@NERC_COMET
@timwright_leeds

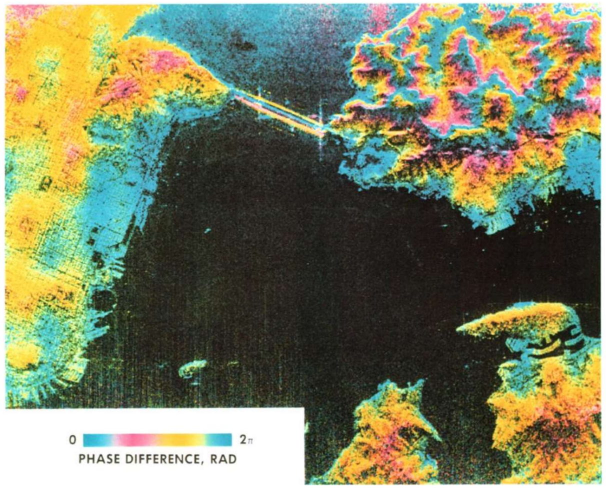
What have we learned about faults from three decades of Tectonic InSAR?

Tim J Wright

COMET, University of Leeds, European Union

The beginnings of tectonic InSAR

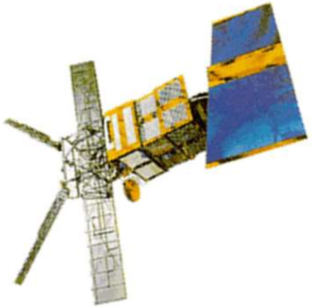
1986: Zebker and Goldstein, topography from airborne InSAR



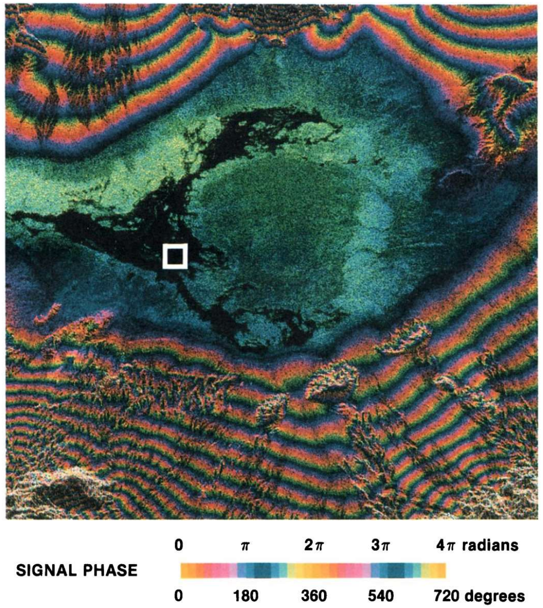
RADAR INTERFEROGRAM, GOLDEN GATE

Plate 1. Radar interferogram of a region near San Francisco, California, representing measured amplitude (brightness of each point) and phase (color). In this image we have corrected the data to remove the expected phase pattern from a flat earth, so that the displayed phase fringes are due mainly to topograhic variation of the terrain. An increase in height is represented as a negative increase in phase. The Golden Gate Bridge is seen threefold, each image at a different phase and time delay due to multiple signal paths to the bridge. This ambiguity, present in most raw radar images, is corrected in the rectification process (see text).

July 1991: Launch of ESA's ERS-1 satellite



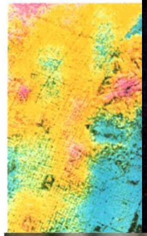
1988: Goldstein et al., 3-day Interferogram from Seasat



July 1993: Massonnet et al., first coseismic interferogram

The beginnings of tectonic InSAR

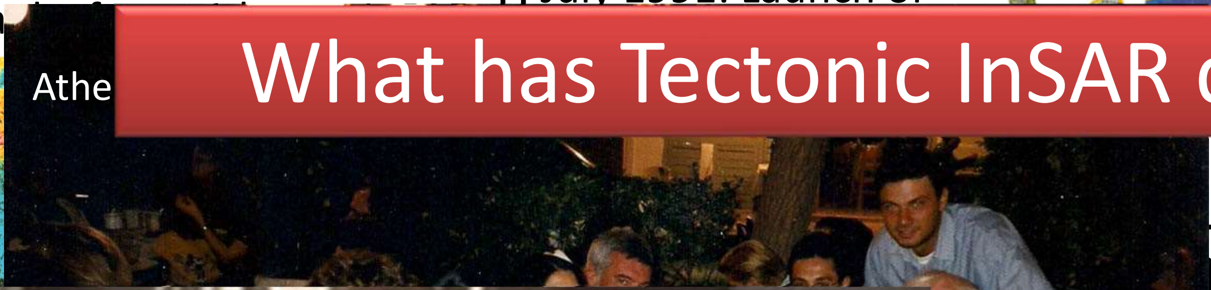
1986: Zebker and Goldstein,
topogra



July 1991: Launch of

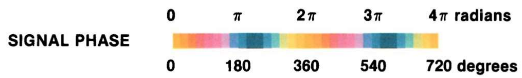
July 1993: Massonnet et al.,
ferogram

Athe

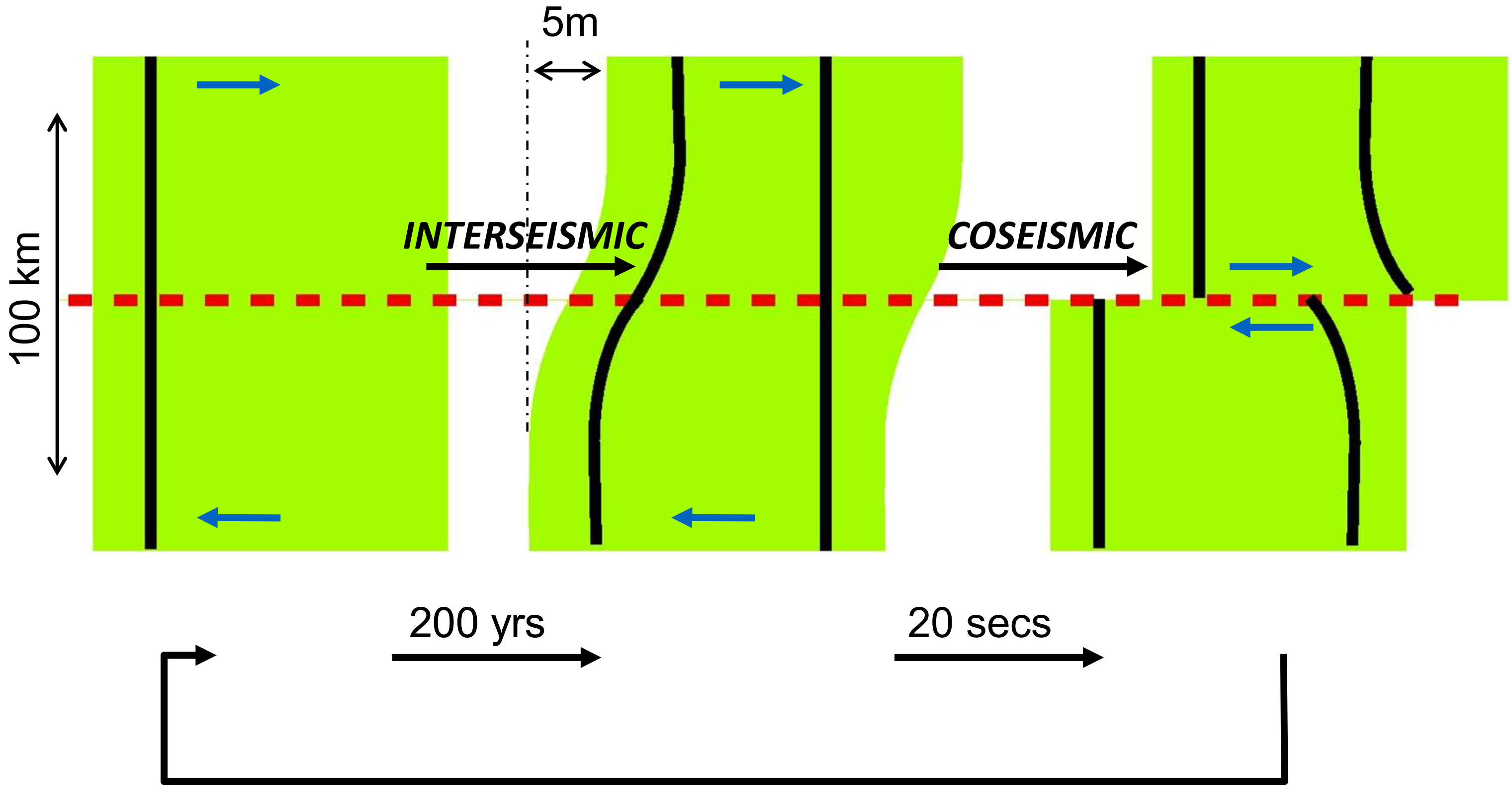


What has Tectonic InSAR done for us?

1988: Goldstein et al., 3-day
Interferogram from Seasat

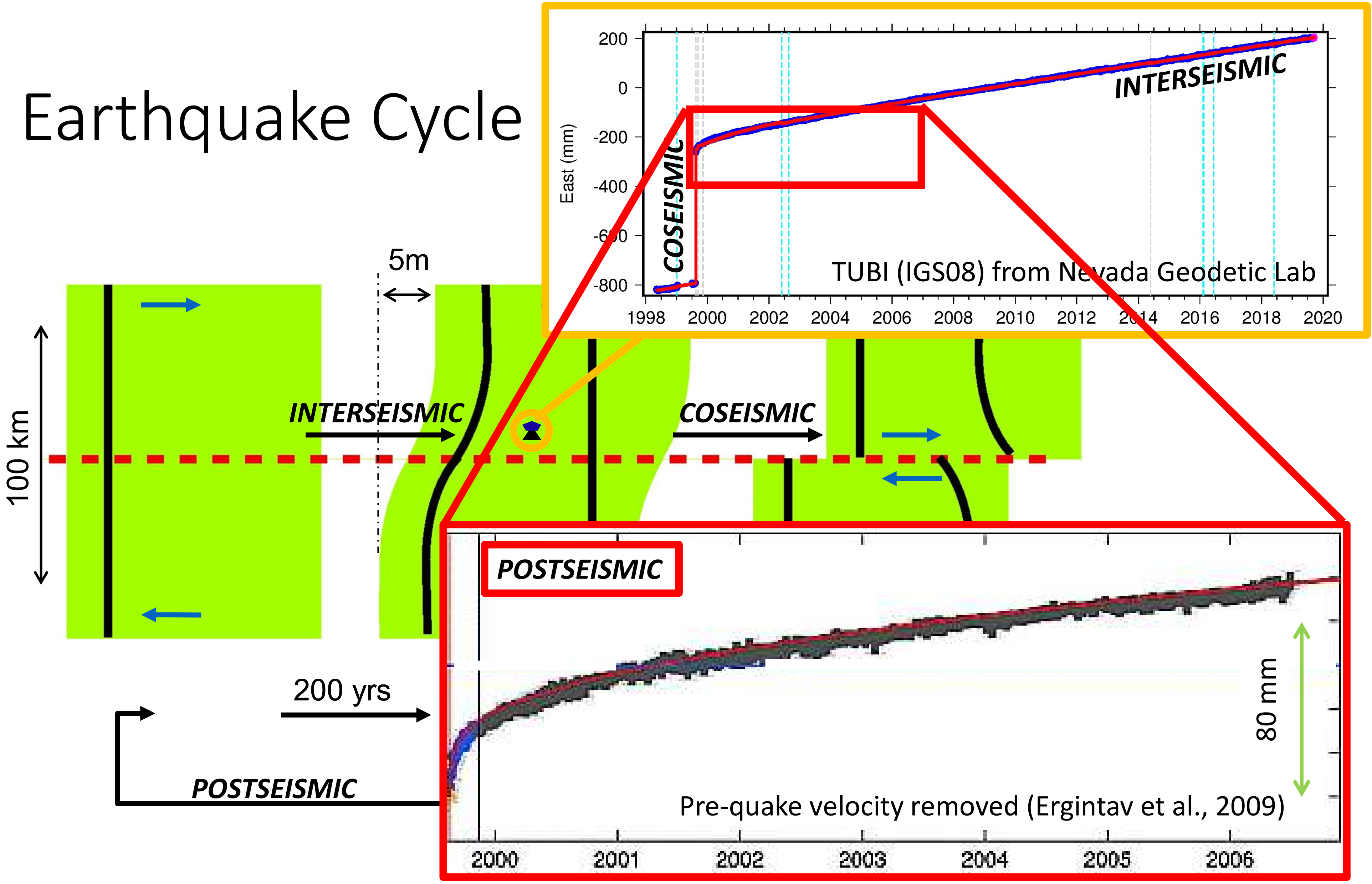


The Earthquake Cycle

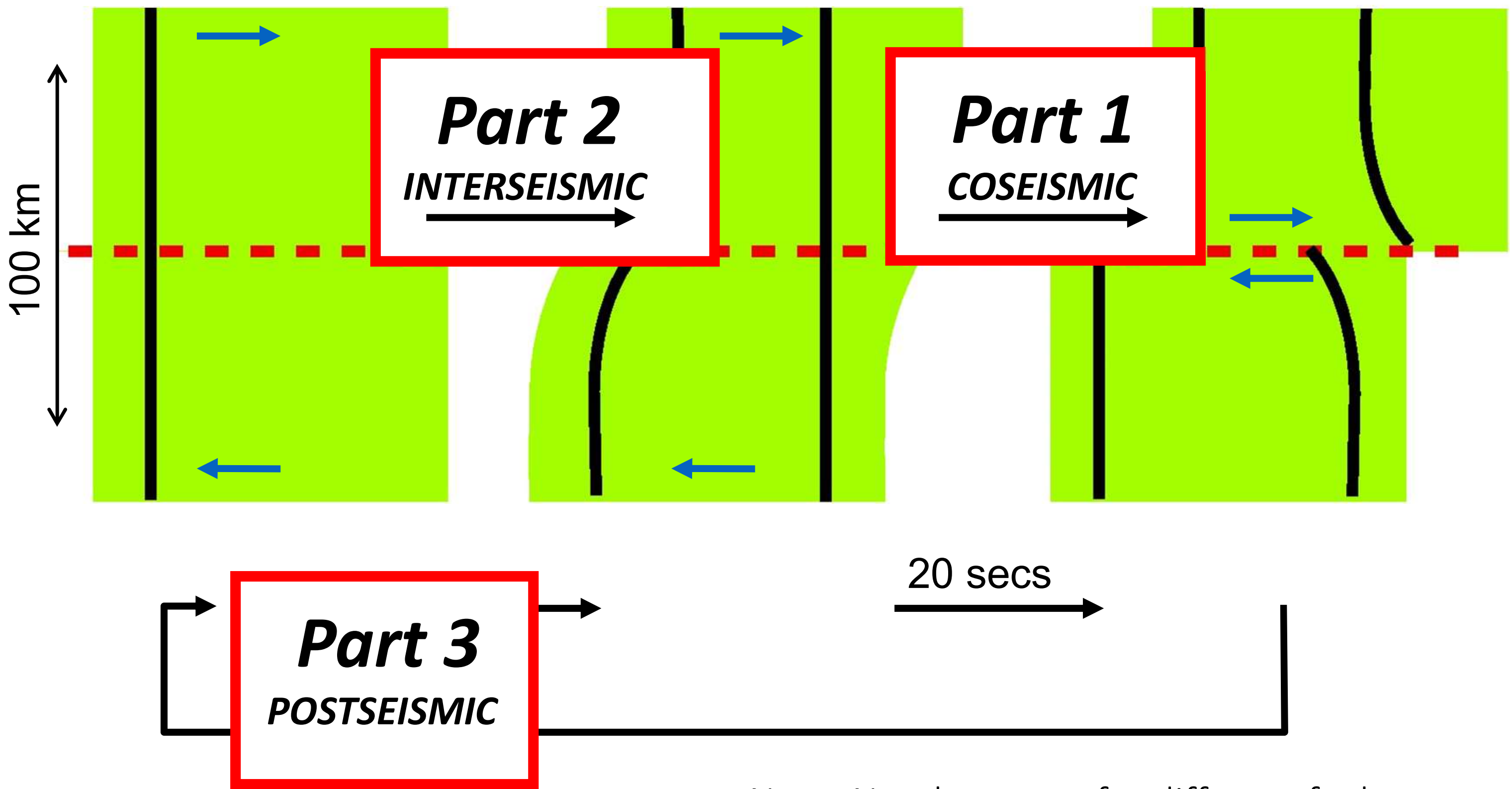


Note: Numbers vary for different faults

The Earthquake Cycle

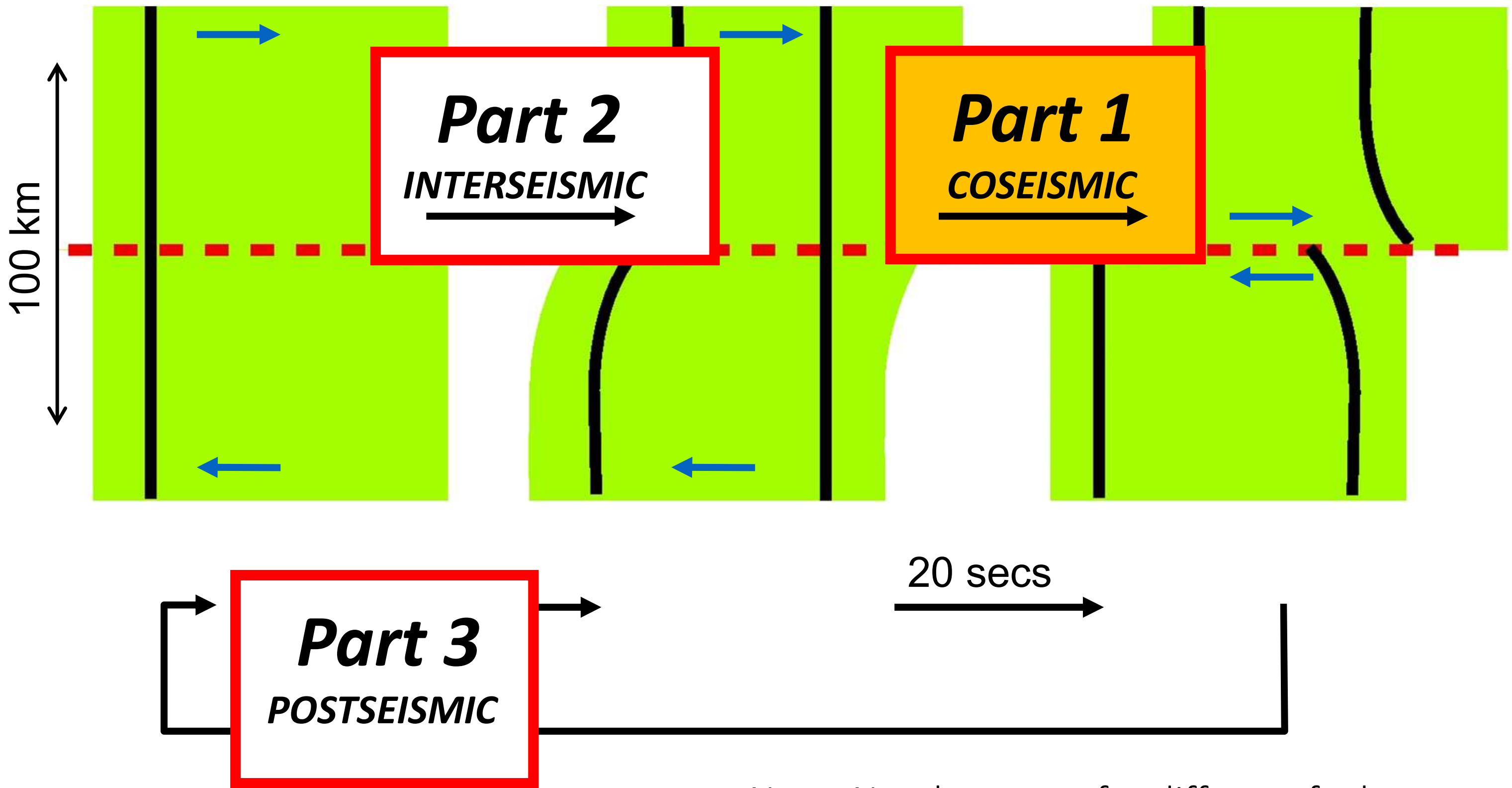


The Earthquake Cycle



Note: Numbers vary for different faults

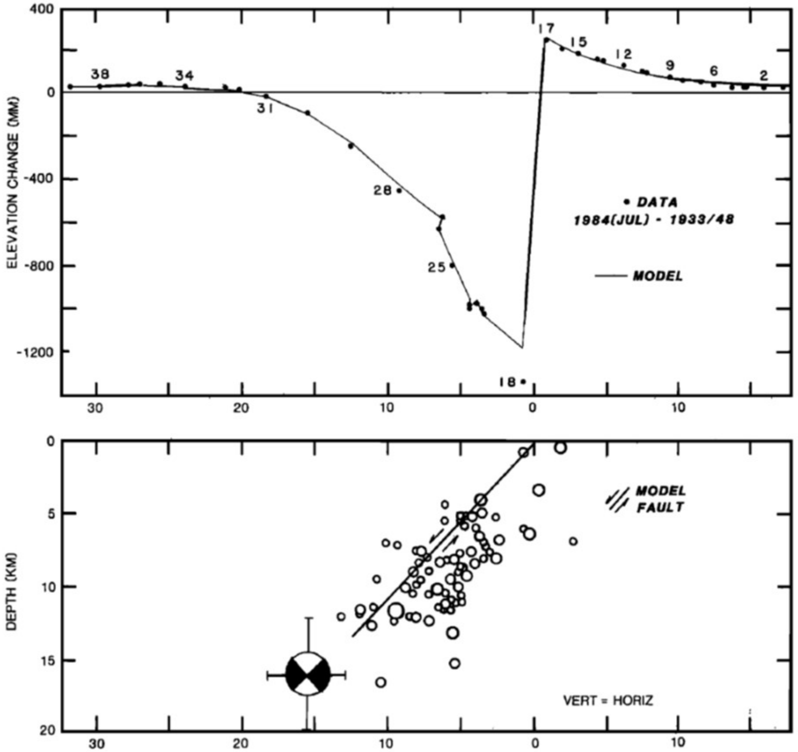
The Earthquake Cycle



Note: Numbers vary for different faults

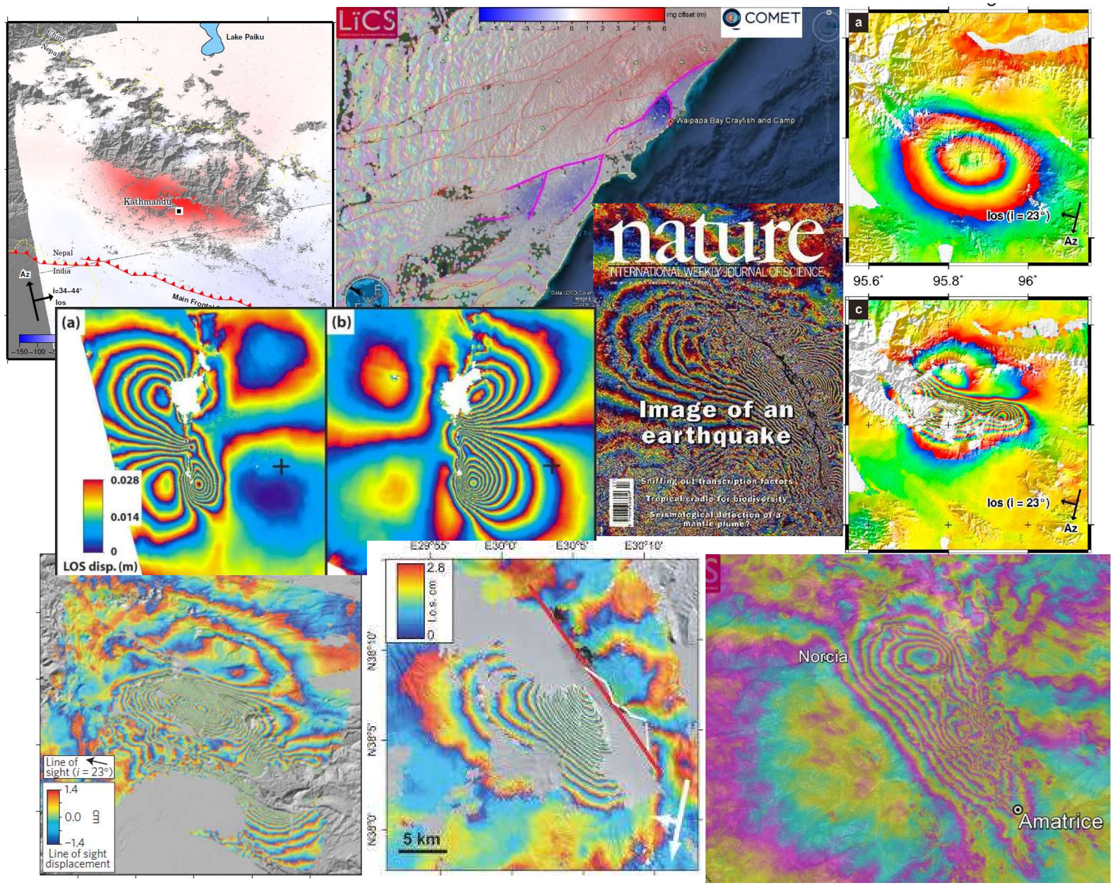
Part 1: What have learned about earthquakes

Before InSAR: 11 earthquakes with *any* geodetic observations

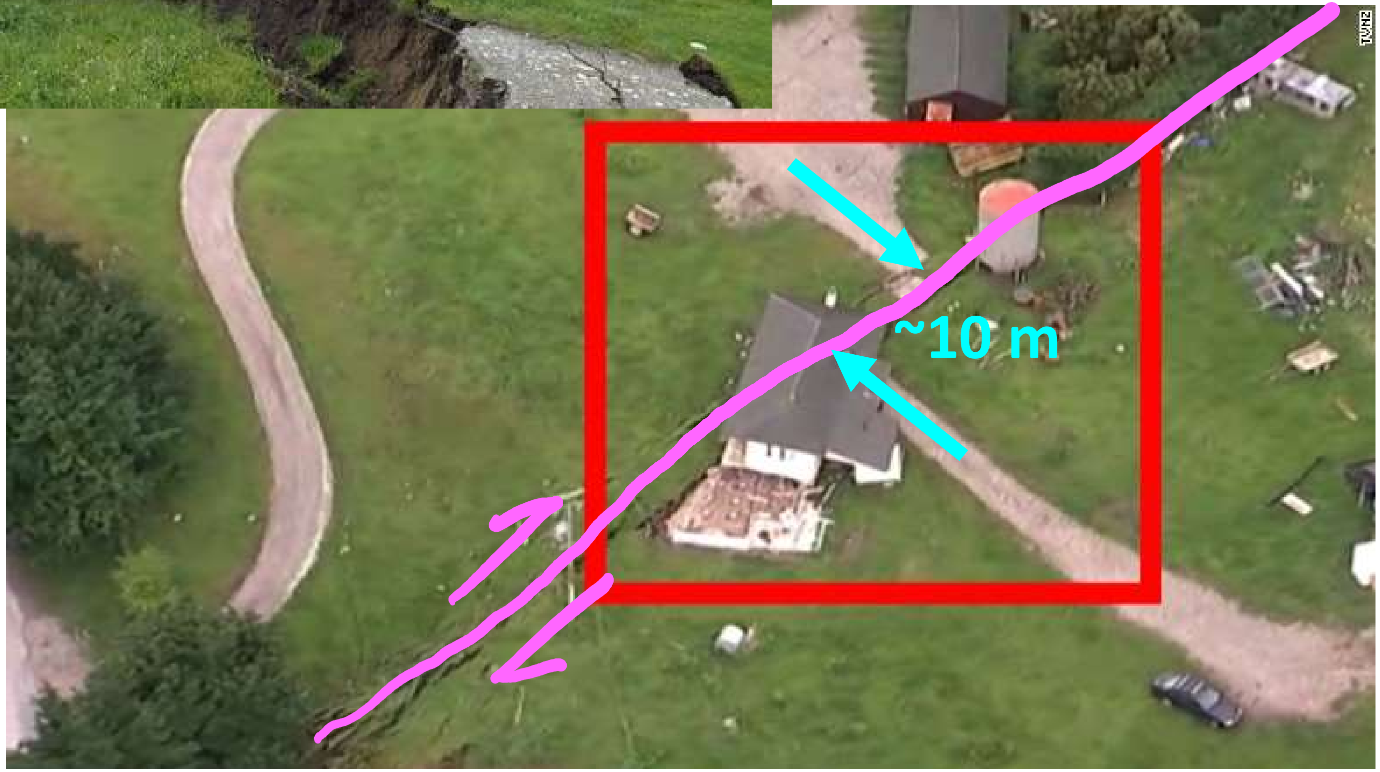


Stein and Barrientos, JGR 1985

Now: ~150-170 earthquakes with dense displacement measurements

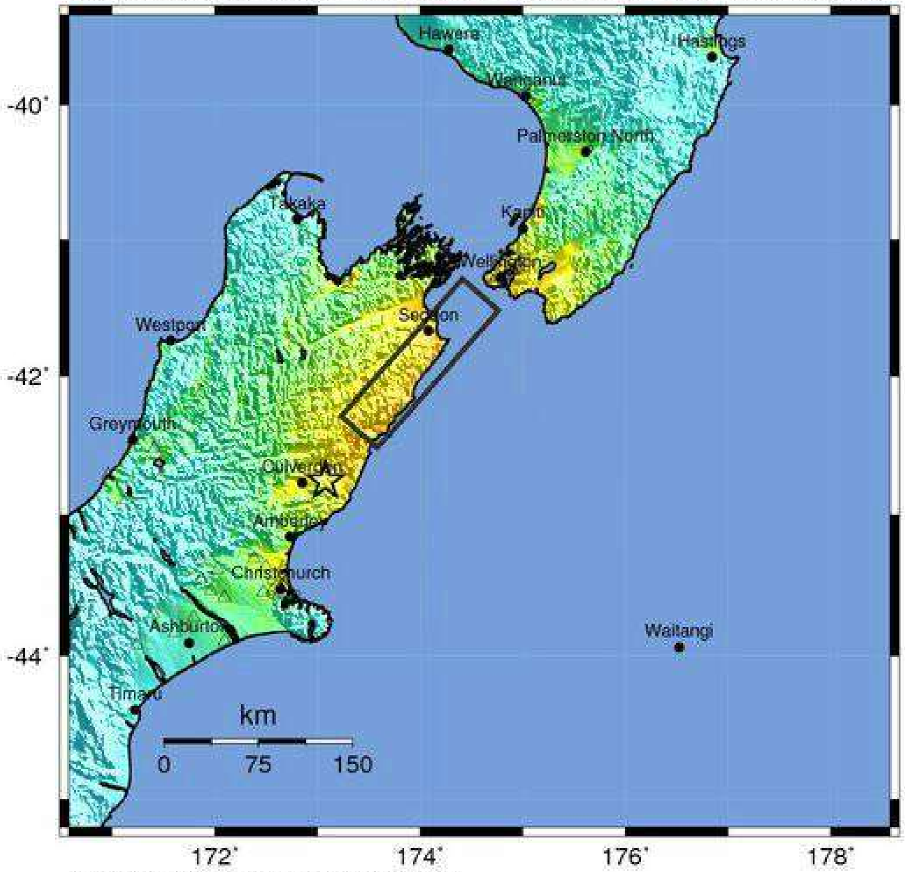


M7.8 New Zealand
13 November 2016



USGS ShakeMap : SOUTH ISLAND OF NEW ZEALAND

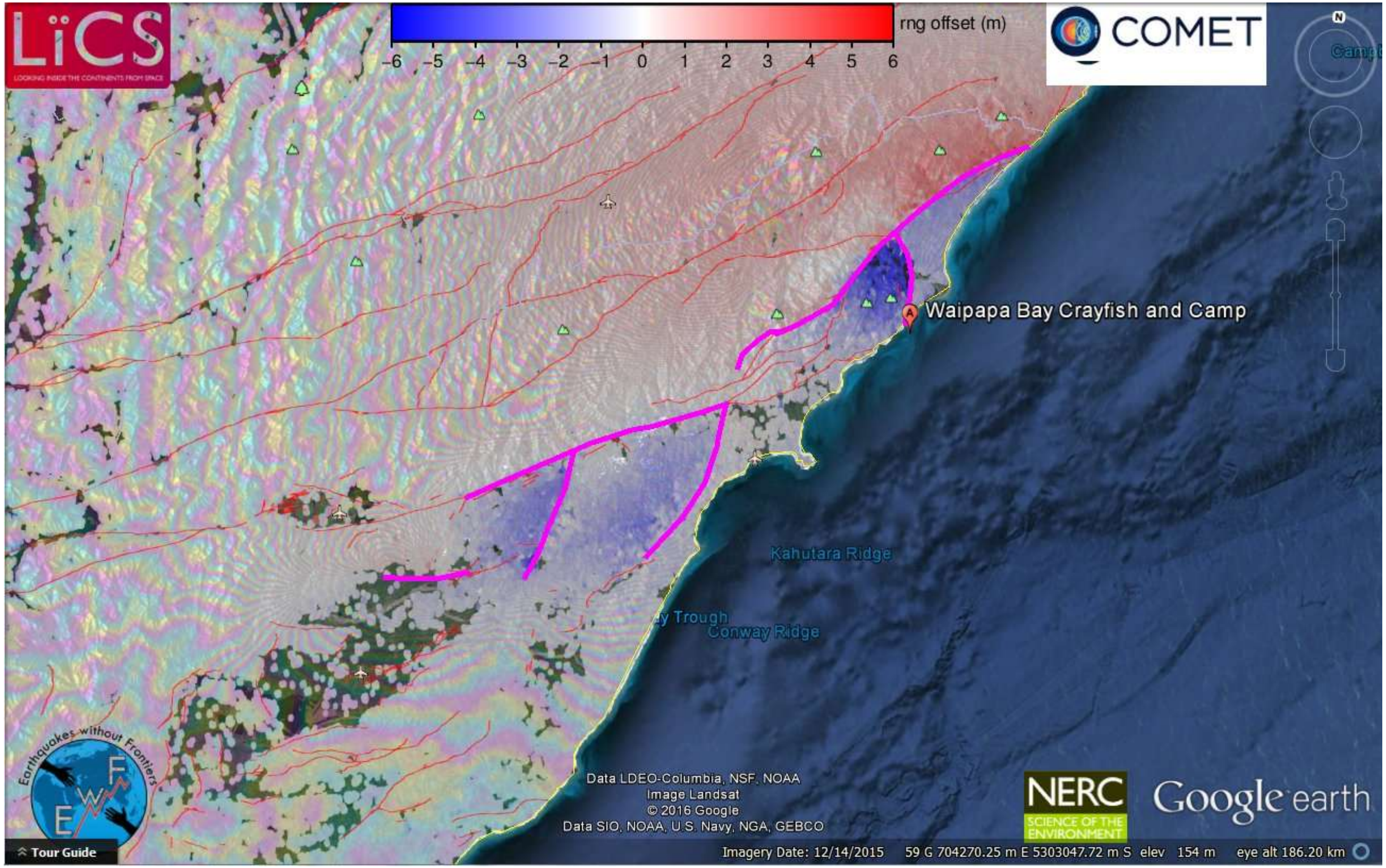
Nov 13, 2016 11:02:56 UTC M 7.8 S42.76 E173.08 Depth: 23.0km ID:us1000778i



Map Version 5 Processed 2016-11-13 14:45:38 UTC

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

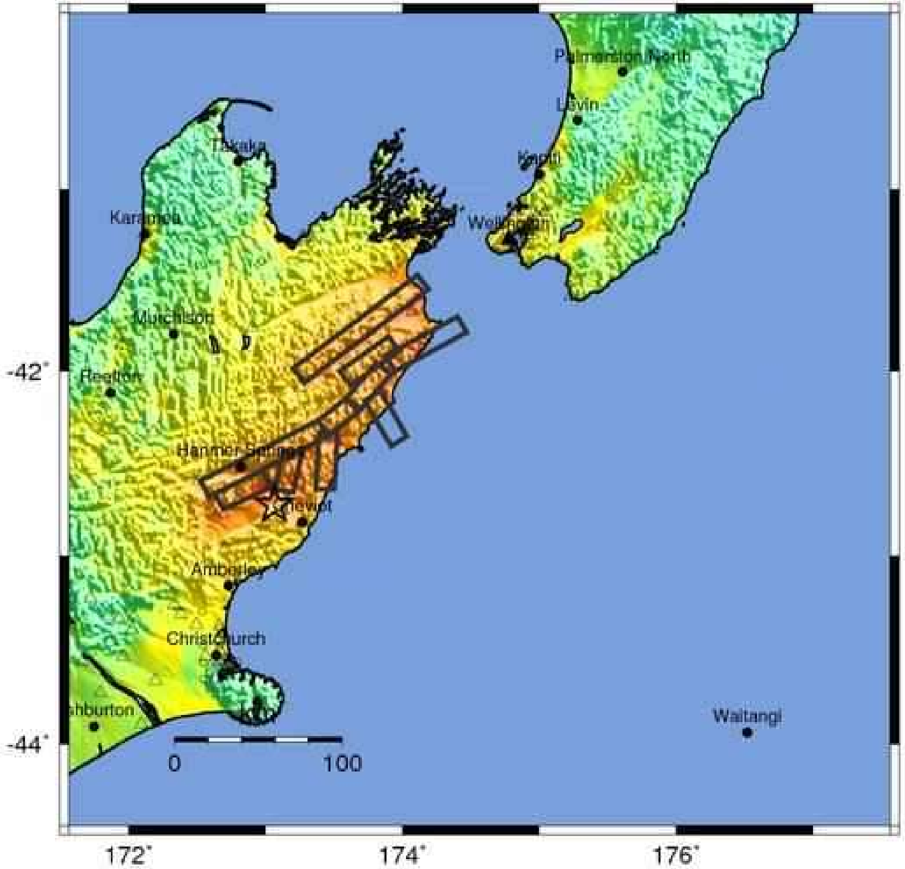
Scale based upon Worden et al. (2012)



First Sentinel-1 result posted online 4.5 hours after satellite acquisition, on 15 November

USGS ShakeMap : SOUTH ISLAND OF NEW ZEALAND

Nov 13, 2016 11:02:59 UTC M 7.8 S42.72 E173.06 Depth: 22.0km ID:us1000778i



Map Version 9 Processed 2016-11-26 14:54:10 UTC

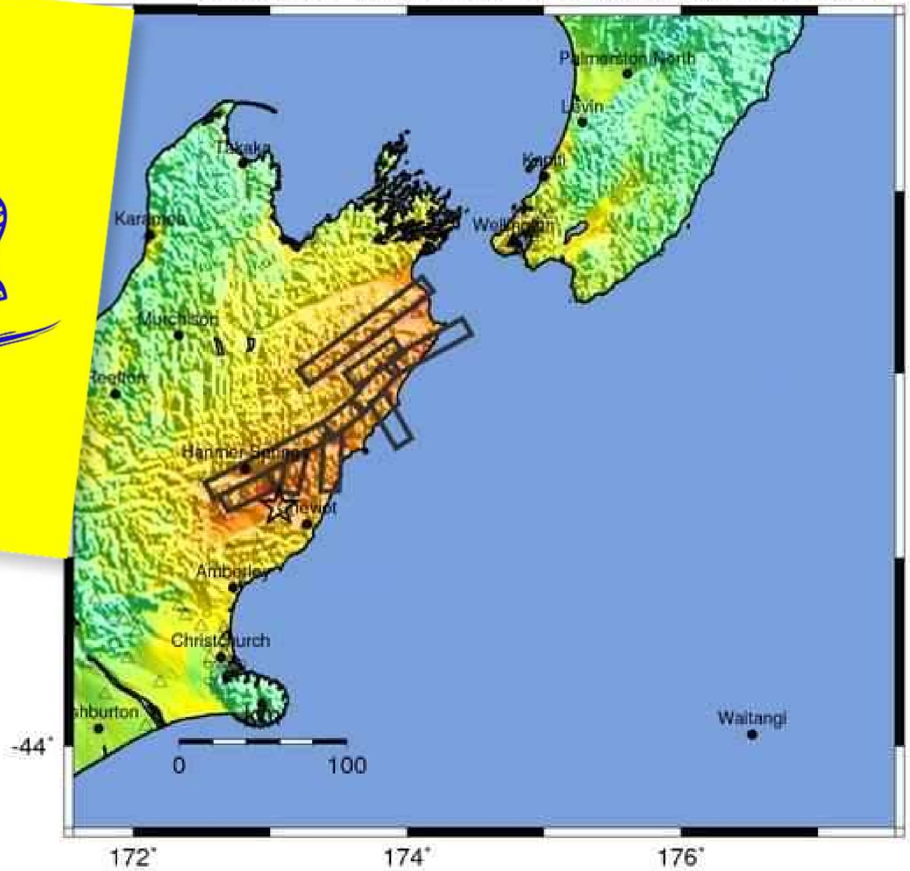
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

So What?

USGS ShakeMap : SOUTH ISLAND OF NEW ZEALAND

Nov 13, 2016 11:02:59 UTC M 7.8 S42.72 E173.06 Depth: 22.0km ID:us1000778i



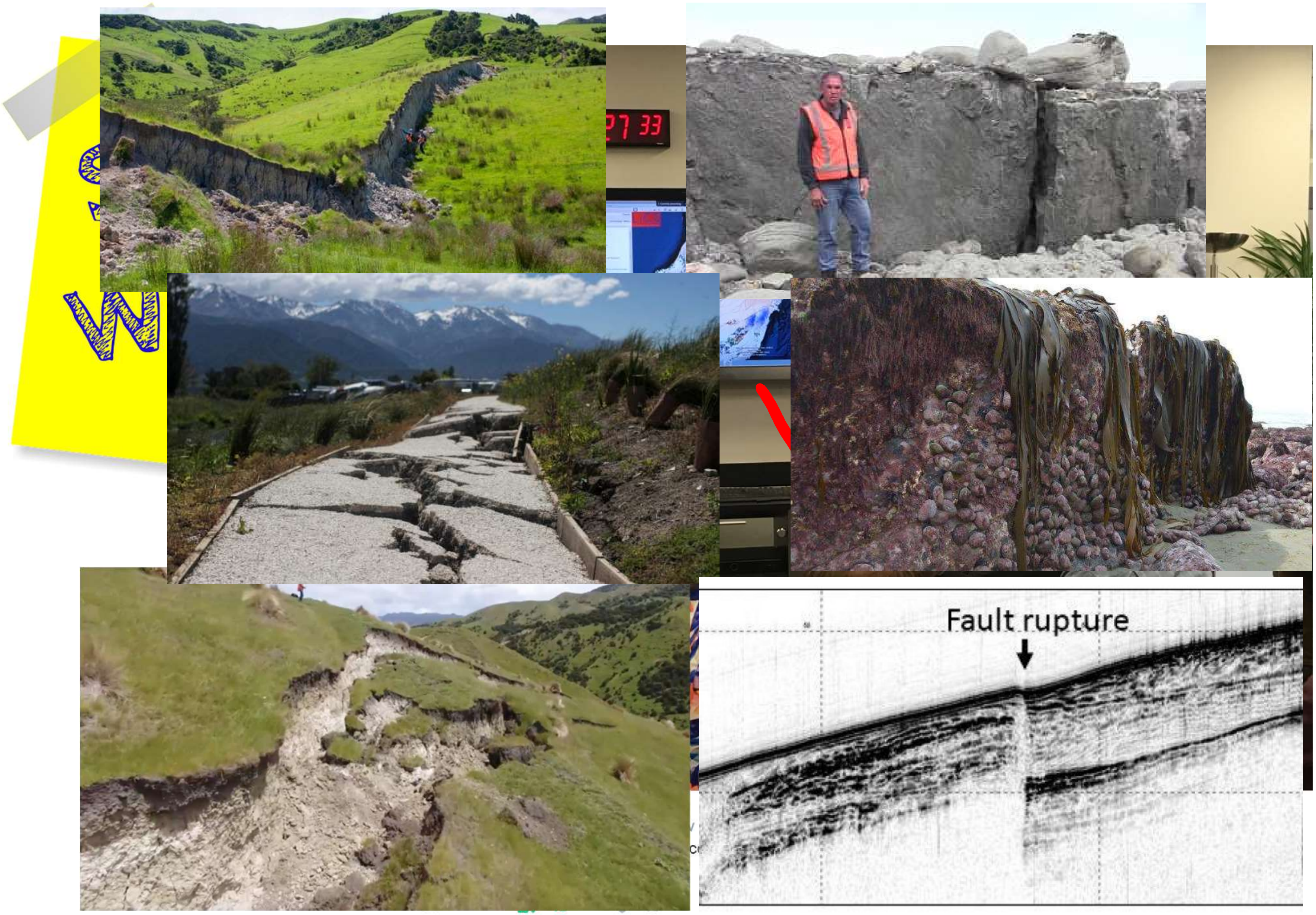
Map Version 9 Processed 2016-11-28 14:54:10 UTC

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

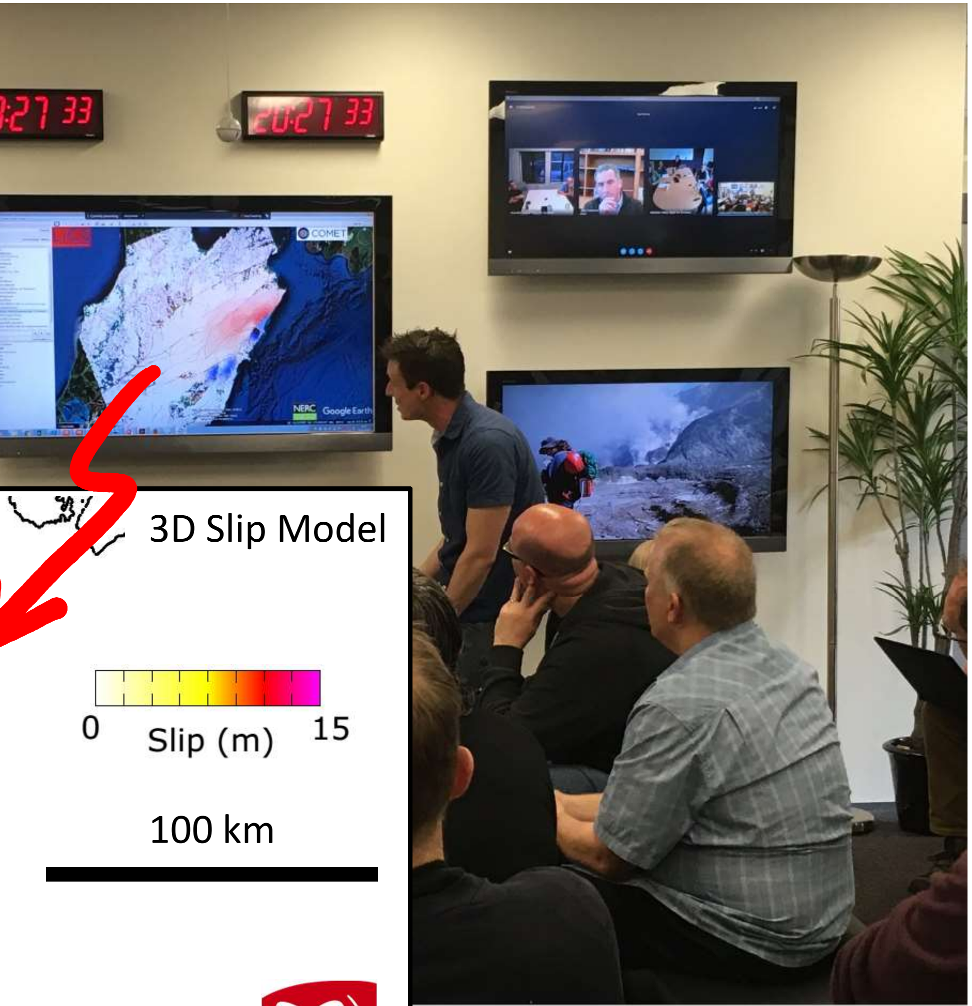
Scale based upon Worden et al. (2012)

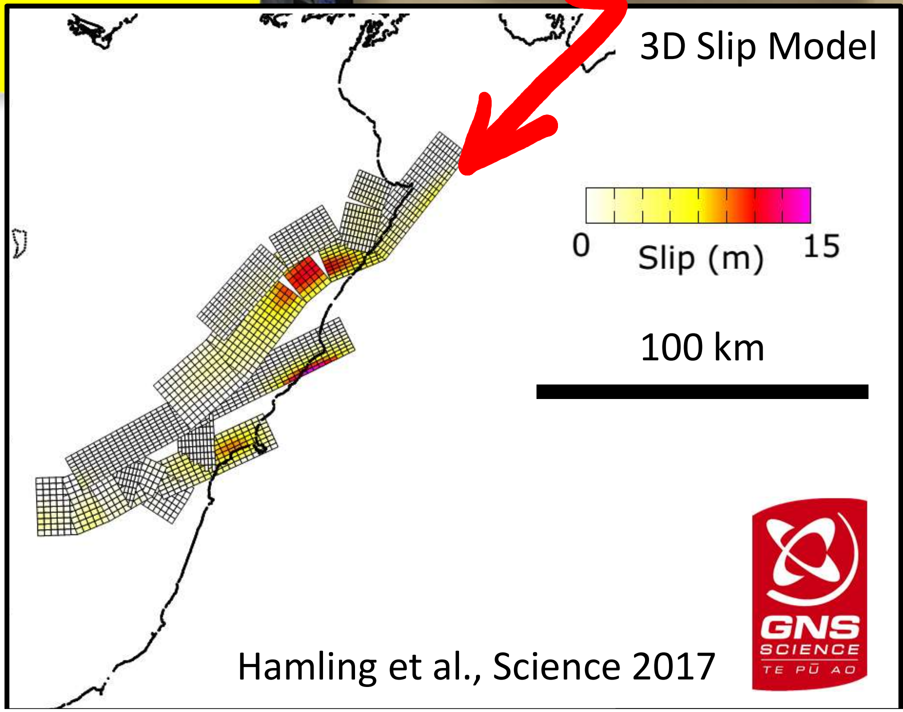
Sigrun Hreinsdottir @gpsRuna · Nov 16
@timwright_leeds Amazing InSAR - complex earthquake rupture. Thanks for all the fringes. With Ian Hamling GNS Science and GeoNet

12 13


Fault rupture

So What?

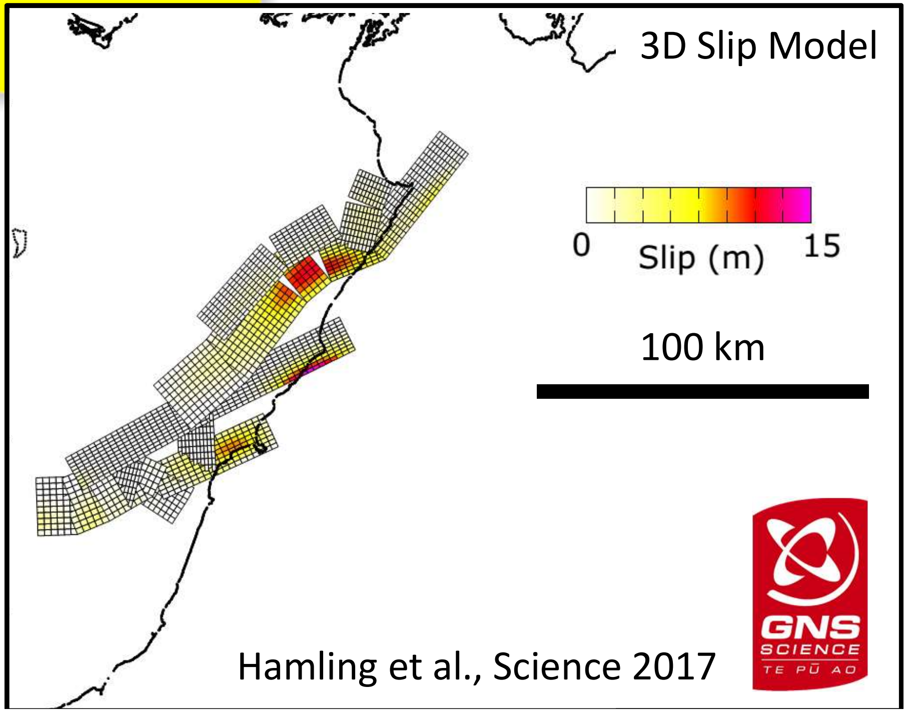




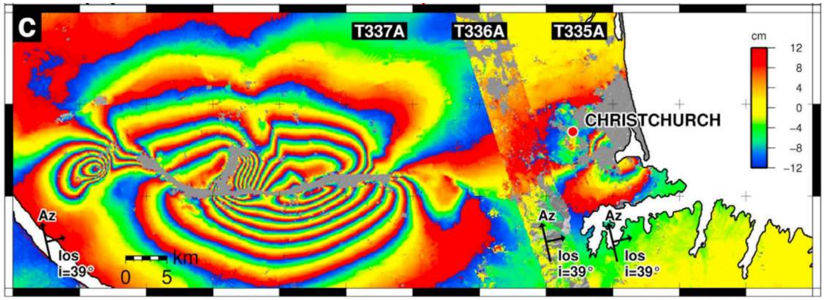
Thanks for all the fringes. With Ian Hamling GNS

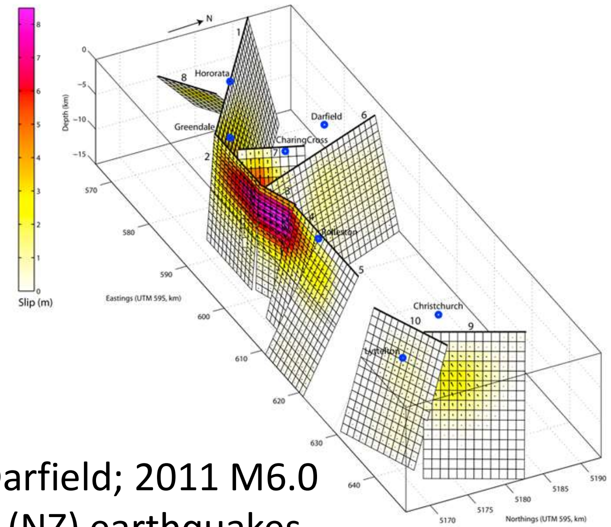
"Rules" broken by the Kaikoura earthquake:

- Earthquake broke a complex network of faults (mapped and unmapped) in several tectonic zones
- Jumps of > 15 km (standard models have 5 km limit)
- Subduction zone and crustal faults moving together

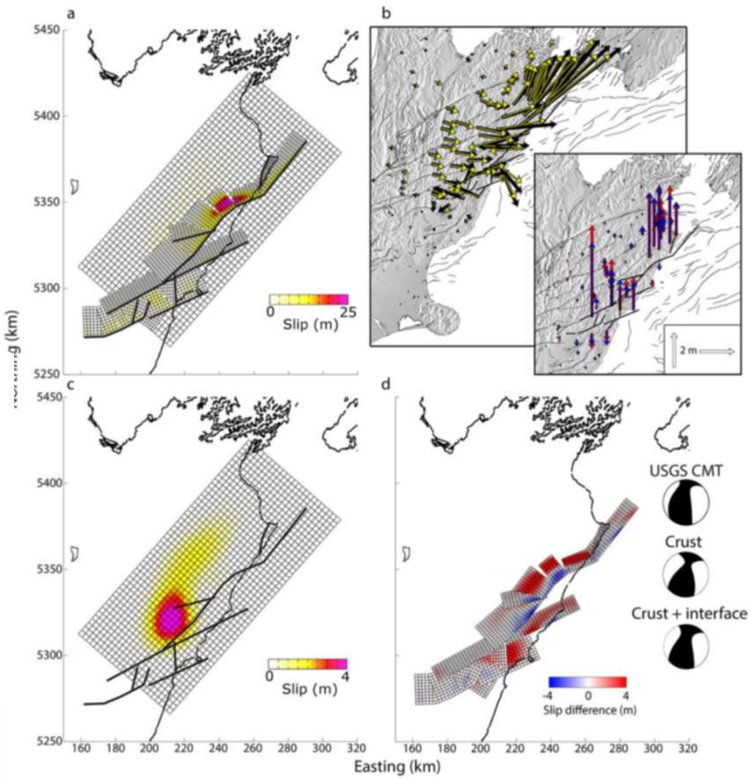


Part 1: What have learned about earthquakes:
(a) Ruptures are more complex than we thought

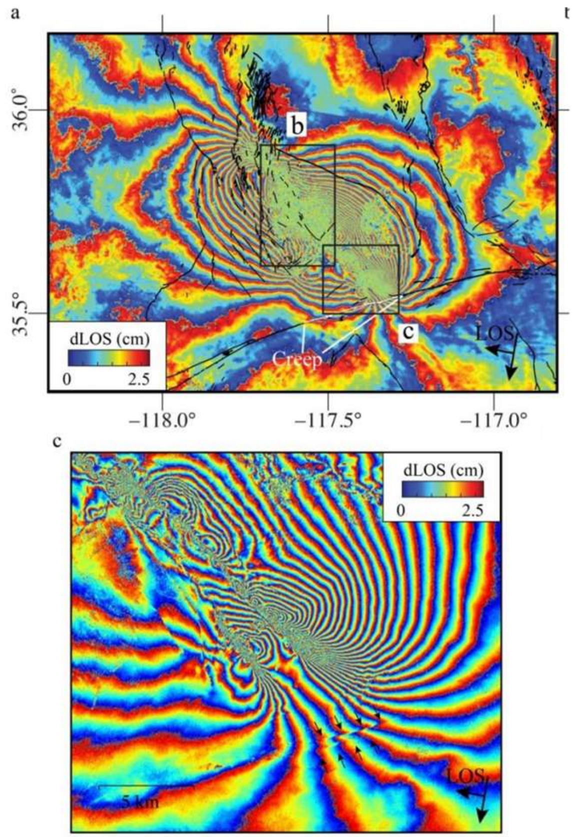




2010 M7.1 Darfield; 2011 M6.0 Christchurch (NZ) earthquakes. (Elliott et al., 2012)

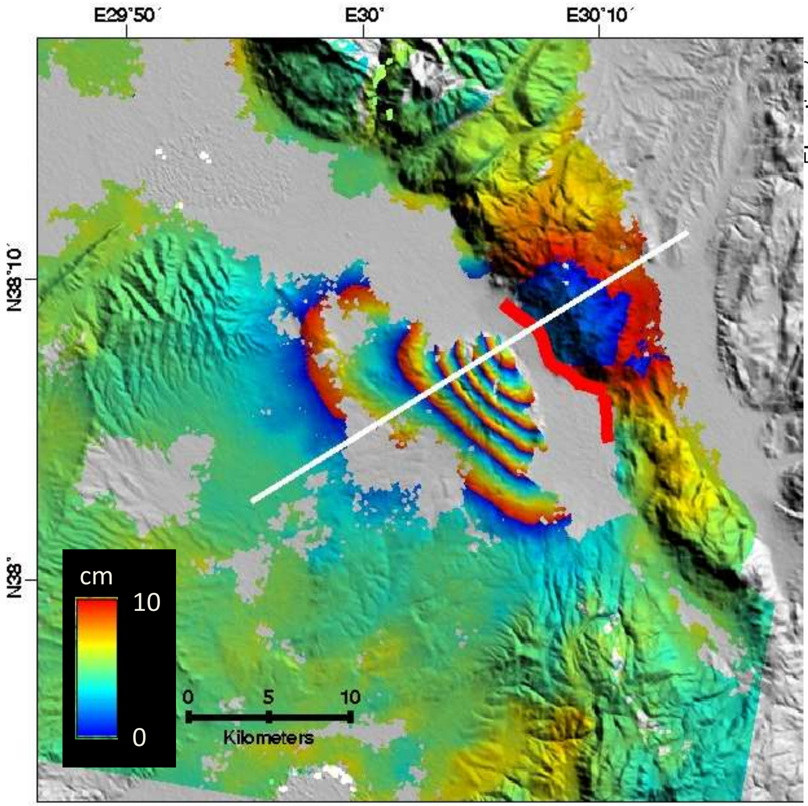


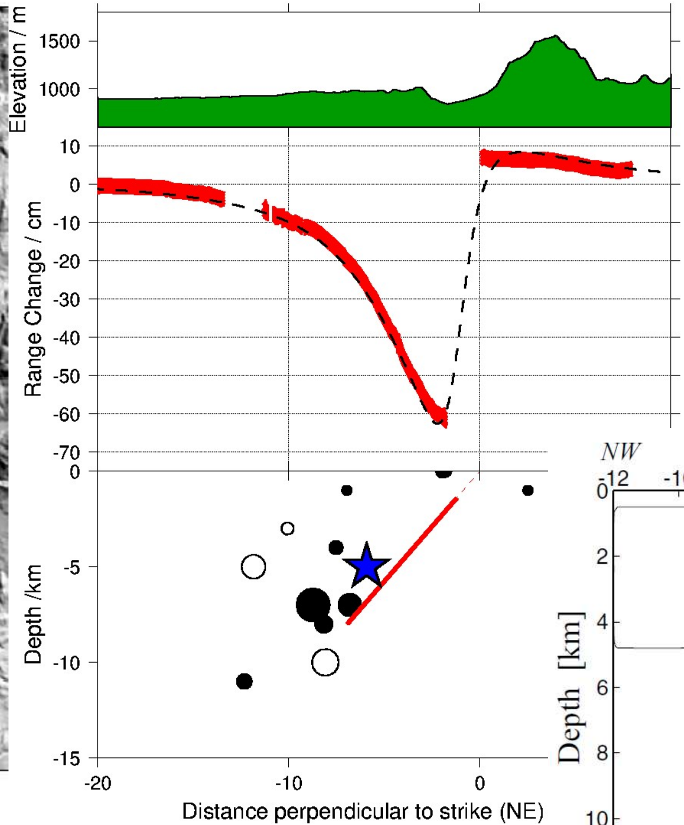
2016 M7.8 Kaikoura (NZ) earthquake. (Hamling et al., 2017)



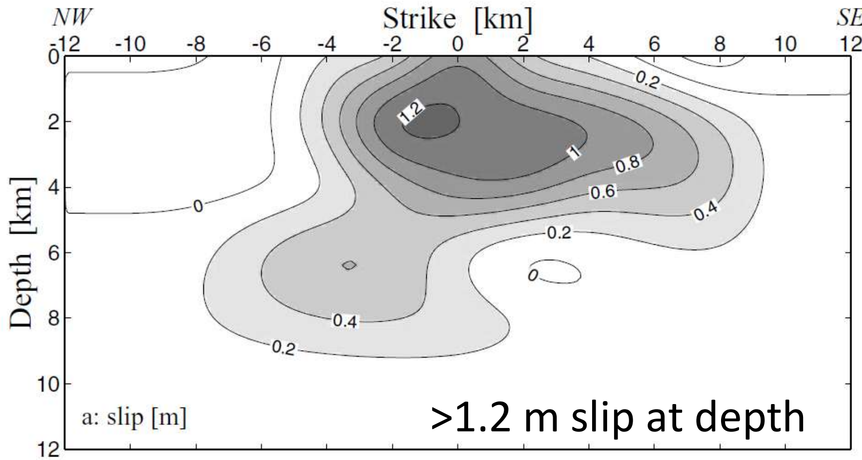
2019 M6.4/7.1 Ridgecrest (California) earthquake sequence. (Barnhart et al., 2019)

Part 1: What have learned about earthquakes:
(b) Surface slip is poor guide to slip at depth





<0.3 m slip at surface

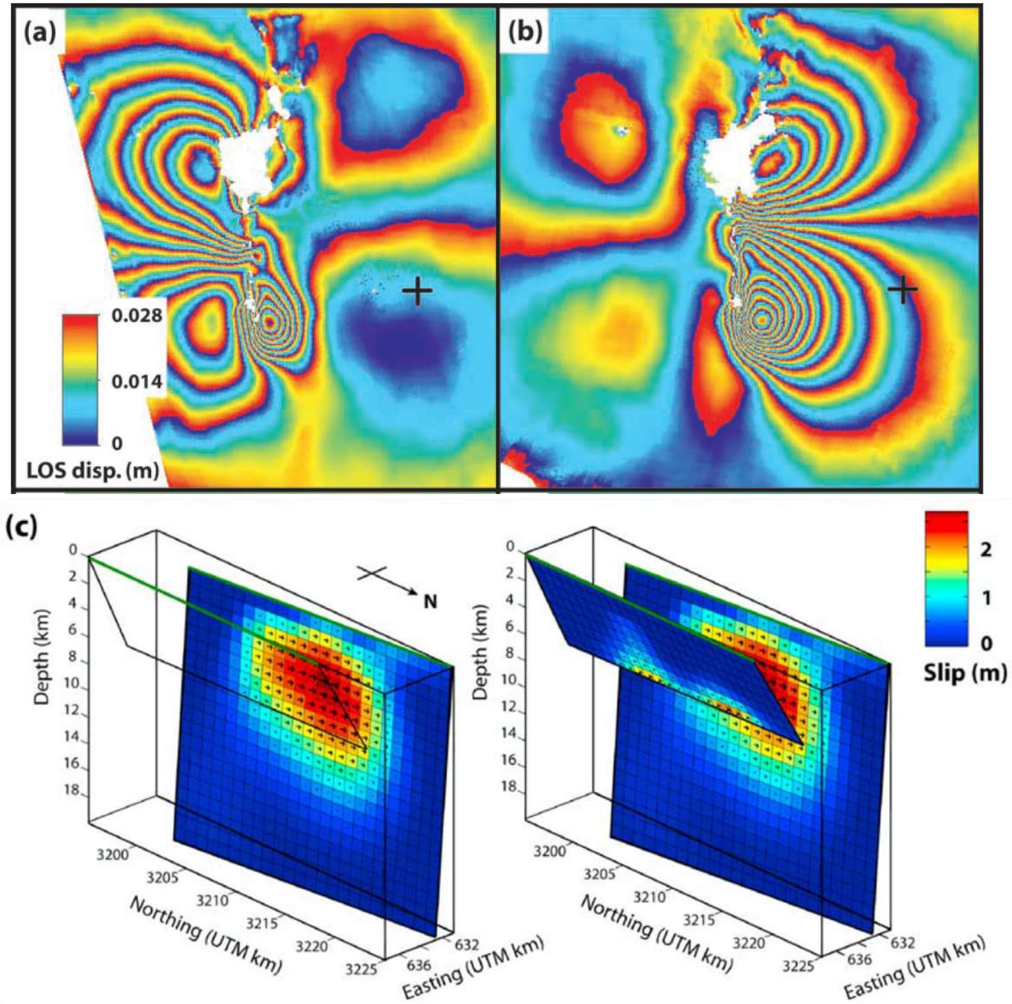


>1.2 m slip at depth

1995 M6.5 Dinar (Turkey).

Wright et al., 1999; Fukahata and Wright, 2008

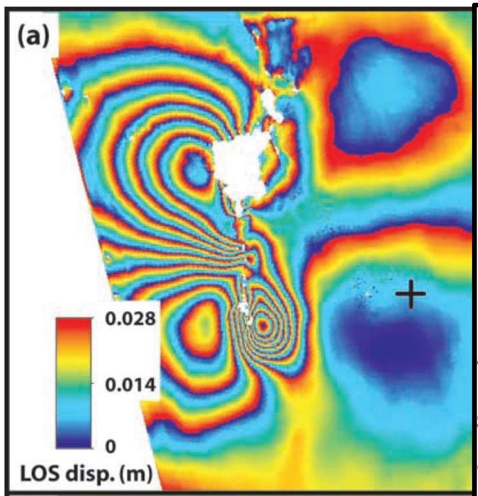
Part 1: What have learned about earthquakes:
(b) Surface slip is poor guide to slip at depth

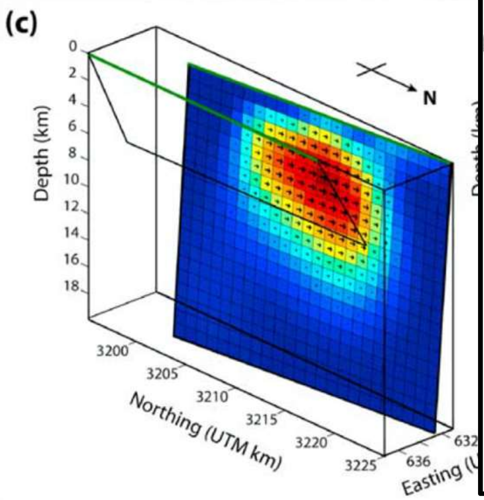


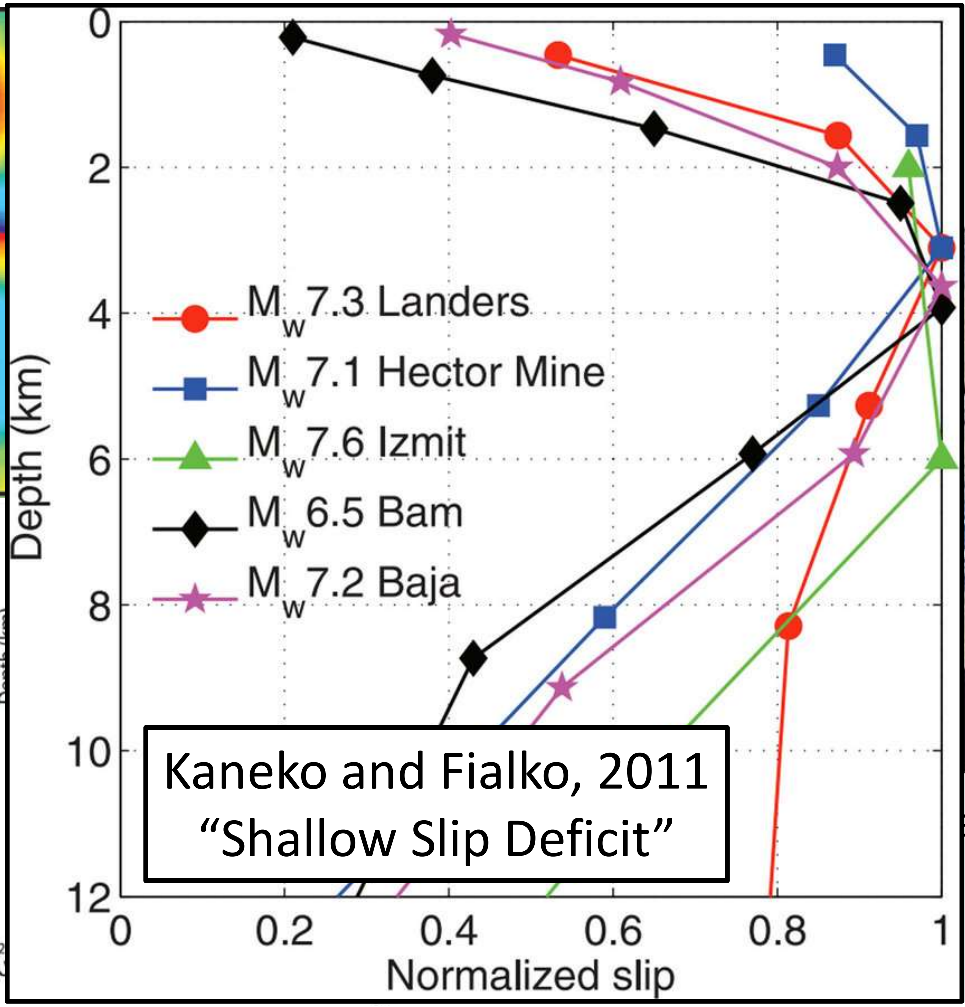
2003 M6.5 Bam (Iran).
Talebian et al., 2004; Funning et al., 2006

25 cm (max) at surface; 2-3 m at depth

Part 1: What have learned about earthquakes:
(b) Surface slip is poor guide to slip at depth





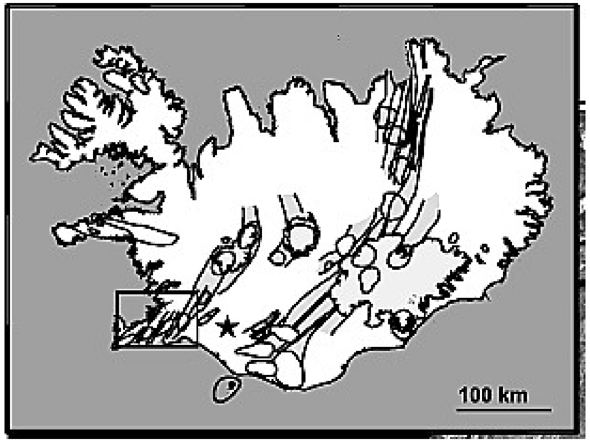


Bam (Iran).

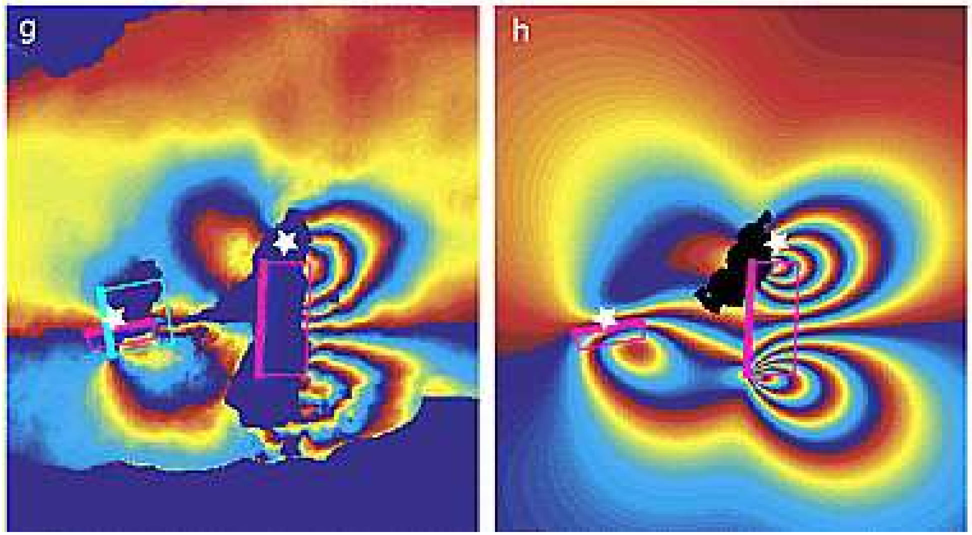
al., 2004; Funning et al., 2006

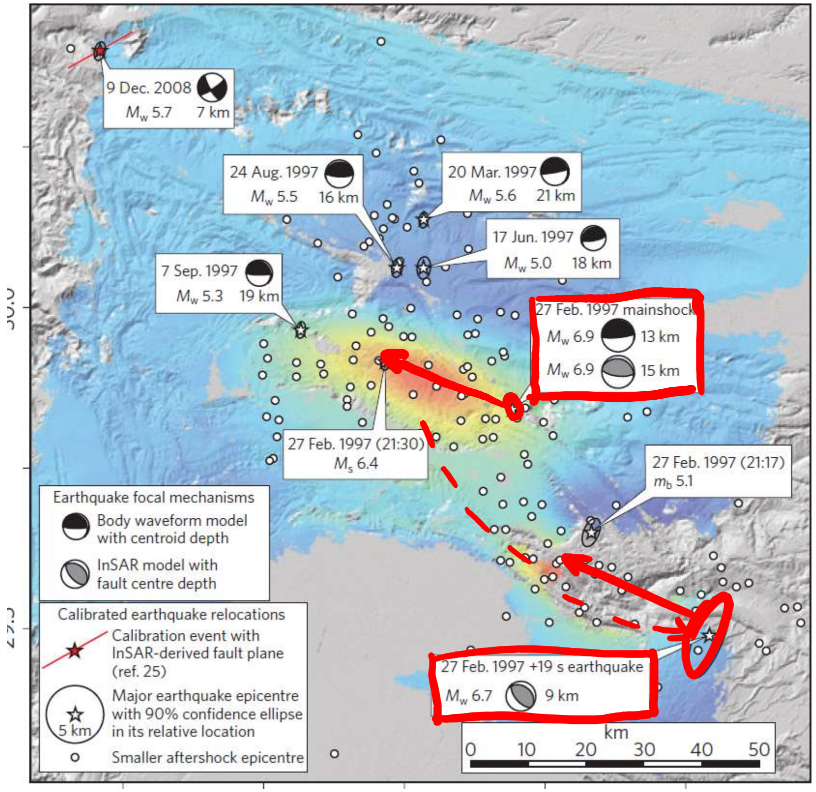
at surface; 2-3 m at depth

Part 1: What have learned about earthquakes:
(c) Earthquakes can be triggered dynamically



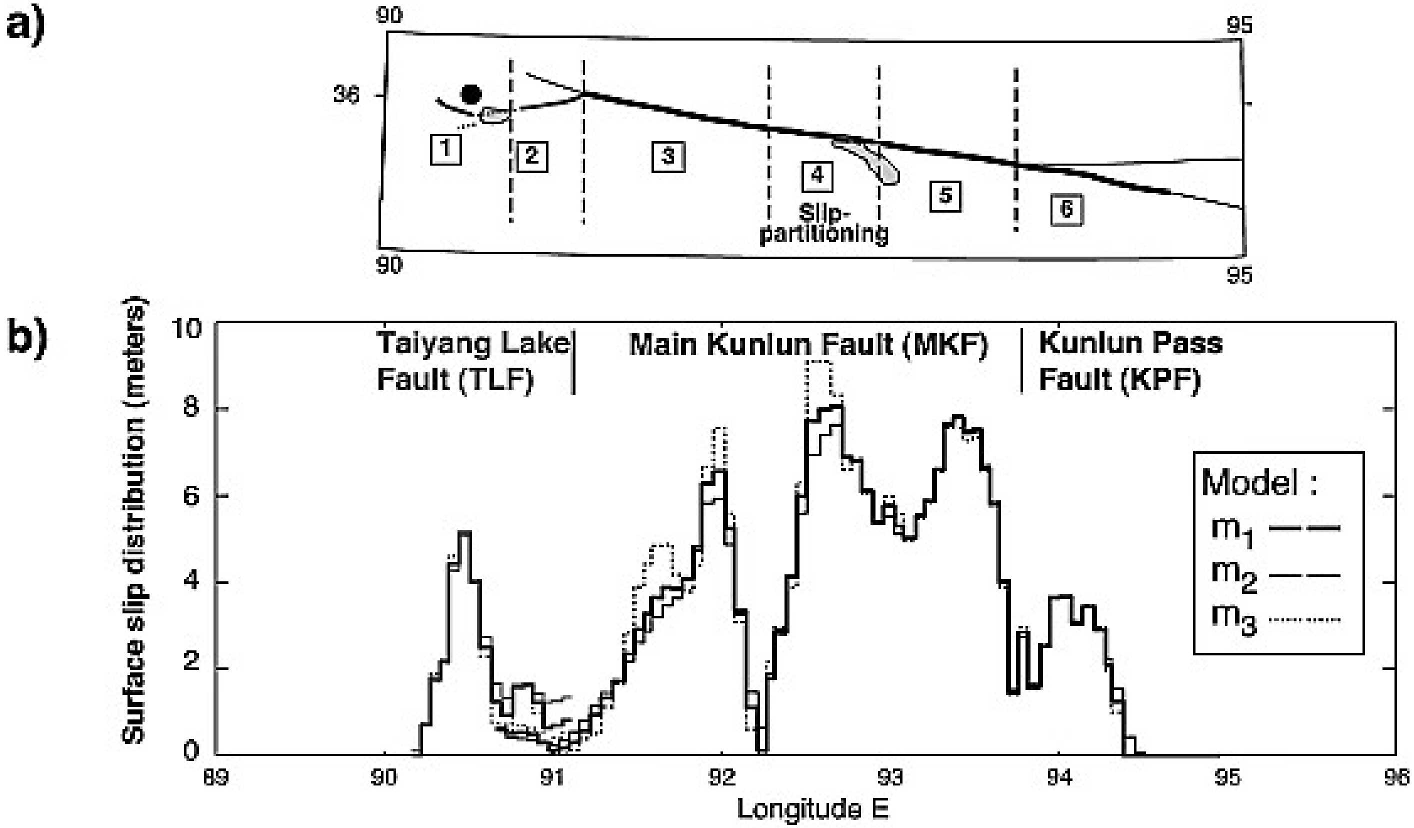
2000 M5.8 triggered by M6.6, 100 km away (not detected by seismology); Pagli et al., 2003





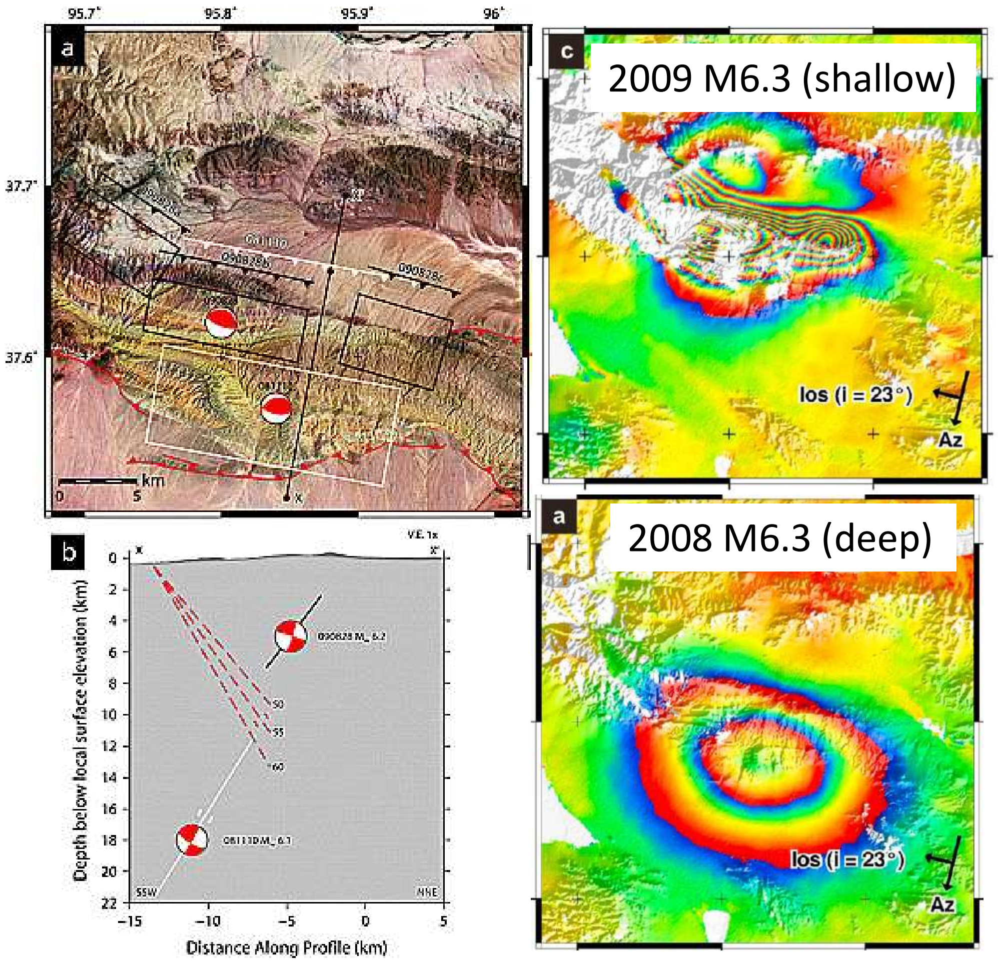
1997 M7.1 Pakistan Earthquake Doublet (separated by 19 s); Nissen et al., 2016

Part 1: What have learned about earthquakes:
(d) Earthquakes can be structurally controlled

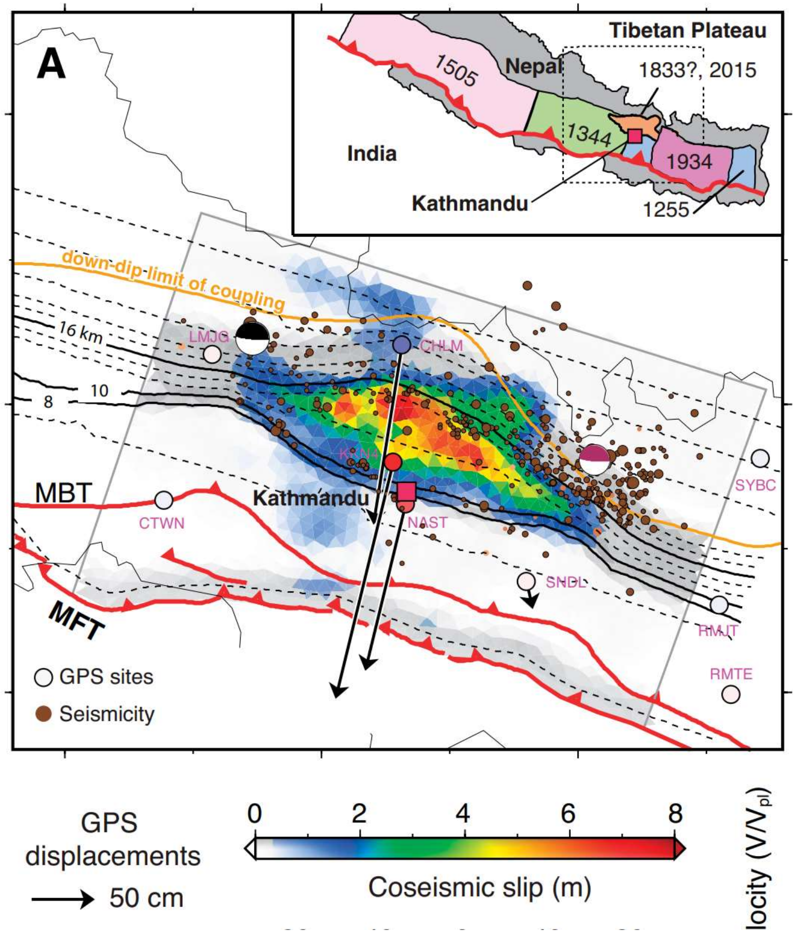


2001 M7.8 Kokoxili (Tibet); Lasserre et al., 2005

Part 1: What have learned about earthquakes:
(d) Earthquakes can be structurally controlled

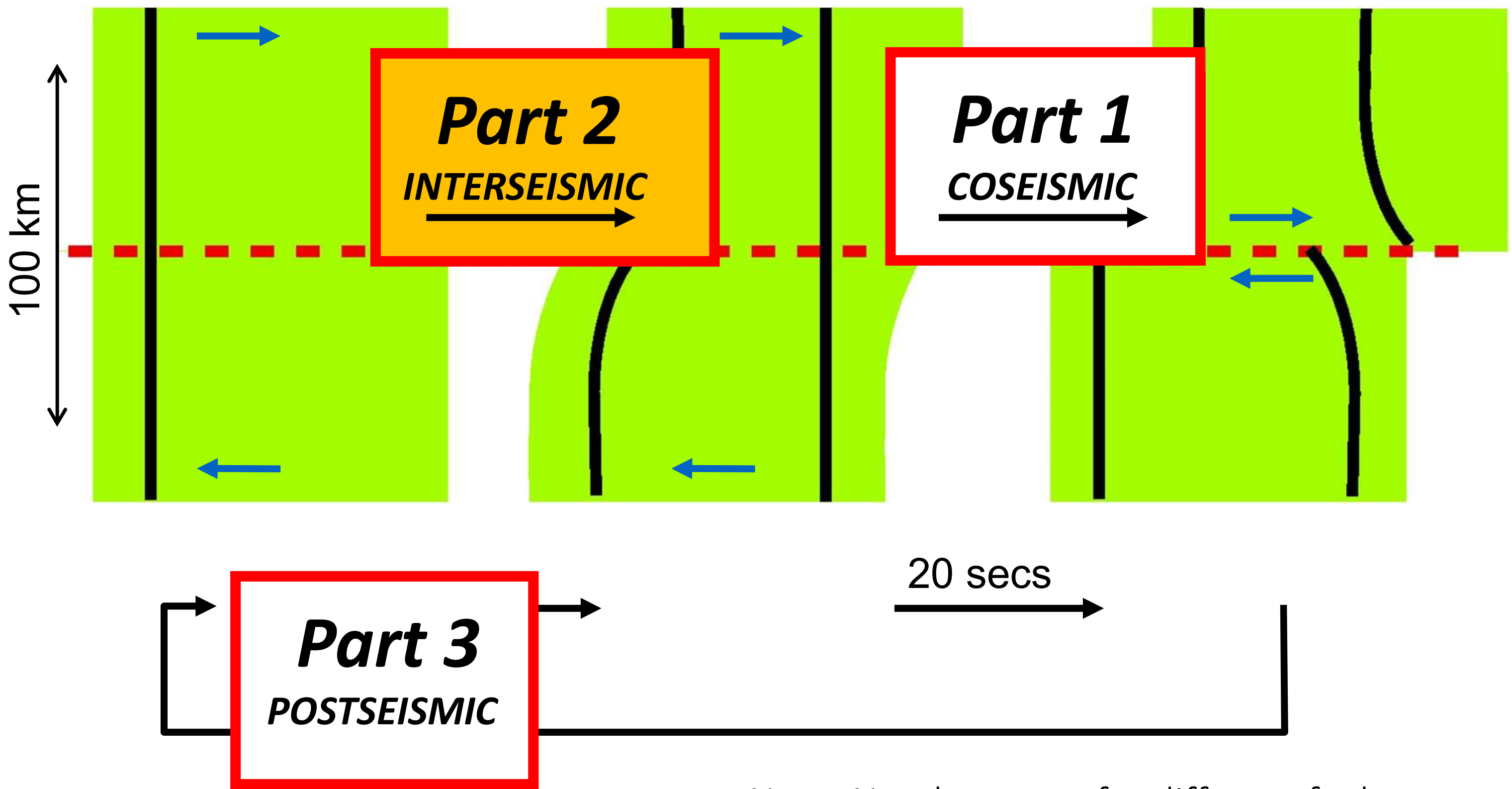


2008/2009 M6.3/6.3 Qaidam; Elliott et al., 2011



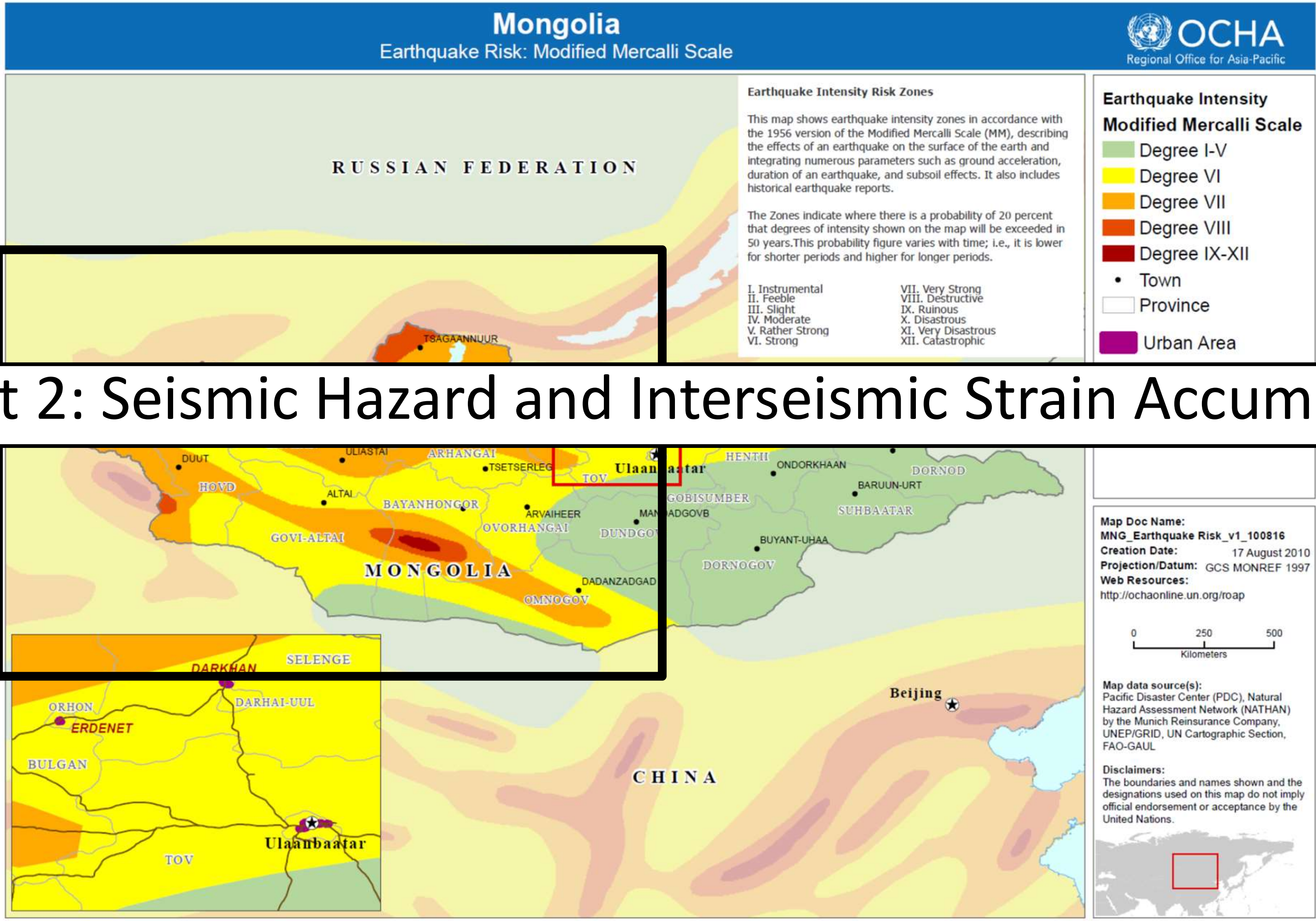
2015 M7.8 Nepal; Qiu et al., 2016

The Earthquake Cycle



Note: Numbers vary for different faults

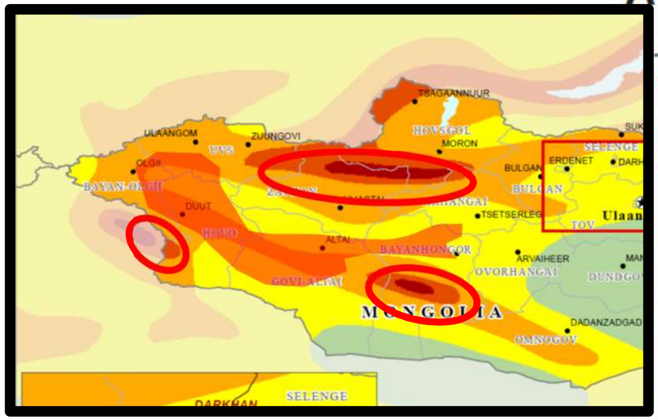
What's the seismic hazard in Mongolia?

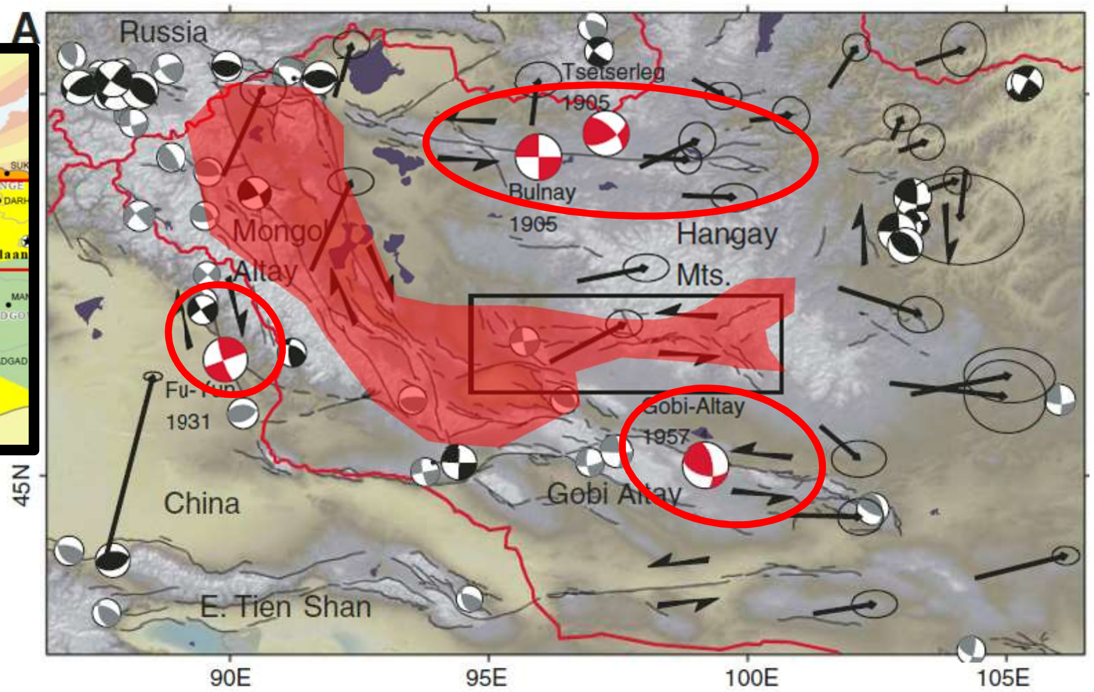


Part 2: Seismic Hazard and Interseismic Strain Accumulation

Reproduced with permission from UN

What’s the seismic hazard in Mongolia?

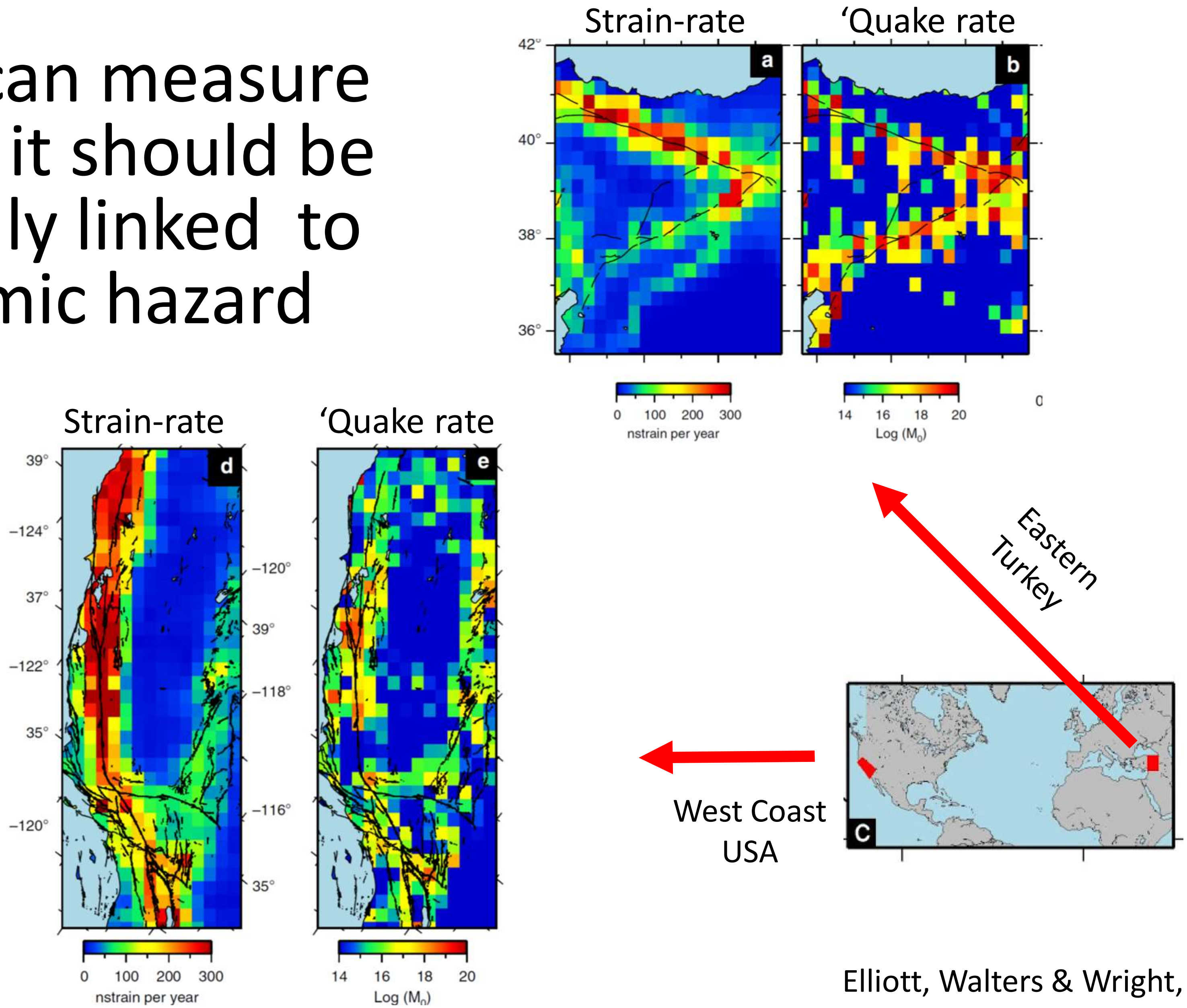




Walker et al., Geology 2007; Reproduced with permission

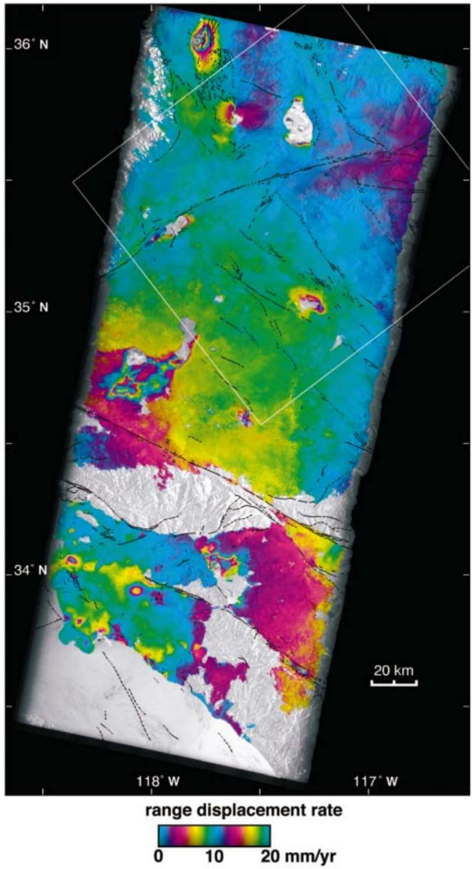
Records of earthquakes are too short for the conventional approach in many areas of the continents

If we can measure strain, it should be causally linked to seismic hazard



Elliott, Walters & Wright, 2016

First measurements of interseismic strain with InSAR



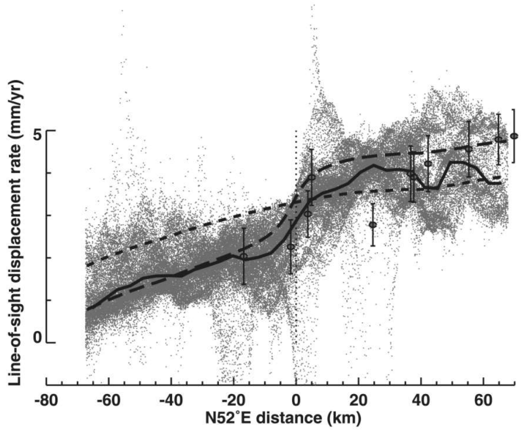
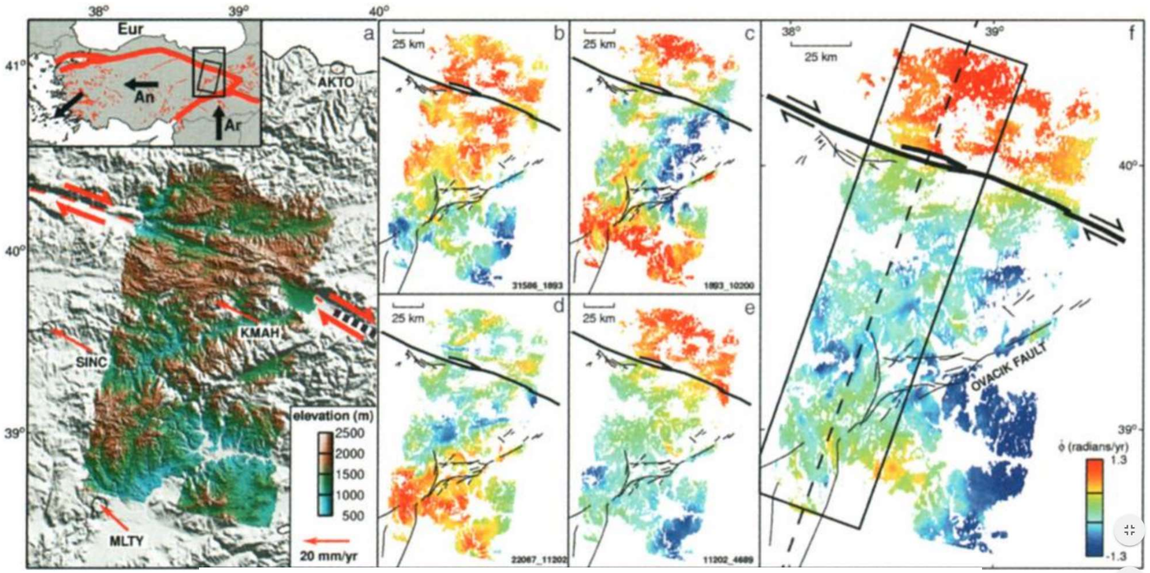
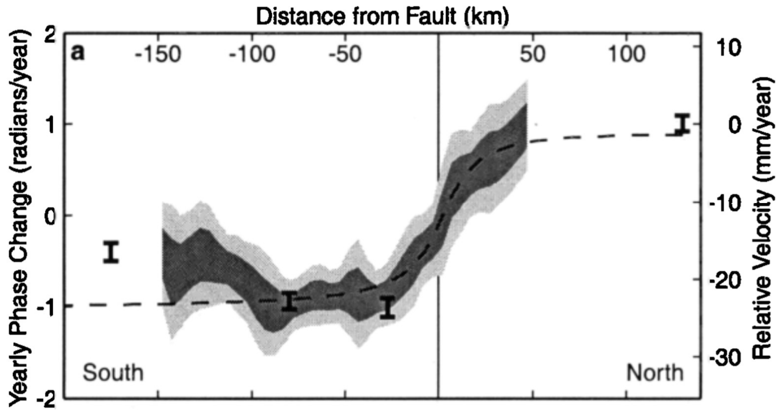


Figure 4. Profiles of observed and modeled line-of-sight displacement projected on vertical plane perpendicular to shear zone. Gray dots are individual data points for all radar-image pixels included in box shown in Figure 3. Solid line shows 2 km running mean of observed displacement along profile length. Note that apparent standard deviation of projected data relative to average profile reflects in part displacement gradient parallel to fault strike and not only error in data. Groups of dots that deviate from dense part of profile are due to ground subsidence near lake shores and to surface displacement associated with Ridgecrest earthquakes (Figs. 1, 3). Short-dash line is profile predicted by long-term velocity model used to estimate interferometric baseline (Shen et al., 1996). Long-dash line is profile predicted by velocity model, including additional buried dislocation along Blackwater–Little Lake fault system. Parameters of added fault are given in text. Black dots and error bars (2σ) are line-of-sight projections of horizontal velocities observed by GPS at stations of Yucca transect (Gan et al., 2000).

the penultimate shear zone cluster centered at 5.5 ka. A similar pattern is observed in eastern Turkey, where the sequence of large earthquakes during the past three centuries suggests that the locations and periods



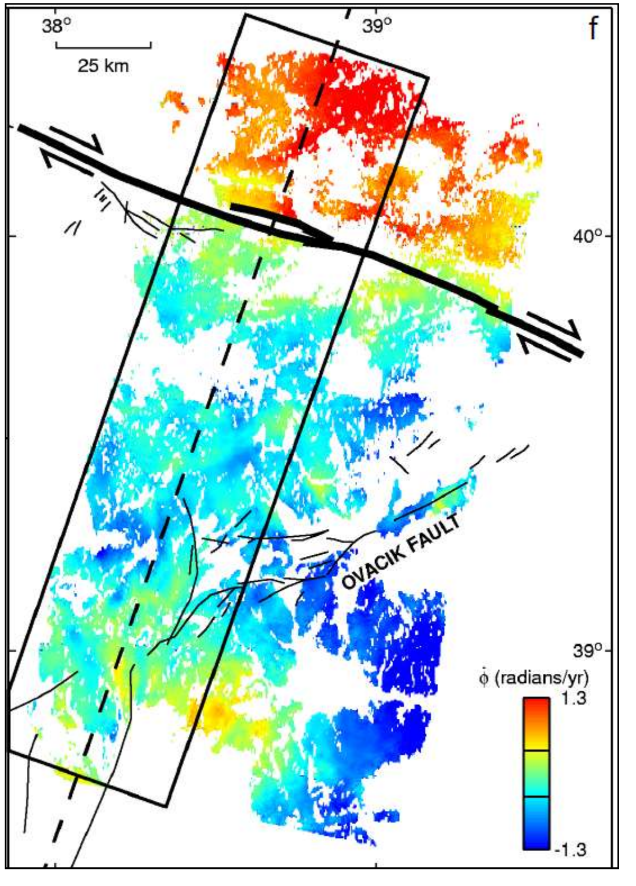


East California Shear Zone;
Peltzer et al., Geology 2001

North Anatolian Fault; Wright, Parsons and Fielding, GRL 2001

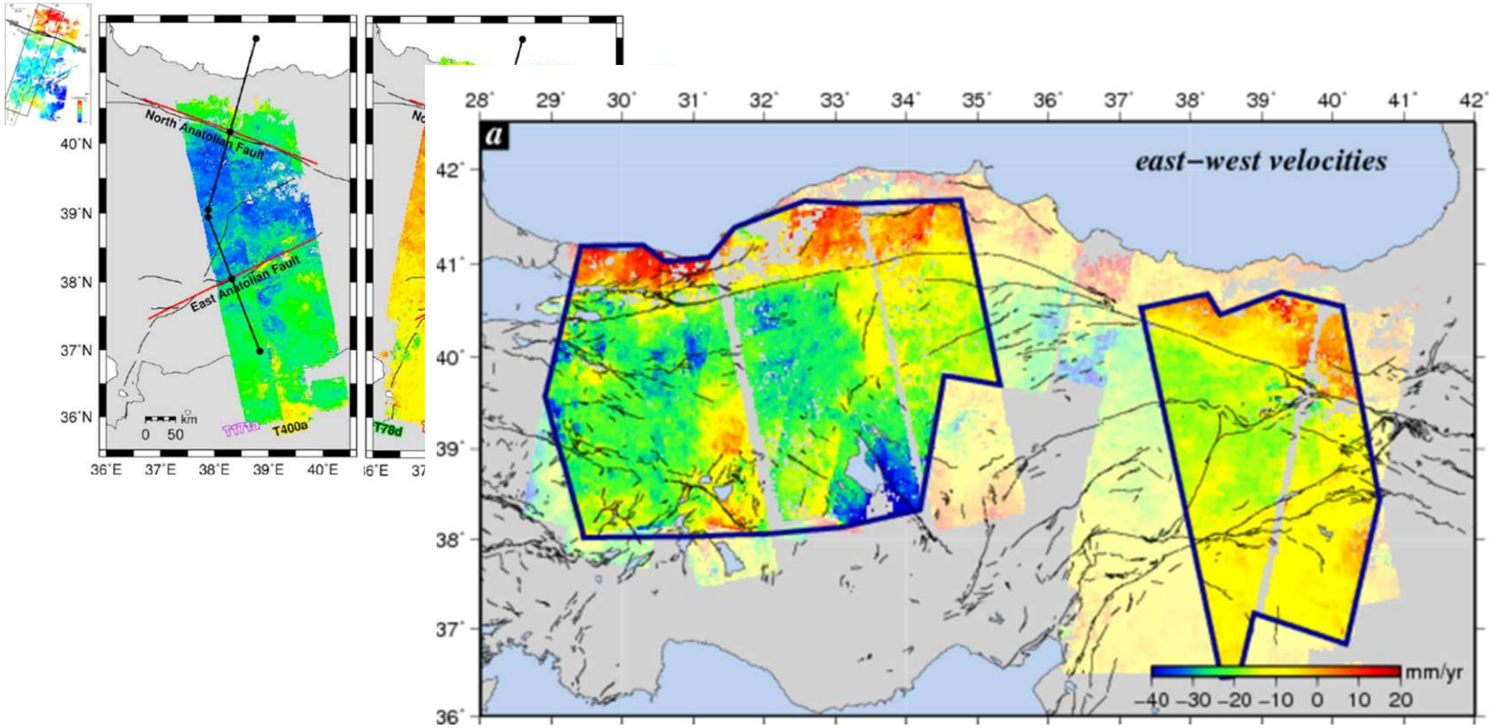
Progress…and the future

- 1 PhD 1997-2000 (Wright): 2 ERS Frames / 100 km of fault / ~20,000 km^2



Progress…and the future

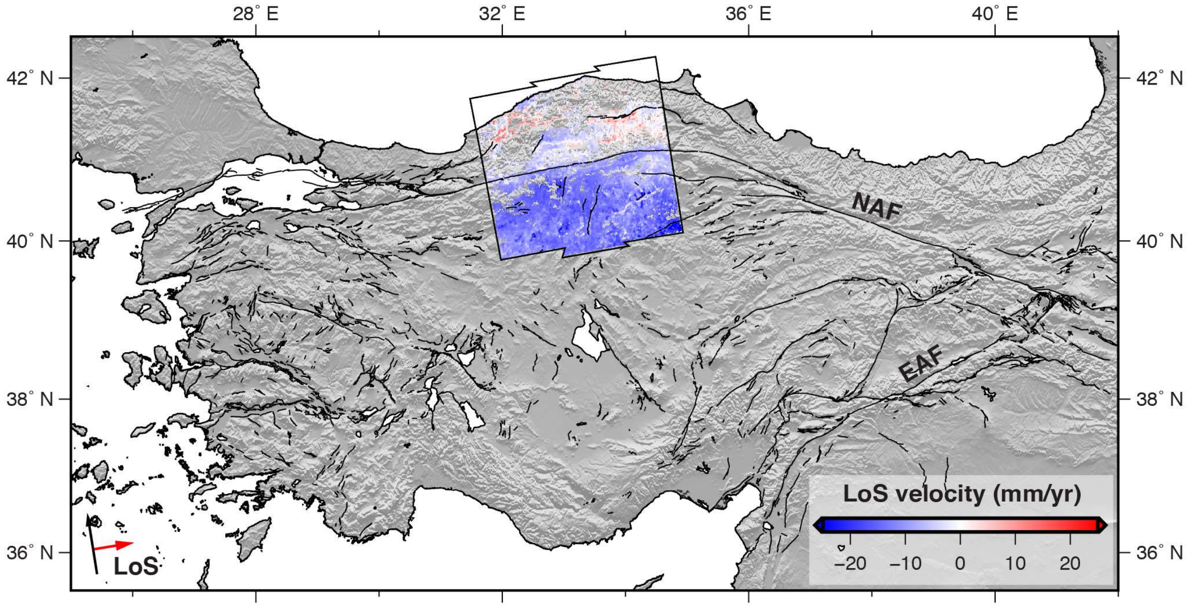
- 1 PhD 1997-2000 (Wright): 2 ERS Frames / 100 km of fault / ~20,000 km^2
- 1 PhD 2009-2012 (Walters): 5 Envisat Tracks / 200 km of fault / ~250,000 km^2
- 1 PhD 2012-2016 (Hussain): 23 Envisat Tracks / entire fault / ~750,000 km^2



Hussain et al., 2018

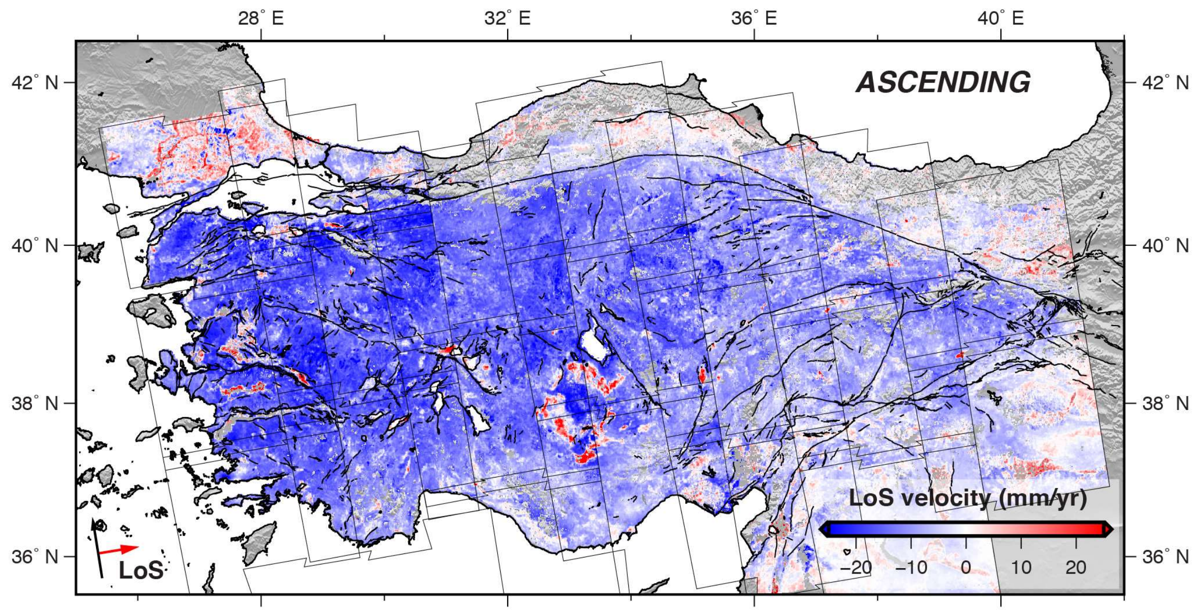
Velocity Field for Turkey from Sentinel-1

(Weiss et al., in prep)



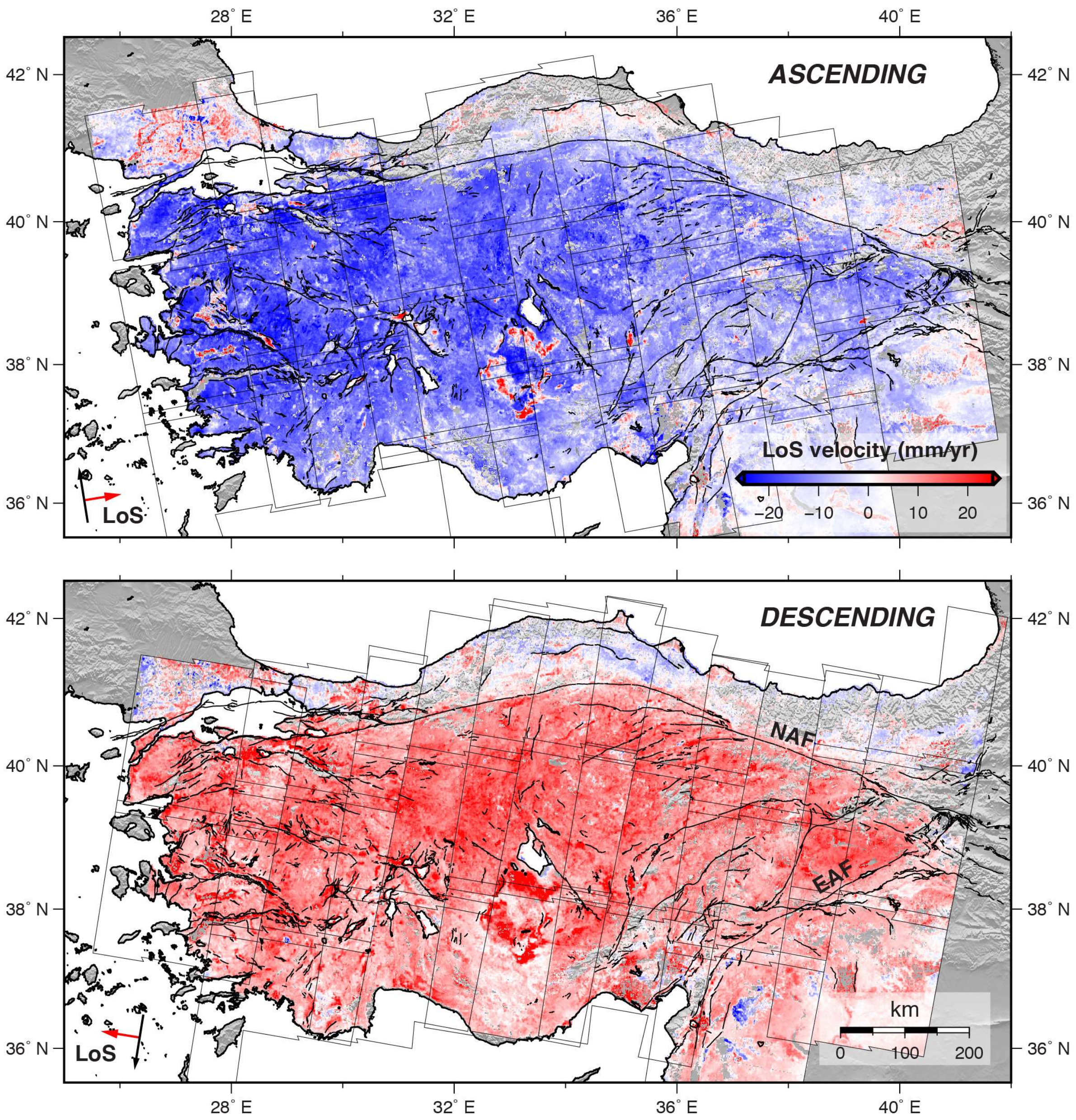
Velocity Field for Turkey from Sentinel-1

(Weiss et al., in prep)



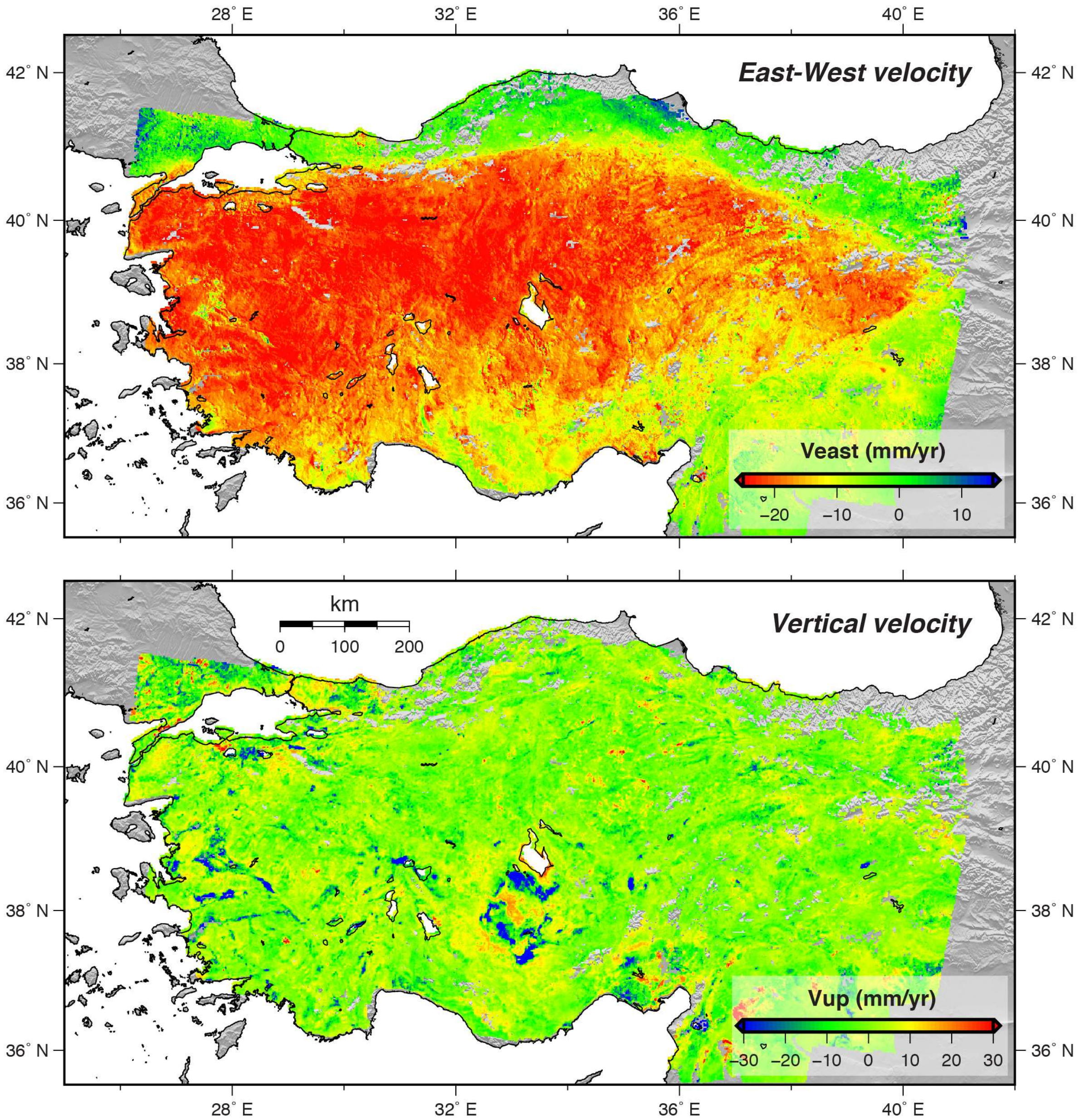
Velocity Field for Turkey from Sentinel-1

(Weiss et al., in prep)

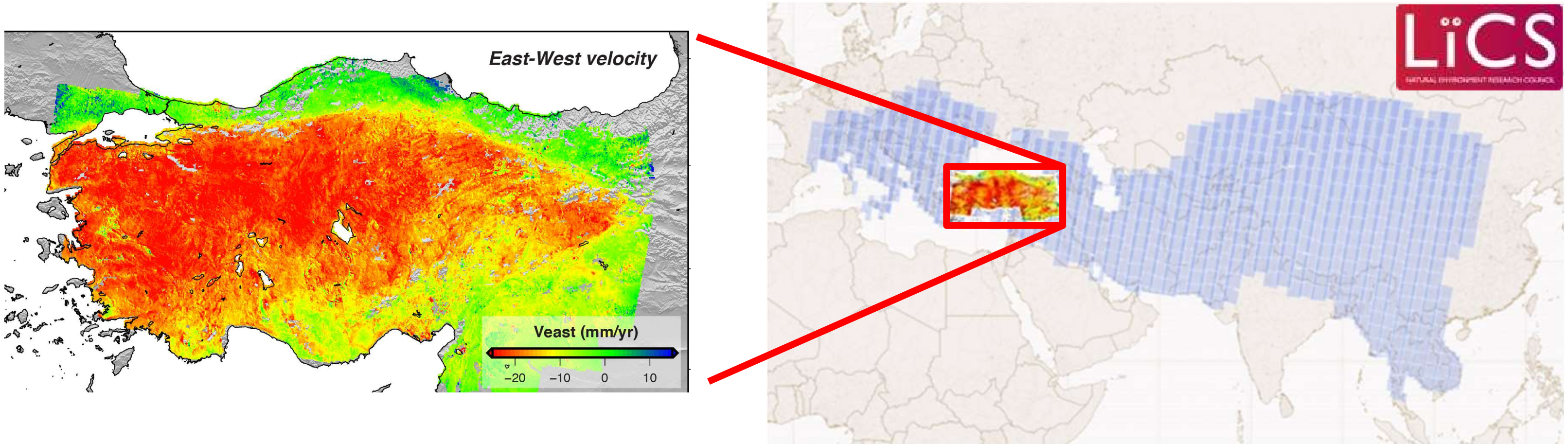


Velocity Field for Turkey from Sentinel-1

(Weiss et al., in prep)



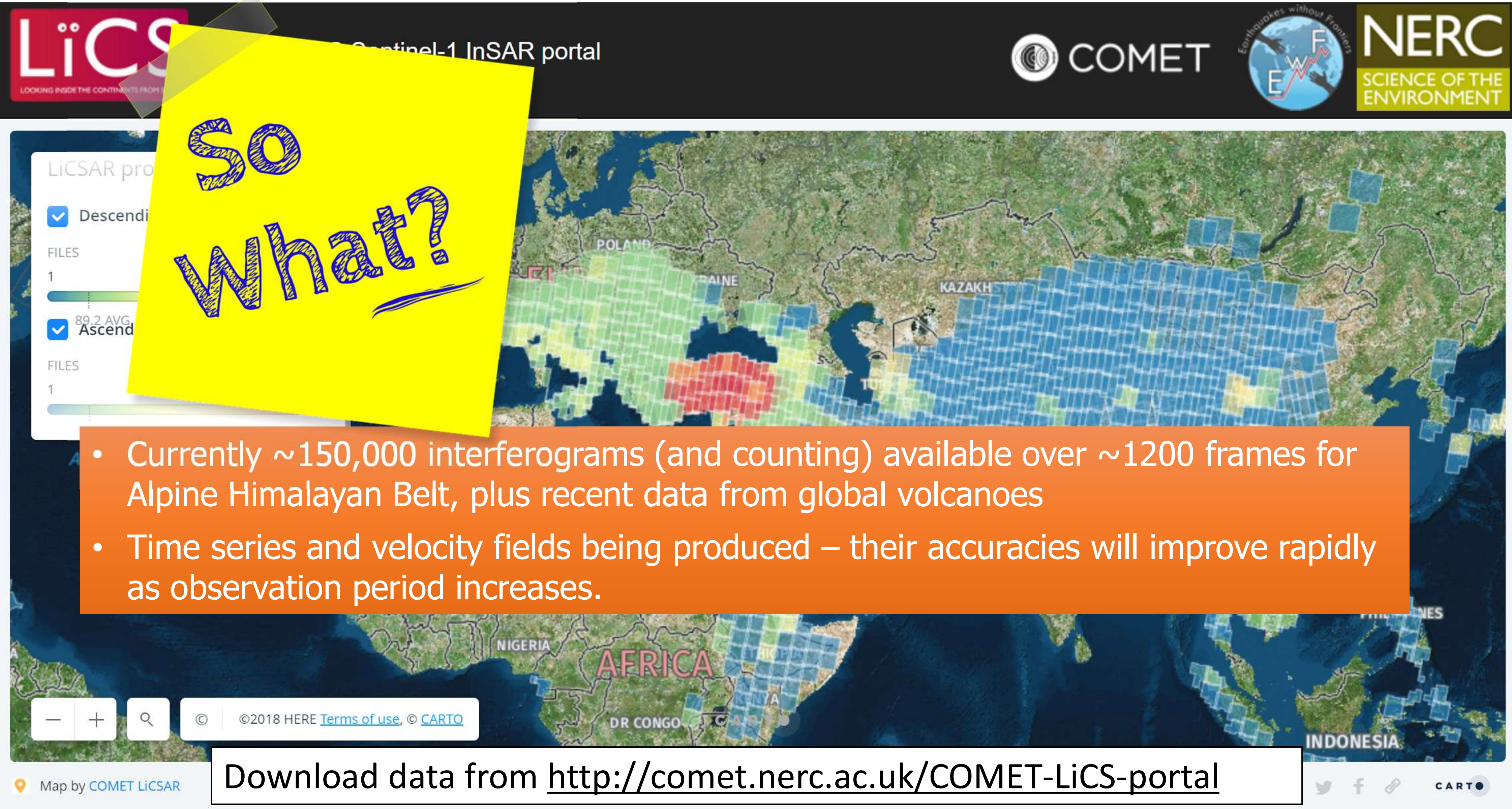
Progress…



- ➢ *4 years of COMET-**LiCS** Sentinel-1 processing **for Anatolia***
  ~500 ifgs/frame x 40 frames = ~20,000 interferograms

- ➢ *~1200 frames for the AHB = ~450,000* interferograms to process*

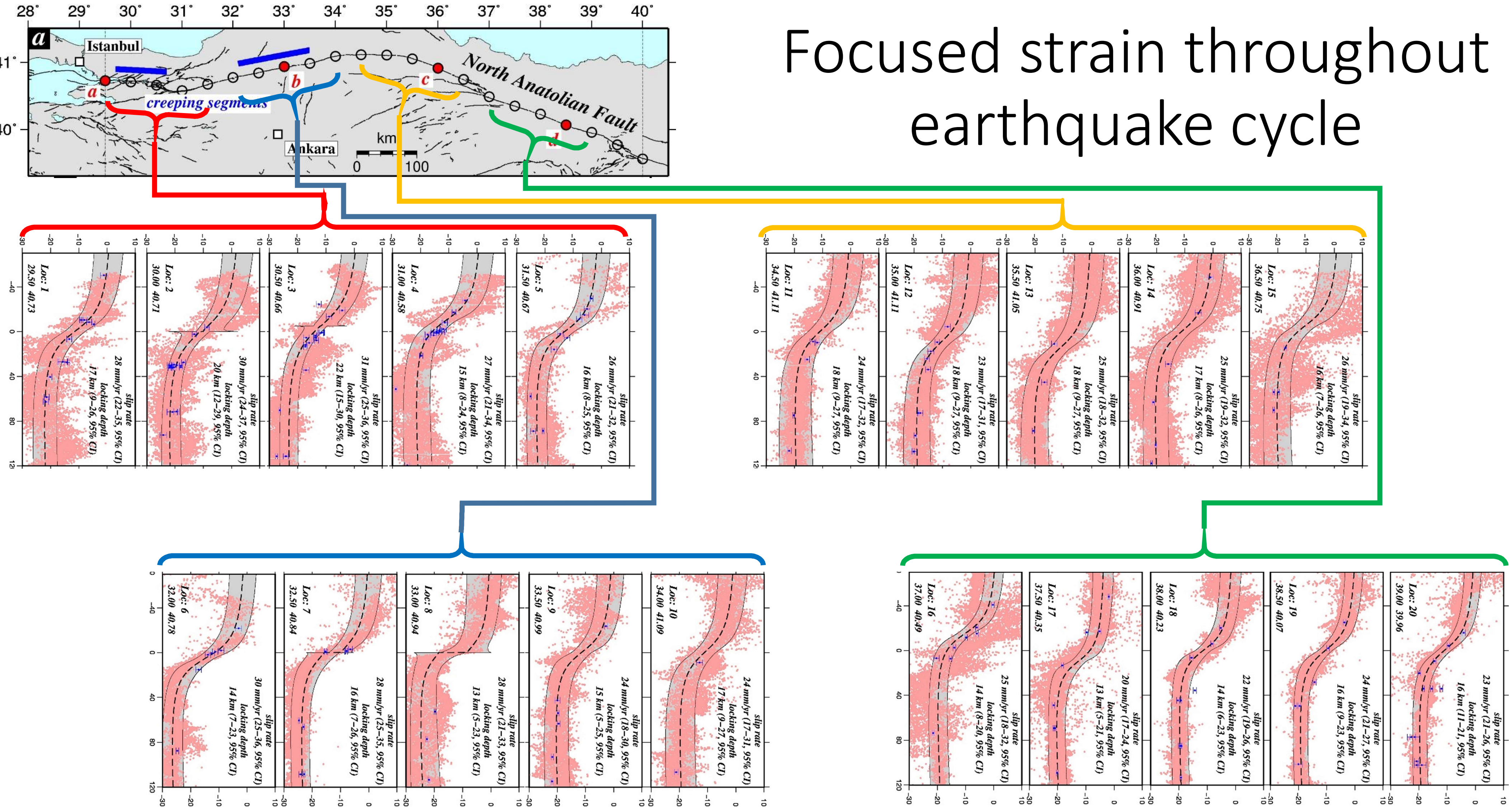
**east of Turkey only 12-day revisit*



- Currently ~150,000 interferograms (and counting) available over ~1200 frames for Alpine Himalayan Belt, plus recent data from global volcanoes
- Time series and velocity fields being produced – their accuracies will improve rapidly as observation period increases.

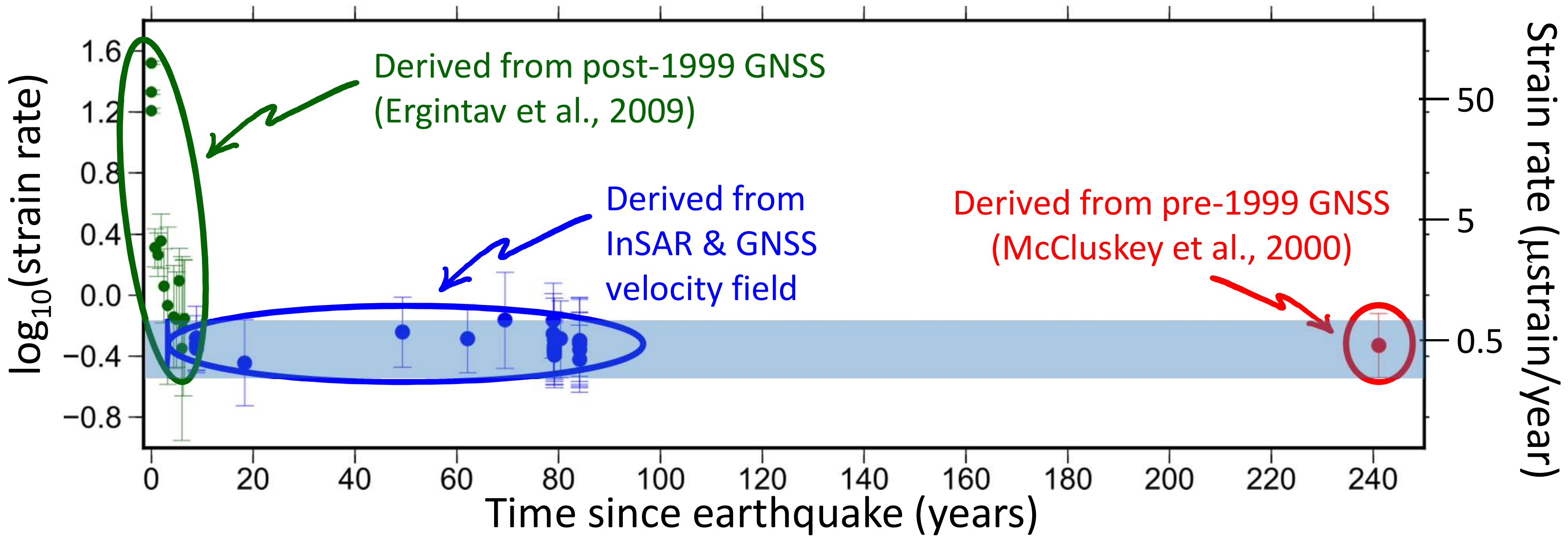
Download data from http://comet.nerc.ac.uk/COMET-LiCS-portal

Focused strain throughout earthquake cycle



Hussain et al., Nat. Comm. 2018

Focused strain throughout earthquake cycle



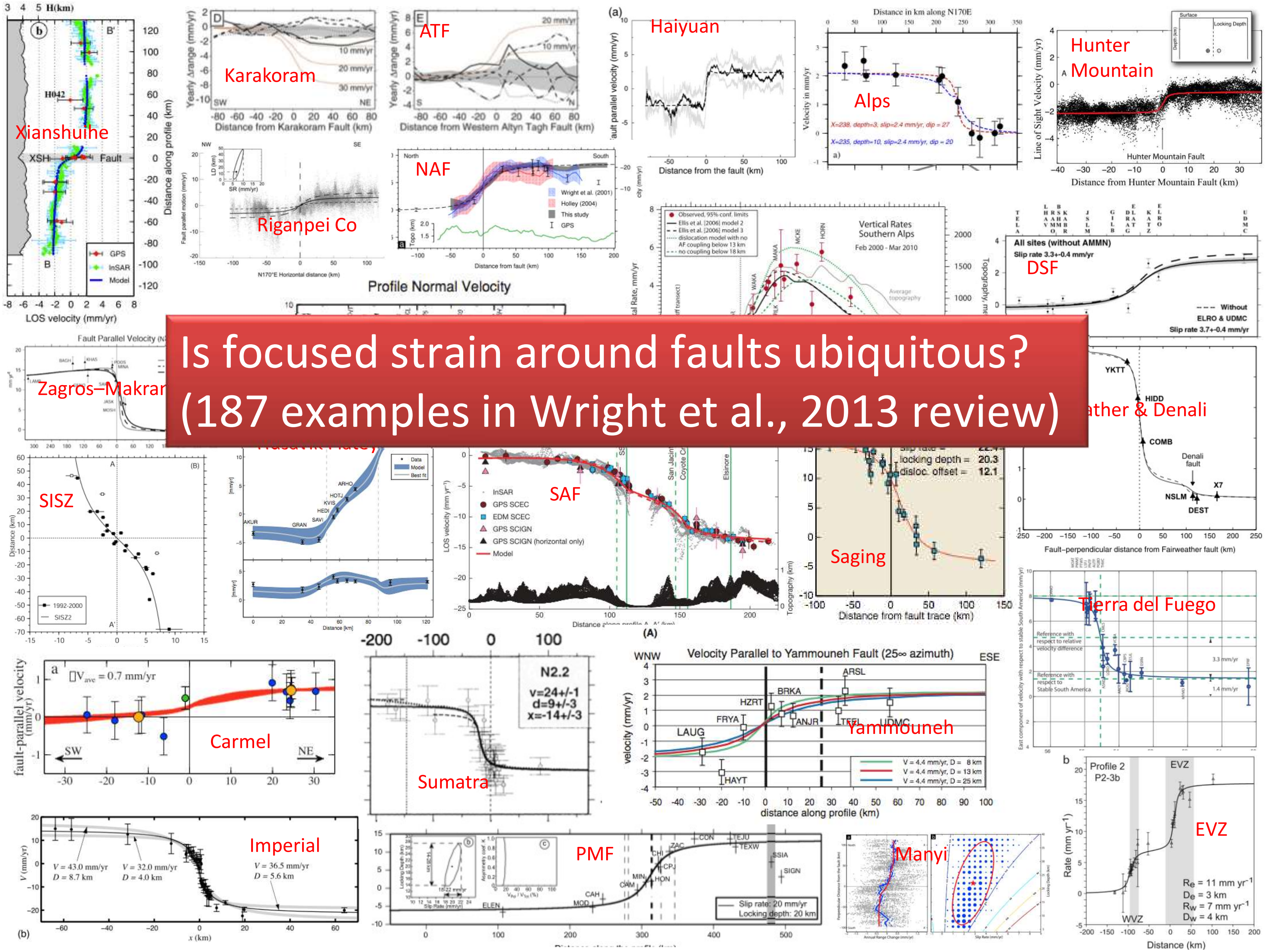
Result: Strain rate along the entire North Anatolian Fault is independent of time since the last earthquake, except in decade following a major earthquake.

Implications: (1) Short term strain → long-term hazard

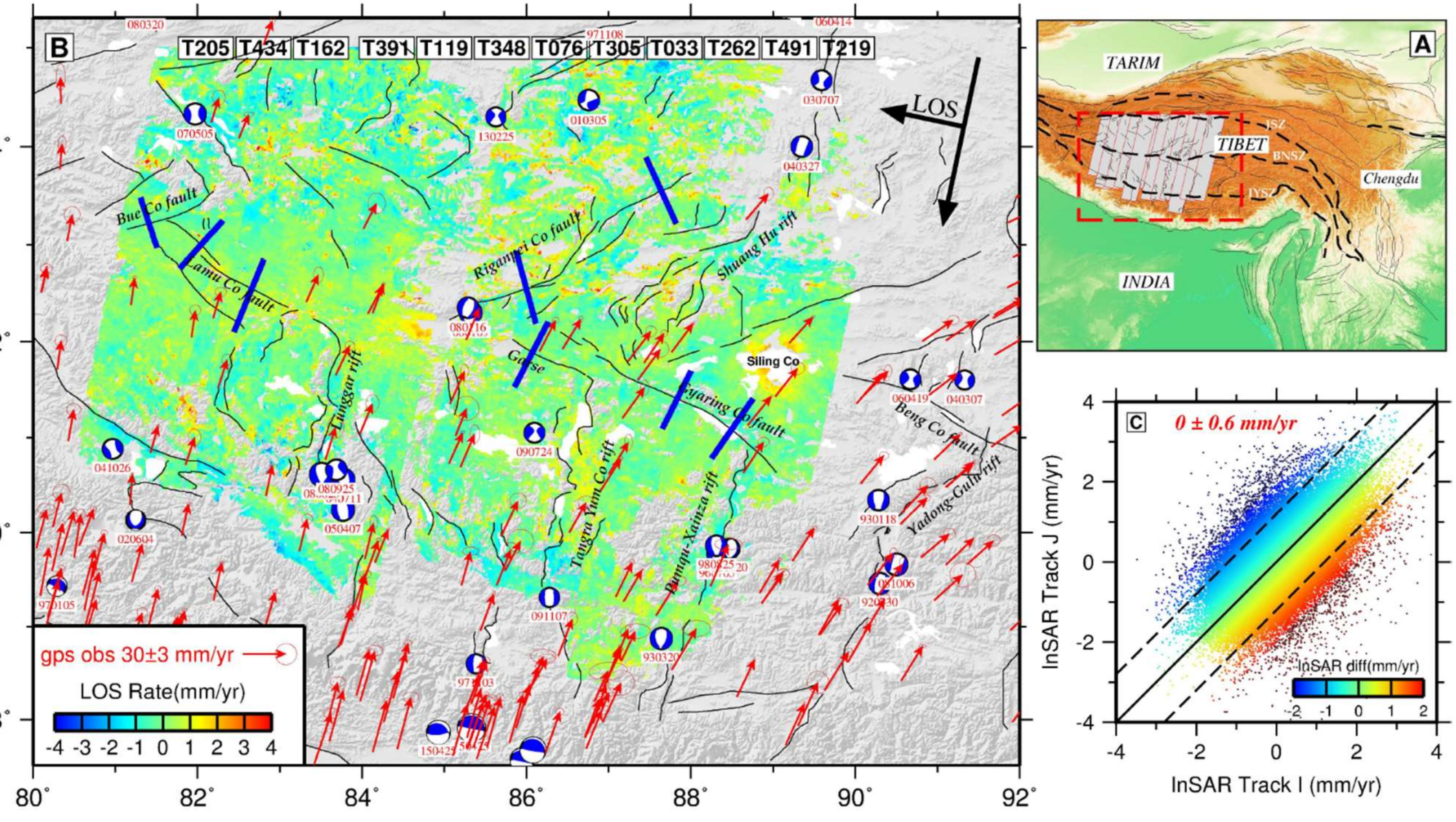
(2) Relaxation time of lower crust > inter-event time (viscosities > 10^{20} Pa s).

Hussain et al., Nat. Comm. 2018

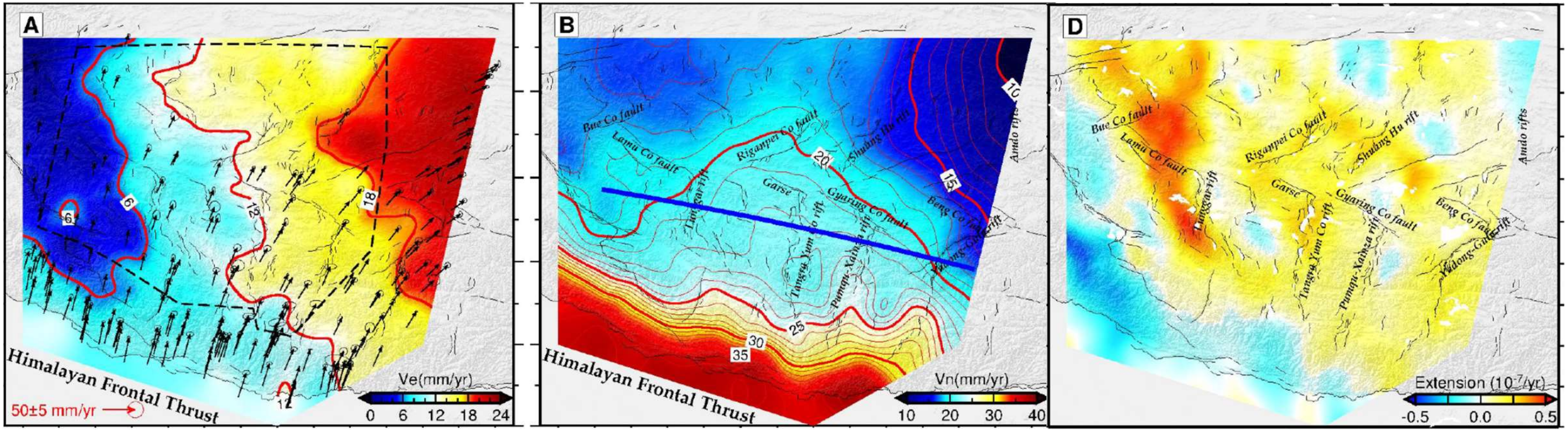
Is focused strain around faults ubiquitous?
(187 examples in Wright et al., 2013 review)



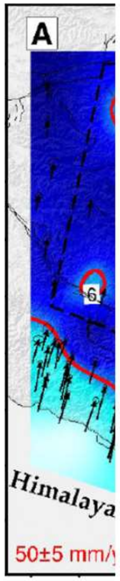
Extension in South Central Tibet (Wang et al., 2019)

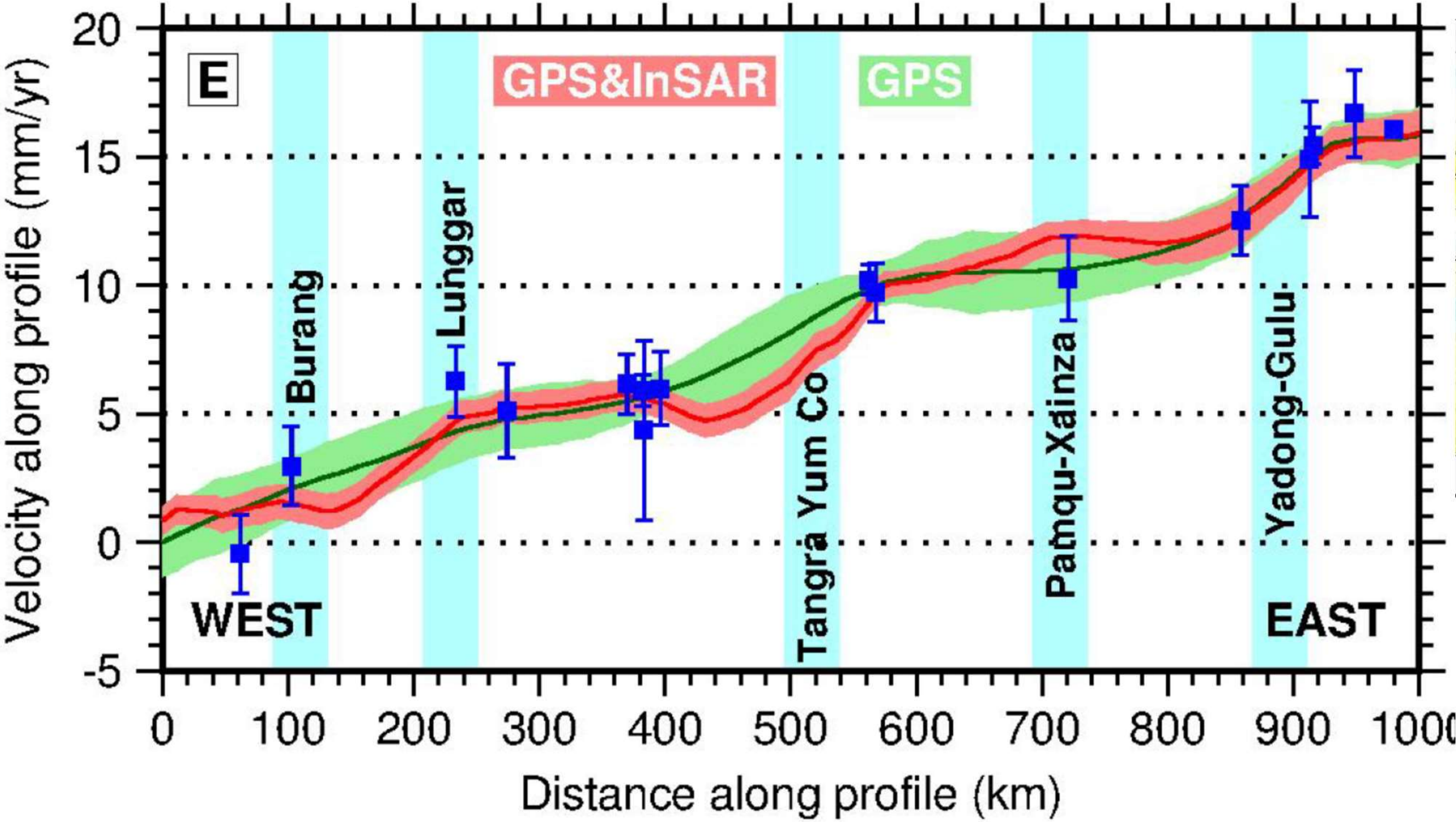


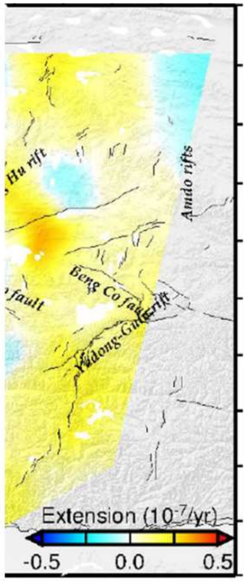
Extension in South Central Tibet (Wang et al., 2019)



Extension in South Central Tibet (Wang et al., 2019)



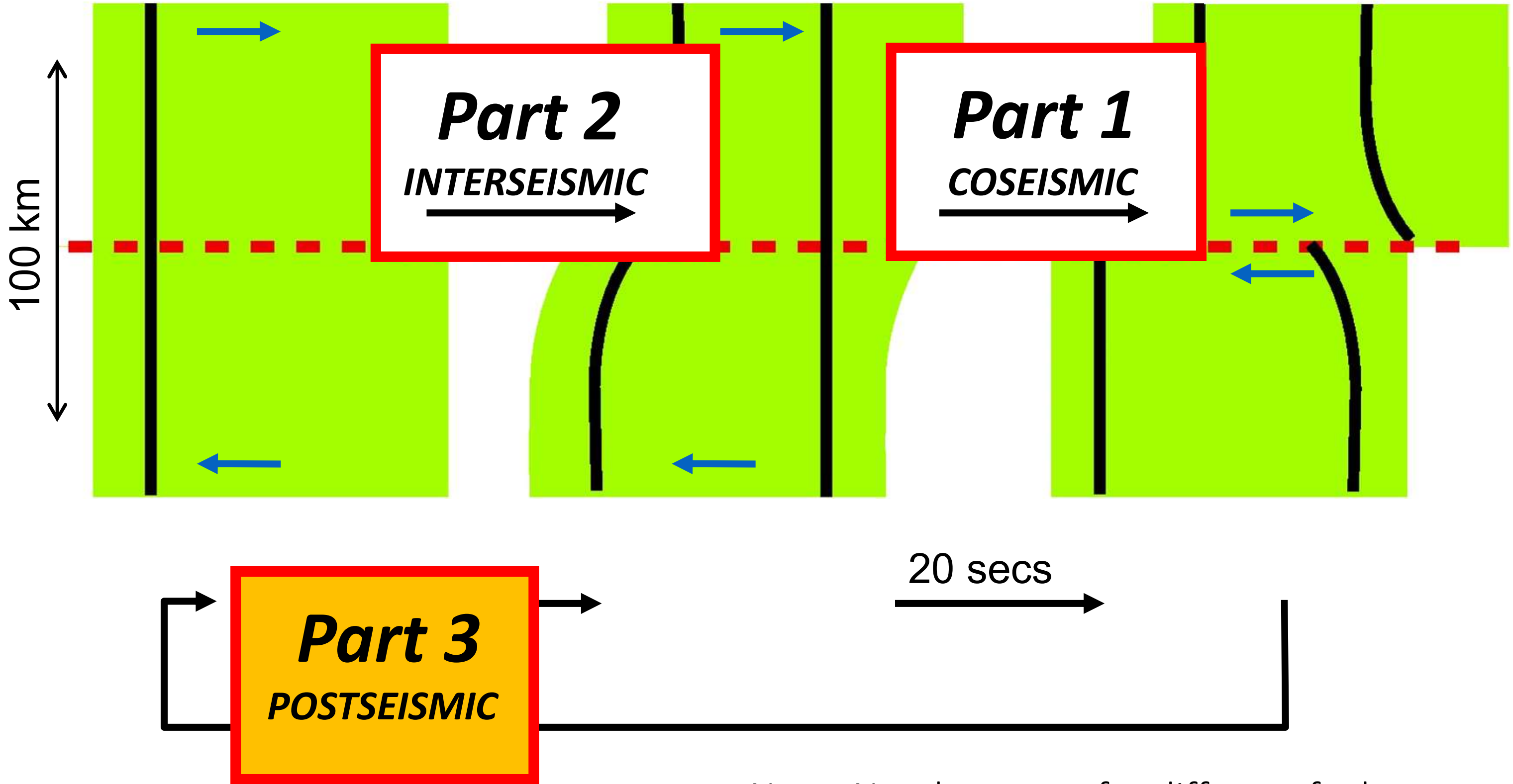




Part 2: Seismic Hazard and Interseismic Strain Accumulation (Key Points)

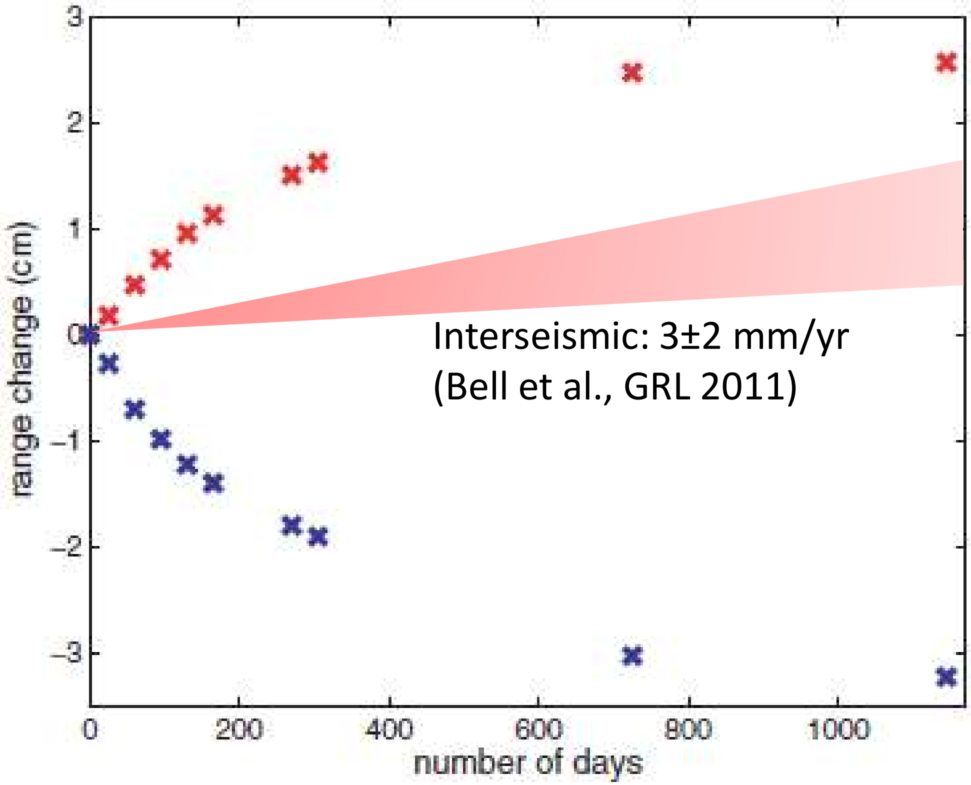
- Measuring Interseismic strain accumulation is challenging with InSAR, but can be done with large data stacks
- Interseismic strain is usually focussed around major faults.
- Strain rate is approx. constant throughout the cycle on the North Anatolian Fault. May not be true elsewhere?
- Uncertainties in strain estimates will reduce as data improves – this will lead to improved seismic hazard models.

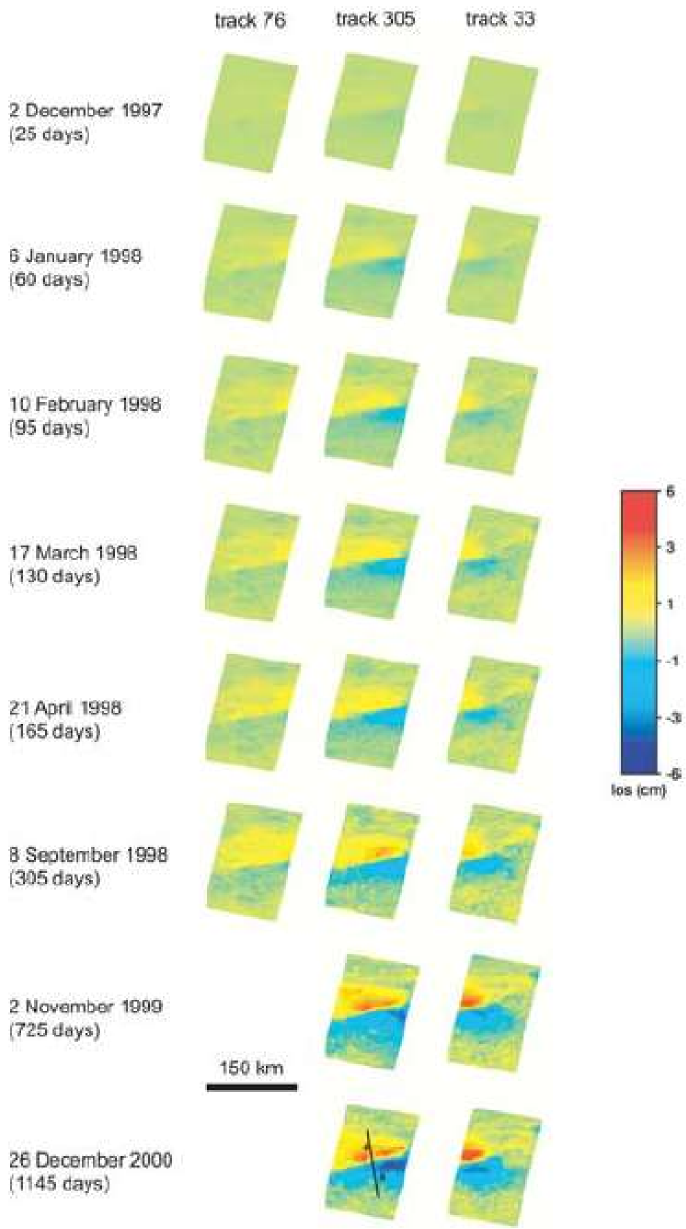
The Earthquake Cycle



Note: Numbers vary for different faults

Part 3: Postseismic deformation and aseismic slip transients





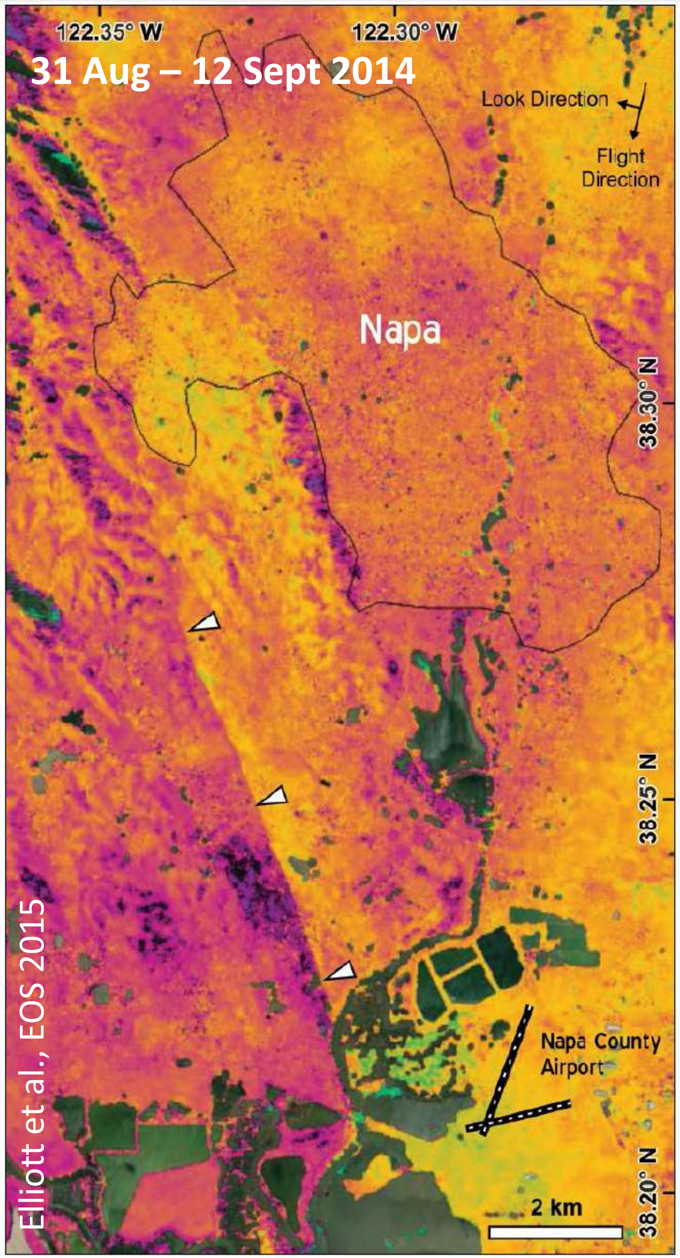
Manyi (Tibet) postseismic from Ryder et al, GJI 2007

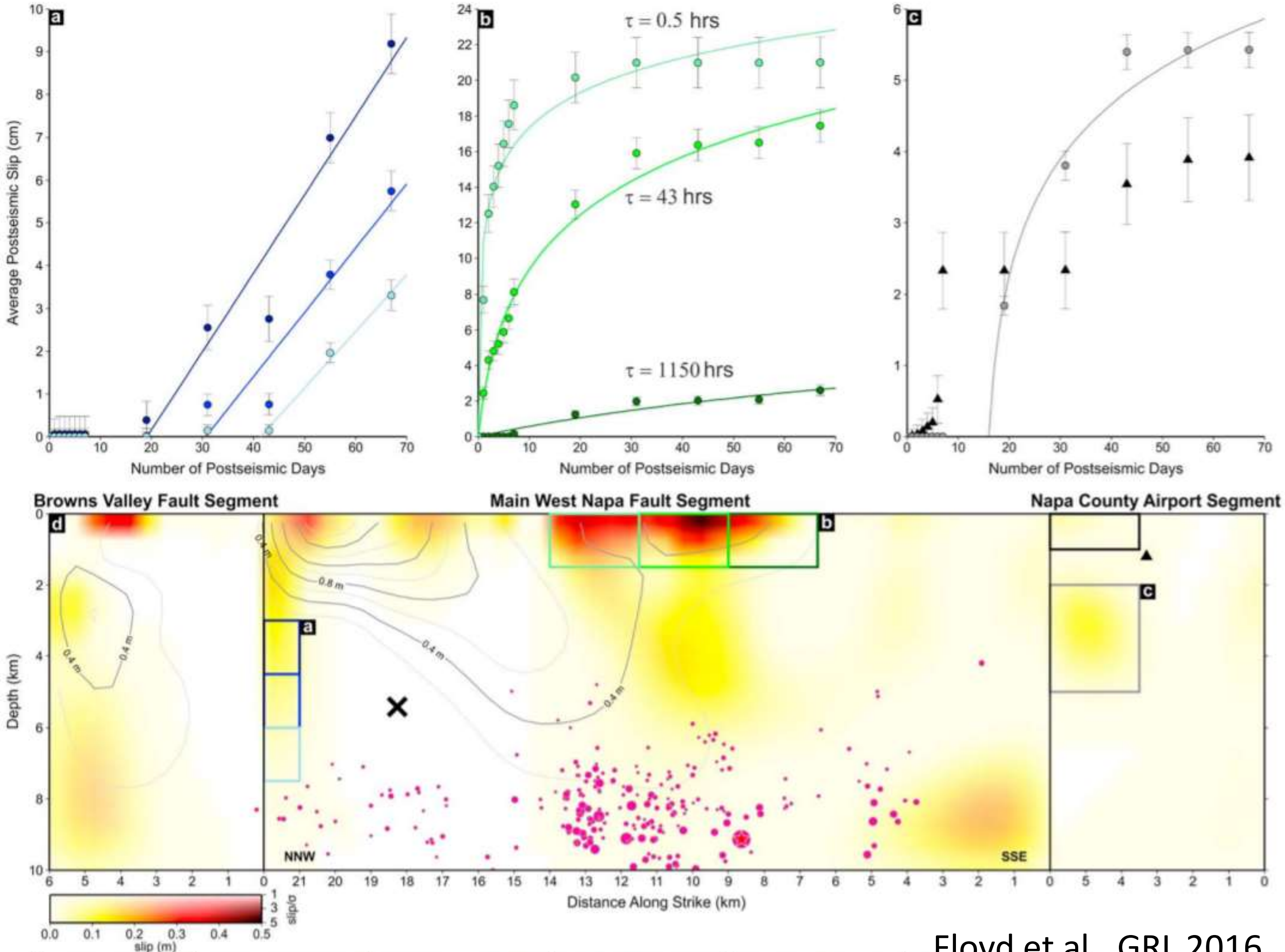
2014 Napa earthquake: August to December afterslip

From: Stephane Baize blog

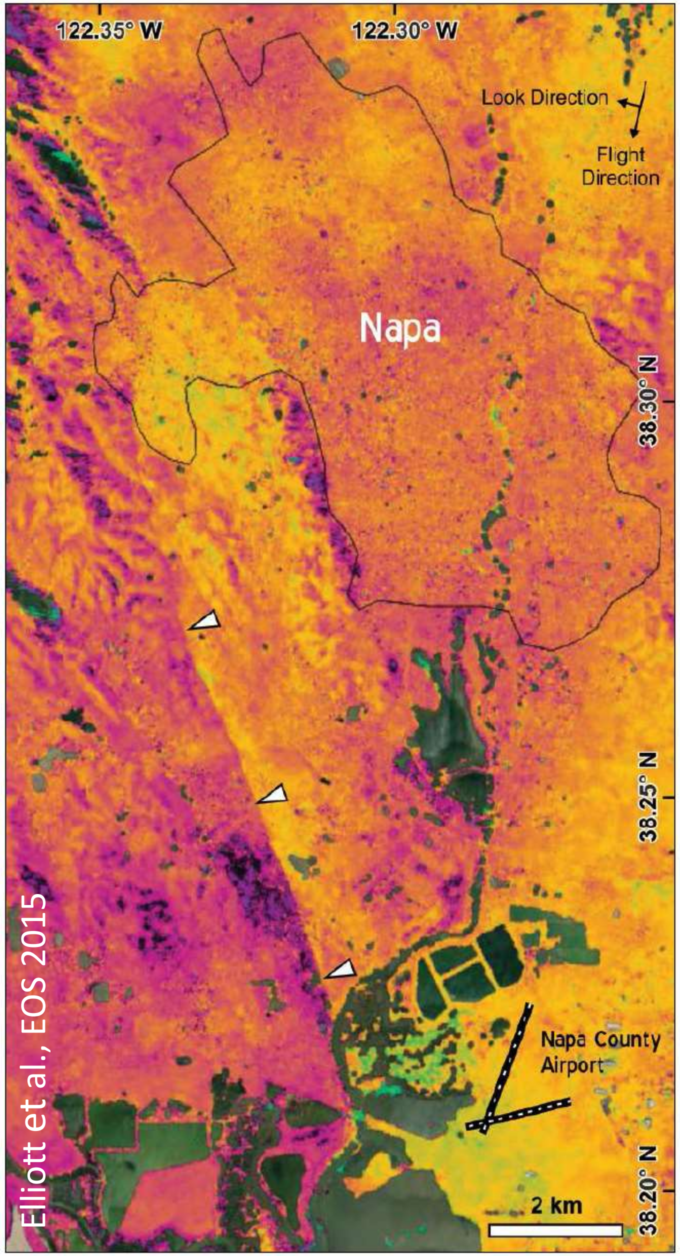
Leaning Oak Road - Napa

http://stephaneonblogger.blogspot.co.uk/2015/11/those-faults-that-move-without-quaking.html



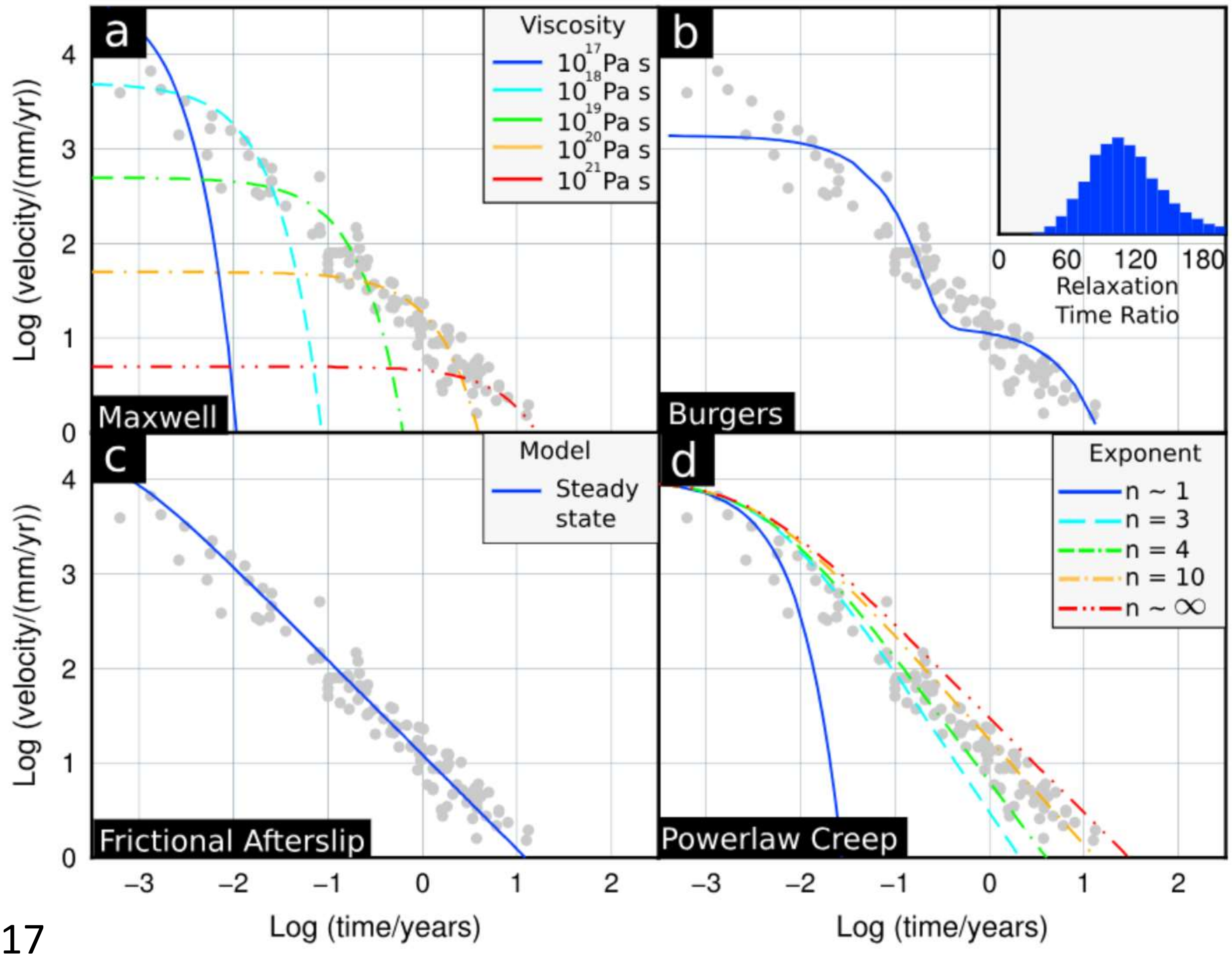


Floyd et al., GRL 2016



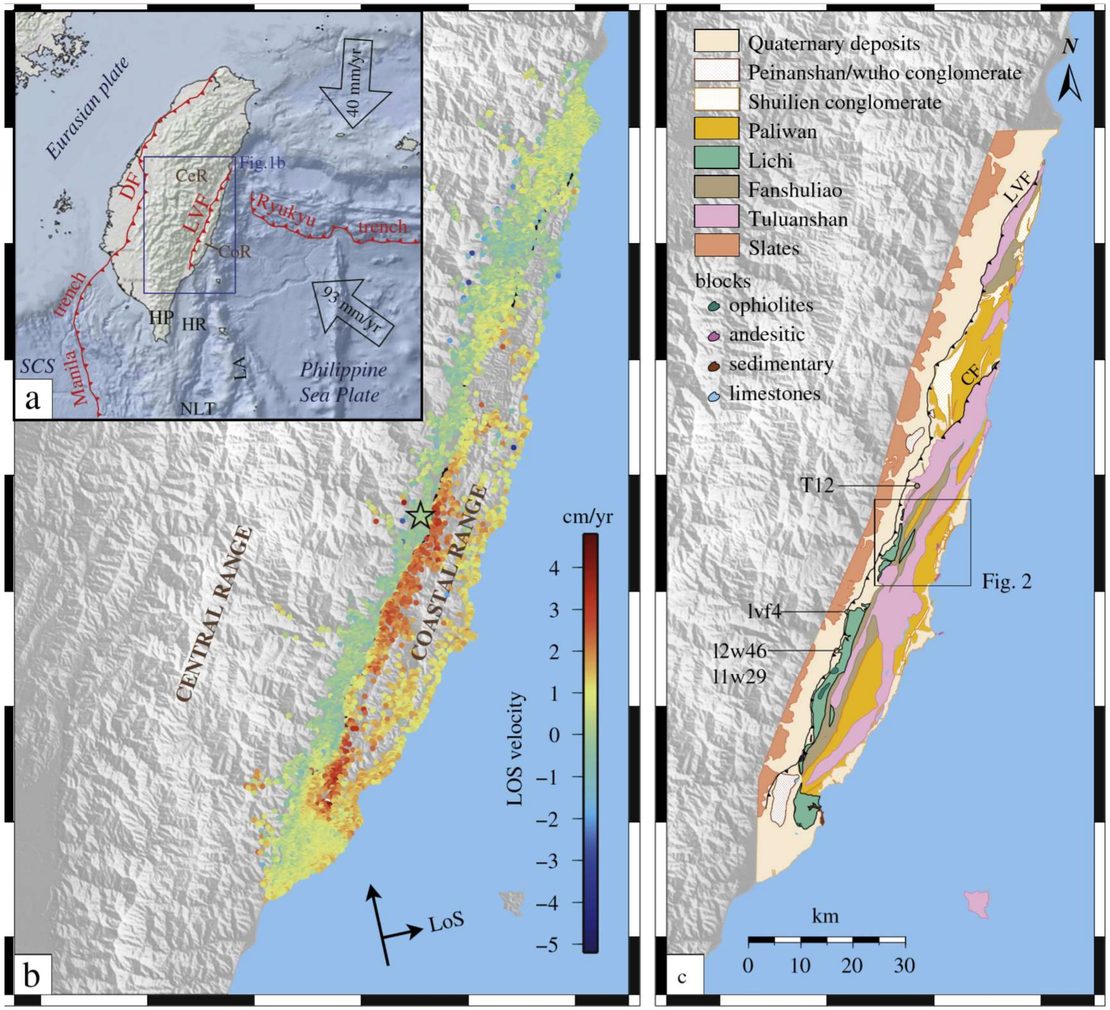
Elliott et al., EOS 2015

Maximum postseismic velocities follow power law ($v \propto t^{-1}$)

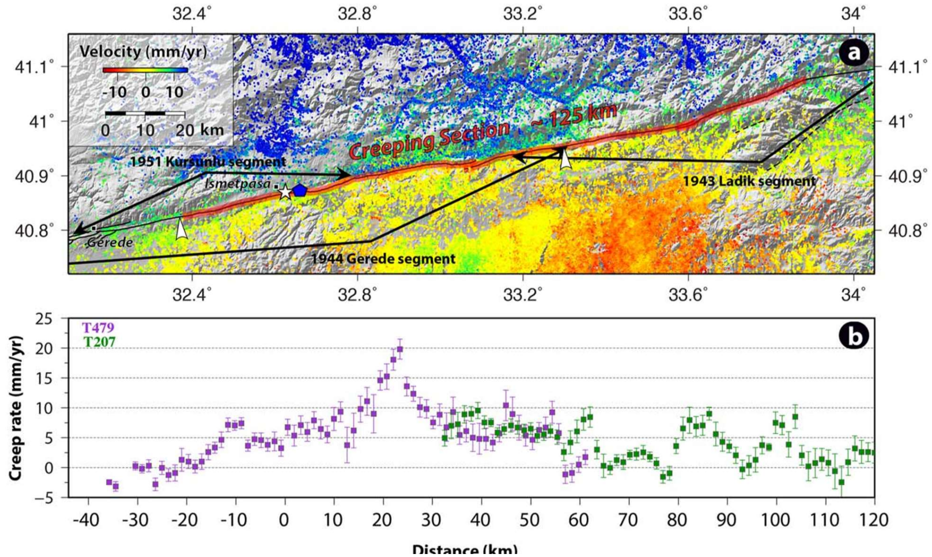


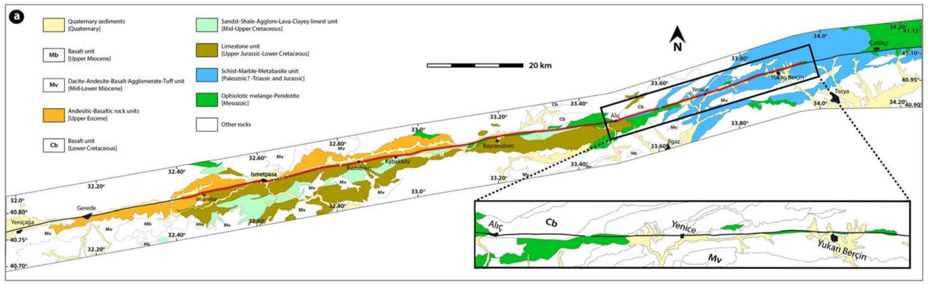
Ingleby and Wright, GRL 2017

Aseismic Creep controlled by lithology



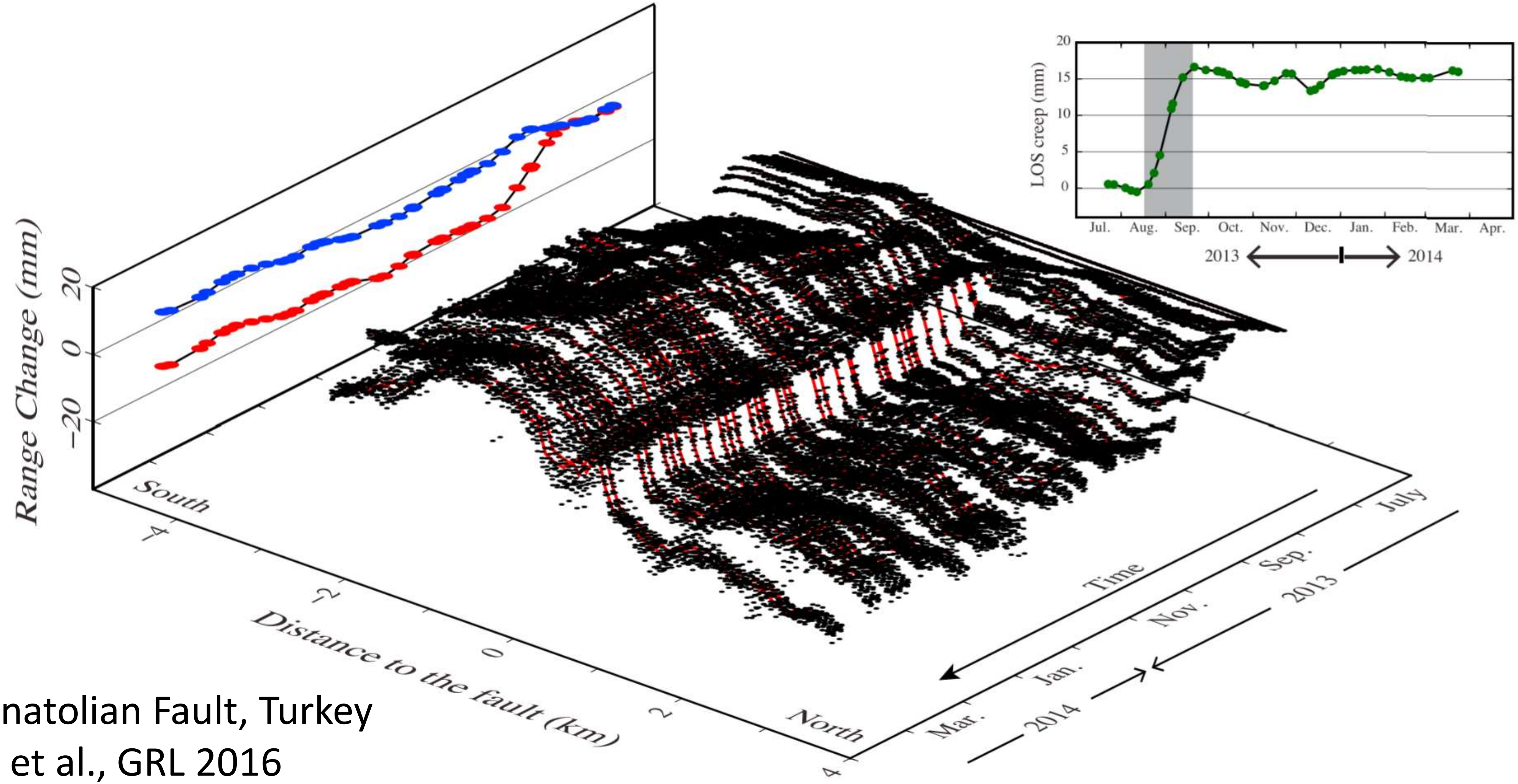
Taiwan; Thomas et al., Tectonophysics 2014





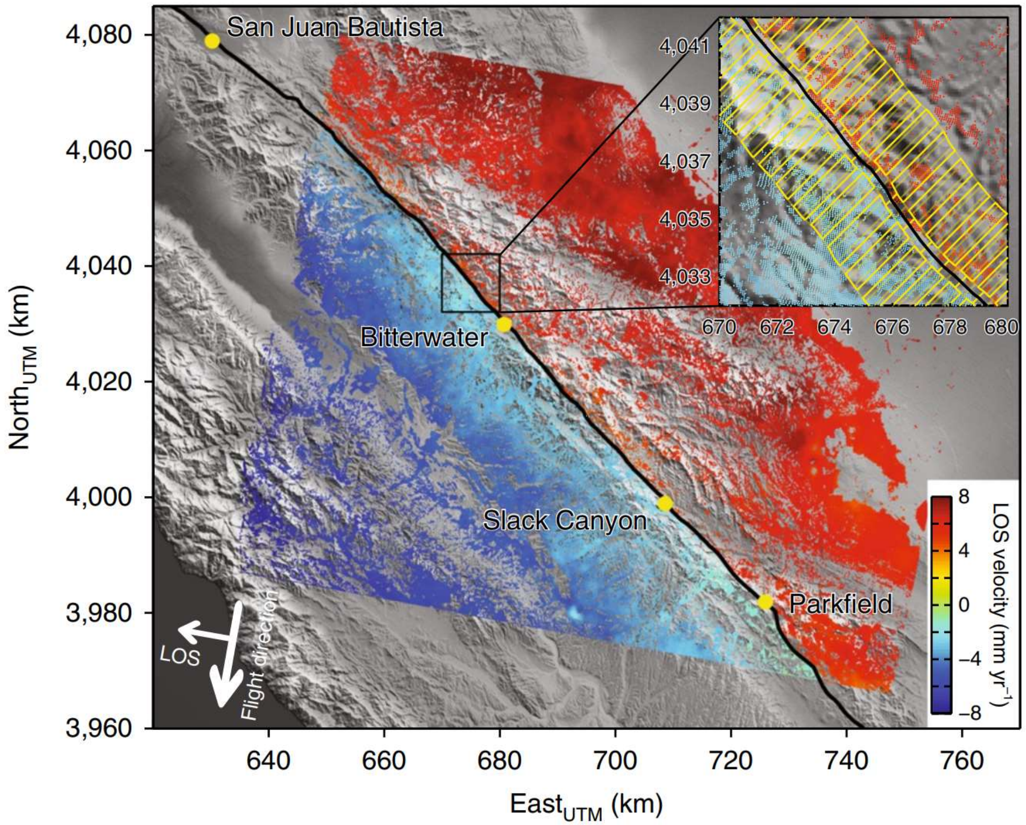
Turkey; Cetin et al., G-cubed 2014

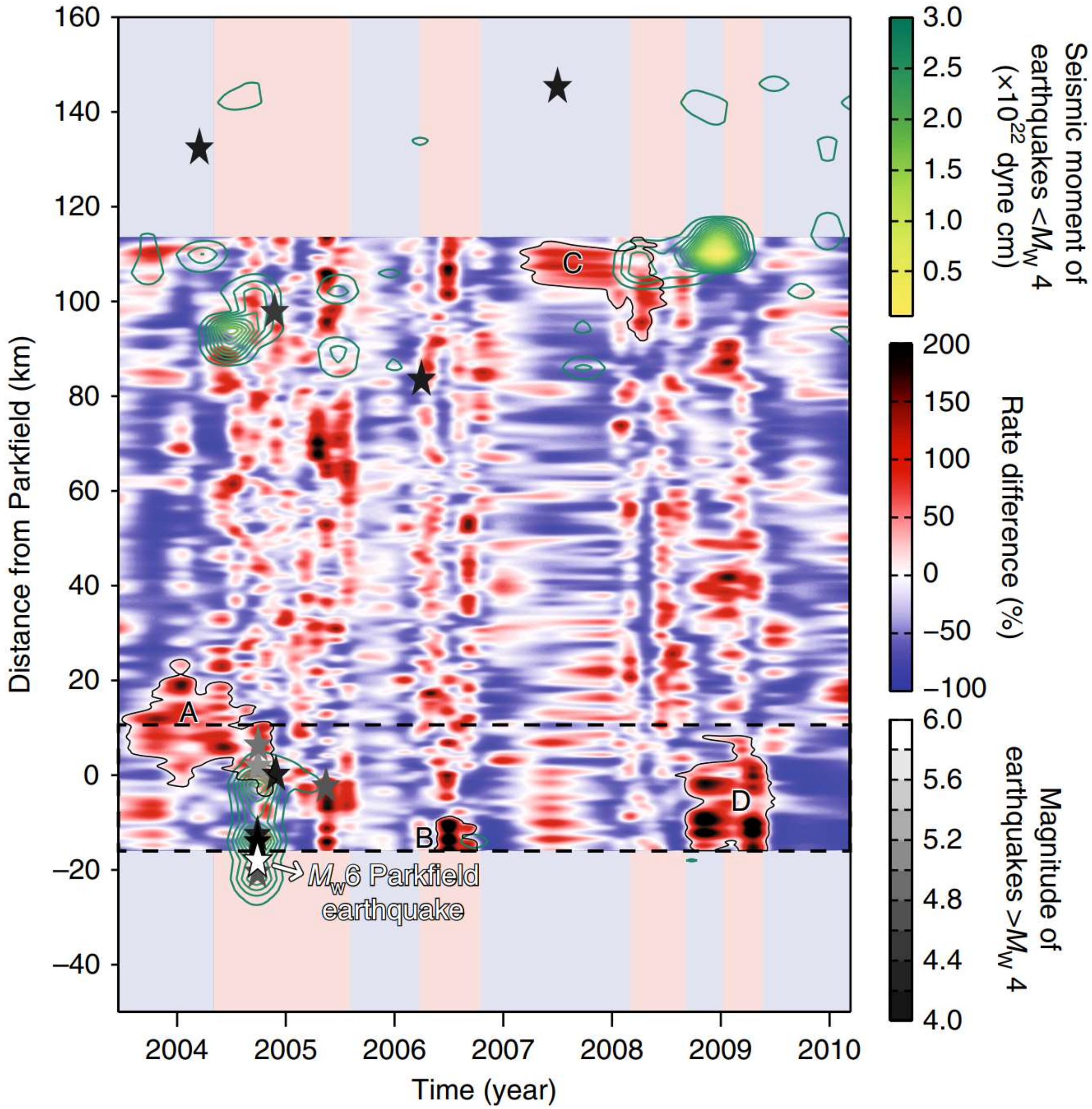
Aseismic Creep Events



North Anatolian Fault, Turkey
Rousset et al., GRL 2016

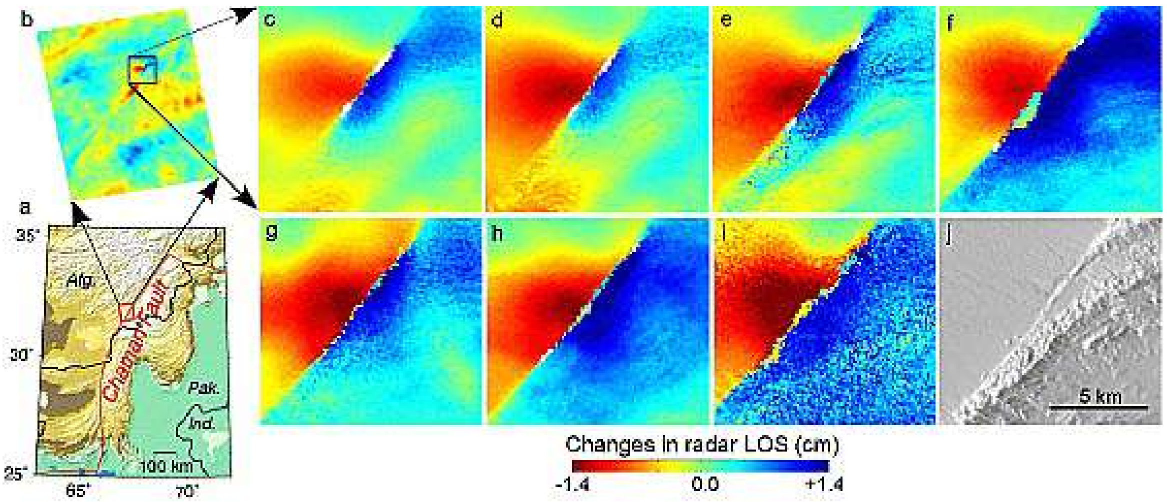
Aseismic Creep Events

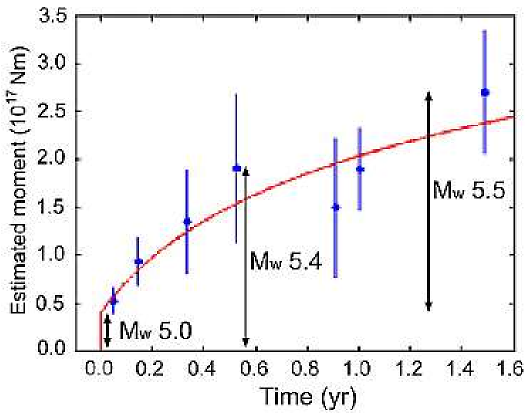




Khoshmanesh and Shirzaei et al., Nat. Geosci., 2018

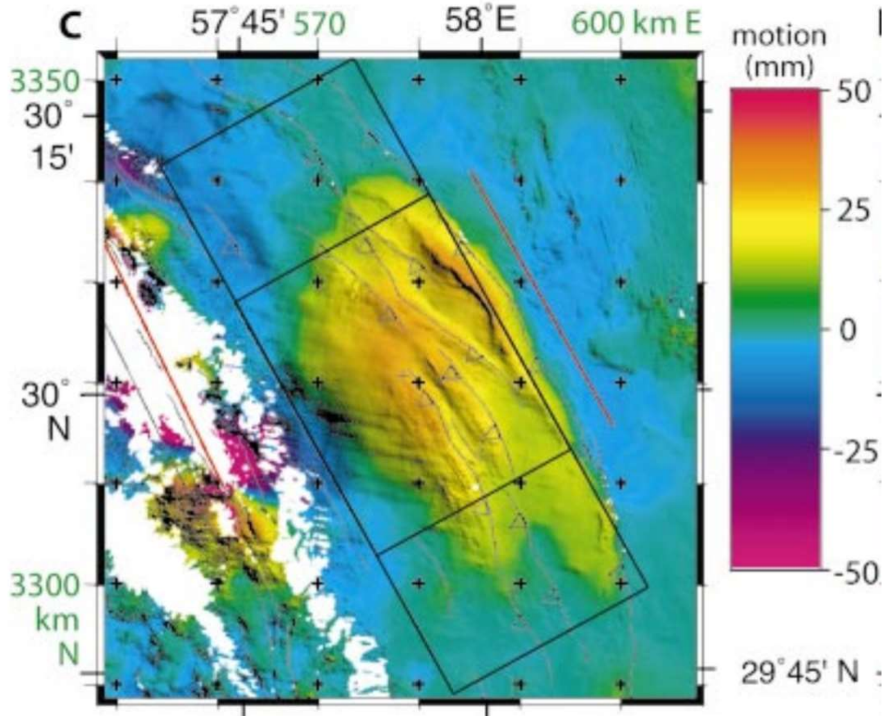
Aseismic Creep Events





Slow earthquake in Chaman Fault Zone (Pakistan); Furuya and Satyabala, 2008

Aseismic movement on fold and thrust belt during 1998 Fandoqa earthquake

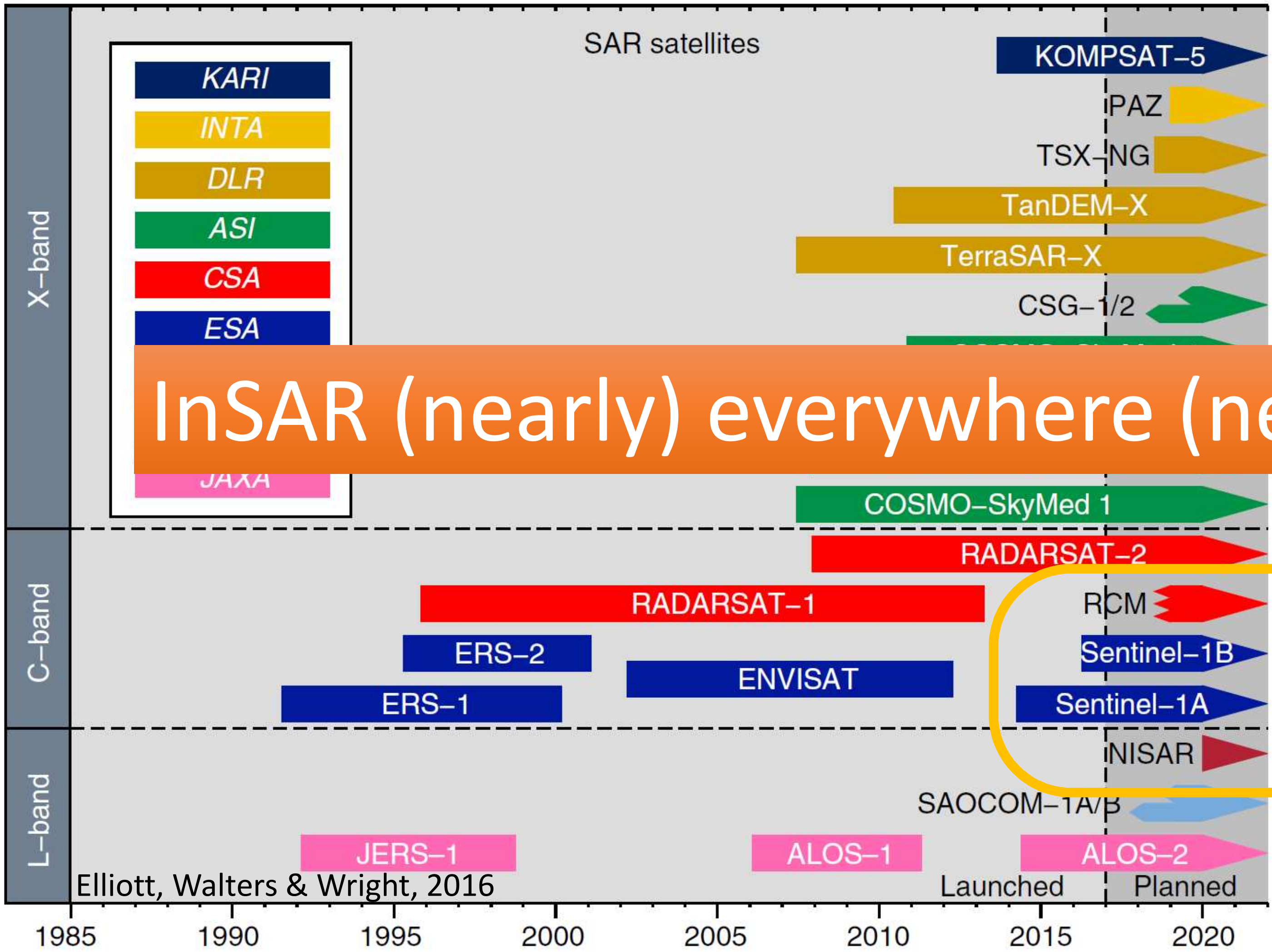


Fielding et al., Geology 2004

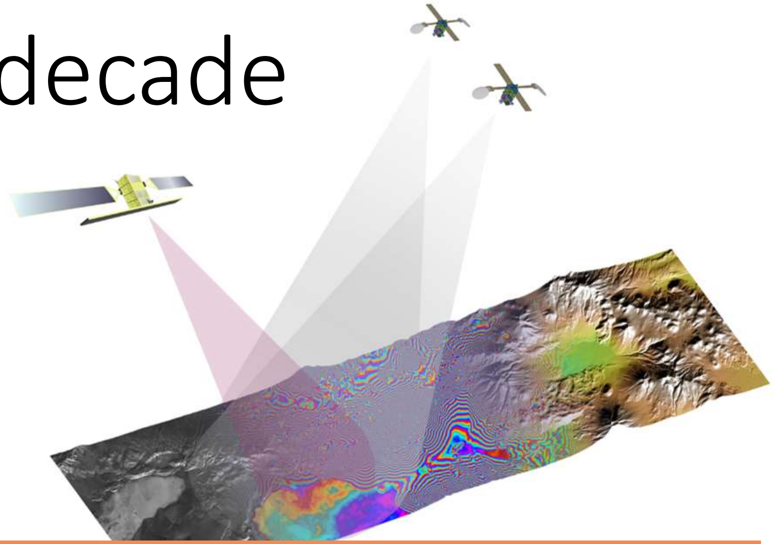
Part 3: Postseismic deformation and aseismic slip transients (key points)

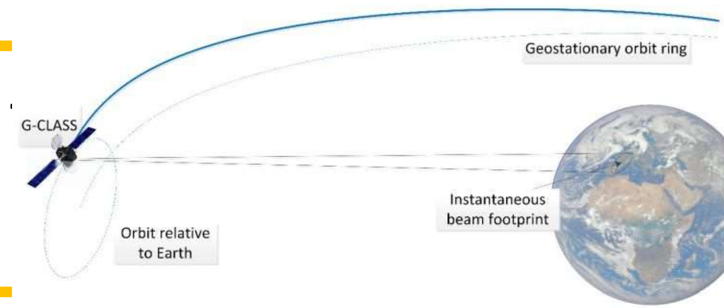
- Details of postseismic transient behaviour can be spatially complex
- But overall, postseismic deformation may be remarkably simple: $v \propto t^{-1}$
- InSAR has helped identify a range of aseismic creep behaviour including time-varying shallow creep, slow earthquakes and triggered slip.

Radar remote sensing in the next decade



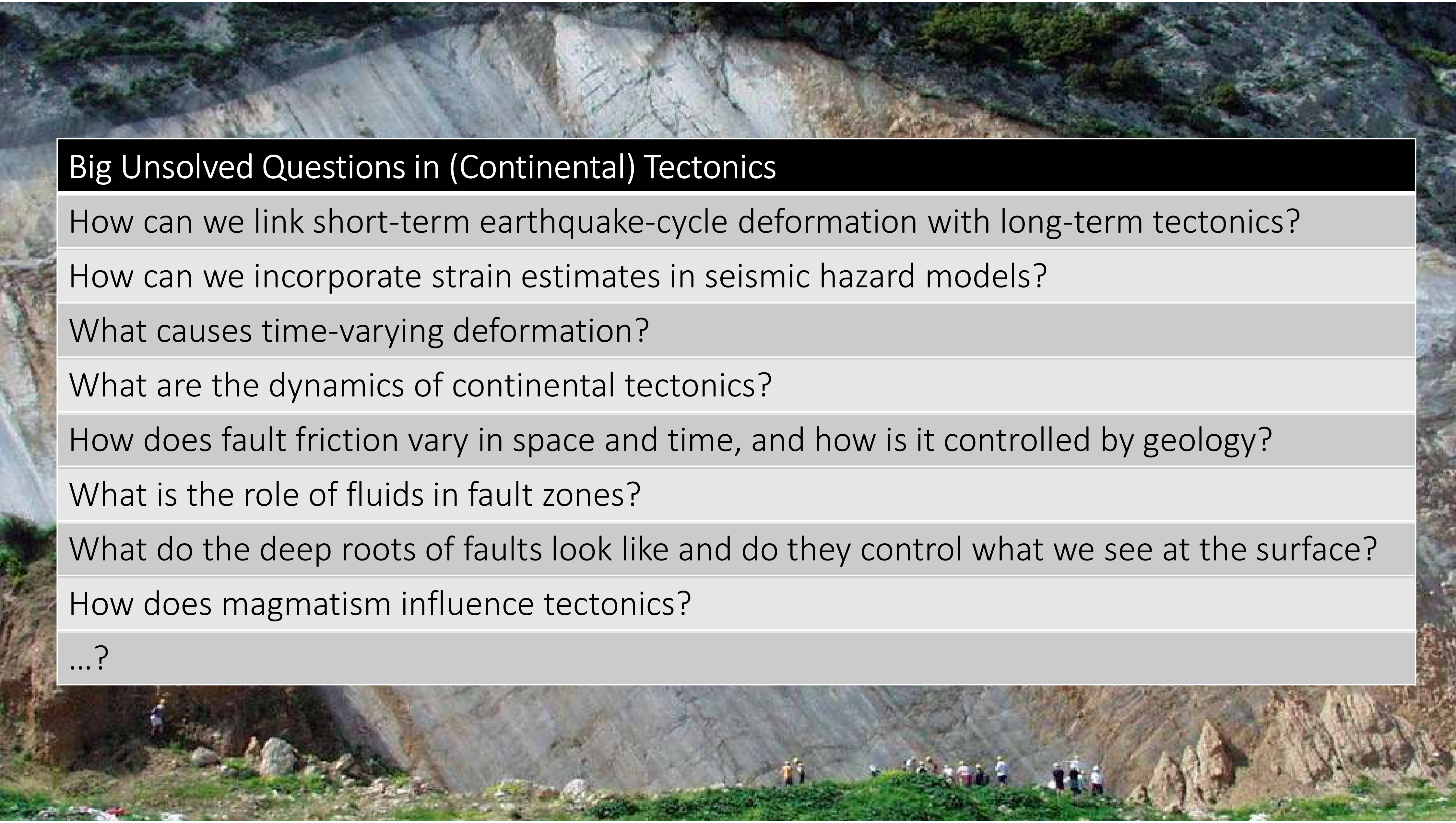
Elliott, Walters & Wright, 2016





EE10 Candidate (2028??)
Hydroterra (formerly G-CLASS)

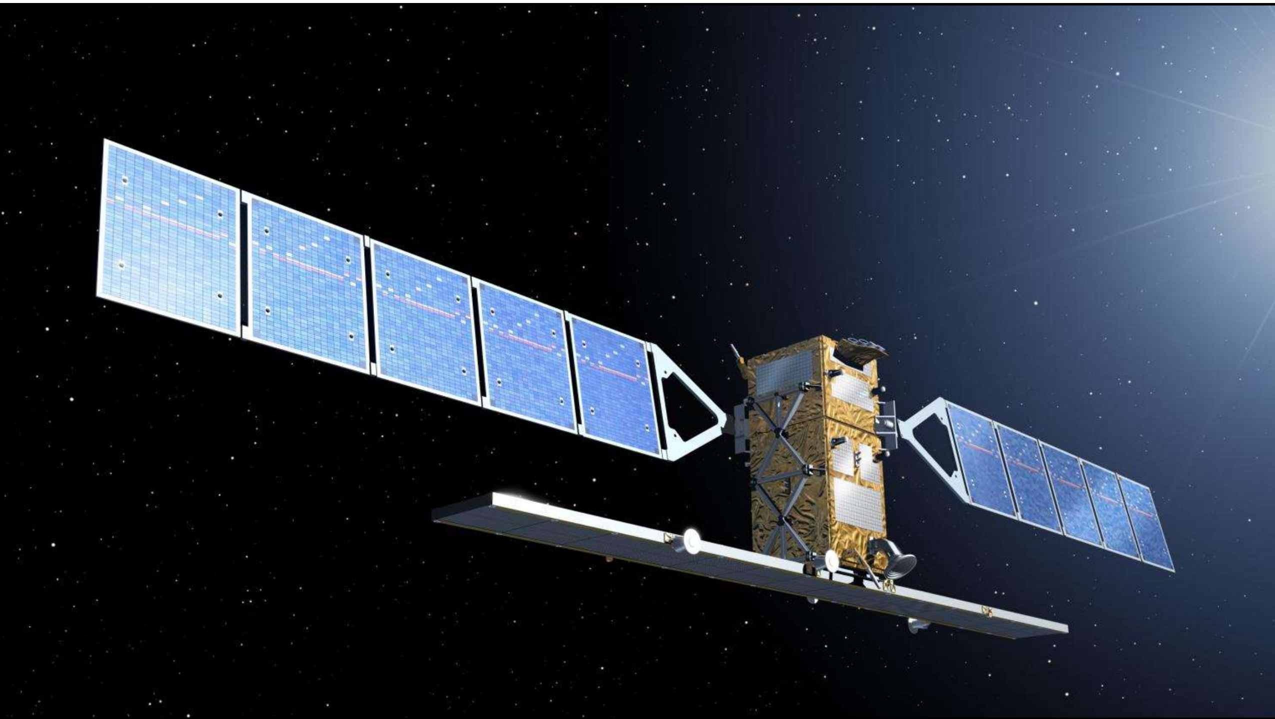
InSAR (nearly) everywhere (nearly) all the time



Big Unsolved Questions in (Continental) Tectonics
How can we link short-term earthquake-cycle deformation with long-term tectonics?
How can we incorporate strain estimates in seismic hazard models?
What causes time-varying deformation?
What are the dynamics of continental tectonics?
How does fault friction vary in space and time, and how is it controlled by geology?
What is the role of fluids in fault zones?
What do the deep roots of faults look like and do they control what we see at the surface?
How does magmatism influence tectonics?
…?

CENTRE FOR OBSERVATION & MODELLING OF EARTHQUAKES, VOLCANOES & TECTONICS

@NERC_COMET
@timwright_leeds



Take Home Messages
Tectonic InSAR is living up to the potential identified by early pioneers.
Earthquakes continue to surprise us and we continue to learn from them
Measuring slow, long-wavelength deformation is more challenging but data from long-duration missions like Sentinel-1 will lead to exciting new discoveries
Trans-national partnerships, collaborations, discussions essential for success

With thanks to colleagues in NERC COMET

CENTRE FOR OBSERVATION & MODELLING OF EARTHQUAKES, VOLCANOES & TECTONICS

UCL

Newcastle University

University of Cambridge

Durham University

University of Bristol

University of Reading

University of Oxford

BGS 1835

University of Liverpool

University of Leeds