



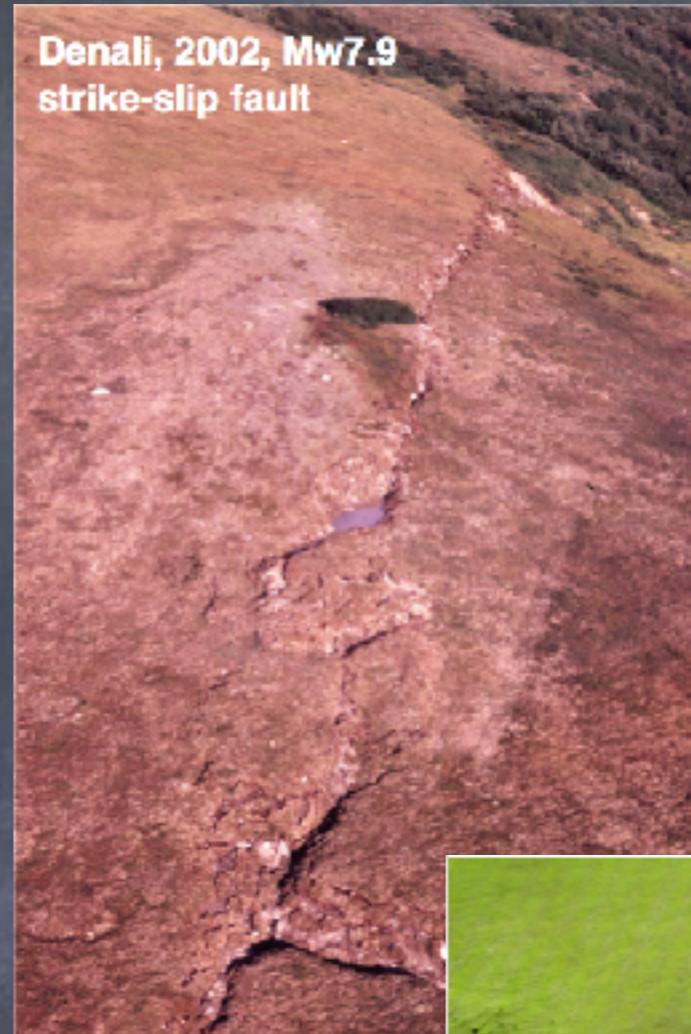
# Observer les déformations de la Terre depuis l'espace: De plus en plus souvent, de plus en plus précis

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Institut de Physique du Globe de Paris - CNRS*

*klinger@ipgp.fr*

*Conférence du Bureau des Longitudes, 7 Novembre 2018*

# *Lors de grands séismes les déformations de surface sont très variées mais pas forcément faciles à mesurer*



les déformations tectoniques créent de la déformation qui est préservée dans le paysage > signature de l'activité des failles



Fuyun fault, thrust scarp < 1m in height

pouvoir mesurer cette déformation  
> décrypter l'activité des failles



*En parallèle du travail de terrain,  
l'imagerie spatiale est devenue un outil  
indispensable pour l'étude de la déformation  
de la croûte terrestre*

- *Petit retour sur l'évolution de l'imagerie  
spatiale pour la mesure des déformations  
de la croûte terrestre*
- *3 exemples de ce qui se fait aujourd'hui  
en imagerie spatiale*

*Environ 10 ans après la théorie de la tectonique des plaques est lancé le programme Landsat*

*> première vision globale avec bonne résolution  
(80m à 40m)*



*Au milieu des années 80, la France lance les premiers satellites de la famille Spot*

*> tps de revisite 26j, résolution 10m*



*Cette nouvelle vision régionale permet le développement des études de tectonique active*

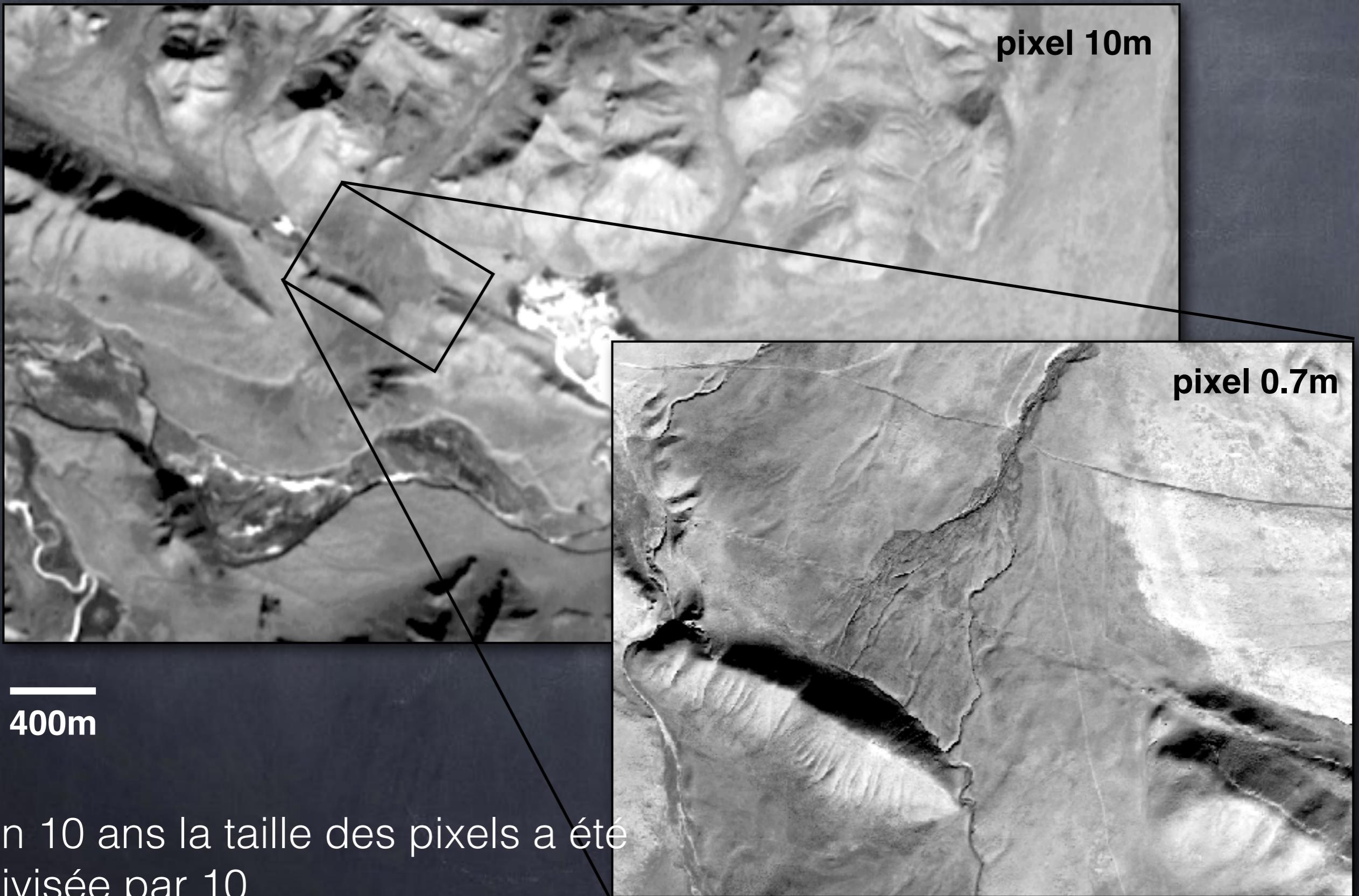


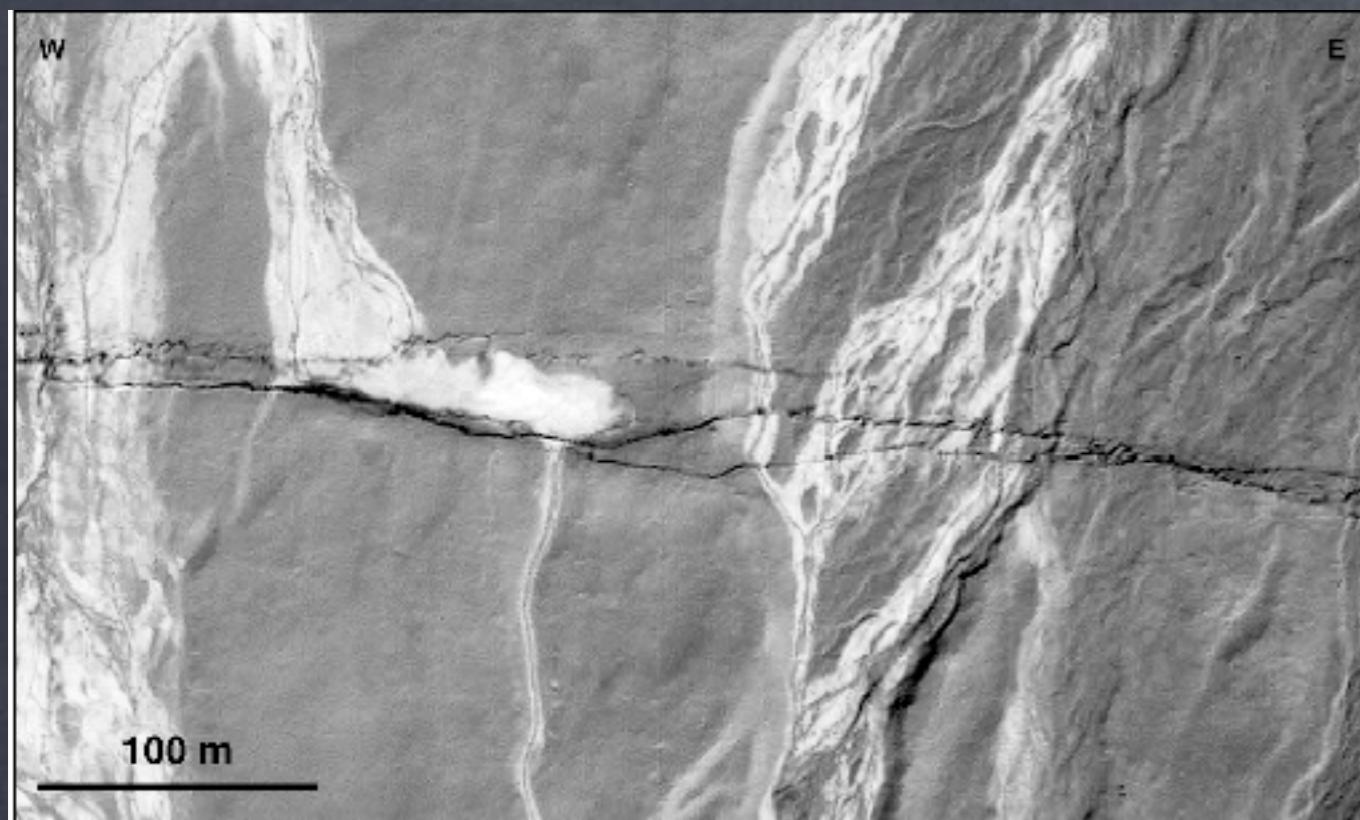
(Massonnet et al., 1993)

*En 1992, 1ère mesure par interférométrie radar (ERS-1) de la déformation associée à un séisme*

*Un pixel hz de 100m pour une résolution verticale de 3cm*

# Les années 2000, l'explosion de la haute résolution

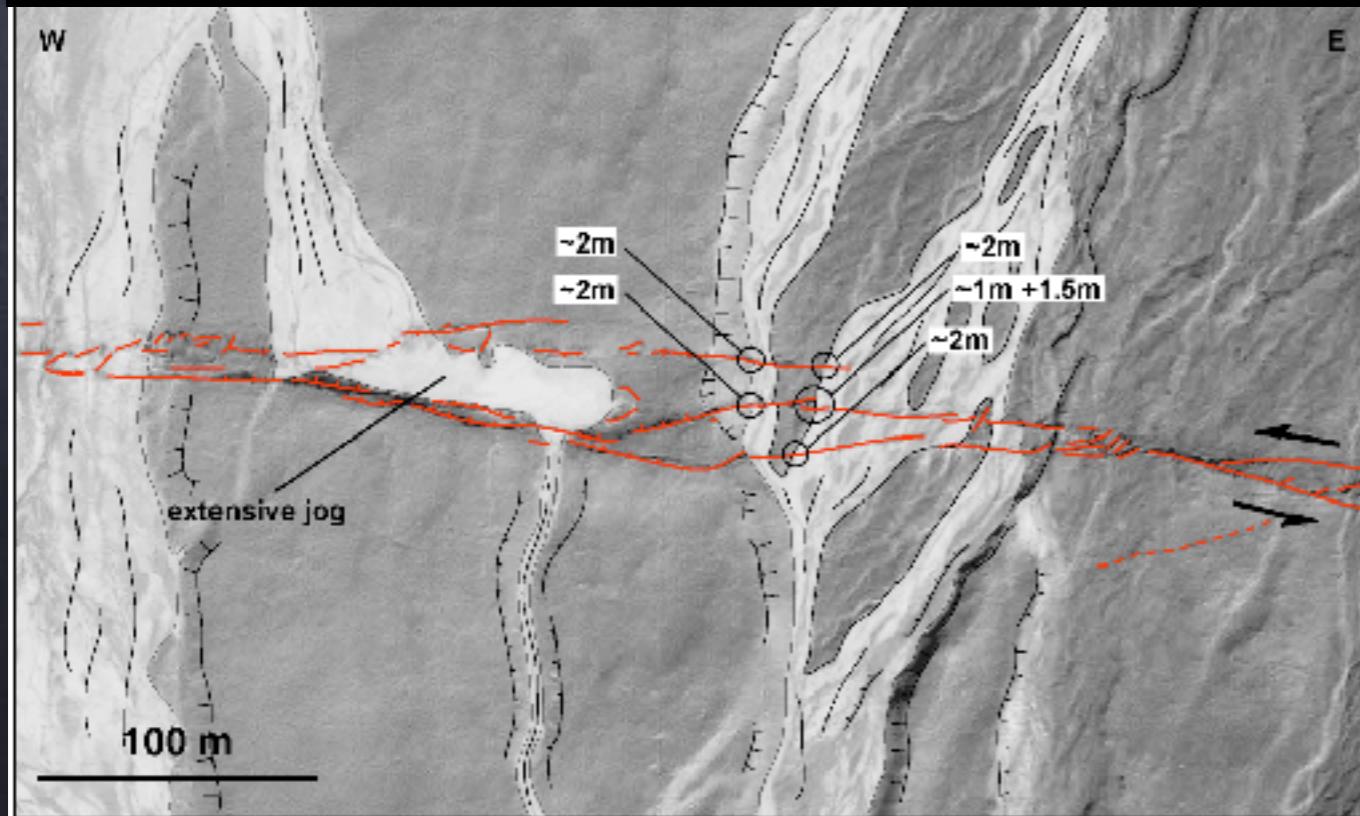




## Détails d'une rupture co-sismique

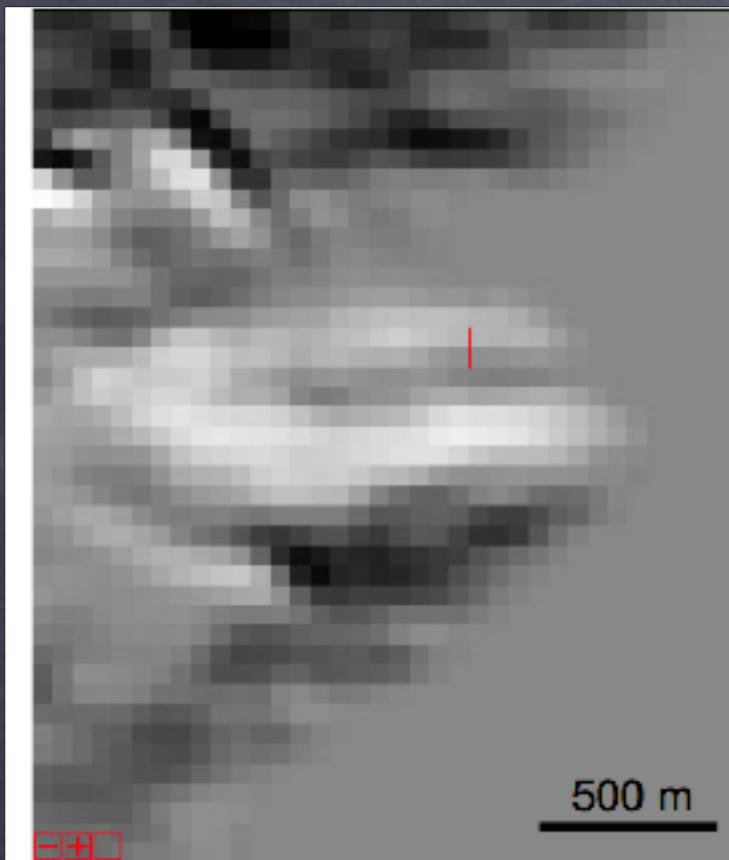
Pour la première fois en 2001 on peut imager une rupture de surface depuis l'espace

Image sat. optique sub-métrique Ikonos

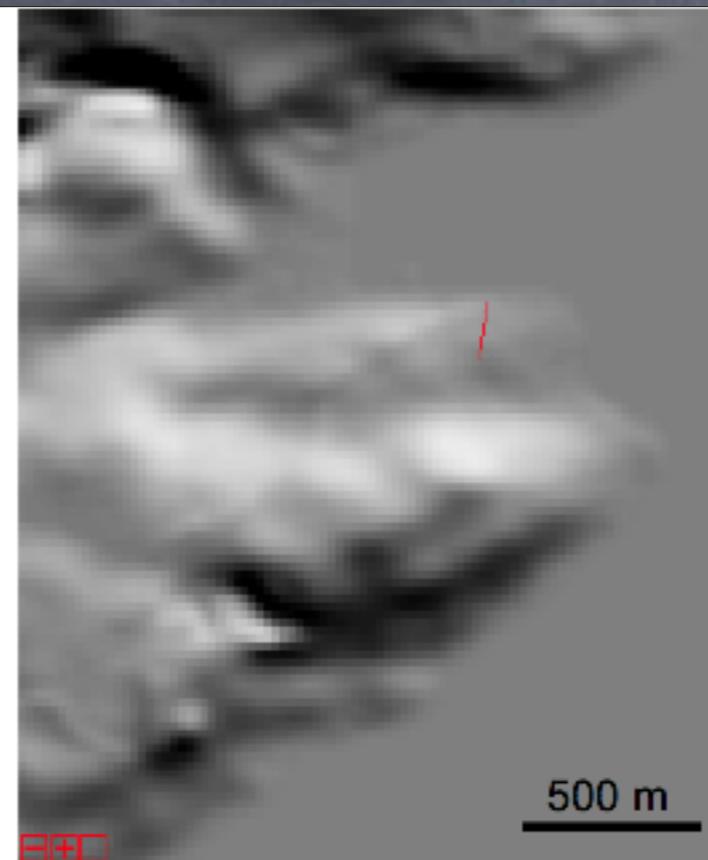


(Klinger et al., 2005)

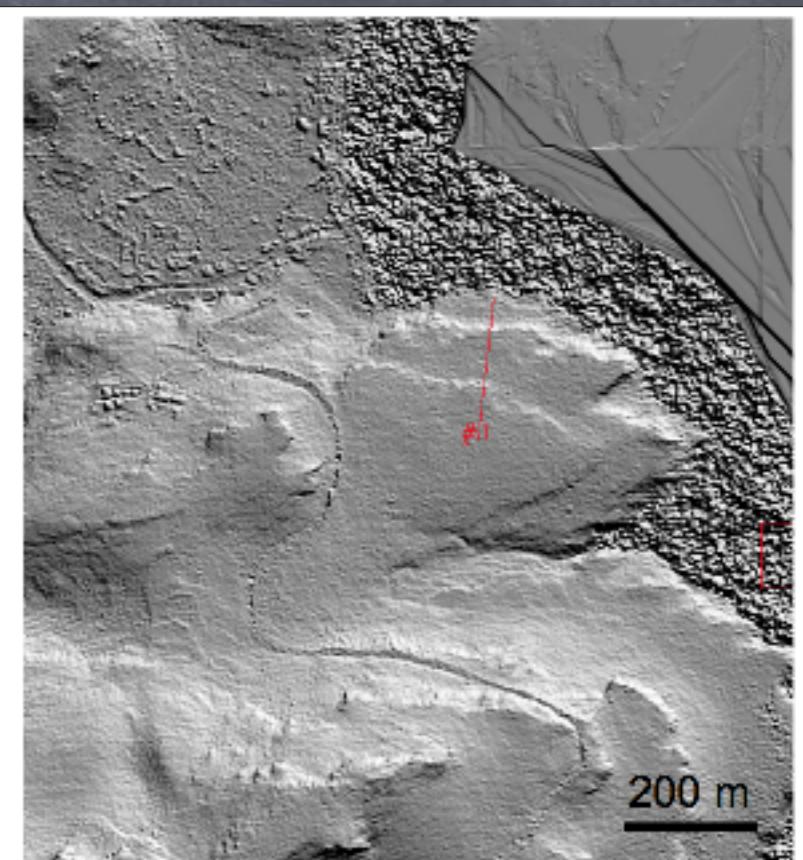
# *meilleures images, meilleure topographie*



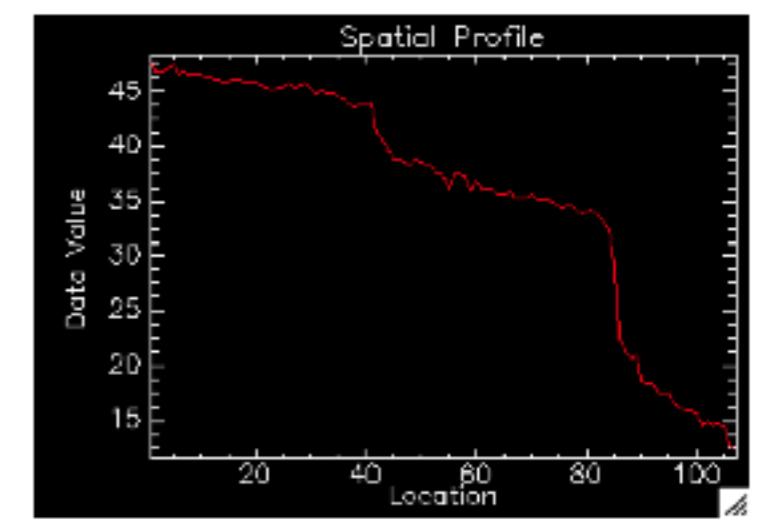
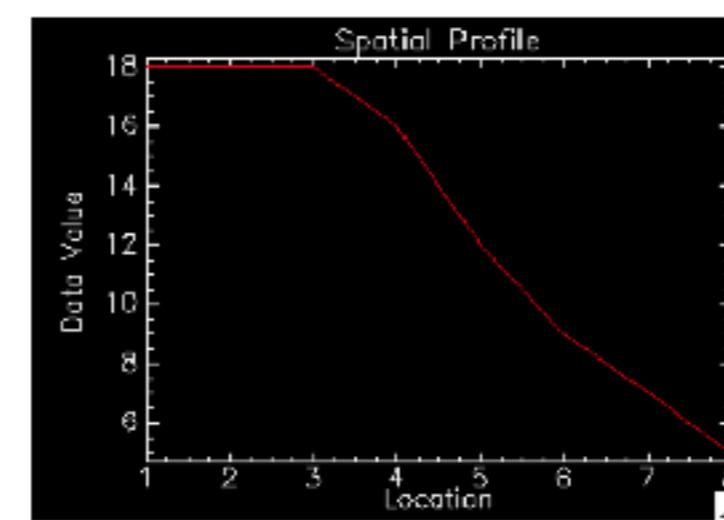
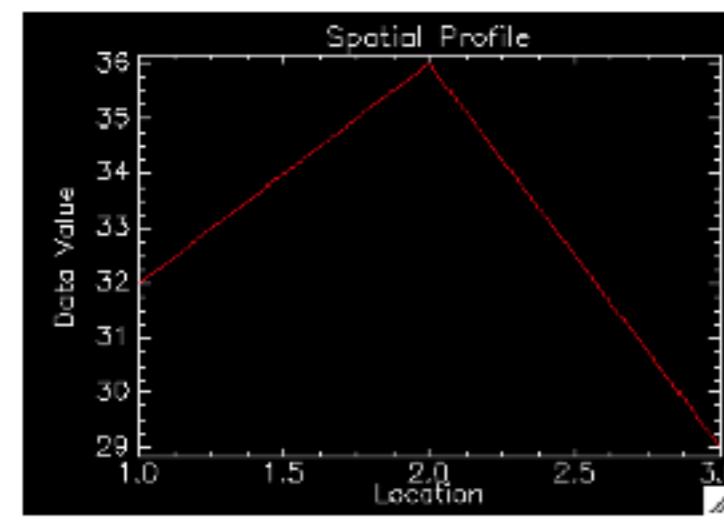
**SRTM3**, résolution 3 arcsec  
(~ 90 m ; année 2000)



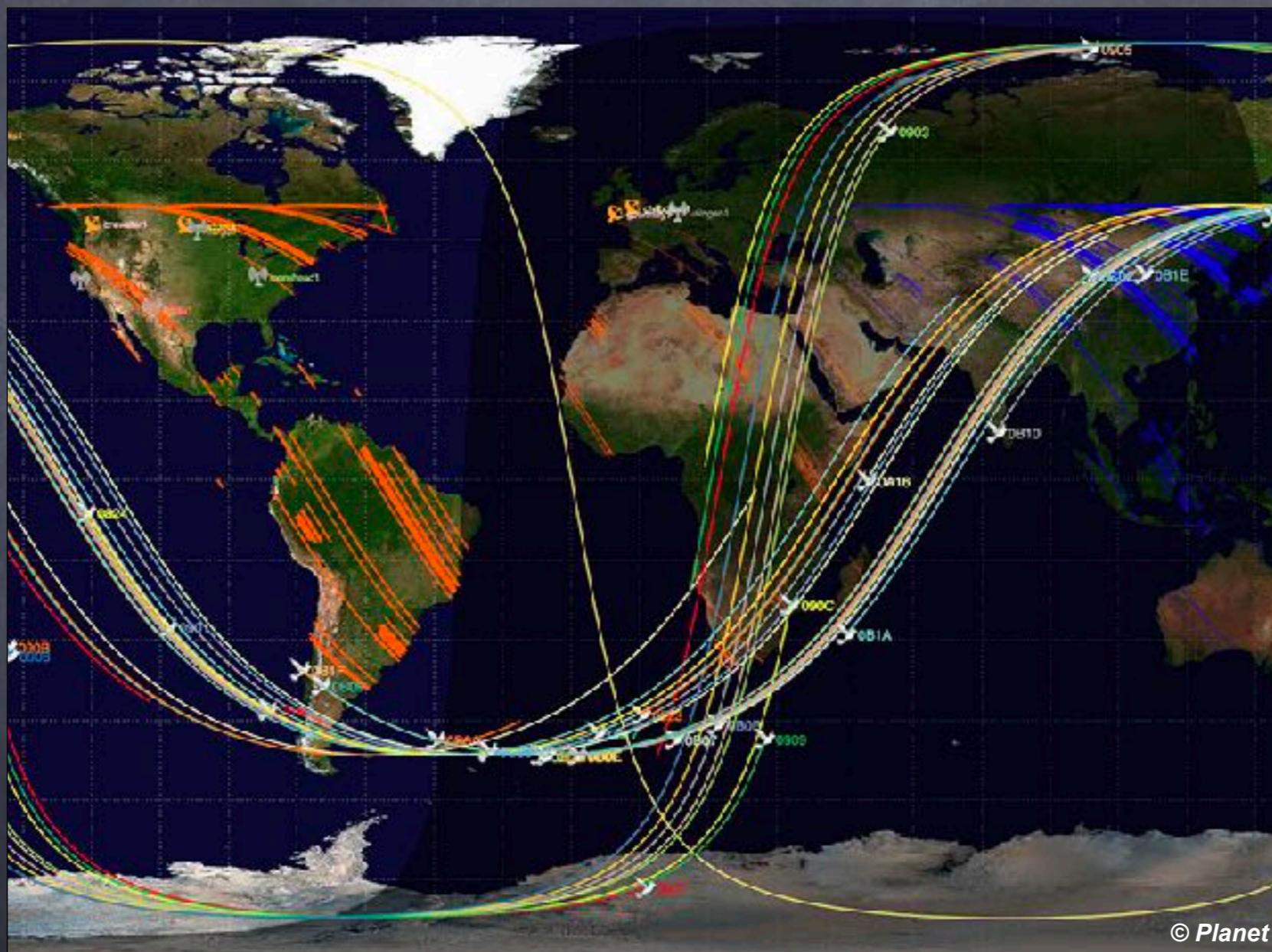
**ASTER GDEM**, résolution 1 arcsec (~ 30 m ; année 2009)



**MNS Pléiades** calculé par  
MicMac, ré-échantillonné à 2 m



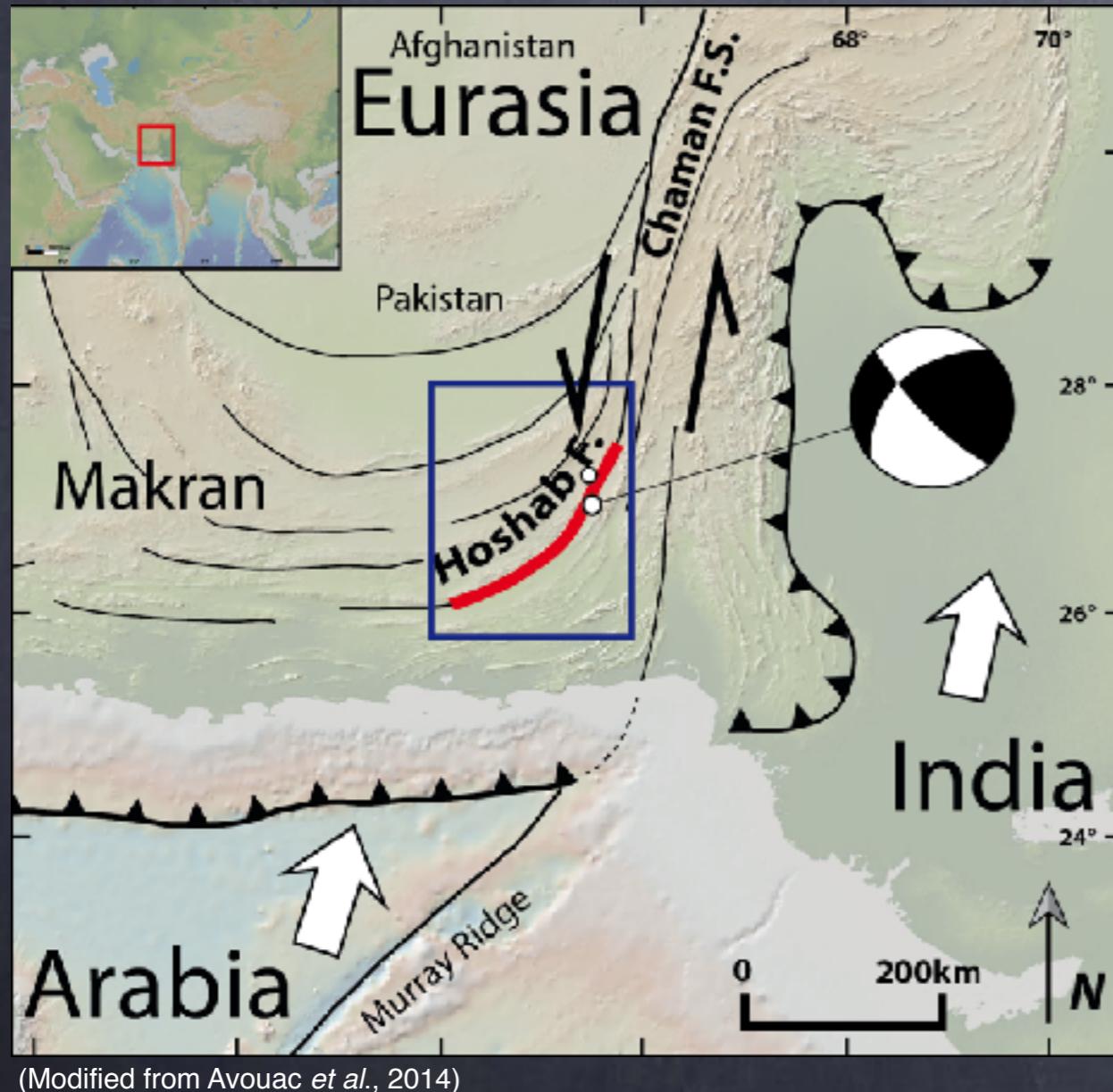
*Aujourd’hui,  
les constellations de satellites permettent  
une revisite quotidienne avec une résolution sub-métrique*



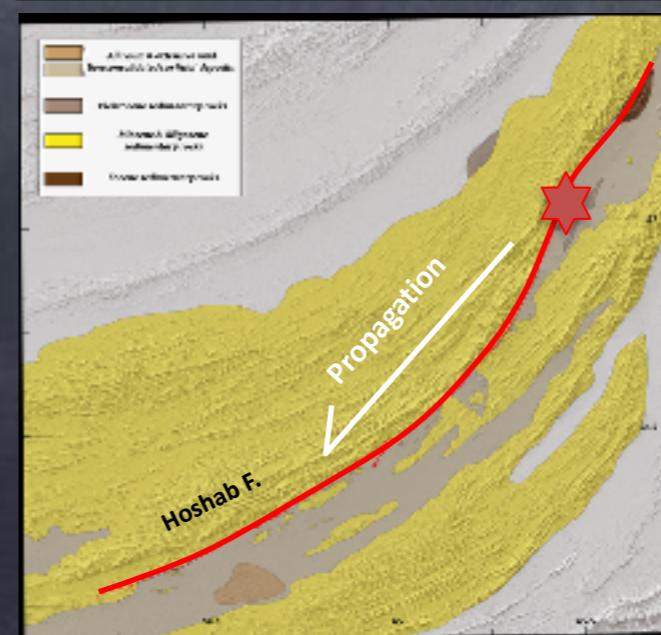
*jusqu'à 200 satellites opérés simultanément*

# Imager la complexité de la rupture depuis l'espace

## Le séisme du Balouchistan, Mw7.8, en 2013



Courtesy of K. Hudnut & A. Khan



(geology after  
Panagos *et al.*, 2011)

Remerciements ++  
A. Vallage et A. Delorme

image pixel < 1m

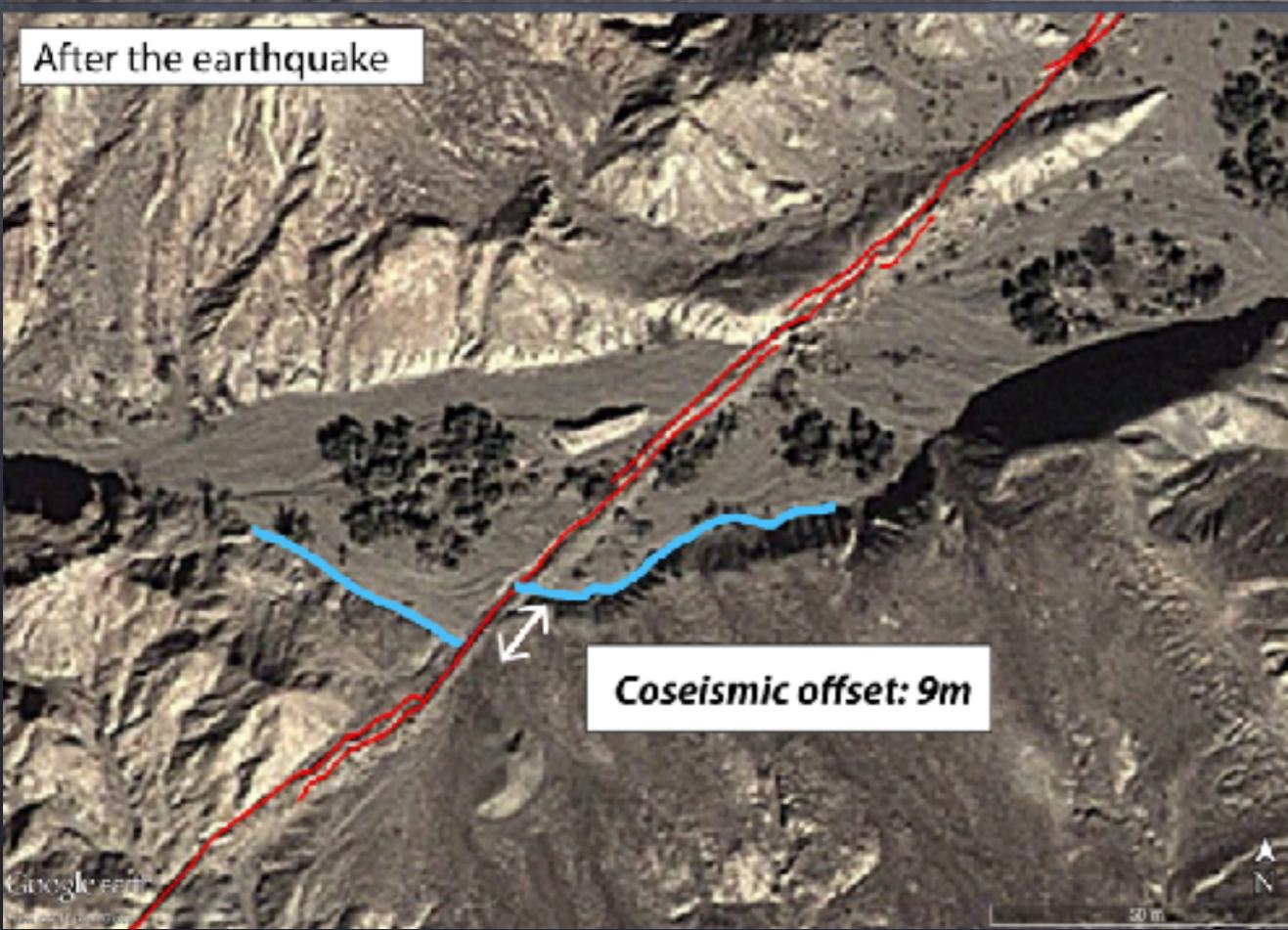


image pixel < 1m



Ground rupture mapping  
using Google Earth™  
(1:500 scale)





## Ground rupture mapping using Google Earth™ (1:500 scale)

Image pixel size < 1m

Different styles of ground rupture  
localization:

- 1) Localized slip

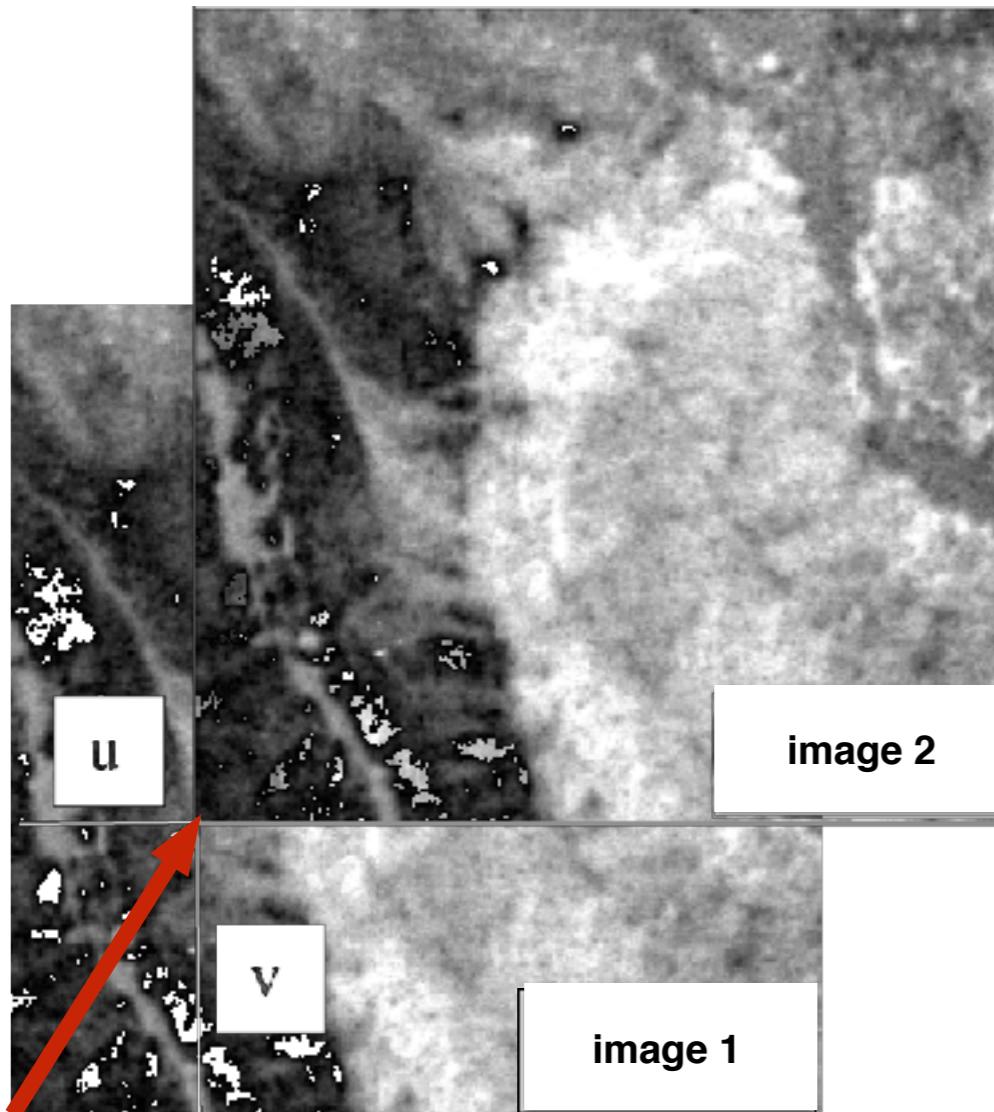
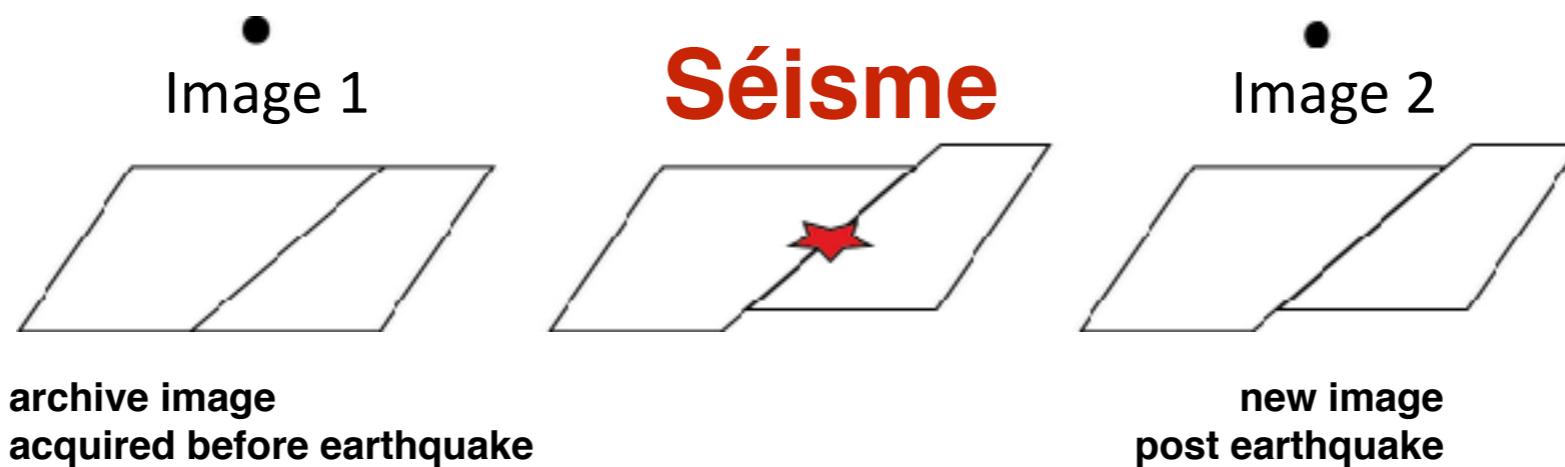
image pixel < 1m



image pixel < 1m



# Corrélation d'images optiques

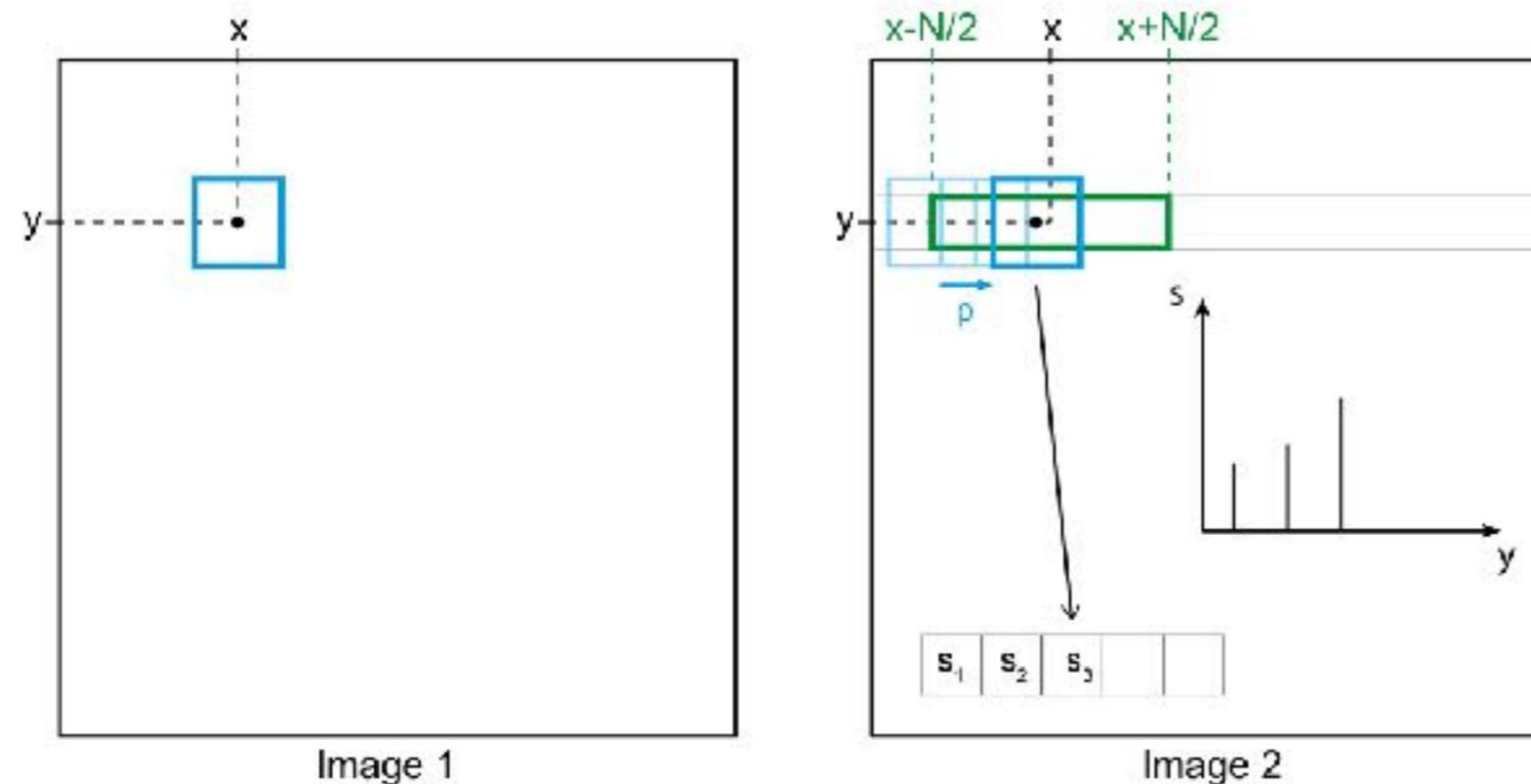
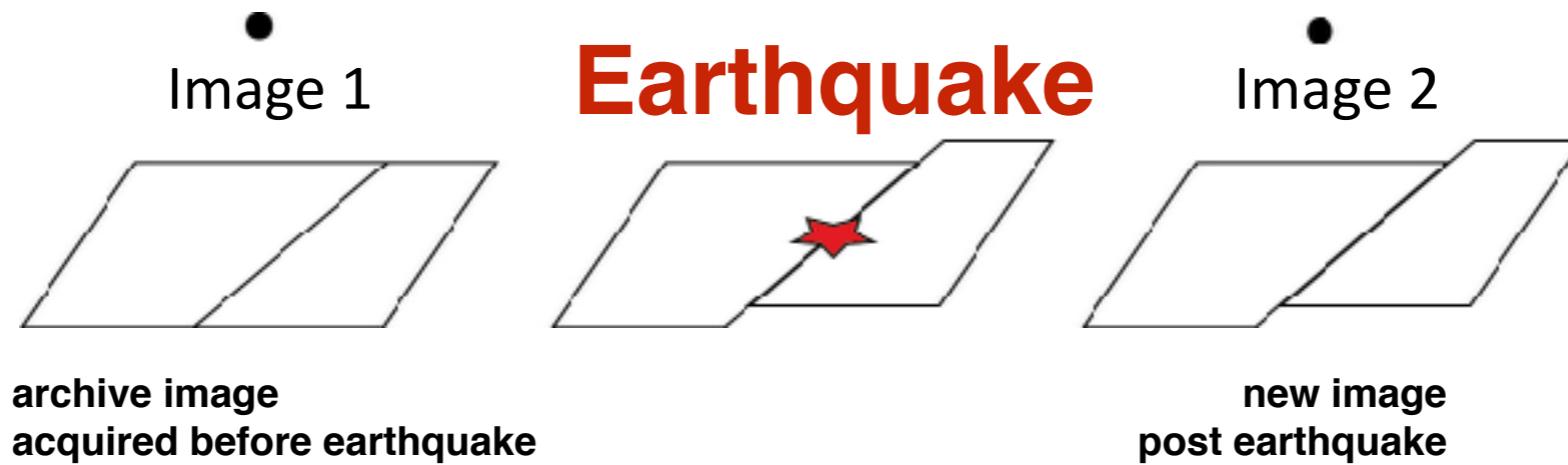


Compute horizontal displacement field using pairs of images

*need good topography!*

- 1) SpatioTriangulation + Orthorectification
- 2) Image correlation (MicMac)
- 3) Post-processing

# Optical image correlation

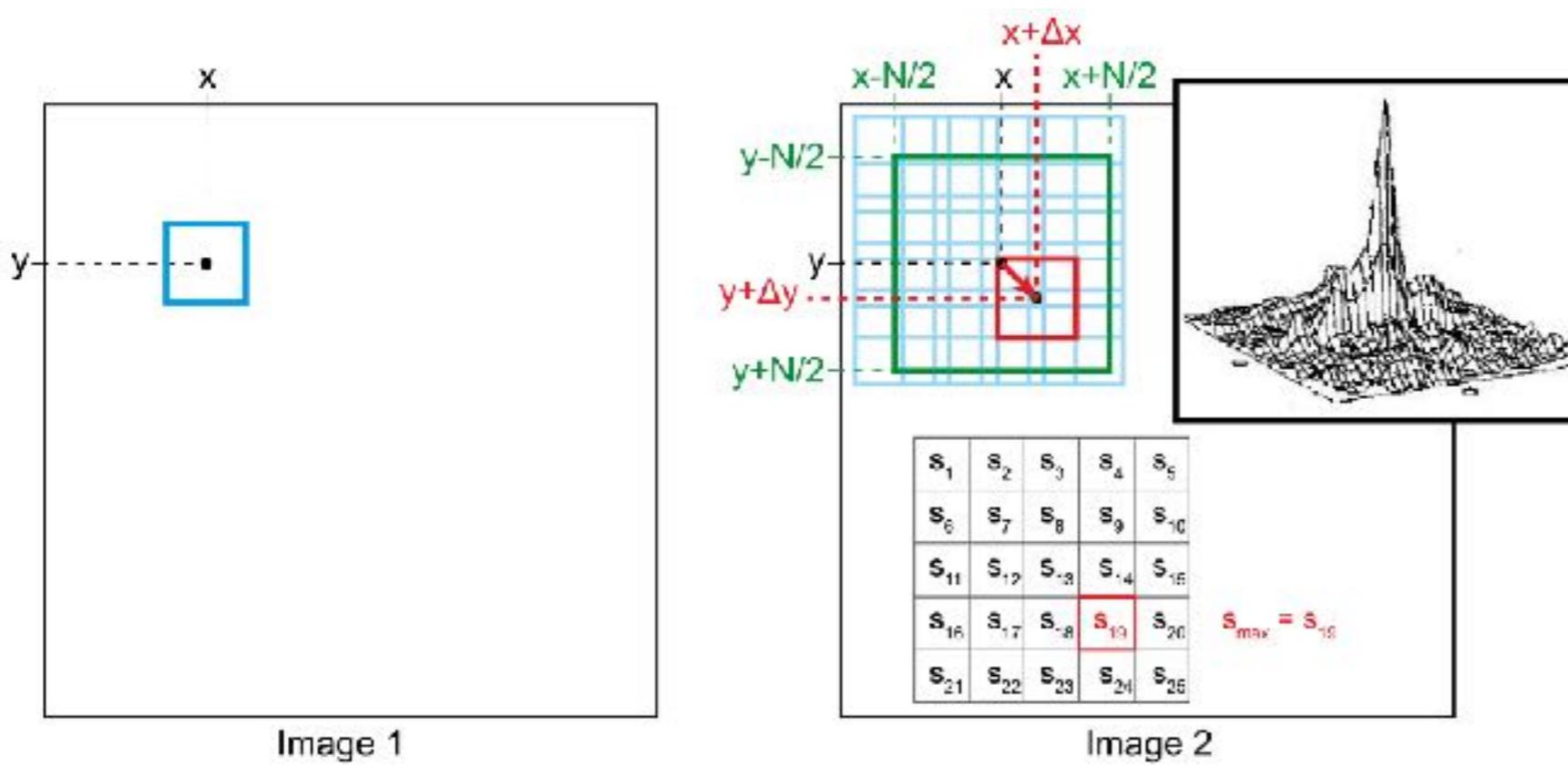
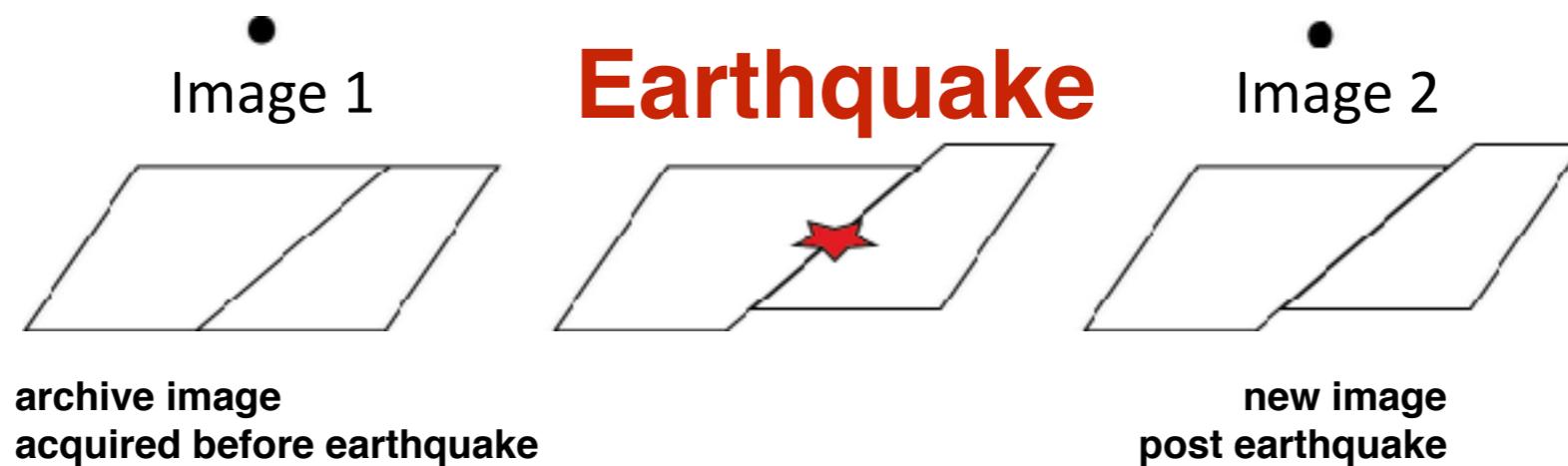


Calculate the horizontal displacement field using pairs of images

- 1) SpatioTriangulation + Orthorectification
- 2) **Image correlation (MicMac)** (IGN + IPGP, soutient CNES)
- 3) Post-processing

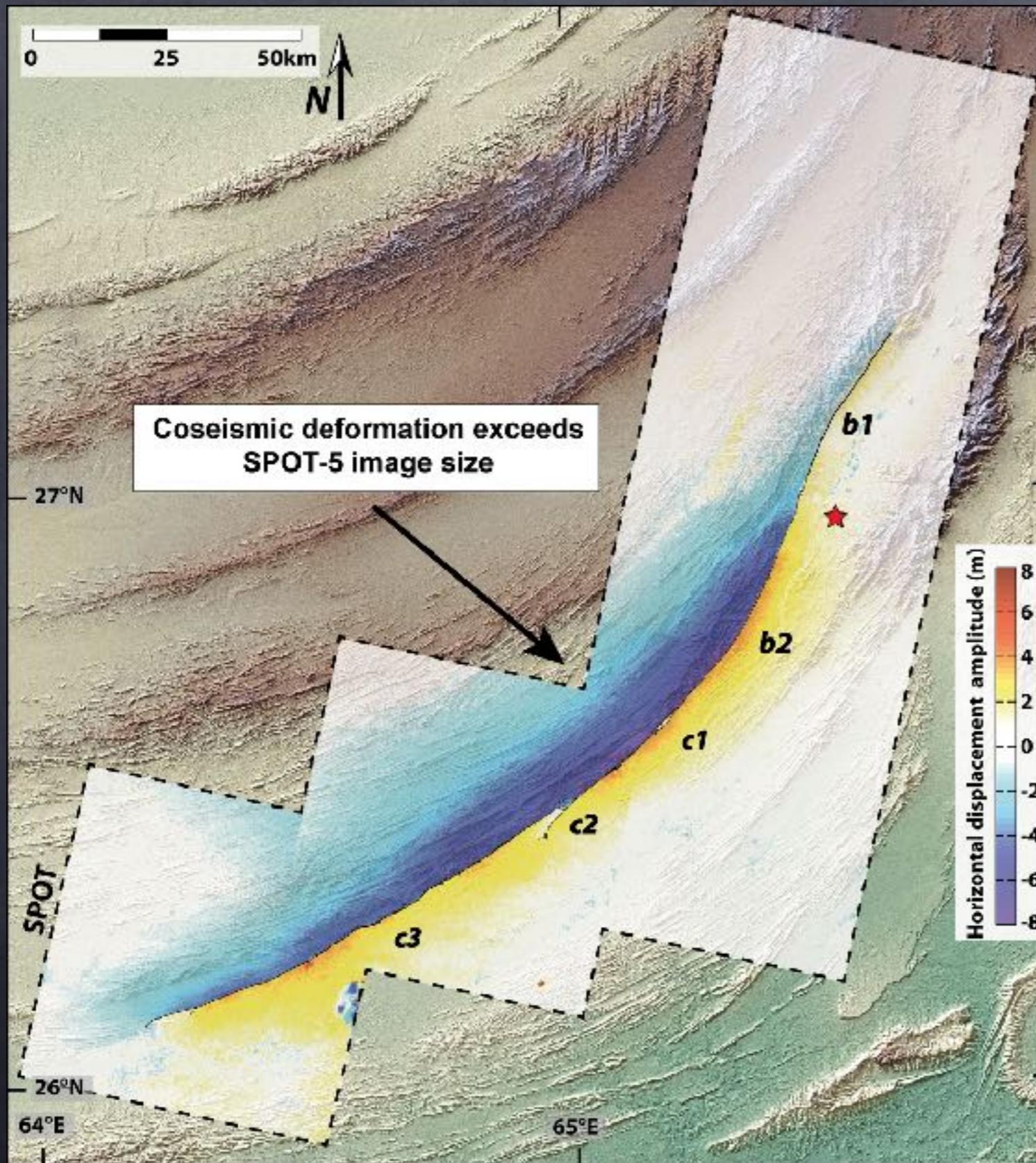
(Rosu et al., 2015; Rupnik et al., 2016)

# Optical image correlation



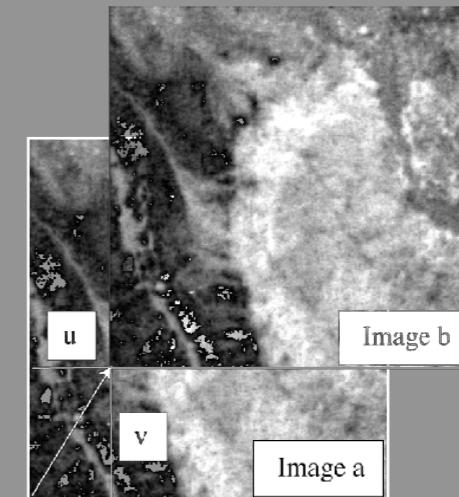
Calculate the horizontal displacement field using pairs of images

- 1) SpatioTriangulation + Orthorectification
- 2) Image correlation (MicMac)
- 3) Post-processing



(Vallage et al., 2015)

### Optical image correlation



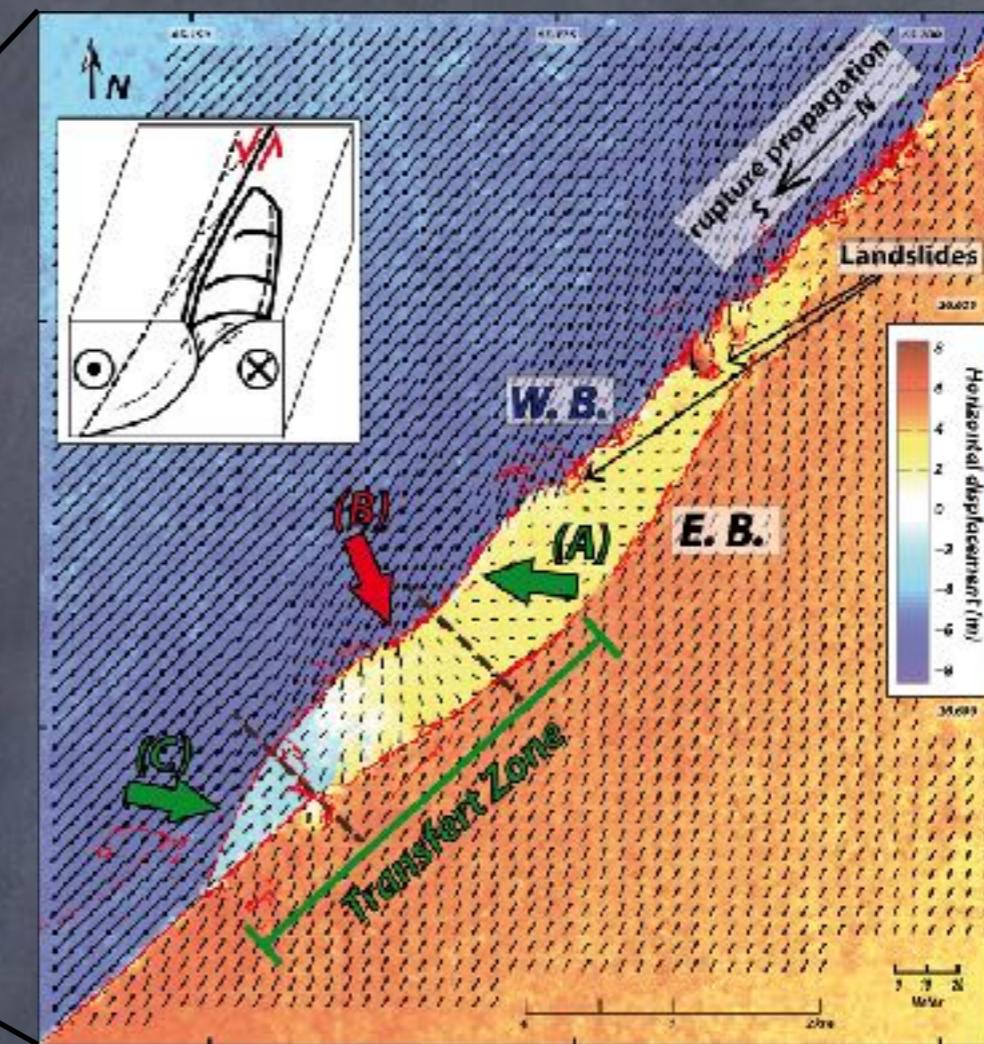
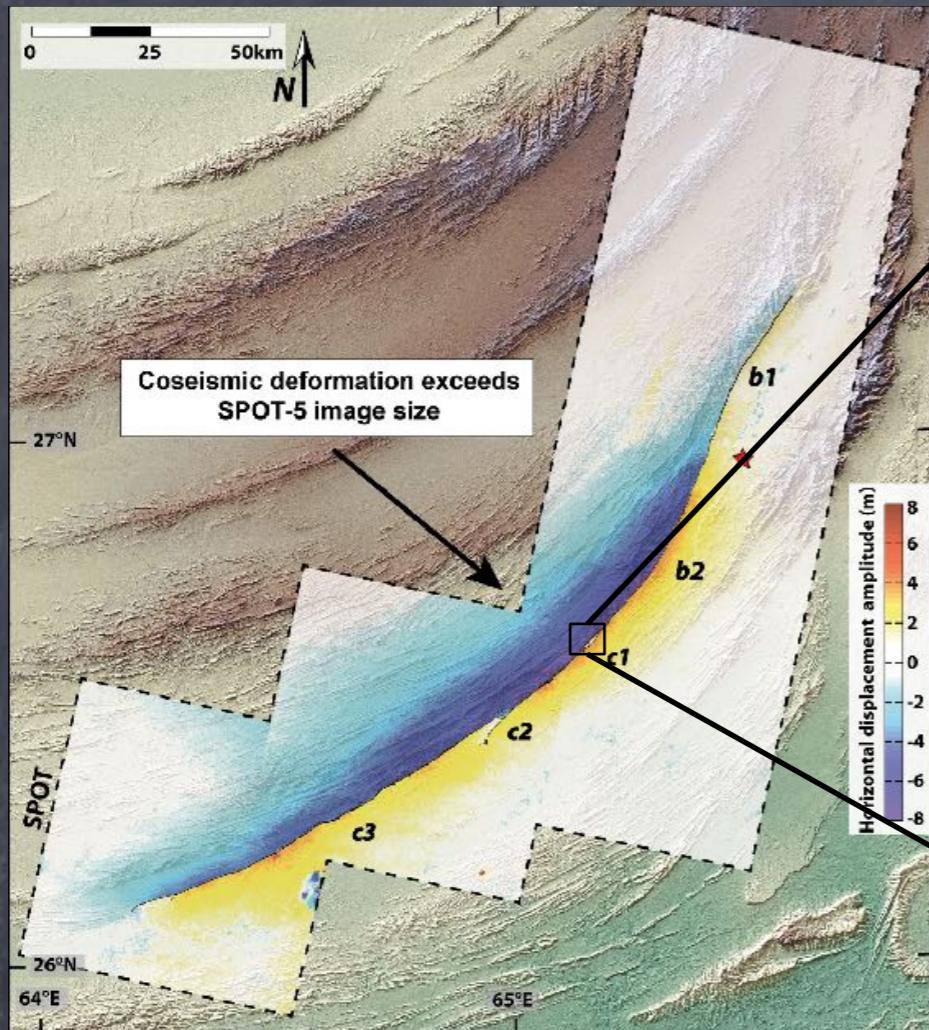
Horizontal displacement field using pairs of images

- 1) SpatioTriangulation + Orthorectification
- 2) Image correlation (MicMac)
- 3) Post-processing

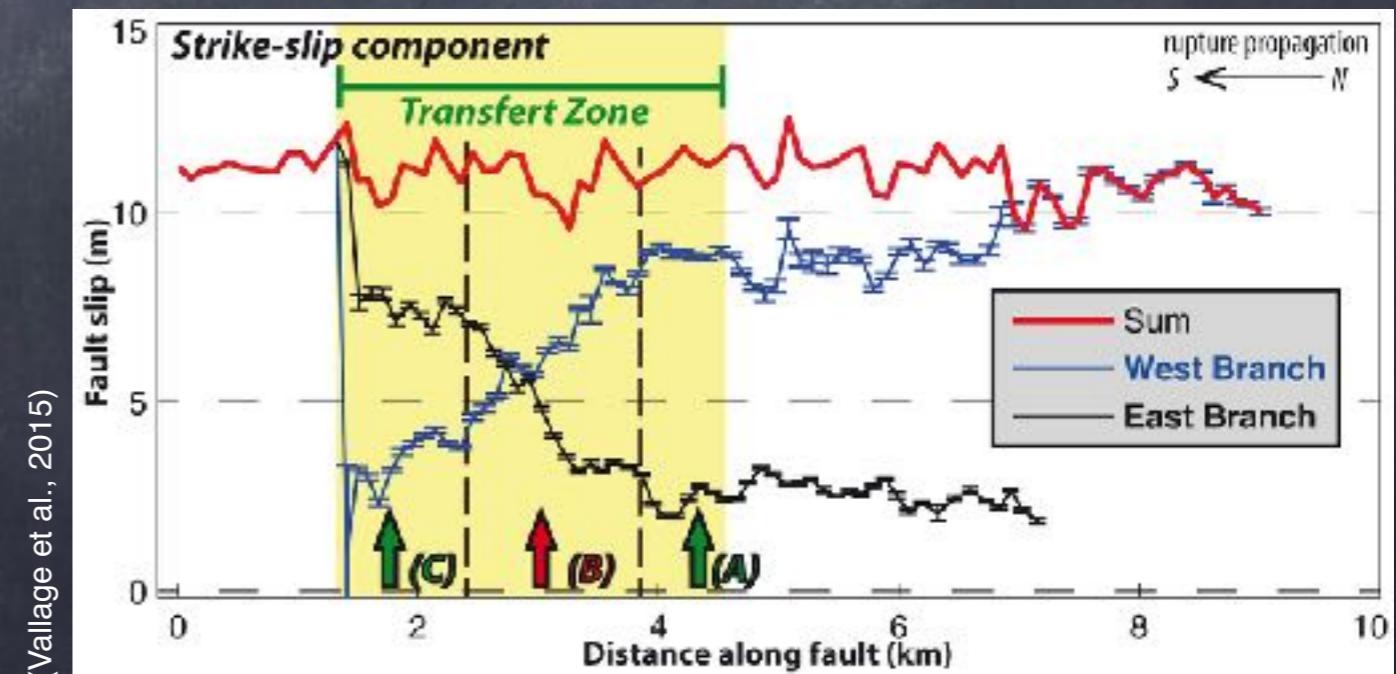
### Horizontal displacement field:

- SPOT-5: 2.5m px size
- Rupture length ~200km
- Amplitude variations (North vs. South)
- Maximum ~14m

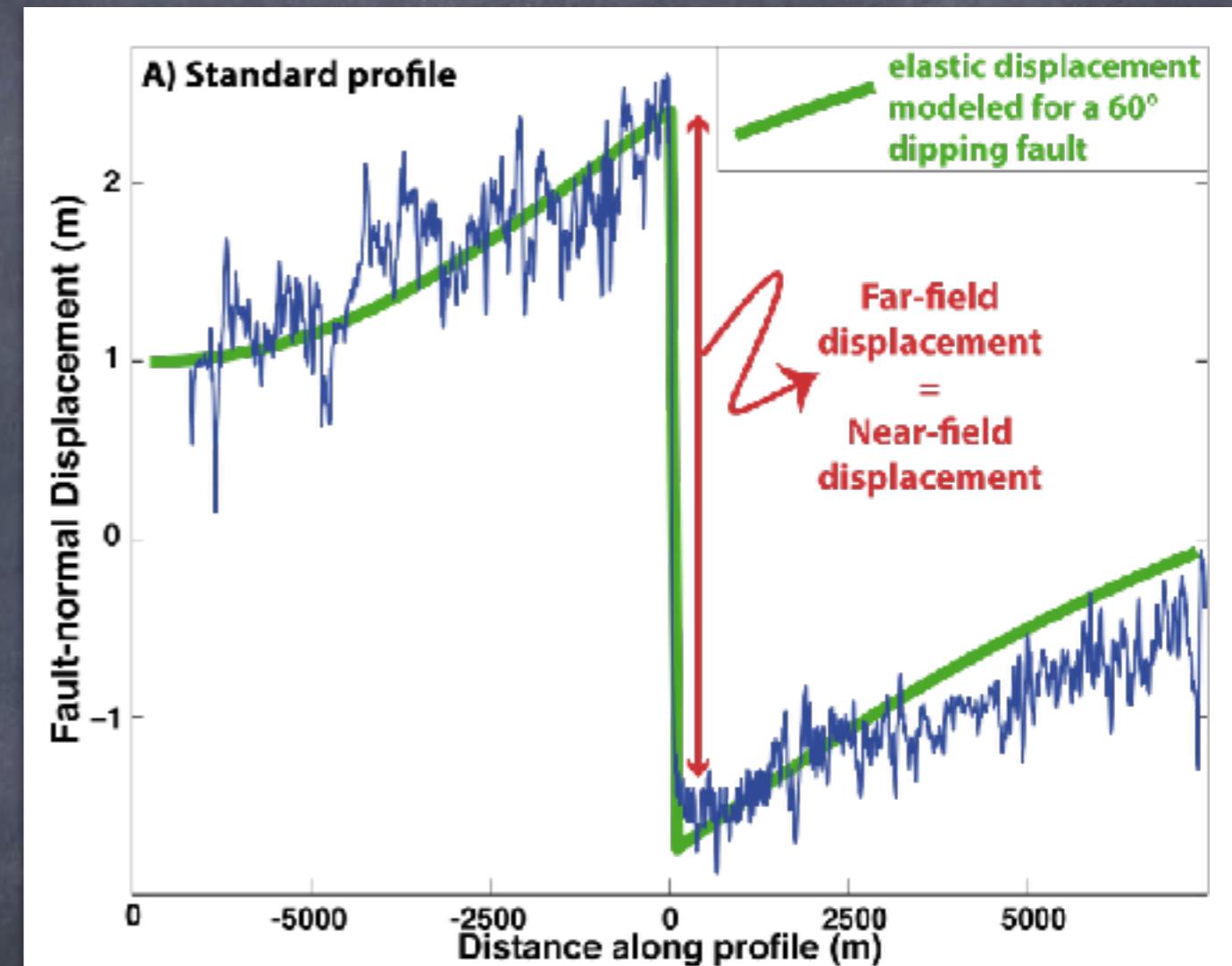
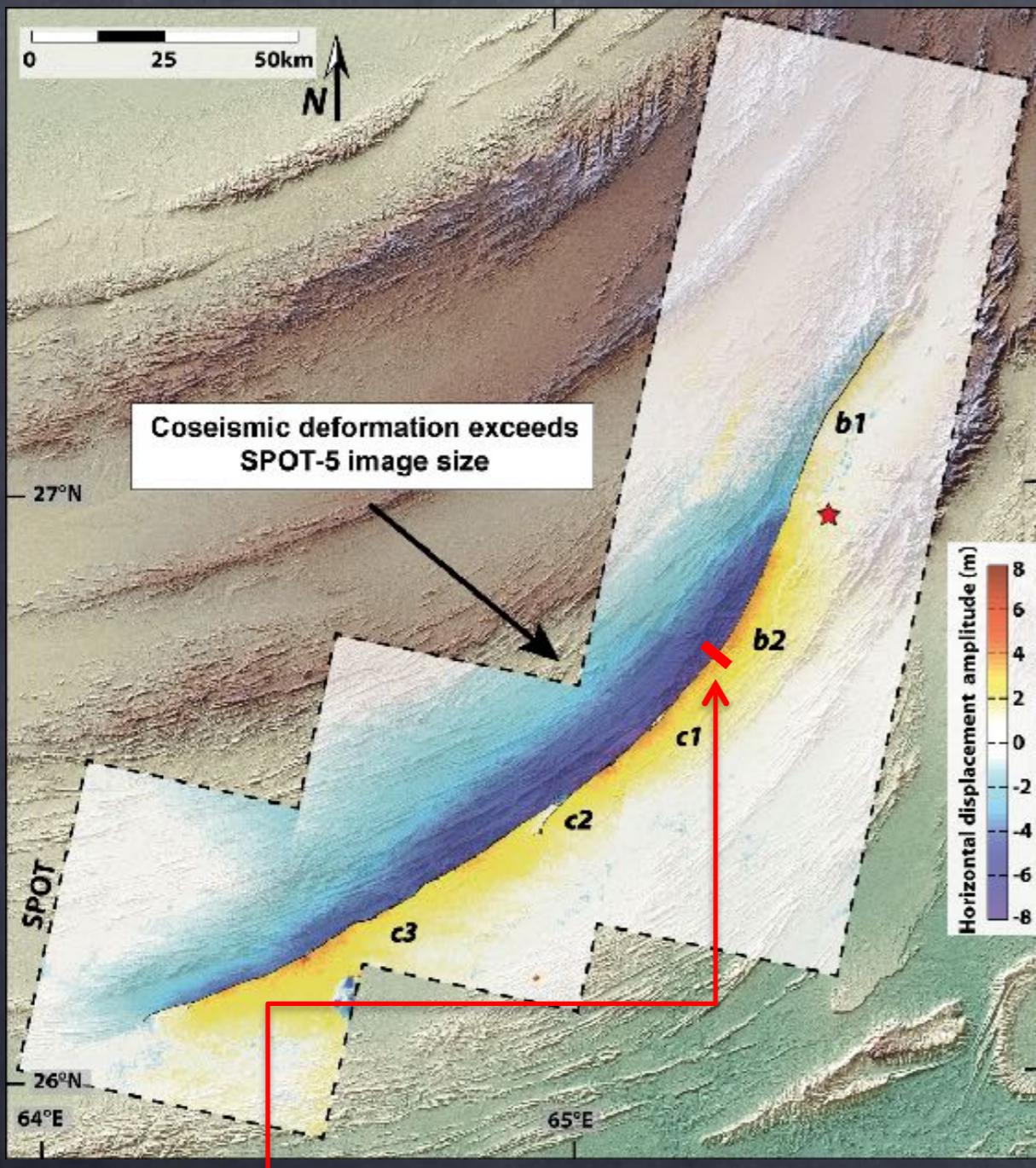
# Slip distrib. in the relay zone



Measure of the deformation  
in the relay zone



# Co-seismic displacement along the rupture

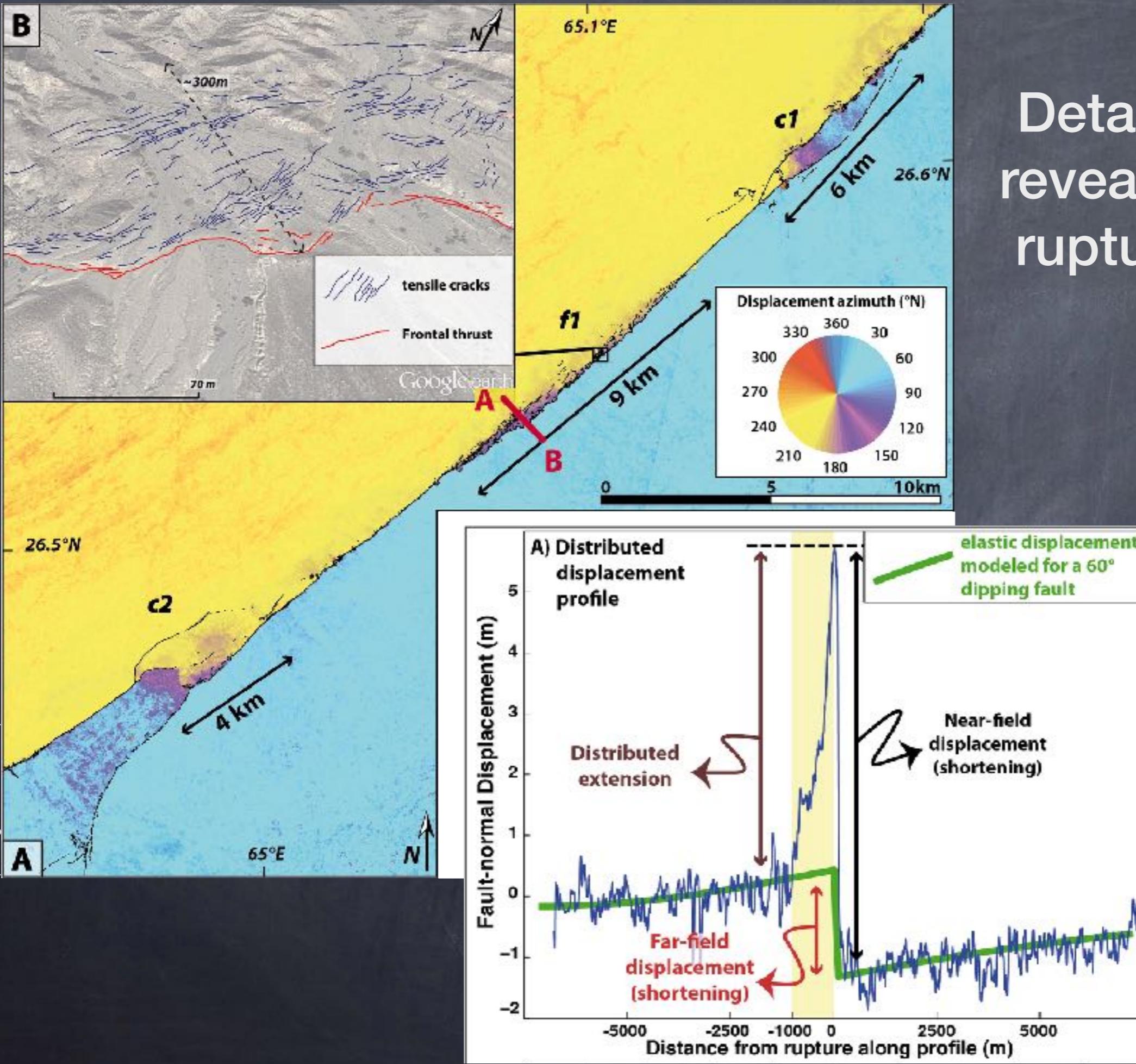


(Vallage et al., 2015)

Profiles:

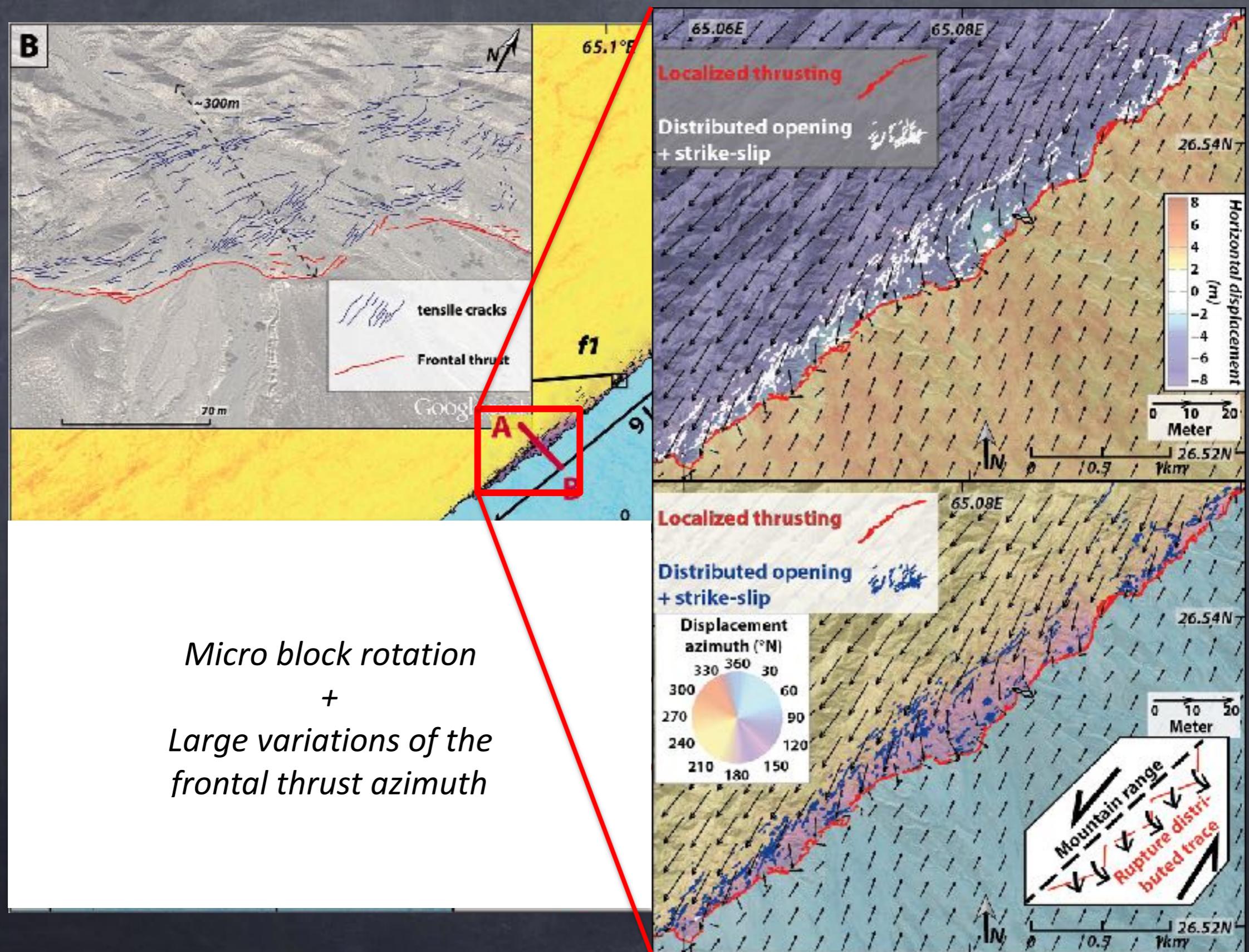
15km long, 100m wide, oriented

Measuring the fault-parallel and fault-normal displacements on both sides of the fault to determine the slip accommodated at the fault



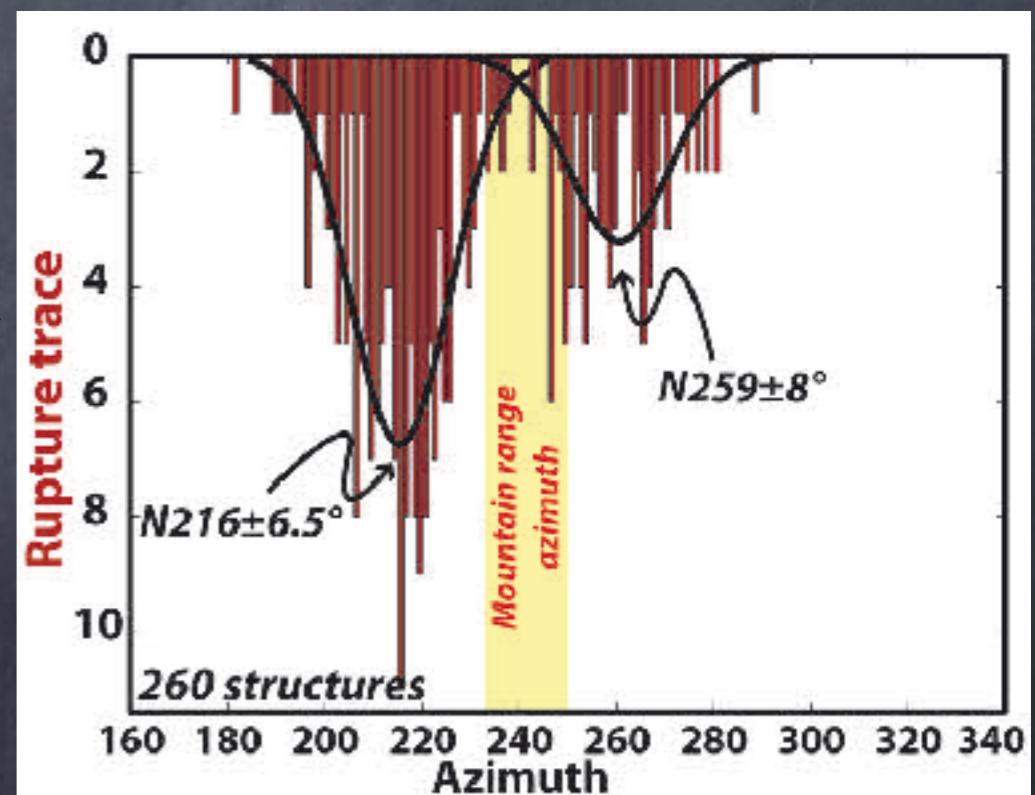
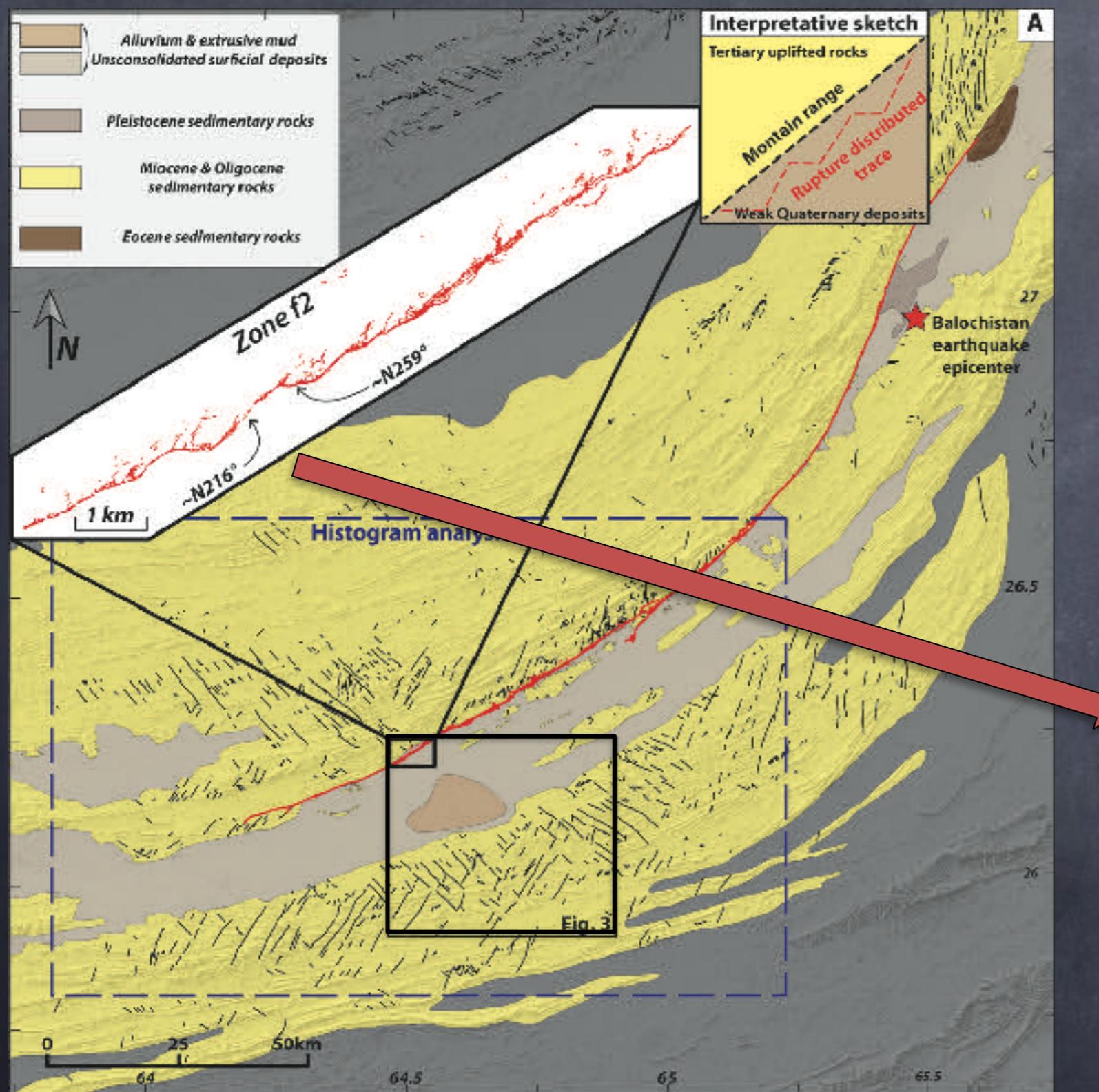
Detailed meas.  
reveals complex  
rupture pattern

# Structural control on surface-rupture pattern

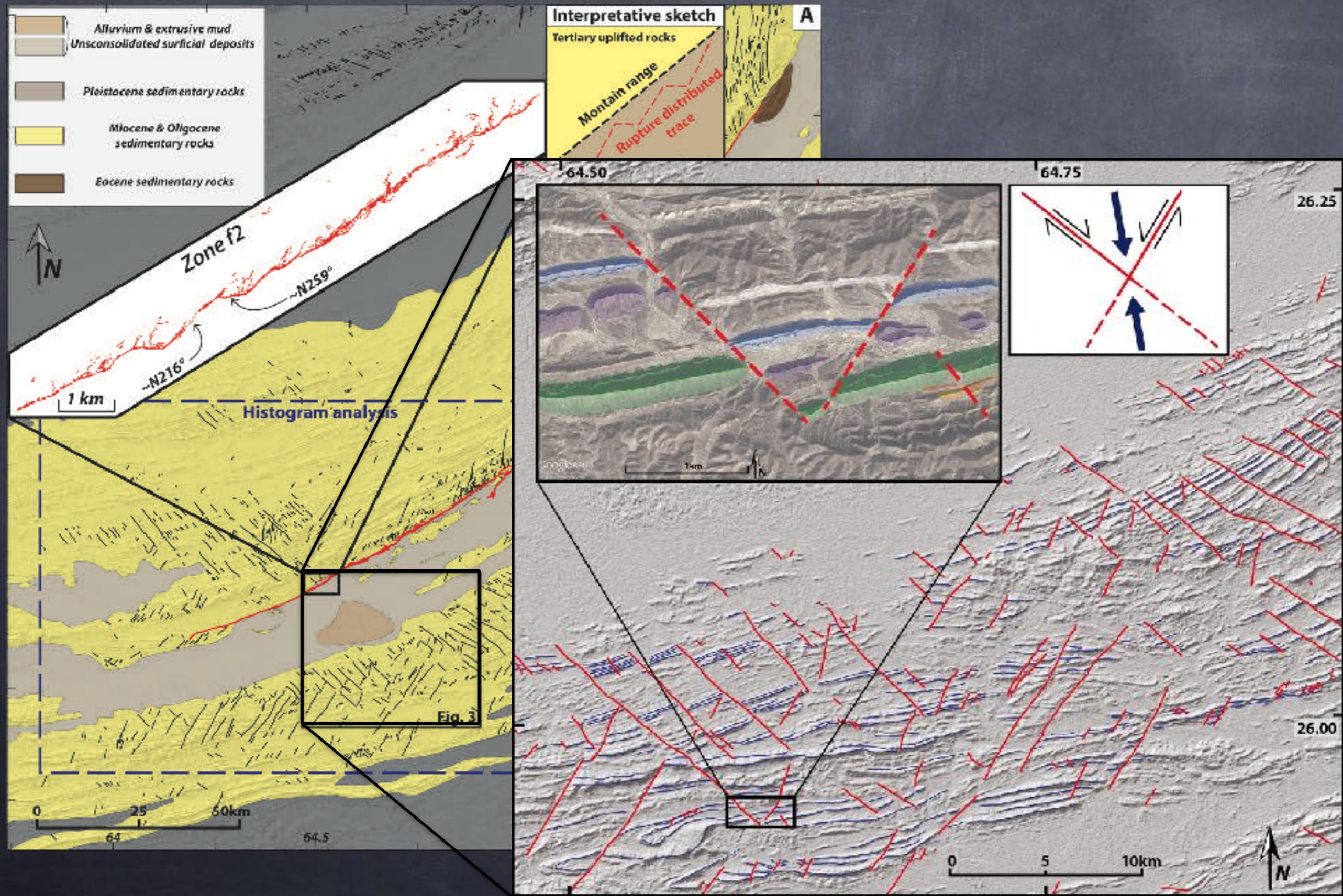


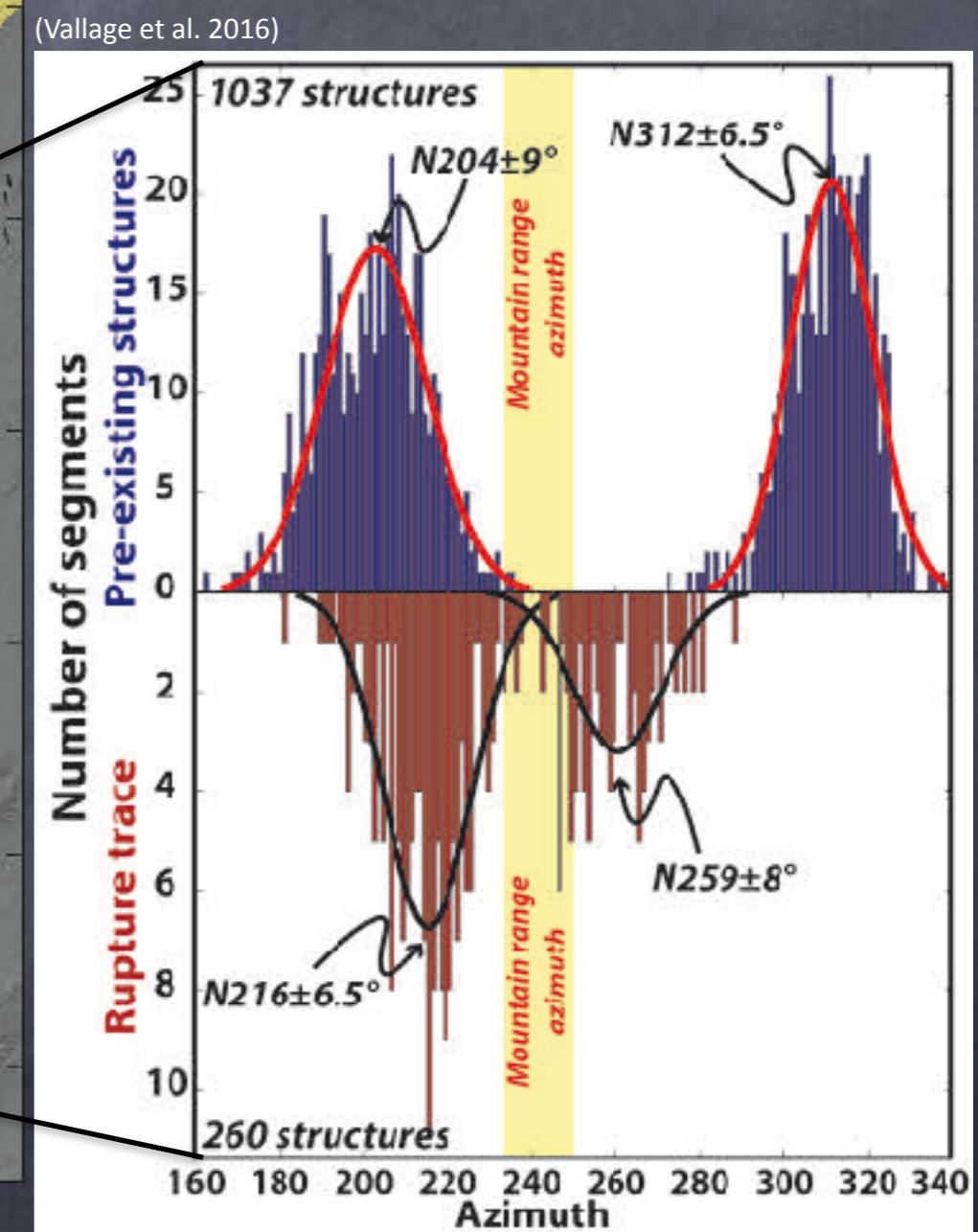
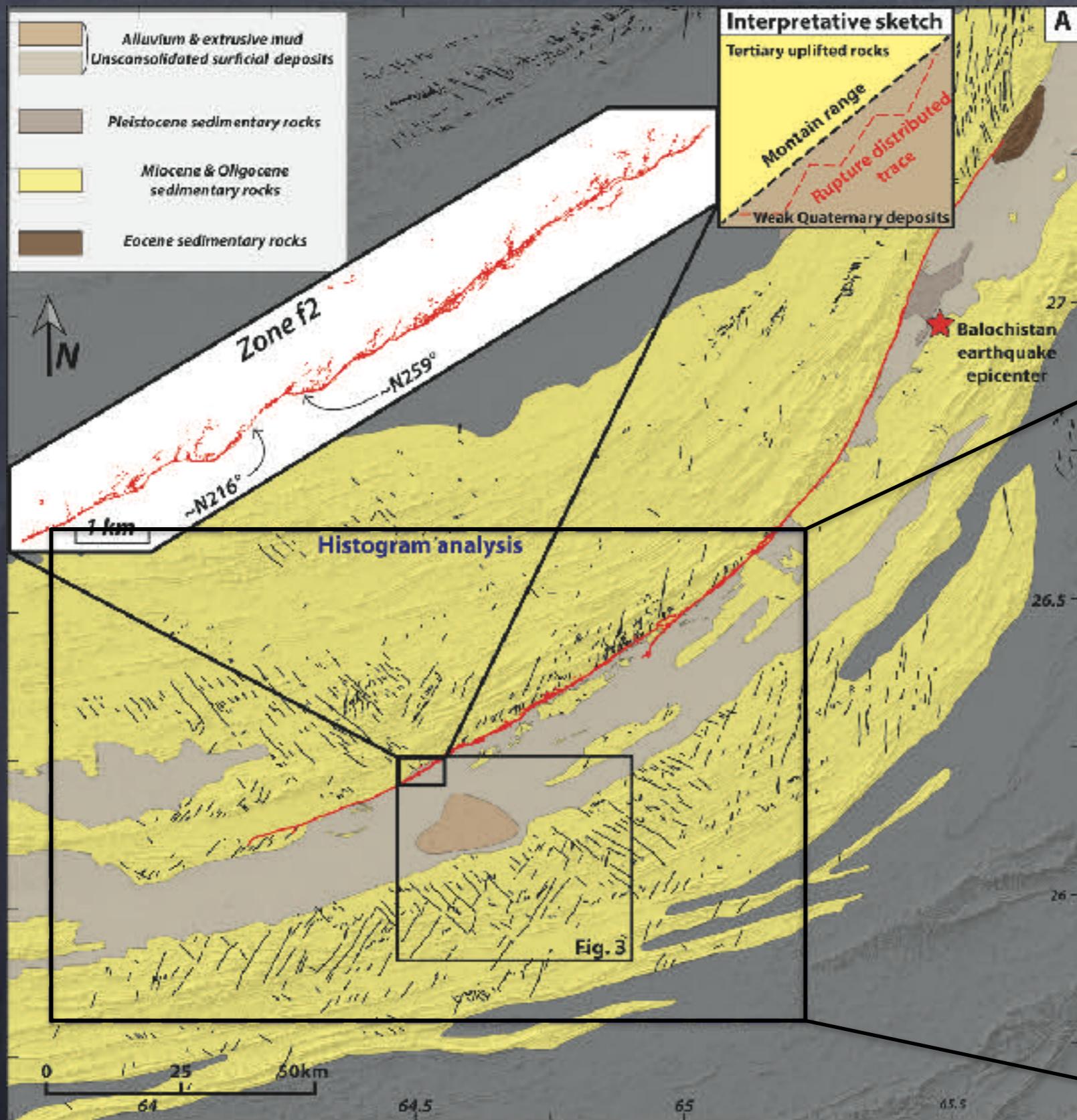
(Vallage et al., 2015)

# Variability of surface-rupture azimuth



# What can we get from regional geology?

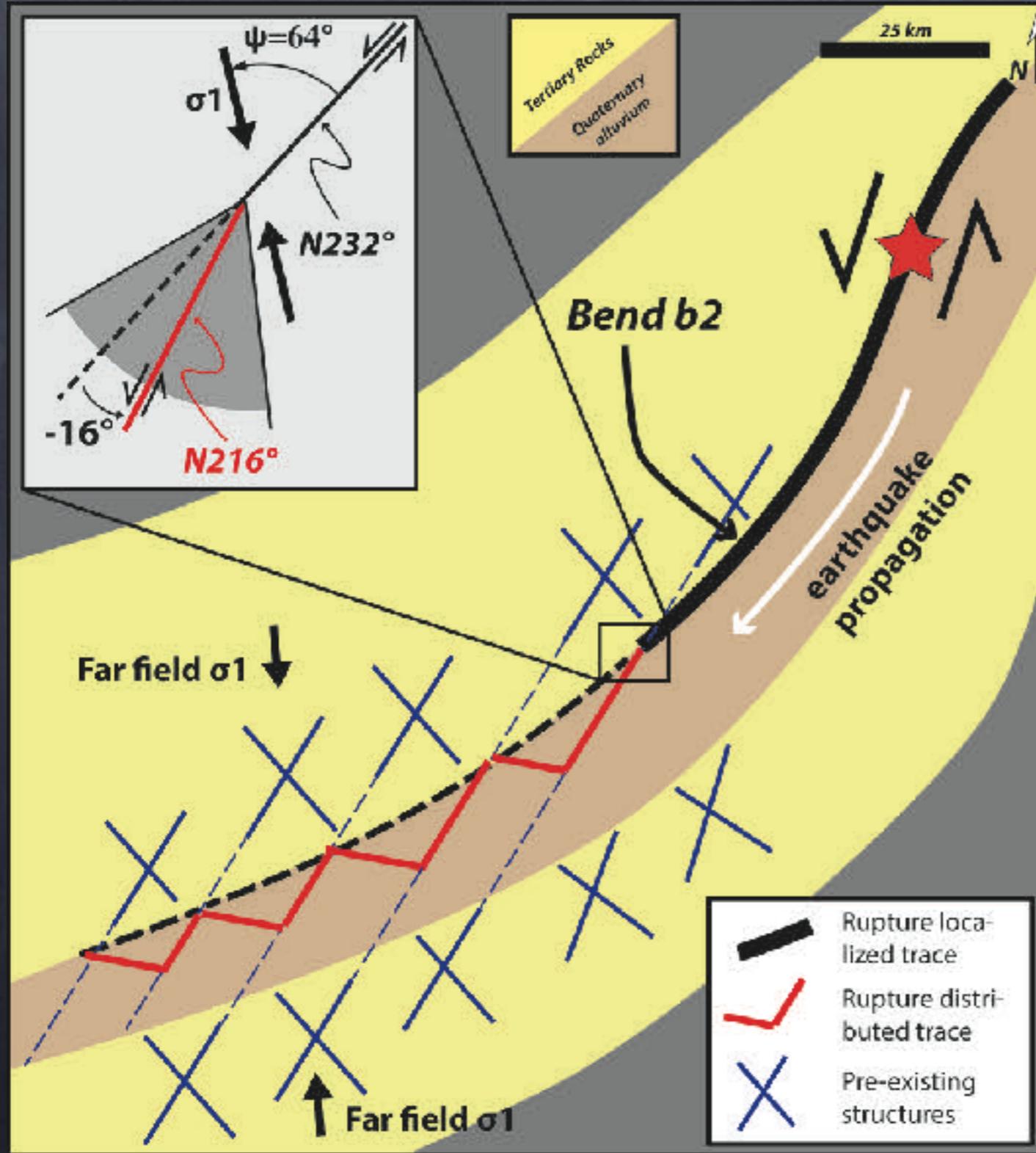




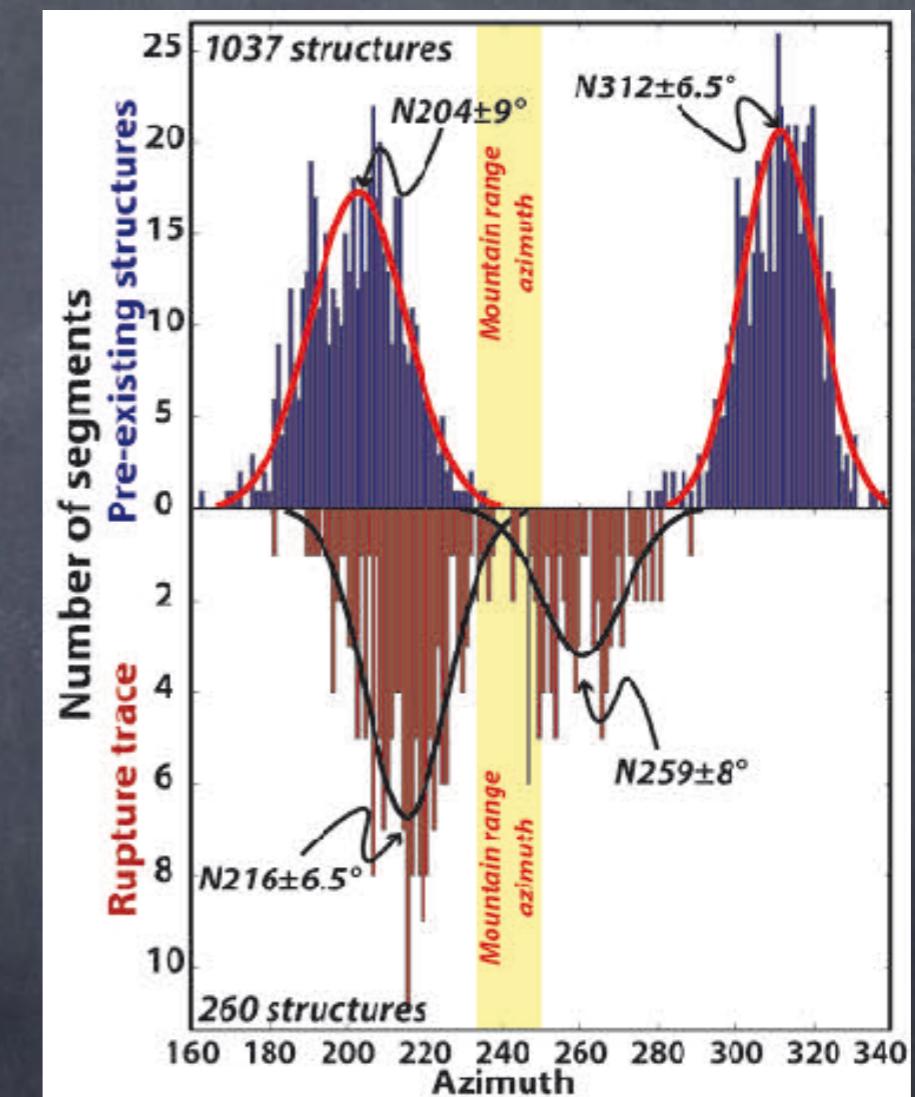
# impact of preexisting geological structures on rupture process

fault branches  
> affect rupture dynamics

Slip distribution  
Energy radiation pattern



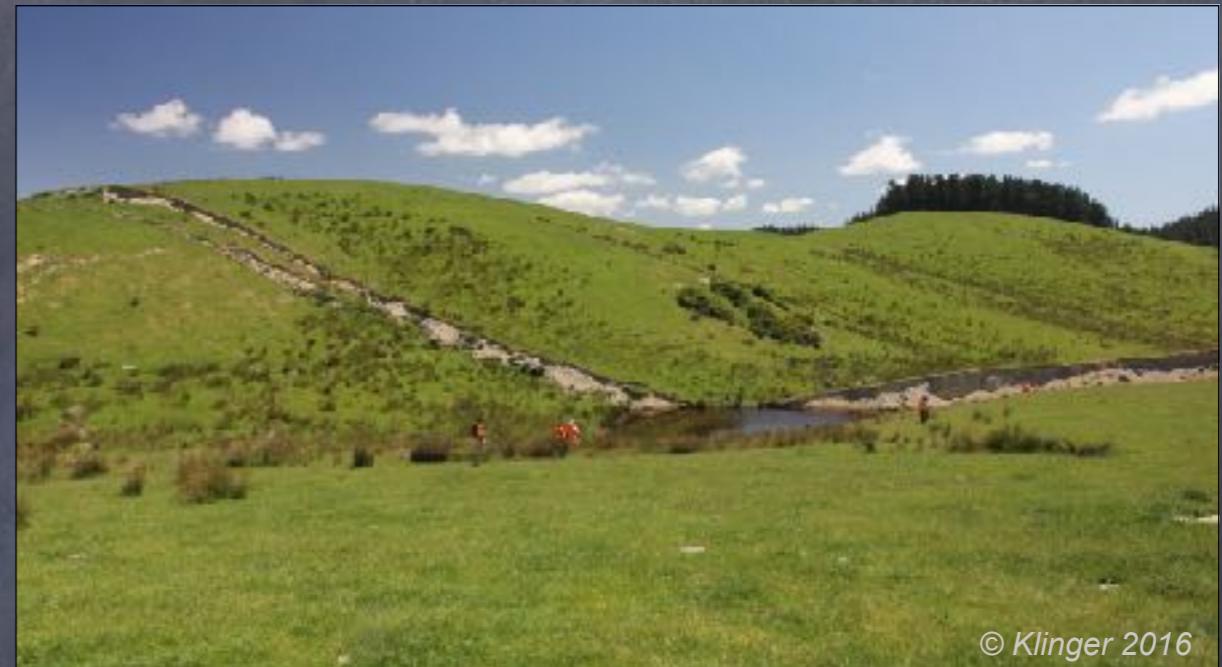
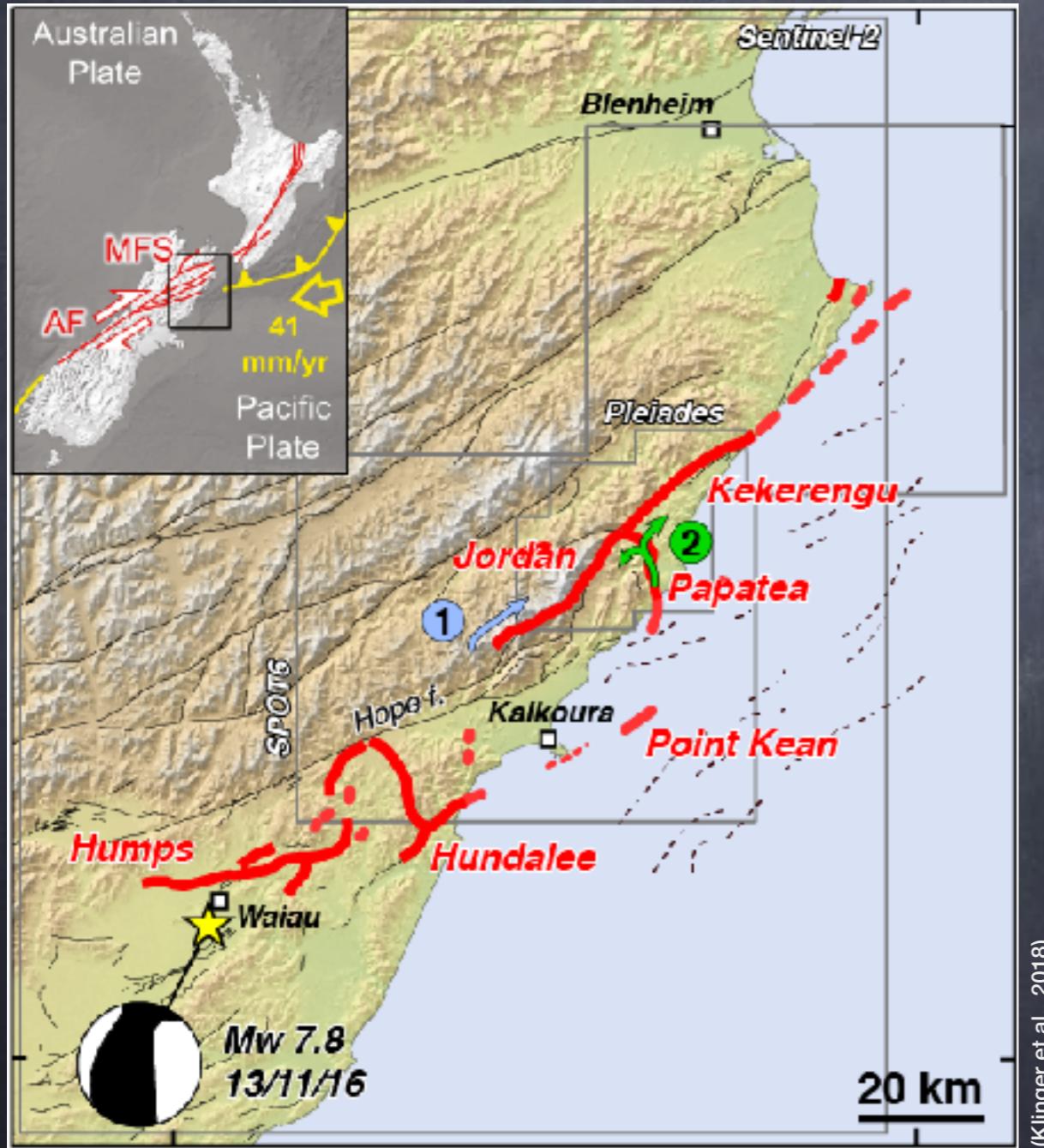
(Vallage et al. 2016)



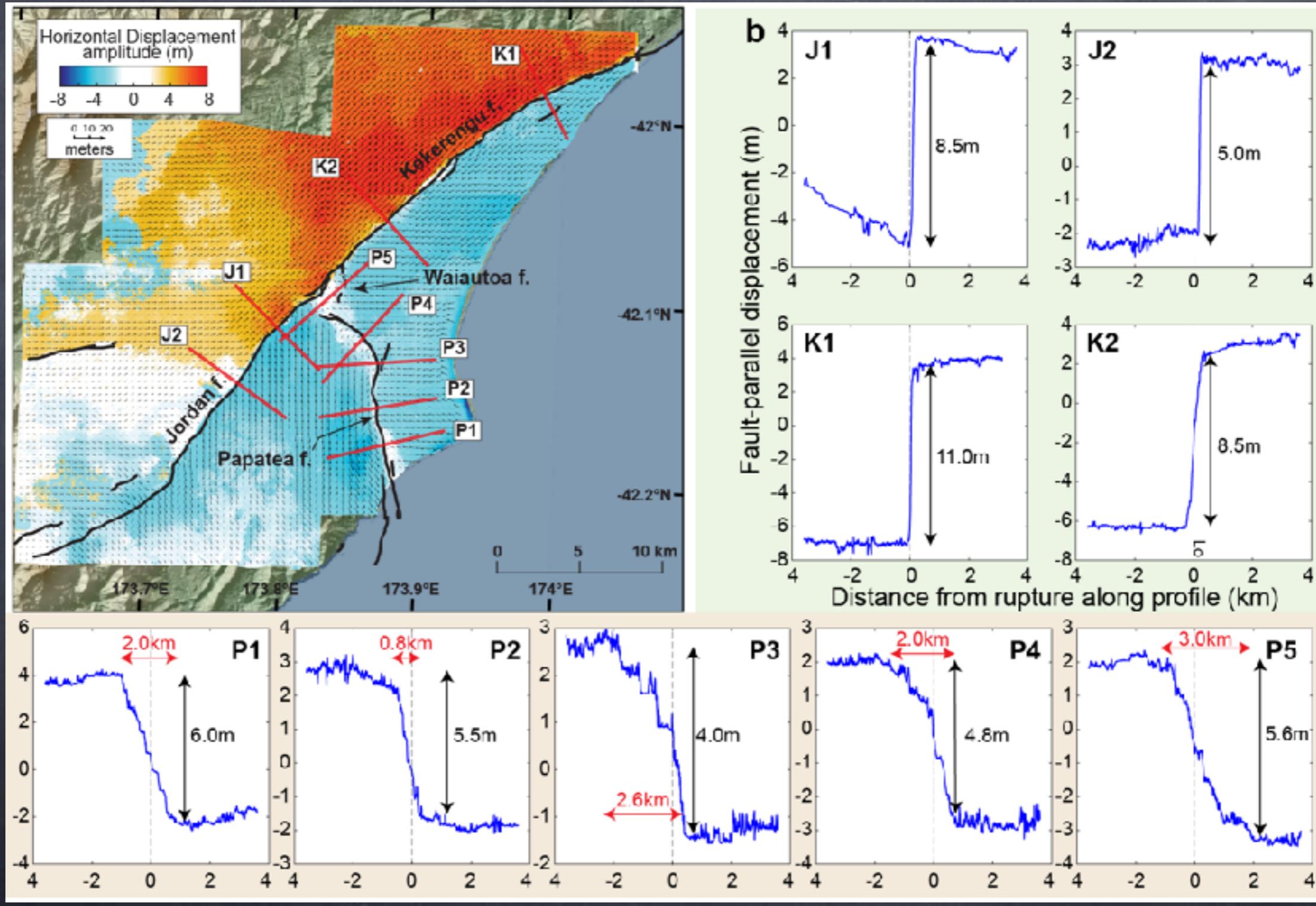
# Le séisme de Kaikoura, Mw7.8, en 2016

Quand une mesure précise des déformations de surface permet de tester différents scénarios de rupture

Remerciements ++  
K. Okubo, J. Champenois  
A. Vallage, et H. Bhat



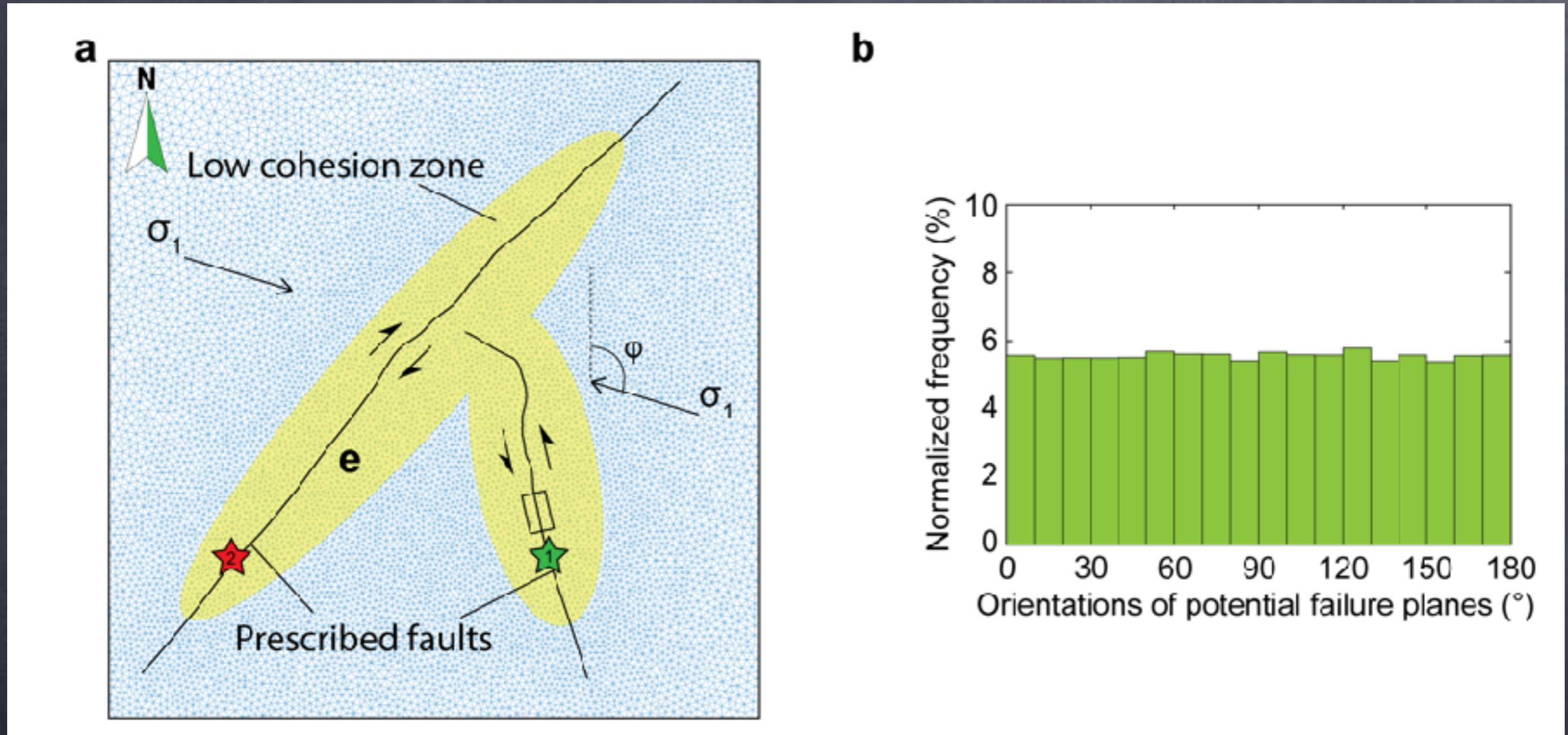
# Horizontal ground deformation from optical satellite image correlation



ground resolution 1.8m

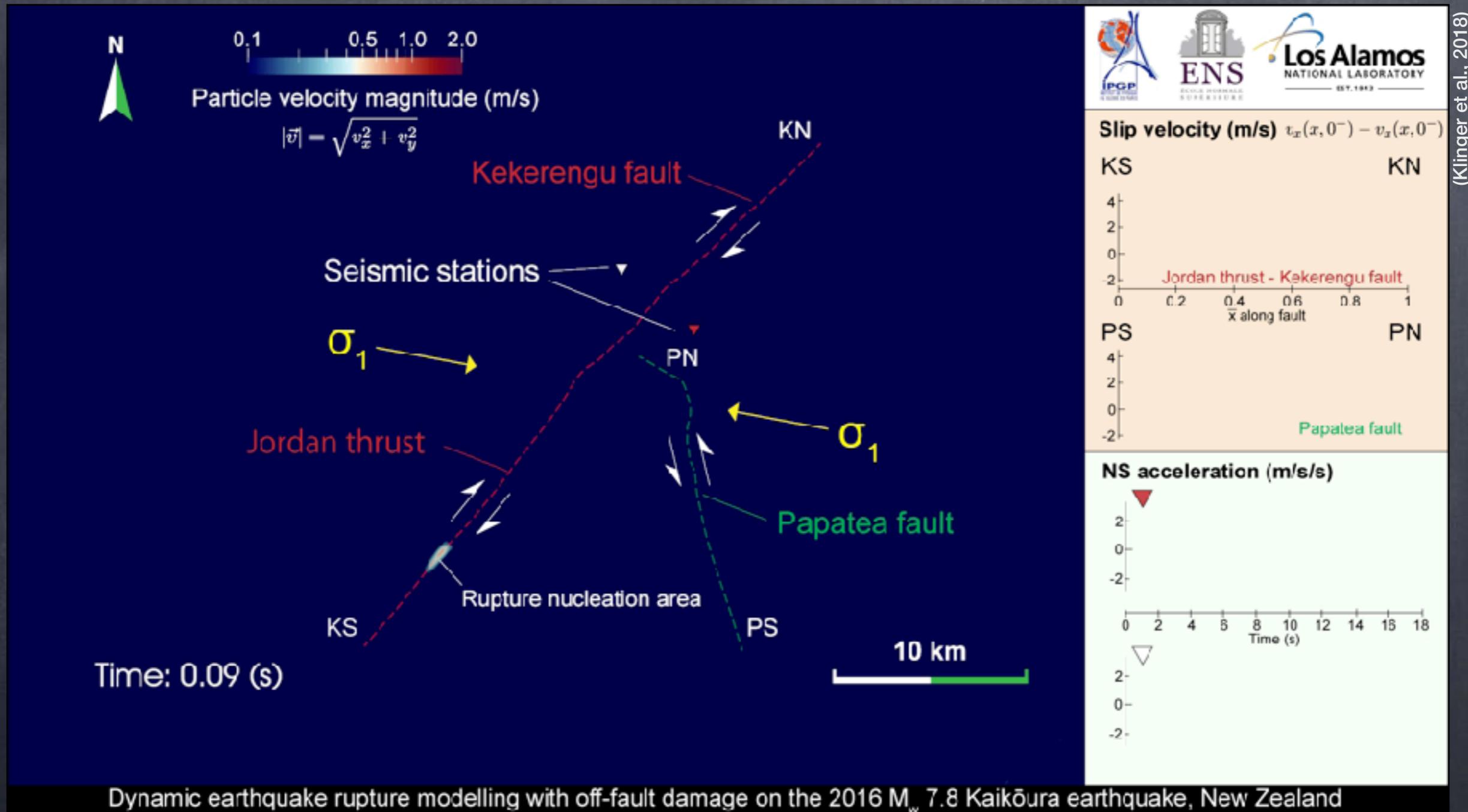
(Klinger et al., 2018)

# Using a rupture model that allows for off-fault damage



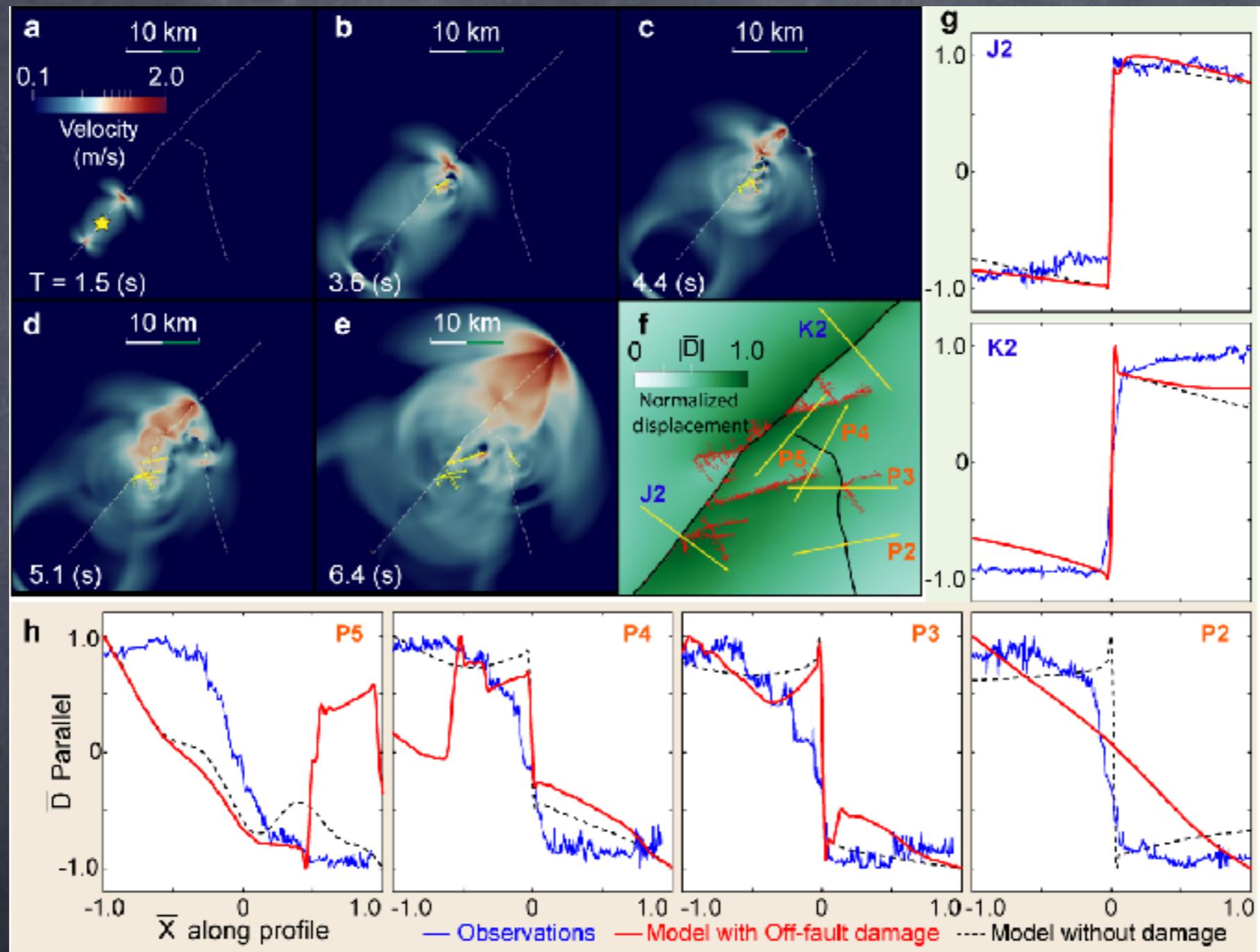
These K. Okubo  
vendredi 9/11  
14h, IPGP

# propagating dynamic rupture with geometry and off-fault deformation



## The Jordan-first scenario

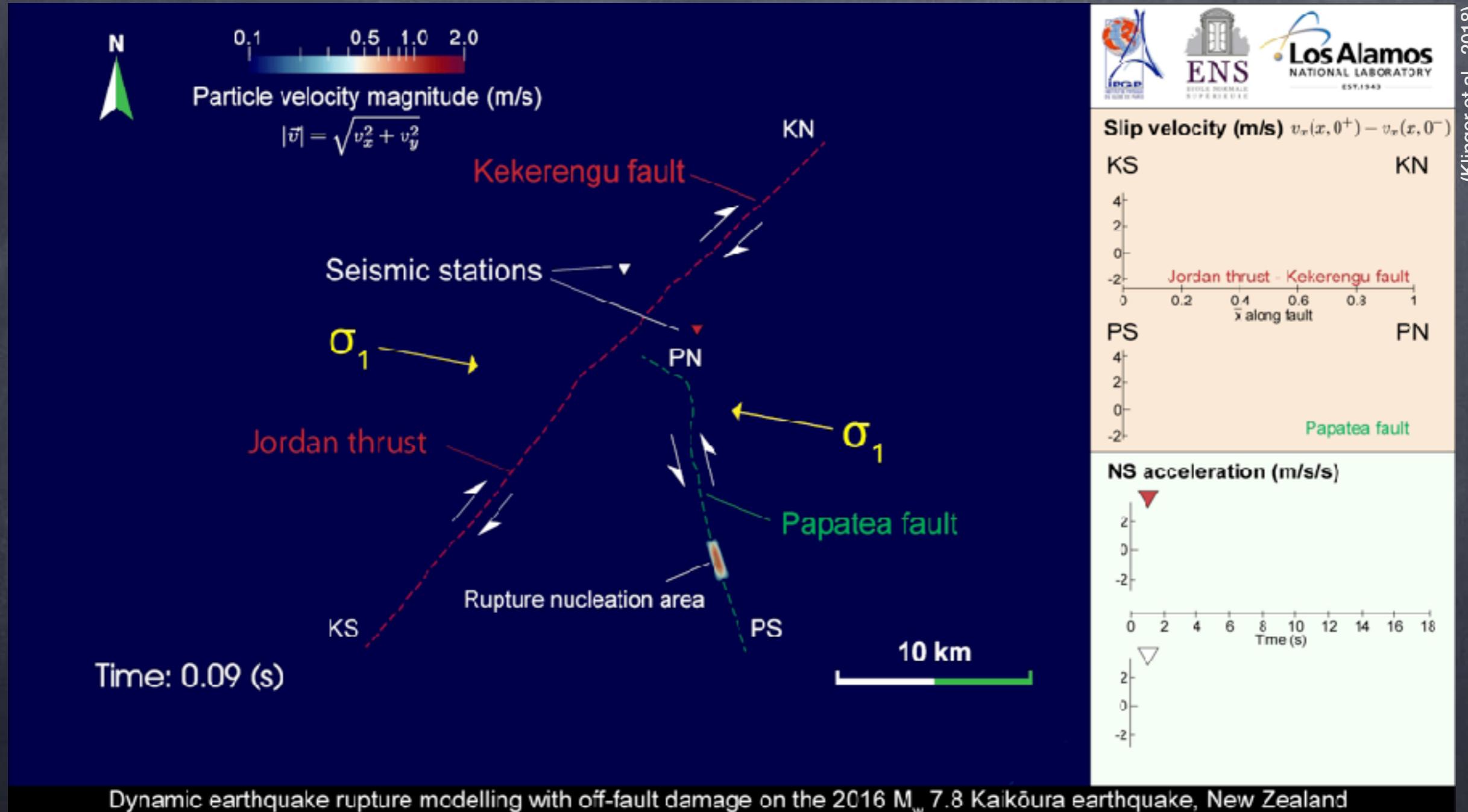
# propagating dynamic rupture with geometry and off-fault deformation



(Klinger et al., 2018)

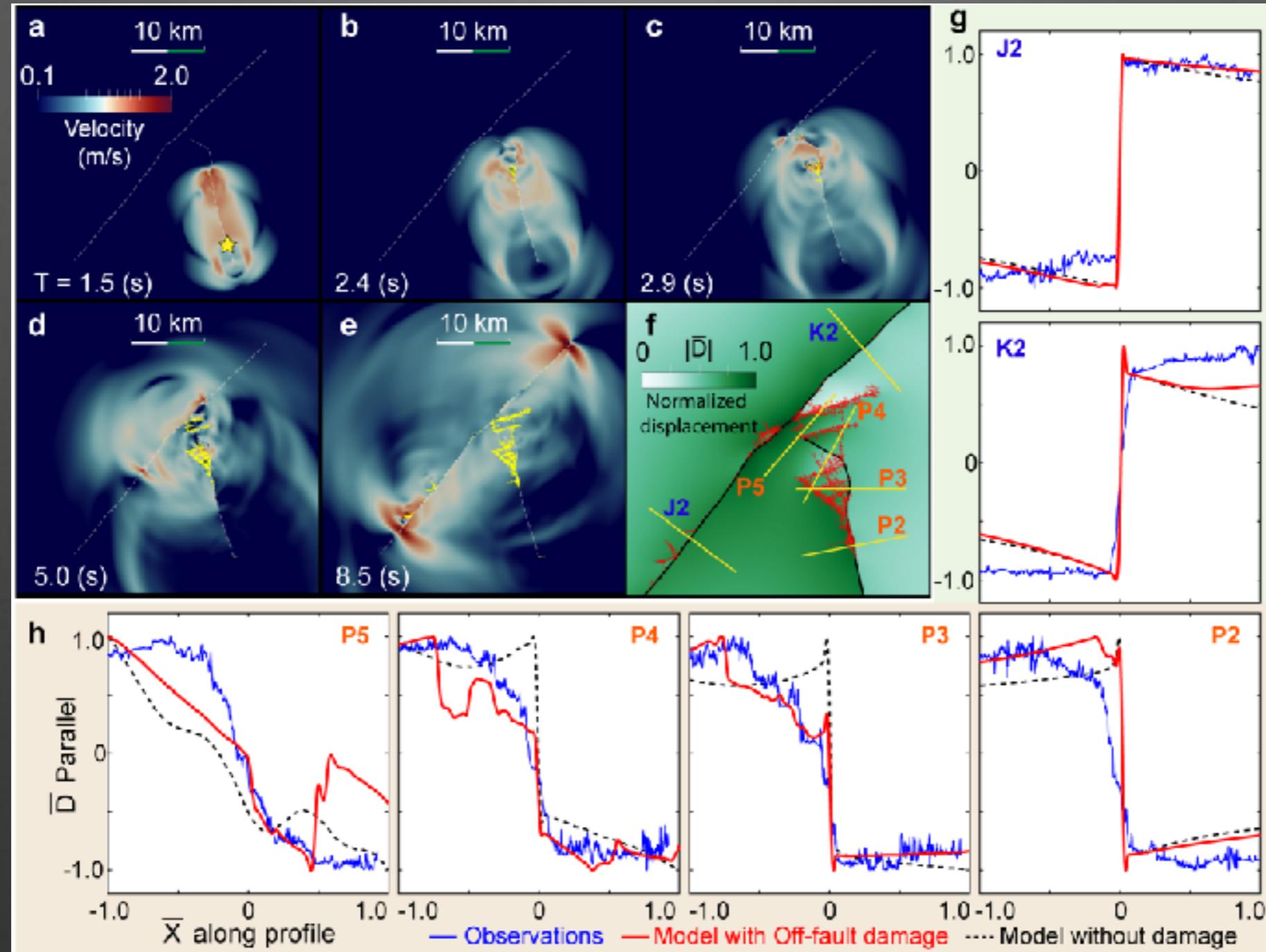
The Jordan-first scenario

# propagating dynamic rupture with geometry and off-fault deformation



## The Papatea-first scenario

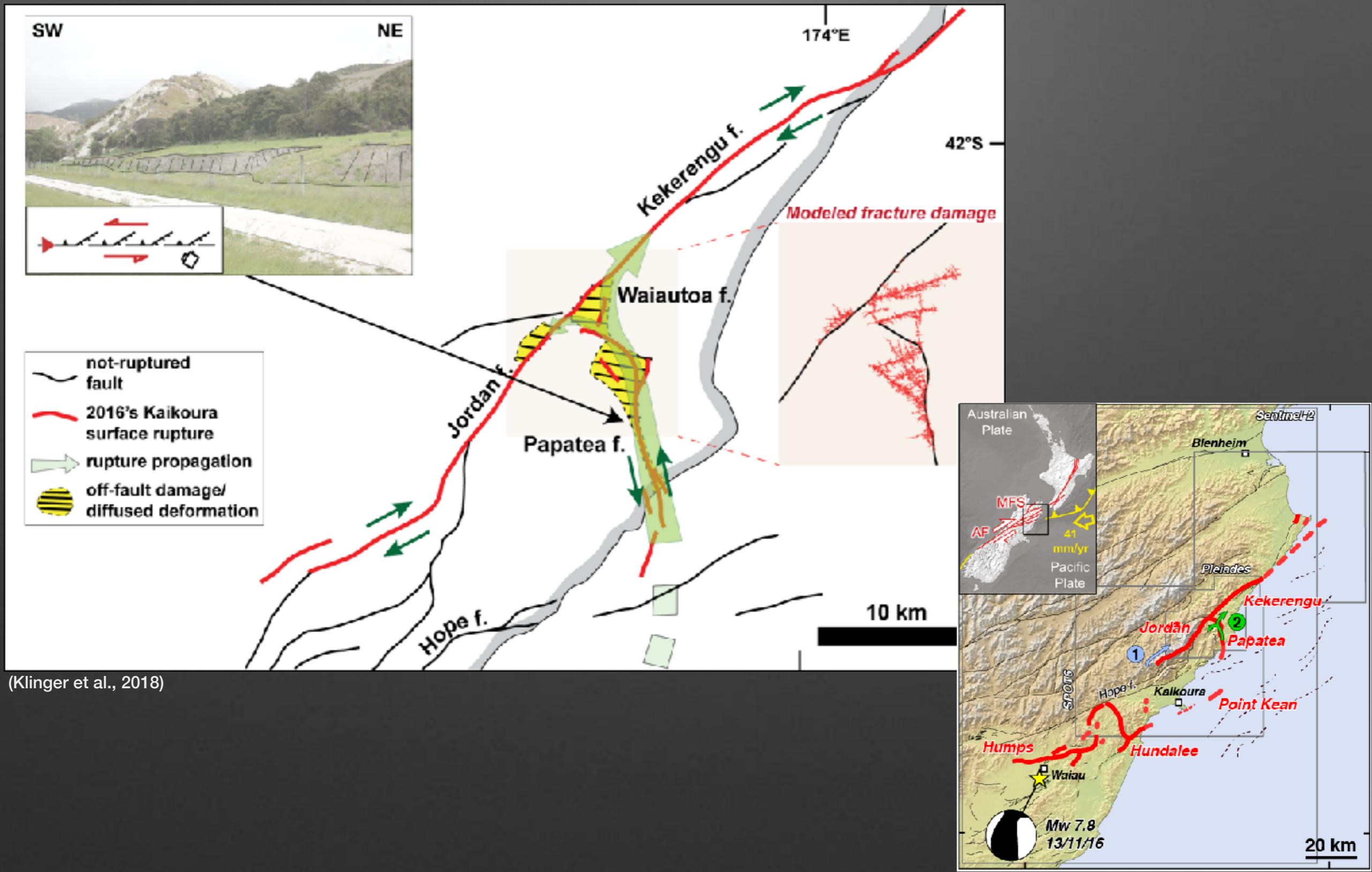
# propagating dynamic rupture with geometry and off-fault deformation



(Klinger et al., 2018)

The Papatea-first scenario

# image correlation + field obs. + rupture modelling -> favor the Papatea-first scenario



# *Le séisme de Pawnee, Mw5.7, en 2016*

## *Mesurer des déformations très petites depuis l'espace*



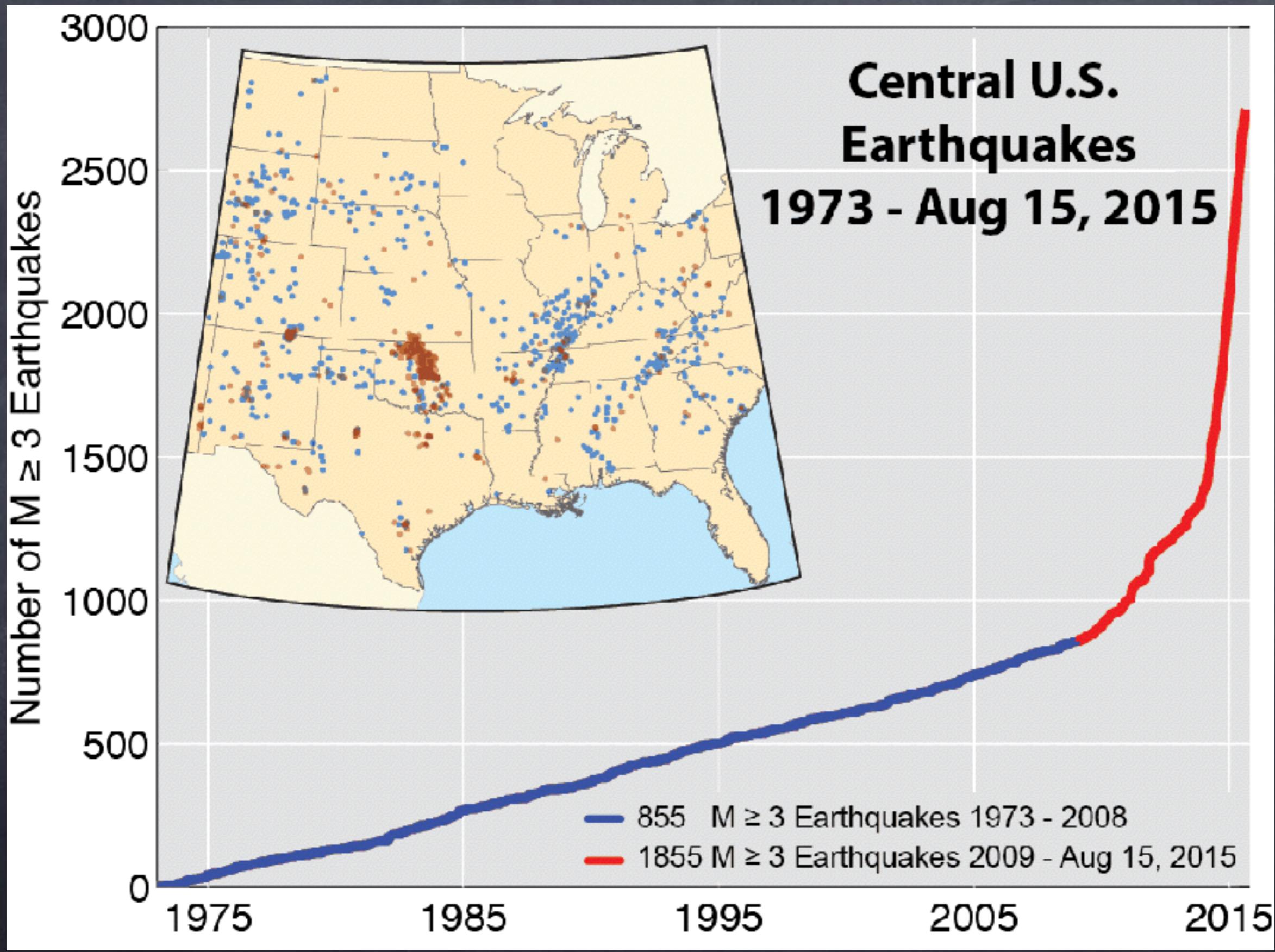
*1 month record (15 Oct - 15 Nov 2015)*

**2015:**  
**857 earthquakes**  
**M3 and over**  
**in Oklahoma**



*Remerciements ++*

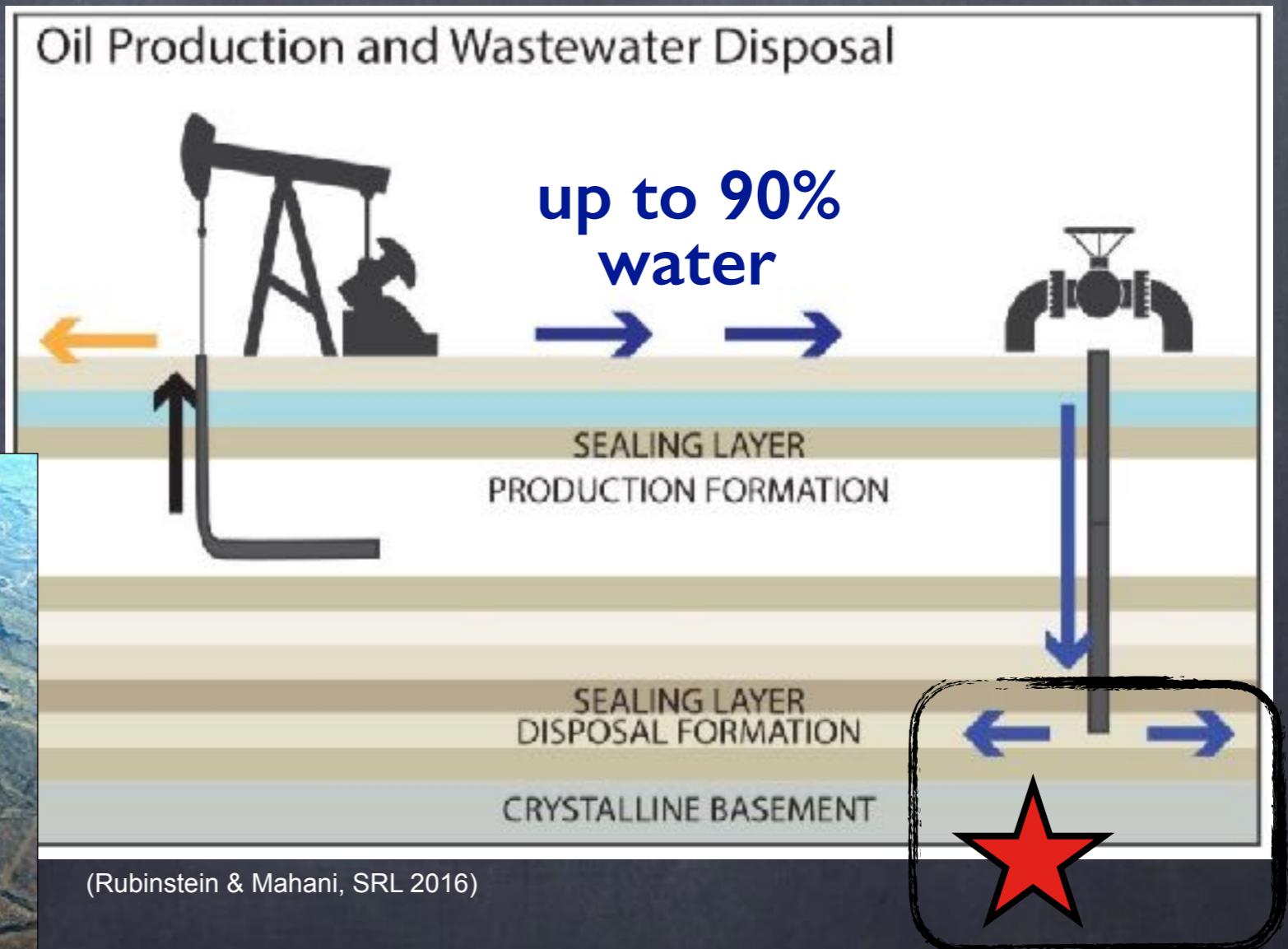
*R. Grandin, M. Vallée, et R. Lacassin*

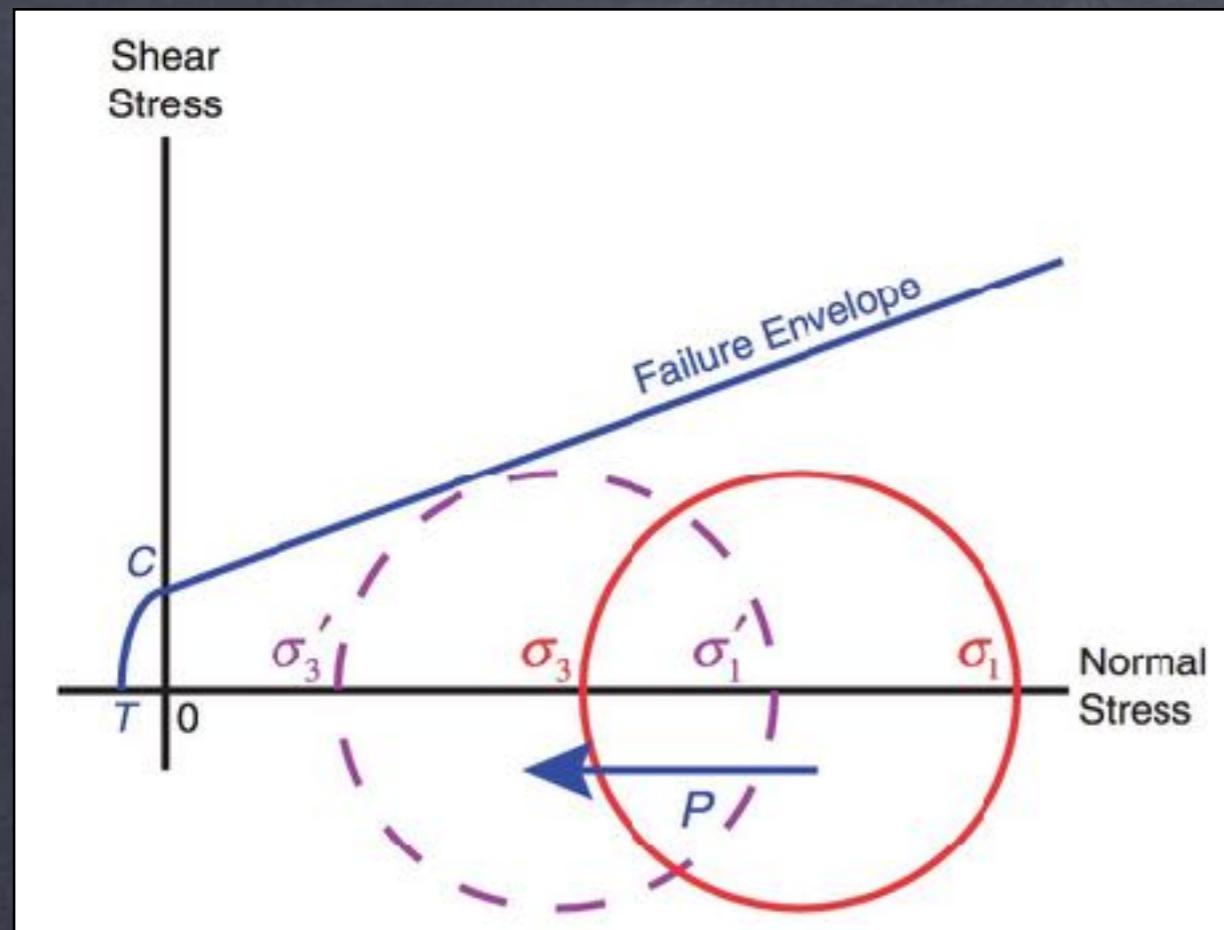


(Rubinstein & Mahani, SRL 2016  
see also Walsh & Zoback, 2015 and many others)

In Oklahoma, up to 90% produced water / 10% of oil

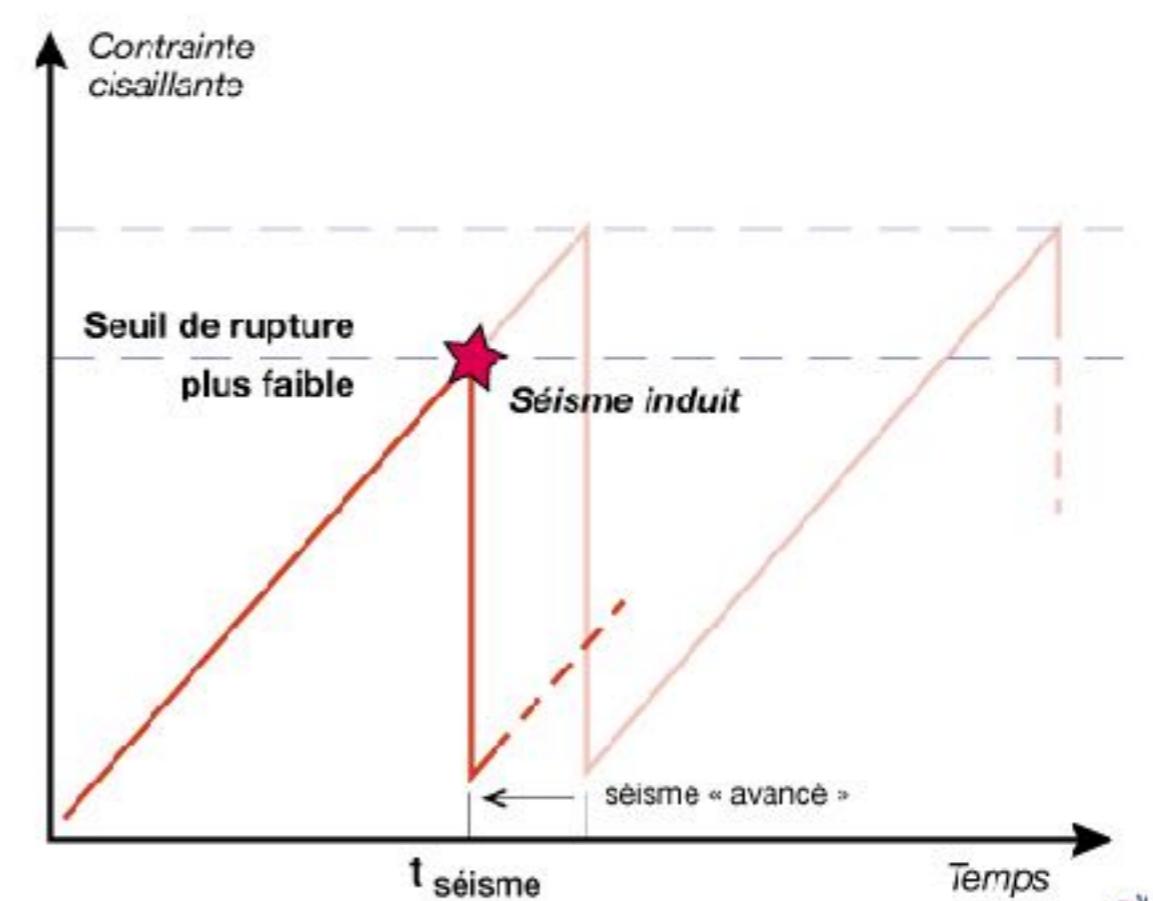
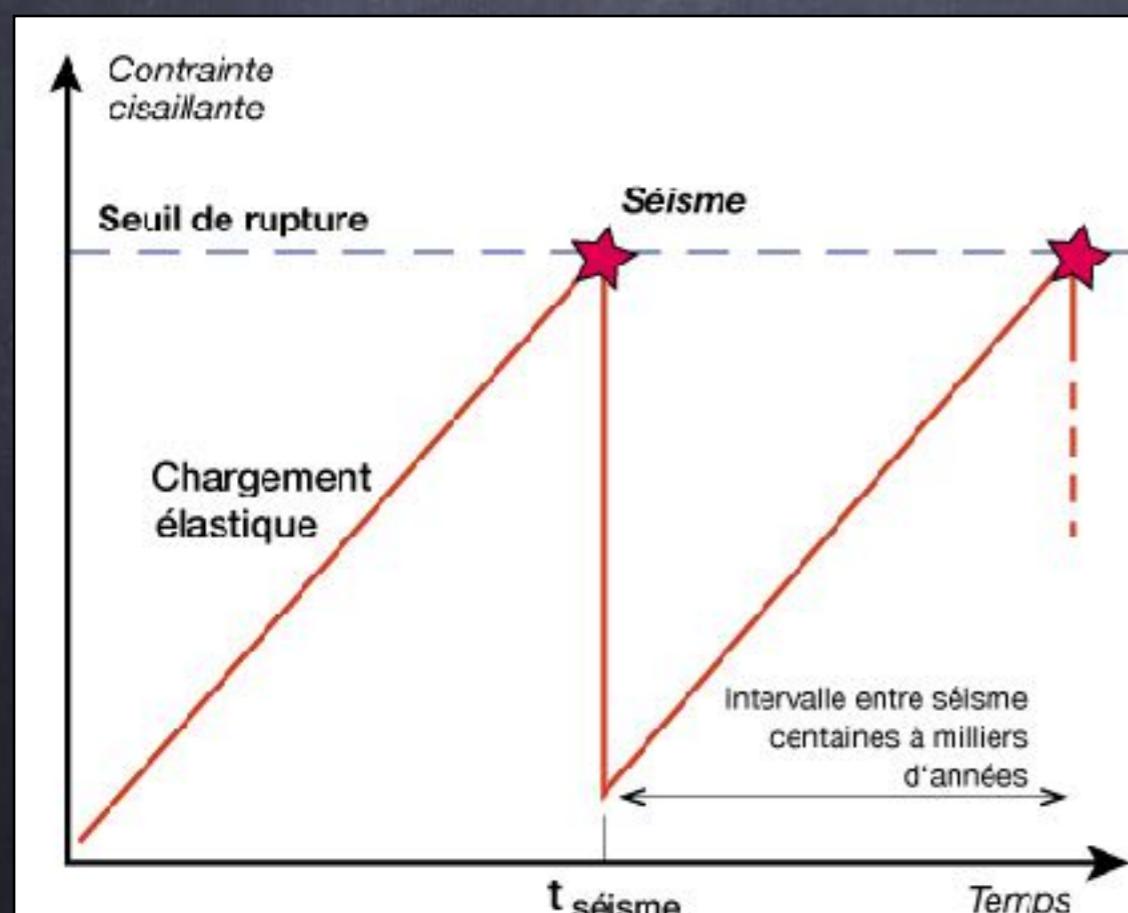
- > Salted wastewater with pollutants
- > Injected in porous rocks near base of sedimentary series just above crystalline basement



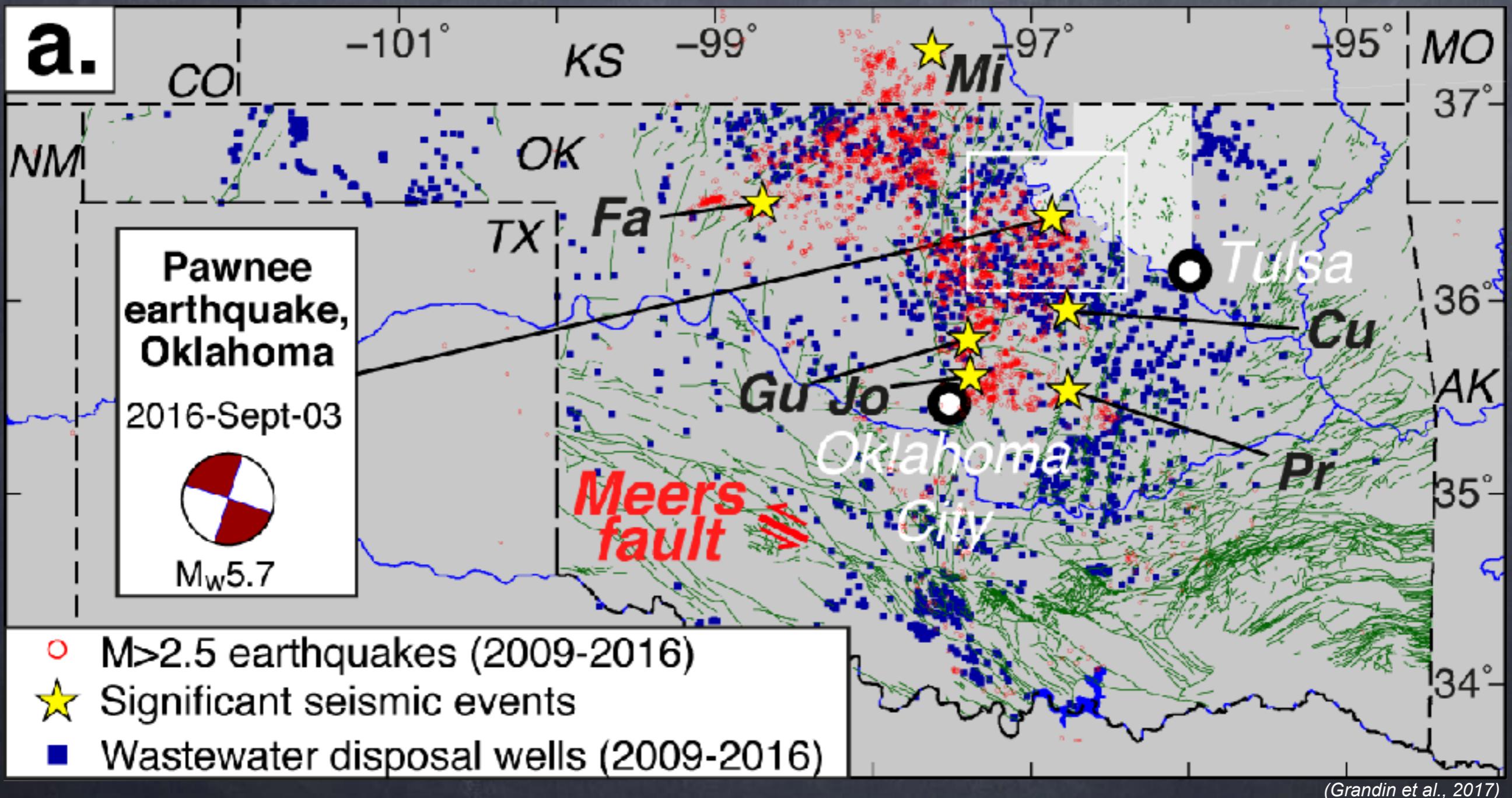


Induced seismicity:  
some  
(too) simple explanations

- > fluid pressure decreases normal stress
- > bring faults closer to rupture threshold



Enhanced seismic activity since 2009  
temporally and spatially correlated with  
increased wastewater injection operations



Pawnee 2016  $M_w 5.7$ : largest earthquake ever recorded in Oklahoma

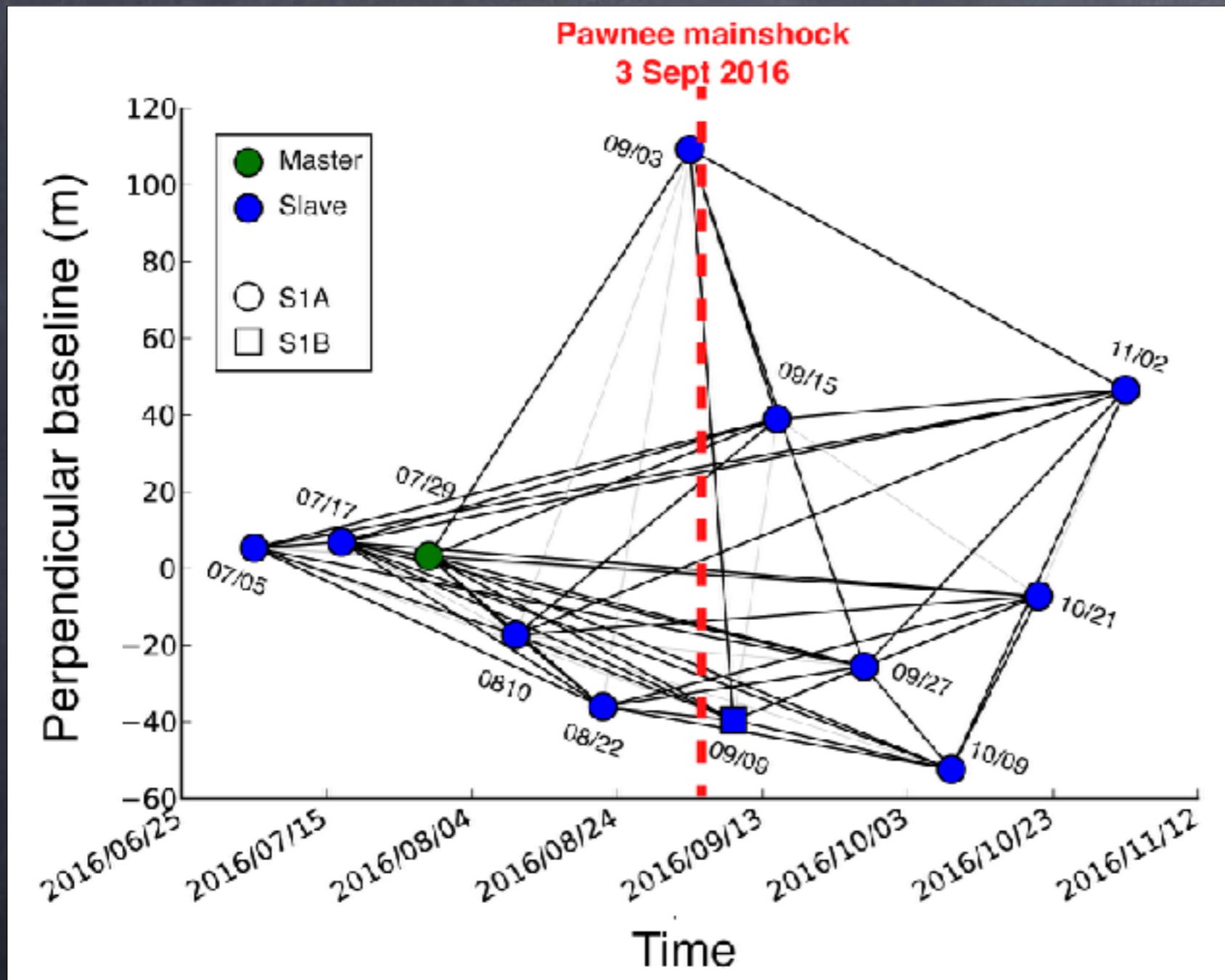
# Sentinel-1 key facts



- Two satellites: S1A (Apr. 2014) and S1B (Apr. 2016)
- C-band system ( $\lambda=5.6\text{cm}$ )
- Novel acquisition mode « TOPS »
- 6 days revisit time and nearly-systematic acquisitions
- Open data (free, real-time, unlimited access to all)

# Sentinel-1 processing

Software: NSBAS (ISTerre/IPGP)



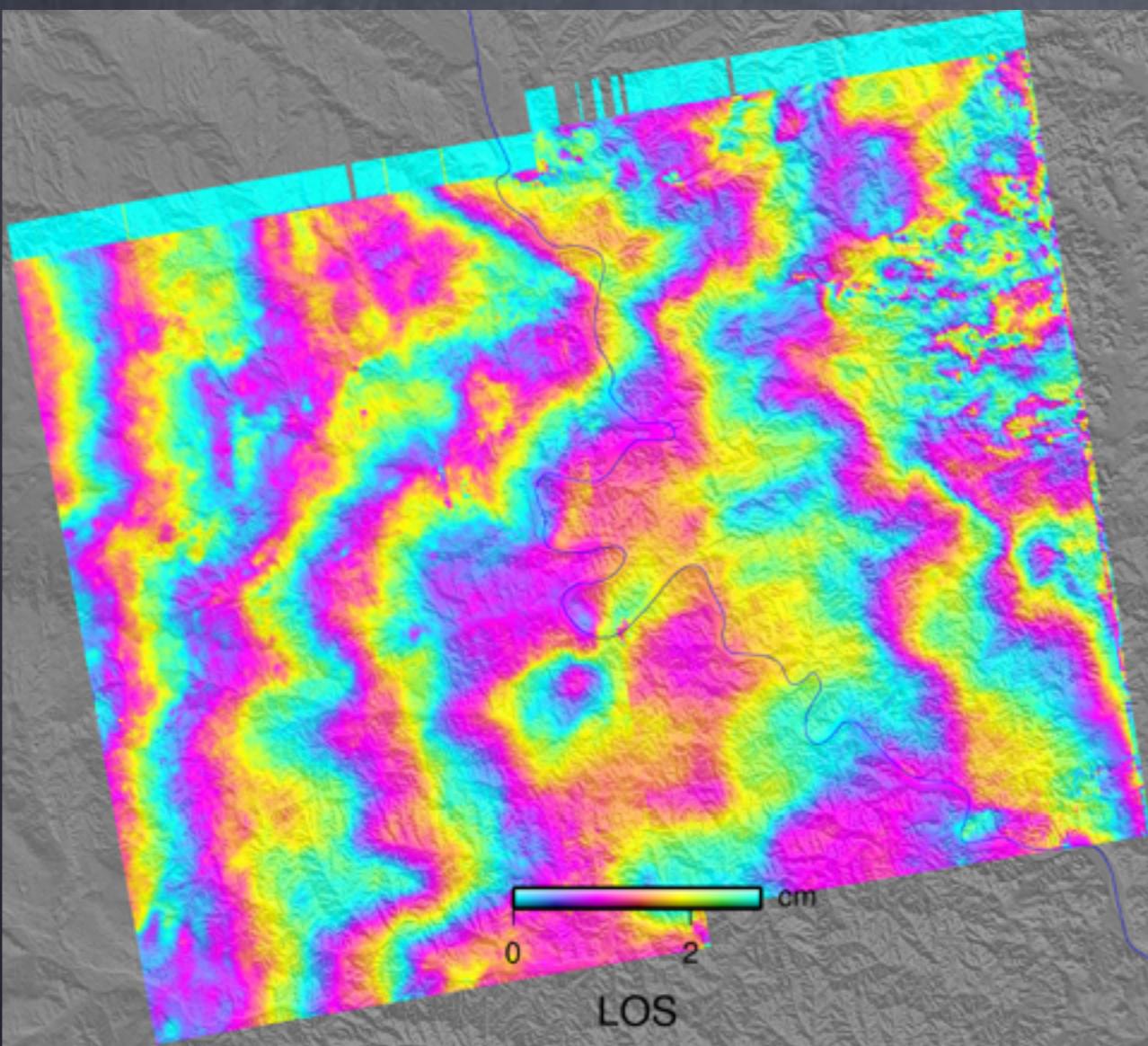
55 interferograms  
computed

—  
11 rejected due to  
poor quality  
(low coherence  
or large atmospheric  
noise)

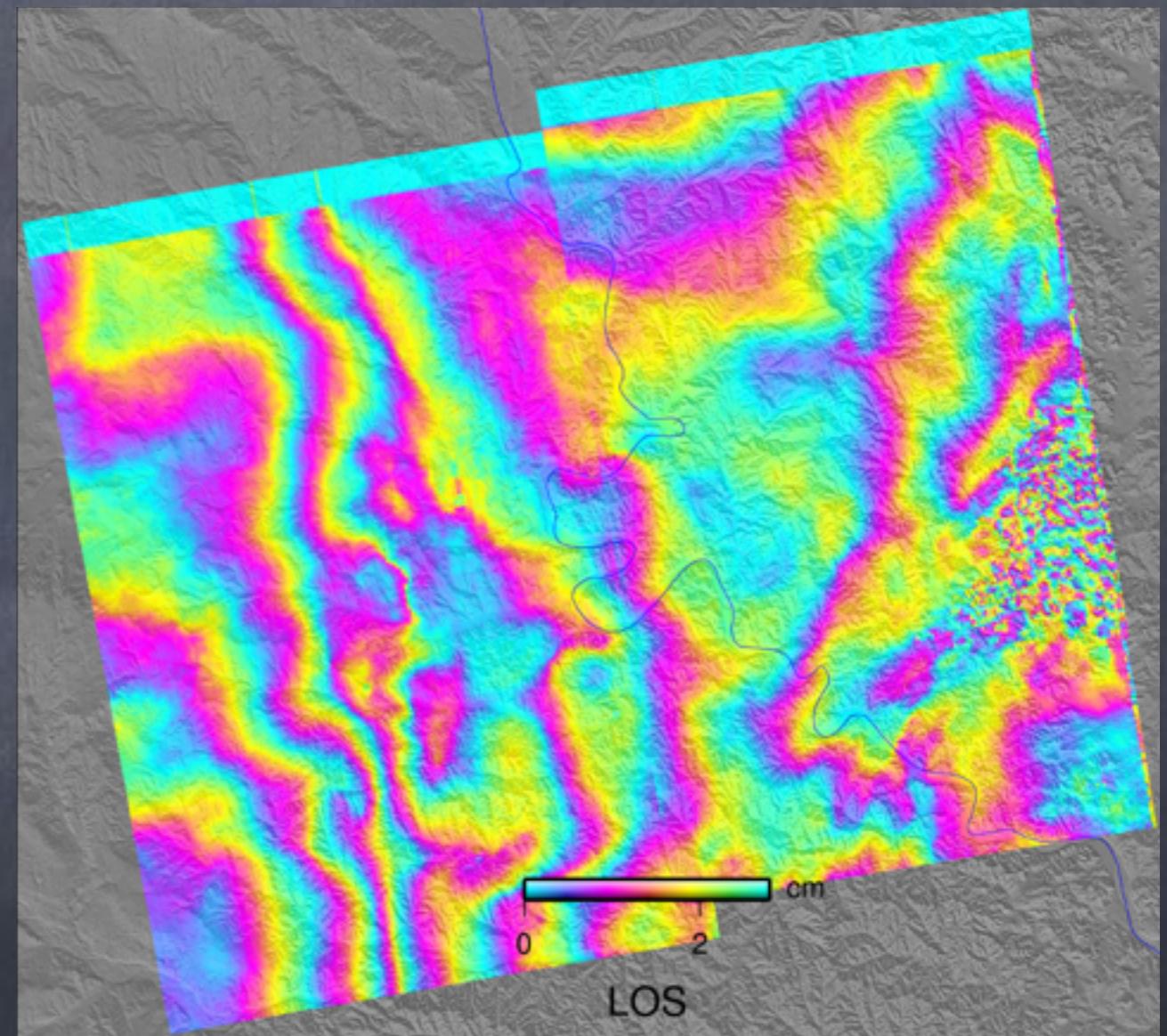
=  
44 interferograms  
kept

# Example of two individual co-seismic interferograms

22 Aug – 9 Sep



3 Sep – 15 Sep

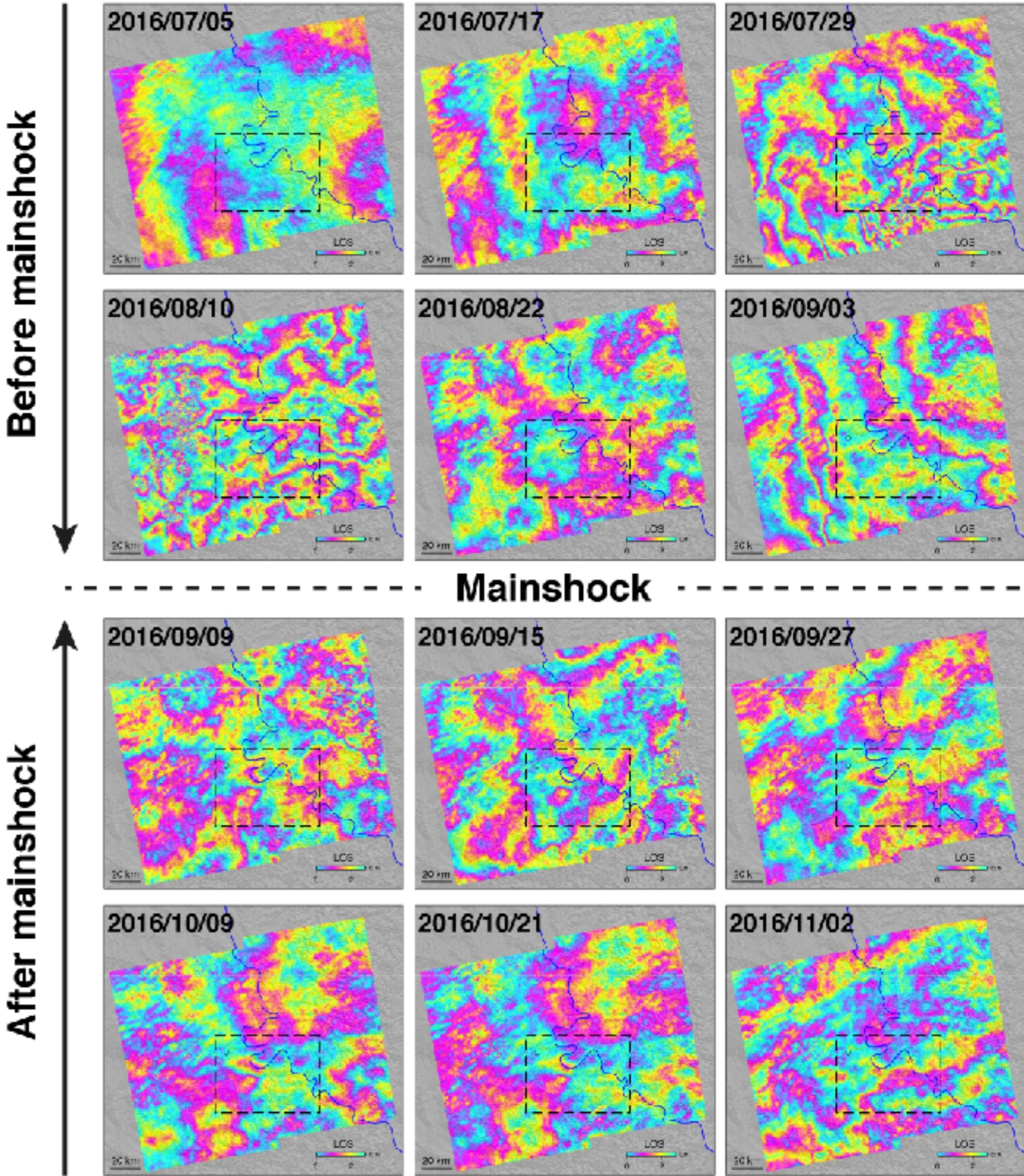


(Grandin et al., 2017)

100 km

# Time-series processing: result

(Grandin et al., 2017)

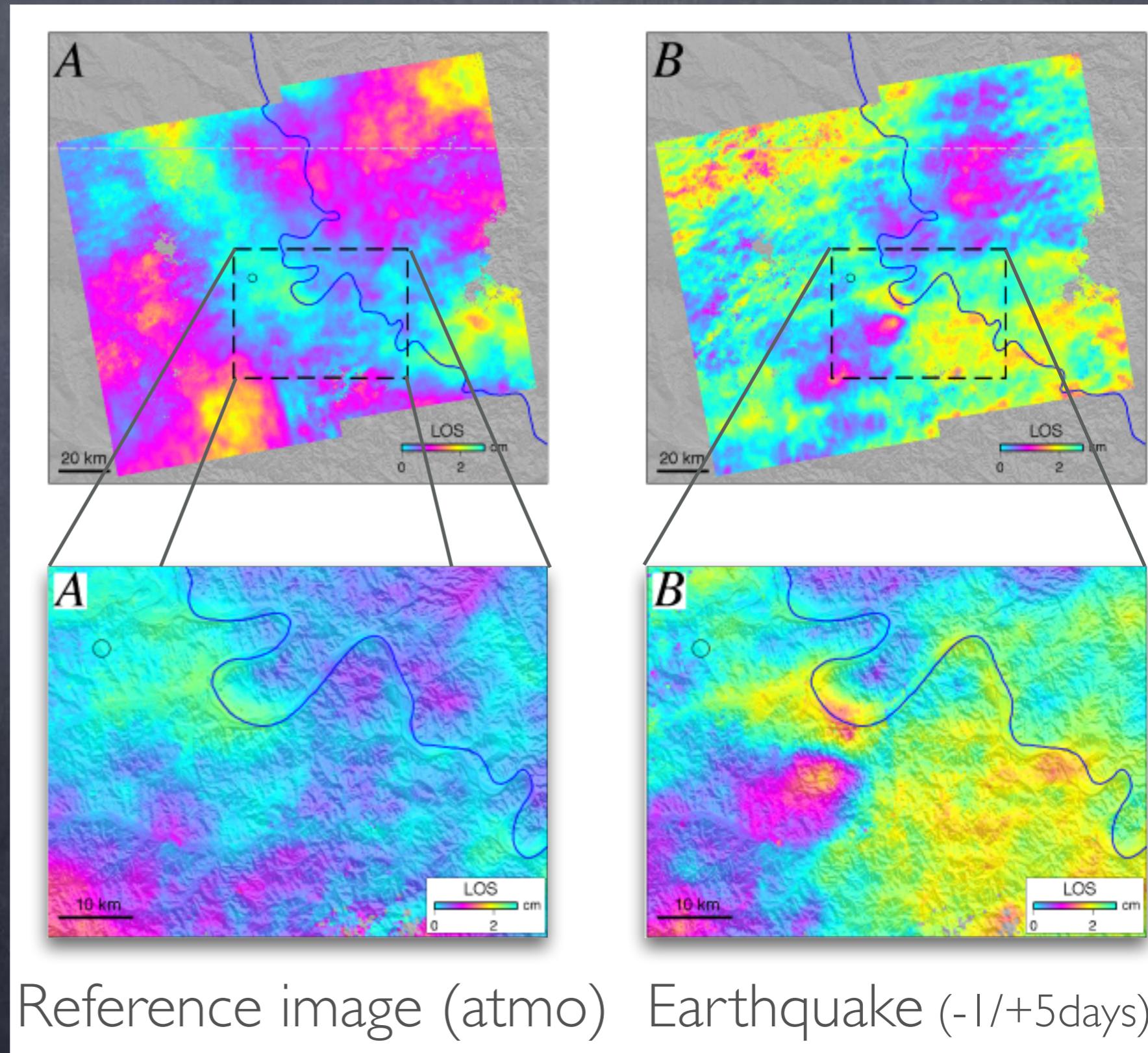
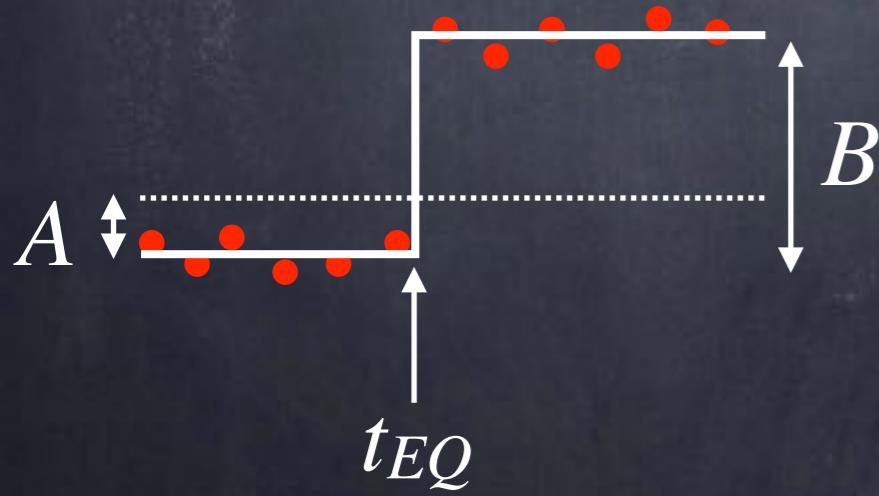


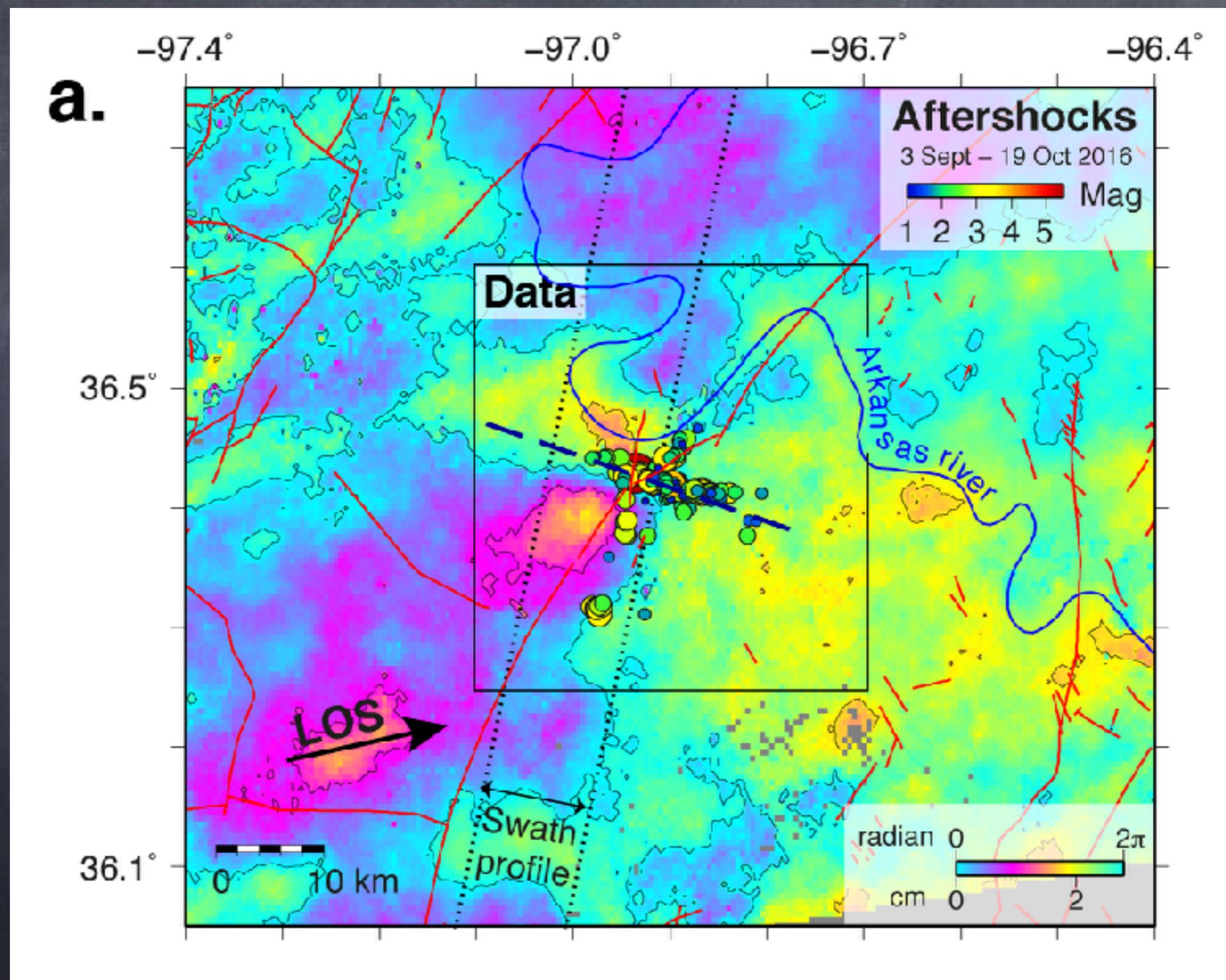
# Extracting earthquake signal from atmospheric fluctuations

(Grandin et al., 2017)

Model:

$$A + \mathcal{H}(t_{EQ}) * B$$



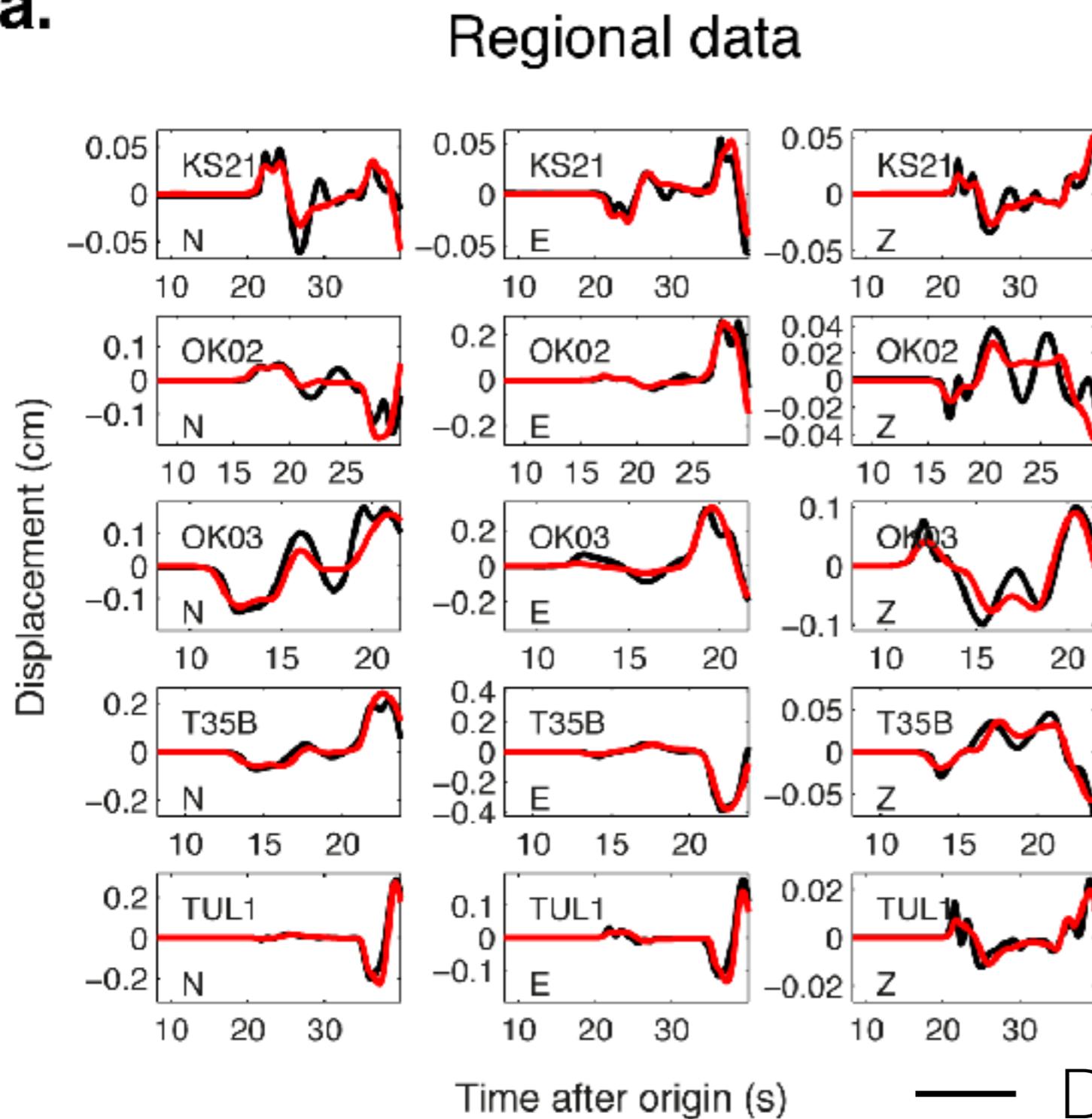


(Grandin et al., 2017)

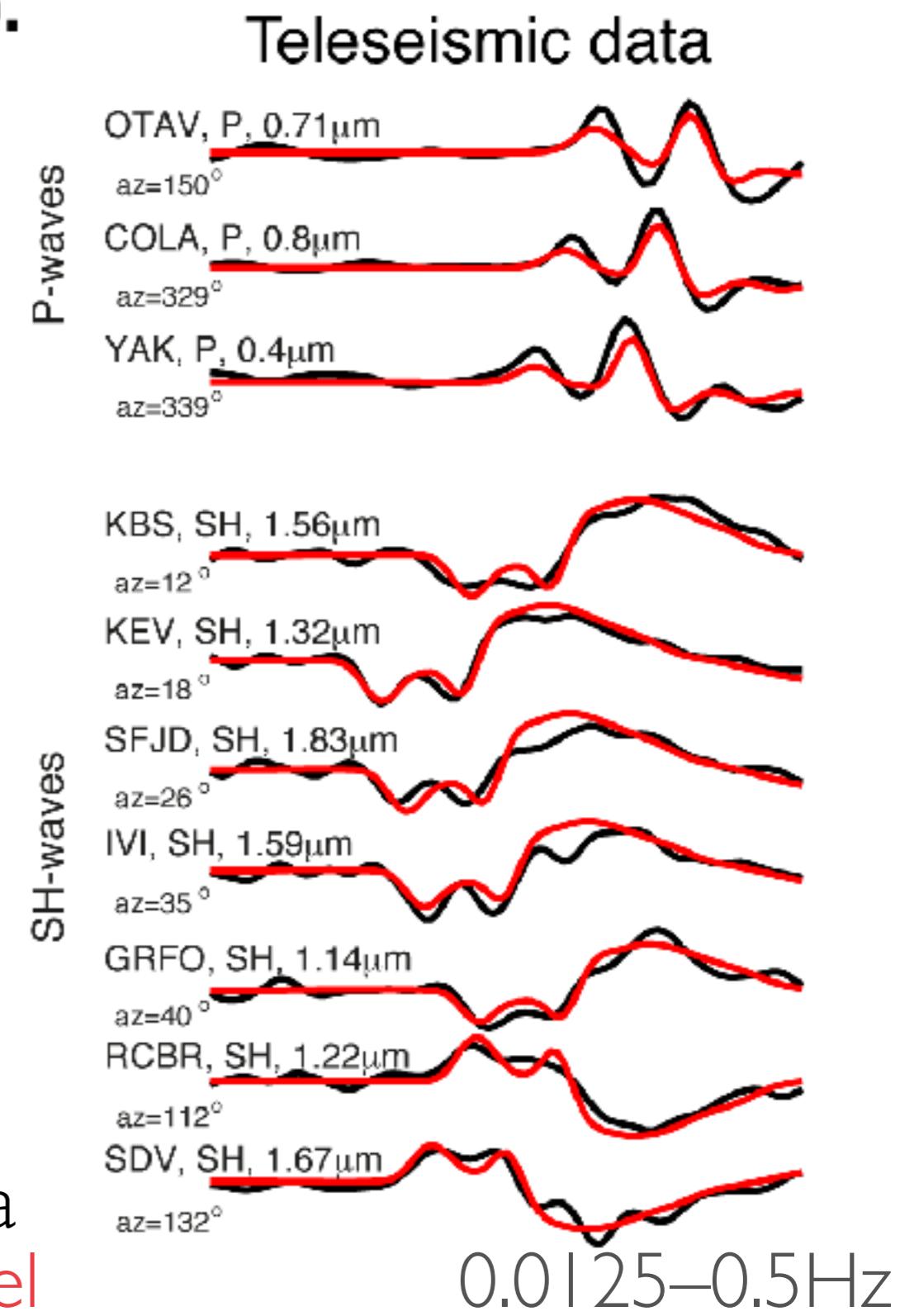
# Finite source kinematic inversion: data

(Grandin et al., 2017)

a.



b.

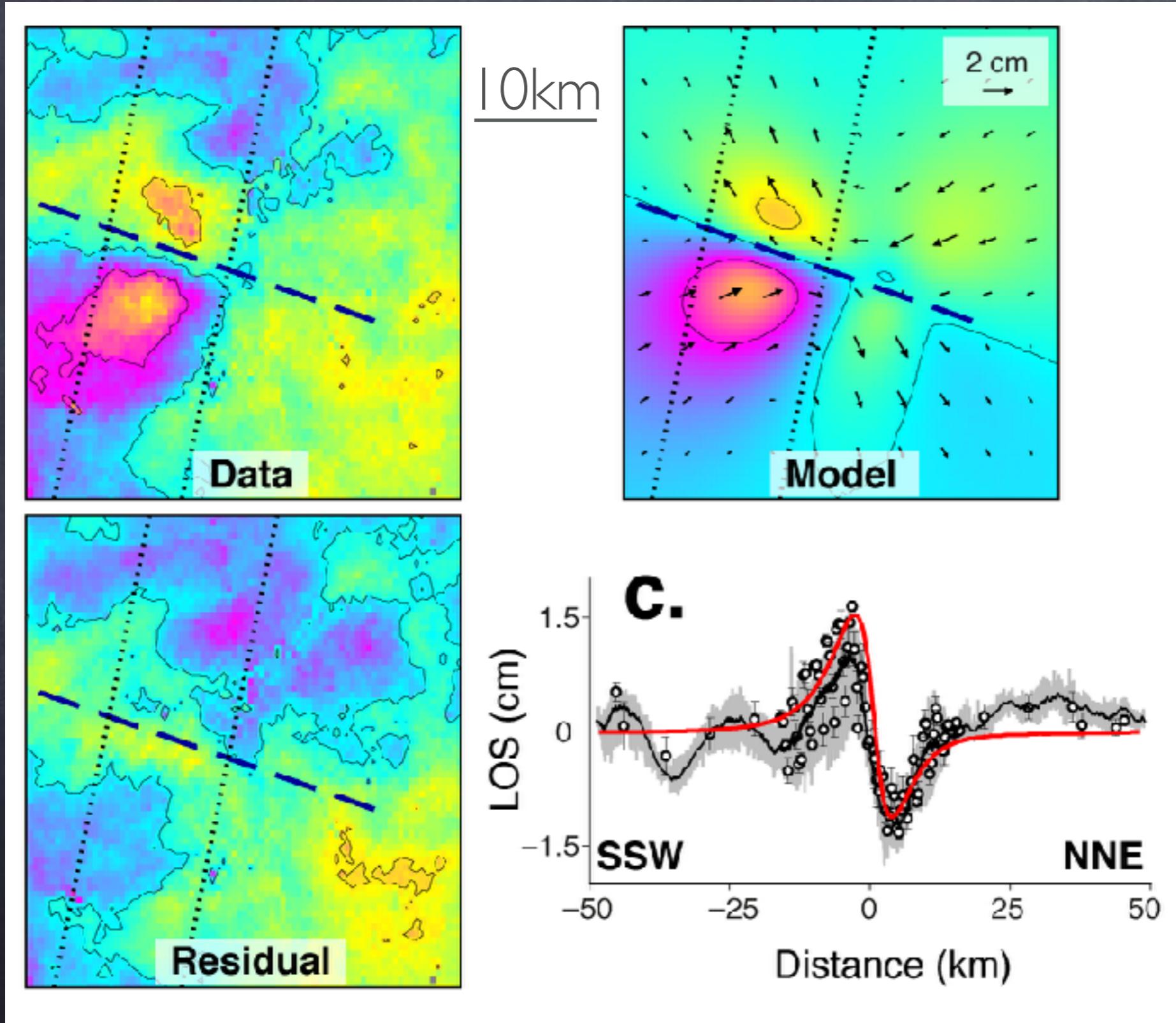


0.02–0.5Hz

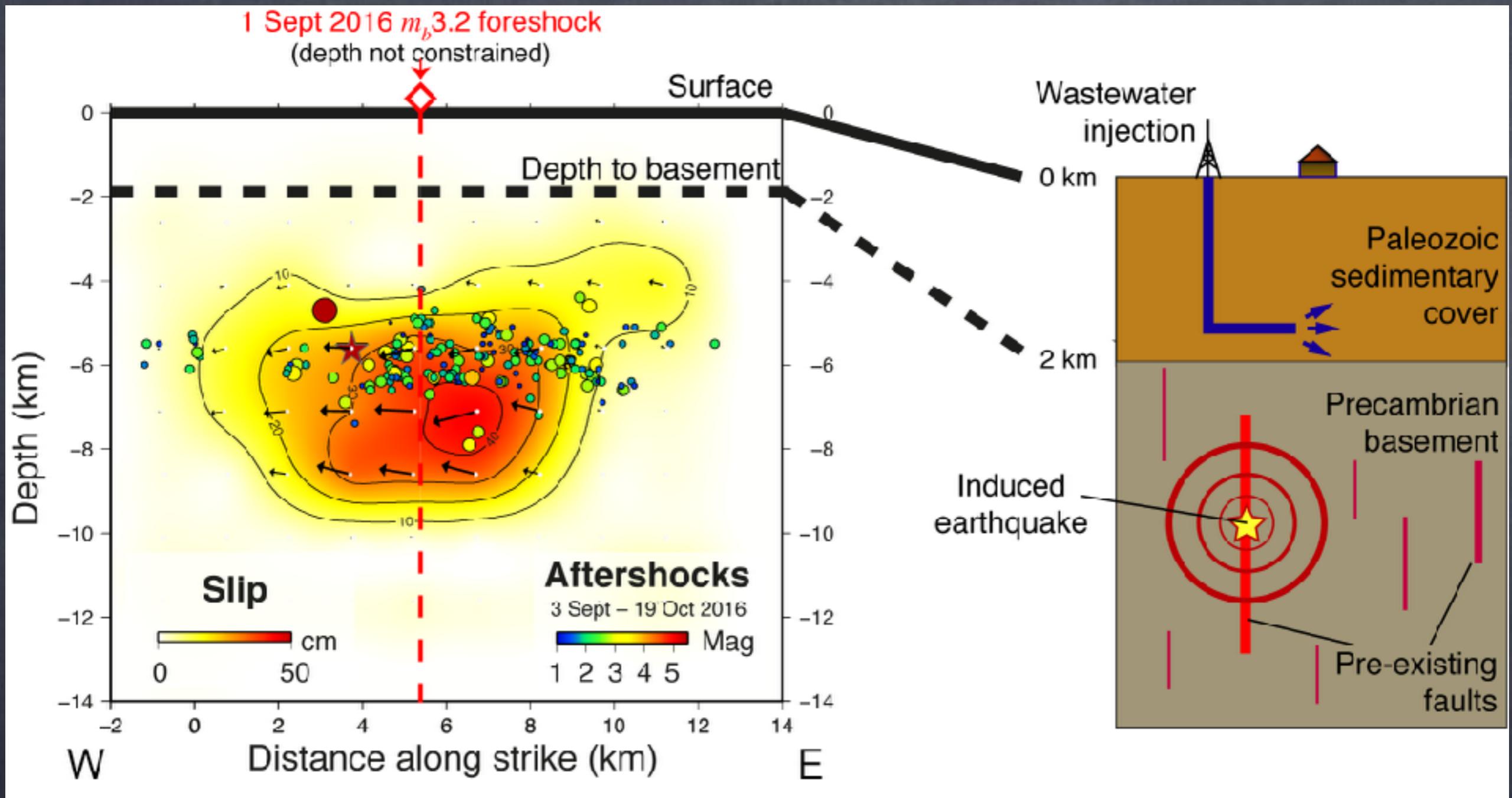


Slip distribution in space and time

# Finite source kinematic inversion: fit with InSAR data



InSAR provides excellent resolution on shallow slip



(Grandin et al., 2017)

Pawnee earthquake was entirely confined in the basement,  
i.e. below the sedimentary cover where wastewater  
injection is carried out.

# *Quelles perspectives pour la mesure des déformations de la croûte terrestre par imagerie satellitaires ?*

**Temps de retour très courts**

> *imagerie de la dynamique des processus: déformation post-sismique et asismique, phénomènes volcaniques, géomorphologie*

**Généralisation de la multistéréo**

> *imagerie directe des déformations en 3D, mesure des changements volumiques*