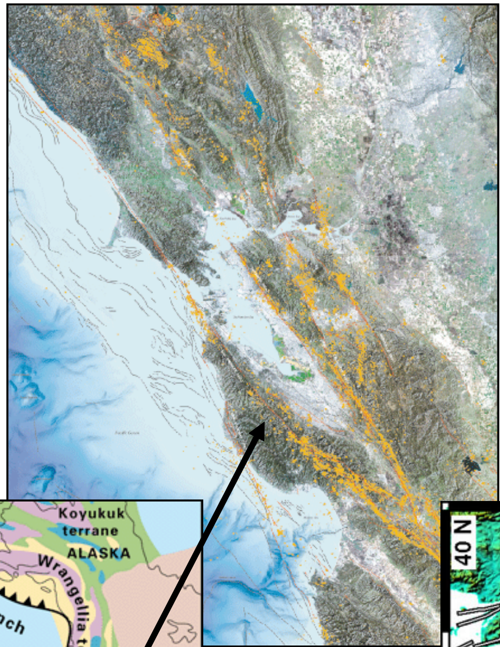
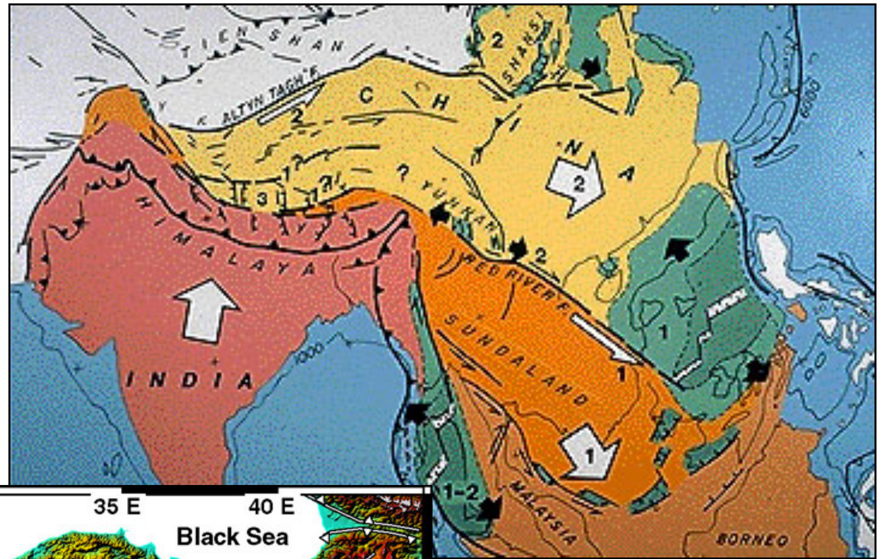
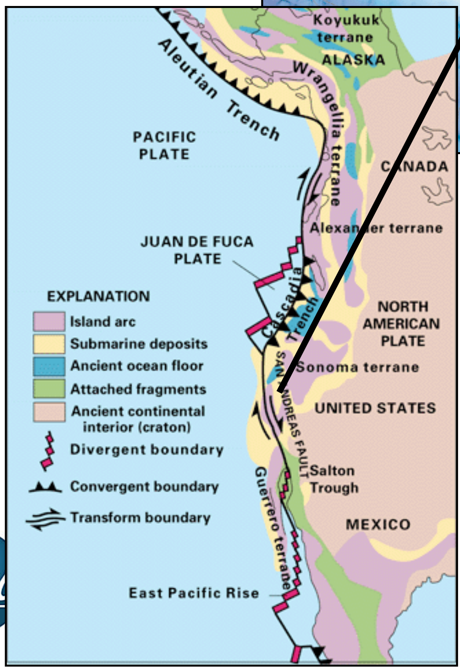
(Strike-slip) Faults & shear zones: strain localization in nature

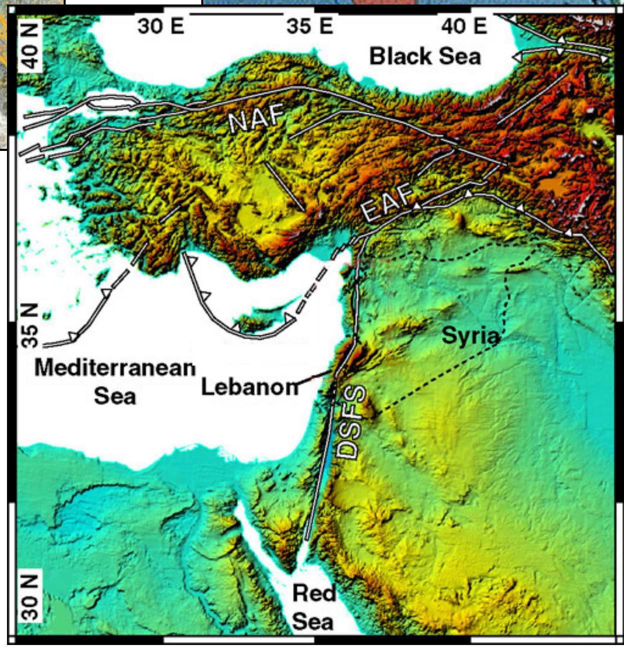
Andréa Tommasi & Alain Vauchez
Géosciences Montpellier

Strike-slip faults: a major component of the continental deformation

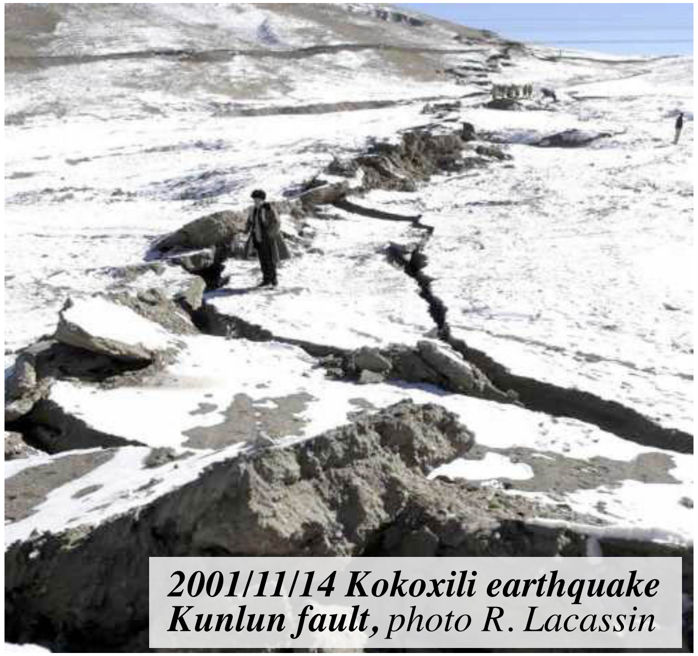








Faults: highly localized deformation @ the surface



2001/11/14 Kokoxili earthquake
Kunlun fault, *photo R. Lacassin*

San Andreas, California, *photo J.C. Bousquet*

Geodetic observations after major earthquakes:
ductile flow beneath the fault
Pollitz et al. (2000, 2001, 2003), Montési (2004, 2005)…

Mantle Flow Beneath a Continental Strike-Slip Fault: Postseismic Deformation After the 1999 Hector Mine Earthquake

Fred F. Pollitz,* Chuck Wicks, Wayne Thatcher
SCIENCE VOL 293 7 SEPTEMBER 2001

How deep do these faults penetrate within the Earth?
How does the deformation (strain distribution) vary with depth ?

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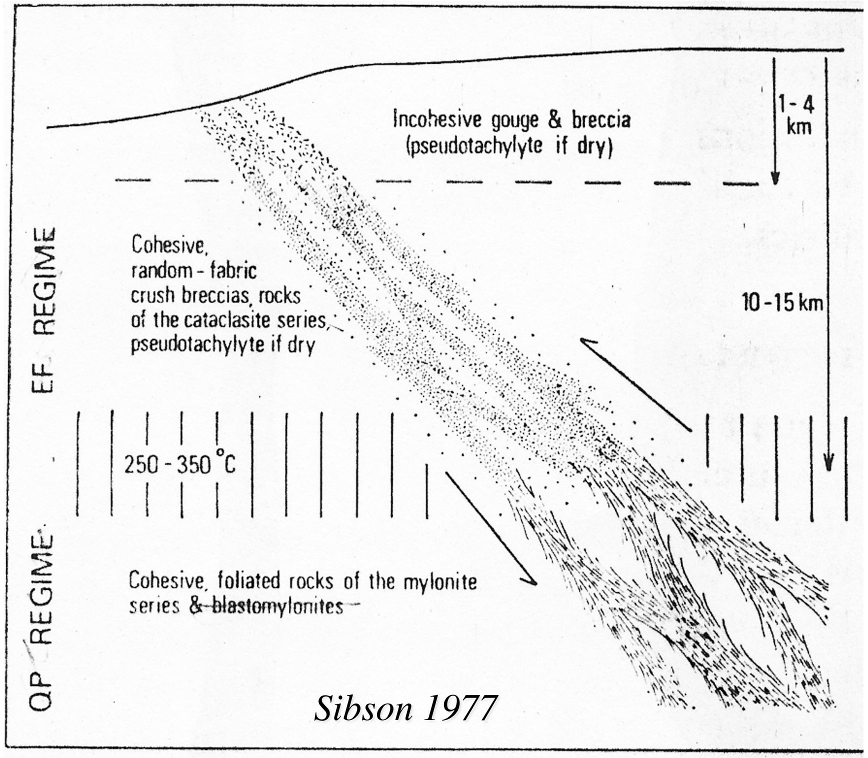
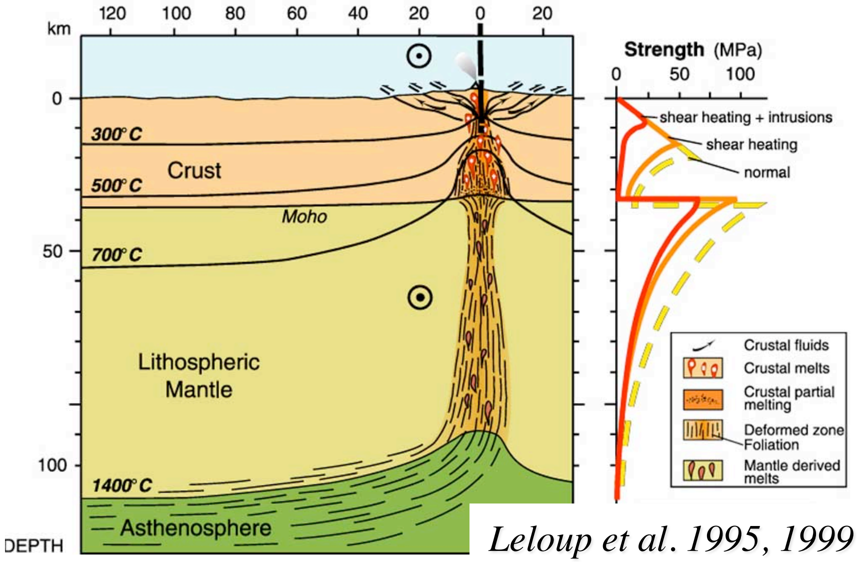
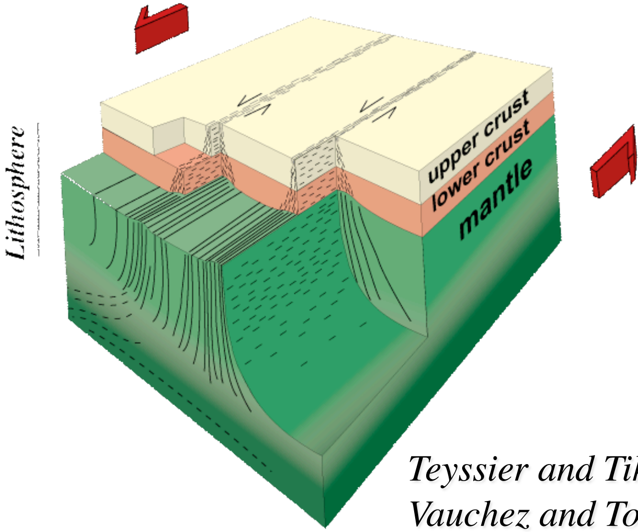


Sibson 1977



Leloup et al. 1995, 1999



Teyssier and Tikoff 1998
Vauchez and Tommasi 2003

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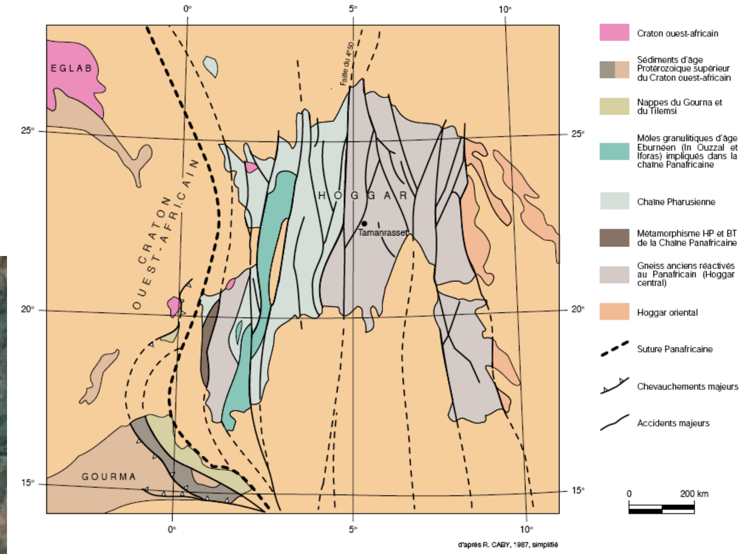
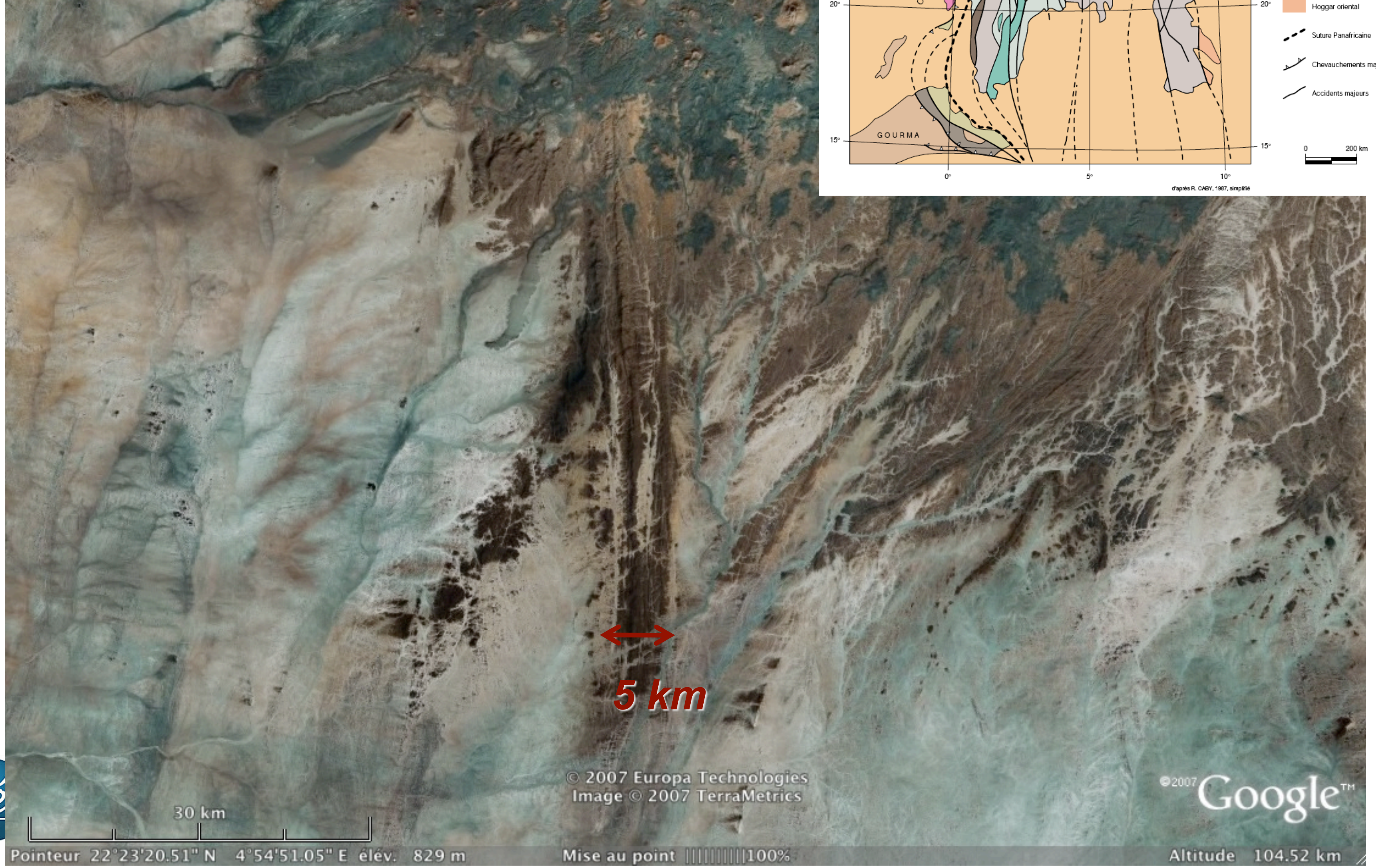
In the upper to middle crust: the 4°50 shear zone in Hoggar

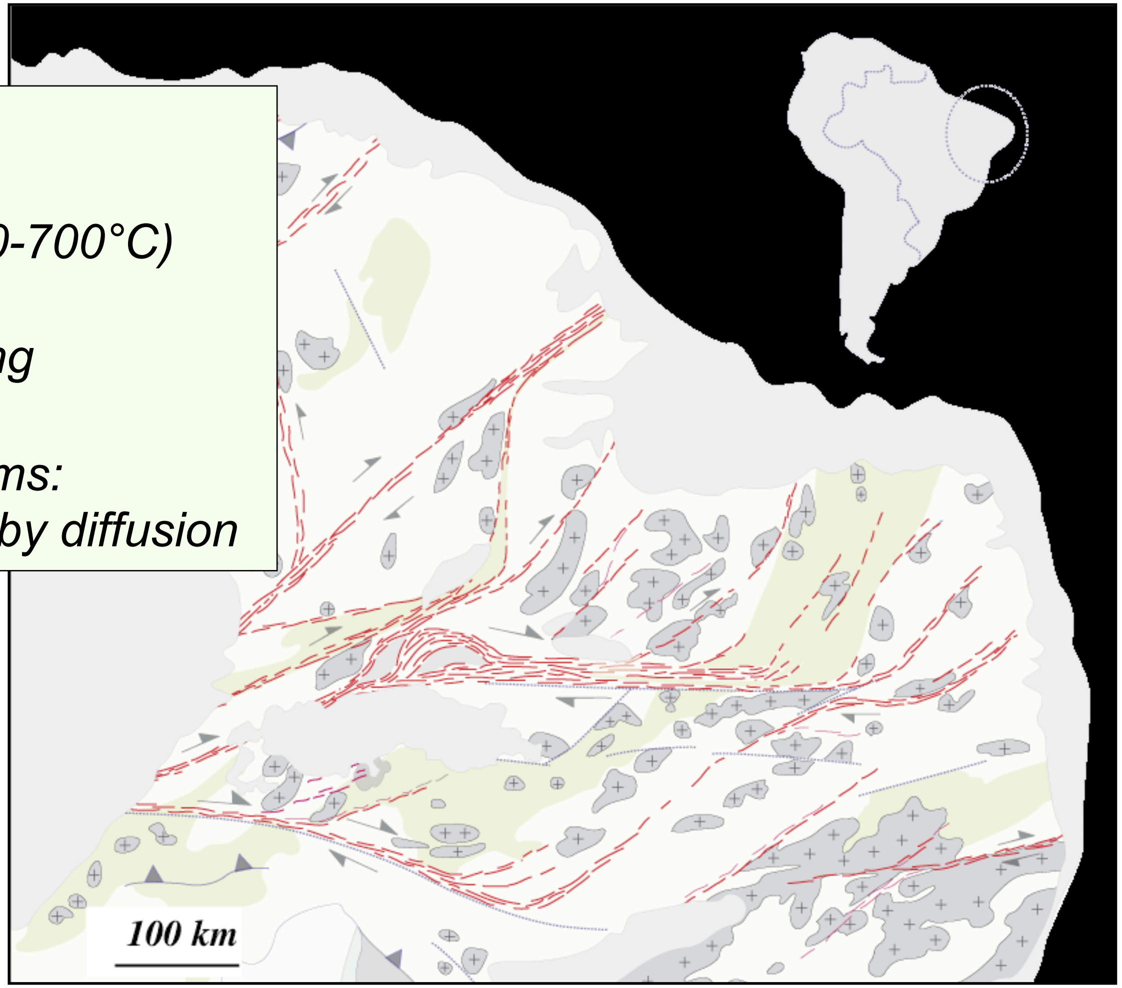




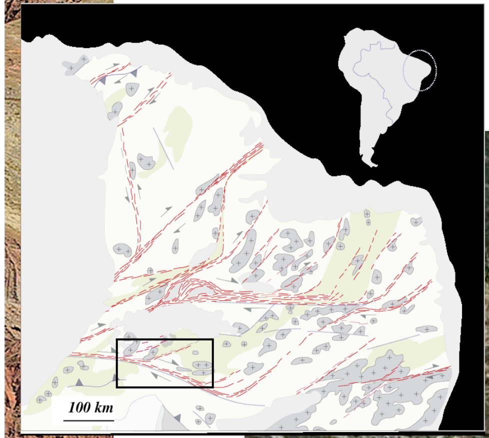
Wrench faults in the middle to lower crust
the Borborema shear zone system (NE Brazil):
localized strike-slip deformation in a partially molten crust

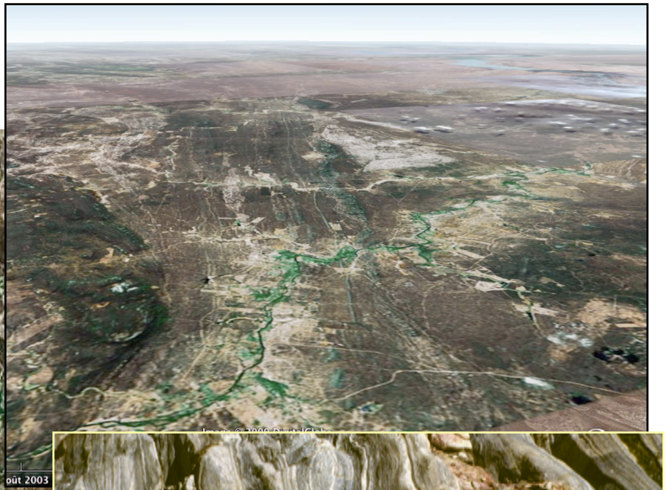
Northeast Brazil:

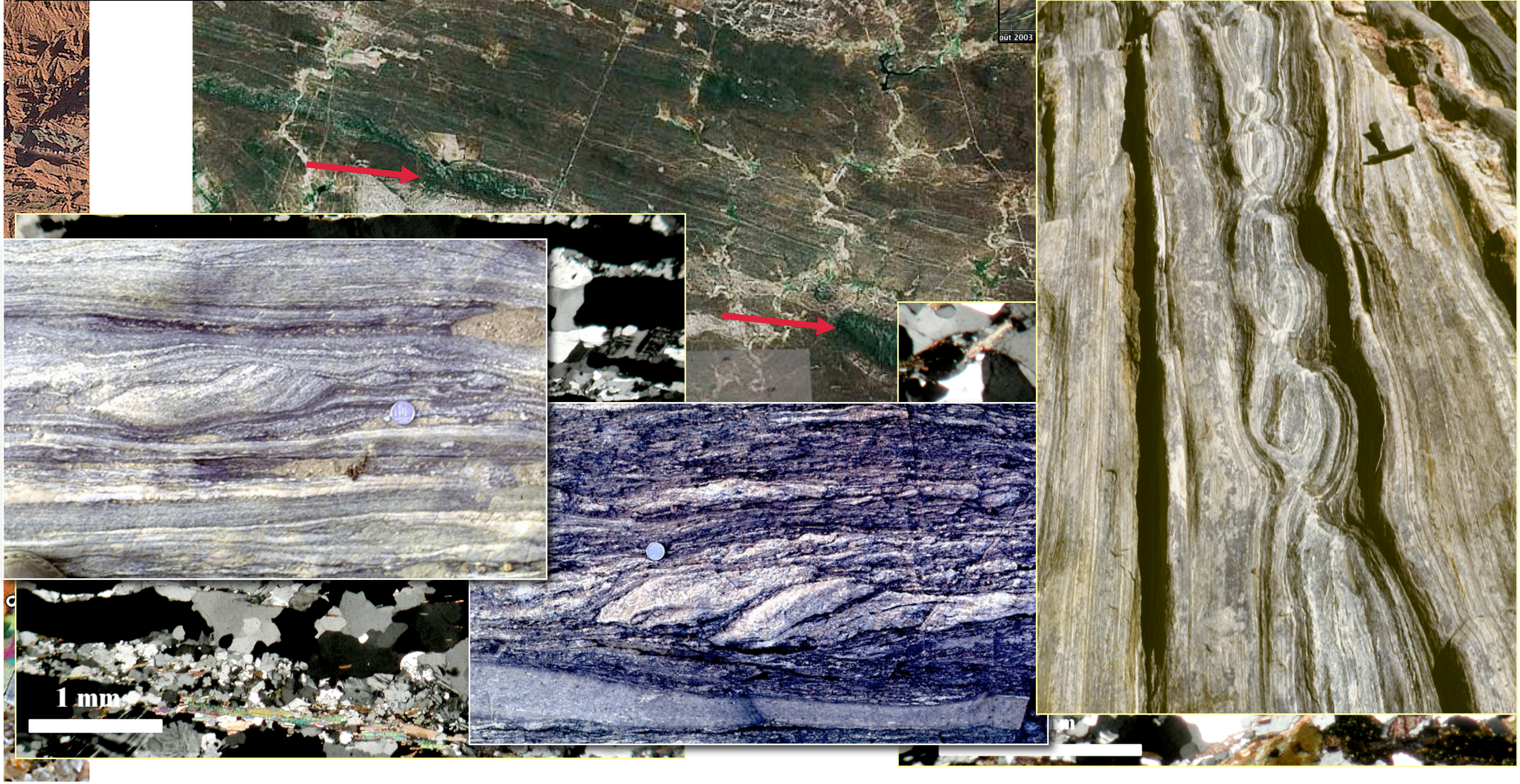
- *Middle crust (15-17km)*
- *HT-LP metamorphism (650-700°C)*
- *Complex geometry*
- *Synkinematic partial melting and magmatism*
- *HT deformation mechanisms: dislocation creep assisted by diffusion*



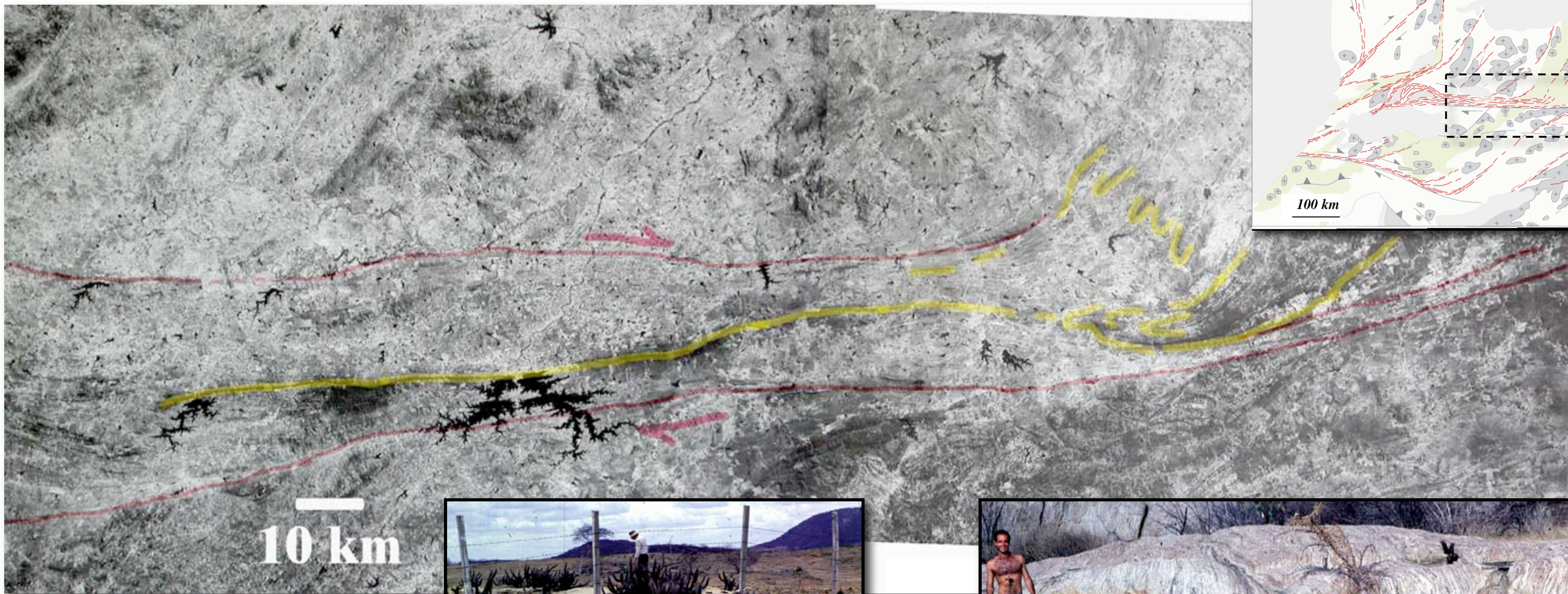
Pernambuco shear zone

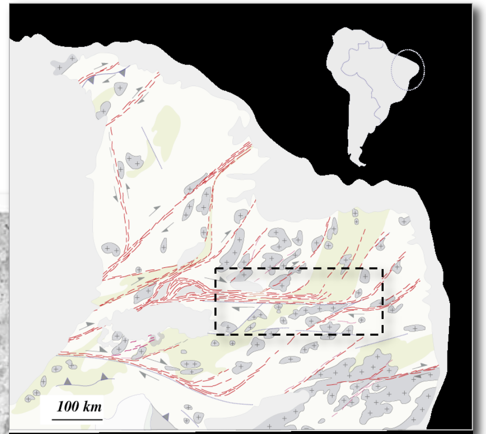


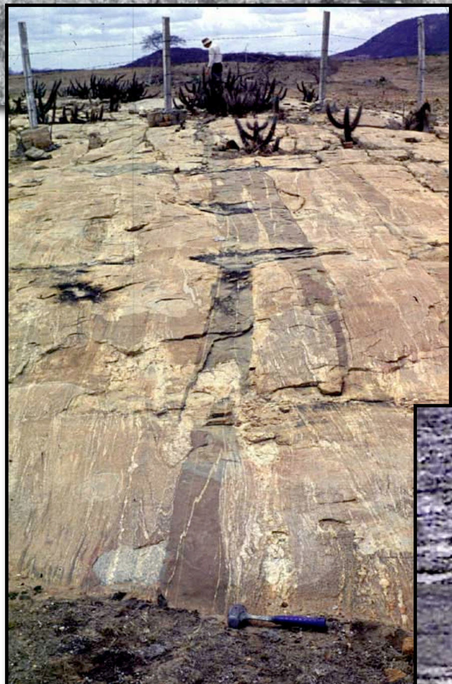




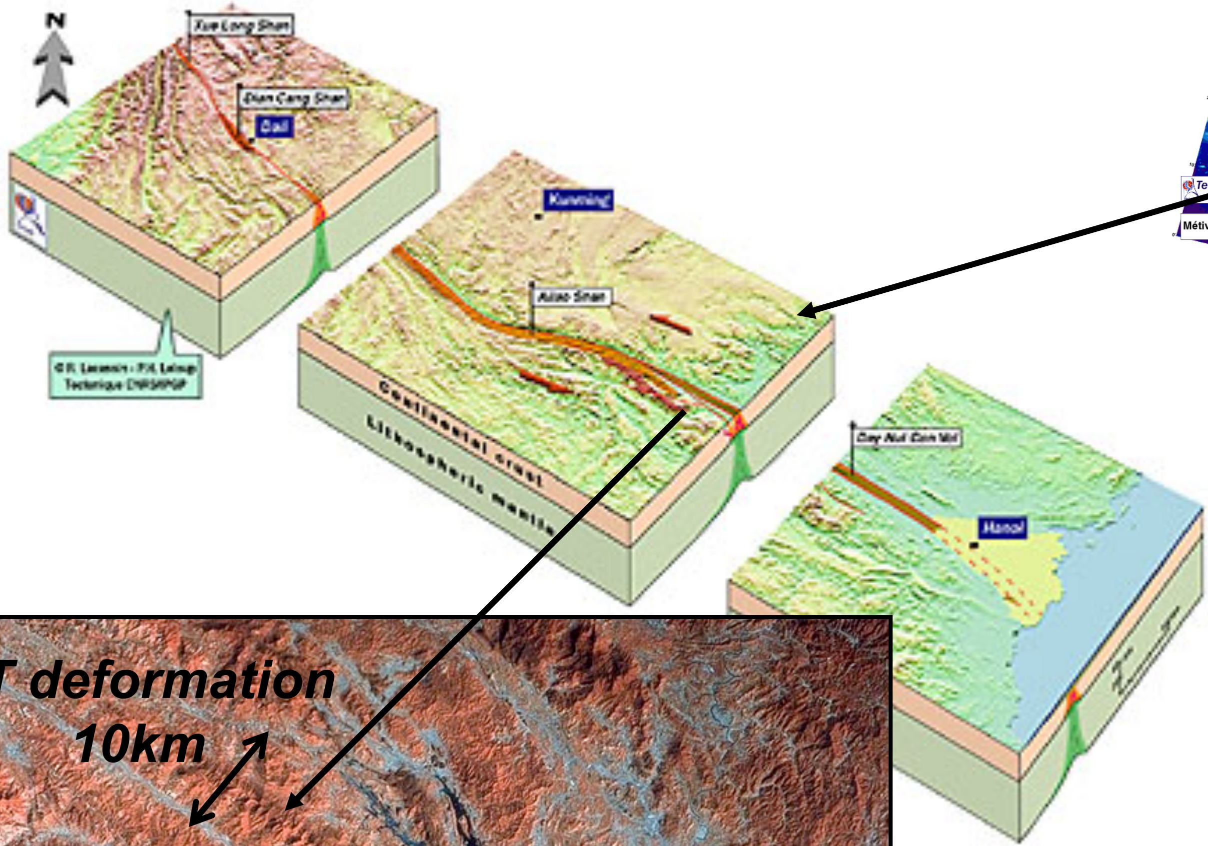
Borborema shear zone system, NE Brazil

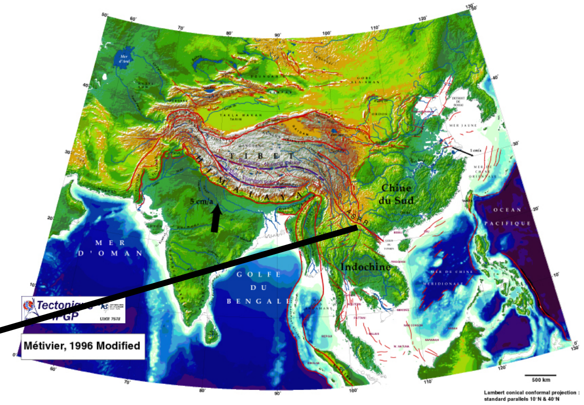


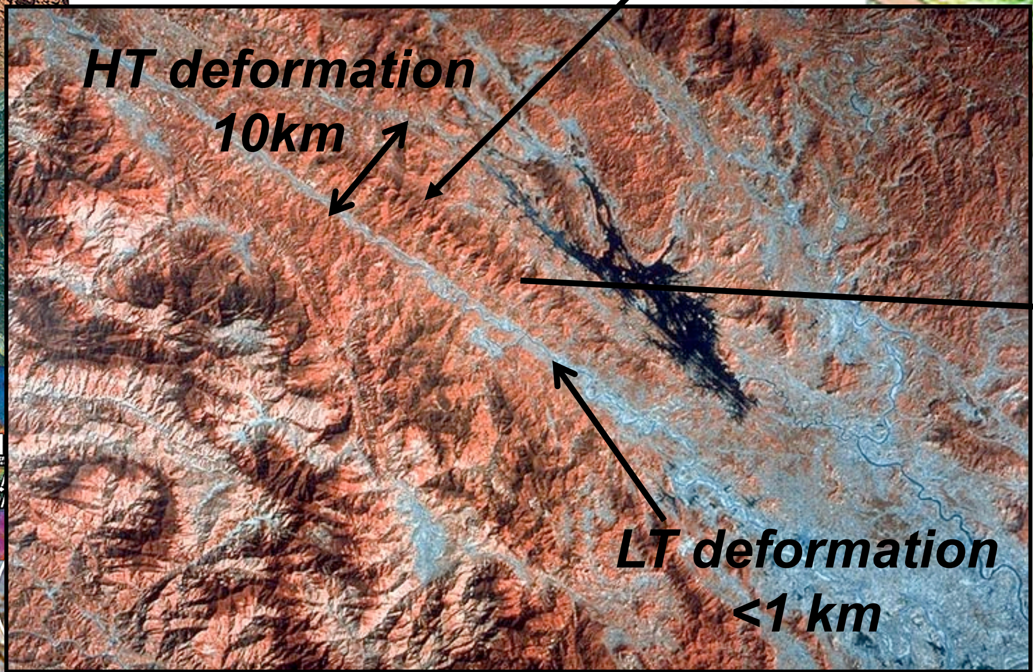


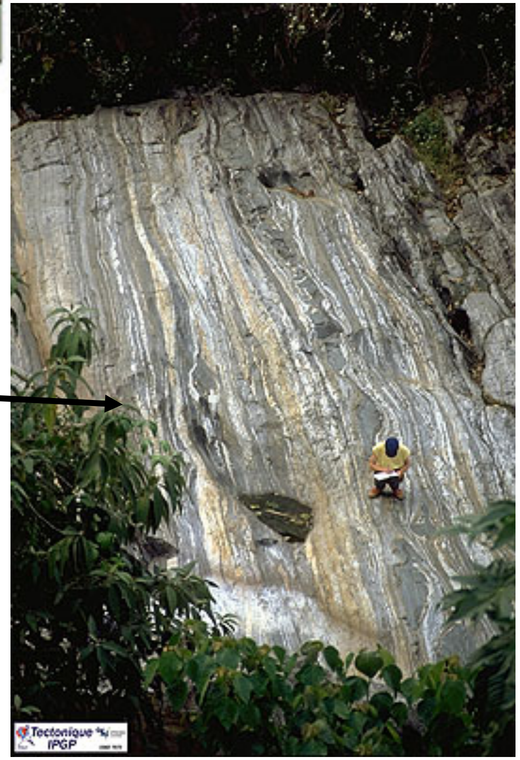


the Ailao Shan - Red River shear zone



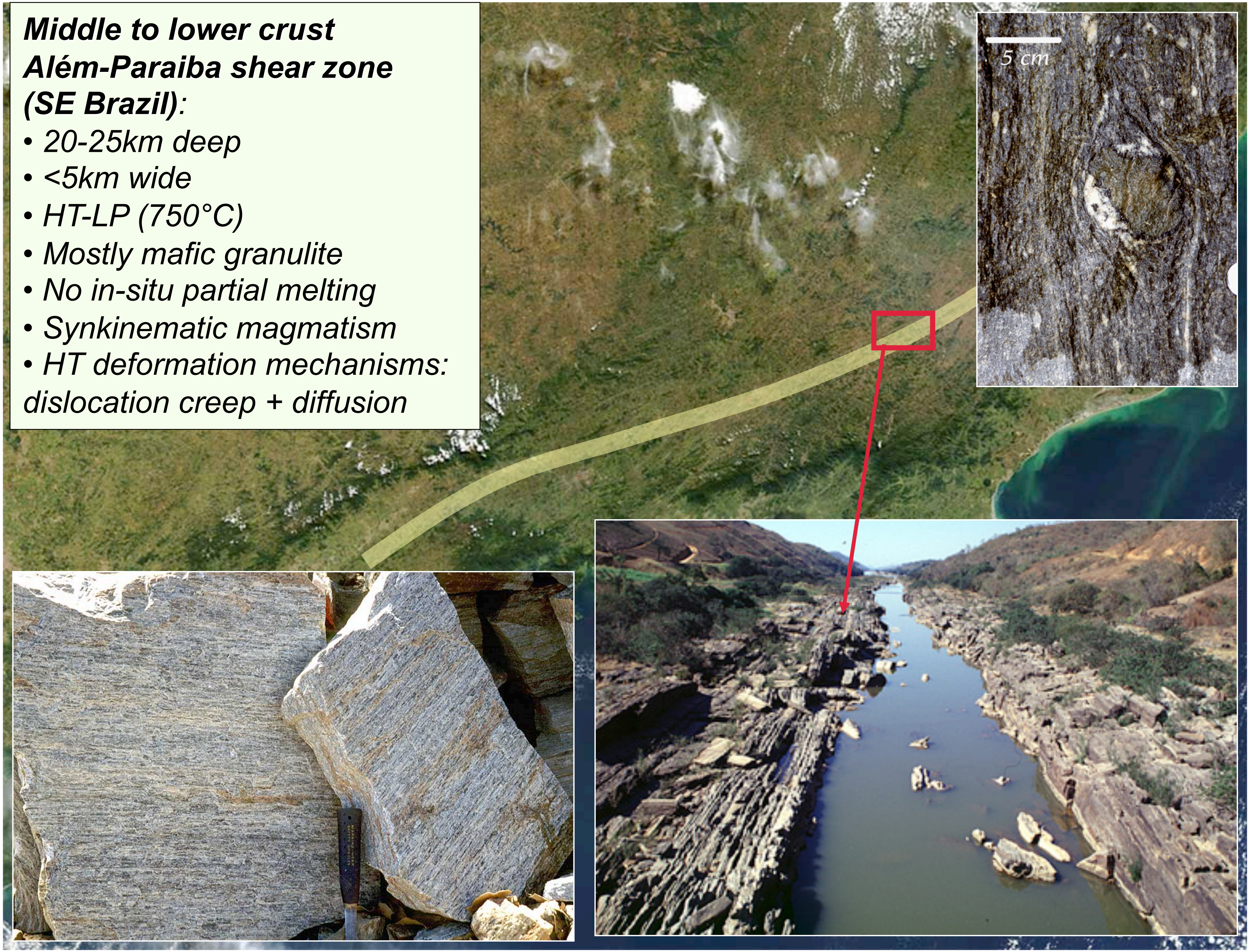






***Middle to lower crust Além-Paraiba shear zone (SE Brazil)*:**

- *20-25km deep*
- *<5km wide*
- *HT-LP (750°C)*
- *Mostly mafic granulite*
- *No in-situ partial melting*
- *Synkinematic magmatism*
- *HT deformation mechanisms: dislocation creep + diffusion*



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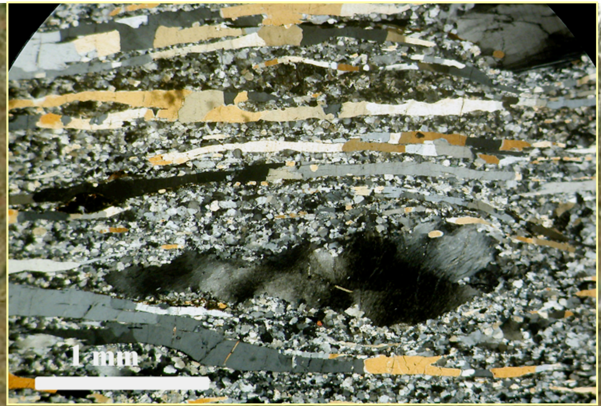
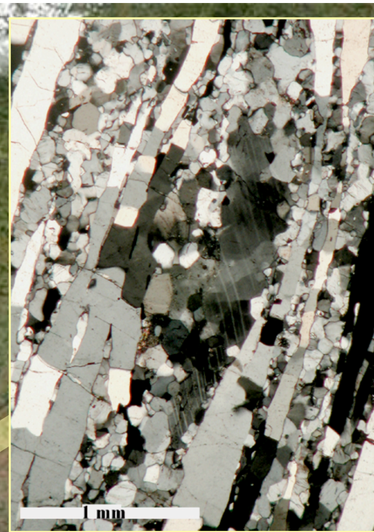
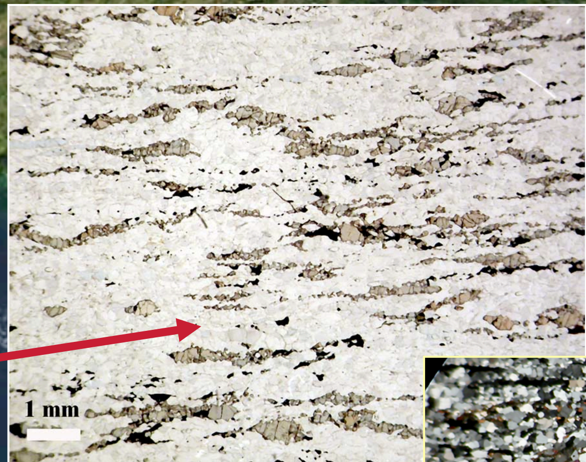
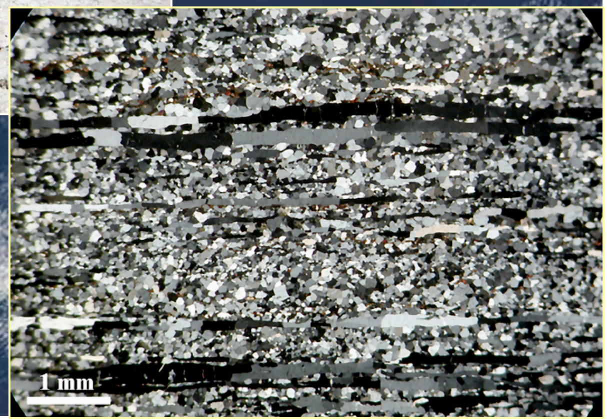


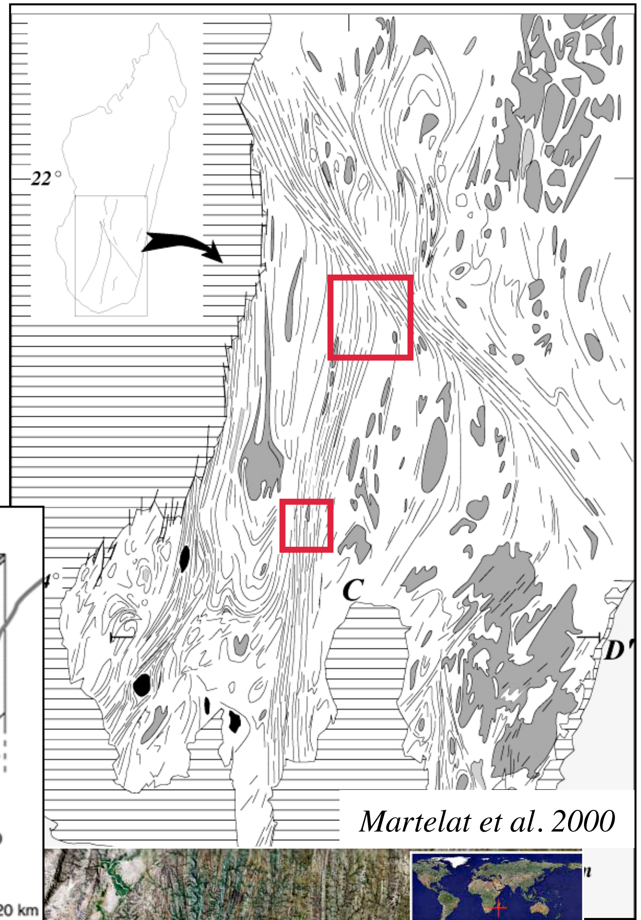




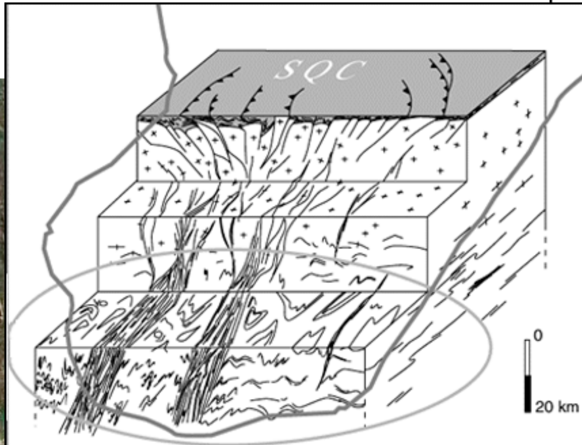


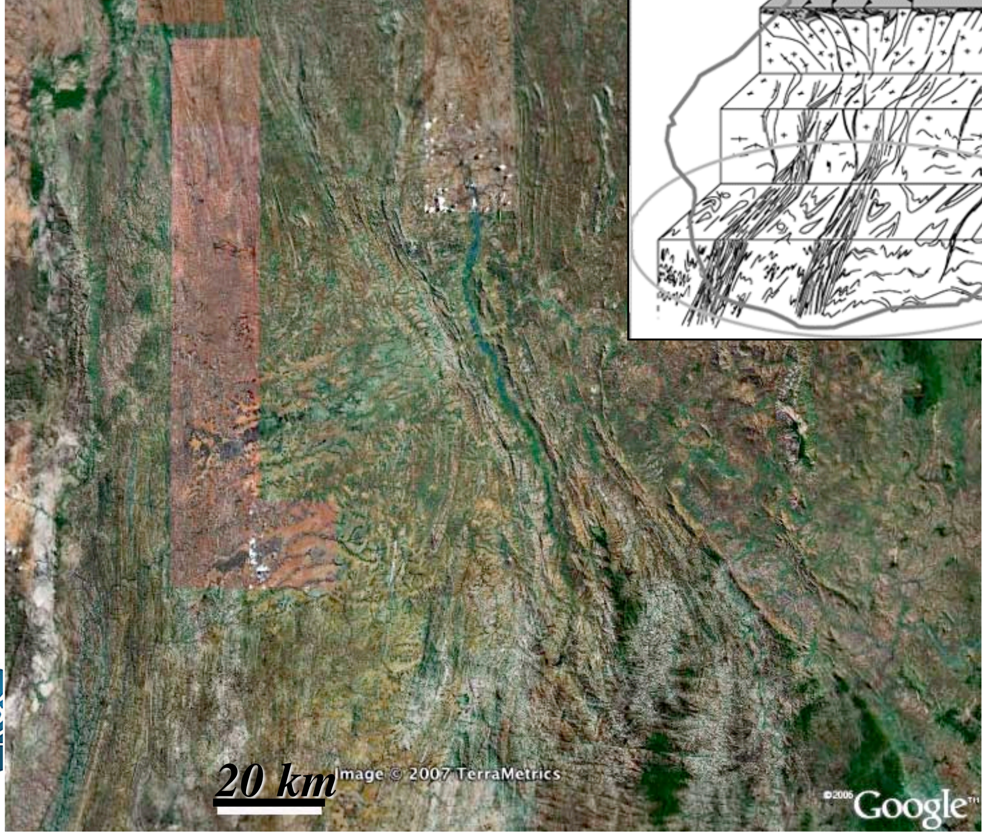
***Madagascar shear zone system*:**

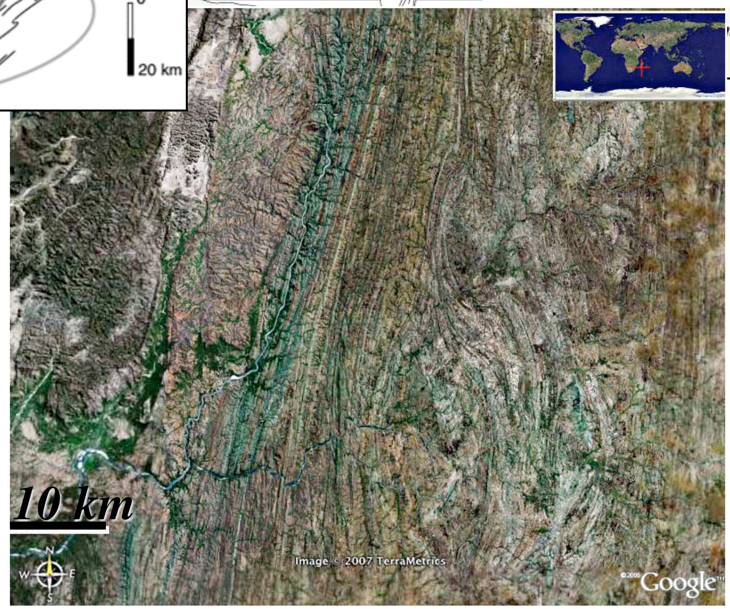
- Felsic middle crust to mafic lower crust
- Faults up to 30km wide
- HT (750°C ± 50°C), low to interm P
- Synkinematic melting and magmatism
- HT deformation mechanisms: dislocation creep + diffusion



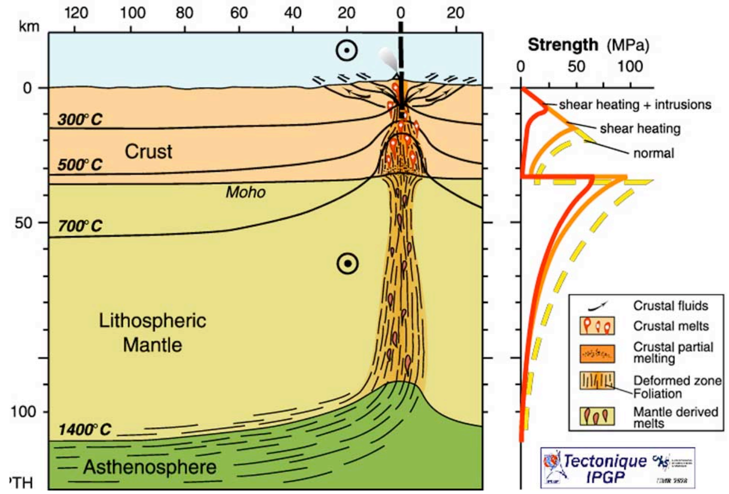
Martelat et al. 2000







Large-scale wrench faults in the ductile crust



Strain localization even at partial melting temperatures, but not very efficient:

- *up to 30km wide shear zones*
- *complex geometries*

- *Deformation under HT, low stress conditions:*
- *“Coarse-grained” mylonites : dislocation creep, but fast diffusion (grain growth)*
- *"intrinsic" strain localization processes (shear heating or grain size reduction) not effective, with exception of mechanical anisotropy due to CPO or compositional layering*

Which processes produce strain localization?

- *coupling to shallow localized deformation*
- *channeling of fluids (magmas, CO_2…)*
- *rheological heterogeneity (lateral gradients in T or in composition)*

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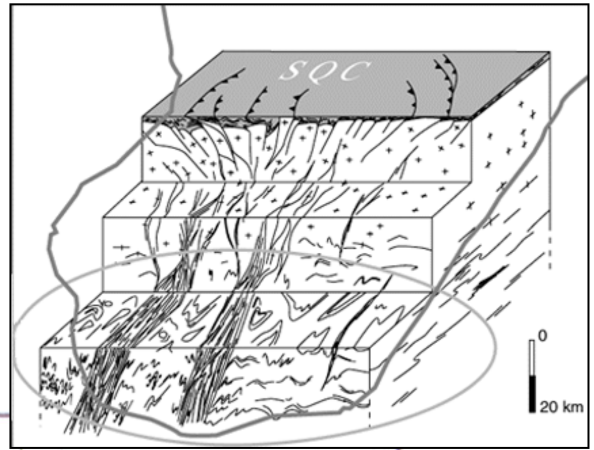
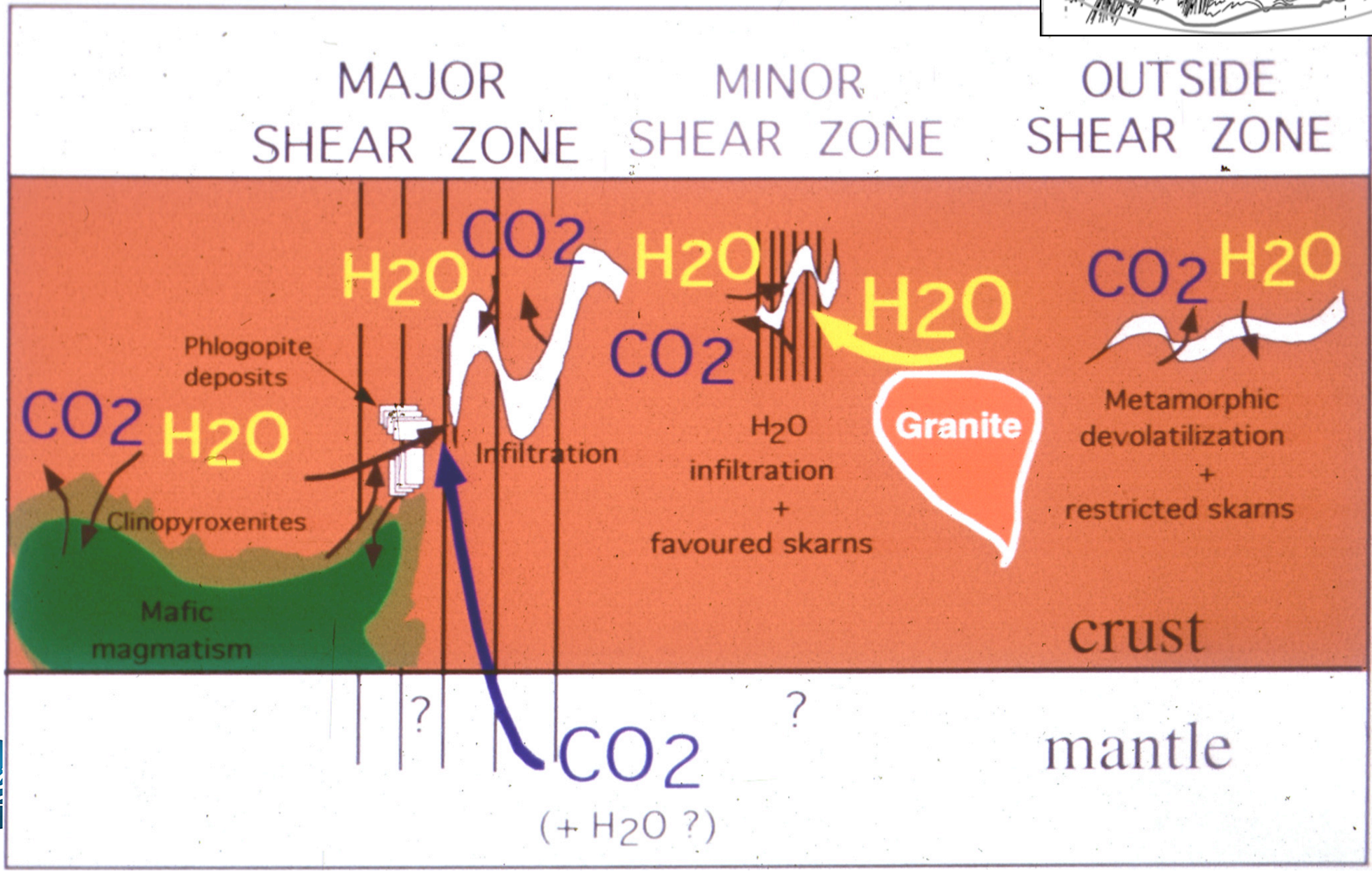
Do these large-scale faults penetrate in the mantle?

Madagascar shear zone system





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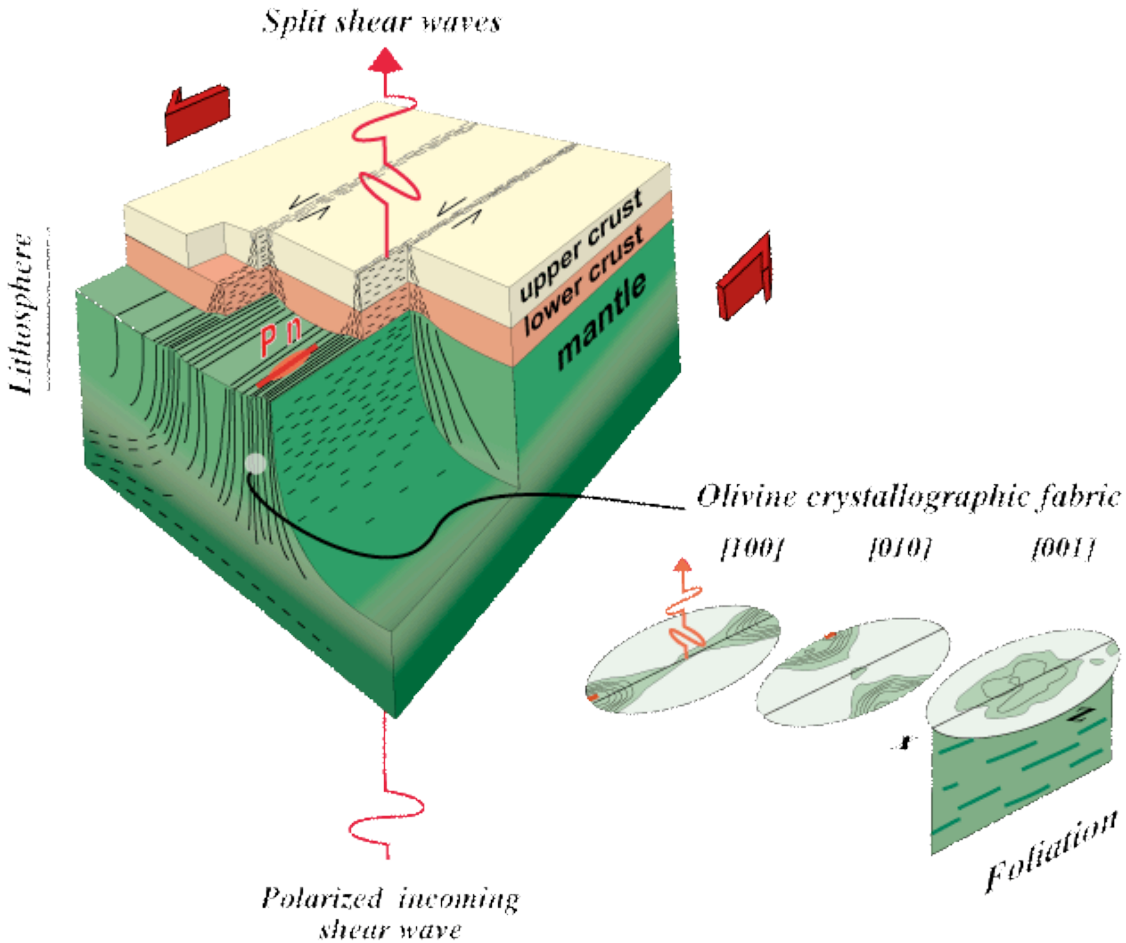
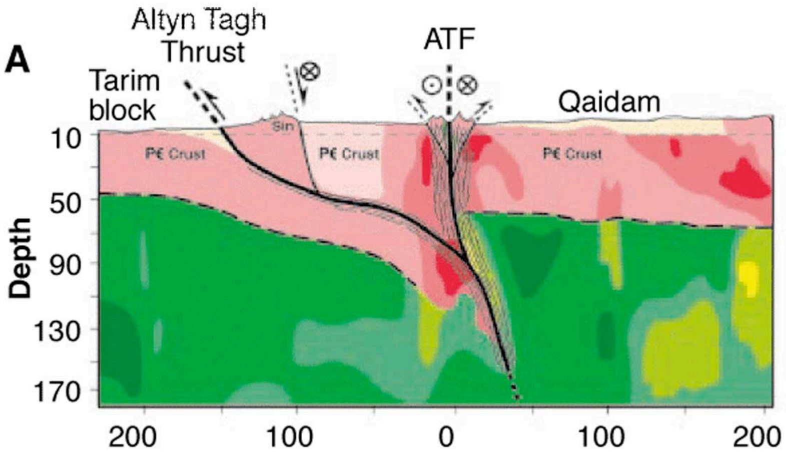


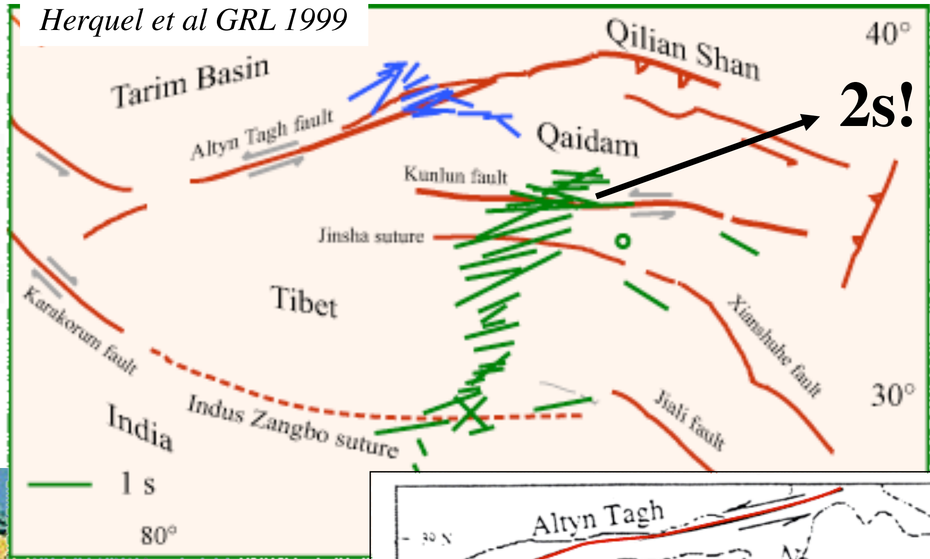
Shear wave splitting:
fast S wave polarized // to the fault, strong delay times

Do these large-scale faults penetrate in the mantle?

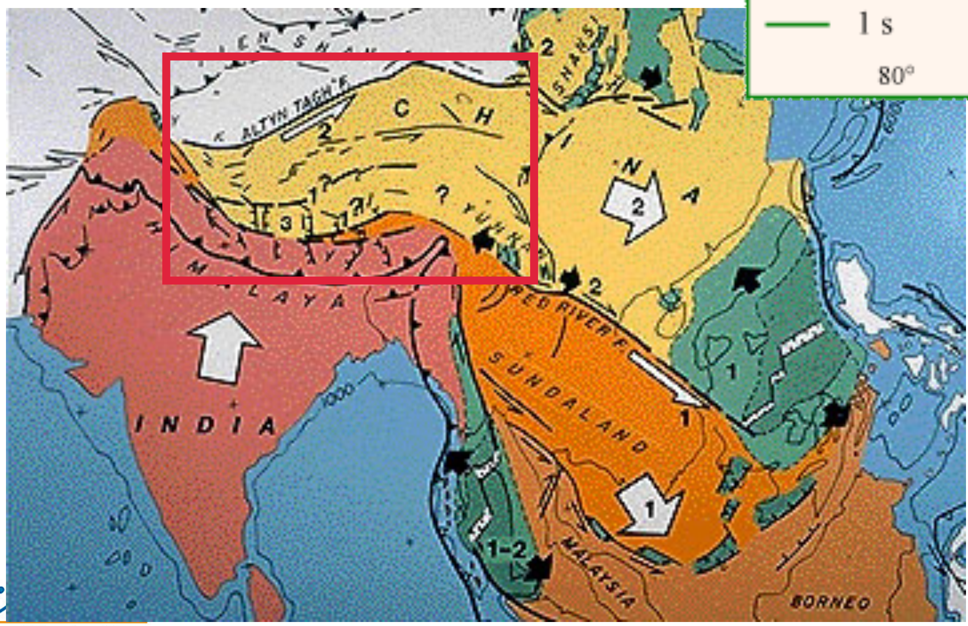
Active faults: Himalaya

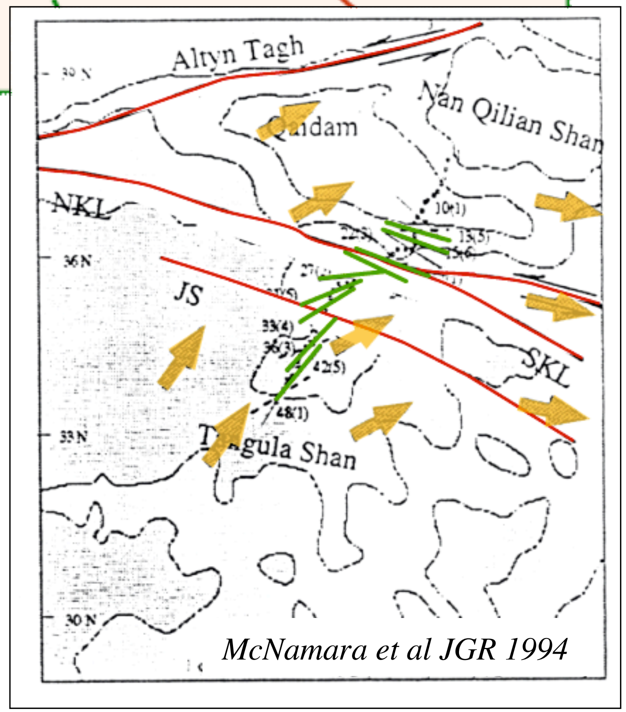


Wittlinger et al. Science 1998



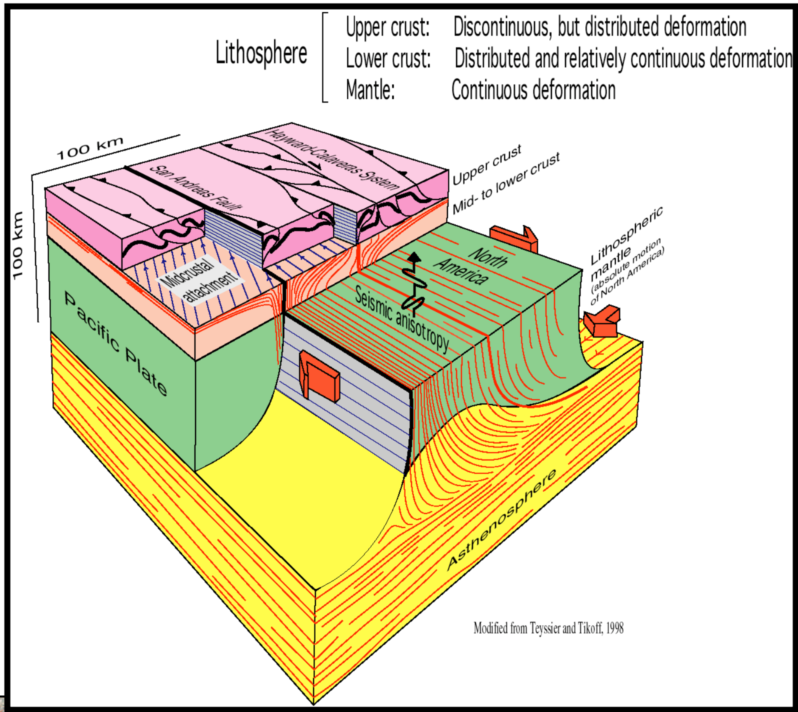
Herquel et al GRL 1999

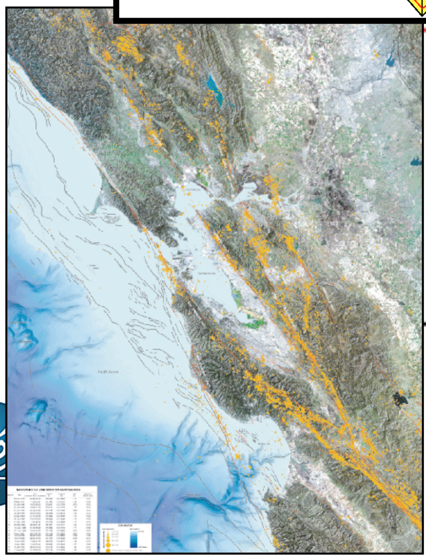




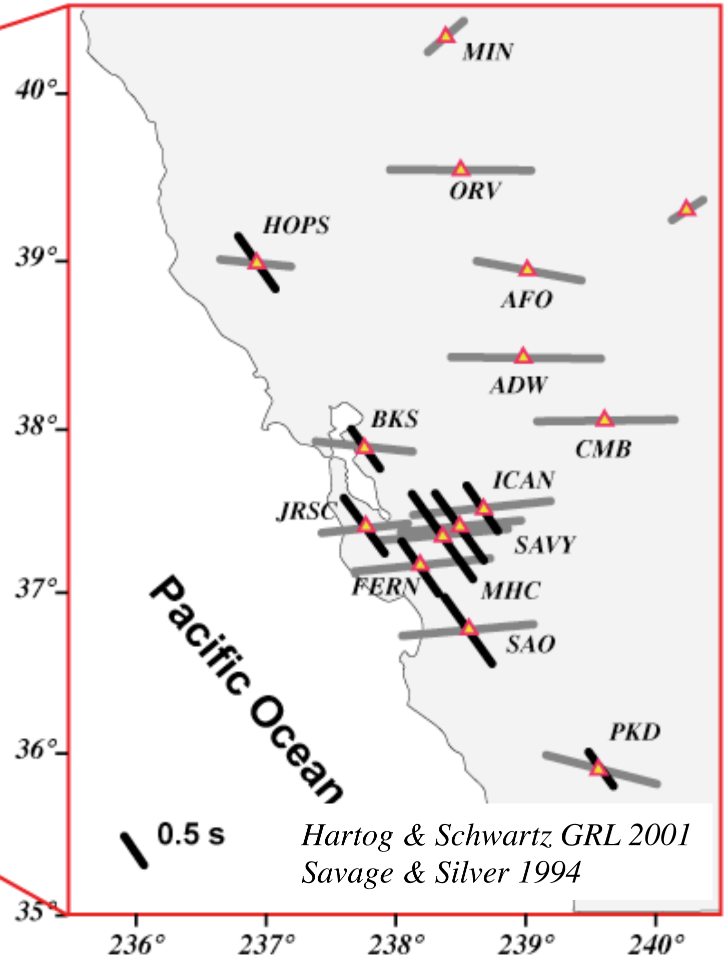
McNamara et al JGR 1994

Do these large-scale faults penetrate in the mantle?



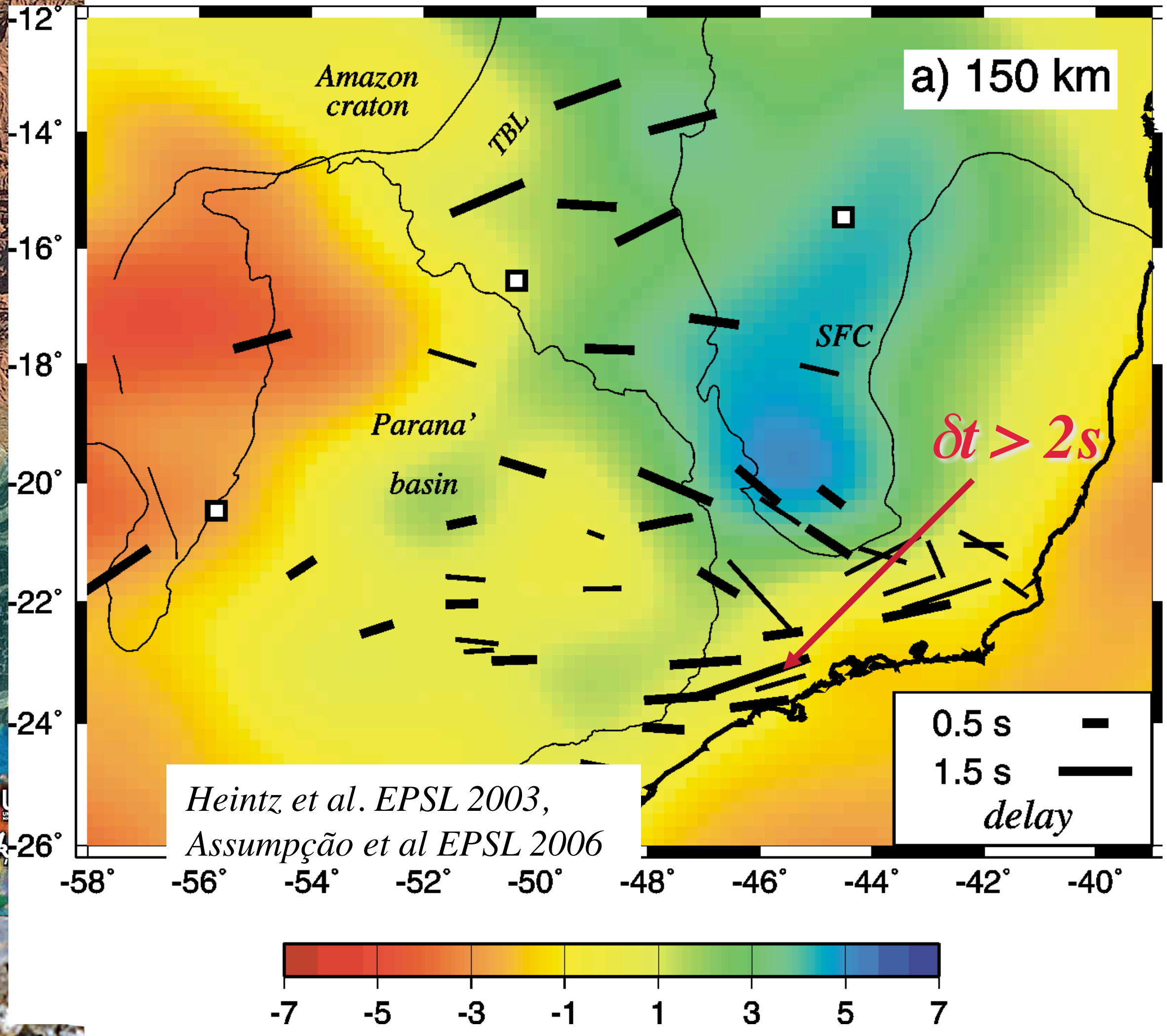


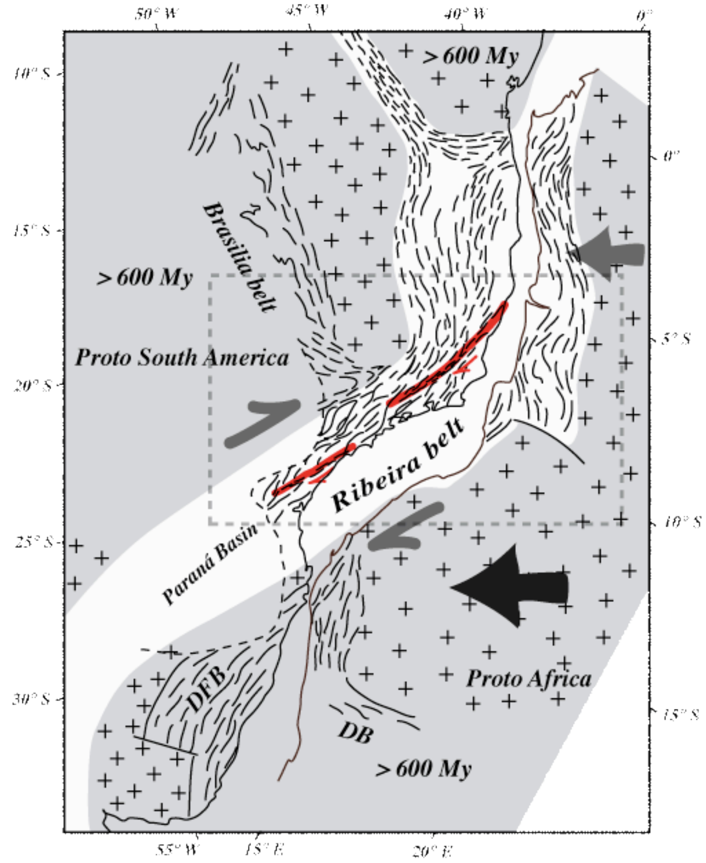
Active faults: San Andreas

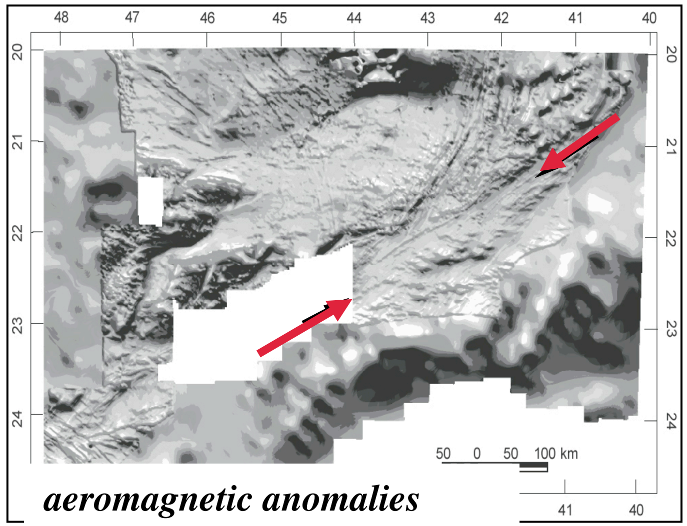


upper anisotropic layer: lithospheric mantle flow // fault

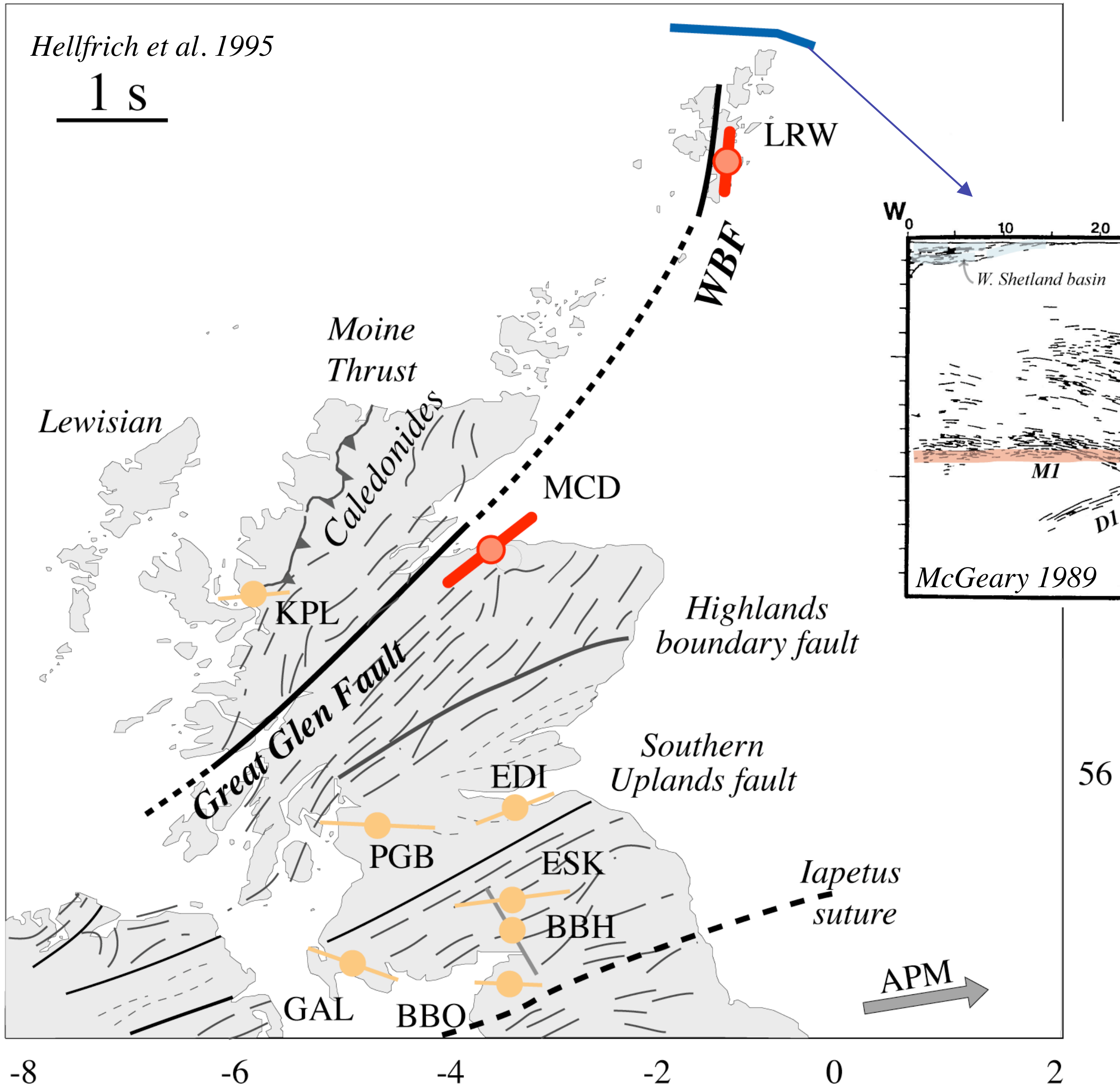
Evidence of coherent crust-mantle deformation: Neoproterozoic wrench faults SE Brazil

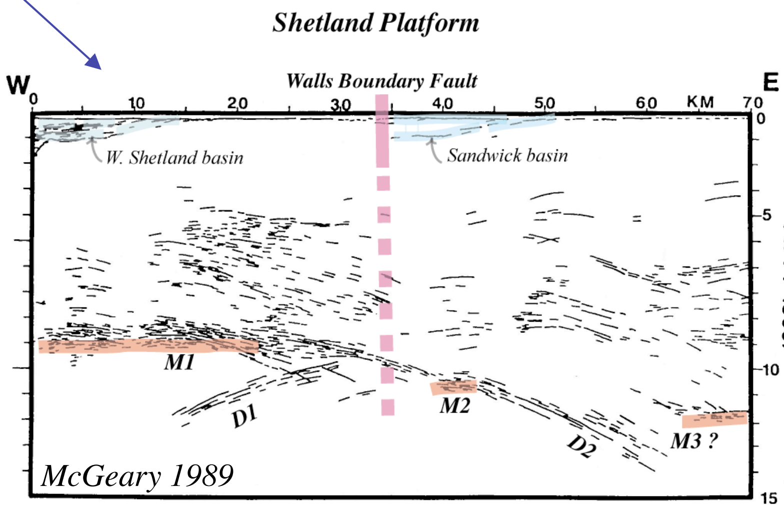






Evidence of coherent crust mantle deformation?
fossil wrench faults: the Great Glenn fault



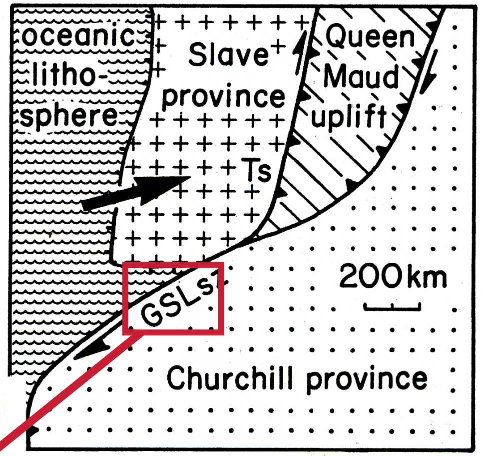


Evidence for coherent deformation of the crust & mantle

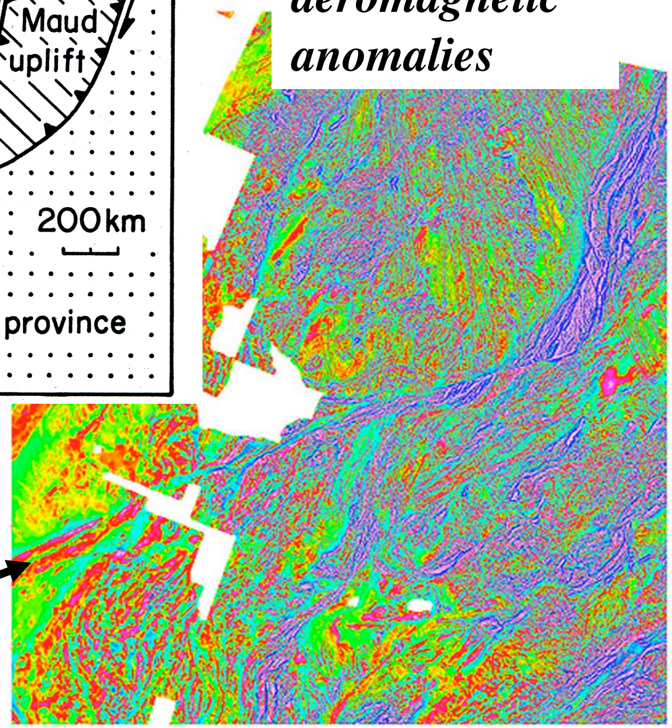
Proterozoic Great Slave Lake shear zone

width at the surface >10km (up to 25km?)

Hanmer et al. 1992; Hoffman 1987

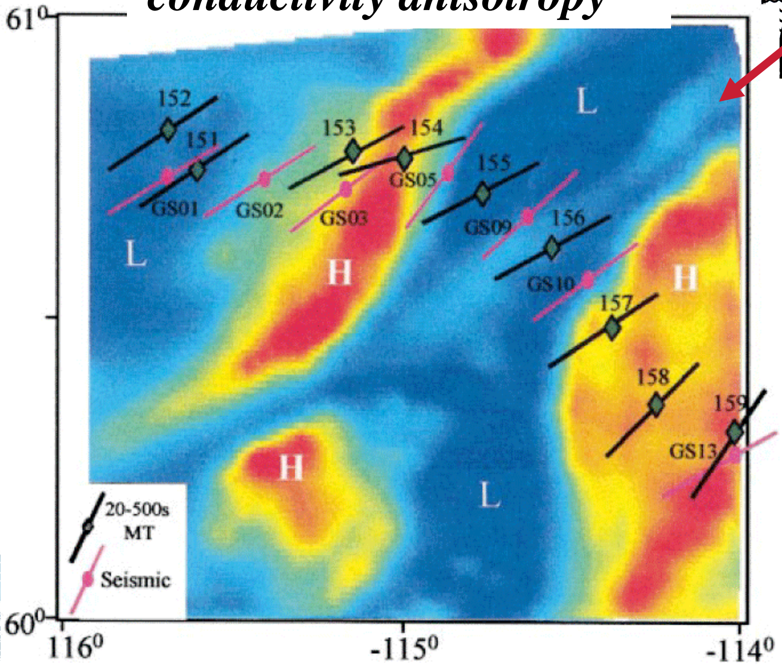


aeromagnetic anomalies



Canada Grid_ 200m - 1st Vertical Derivative
Commission géologique du Canada

seismic & electrical conductivity anisotropy



Wu et al. 2002

North Anatolian Fault: no associated anisotropy

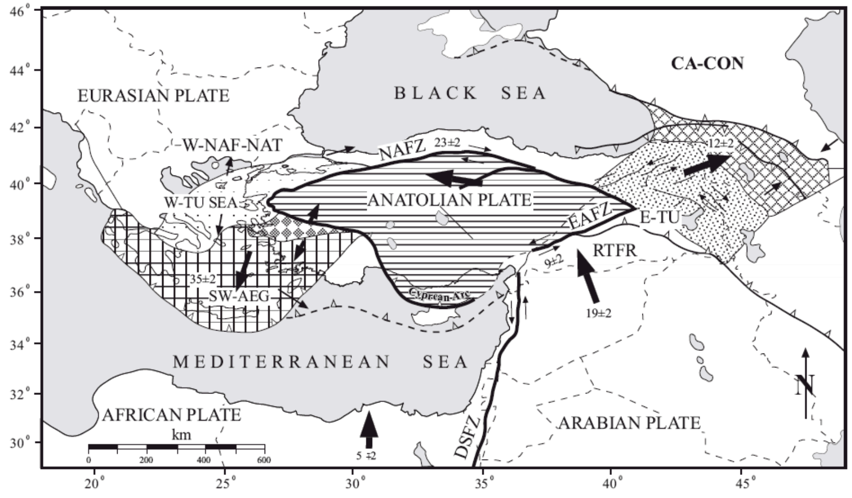
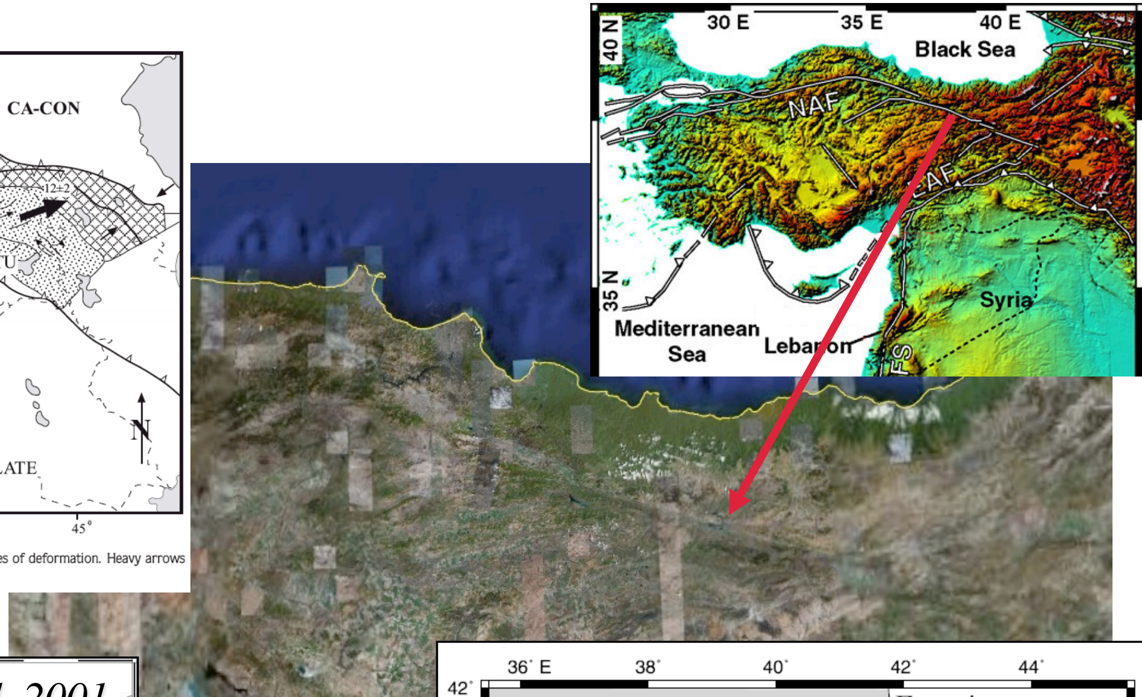
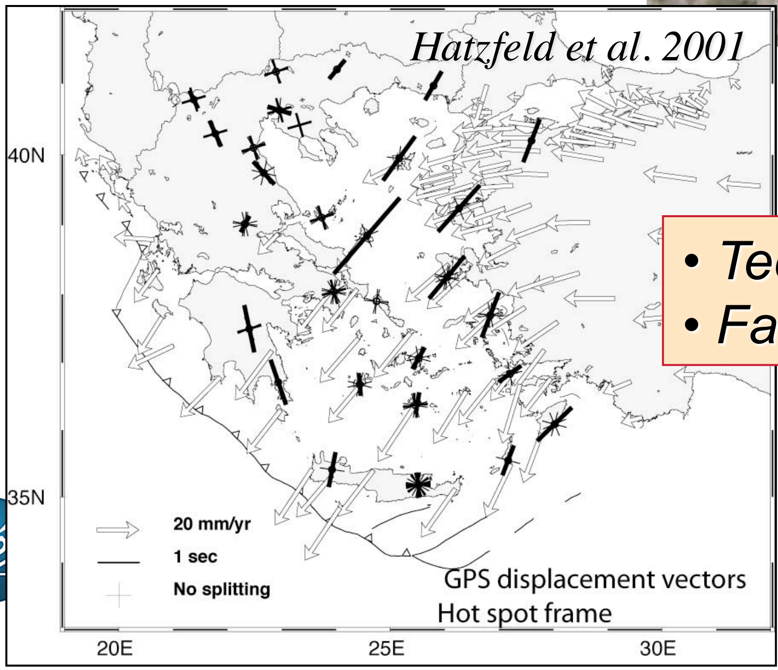
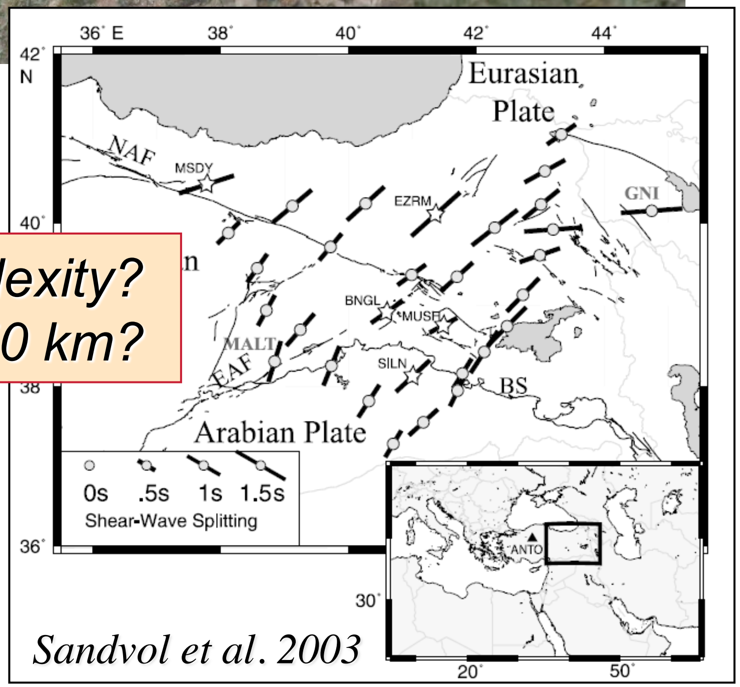


Figure 1. Kinematics of Turkey and surrounding area. Hatched areas show the coherent motion of specific zones of deformation. Heavy arrows indicate the generalised regional motions in mm/yr (after McClusky *et al.* 2000).





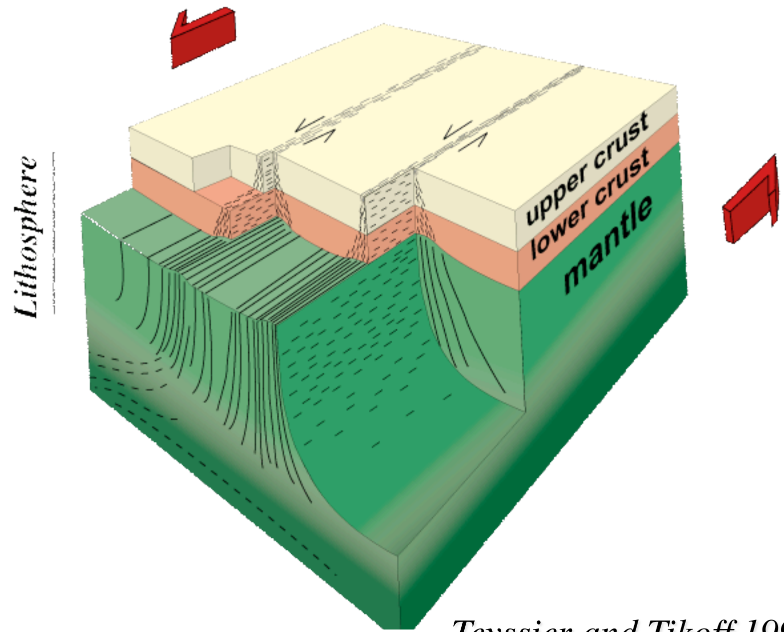
- *Tectonic complexity?*
- *Fault width < 50 km?*



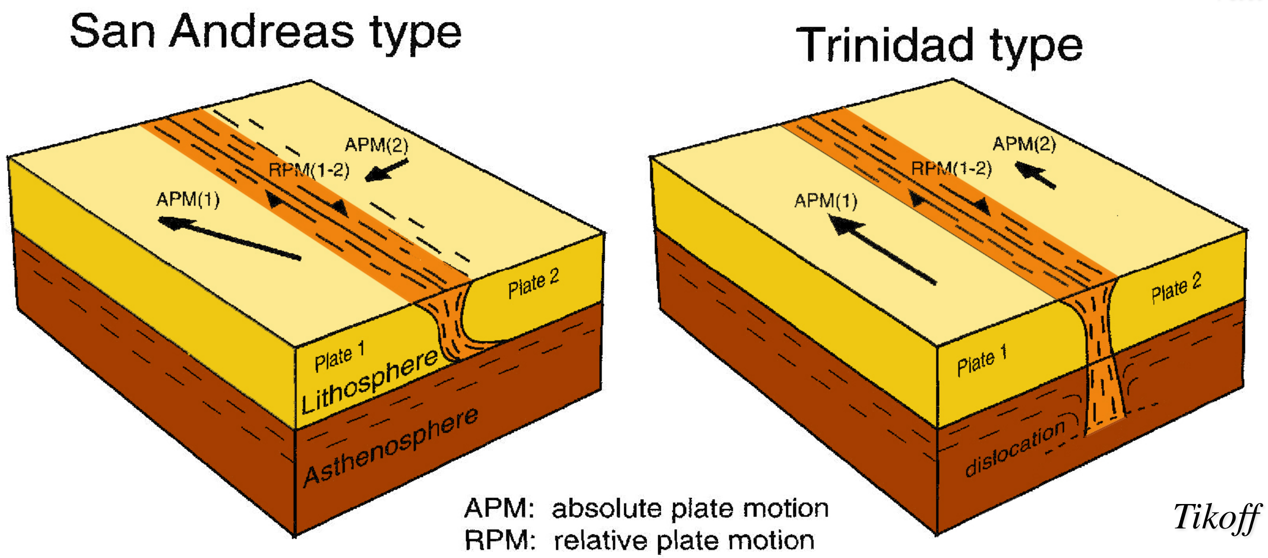
Continental-scale wrench faults in the deep crust & mantle

Seismic anisotropy:

- *Most (but not all?) large wrench faults deform the lithospheric mantle*
- *Fault width in the mantle >50km (w<<50km: no related seismic anisotropy)*
- *Delay times >2s : Coherent flow directions in the lithosphere and asthenosphere*



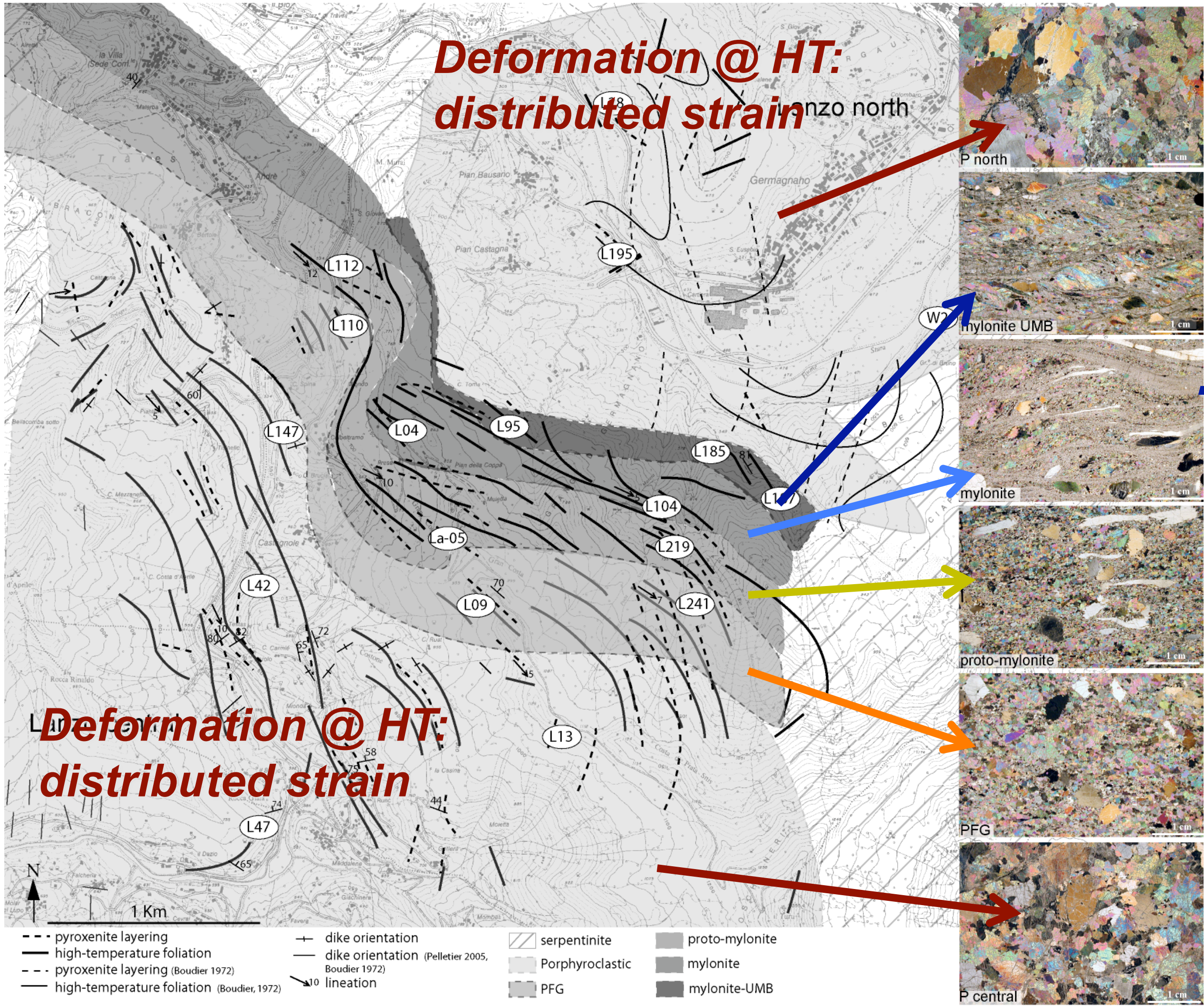
Teyssier and Tikoff 1998
Vauchez and Tommasi 2003



Tikoff et al. 2004

Intrinsic strain localization in the lithospheric mantle?

Lanzo



➔mm

For more details see poster by M.A. Kaczmarek!

deformation under decreasing P,T conditions (>1000-750°C, <1GPa):

- *progressive strain localization (1km➔600m➔300m➔<100m)*
- *grain size reduction (higher deviatoric stresses & strain rates)*
- *when & where?*

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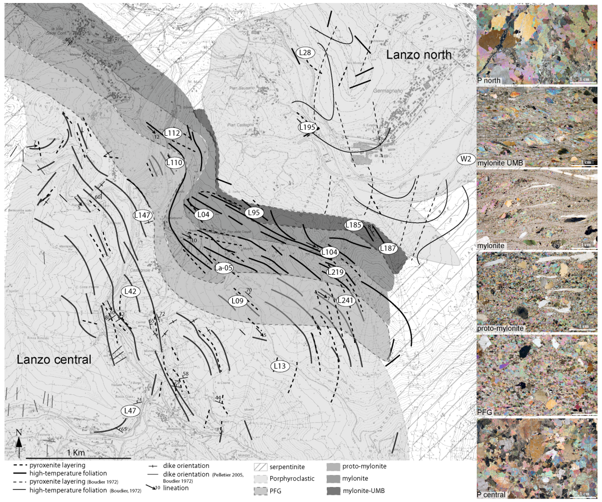
Shear zones in the mantle

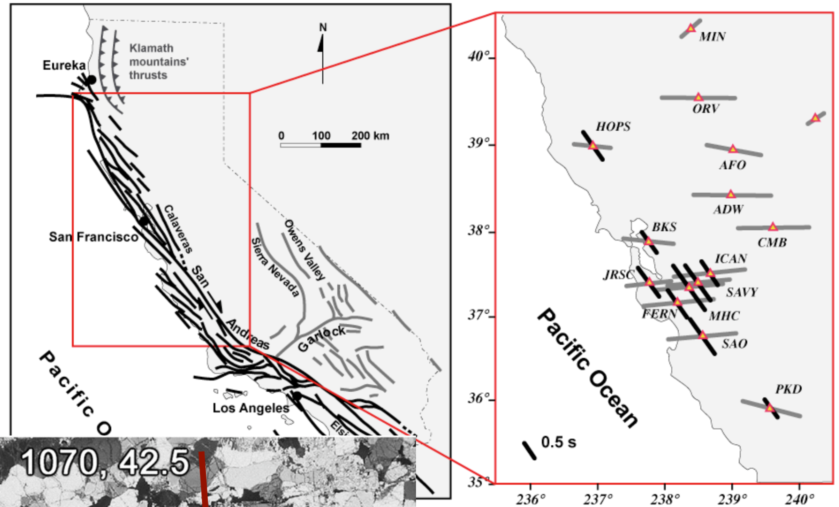


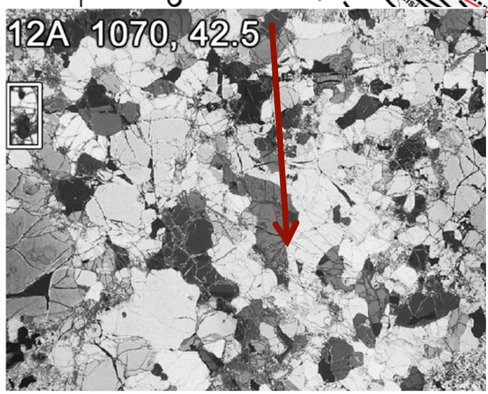
- *Mylonitic zones in the mantle ≤ 1km*
  - *weak olivine CPO = weak anisotropy*

≠

•Strong seismic anisotropy in a ≥50 km wide zone beneath active and fossil strike-slip faults

• Coarse-grained mantle xenoliths





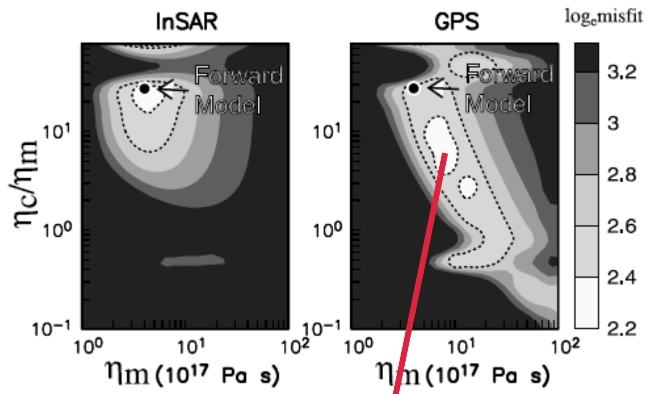
Titus et al. 2007

How does the uppermost lithospheric mantle deform?

Open question : Rheology of the uppermost mantle

✓ *Modeling of post-seismic strain:*

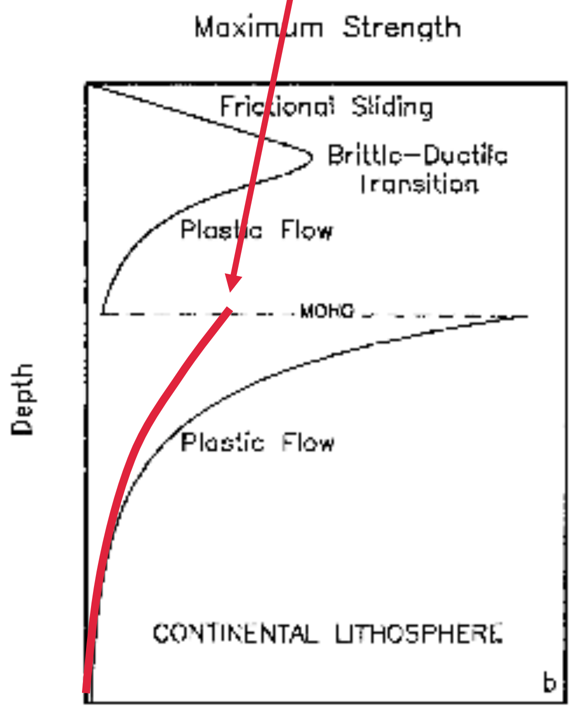
➔ *uppermost mantle viscosity << predictions based on HT lab experiments*



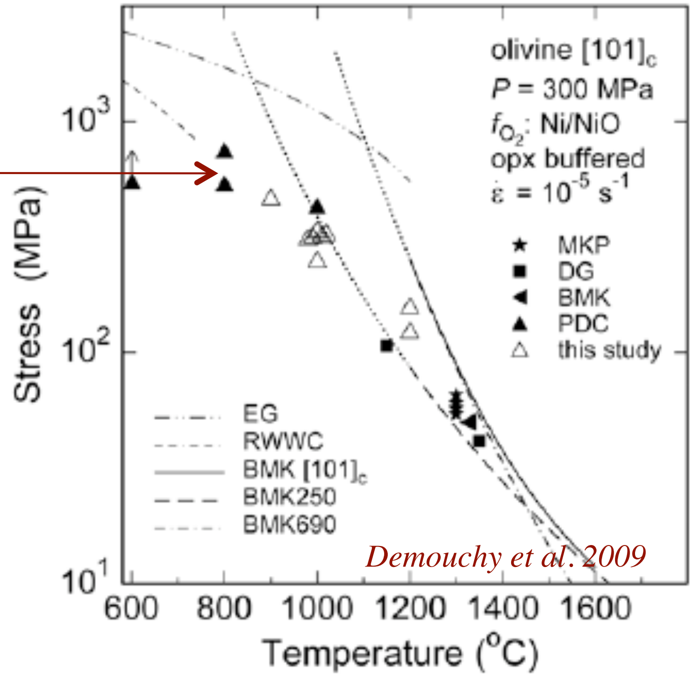
Pollitz et al. 2001

✓ *Clear seismic anisotropy signature, while LT, high stress deformation of peridotites*

➔ *weak CPO & anisotropy!*



New experiments: Olivine @ 900-800°C 1-2 orders of magnitude weaker than predicted by extrapolation of HT power laws!



Demouchy et al. 2009

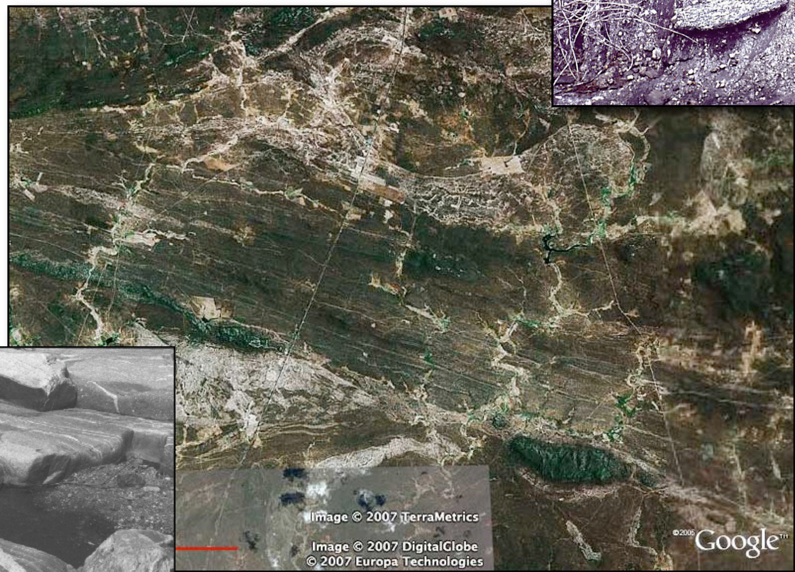
Géosciences Montpellier

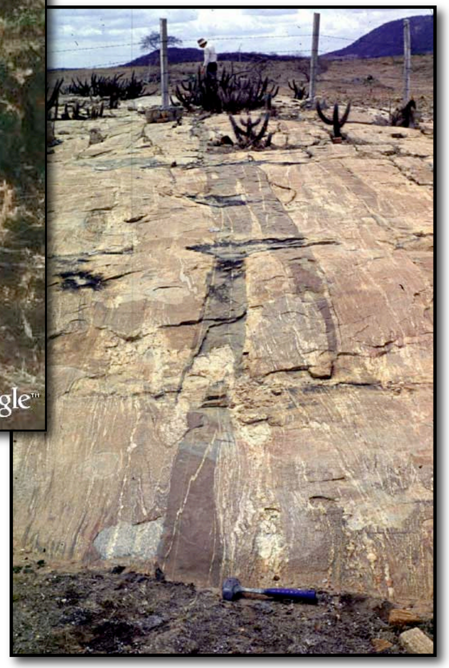
Which processes produce strain localization processes in the ductile deep crust and mantle?

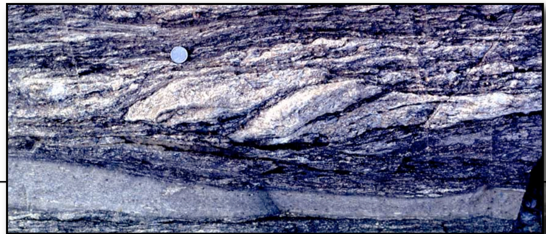
At HT intrinsic strain softening processes not very effective…

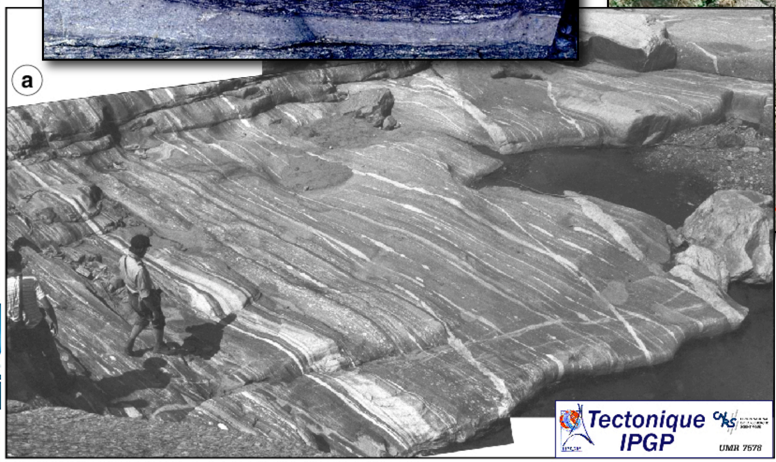
How to weaken a ductile fault?

- *Magmas? Other fluids?*



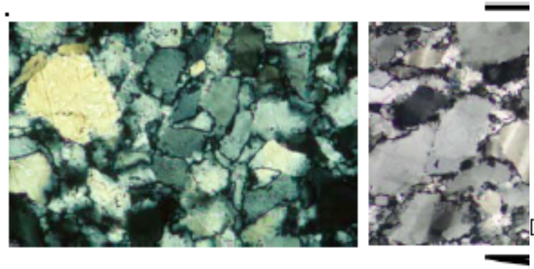


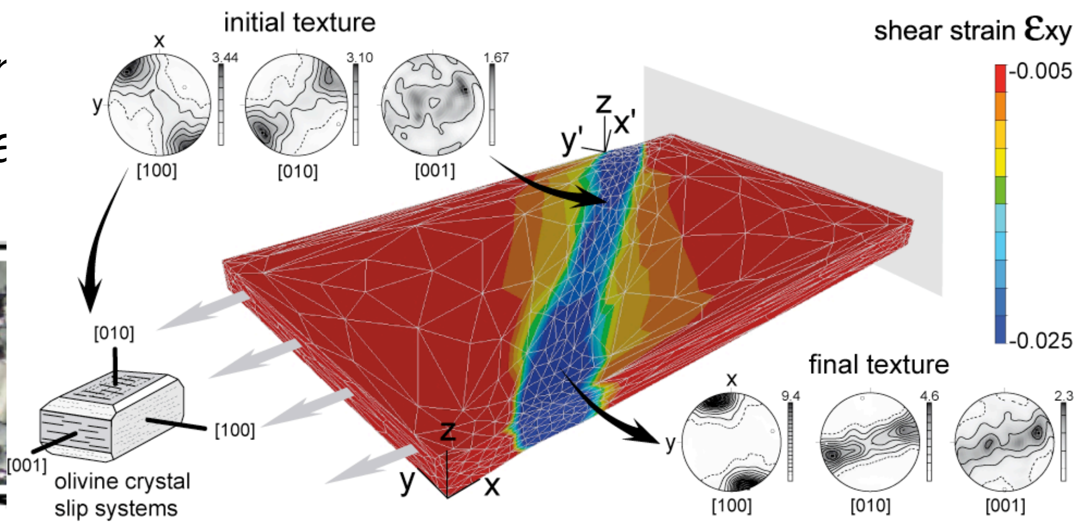


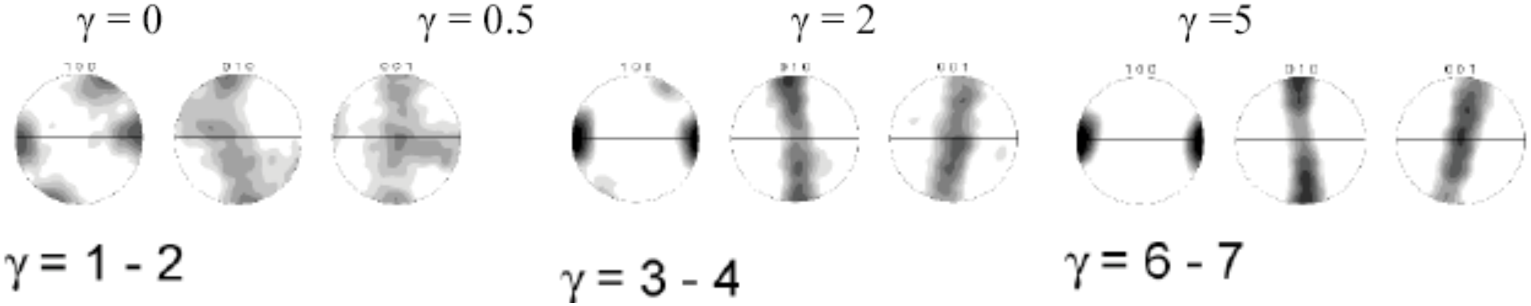


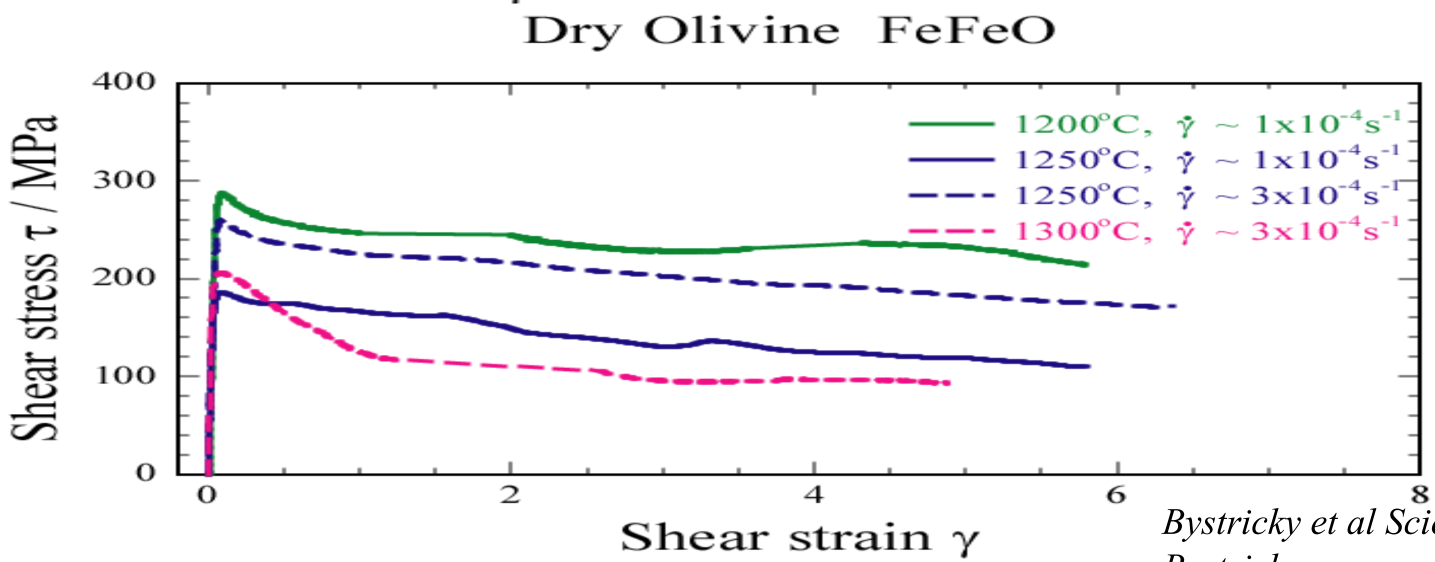
Olivine CPO-induced r

Strain wea







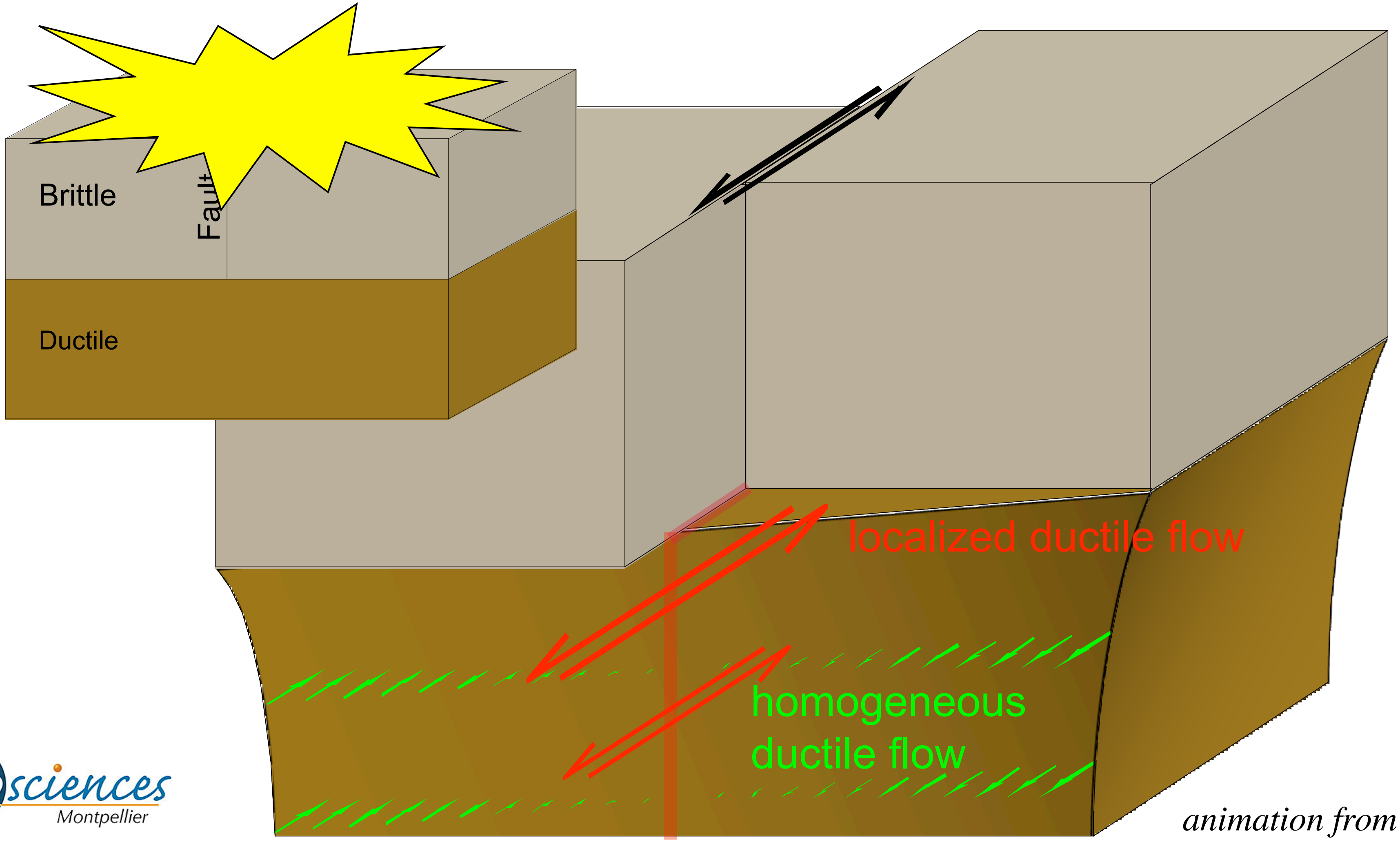


Bystricky et al Science 2003

Bystricky, pers. commun.

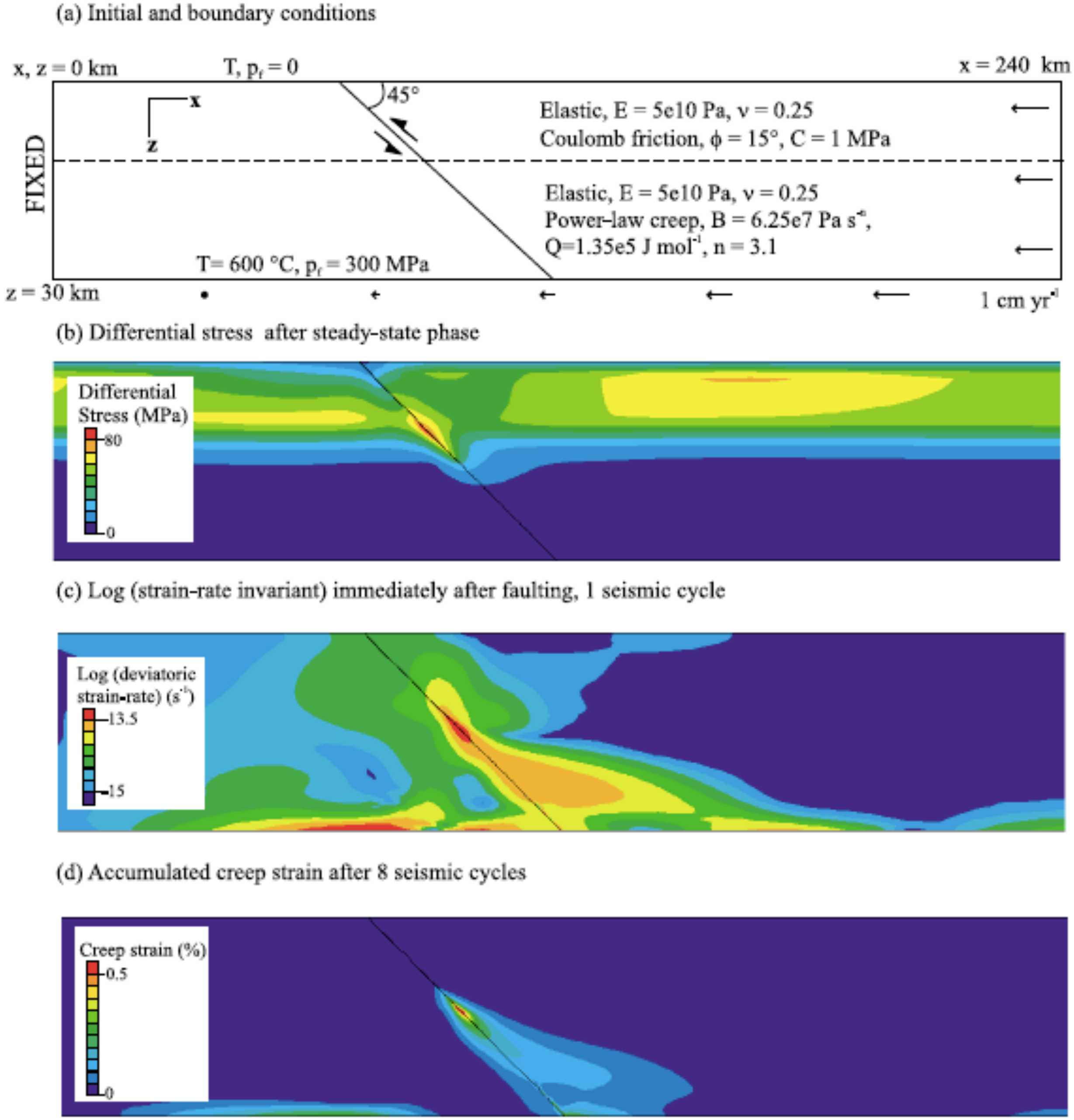
Localization controlled by the brittle crust?

- *Effect of large earthquakes on strain localization in the ductile regime?*



animation from
Laurent Montési

S. ELLIS AND B. STÖCKHERT: IMPOSED STRAIN LOCALIZATION IN THE LOWER CRUST ON SEISMIC TIMESCALES



Earth Planets Space, **56**, 1103–1109, 2004