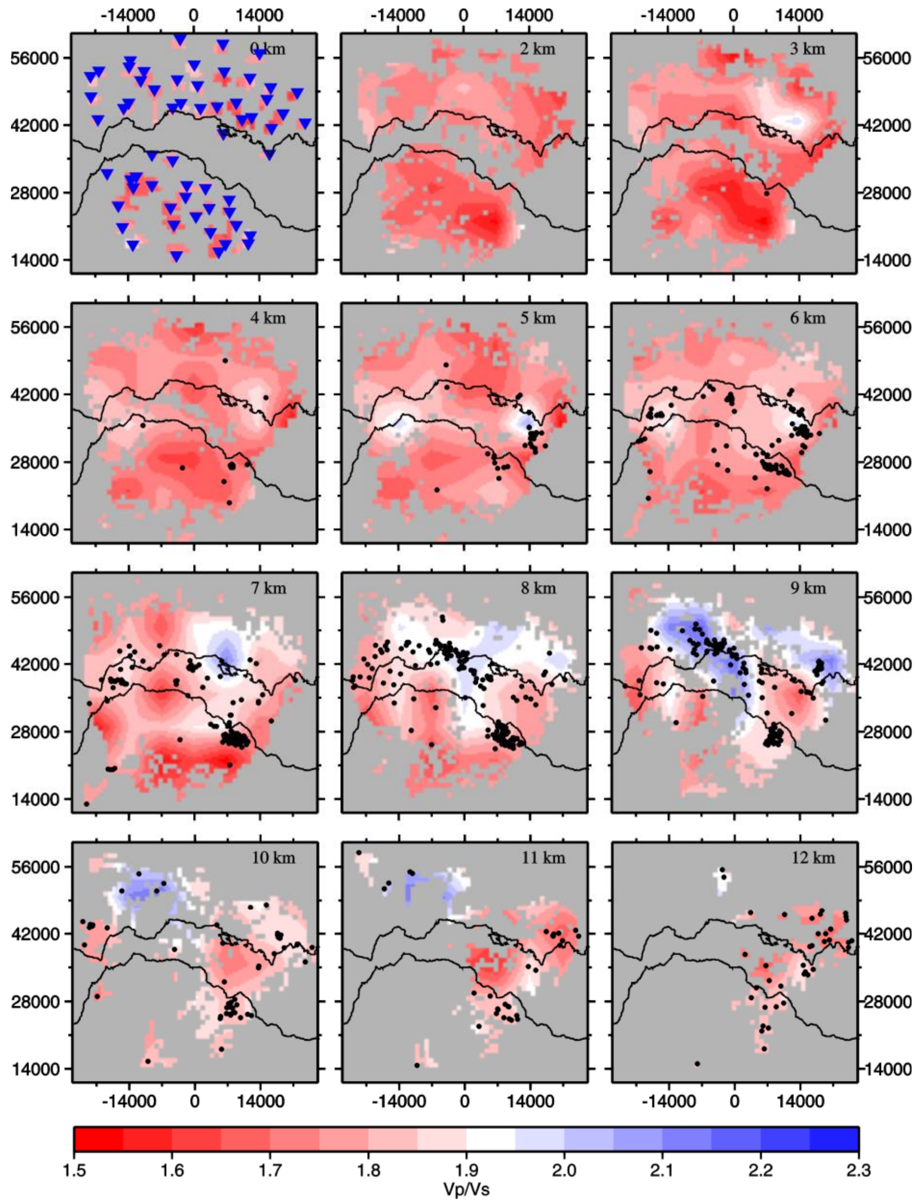
- (Instantaneous) envelopes
- amplitude decrease with offset (AVO)
- amplitude decrease with frequency (attenuation – broadband records)

Correct physical description of amplitude variation

Tools for predicting accurately these observations

T* tomography

Corinth tomography



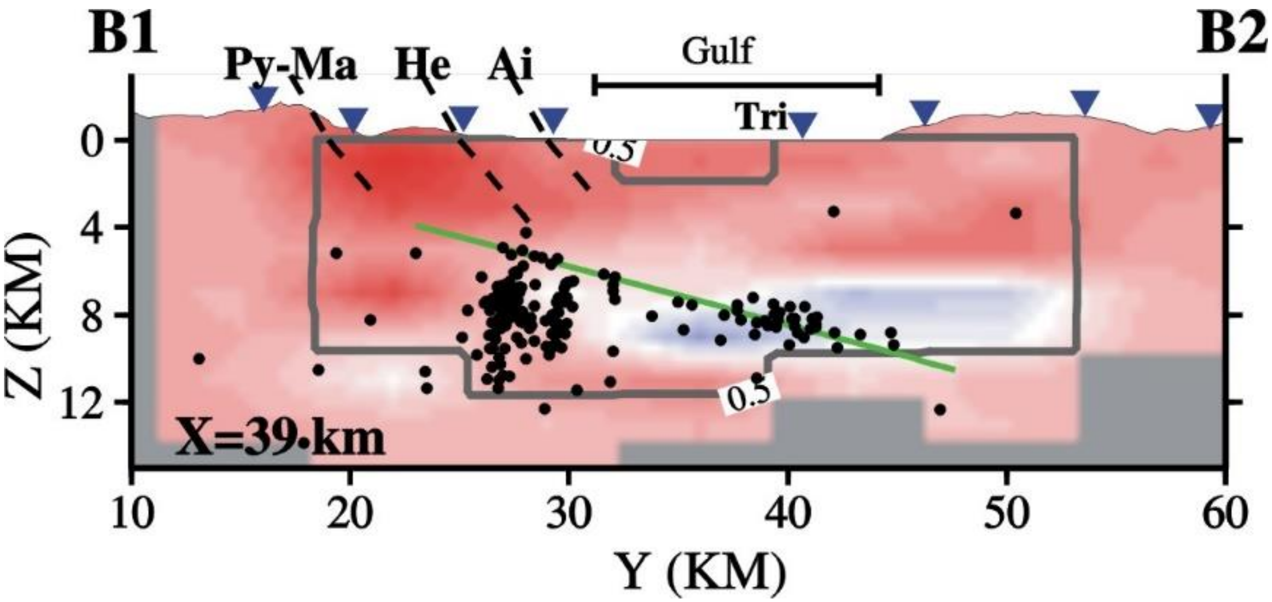
PhD of Diana Latorre (2004)

Vp/Vs image deduced from the Vp and Vs tomographic models

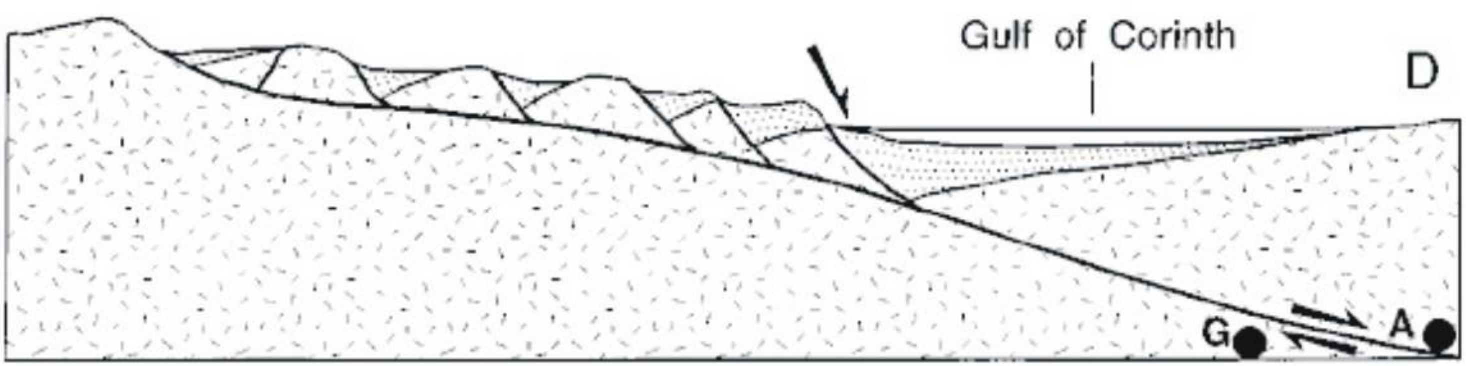
- Vp/Vs value may discriminates lithology.
- Variations depend on porosity and fluid saturation.

Fluid combined with soft material may help sliding a thick block over another one. The tilting mechanism is not mandatory (the extension factor β of oceanic margin)

Corinth tomography



?



Oseberg Ray+Born imaging

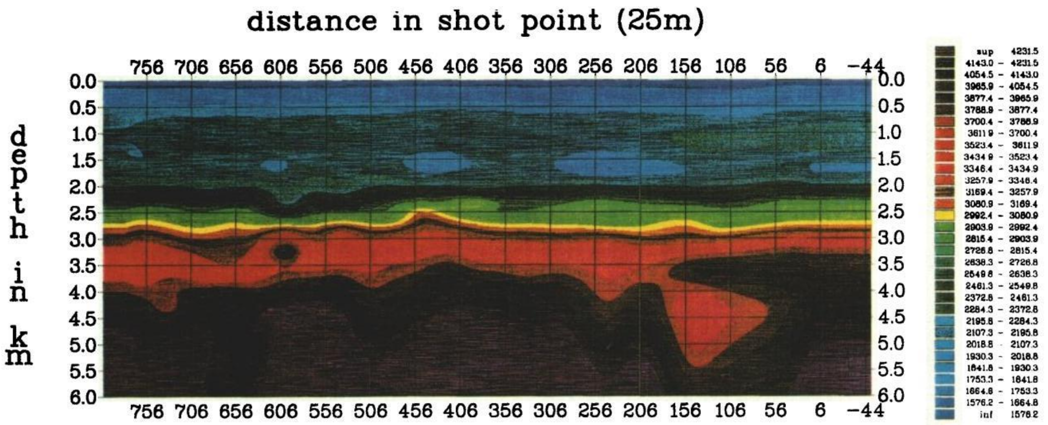


FIG. 8. Background velocity model for the Oseberg Field profile selected for asymptotic inversion. Velocities were obtained by standard velocity analysis provided to us together with the data set.

Macro-velocity model built from velocity analysis …

?

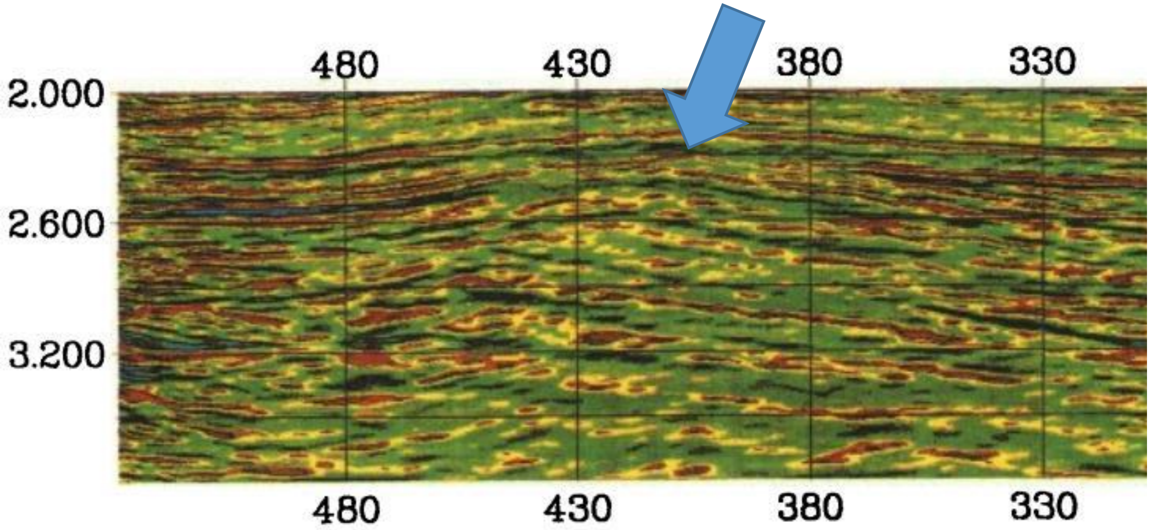
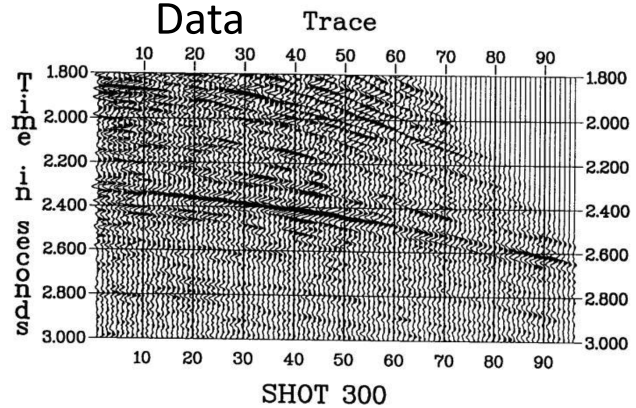
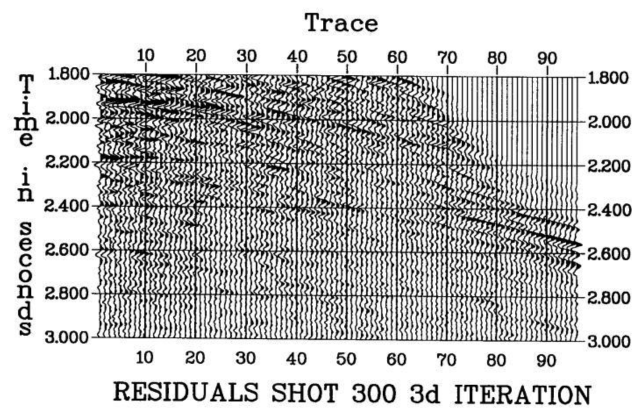


FIG. 10. Velocity perturbations inverted in the smaller target zone of the Oseberg profile; different panels.

Data





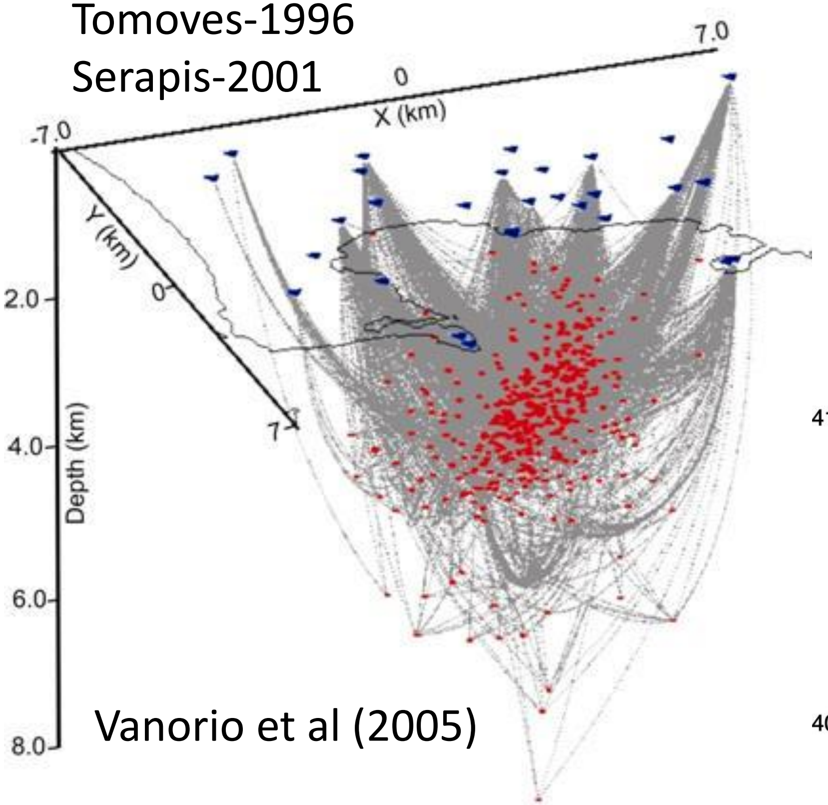
Lambaré et al (1992)

Energy has been removed …

Puzzle of Napolitean volcanoes

Tomoves-1996

Serapis-2001



Vanorio et al (2005)

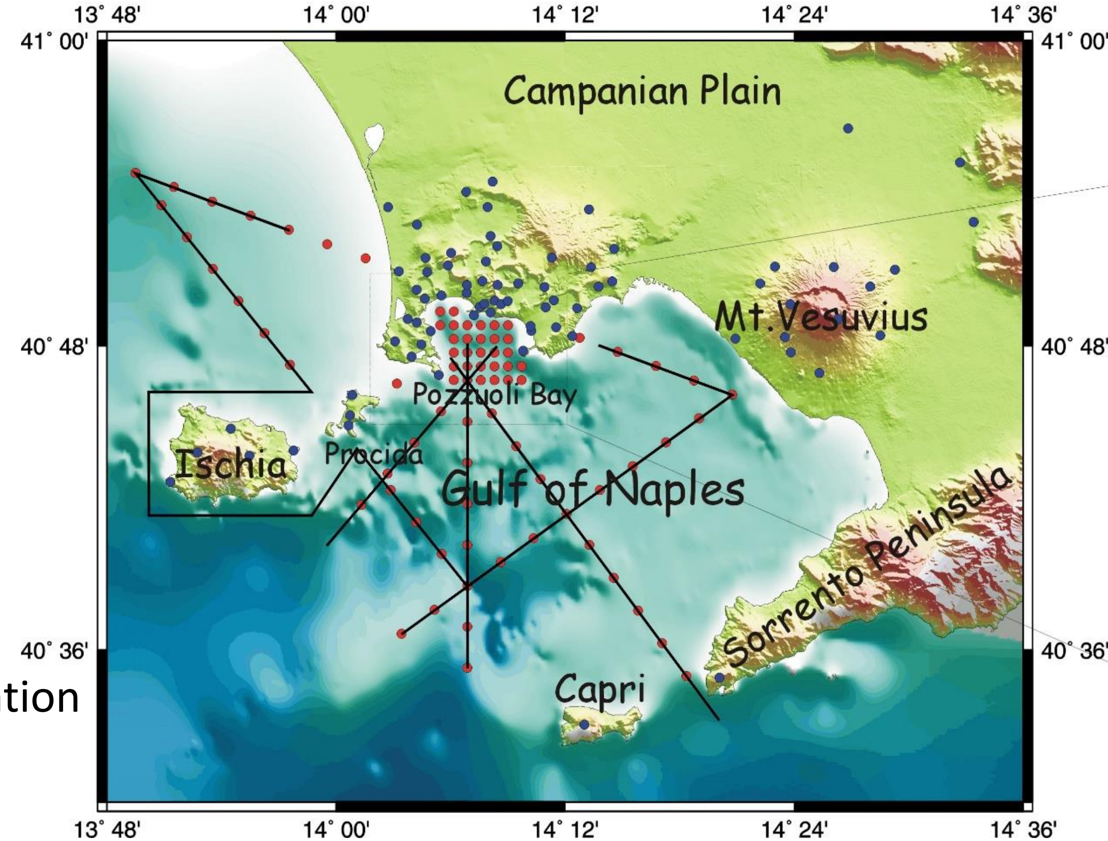
?

A long-term adventure
by Aldo Zollo … and many people

The 1982-1984 bradyseismic crisis

Passive and active seismic experiments

Three attempts for amplitude interpretation on this target: we partially succeed!



Progress in traveltime tomography

Traveltime tomography: still strongly based on 90's

methodology (as far as I can see) …

small computer requirement …

Questions:

Grand-daddy research

why images are so smooth!

how to use differential information (DD strategy)!

debates regarding theoretical features (understanding)!

Full waveform inversion: intense search activity

many groups are involved …

HPC implications …

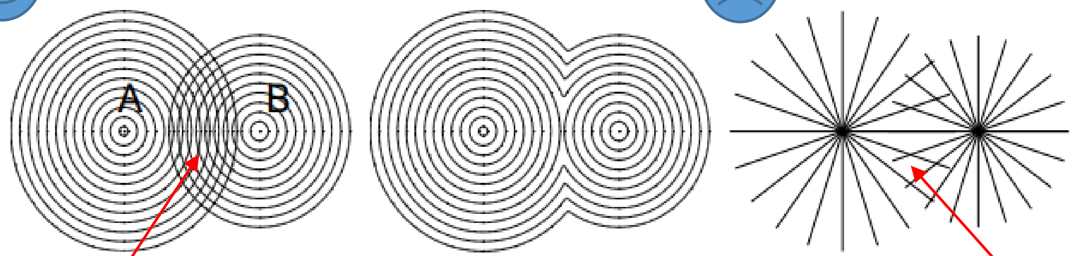
Fashionable research

Seismic imaging: phase versus wave

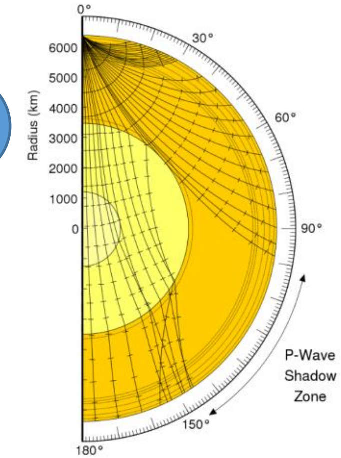
Wave equation
Linear PDE

Eikonal equation
Non-linear PDE

Ray equation
Non-linear ODE



(a) Helmholtz solution (b) Eikonal equation (c) Ray tracing



only sum! (Runborg, 2007) Both but singular or shadow!

- ❑ Traveltime tomography cannot consider beating waves!

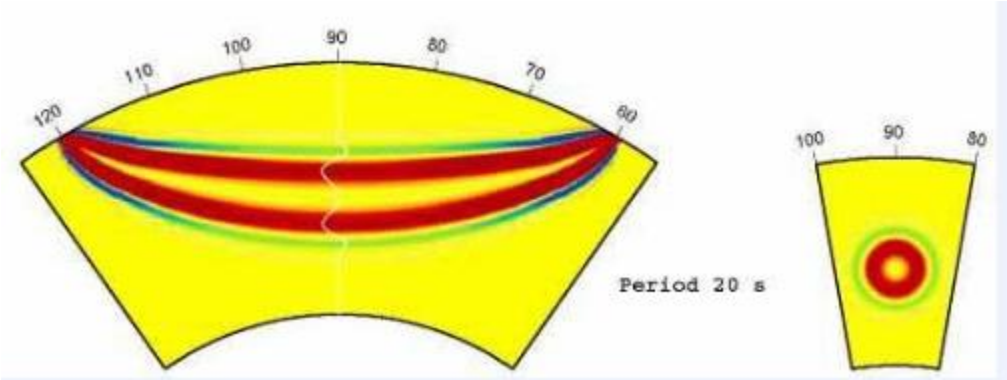
- ❑ Full waveform inversion does! as well as wave-equation traveltime tomography

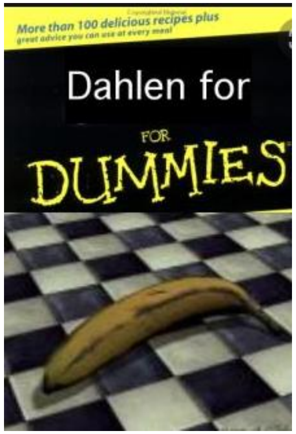
No free lunch: not only computer resources but possible leakage between model parameters (speed versus attenuation, compression versus shear interpretation and so on … anisotropy, acoustic approx.)

(Almomin & Biondi, 2012; Li & Chauris, 2017; Sun et al, 2017; Djebbi & Alkhalifah, 2020 …)

Banana-Doughnut debate

https://www.geoazur.fr/GLOBALSEIS/nolet/BDdiscussion.html





(Dahlen et al, 2000; Dahlen & Nolet, 2005; Nolet, 2008)

Phase/time tomography based on Eikonal does not provide the so-called BD shape promoted by Dahlen & Nolet … !!!

Such shape is related to **ray concept** (and not to the **time/phase concept** for which the zero-sensitivity along the ray does not exist)

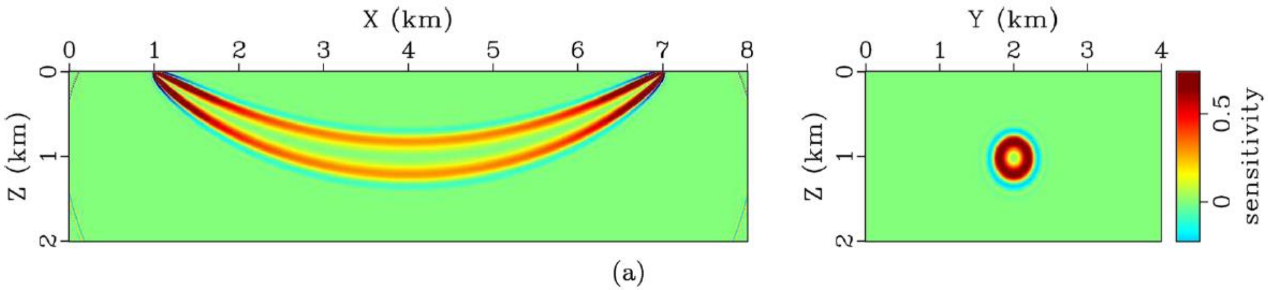
Many authors have tried to understand better this theoretical contradiction …

My understanding of this debate

When considering phase information

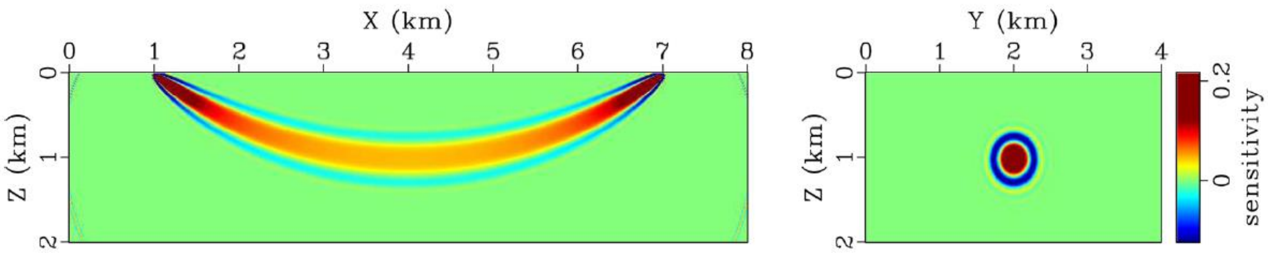
DIFFRACTION EFFECT NOT INCLUDED IN RAY APPROACH
DIFFRACTION EFFECT CAN BE INCLUDED IN THE SO-CALLED EIKONAL APPROACH

RAY SK



(From Djebbi & Alkhalifa, 2014)

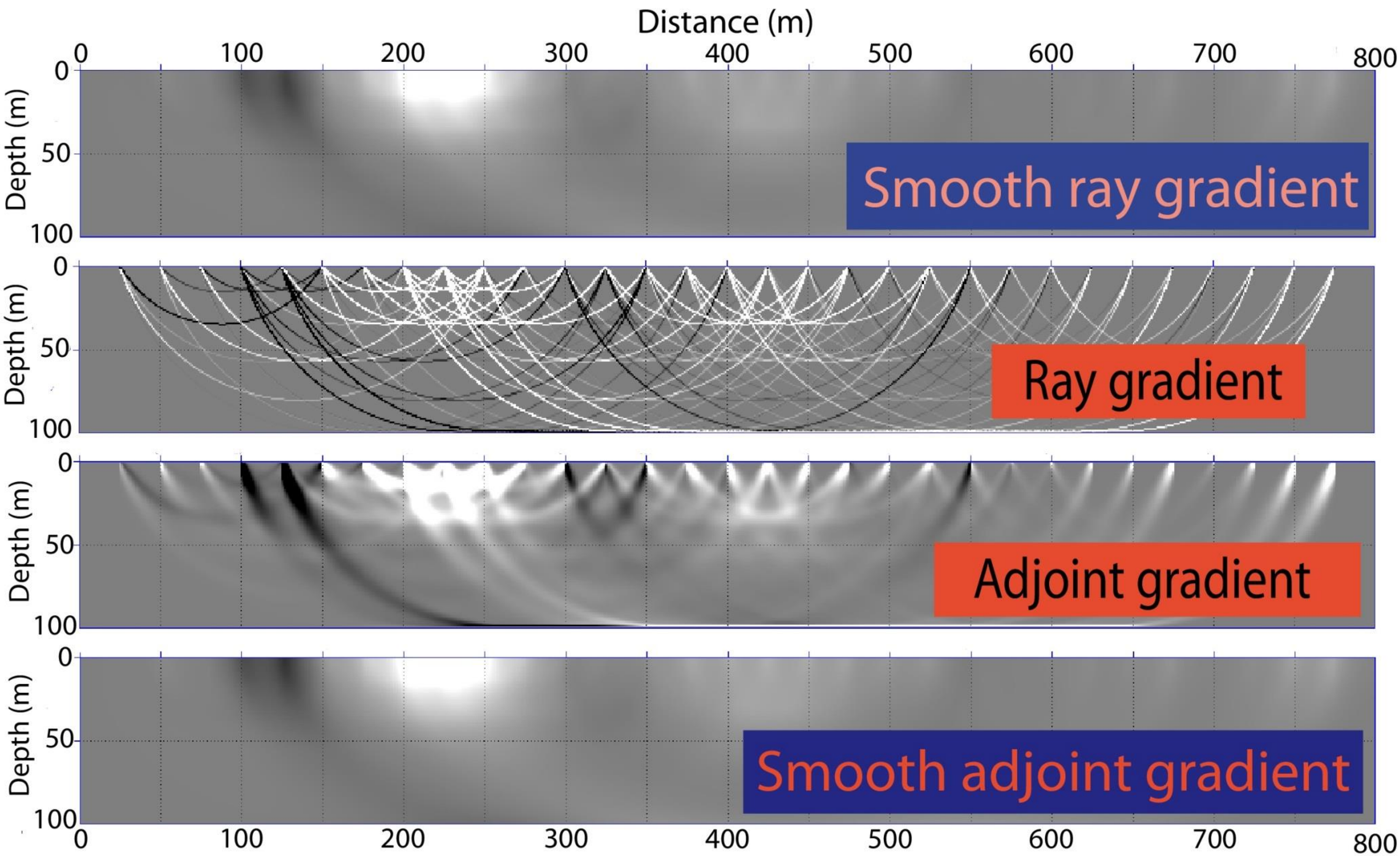
EIK. SK



Outcome of this debate: is it really important for applications?

My negative option (2014) has moved to a more positive one (2019) …

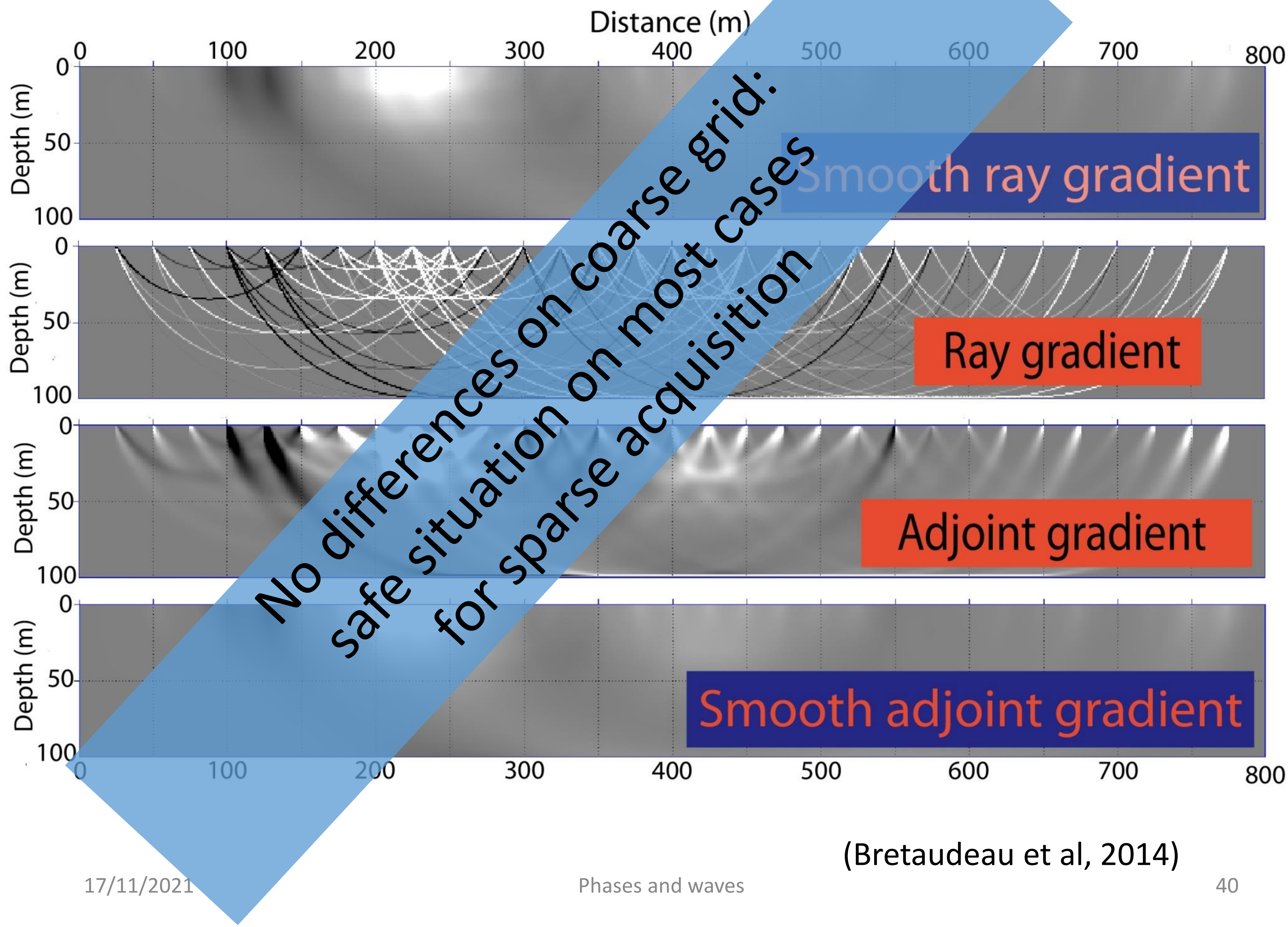
Projection of gradients on discrete model



Eikonal=Adjoint

(Bretaudeau et al, 2014)

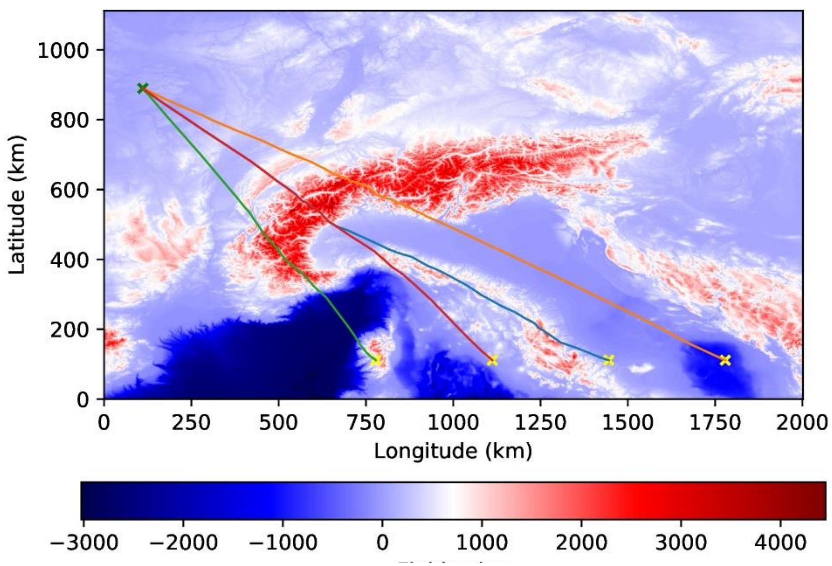
Projection of gradients on discrete model



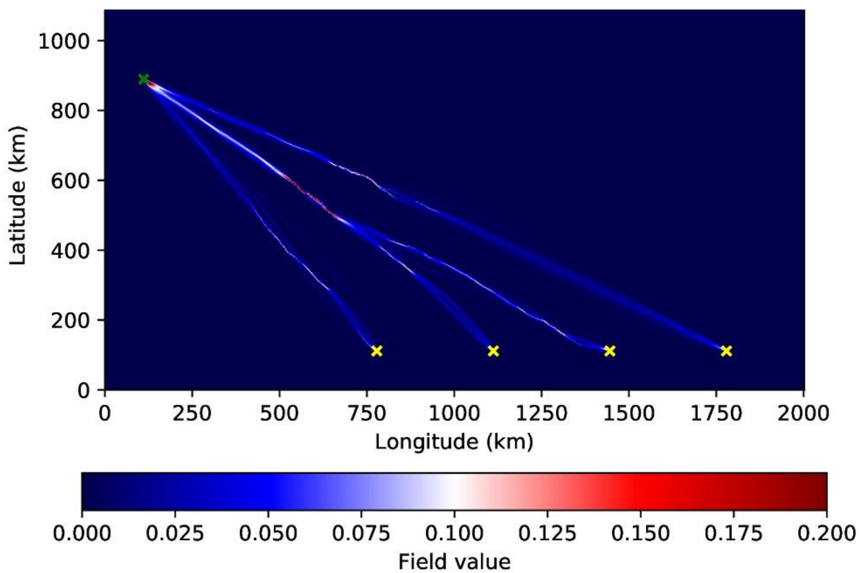
(Bretaudeau et al, 2014)

Dense array: is it still true?

Ray SKs



Adjoint=Σ Eikonal SKs



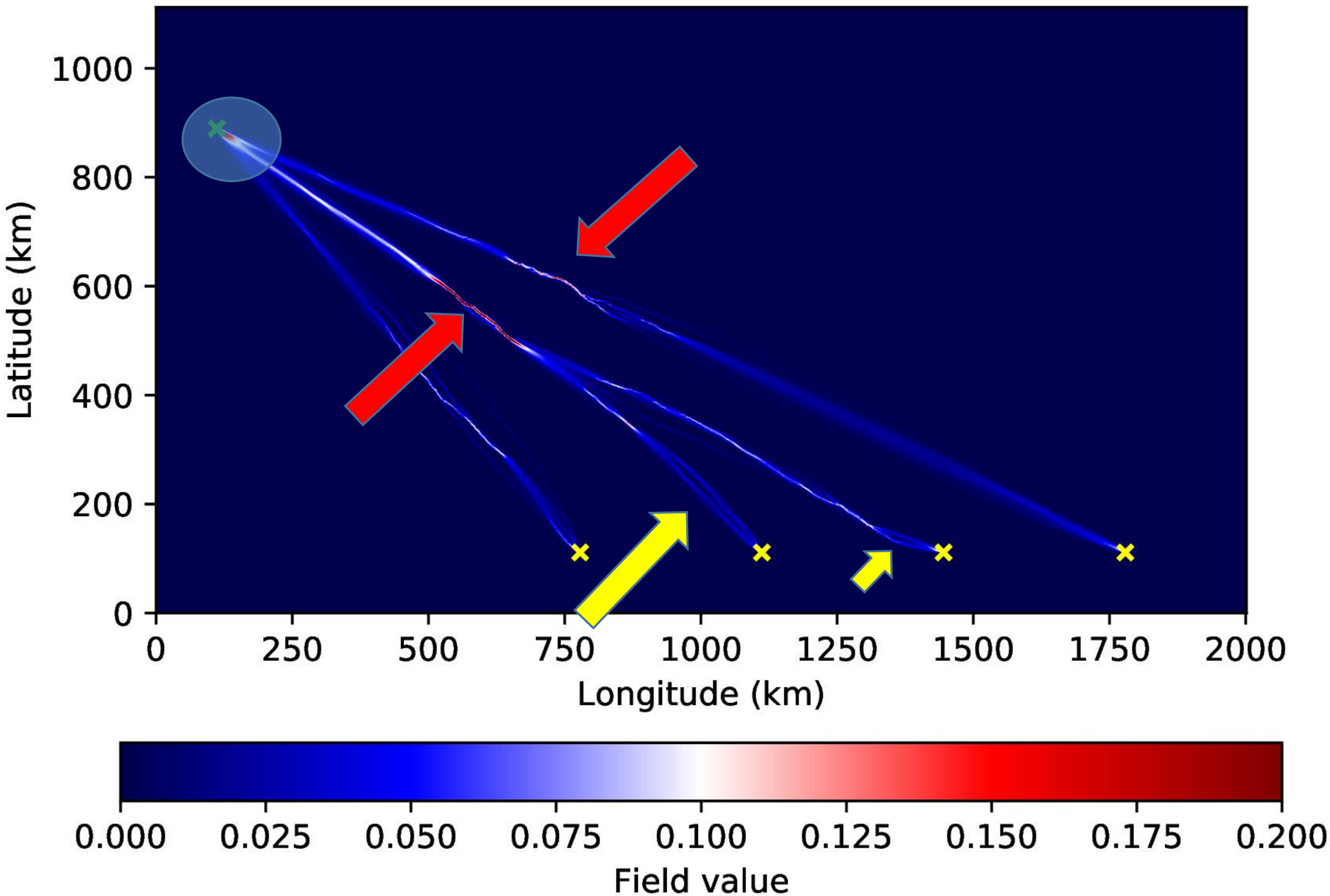
Toy example:
topography taken as velocity perturbation
(mimicking HF pattern)

Rays: same value (ray length) of the sensitivity (velocity impacts only the ray path itself)

Eikonal SK exhibits more complex pattern: variable values along the trajectory !!!

SKs: different values with possible different paths before reaching the station

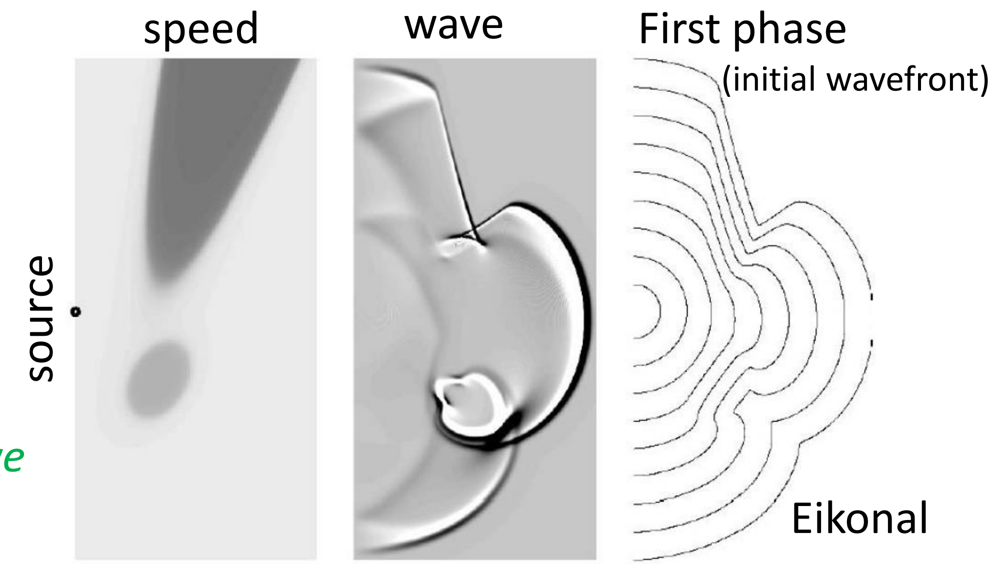
SKs



Latitude (km)
1000
800
600
400
200
0
0
250
500
750
1000
1250
1500
1750
2000
Longitude (km)
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
Field value

Eikonal: a more general concept?

(Runborg, 2007)



A non-familiar interpretation of phases

(often associated to HF approximation)

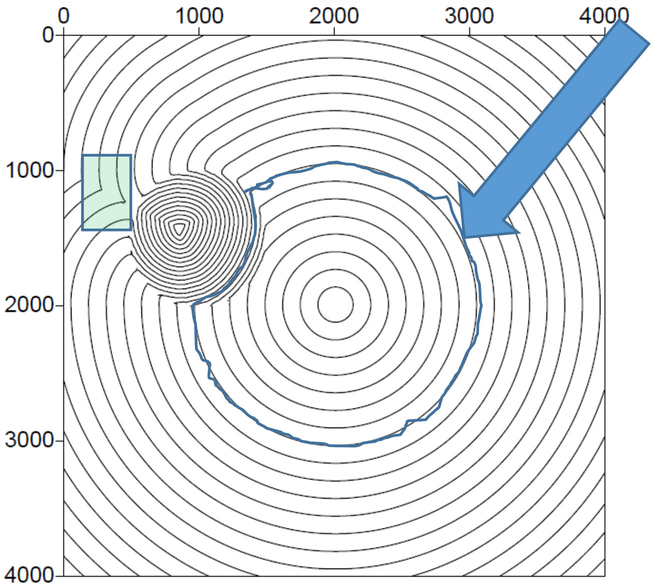
Wave disturbance (field discontinuity)

valid for any media

single value and always an answer

observable: continuous wavefronts

but discontinuous derivative



Line of same dansers

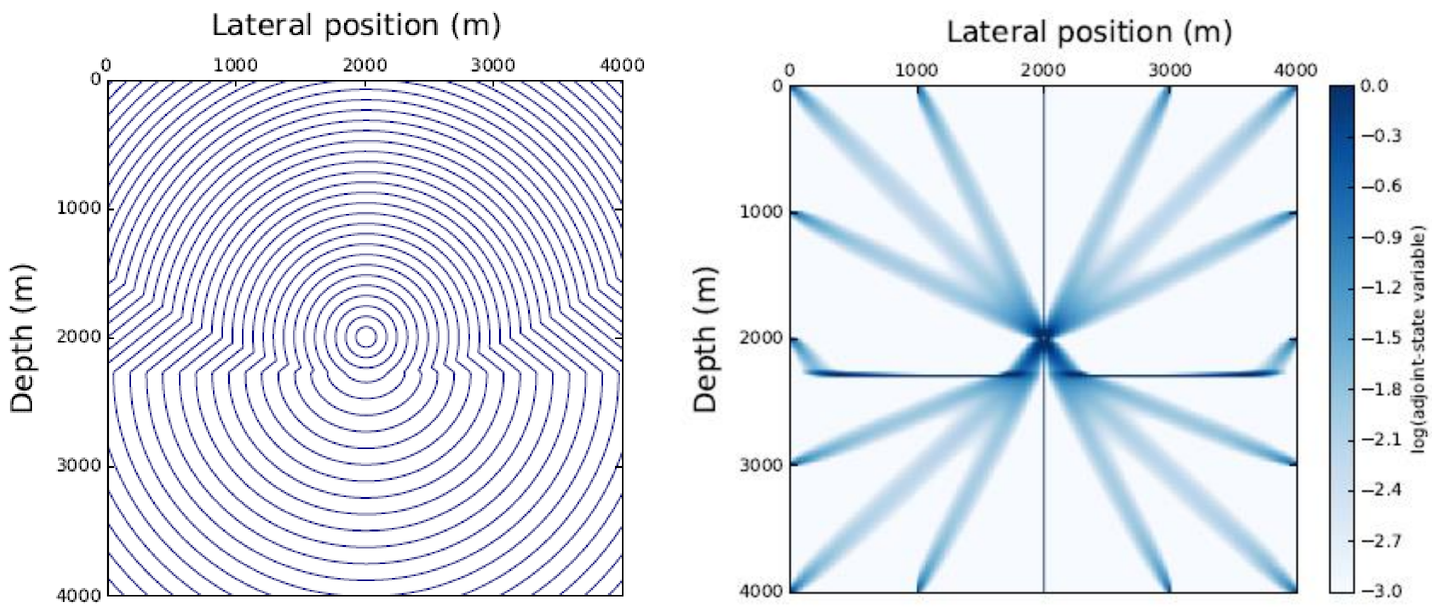
Wavefront: particles moving a synchronized way. They are in phase.

(Le Bouteiller, 2018)

Diffraction effects included ($u \propto \omega^{1/2}$)

Eikonal (time/phase) sensitivity kernel (SK)

(Le Bouteiller, 2019)



RD:
SK field

Reverse differentiation gives Eikonal sensitivity kernels:
where to insert velocity anomalies to match time data (sum of kernels over receivers) (Taillandier, 2009; Lelièvre et al, 2011; Tavakoli F. et al, 2017, 2019; Sambolian et al, 2019, 2021; Tong, 2021)

Sensitivity kernel defines zones of velocity perturbation affecting the time/phase at the receiver (regardless of the frequency content of waves!)

Forward differentiation (FD): **slowness perturbation -> time perturbation**

For a given point x, $\delta u(x) \rightarrow \delta T(.)$ everywhere

Reverse differentation (RD): **time perturbation -> slowness perturbation**

For a given point x, $\delta T(x) \rightarrow \delta u(.)$ everywhere

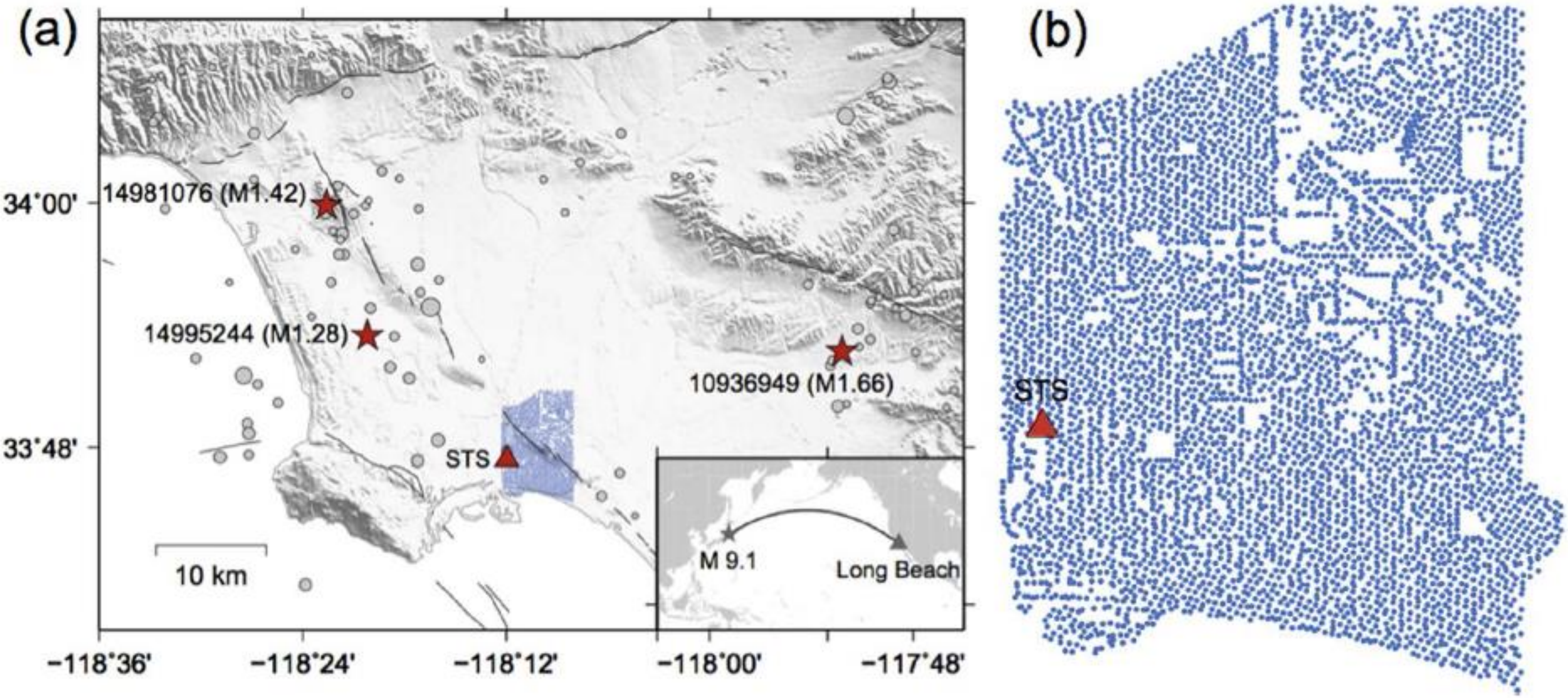
i.e. time residual at a given station

Ray linear relation

$$T(x, u + \varepsilon\delta u) = T(x, u) + \varepsilon \int_{source}^{receiver} \delta u \, dl$$

Locally, the ray sensitivity is the length of the ray inside the cell of the grid

only a geometrical value: arclength



How to take benefit of such density?

Back-azimuth observables

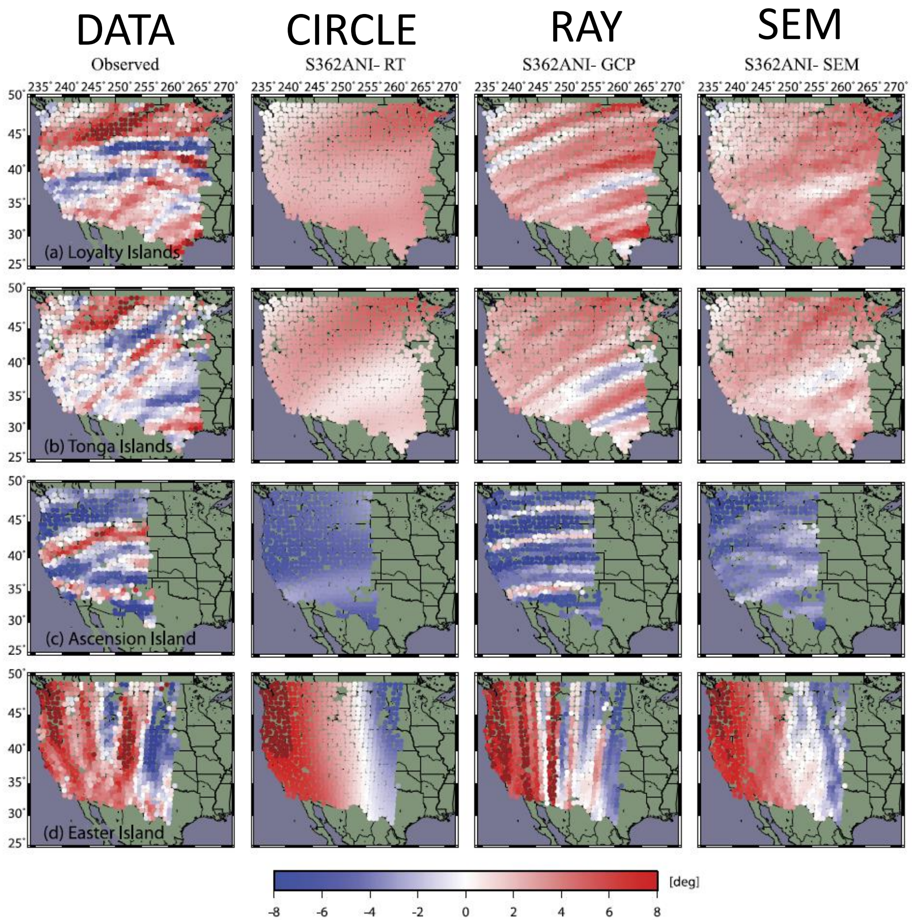


Figure 7 from Foster, Ekström & Hjörleifsdottir (EPSL, 2014)

For 4 earthquakes,
measured arrival angles across the USArray network &
predicted angles for a S362ANI model using
(1) great-circle approximation,
(2) ray tracing and
(3) SEM modeling (interference issue)

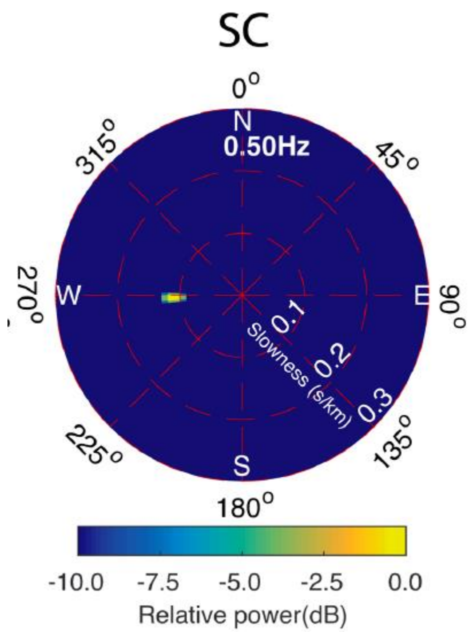
Observables have more information than those predicted by built Earth models

Improving tomographic approaches for honoring both traveltimes (or phases) and azimuthal (and/or slowness) measurements?

(Hu & Menke, 1992)
(Yanoskaya, 1996)

Slowness & back-azimuth observables

station SEAA



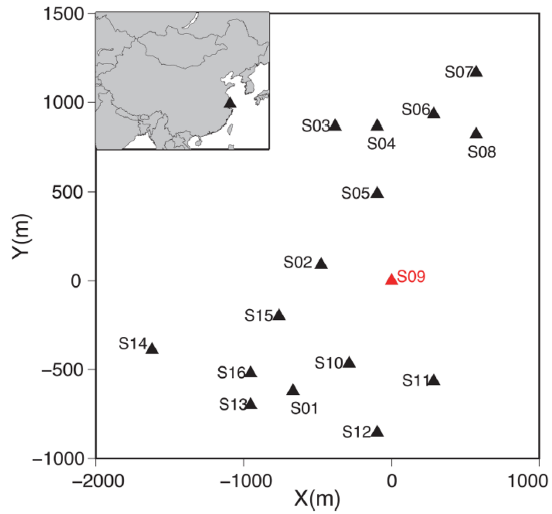
Azimuthal angle and apparent slowness

(from figure 16 of Hu, Zhang & Yu; GJI 2019)

for Wenchuan 2008 earthquake

SEAA: sub-array of 16 sensors

ChineseArray



Slowness=ray parameter=slope

Increasing density of stations offer us new observables such as slowness and back-azimuth observables aside traveltime observables (nonlinear time series analysis)

Option A+ and Option B

Using dynamic observables (option A+)

Or

Using records as they are (option B)

- Deep understanding of the wave propagation physics (PDE?)
- High-quality data: reinforced acquisition protocol
- Accurate prediction of true wavefields (beyond waveforms)

Another story, next time

Migration versus FWI: linear vs non-linear

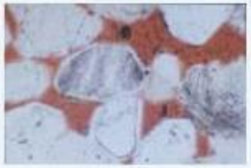
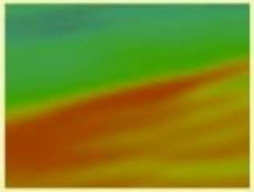
➢ Migration: an efficient linear process with always an answer you may like it or not (interpreters are key experts). *(very robust to amplitude errors)*

➢ FWI: a costly non-linear process with often no answers!
This makes students rather frustrated… *(amplitude influence)*
*(easier li*fe for interpreters ☺)

➢ FWI: when it works (needing not only smart students but high-quality data), potential quite interesting interpretation with physical quantities!

Final goal of deterministic seismic imaging
(not yet crust/reservoir characterization)

Model # Medium

  μm	**Micro-scale**	Physical parameters: mineral composition, gas, liquid …
	upscaling ↓	
 < or ~ m	**Meso-scale**	Inference parameters: one solid skeleton and one fluid. Gassmann rheology Porosity, saturation, tortuosity, consolidation parameter …
	downscaling ↑	
 > 10*m	**Macro-scale** (Investigated by FWI)	Model parameters: velocities, attenuation, anisotropy, density for seismic waves

From Dupuy's PhD (2011)

Main take-way message

- Crust is a complex body where waves interact with matter with # illuminations

- Propagation in the crust may go beyond simple partial differential equation modeling.

- Kinematic observables: robust measurements (improved quality, thanks to multiscale arrays!)

- Zeroth-order robust physics (accurate modeling of rather stable wave propagation quantities)

Take-away message

- Room for progress in kinematic tomography (times, angles, *time curvature*)

- Dense arrays: new imaging approaches (time reversal concept of Claerbout)!

- Mitigating the curse of computer resources opening the road to UQ ....

For kinematic tomography, we should proceed with the same effort than the one devoted to FWI since the beginning of this century

Could also help FWI to the right path of imaging (especially for multiple parameters): another story ☺

- Massive data
- Computer resources

How lucky are you?

How responsable you are!

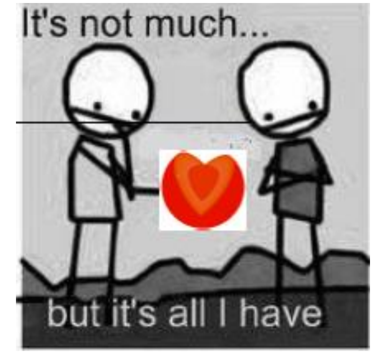
Smart (and well-trained) people for mastering these data with sophisticated and efficient approaches

For better knowledge of the shallow crust of the Earth (needed for our modern society)

Subsurface should not be our garbage can … but the unique place for resilient storage!

Many thanks for this masterclass initiative giving me the opportunity to draw potential research topics on kinematic attributes tomography without disregarding dynamic attributes inversion …

Many thanks to sponsors of the SEISCOPE consortium supporting FWI research,

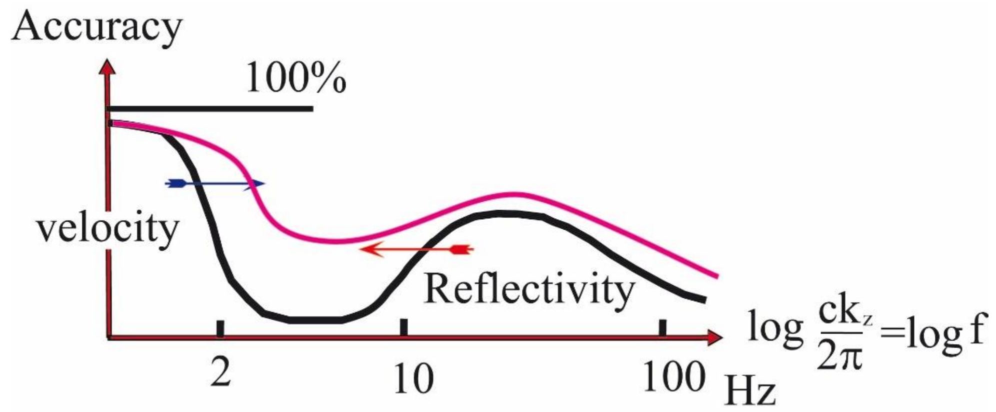


Thank you very much

For your attention

Questions?

Broadband sources
Complete illumination of targets



The dream …

Merging the velocity-model building and the migration into one integrated task when considering full waveforms

Continuous sampling of the wavenumber spectrum and filling the intermediate wavelength gap.

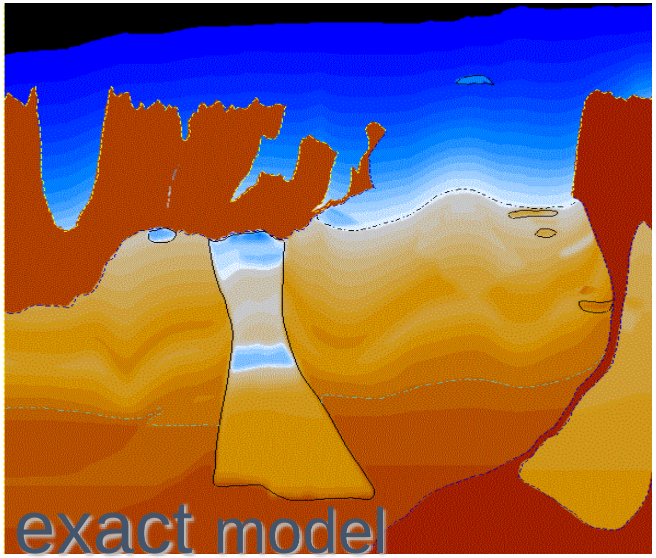
Tarantola (1984, 1987)

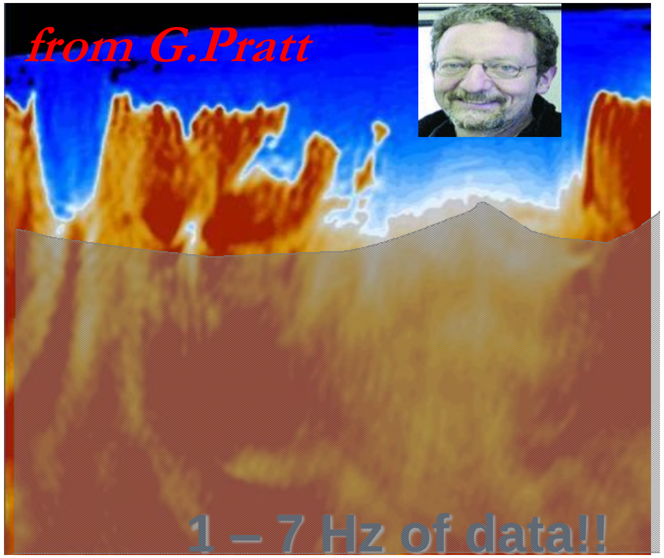
Amplitude: essential contribution

Low frequency information

2D synthetic example

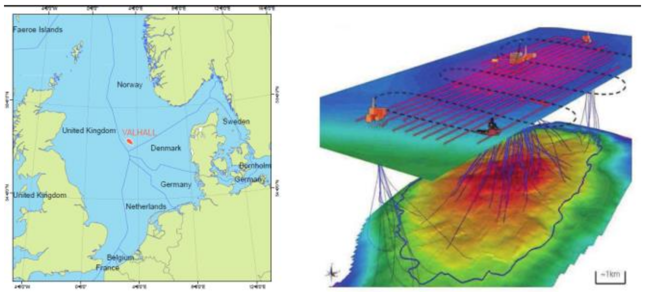
Pratt & Brenders (2004)



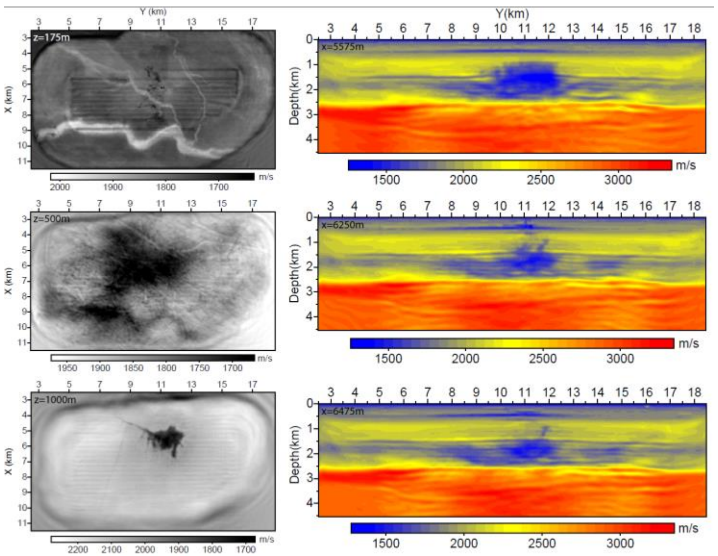


Benefit from waves, even when phases interfere

3D real example:
Valhall oil field

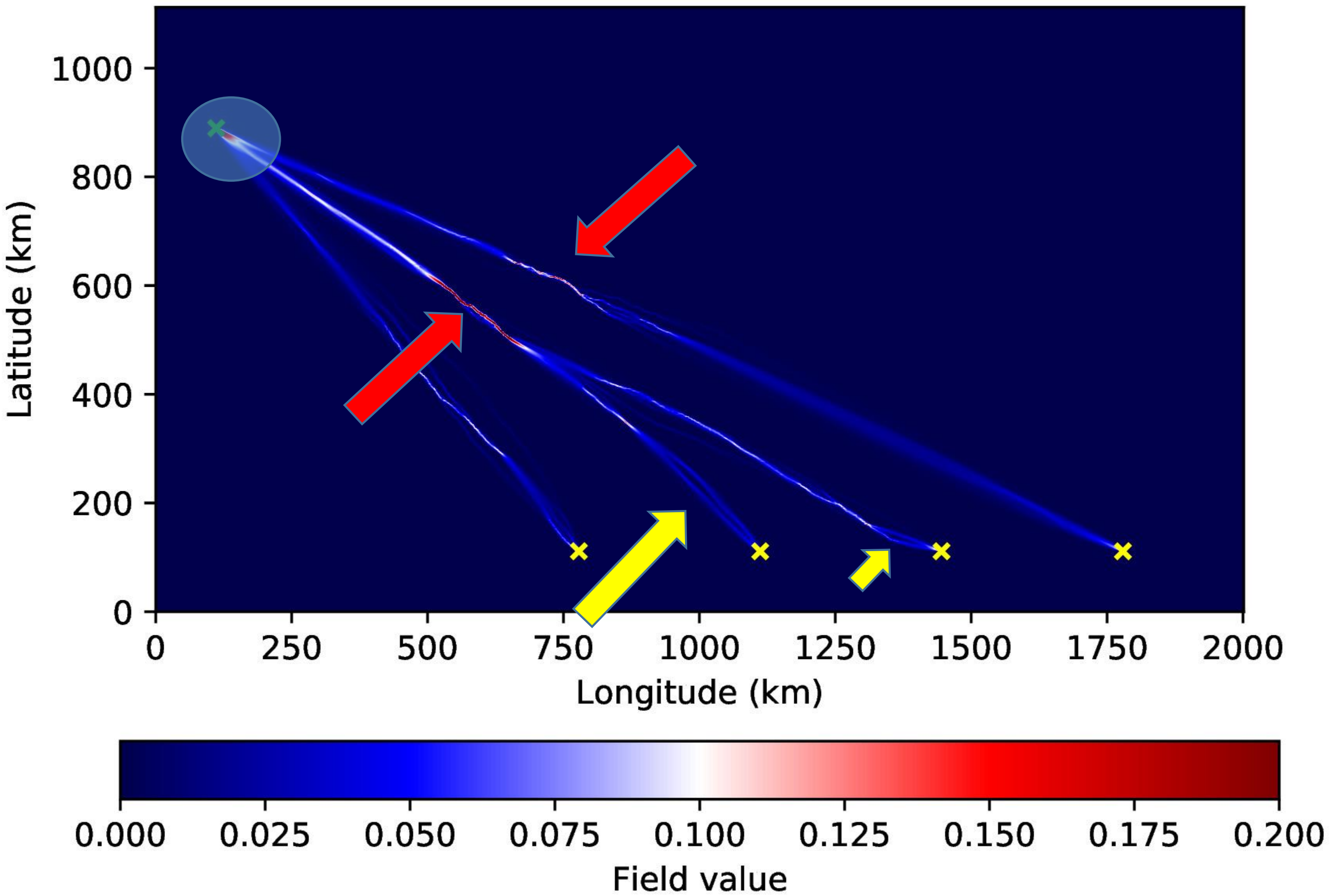


(Warner et al., 2008; Sirgue et al., 2010 …)



Operto et al. (2013,2015)

SKs



1000
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Latitude (km)
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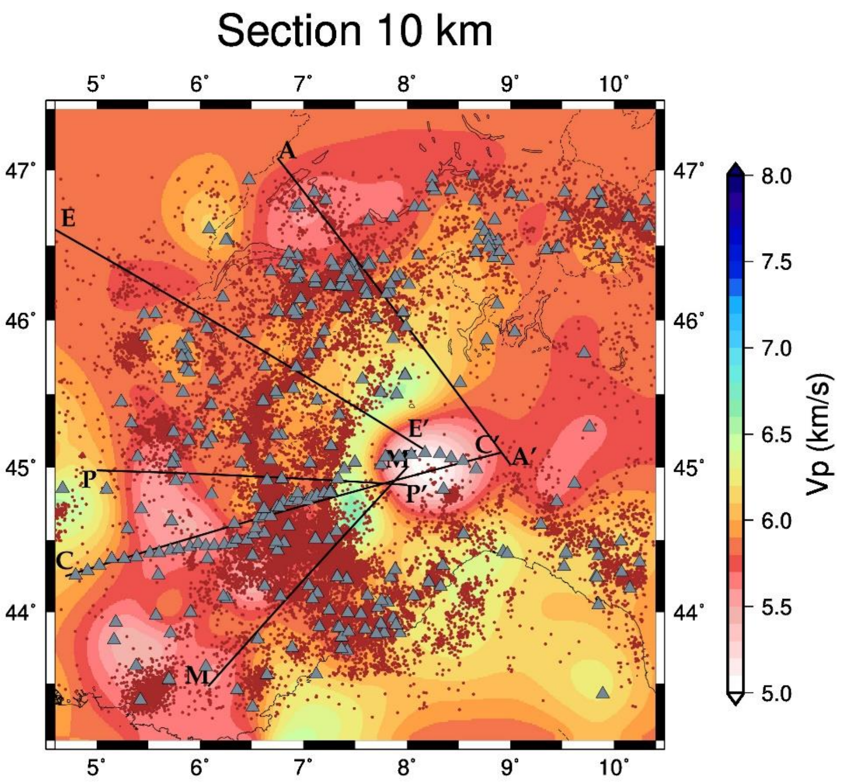
250
500
750
1000
1250
1500
1750
2000
Longitude (km)
0.000
0.025
0.050
0.075
0.100
0.125
0.150
0.175
0.200
Field value

Traveltime tomography: resolution!



Alps Zone:Traveltime tomography

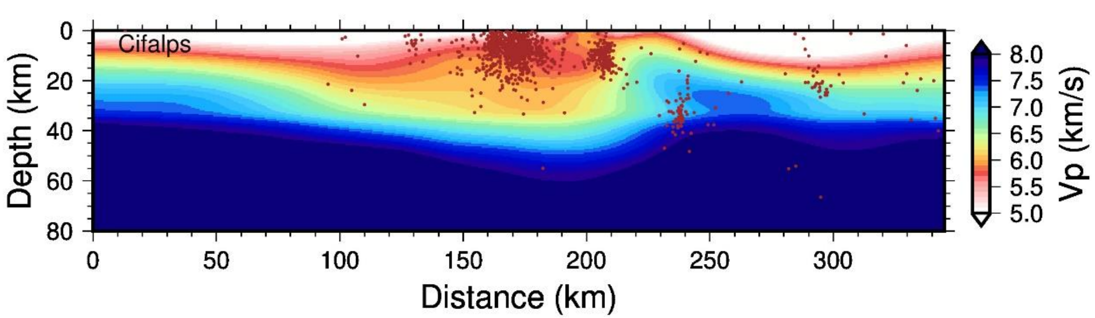
Seismic networks become denser and denser!

Picking strategy: manual, automatic?

Other kinematic observables: slowness and azimuth angles?

or more!

CIFALPS profile (CC’)



I am running now this 90’s tool over 1 500 000 picks coming from 30 years of data on a PC (big thanks to many people) for these manual picks)

On the use of FD & RD

Travel time tomography: we need

- Eikonal solver (time; non-linear PDE)
- RD solver (time SK; linear PDE)   (often approximated by rays!)

« Slope » tomography (based on time and time gradient): we need

- Eikonal solver (time; non-linear PDE)
- RD solver (time SK; linear PDE)
- *FD solver (time gradient; linear PDE)*
- *RD solver (time gradient SK; linear PDE)*

90's tentatives got poor impacts…

sometimes known as polarization tomography using backazimuth measurements (arrays!)

Picking strategy: industrial expertise

Automatic strategy was mandatory for industrial datasets (80's!)

Massive Dense volumetric time & slope picking strategy

for reflection traveltime tomography (beyond velocity analysis)

Automatic strategy is fastly percolated intho academic seismological community with increasing dense networks

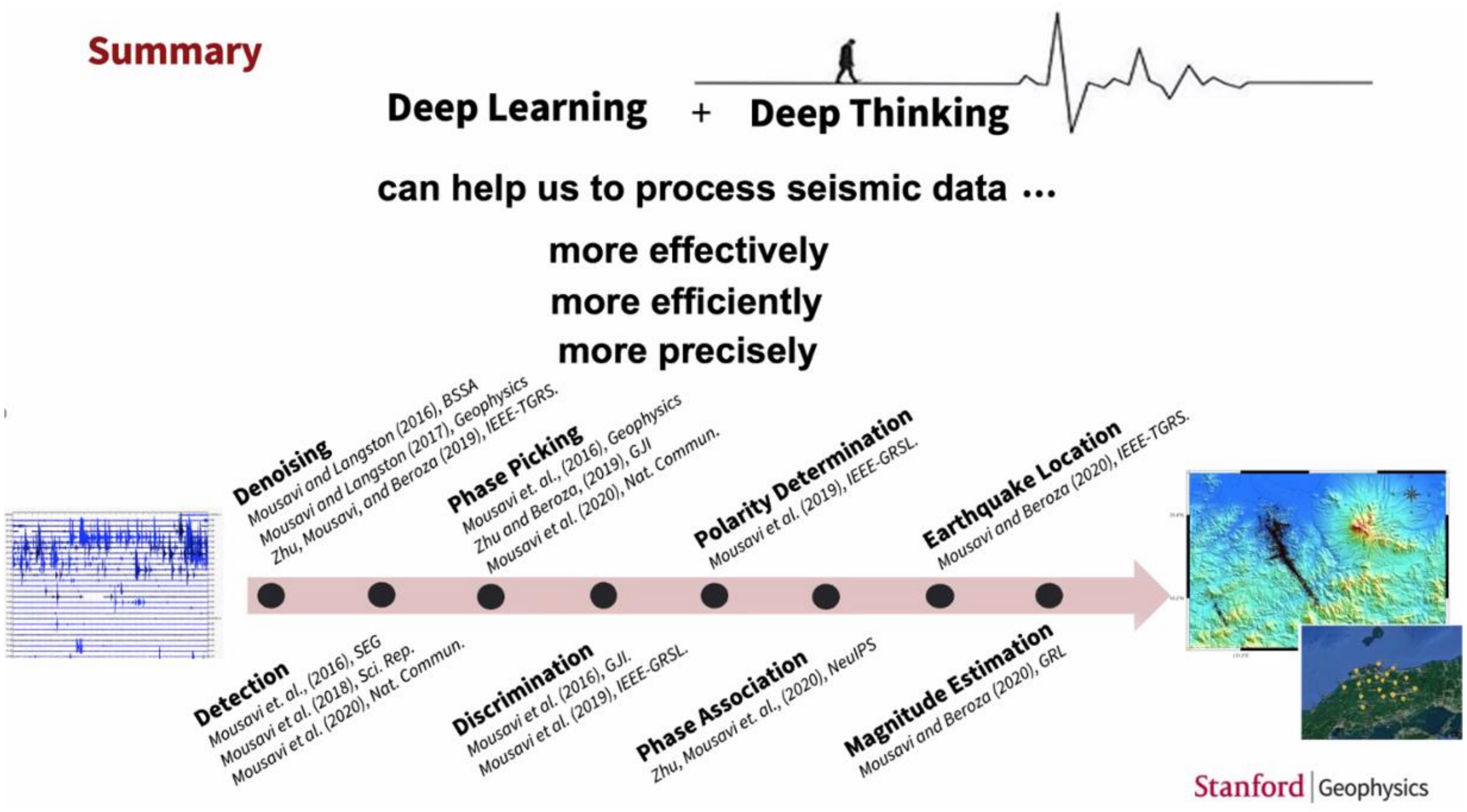
From **manual strategy** (SEISAN software?) to automatic one (but often single-station with xC components) picking strategy (EarthWorm software?) for academic datasets (00's)

Local arrays with few sensors (at least one 3C and many 1C):

9C = 3C + 6 1C seems to become a standard in seismic microzoning

Picking strategy: impressive progress

Very exciting novel methods based on
unsupervized or supervized machine-learning approaches



From a WS at LANL (2021)

S.M. Mousavi & G. Beroza (ArXiv:1912.01144v1, 2019)

FWI: using records …

Pr. A. Tarantola

1st paper on FWI: Geophysics, 1984

Full Waveform Inversion
FWI

No prior identification ->
No prior scale separation!

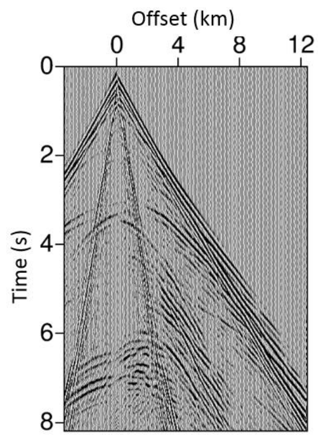
Seismic imaging workflows

SEISCOPE

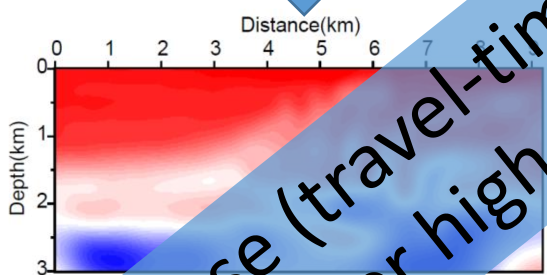
Phase (traveltime for non-dispersive wave) drives imaging

Phase (travel-time) is still the robust ingredient for high-resolution seismic imaging

Data



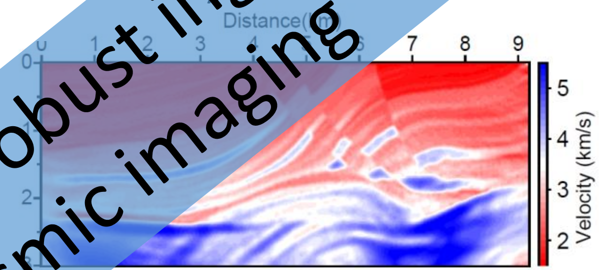
low-k



Macro-model based on velocity analysis

FWI

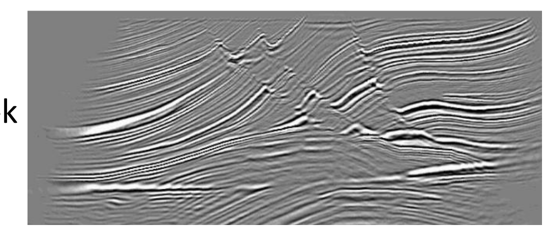
Quantitative model?
Velocity based on waveform



LSRTM

RTM
or
PDM

high-k



Qualitative model?
Reflectivity based on migration

ACRONYMS FOR FWI VARIATIONS: AWI, WRI, TFWI, EWI, JFWI, MBTT, AEWI …

Option A+ and Option B

Using dynamic observables
Or Using records as they are

Acquisition design (source & receiver positioning & orientation?)

Time synchronization (GPS now! Clock precision < 1 ms -> 0.1ms)

Amplitude calibration (instrument!; installation coupling!)

relative values more than absolute values (still not differential)

(wavefield -> waveform) relaxes installation & experimental procedure !

Source knowledge (source signature; radiation pattern)

quite challenging for natural sources (earthquakes: focal mechanism)

still difficult for active sources (shots, blasts: source signal s(t))

(wavefield -> waveform) mitigates these issues

Deep understanding of the physics of wave propagation

Tools of accurate prediction of waveforms (wavefields!)