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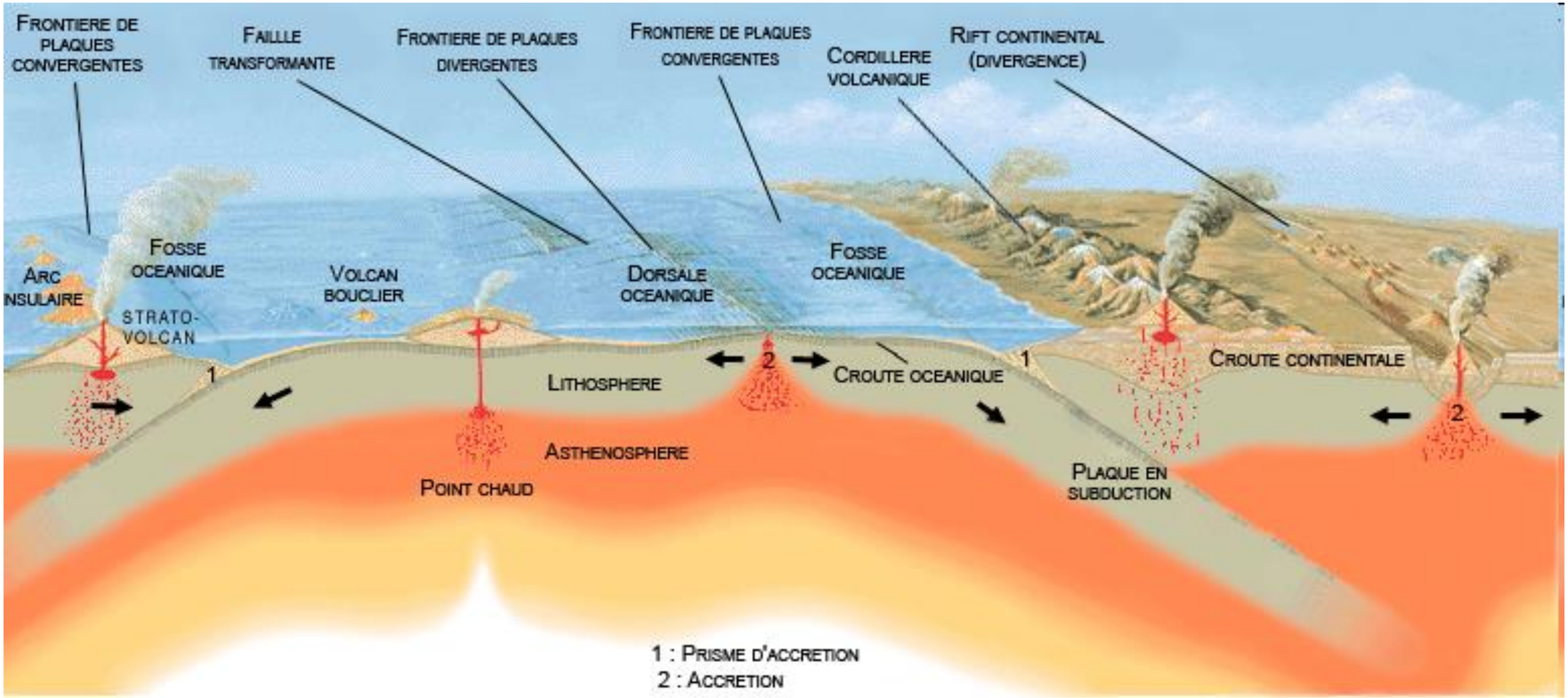
4-D seismology at volcanoes: Probing the inside of volcanoes

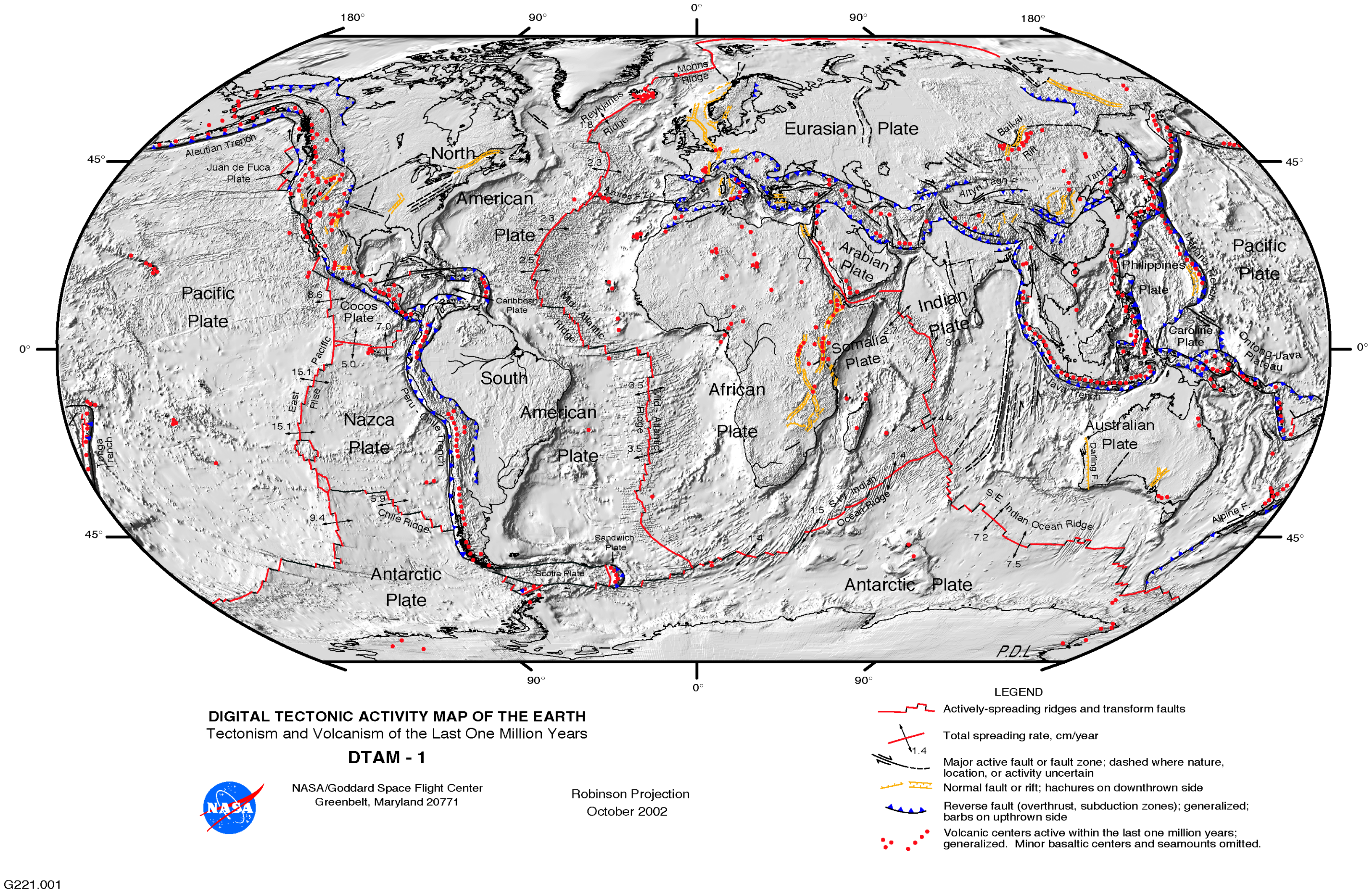
Florent Brenguier

INTRODUCTION

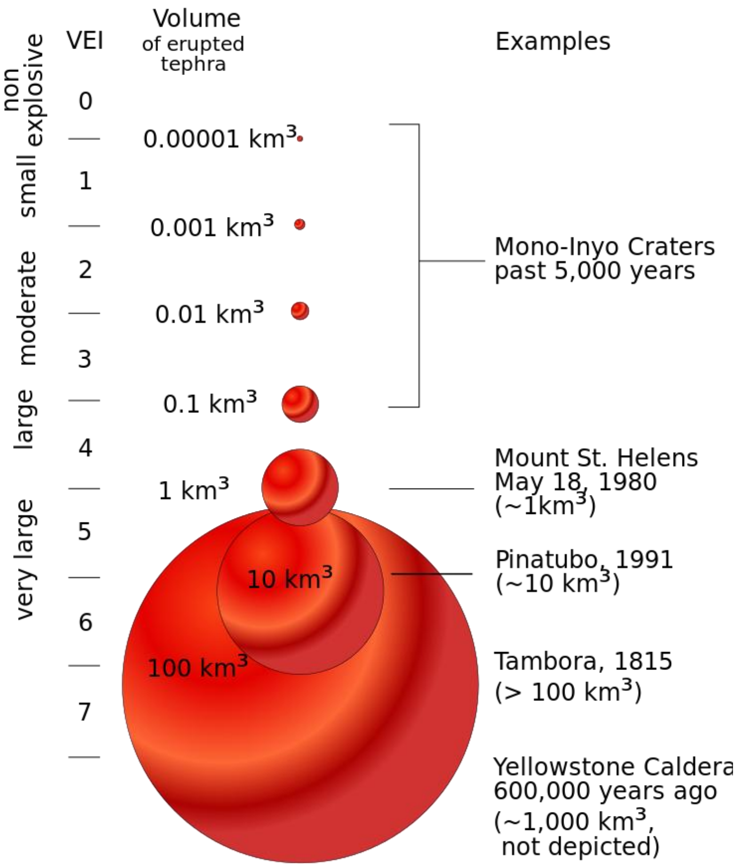
The origin of volcanic activity

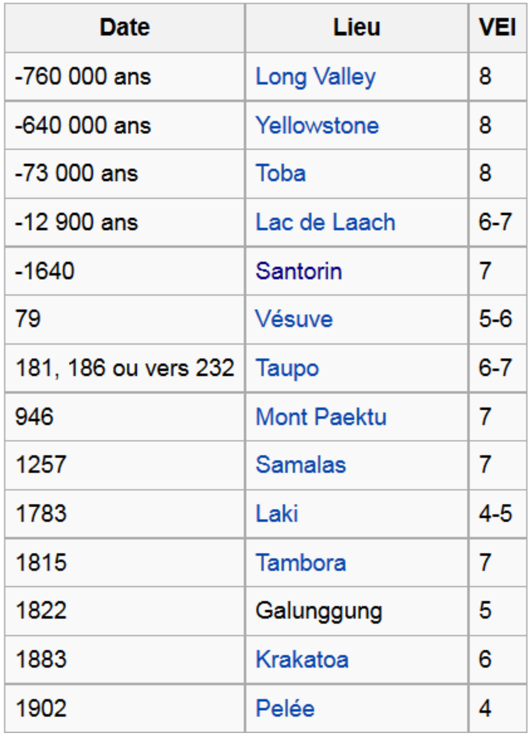


Volcanoes are clustered in active tectonic regions



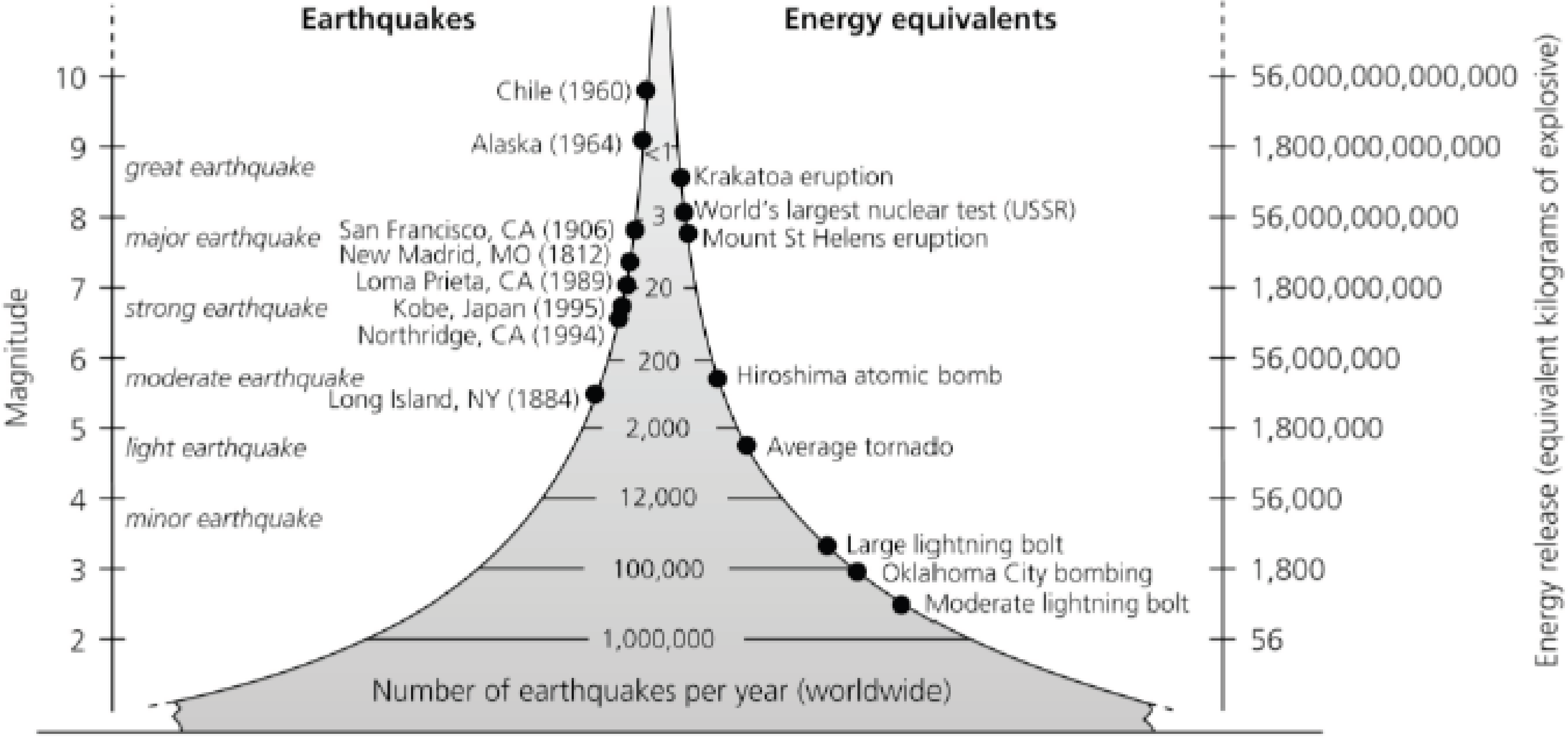
Large historical eruptions





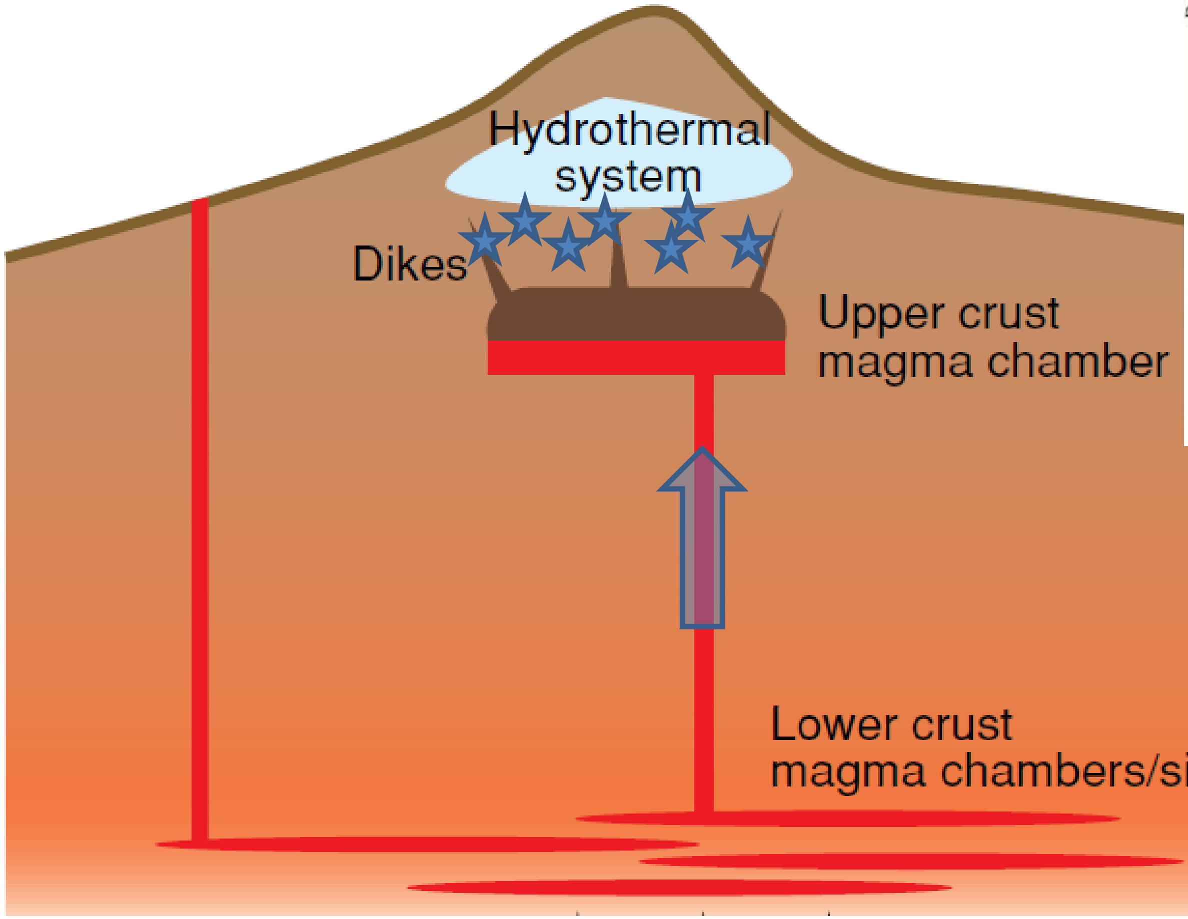
Date	Lieu	VEI
-760 000 ans	Long Valley	8
-640 000 ans	Yellowstone	8
-73 000 ans	Toba	8
-12 900 ans	Lac de Laach	6-7
-1640	Santorin	7
79	Vésuve	5-6
181, 186 ou vers 232	Taupo	6-7
946	Mont Paektu	7
1257	Samalas	7
1783	Laki	4-5
1815	Tambora	7
1822	Galunggung	5
1883	Krakatoa	6
1902	Pelée	4

The energy released by large eruptions

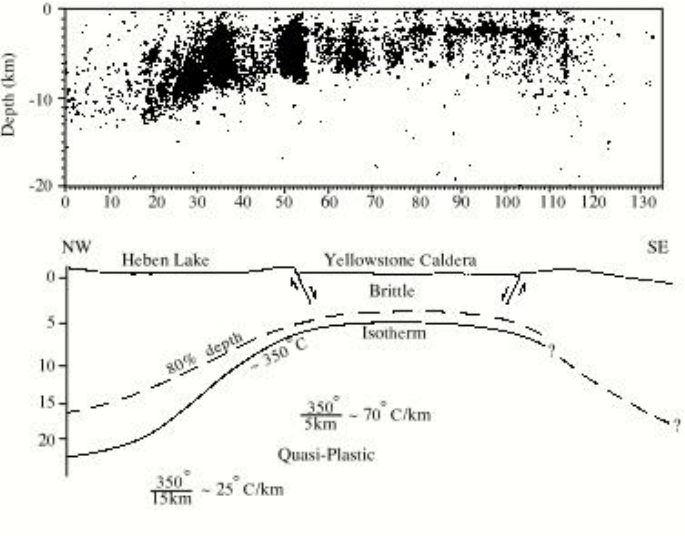


(IRIS)

Magma from the mantle to eruptions

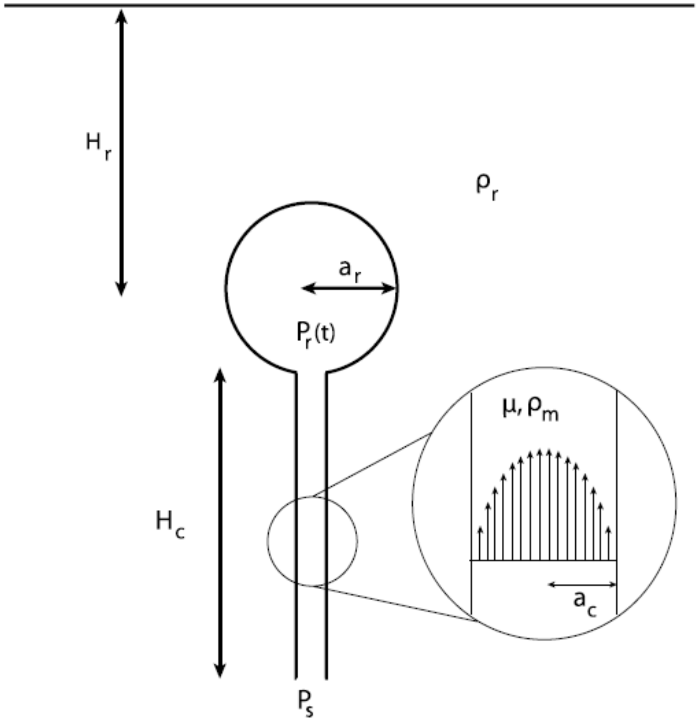


Sketch from Manga and Brodsky, 2006

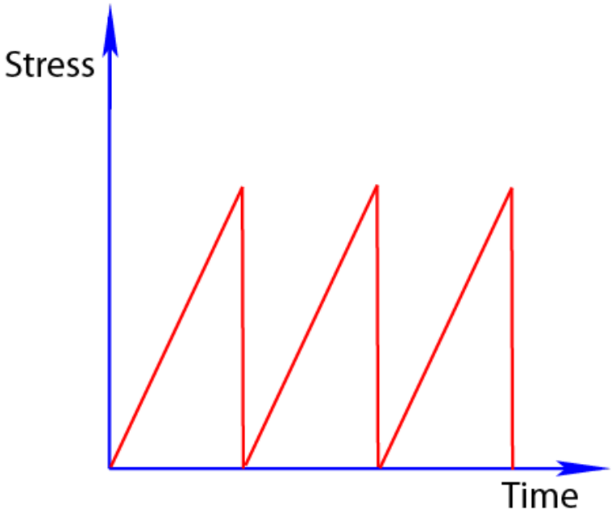


Depth view of Yellowstone's earthquakes

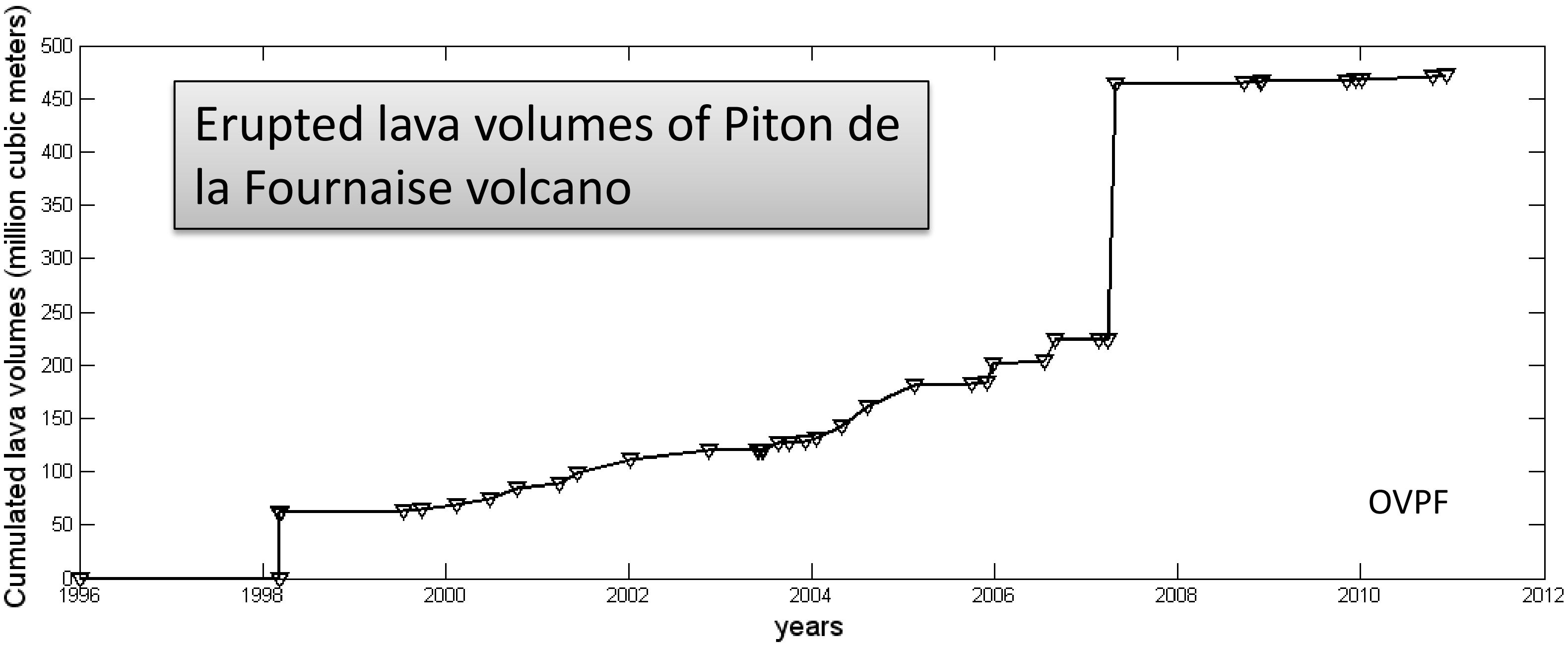
The simplest models of **volcanic systems** predict a **regular temporal distribution** of volcanic eruptions (steady deep processes of magma transport)

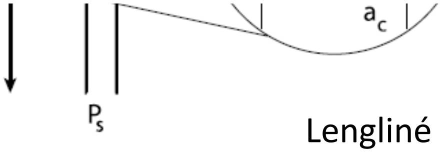


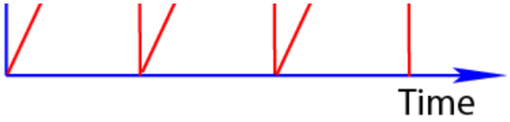
Lengliné et al., *JGR*, 2008



The simplest models of **volcanic systems** predict a **regular temporal distribution** of volcanic eruptions (constant source of pressure)

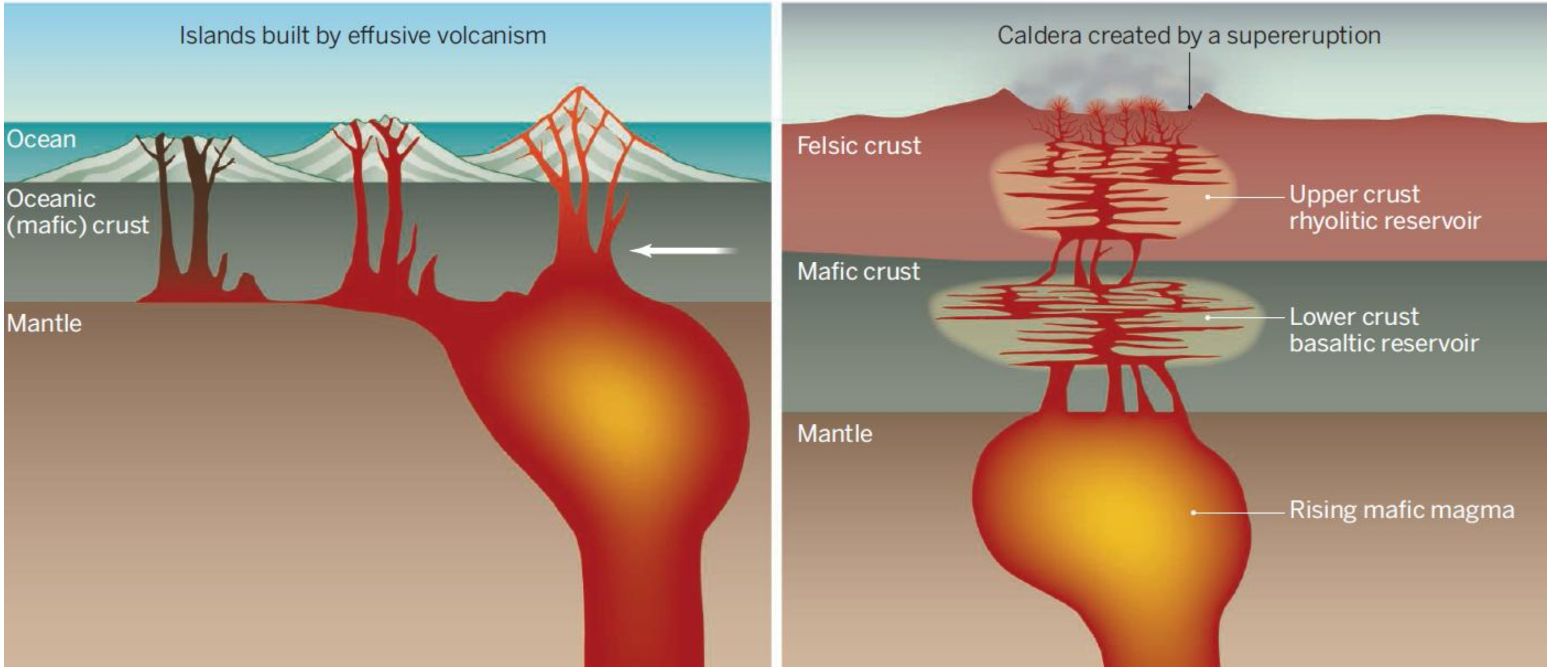

Erupted lava volumes of Piton de la Fournaise volcano





Lengliné et al., *JGR*, 2008

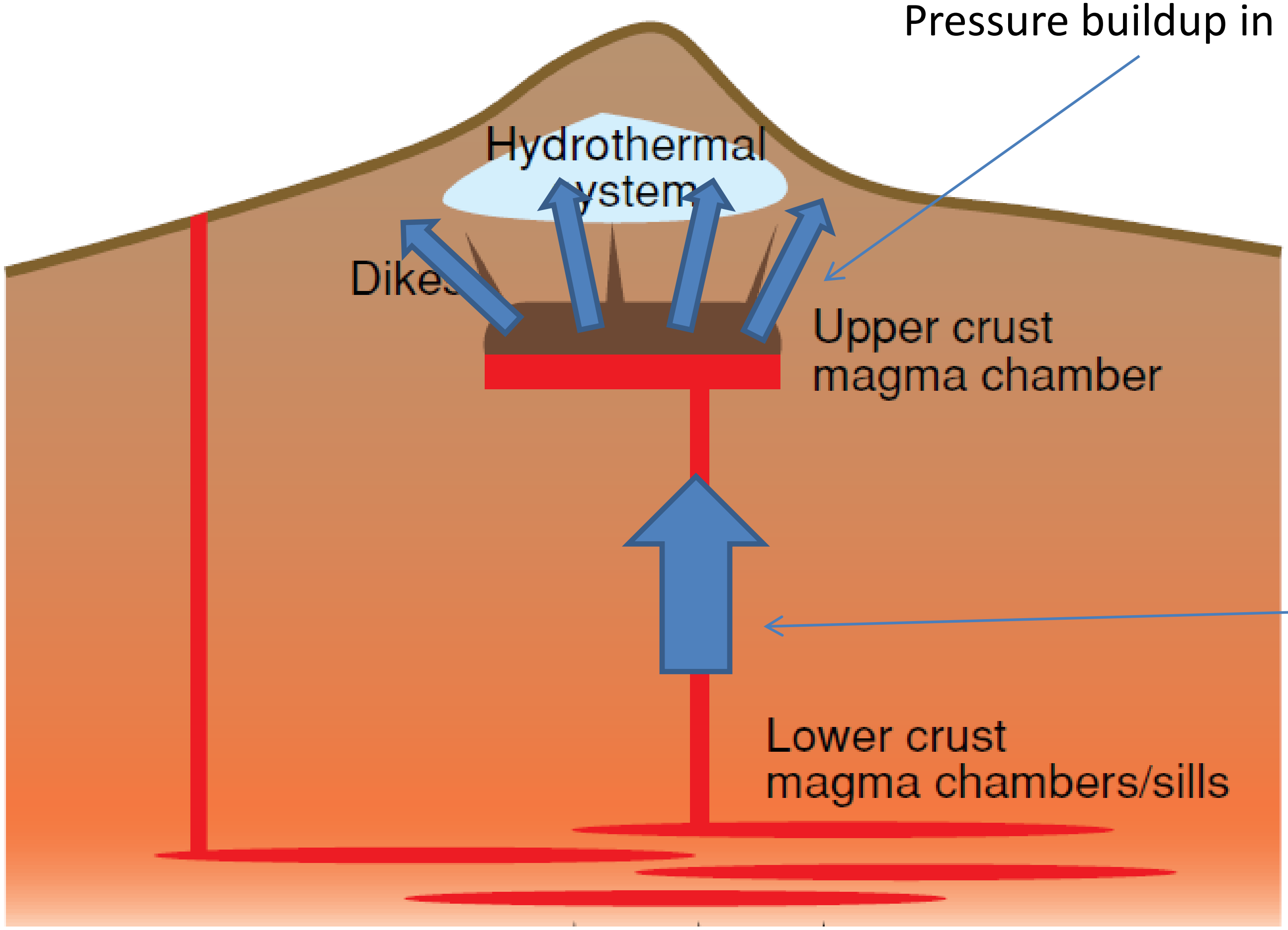
Volcanic systems are complex – Their structure control eruption type



Shapiro, Koulakov, Science, 2015

Heterogeneous structures with different mechanical properties → Need for a 3D imaging

Volcanoes are extremely complex systems with transient processes interacting together

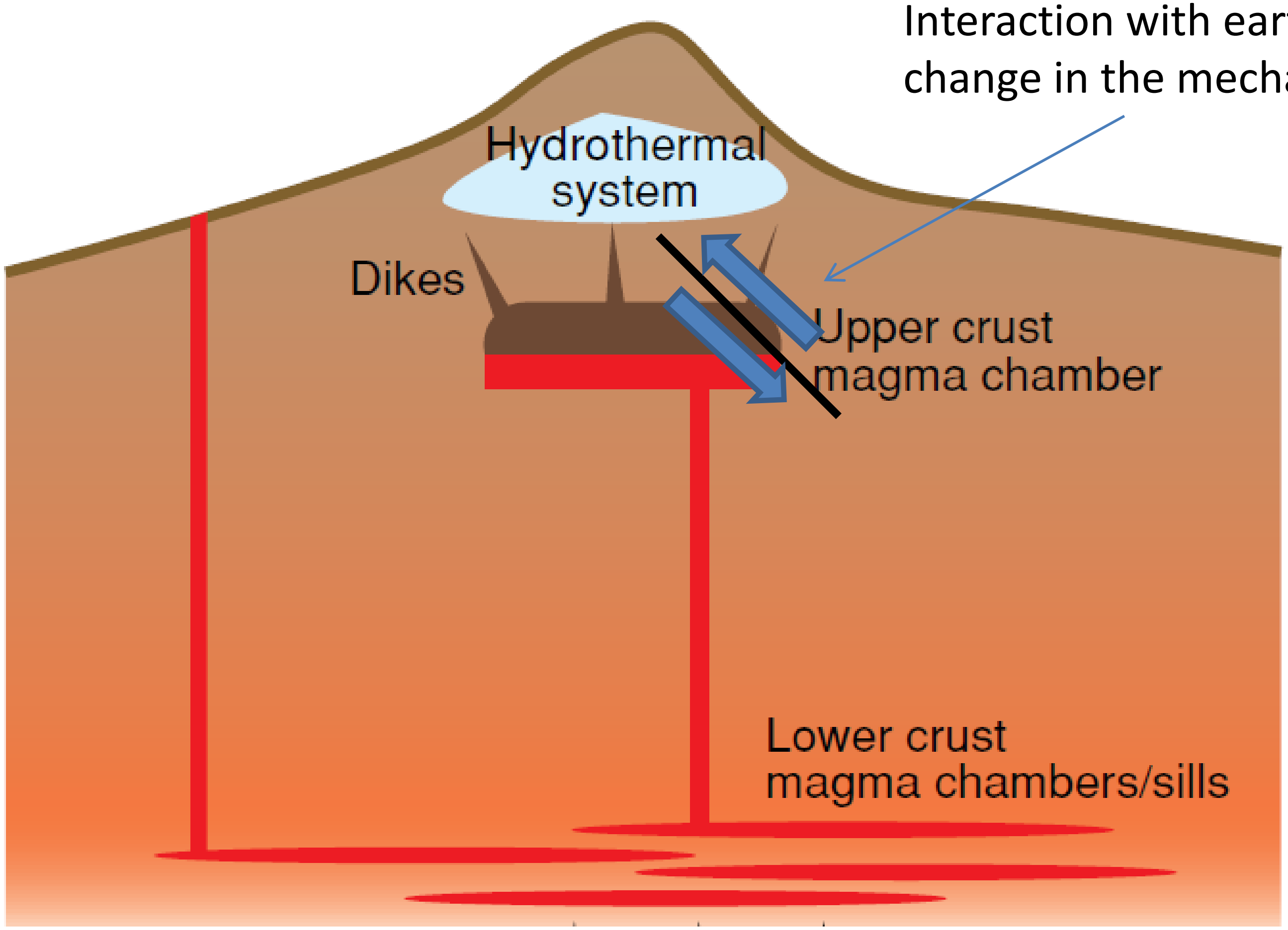


Pressure buildup in reservoirs

Magma transport at depth

Need for a 3D+time (4D) imaging

Volcanoes are extremely complex systems with transient processes interacting together



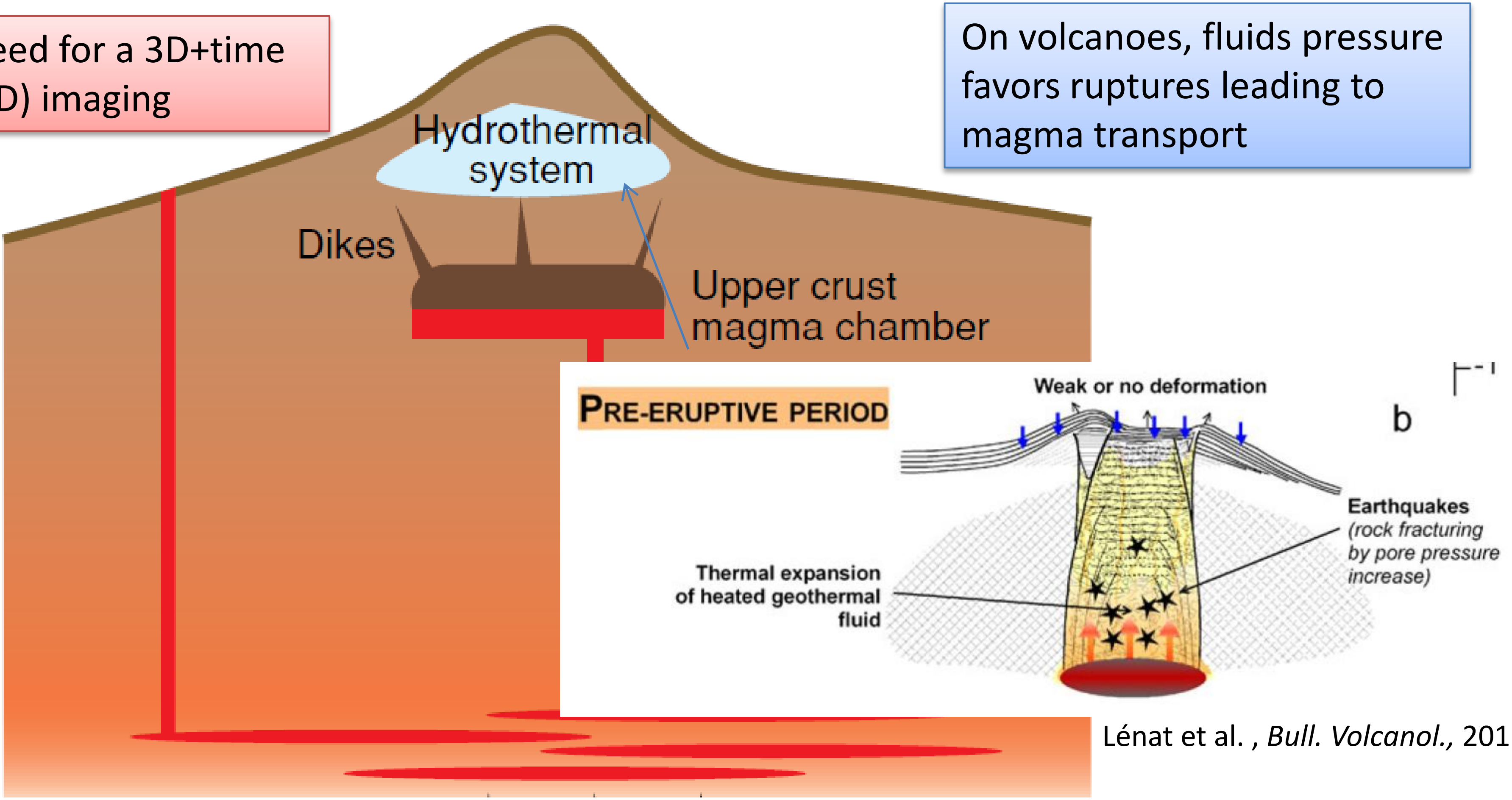
Interaction with earthquakes, rock rupture: change in the mechanical properties

Need for a 3D+time (4D) imaging

Volcanoes are extremely complex systems with transient processes interacting together

Need for a 3D+time (4D) imaging

On volcanoes, fluids pressure favors ruptures leading to magma transport

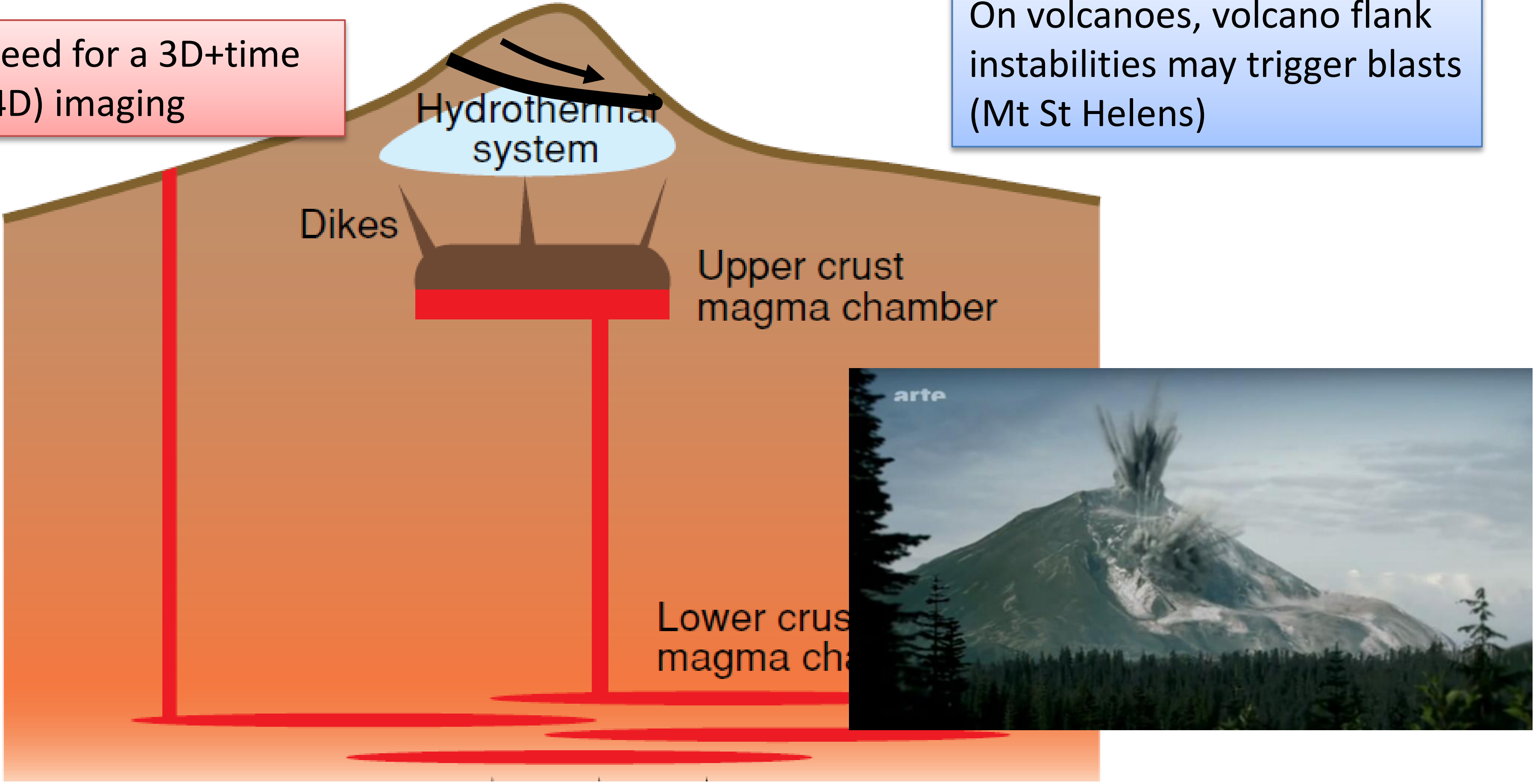


Lénat et al. , *Bull. Volcanol.*, 2011

Volcanoes are extremely complex systems with transient processes interacting together

Need for a 3D+time (4D) imaging

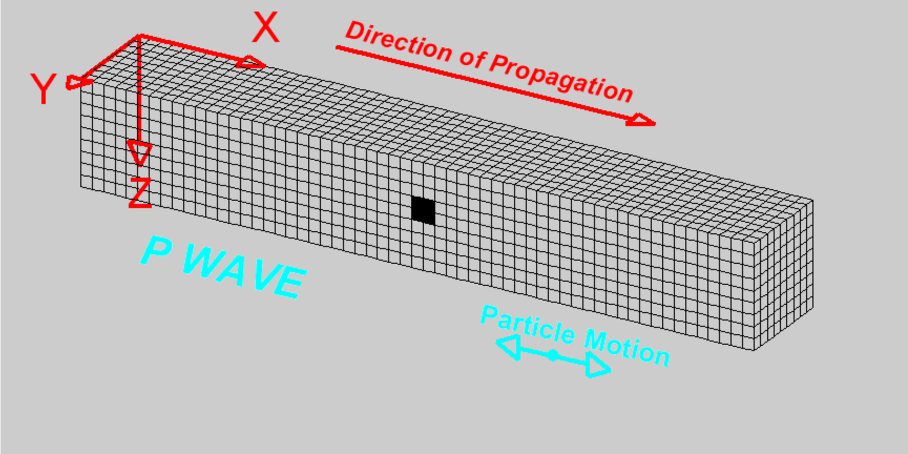
On volcanoes, volcano flank instabilities may trigger blasts (Mt St Helens)



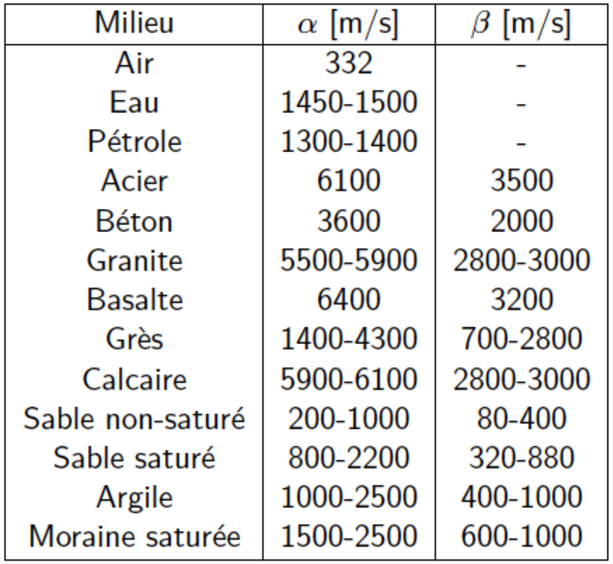
METHOD

3D Tomography

P-waves

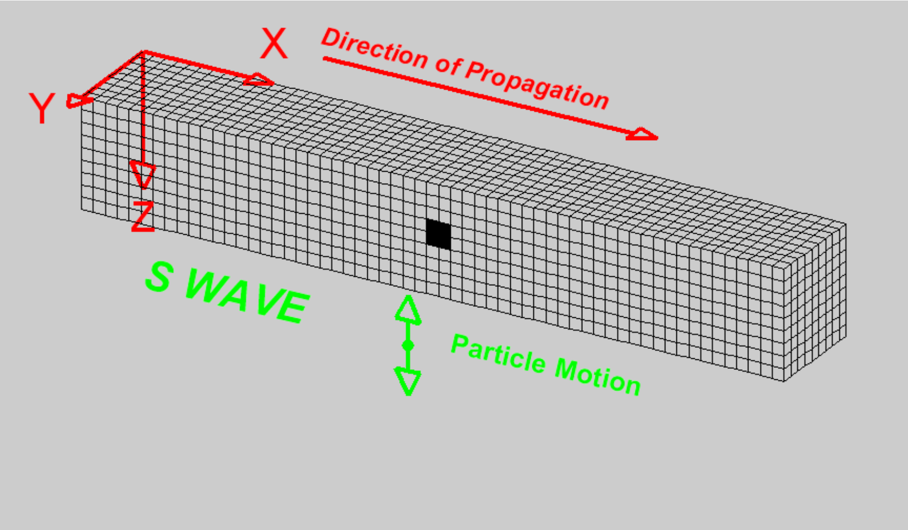


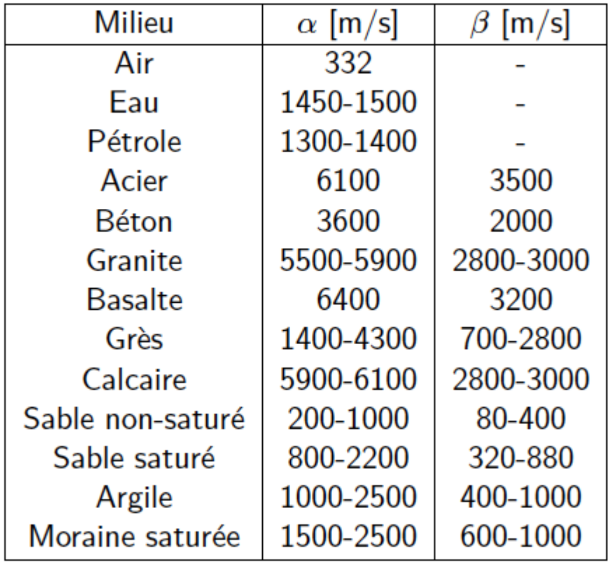
$$\alpha=\sqrt{\frac{\lambda+2\mu}{\rho}}$$



Milieu	α [m/s]	β [m/s]
Air	332	-
Eau	1450-1500	-
Pétrole	1300-1400	-
Acier	6100	3500
Béton	3600	2000
Granite	5500-5900	2800-3000
Basalte	6400	3200
Grès	1400-4300	700-2800
Calcaire	5900-6100	2800-3000
Sable non-saturé	200-1000	80-400
Sable saturé	800-2200	320-880
Argile	1000-2500	400-1000
Moraine saturée	1500-2500	600-1000

S-waves





Milieu	α [m/s]	β [m/s]
Air	332	-
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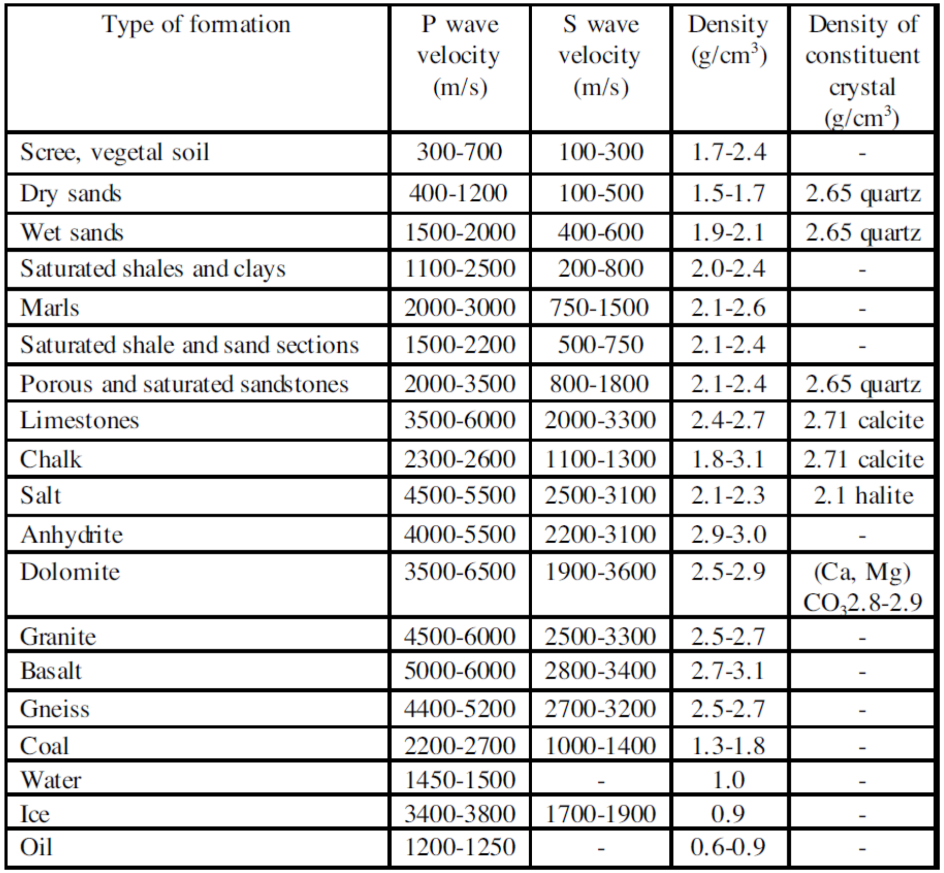
Sable non-saturé	200-1000	80-400
Sable saturé	800-2200	320-880
Argile	1000-2500	400-1000
Moraine saturée	1500-2500	600-1000

$$\boxed{\beta=\sqrt{\frac{\mu}{\rho}}}$$

There is a need to scan the interiors of volcanoes in order to elucidate these ongoing processes



Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm^3)	Density of constituent crystal (g/cm^3)
Scree, vegetal soil	300-700	100-300	1.7-2.4	-
Dry sands	400-1200	100-500	1.5-1.7	2.65 quartz
Wet sands	1500-2000	400-600	1.9-2.1	2.65 quartz
Saturated shales and clays	1100-2500	200-800	2.0-2.4	-
Marls	2000-3000	750-1500	2.1-2.6	-
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4	-
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4	2.65 quartz
Limestones	3500-6000	2000-3300	2.4-2.7	2.71 calcite
Chalk	2300-2600	1100-1300	1.8-3.1	2.71 calcite
Salt	4500-5500	2500-3100	2.1-2.3	2.1 halite
Anhydrite	4000-5500	2200-3100	2.9-3.0	-
Dolomite	3500-6500	1900-3600	2.5-2.9	(Ca, Mg) $CO_3$2.8-2.9
Granite	4500-6000	2500-3300	2.5-2.7	-
Basalt	5000-6000	2800-3400	2.7-3.1	-
Gneiss	4400-5200	2700-3200	2.5-2.7	-
Coal	2200-2700	1000-1400	1.3-1.8	-
Water	1450-1500	-	1.0	-
Ice	3400-3800	1700-1900	0.9	-
Oil	1200-1250	-	0.6-0.9	-

→ Seismic tomography

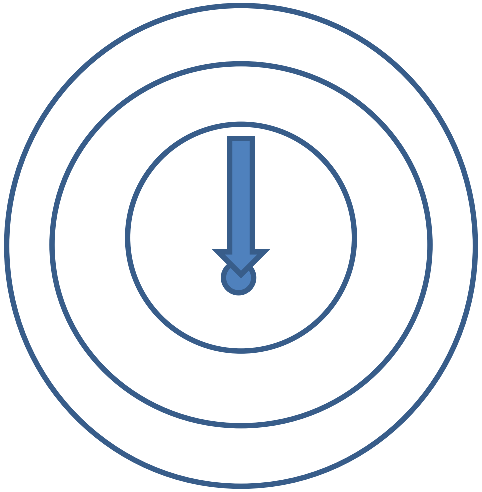
La fonction de Green : réponse du milieu à une force ponctuelle

Solution

$$u(x,t) = \boxed{G(x,t;xo,to)} \otimes \boxed{f(xo,to)}$$

Fonction de Green

Forces appliquées



$$\varphi(R,t) = \frac{1}{4\pi\rho\alpha^2}\frac{1}{R}f\left(t-\frac{R}{\alpha}\right)$$

$$u_i(\mathbf{x},t) = X_0 * G_{ij} \qquad \text{(in the notation of Chapter 3)}$$

$$= \boxed{\frac{1}{4\pi\rho}\left(3\gamma_i\gamma_j-\delta_{ij}\right)\frac{1}{r^3}\int_{r/\alpha}^{r/\beta}\tau X_0(t-\tau)\,d\tau}$$

$$+\boxed{\frac{1}{4\pi\rho\alpha^2}\gamma_i\gamma_j\frac{1}{r}X_0\left(t-\frac{r}{\alpha}\right)} - \boxed{\frac{1}{4\pi\rho\beta^2}\left(\gamma_i\gamma_j-\delta_{ij}\right)\frac{1}{r}X_0\left(t-\frac{r}{\beta}\right)}.$$

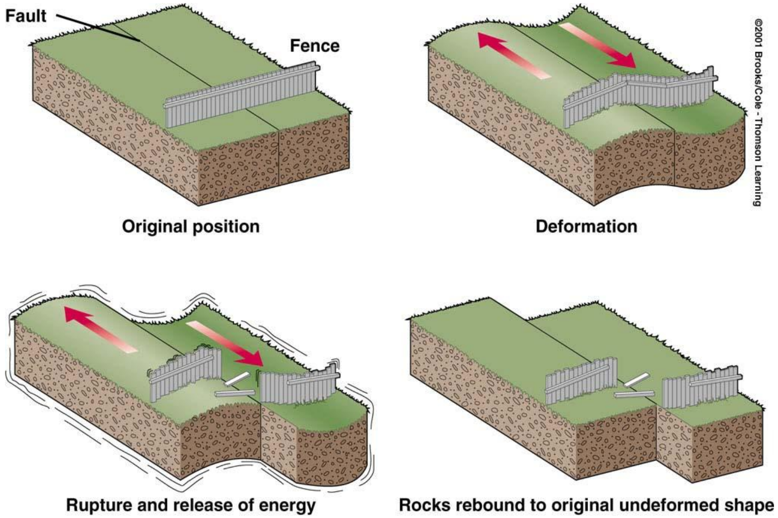
Champ proche

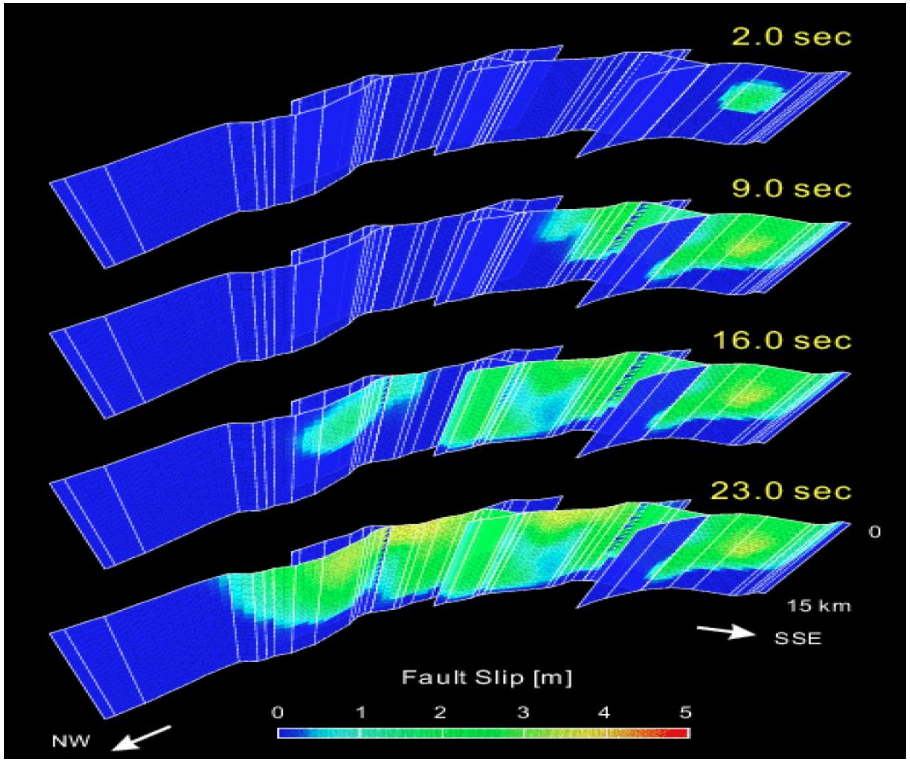
Onde P

Onde S

Aki and Richard

Seismic waves - source

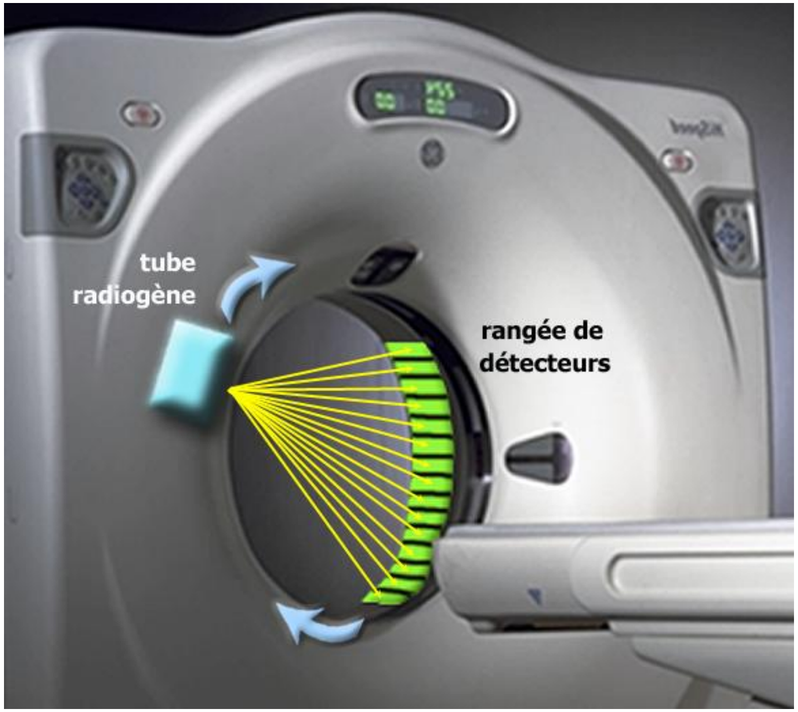




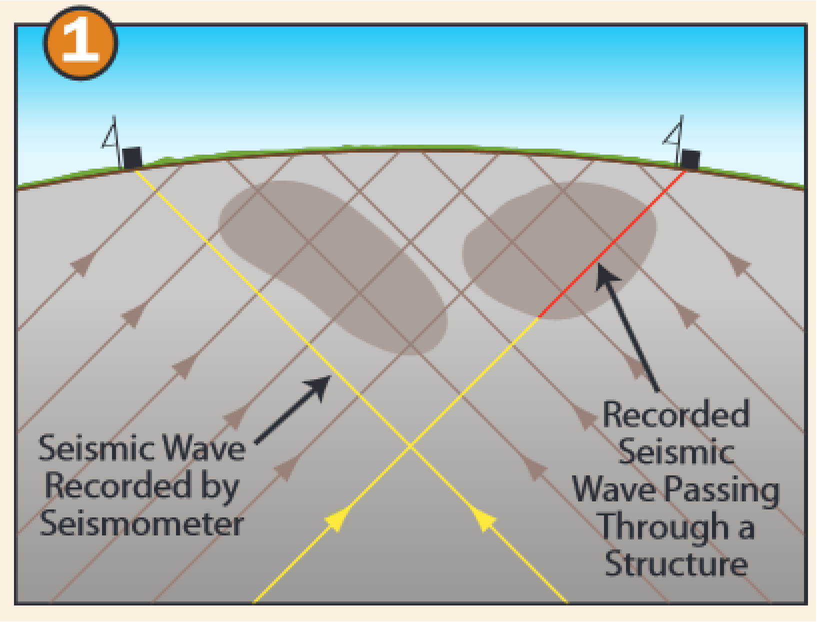
Aochi et al. 2003

Method - tomography

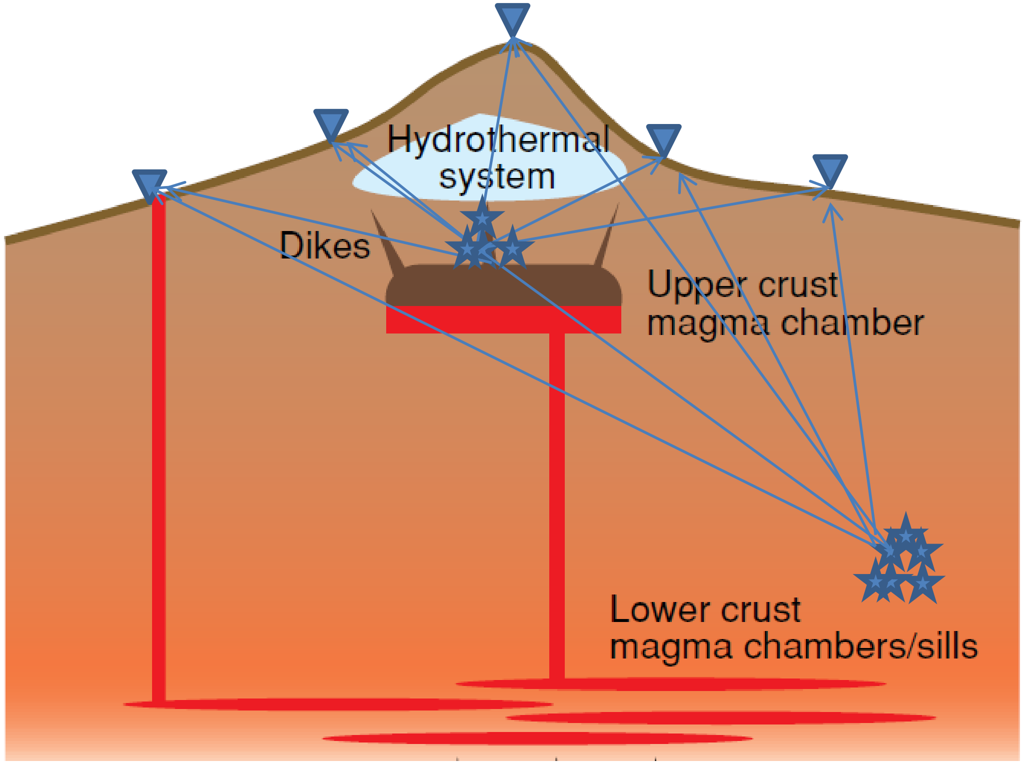
Computed Tomography scanner

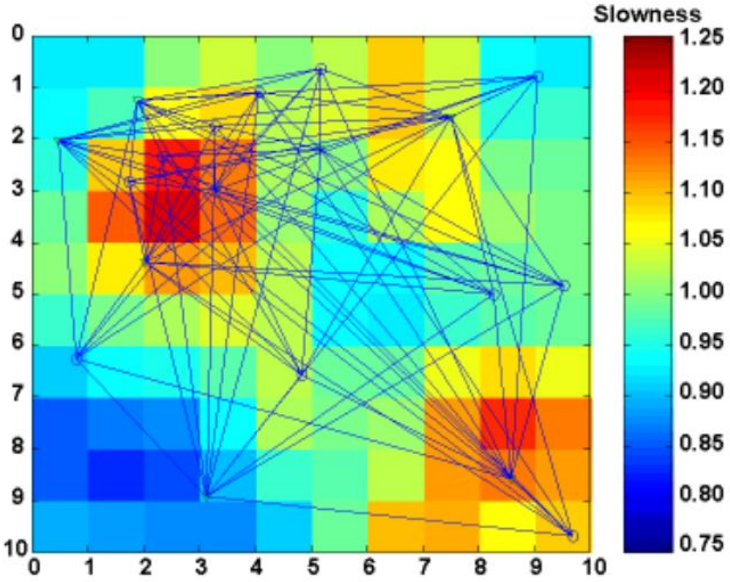


Seismic tomography



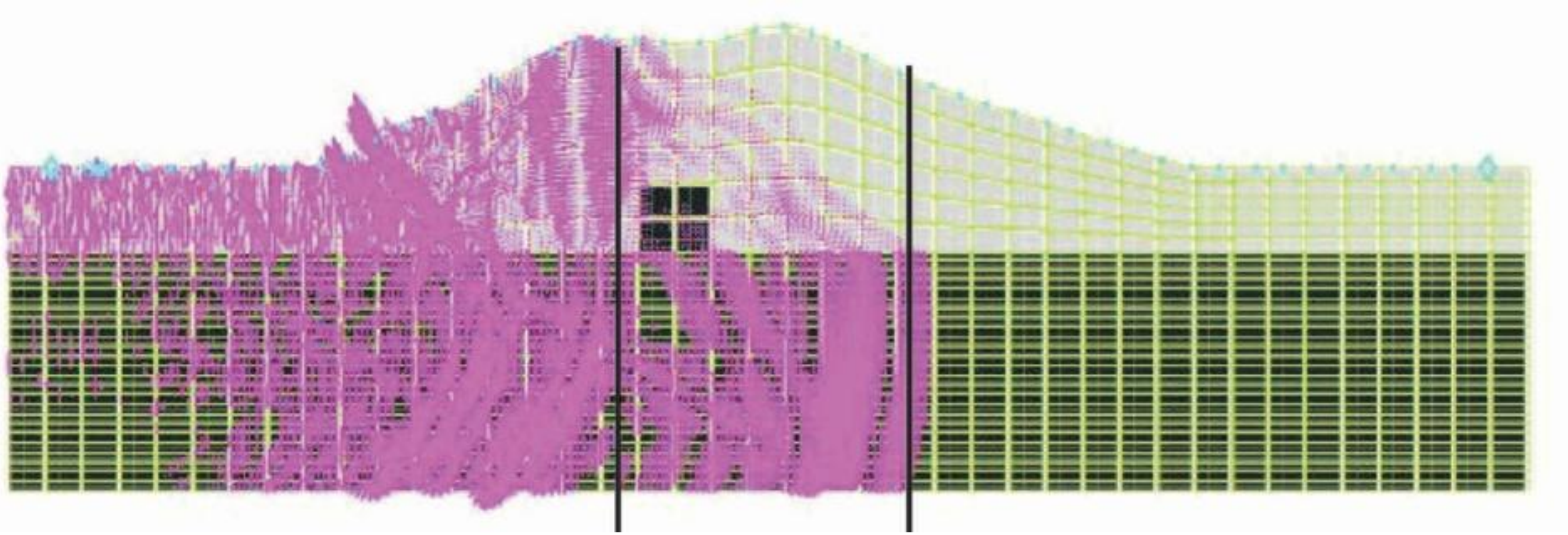
Earthquakes as seismic sources
Highly underdetermined system
(fewer equations than unknown)



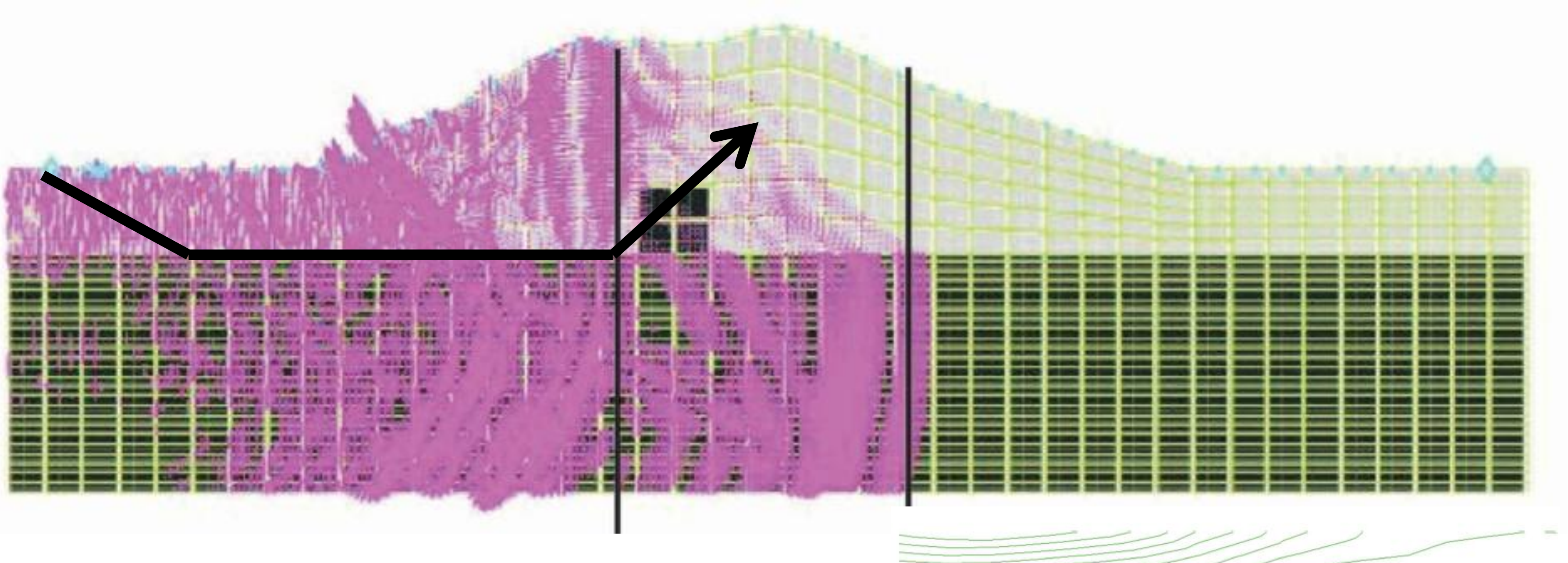


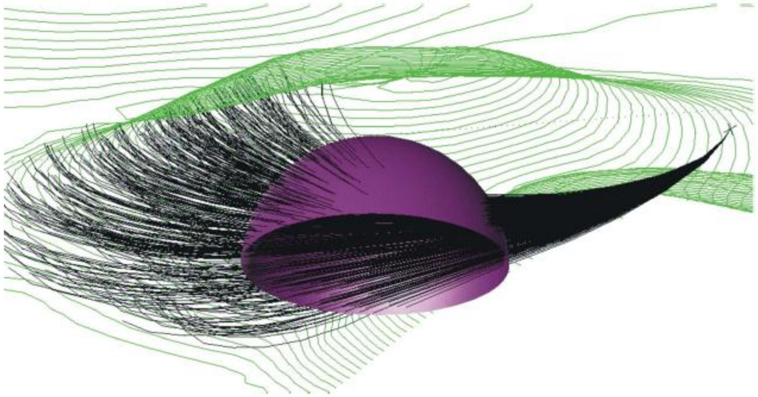
- ✓ Unknown position of the sources
- ✓ Sources are clustered in space

Uncertainty from limitations of the ray theory

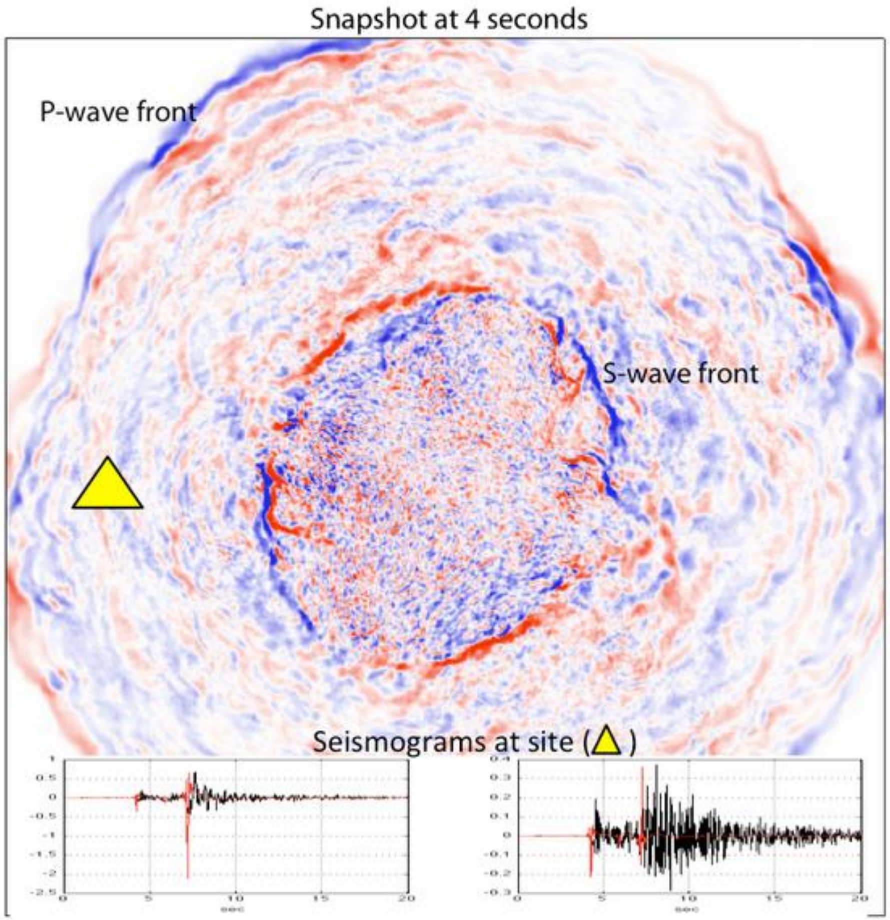


Uncertainty from limitations of the ray theory



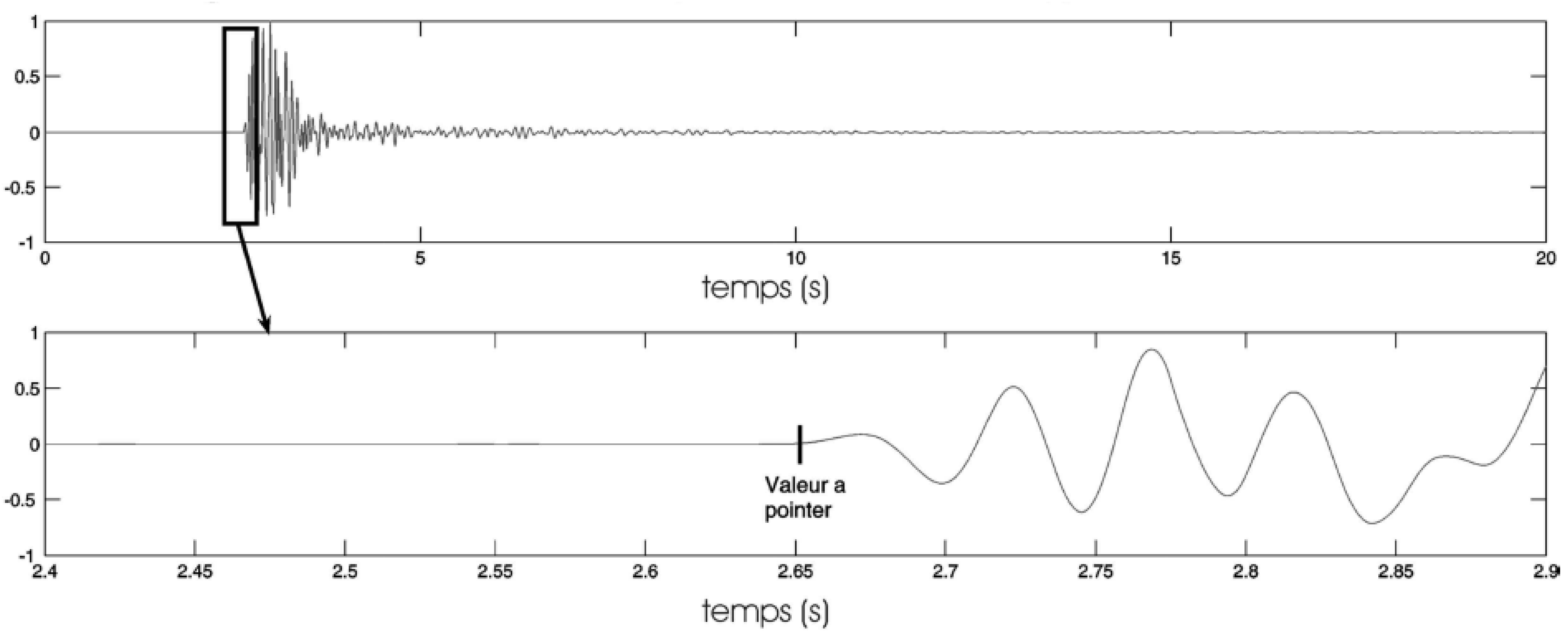


Uncertainty from limitations of the ray theory

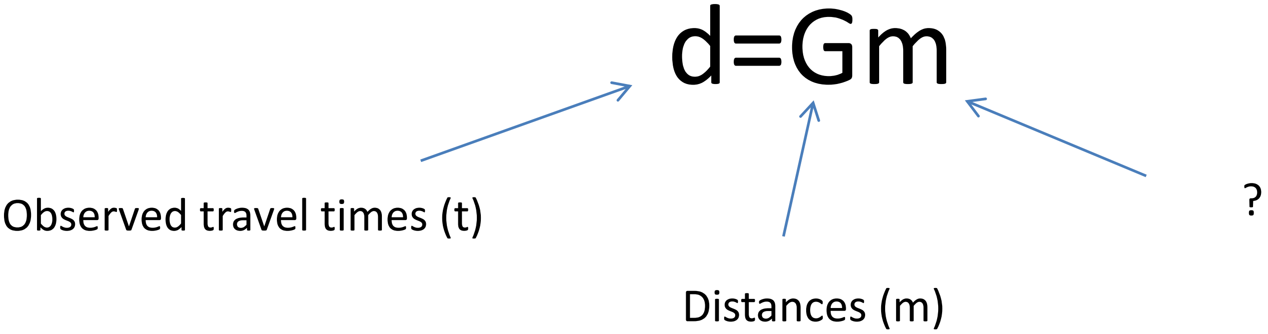


- ✓ Scattering plays a key role in wavefront healing

Uncertainty on observation



Inversion for a velocity model



$$d = Gm$$

Observed travel times (t)

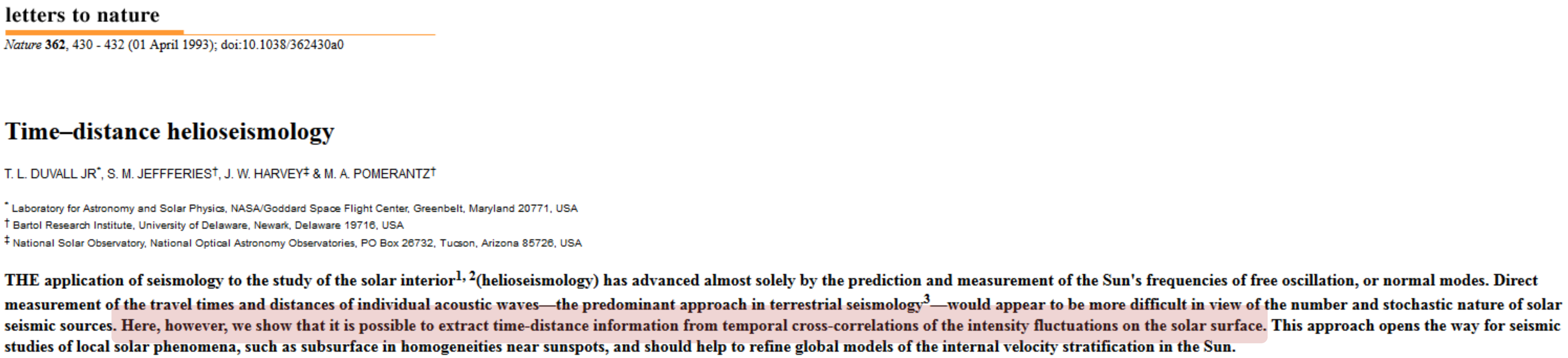
Distances (m)

?

$$m = \left(G^t C_d^{-1} G + \alpha . C_m^{-1}\right)^{-1} G^t C_d^{-1} d$$

Tarantola, 2002

Source-less seismology: a revolution



letters to nature

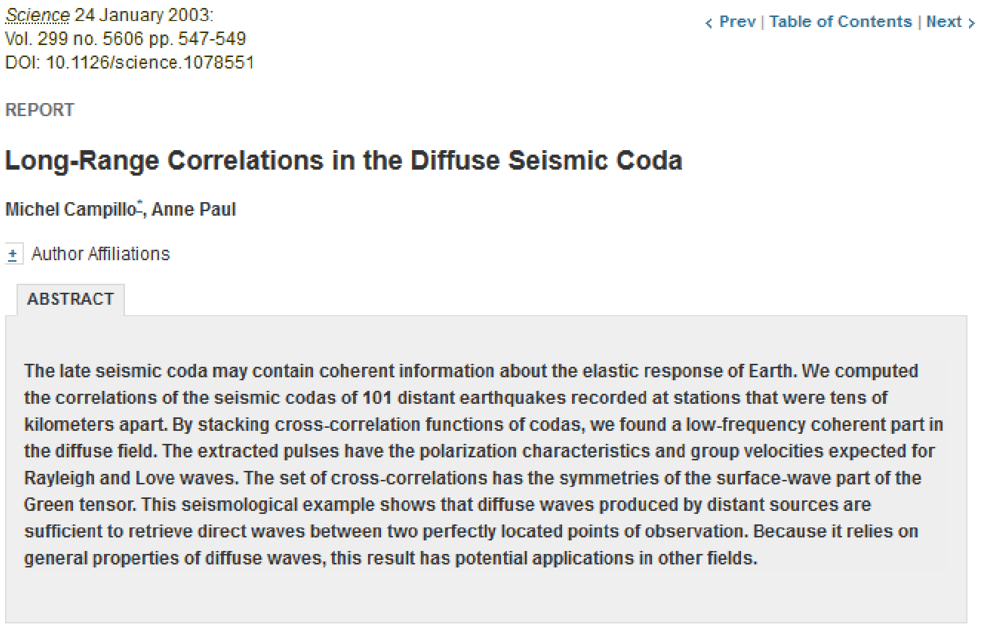
Nature **362**, 430 - 432 (01 April 1993); doi:10.1038/362430a0

Time–distance helioseismology

T. L. DUVALL JR[*], S. M. JEFFFERIES[†], J. W. HARVEY[‡] & M. A. POMERANTZ[†]

[*] Laboratory for Astronomy and Solar Physics, NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
[†] Bartol Research Institute, University of Delaware, Newark, Delaware 19716, USA
[‡] National Solar Observatory, National Optical Astronomy Observatories, PO Box 26732, Tucson, Arizona 85726, USA

THE application of seismology to the study of the solar interior[1, 2](helioseismology) has advanced almost solely by the prediction and measurement of the Sun's frequencies of free oscillation, or normal modes. Direct measurement of the travel times and distances of individual acoustic waves—the predominant approach in terrestrial seismology[3]—would appear to be more difficult in view of the number and stochastic nature of solar seismic sources. Here, however, we show that it is possible to extract time-distance information from temporal cross-correlations of the intensity fluctuations on the solar surface. This approach opens the way for seismic studies of local solar phenomena, such as subsurface in homogeneities near sunspots, and should help to refine global models of the internal velocity stratification in the Sun.



Science 24 January 2003:
Vol. 299 no. 5606 pp. 547-549
DOI: 10.1126/science.1078551

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REPORT

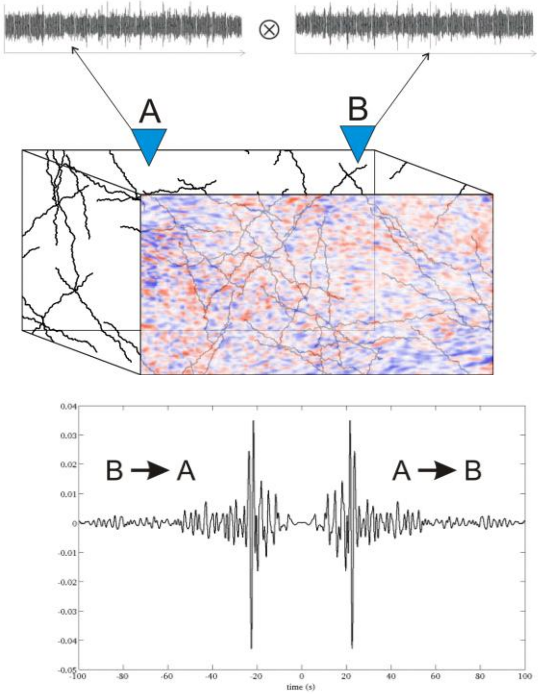
Long-Range Correlations in the Diffuse Seismic Coda

Michel Campillo[*], Anne Paul

± Author Affiliations

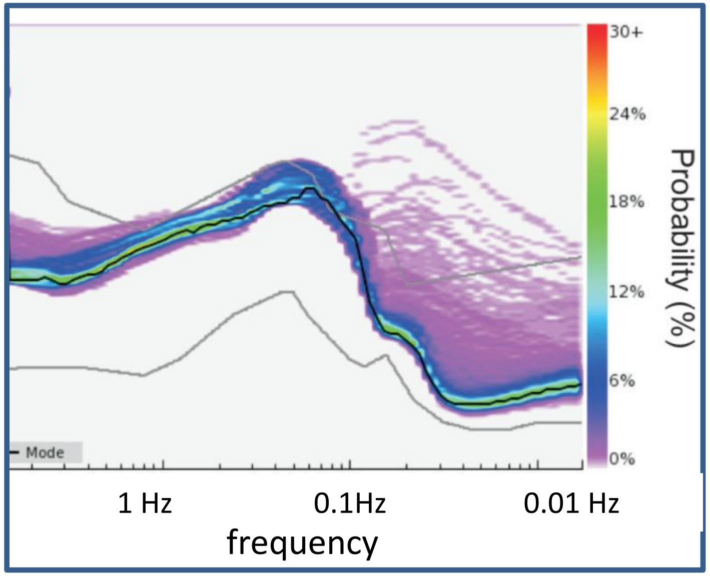
ABSTRACT

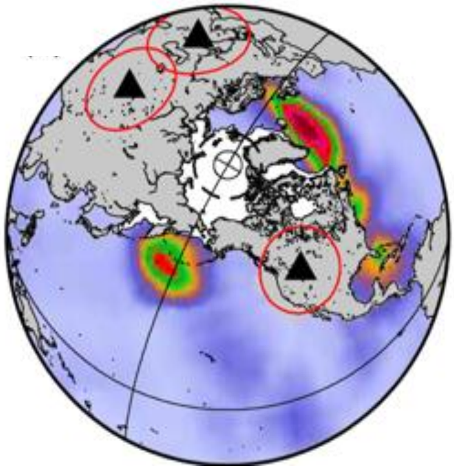
The late seismic coda may contain coherent information about the elastic response of Earth. We computed the correlations of the seismic codas of 101 distant earthquakes recorded at stations that were tens of kilometers apart. By stacking cross-correlation functions of codas, we found a low-frequency coherent part in the diffuse field. The extracted pulses have the polarization characteristics and group velocities expected for Rayleigh and Love waves. The set of cross-correlations has the symmetries of the surface-wave part of the Green tensor. This seismological example shows that diffuse waves produced by distant sources are sufficient to retrieve direct waves between two perfectly located points of observation. Because it relies on general properties of diffuse waves, this result has potential applications in other fields.



Seismic noise on Earth

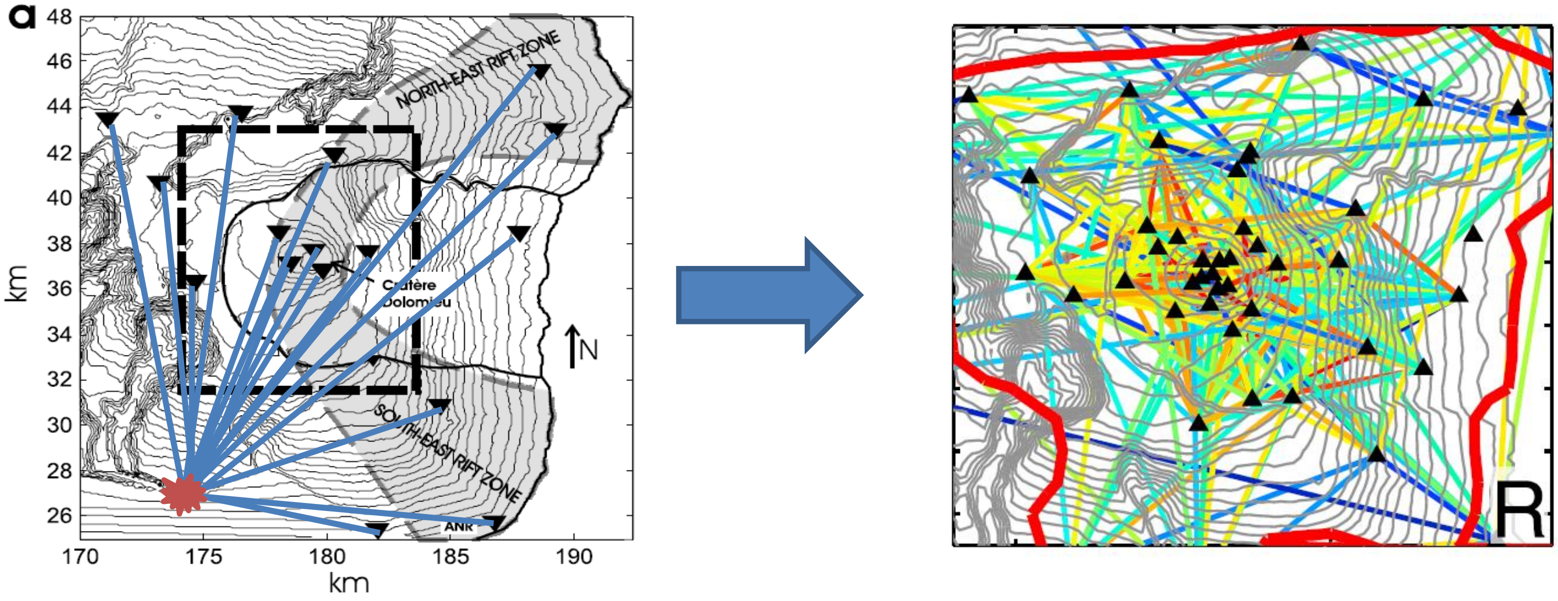
Spectrum of seismic noise



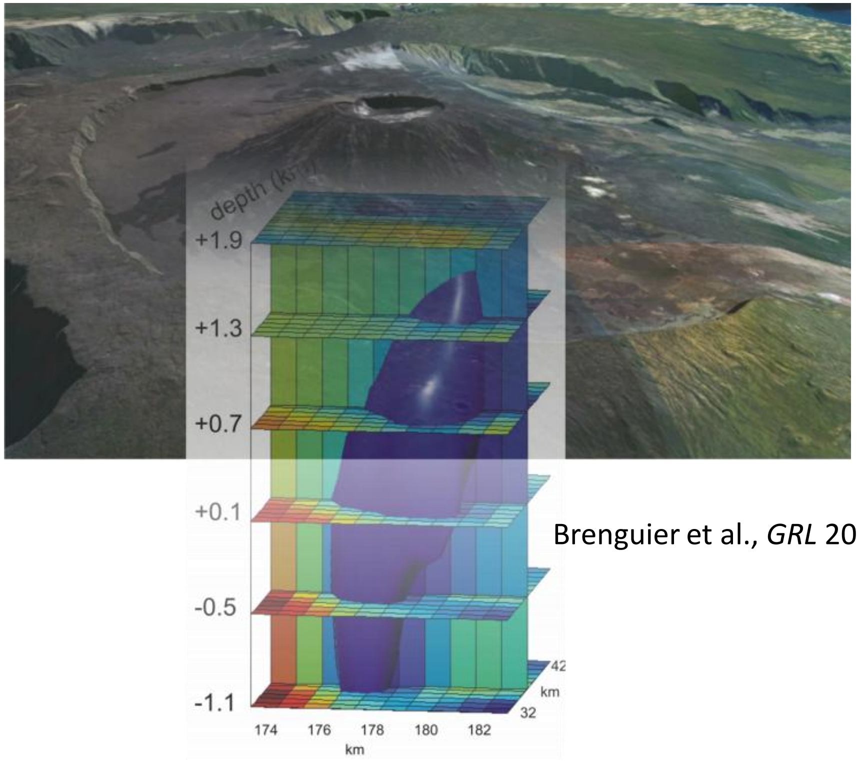


Hillers et al., *GGG*, 2012

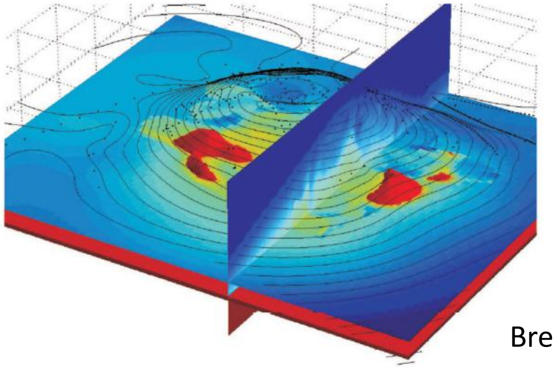
Increased number of ray paths



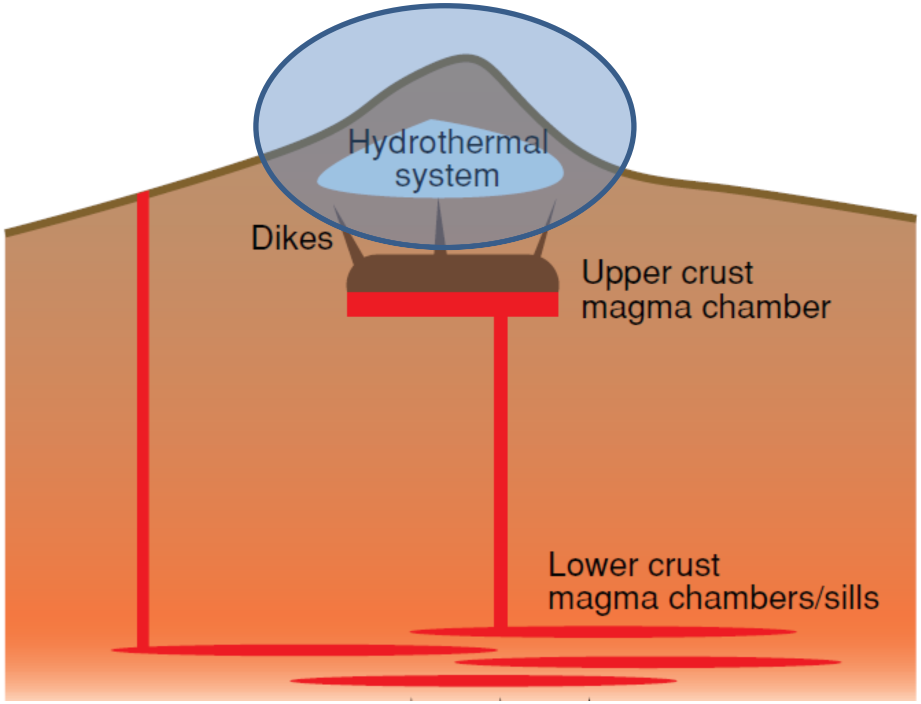
Tomography results on volcanoes – the edifice



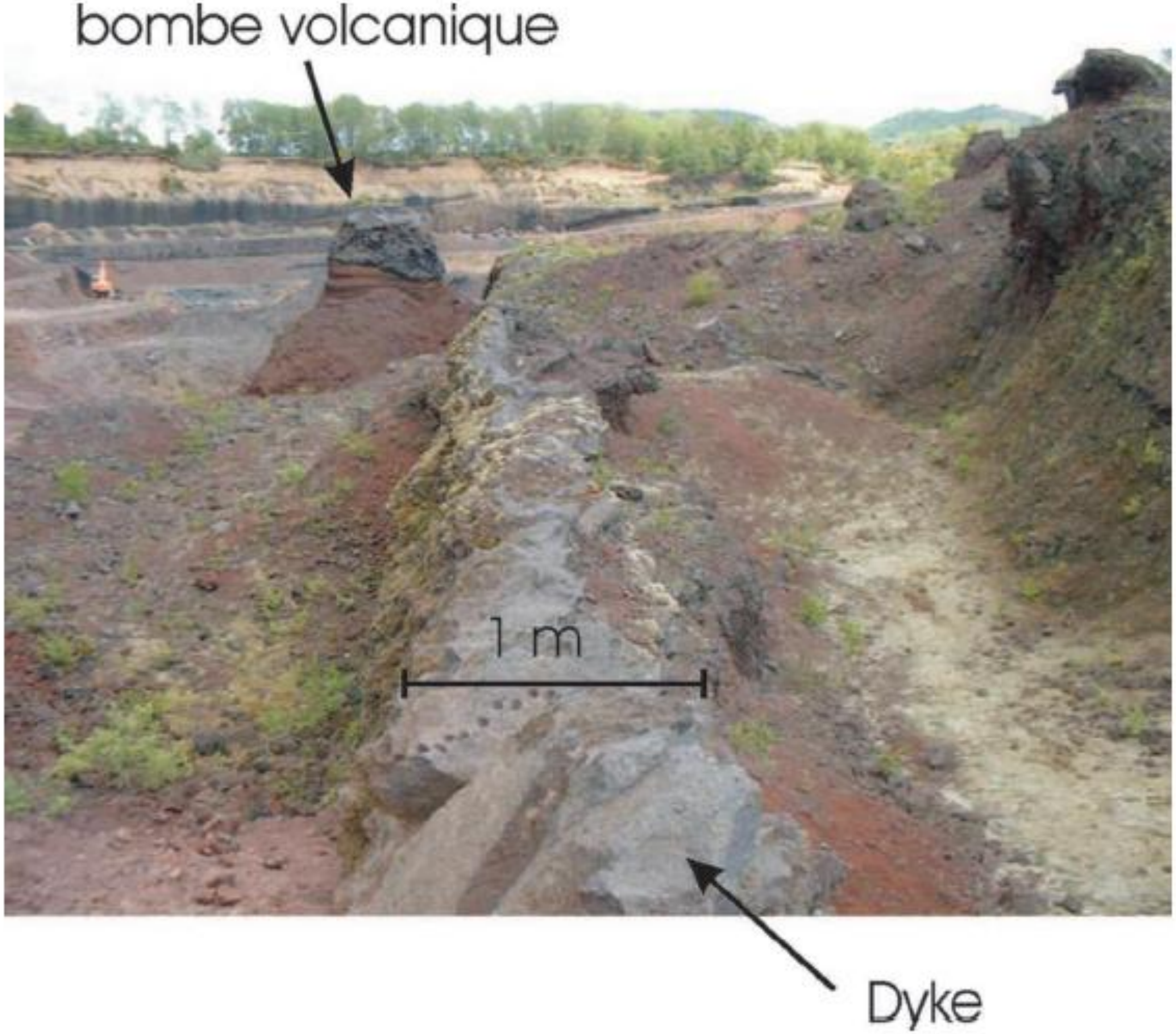
Brenguier et al., *GRL* 2007



Brenguier et al., *GRL*, 2006

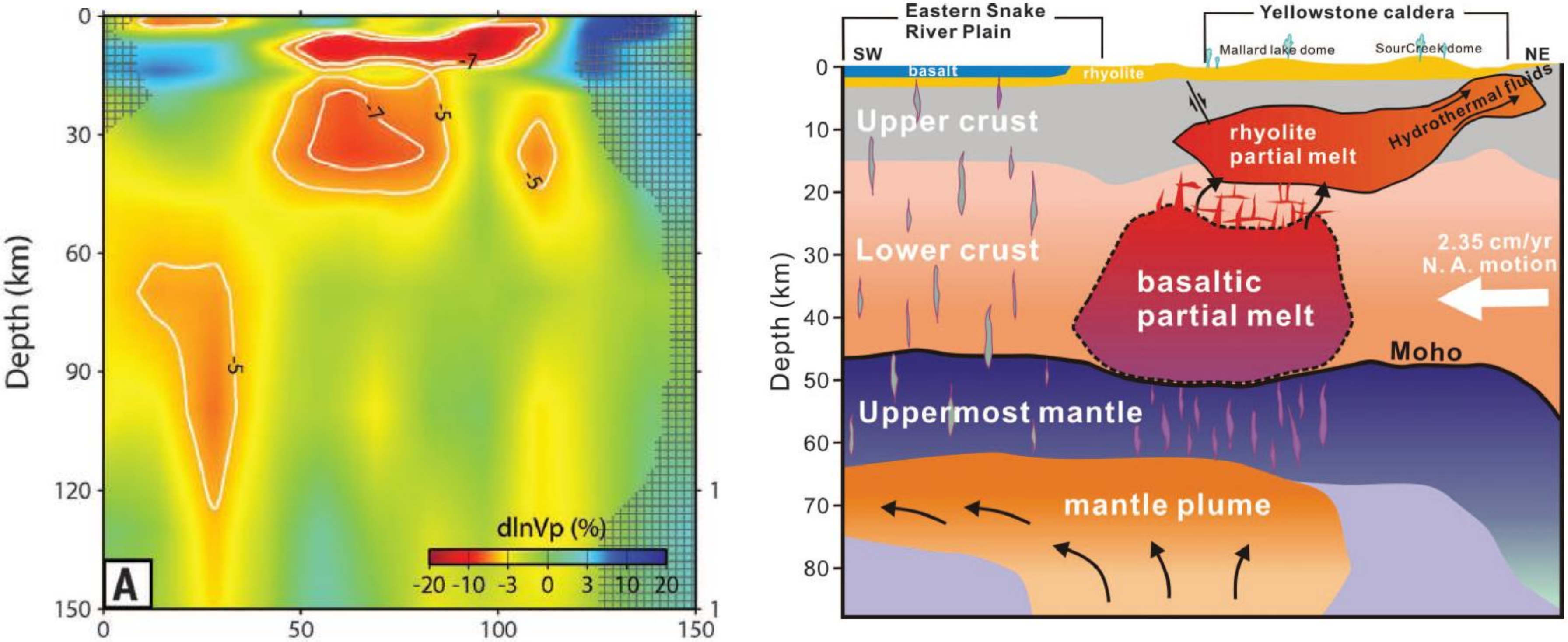


Where is this picture taken?



Tomography results on volcanoes – the crust

Yellowstone



Huang et al. Science 2015

METHOD

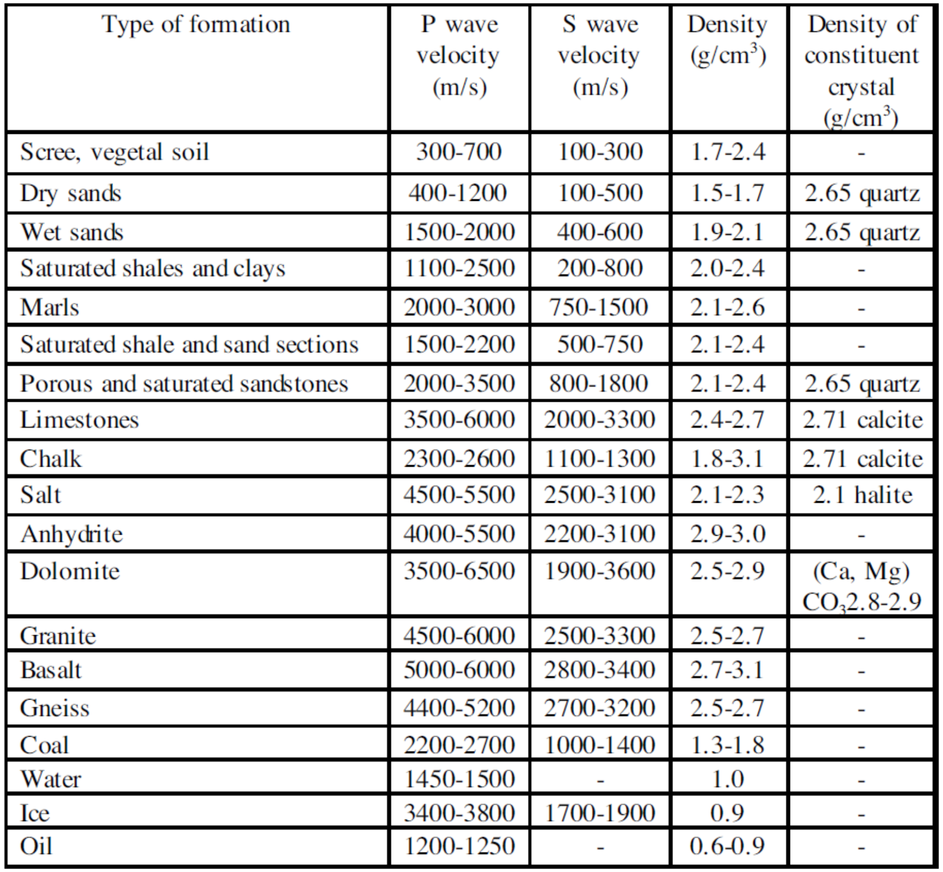
4D Tomography
(3D + time)

There is a need to scan the interiors of volcanoes in order to elucidate these ongoing processes

Seismic tomography

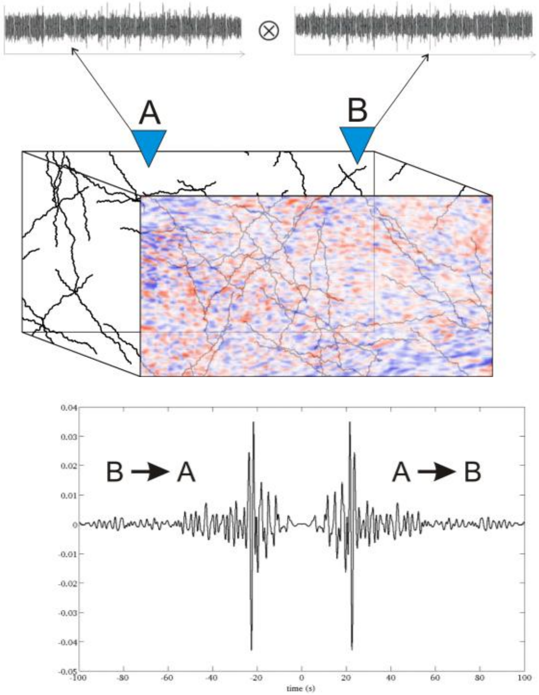
Seismic velocities are sensitive to:

- ✓ Stress changes (stress-meter)
- ✓ temperature changes
- ✓ Fluid content
- ✓ Crack density

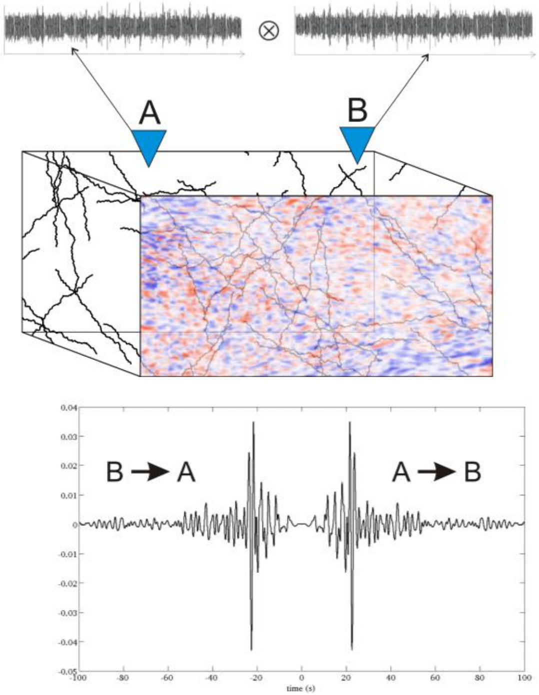


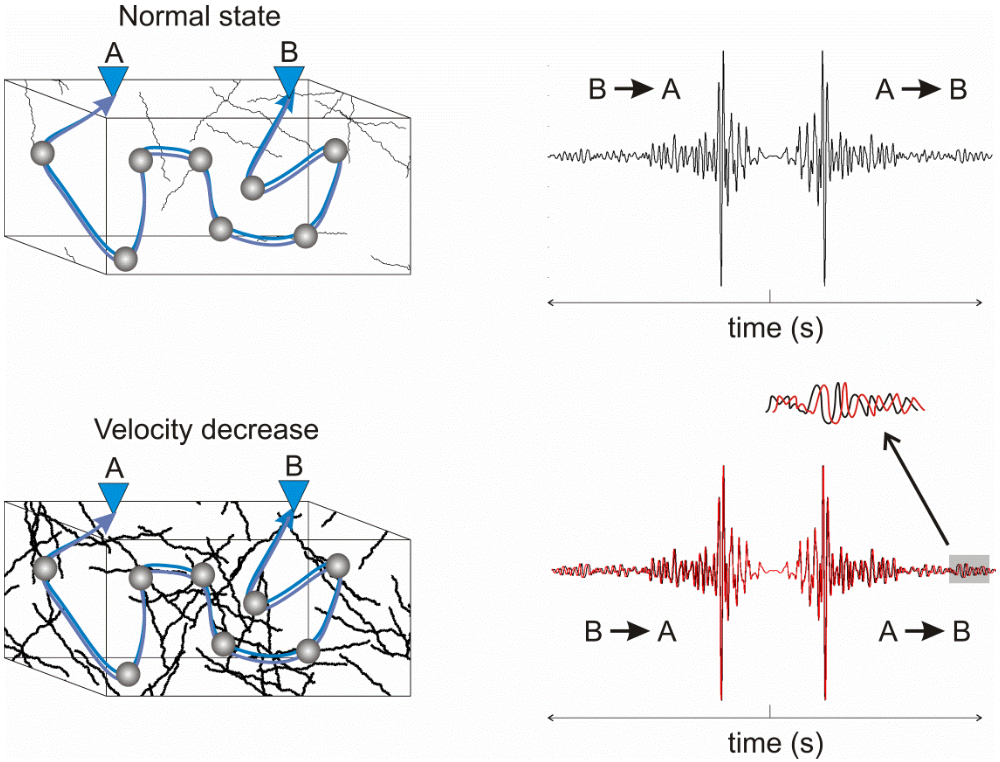
Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm^3)	Density of constituent crystal (g/cm^3)
Scree, vegetal soil	300-700	100-300	1.7-2.4	-
Dry sands	400-1200	100-500	1.5-1.7	2.65 quartz
Wet sands	1500-2000	400-600	1.9-2.1	2.65 quartz
Saturated shales and clays	1100-2500	200-800	2.0-2.4	-
Marls	2000-3000	750-1500	2.1-2.6	-
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4	-
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4	2.65 quartz
Limestones	3500-6000	2000-3300	2.4-2.7	2.71 calcite
Chalk	2300-2600	1100-1300	1.8-3.1	2.71 calcite
Salt	4500-5500	2500-3100	2.1-2.3	2.1 halite
Anhydrite	4000-5500	2200-3100	2.9-3.0	-
Dolomite	3500-6500	1900-3600	2.5-2.9	(Ca, Mg) CO$_3$2.8-2.9
Granite	4500-6000	2500-3300	2.5-2.7	-
Basalt	5000-6000	2800-3400	2.7-3.1	-
Gneiss	4400-5200	2700-3200	2.5-2.7	-
Coal	2200-2700	1000-1400	1.3-1.8	-
Water	1450-1500	-	1.0	-
Ice	3400-3800	1700-1900	0.9	-
Oil	1200-1250	-	0.6-0.9	-

Problem: Earthquakes as seismic sources are not repetitive enough -> **Seismic noise again**

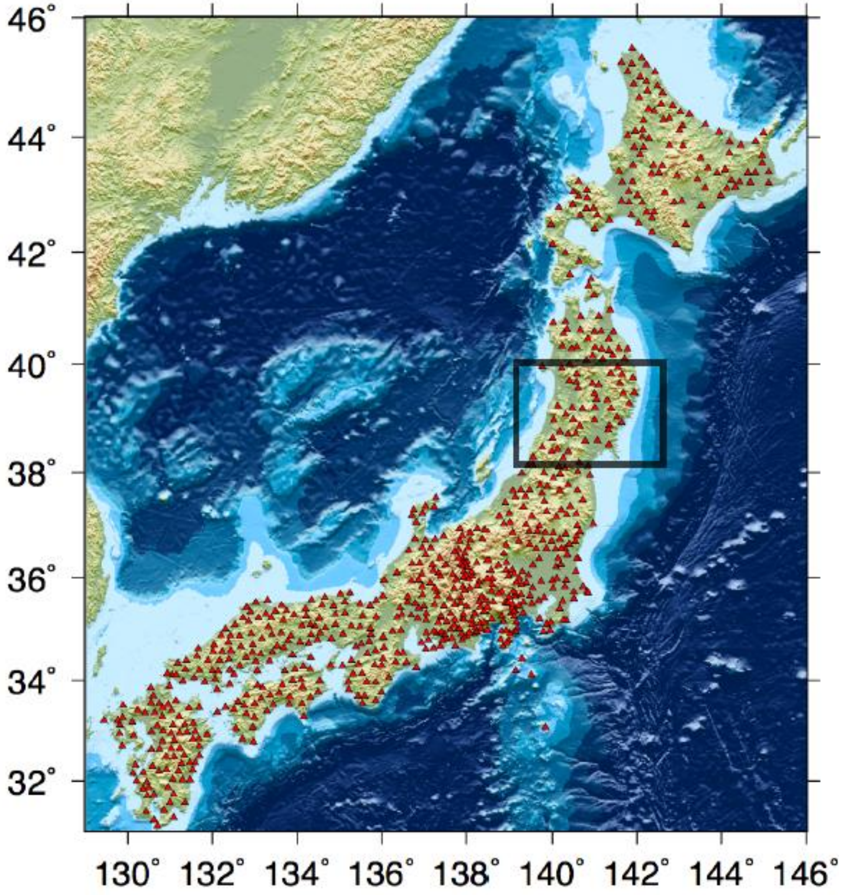


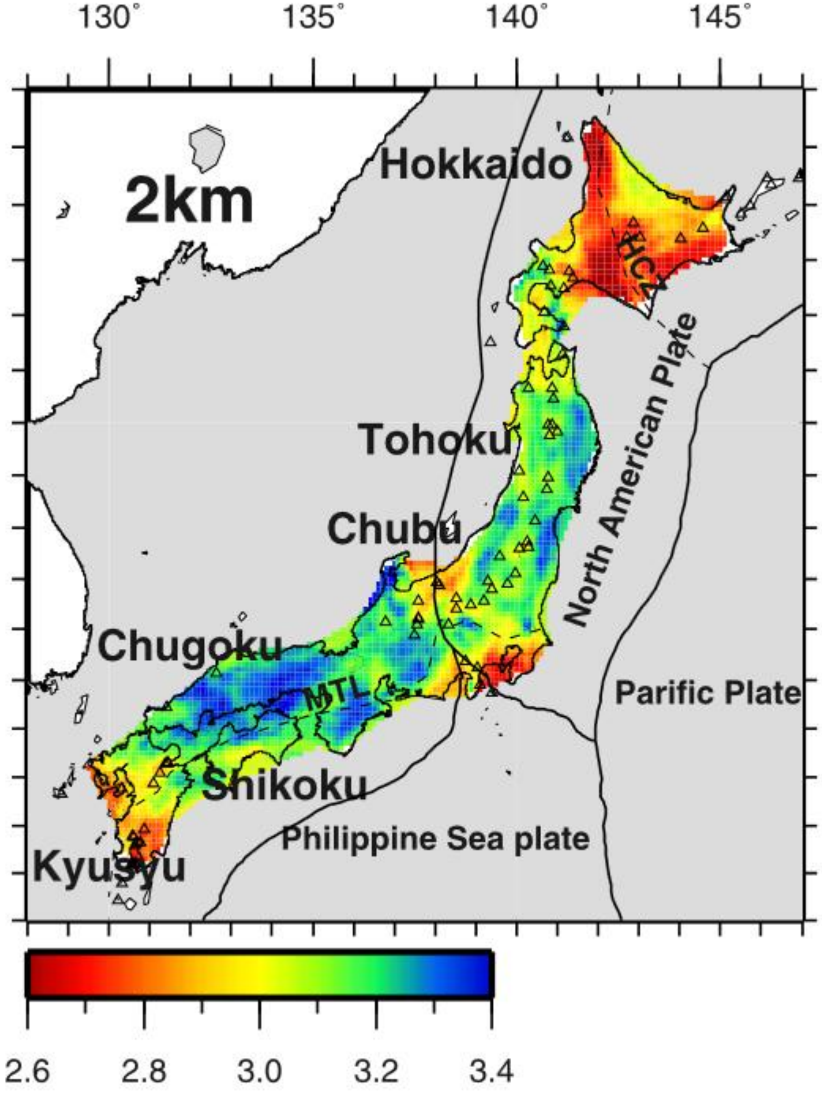
Problem: Earthquakes as seismic sources are not repetitive enough -> **Seismic noise again**



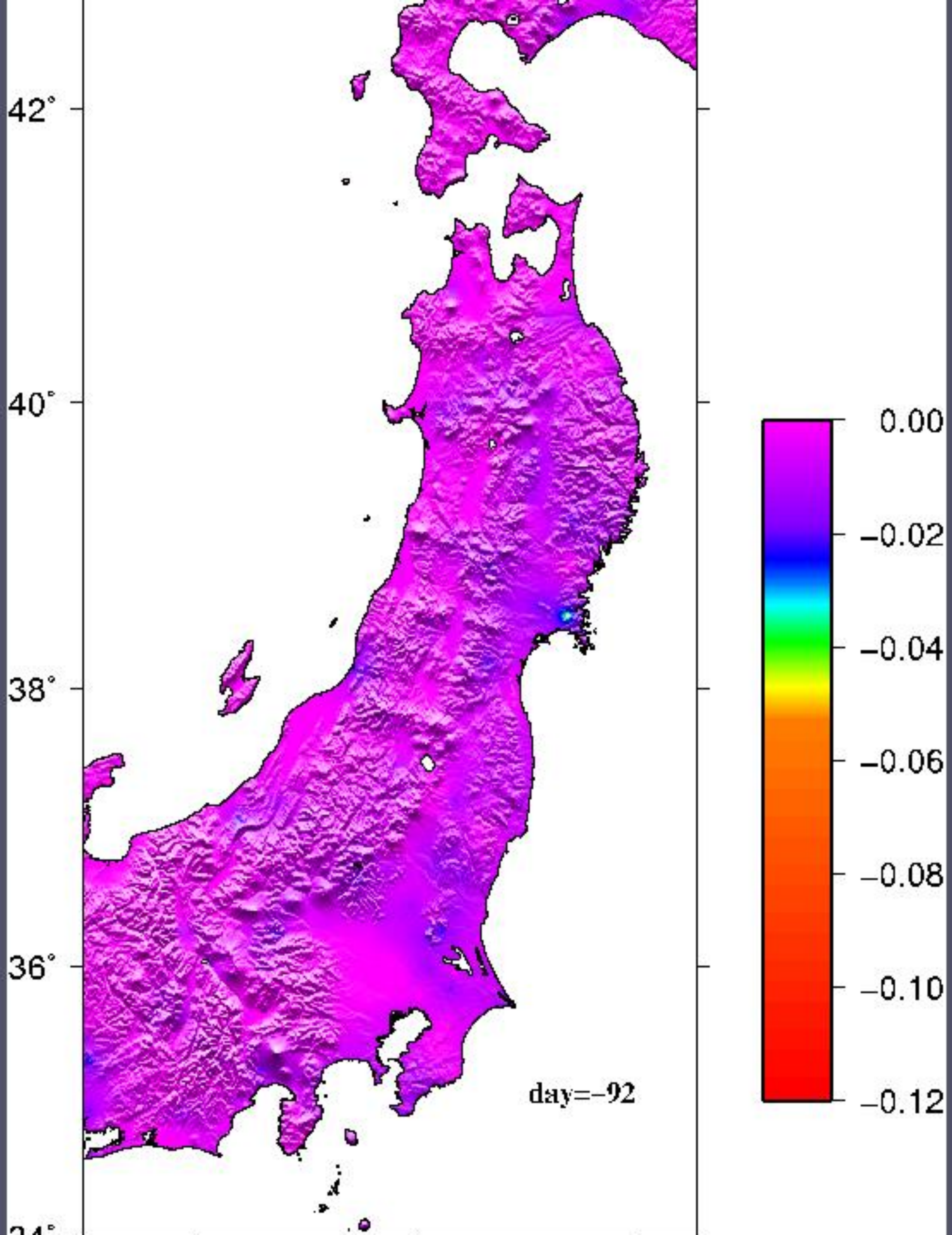


3-D tomography - Japan



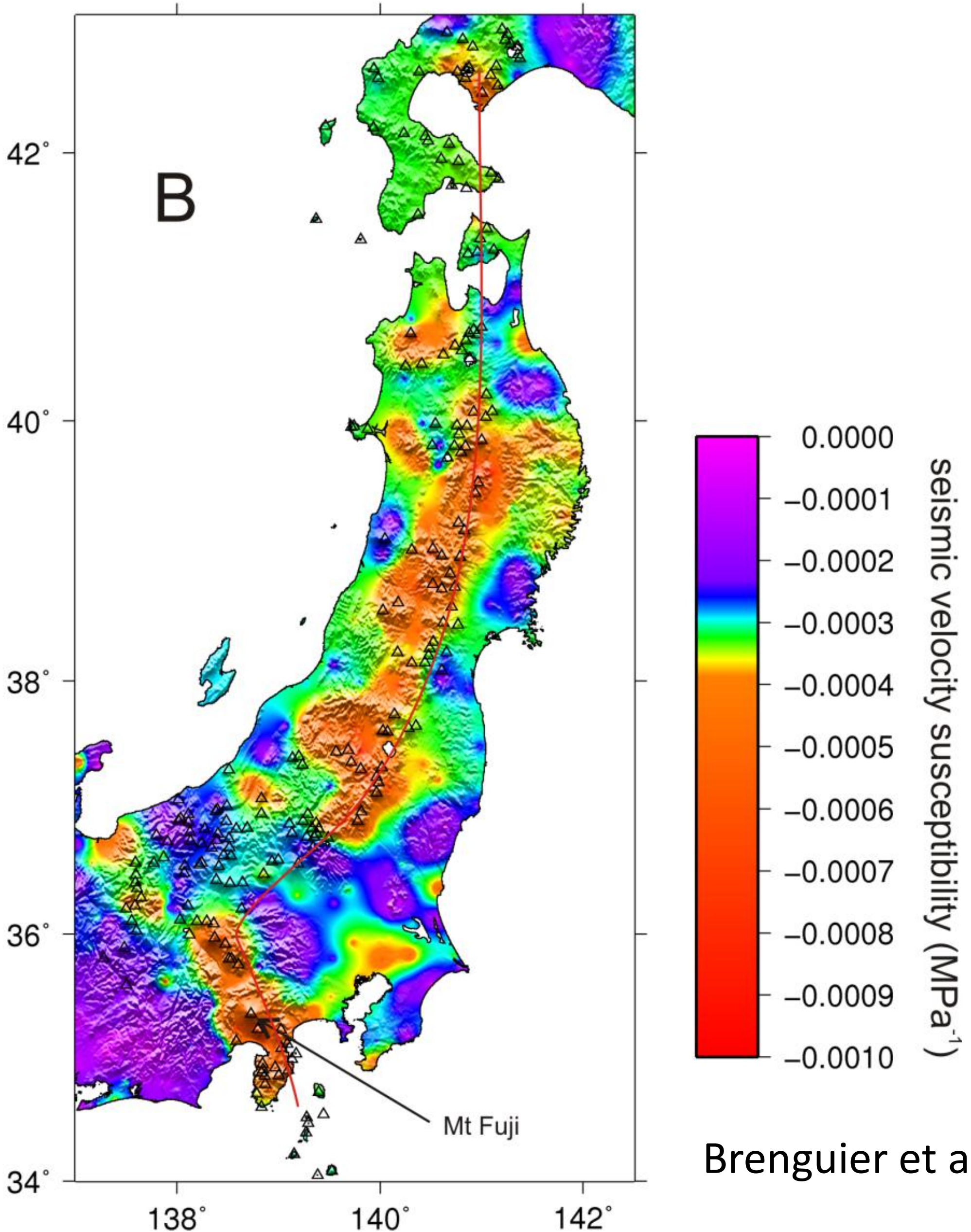


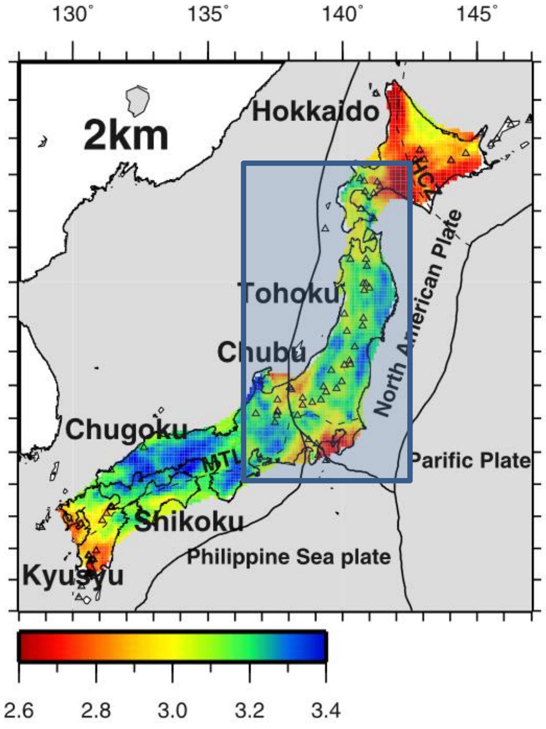
Nishida et al. 2008



42°
40°
38°
36°
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
−0.12
day=-92

4D allows imaging dynamic processes

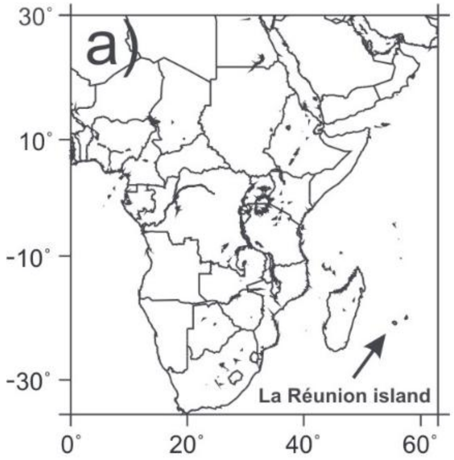


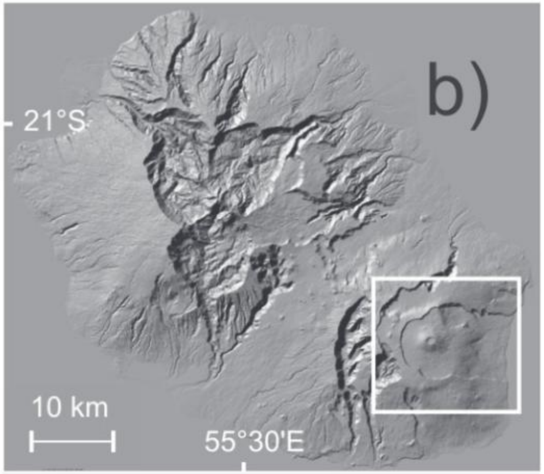


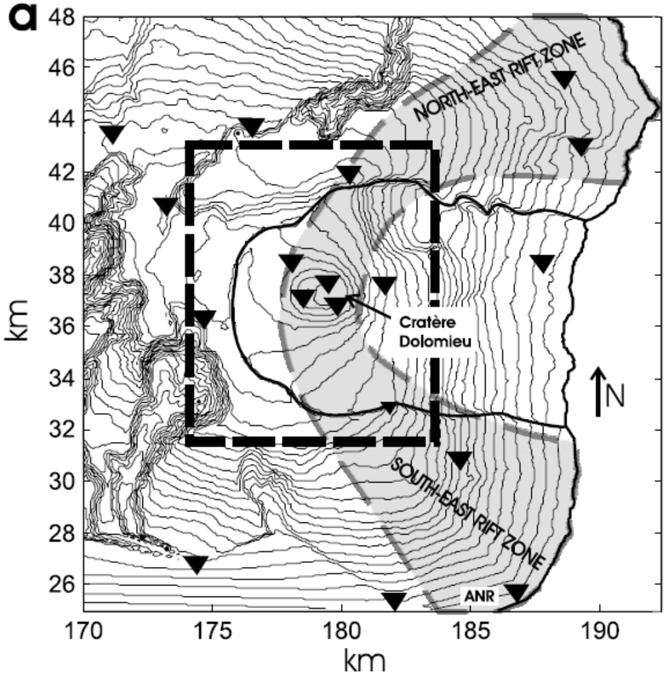
Brenguier et al., *Science*, 2014

Case study: Piton de la Fournaise Volcano

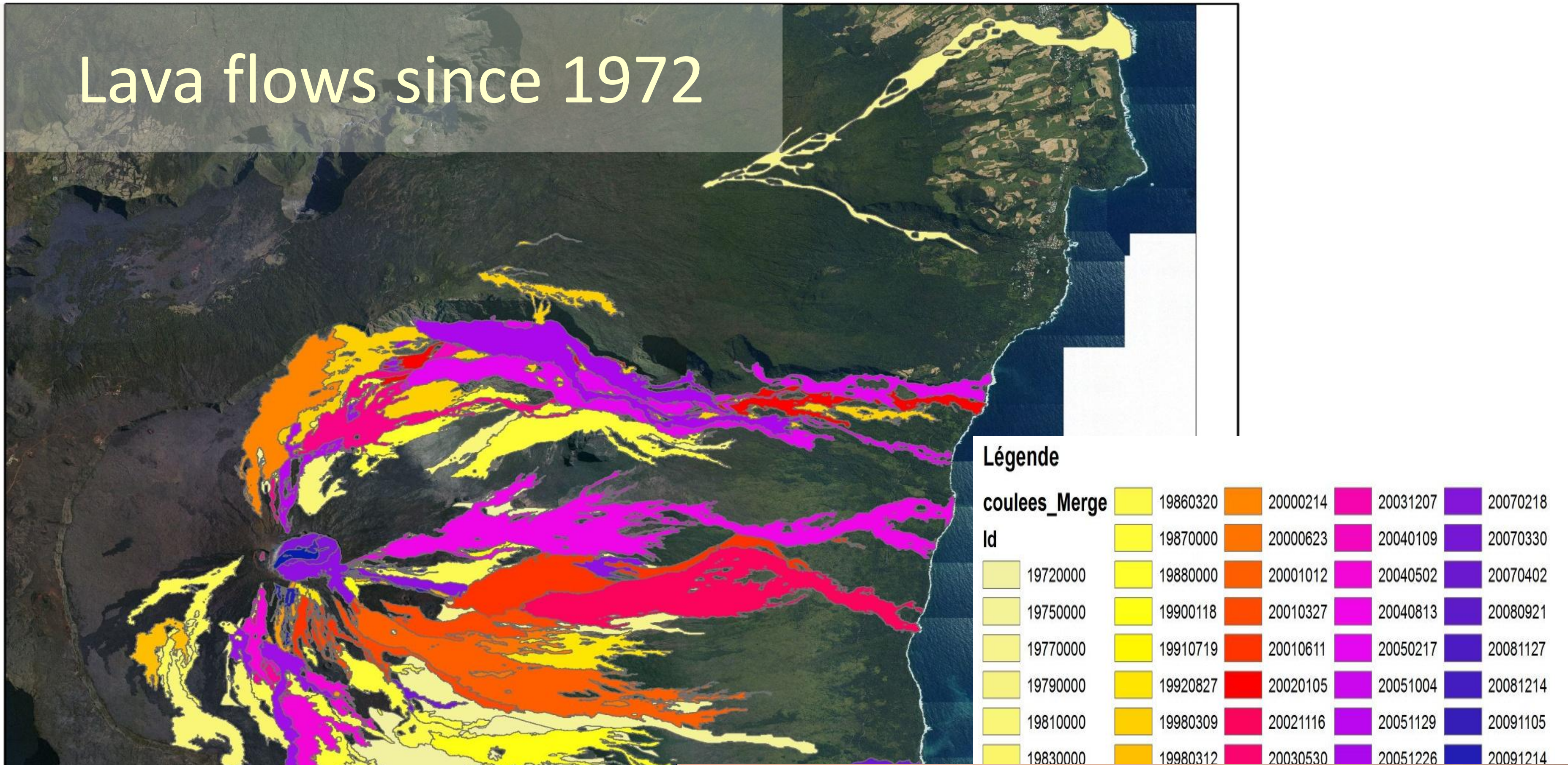
Piton de la Fournaise: a volcano laboratory







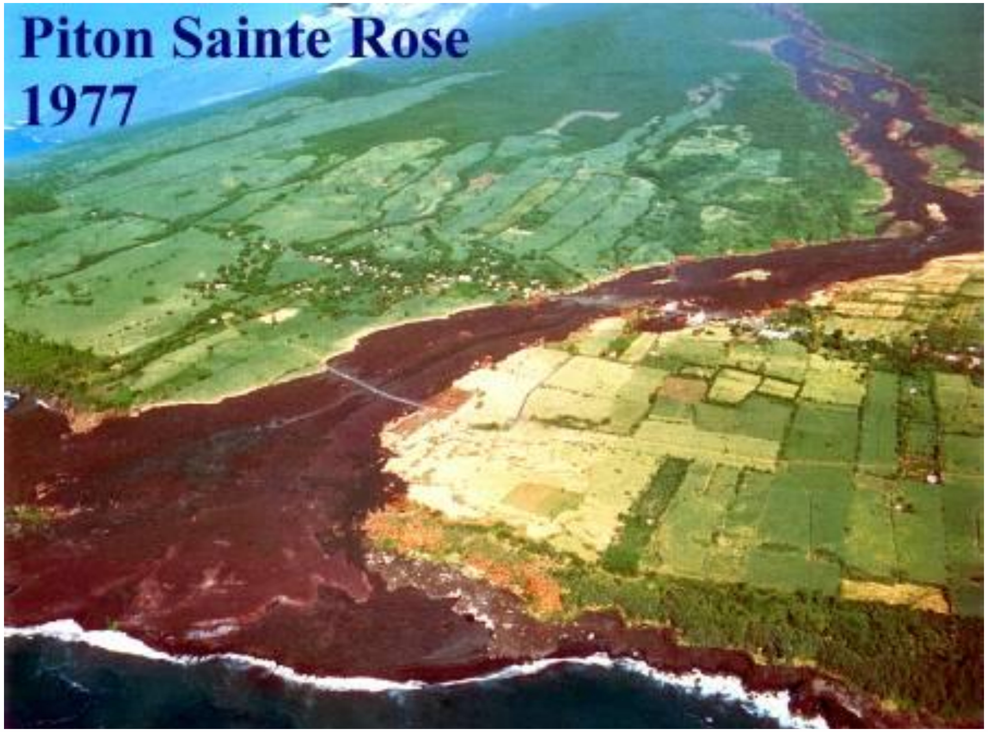
Lava flows since 1972



Réalisé par N. Bigay (Informations coulées : T. Staudach

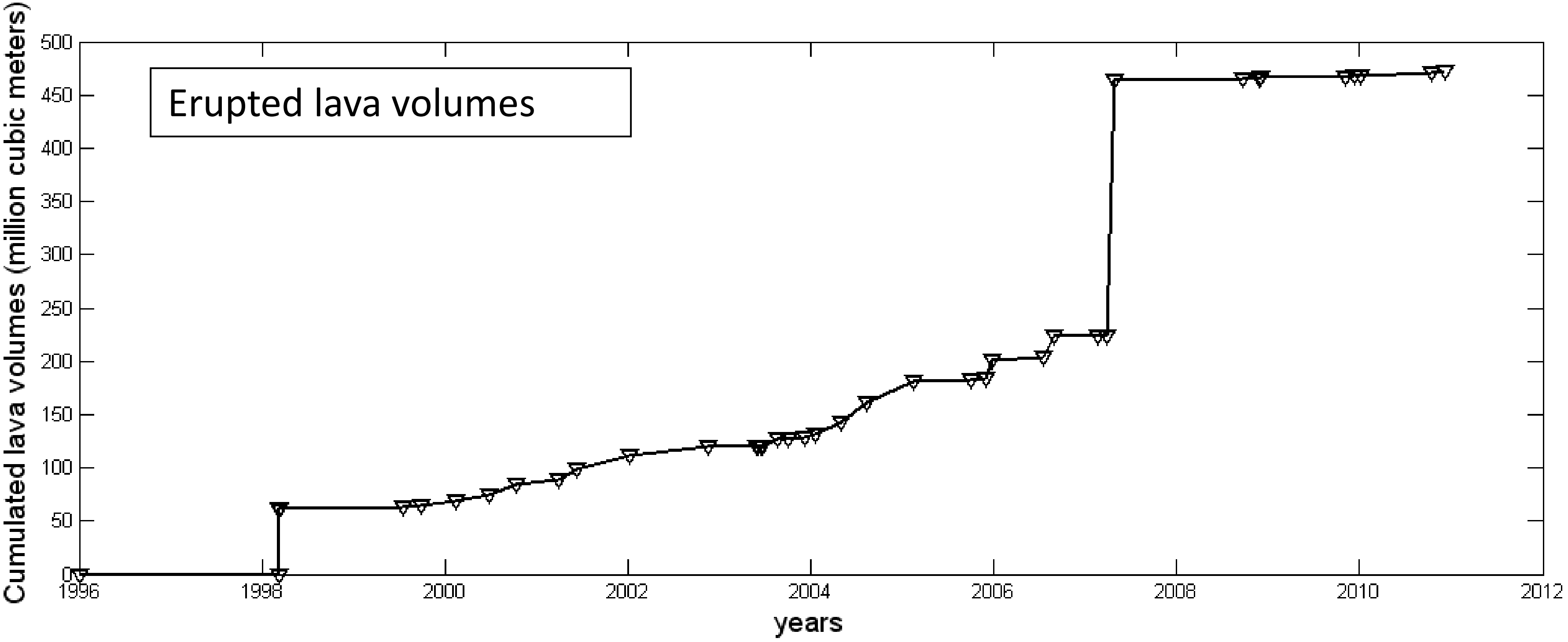
© Pierre Choukroun

Eruptions hors-enclos



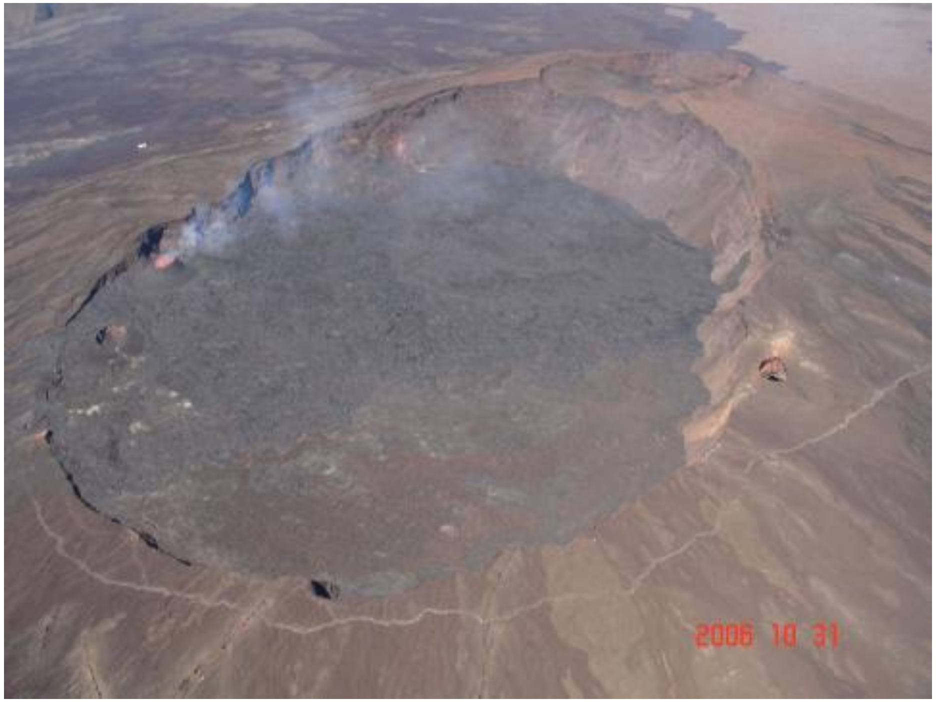
Coulée de lave de 1977 encerclant l'église de Piton Sainte-Rose

Piton de la Fournaise Volcanic activity


Erupted lava volumes

Collapse of the central crater in 2007

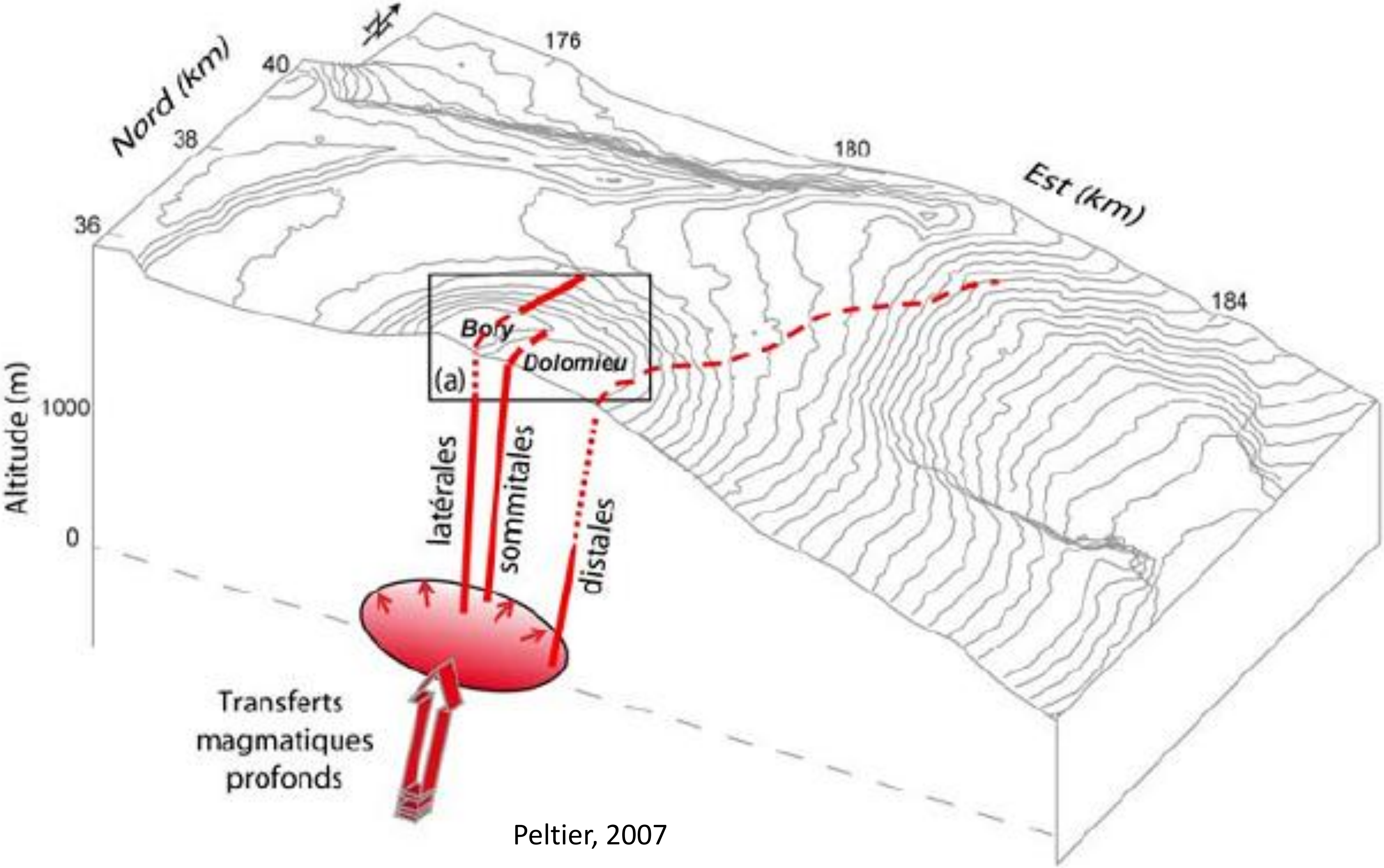
Crater collapse on April 2007



31 oct 2006

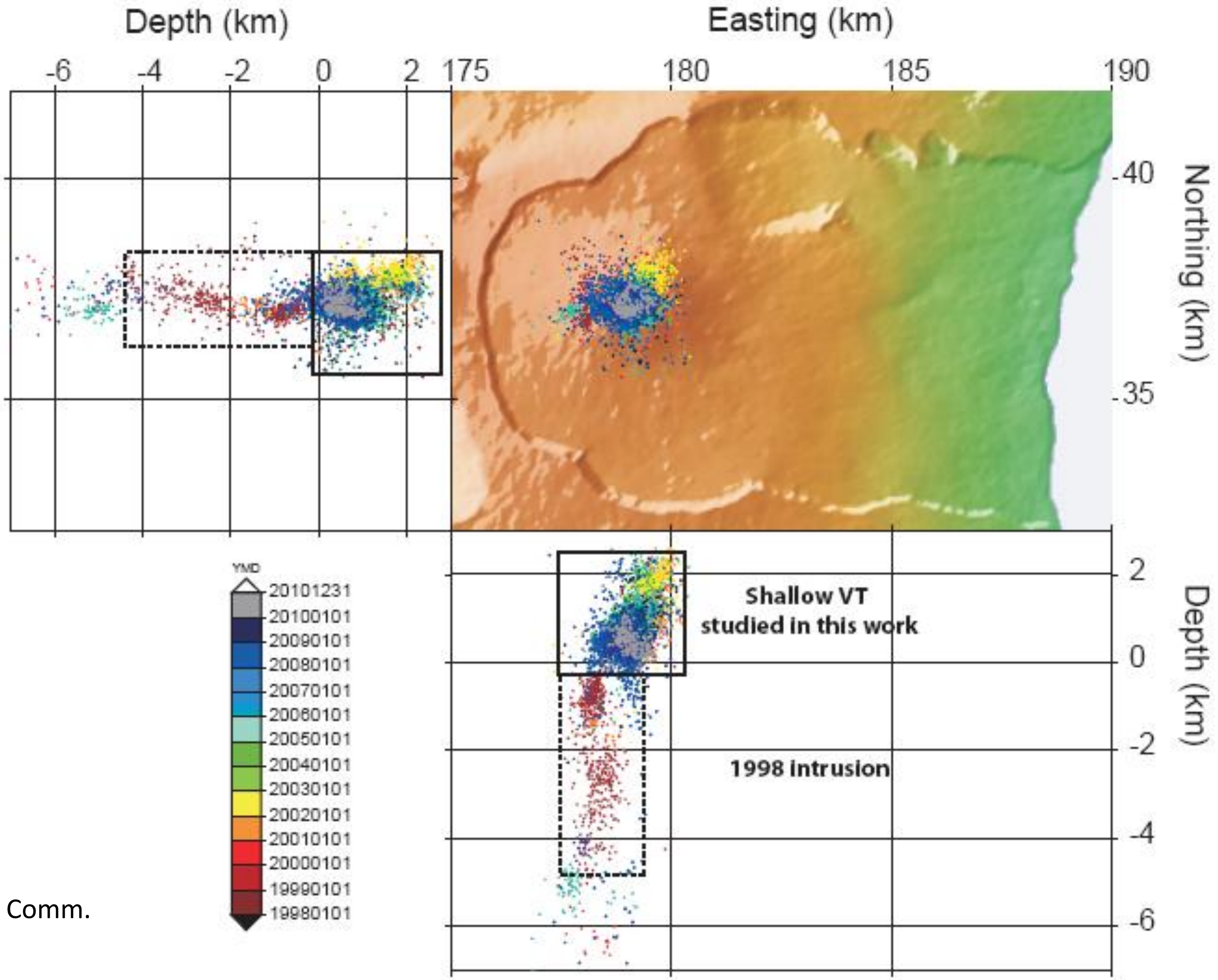
17 avril 2007

Inside Piton de la Fournaise Volcano



Peltier, 2007

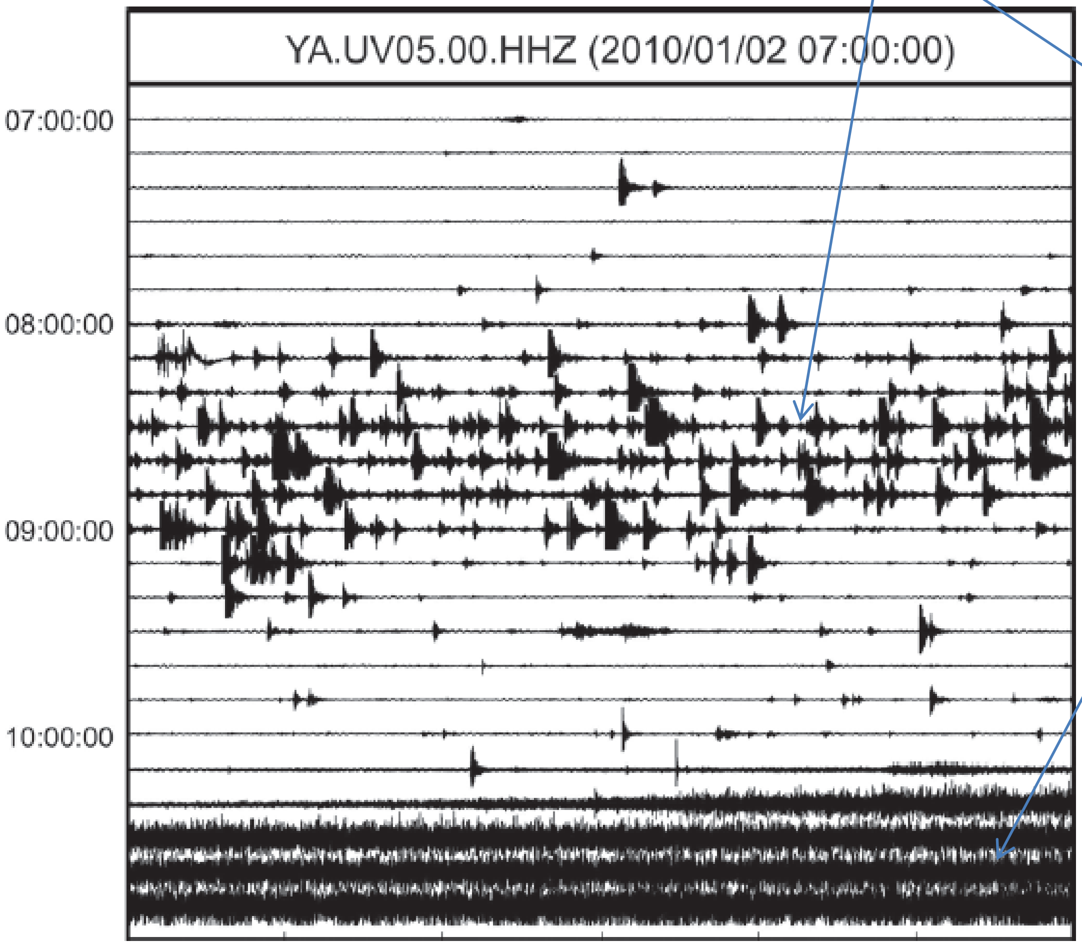
Piton de la Fournaise Seismic activity

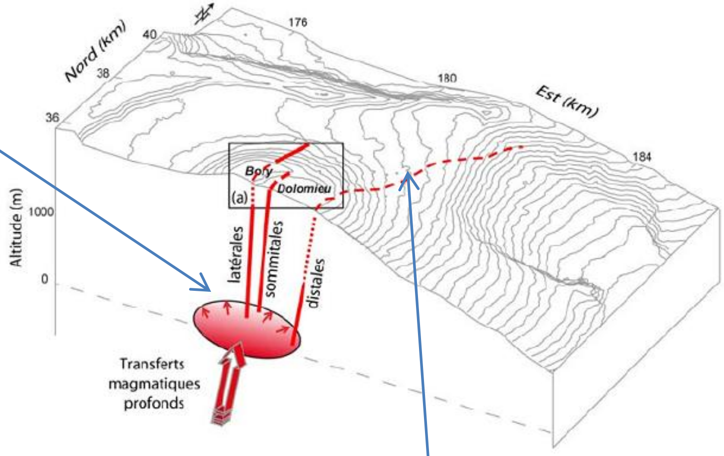


V. Ferrazzini, pers. Comm.

A variety of seismic signals on volcanoes!

Volcano-tectonic earthquakes

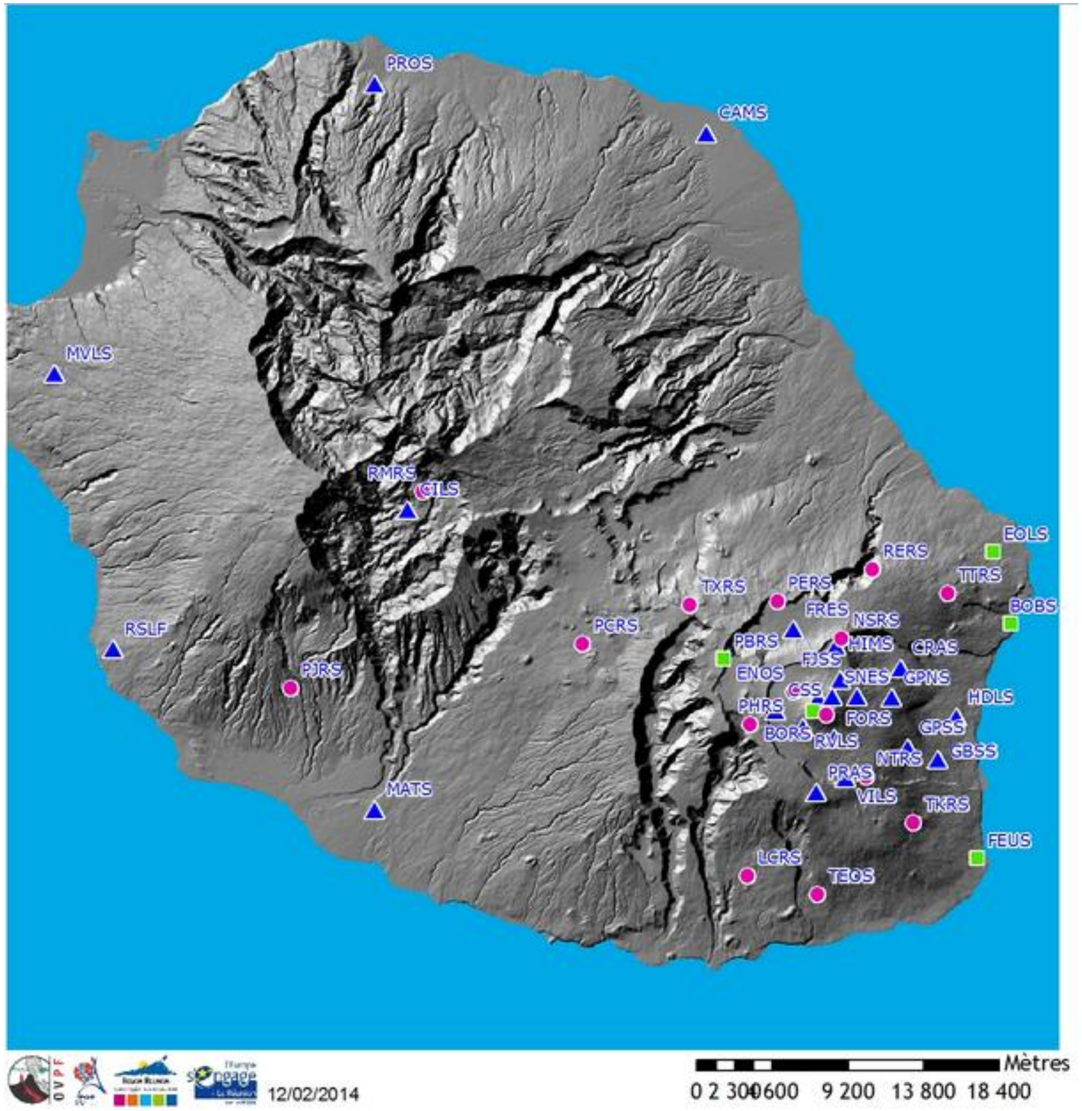


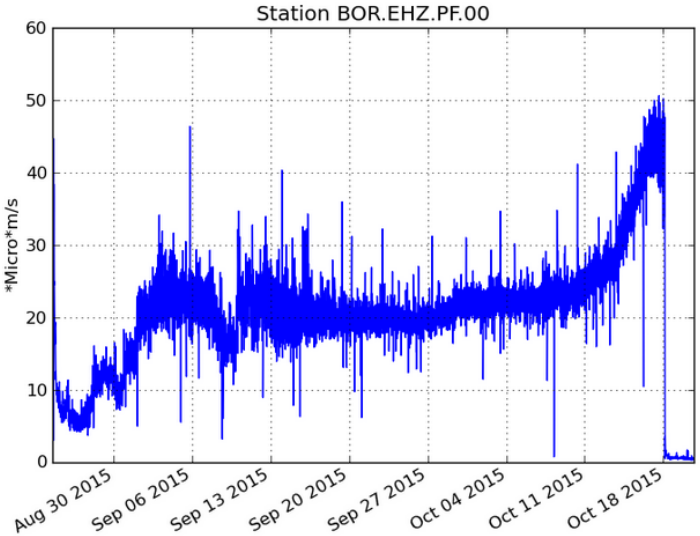


Volcanic Tremor

Data acquisition, The life of a volcano observatory

L’Observatoire du Piton de la Fournaise





Montrer film undervolc avec détails acquisition données, 1:20

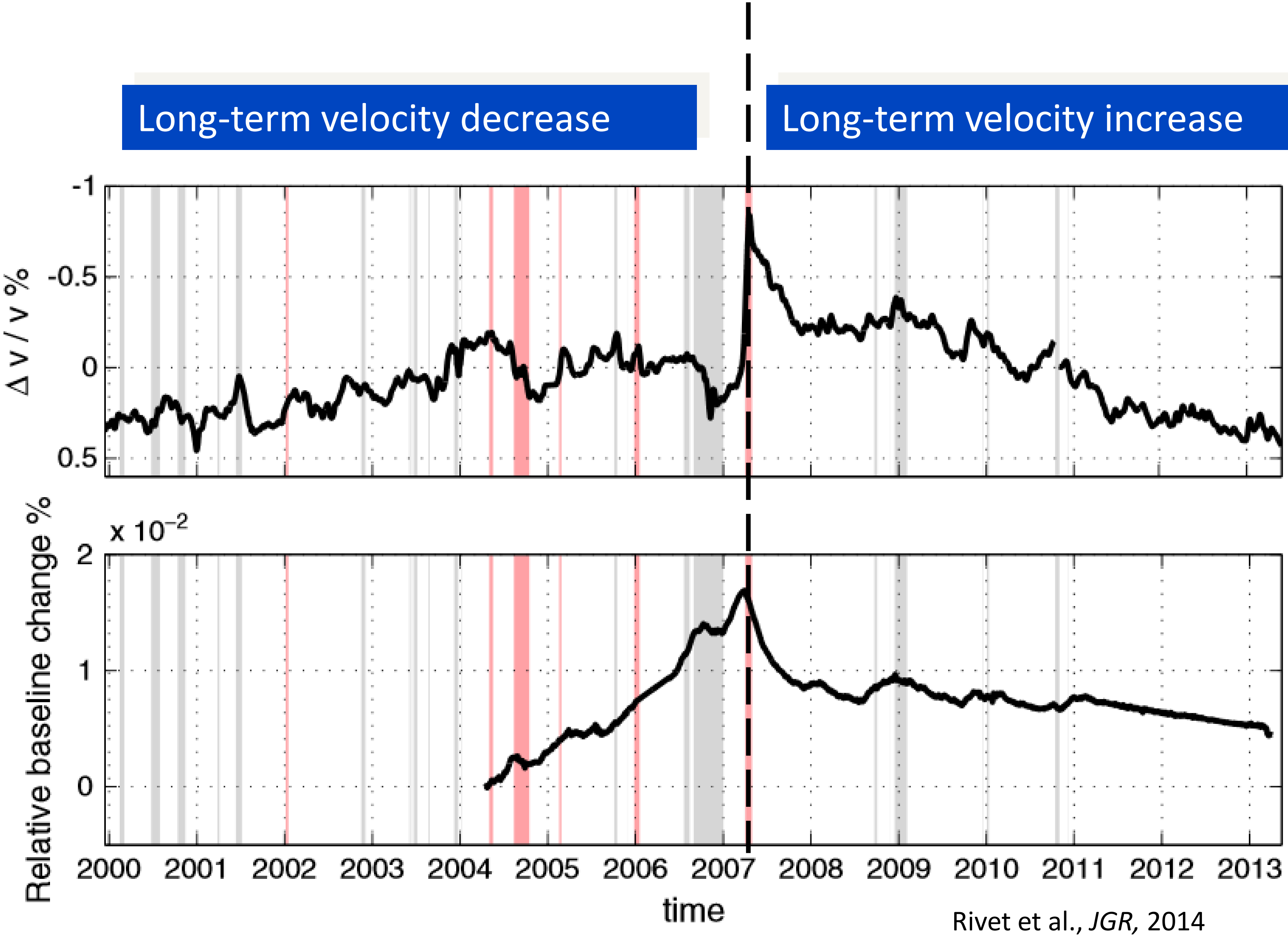
[redacted]

What 4D seismic imaging tells us

Long-term velocity changes

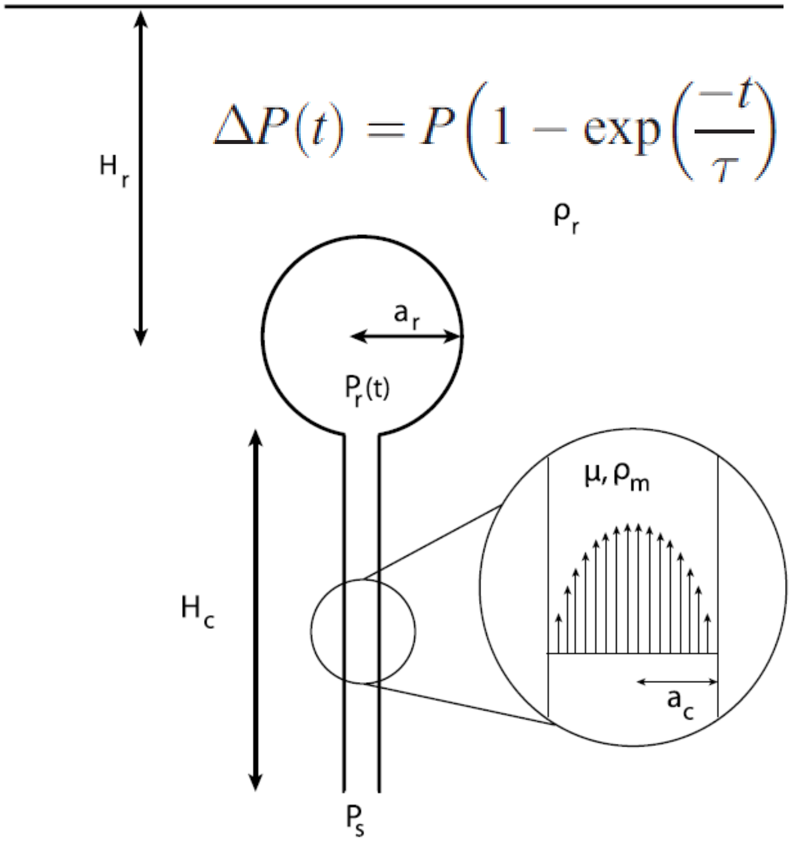
Long-term velocity decrease

Long-term velocity increase



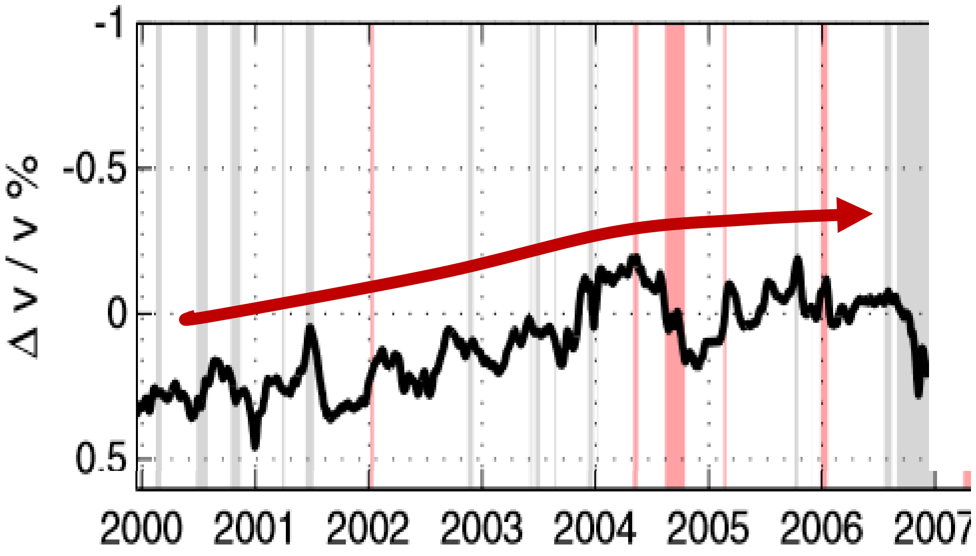
Rivet et al., *JGR,* 2014

A model for long-term pressure buildup



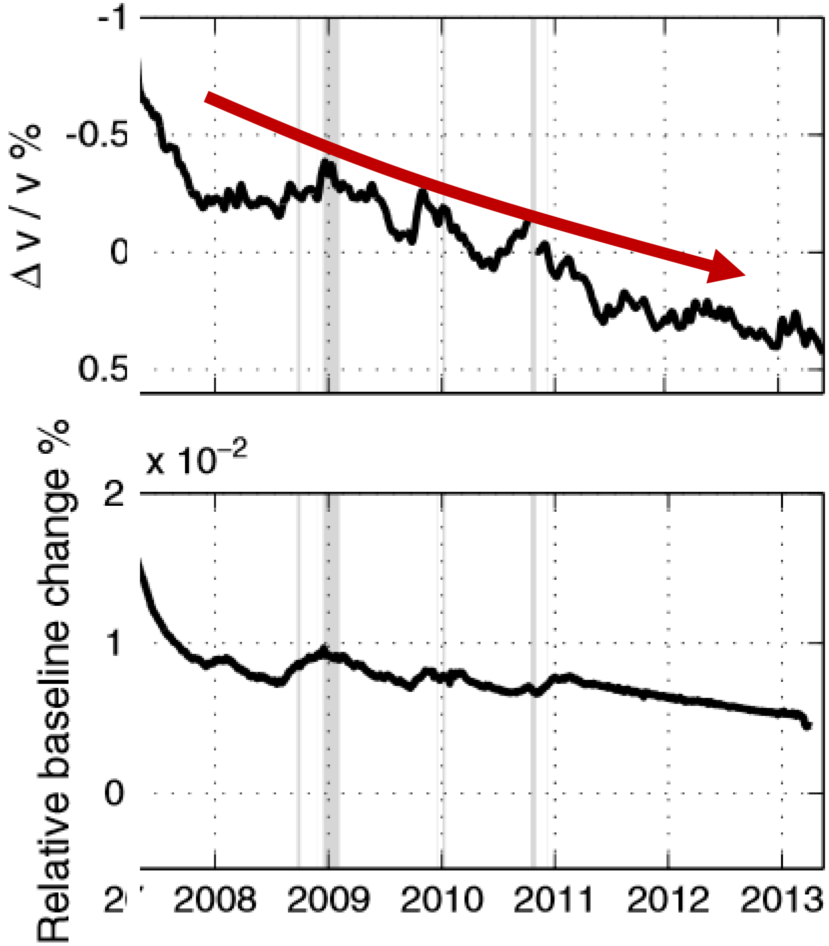
$$\Delta P(t) = P\left(1 - \exp\left(\frac{-t}{\tau}\right)\right)$$

Lengliné et al., *JGR*, 2008



Simple elastic models predict a **slowing down** of pressure buildup with time.

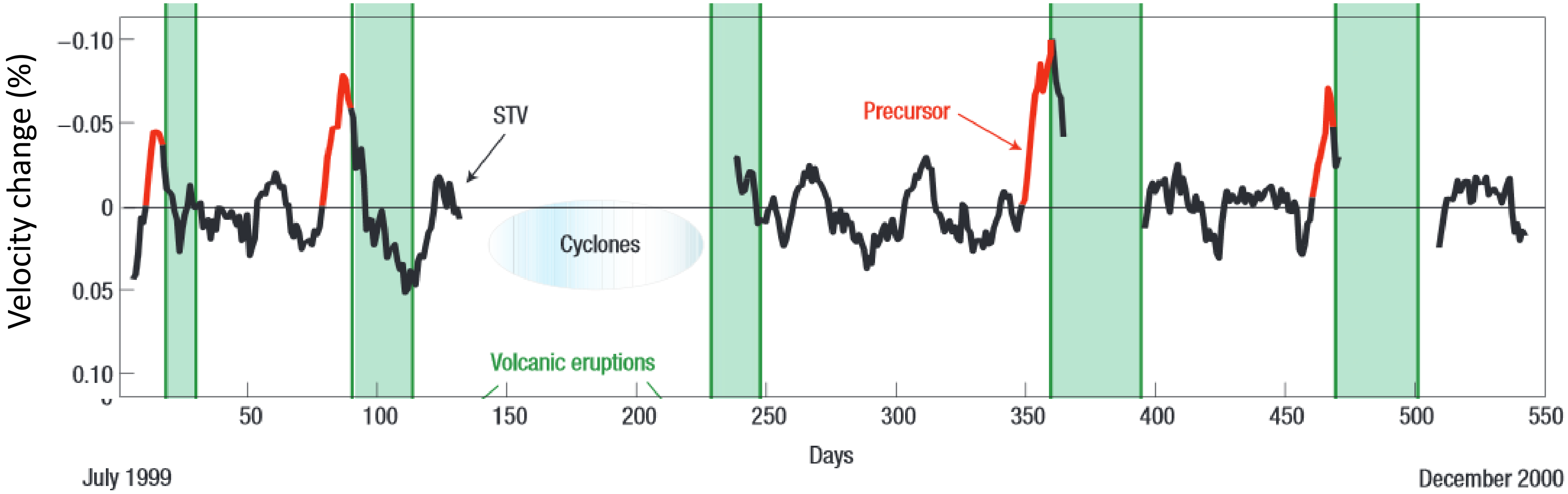
Relaxation following the large 2007 eruption



Large 2007 eruption:

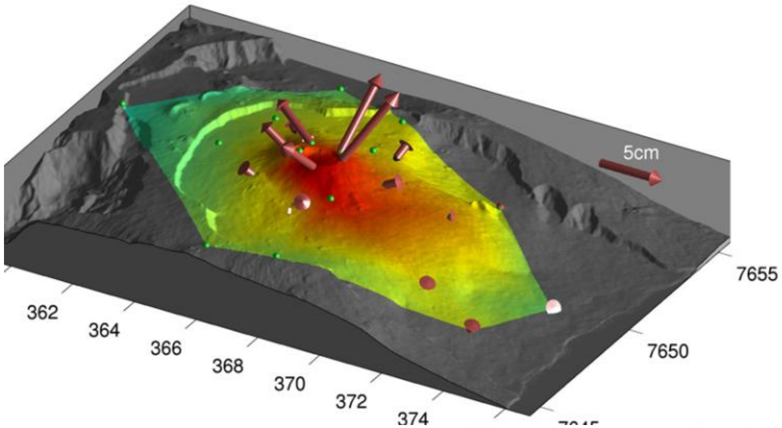
- Magma withdrawal
- Increase of seismic velocity associated with edifice deflation

Short-term pre-eruptive velocity changes



Brenguier et al., *Nature Geosc.,* 2008

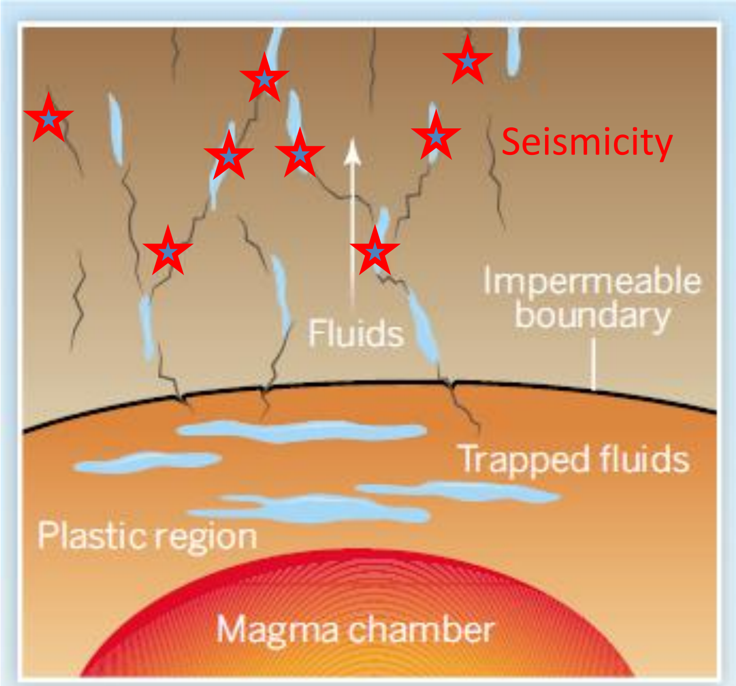
Very small (0.01 %) pre-eruptive seismic velocity changes were initially interpreted as the effect of a **pressure source**



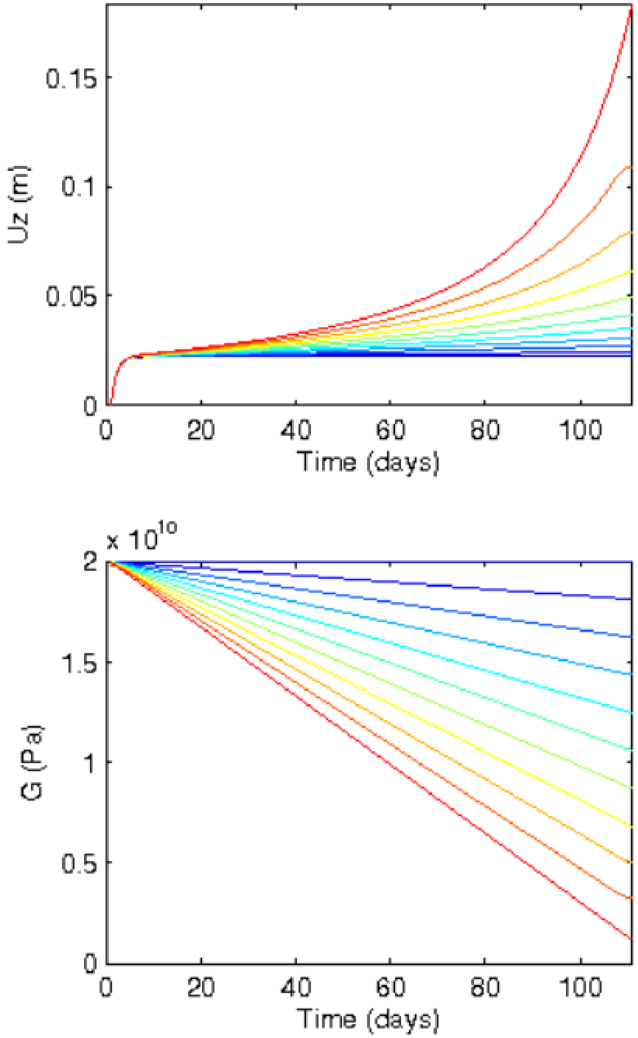
Sens-Schönfelder et al., JVGR, 2014

A damage model for short-term eruption preparation

Damage is:
- Seismicity (direct and dynamic)
- Decrease of stiffness
- Increased deformation
- Increased permeability
- Decompression of volcanic fluids leading to eruptions



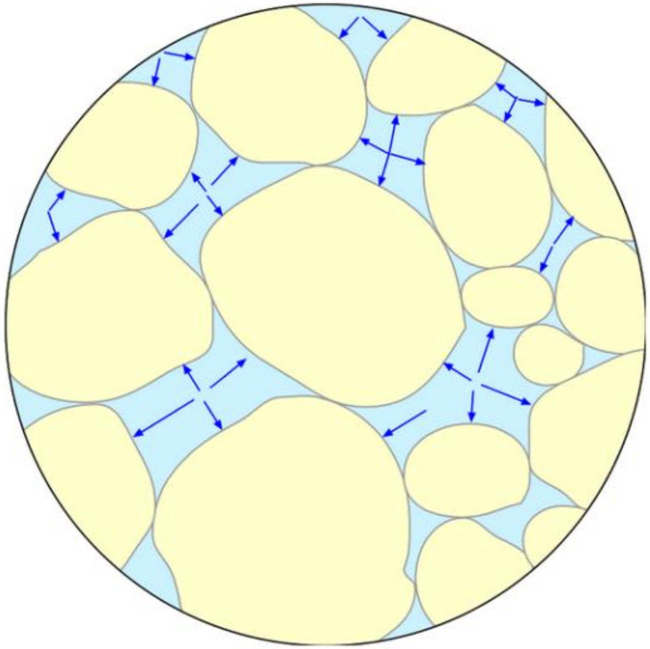
Sketch from Prejean and Haney, 2014

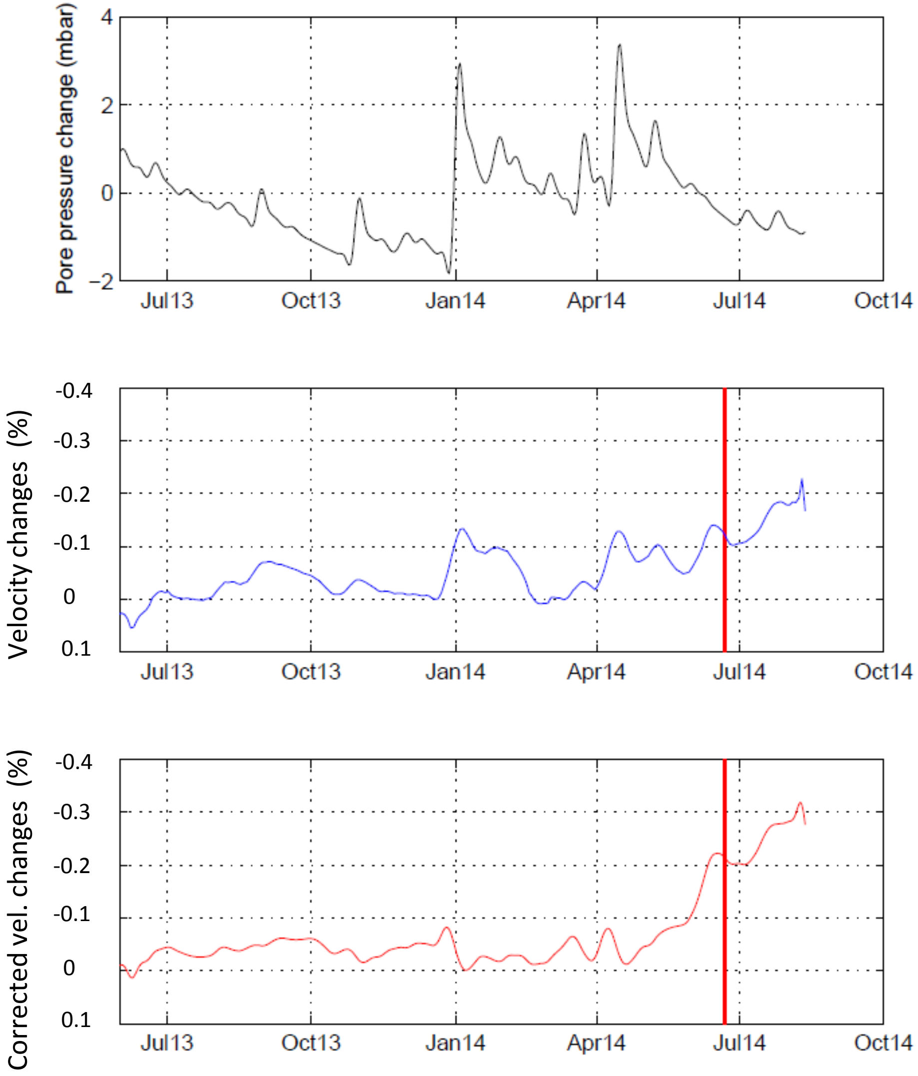


Carrier et al. 2015

Environmental effects

Strong **rainfall** generates pore pressure increases as much as 1 kPa at 1 km depth





Rivet et al. 2015

The April 2007 eruption

Small flank eruption on March 30th, large distal eruption on April 2nd and crater collapse on April 5th.

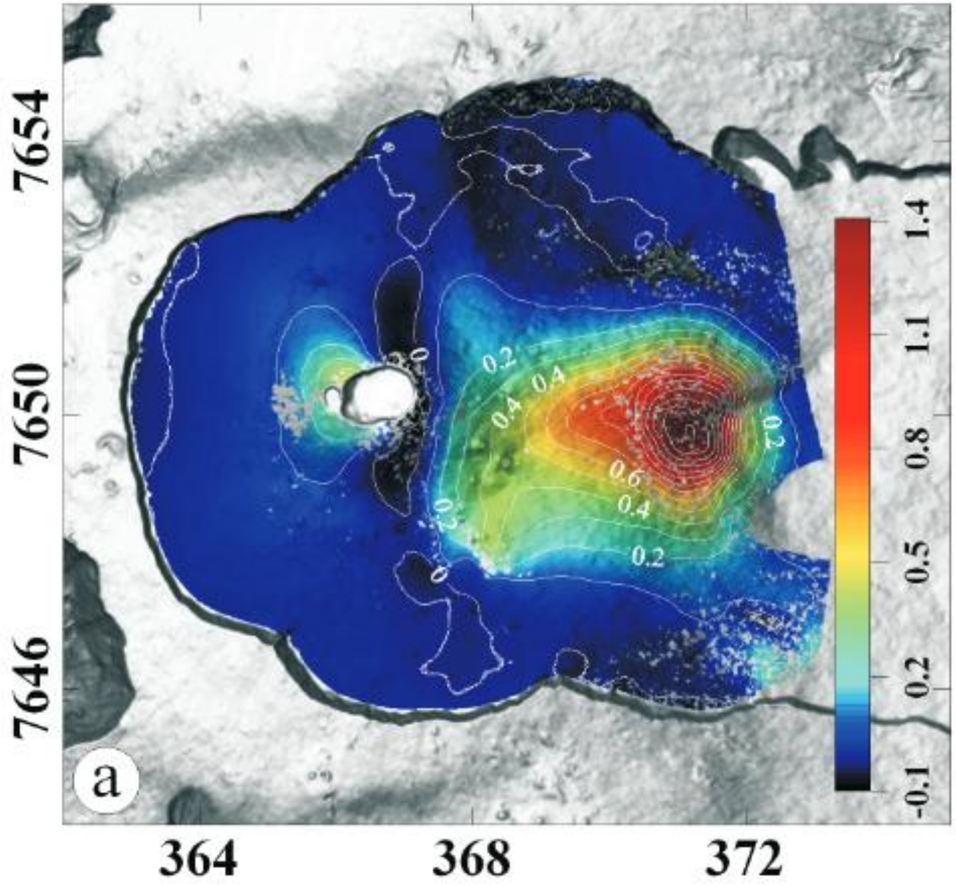


Figure from J.-L. Froger, OPGC

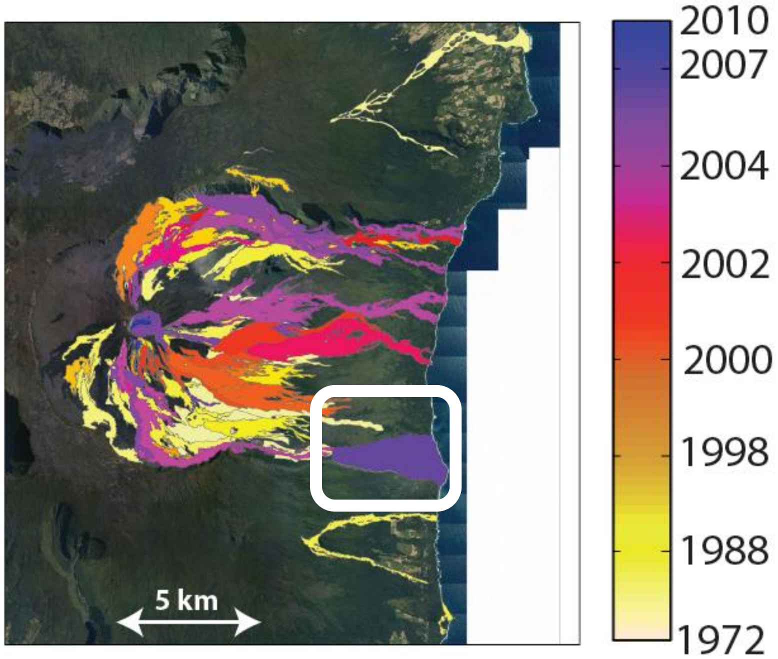
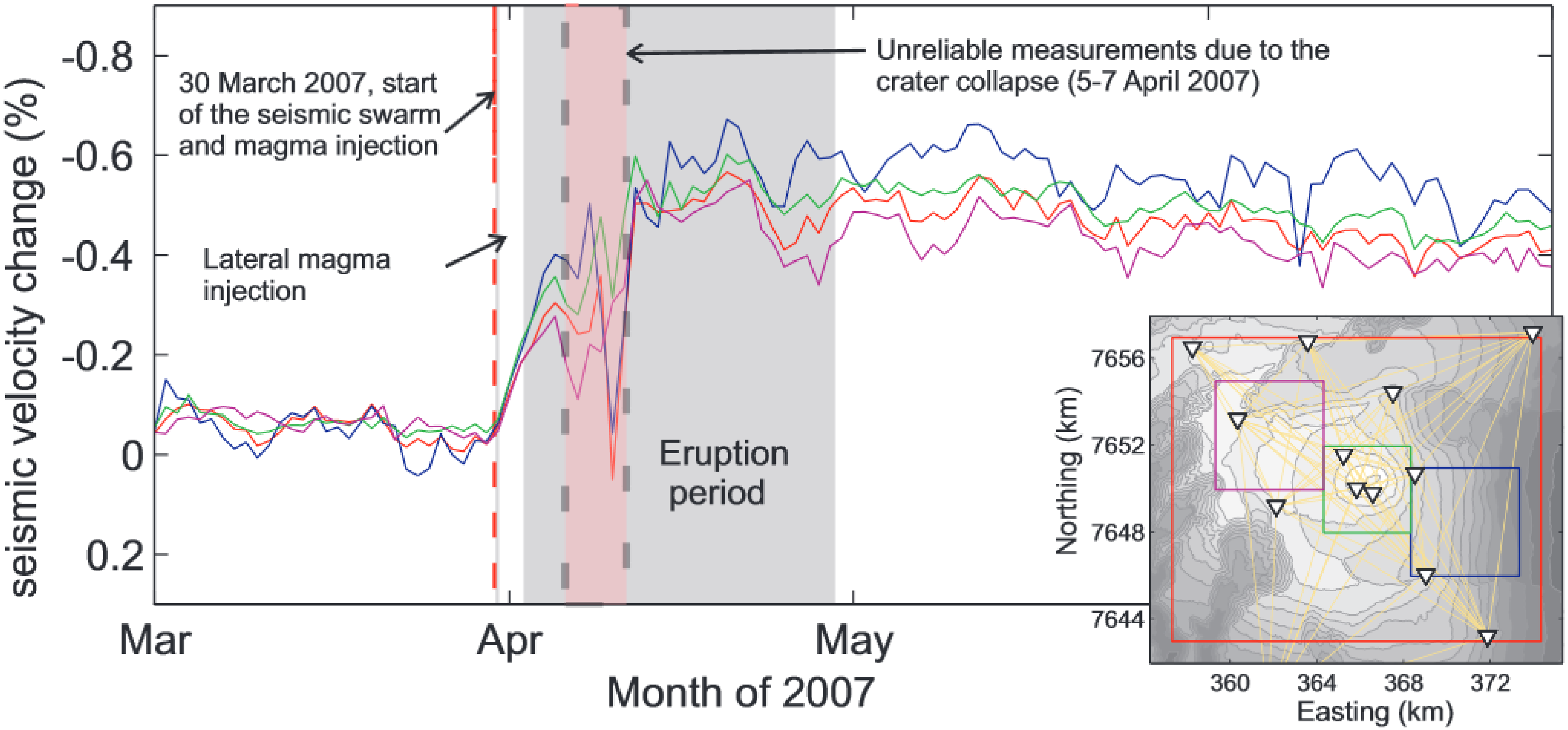


Figure from OVPF, T. Staudacher

Triggered flank movement

The flank movement started on March 30 and likely controlled the extrusion of a large volume a lava



Clarke et al., *GJI,* 2013

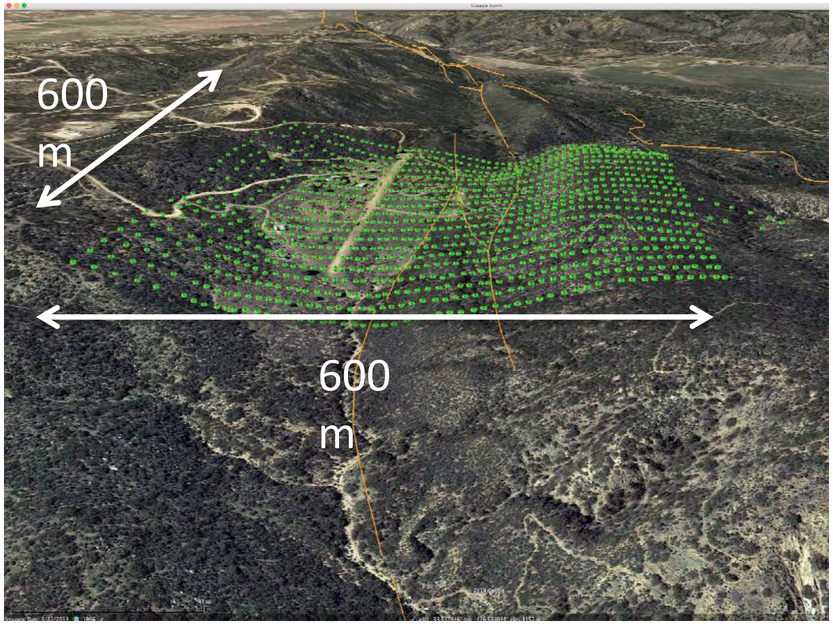
Volcano seismic probing in 2020

Standard seismic station

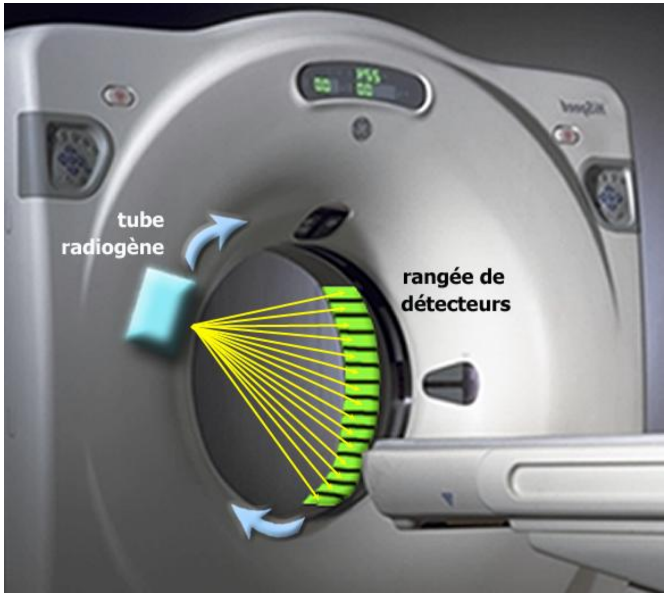
- ✓ 15 000 €
- ✓ 20 kg

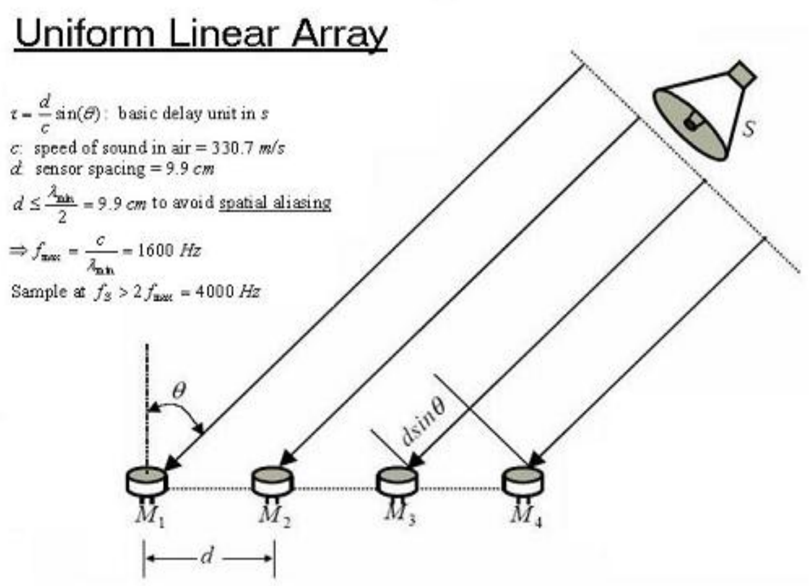
New nodal technology

- ✓ 2 000 €
- ✓ 2.5 kg



Computed Tomography scanner





Uniform Linear Array

$\tau = \frac{d}{c}\sin(\theta)$: basic delay unit in s

c: speed of sound in air = 330.7 m/s

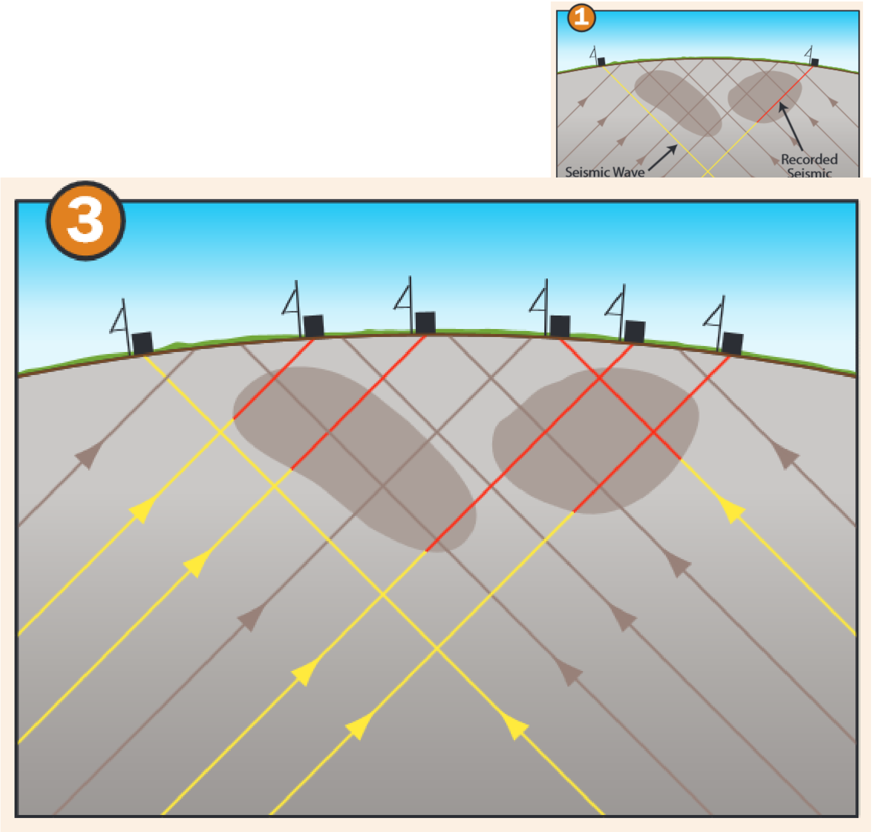
d: sensor spacing = 9.9 cm

$d \le \frac{\lambda_{min}}{2} = 9.9\ cm$ to avoid spatial aliasing

$\Rightarrow f_{max} = \frac{c}{\lambda_{min}} = 1600\ Hz$

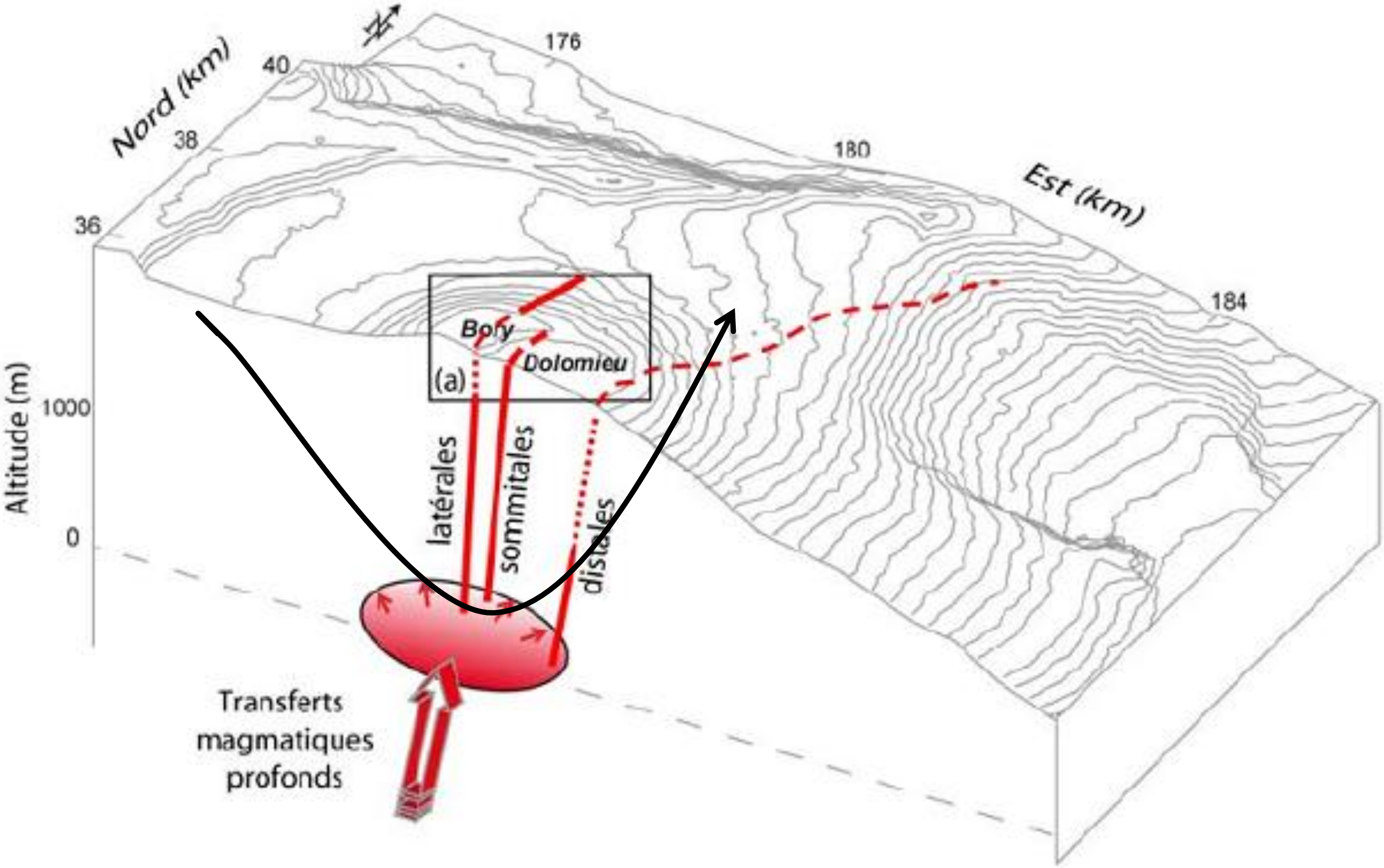
Sample at $f_S > 2 f_{max} = 4000\ Hz$

Seismic tomography with arrays



Measure waves directivity

Probing the magma reservoir



Peltier et al., *JVGR*, 2007

Probing the magma reservoir

300 seismometers!

4 | Le Monde Mercredi 16 juillet 2014 | SCIENCE & MÉDECINE | ÉVÉNEMENT

Volcans

Dans les entrailles du piton de la Fournaise

GÉOLOGIE

Sur l'île de la Réunion, des chercheurs mettent en œuvre le projet VolcArray, dont l'objectif est de visualiser, pour la première fois, la chambre magmatique d'un volcan

VIVIANE THIVENT
La Réunion

C'est fini l'époque des Krafft, ce couple de volcanologues en combinaison blanche dont les images ont fait le tour du monde : aujourd'hui, la volcanologie, c'est une affaire de calculs, d'ordinateurs. Tout peut se faire à distance, de son bureau. » L'affirmation, faite à froid dans les locaux de l'Institut des sciences de la Terre (ISTerre) de Grenoble, est de Florent Brenguier. Quelques mois plus tard, ce jeune chercheur a de quoi déchanter. A quatre pattes sur le flanc ouest du piton de la Fournaise, sous une pluie rendue agressive par le froid et le vent, il essuie, agite, tapote sans relâche des connectiques détrempées qui refusent d'activer l'un des 300 capteurs qu'il compte installer sur ce volcan réunionnais.

Objectif ? Créer, pendant un mois, trois antennes carrées de 100 capteurs chacune et de 500 mètres de côté, qui agiront comme des « télescopes » tournés non pas vers le ciel, mais vers l'intérieur du volcan. Vers une zone précise, située à trois kilomètres de profondeur, juste au-dessus du niveau des mers, et qui pour-

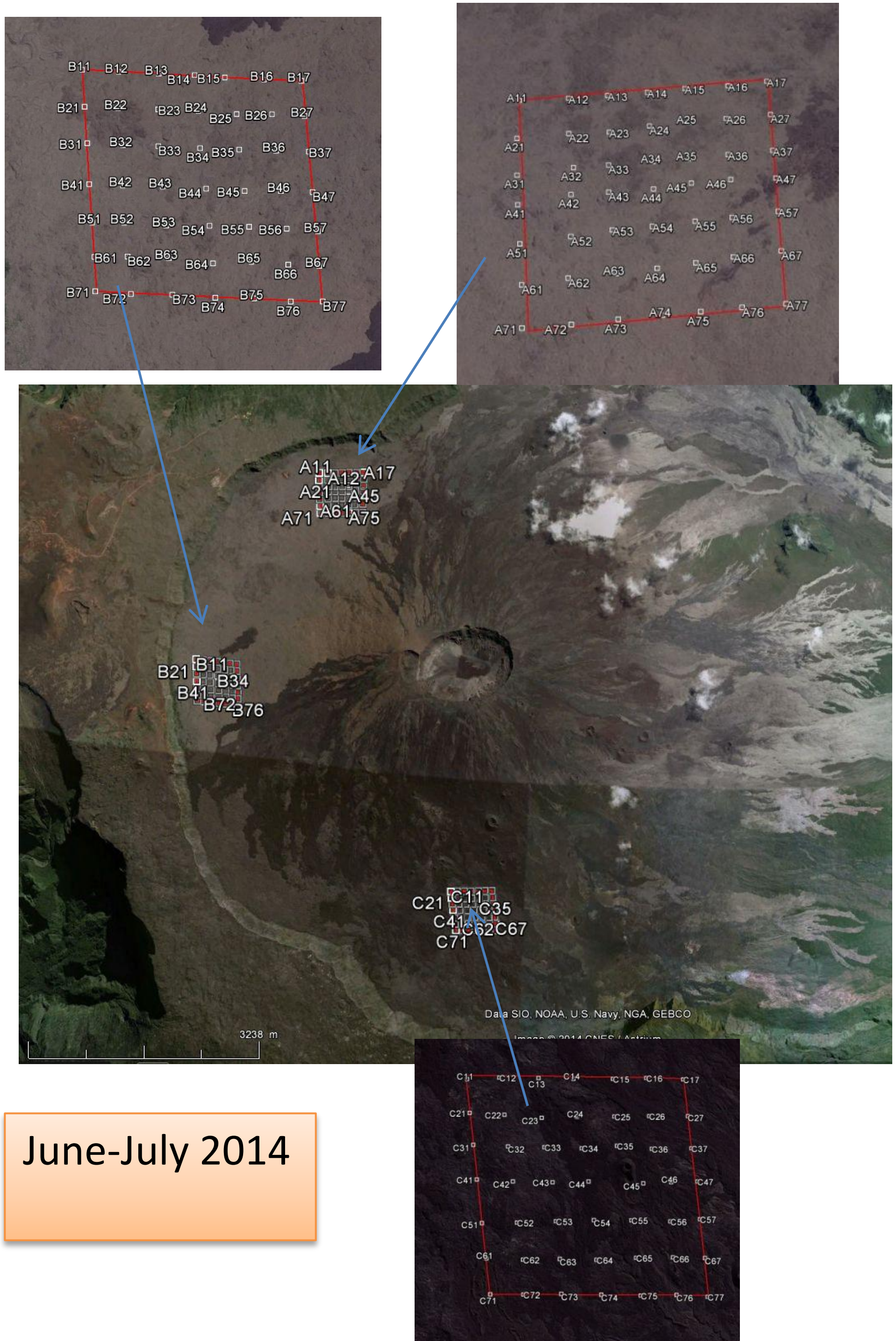
grette le chercheur en essuyant d'un revers de manche le filet d'eau qui ruisselle sous son nez. *Mais, avec ce temps, l'engin n'a pu décoller. Et comme on ne dispose que de trois jours de terrain, on a décidé d'installer l'antenne la plus accessible à pied.* » Ce matin-là, au lever du soleil, une vingtaine de personnes, des stagiaires, techniciens, ingénieurs, chercheurs, ont ainsi relevé le défi. Et avec enthousiasme, même. Ce qui, quelques heures plus tard, n'est plus vraiment le cas.

Comme en témoigne l'attitude des trois gaillards qui, autour de Florent Brenguier, tremblent en silence, les bras étirés par des petits ballotins jaunes, de 2,5 kg chacun. Les fameux capteurs de VolcArray, des sismomètres tout-terrain – ou « nodes » – développés par l'industrie pétrolière pour enregistrer les plus infimes vibrations du sol. S'ils étaient activés, c'est sûr, ils enregistreraient sans peine les spasmes de leurs porteurs.

« Florent aux autres équipes : *j'ai un problème, quelqu'un pourrait-il m'apporter un câble et un boîtier de commande ?* » L'ap-

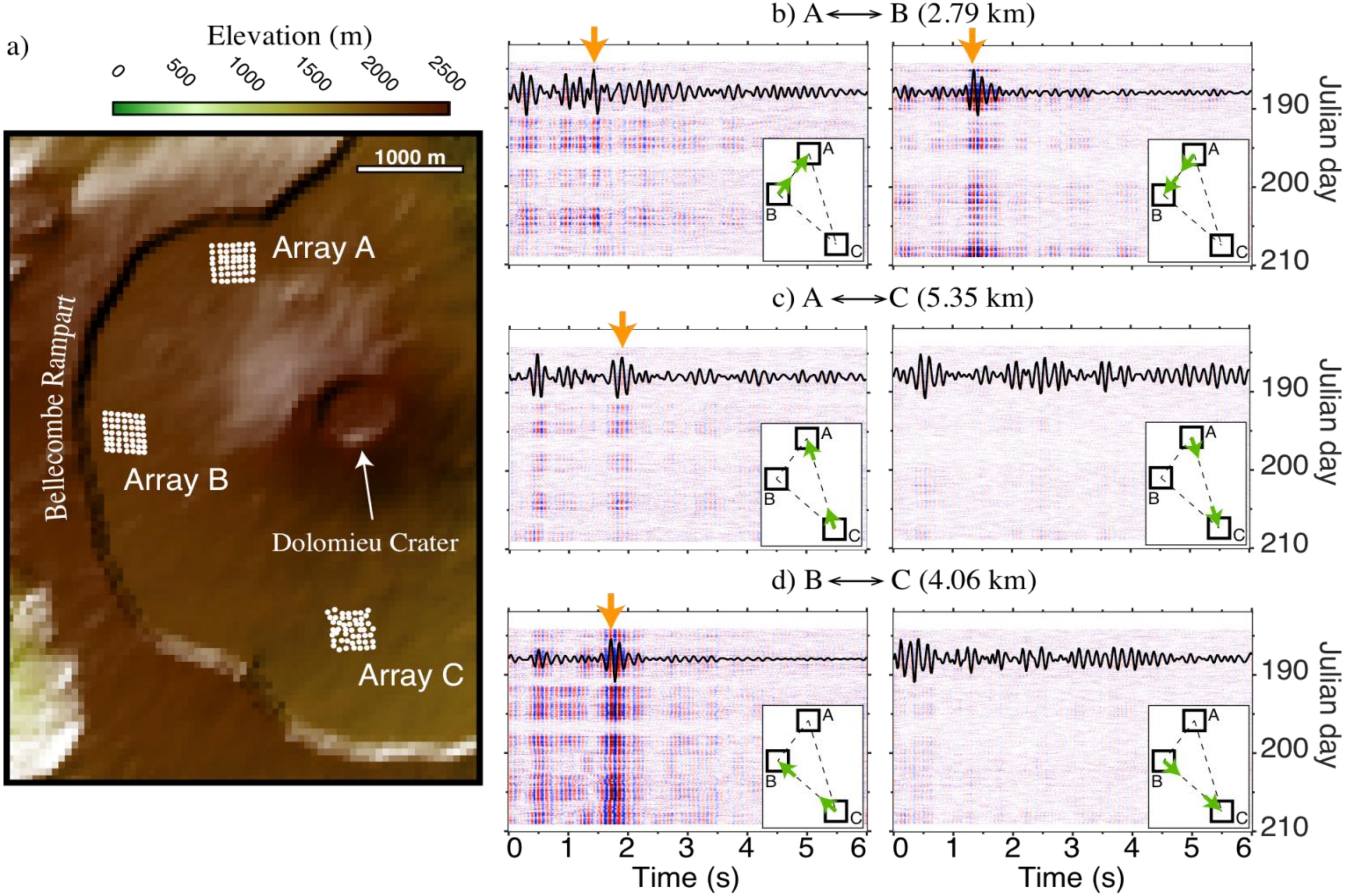
Trois cents capteurs agiront comme des télescopes

Philippe Kowalski, directeur adjoint de l'Observatoire volcanologique du piton de la Fournaise (au premier plan), et Florent Brenguier, sismologue, en réunion de préparation pour leur mission.



June-July 2014

Probing the magma reservoir



Nakata et al., *GRL*, 2016

Montrer film VolcArray – 12 minutes