Seismic vs. aseismic deformation in fault rocks and rock deformation experiments

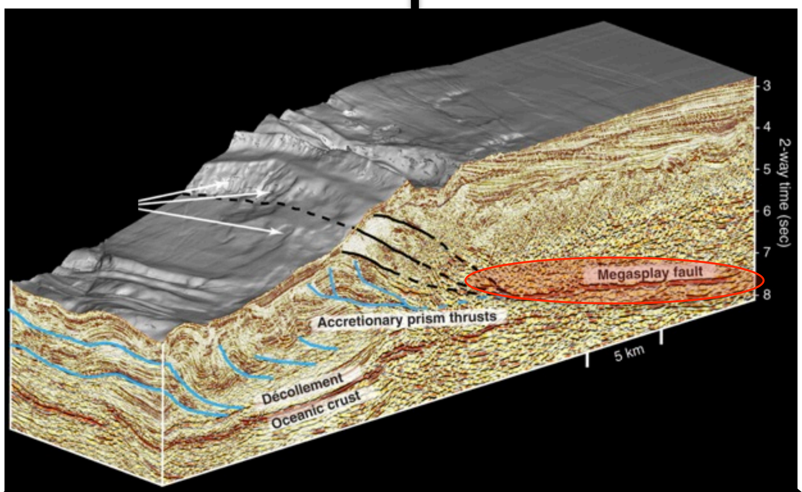
Cristiano Collettini

European Research Council
SEVENTH FRAMEWORK PROGRAMME
"Ideas" Starting Grant
GLASS: 259256

Our understanding of the mechanics of earthquakes and faulting

Seismologists/Geophysicists

Geologists



Experimentalists

Our understanding of the mechanics of earthquakes and faulting

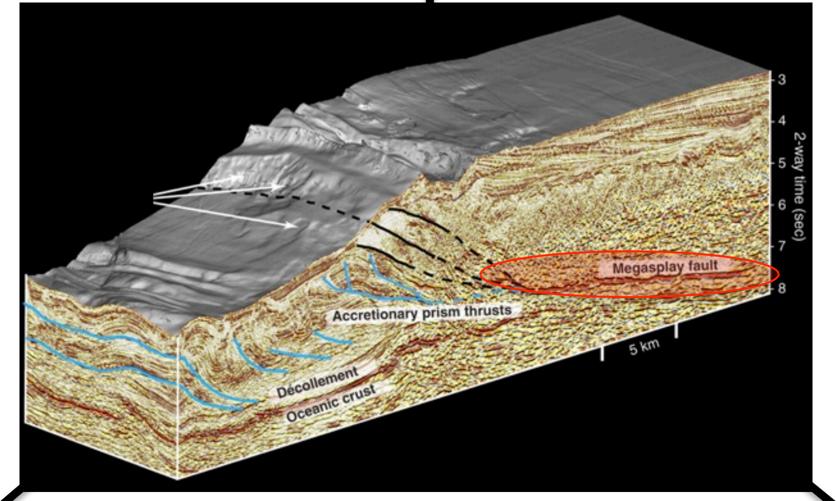
Seismologists/Geophysicists

Seismological and geodetic data
Fast (s) and slow (d-y) deformation

"Normal" Earthquakes
Afterslip
VLF events
Slow earthquakes
Creep

Remote techniques

Fault rocks ?
Deformation mech?
Evolution with time?



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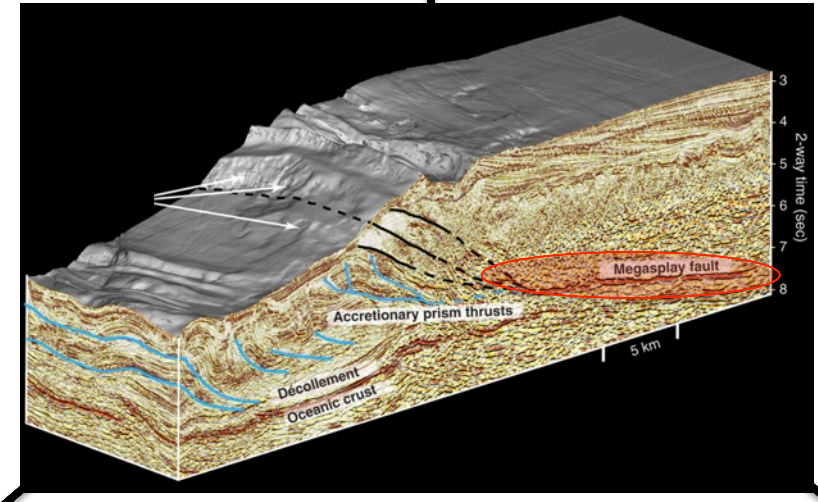
Geologists

Study of ancient and exhumed faults
Long-term deformation (up to Ma)

Textural evolution
Mineralogical evolution
Fluid involvement

No seismic signals

Normal earthquakes ?
Afterslip ?
Creep ?
LFE ?



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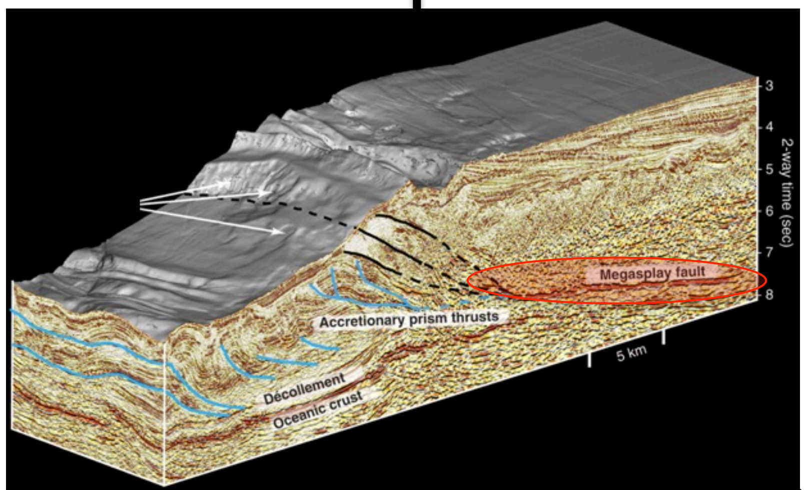

Experimentalists

Test physical properties of fault rocks
Reproduce the physics of faulting

Friction, velocity dependence of friction, fluid flow, microEQs

Scaling problem between experimental (mm-cm) faults and natural (km) faults

Our understanding of the mechanics of earthquakes and faulting

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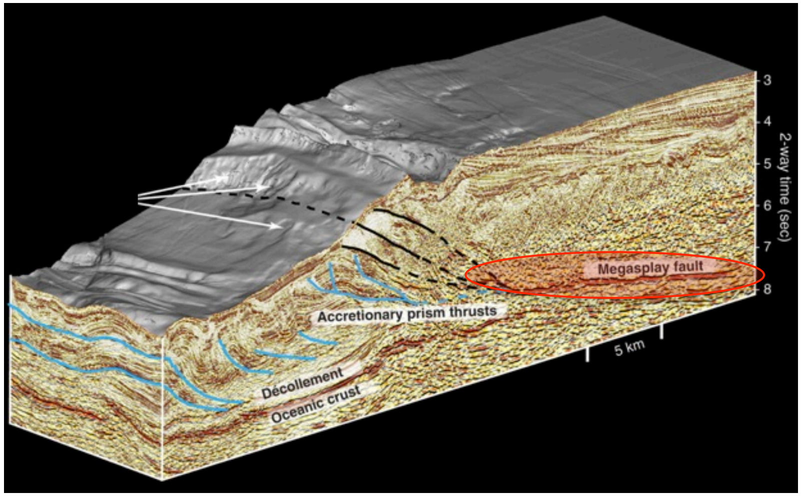

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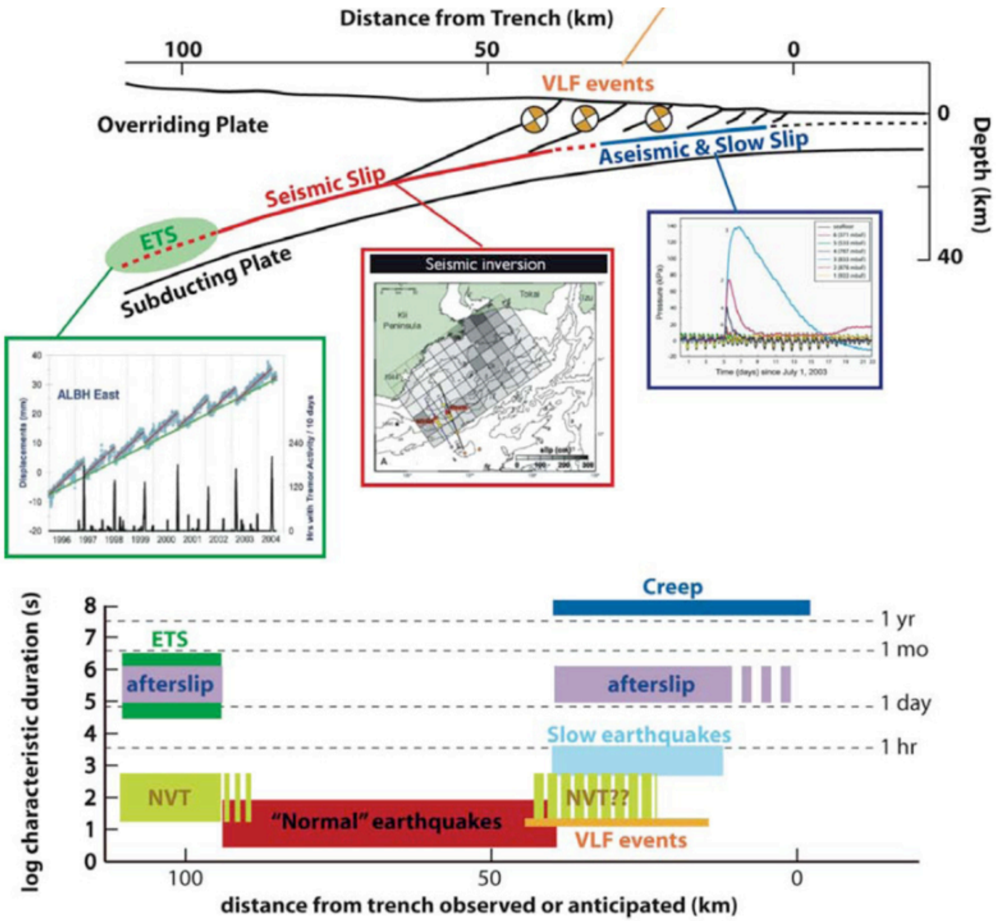
The spectrum of fault slip-behavior documented during this week is the result of different slip processes occurring along faults. These processes produce fault rocks.



Saffer et al., 2009

Introduction

Natural fault rocks and microstructures

Lab. experiments for slip behavior and microstructures

1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

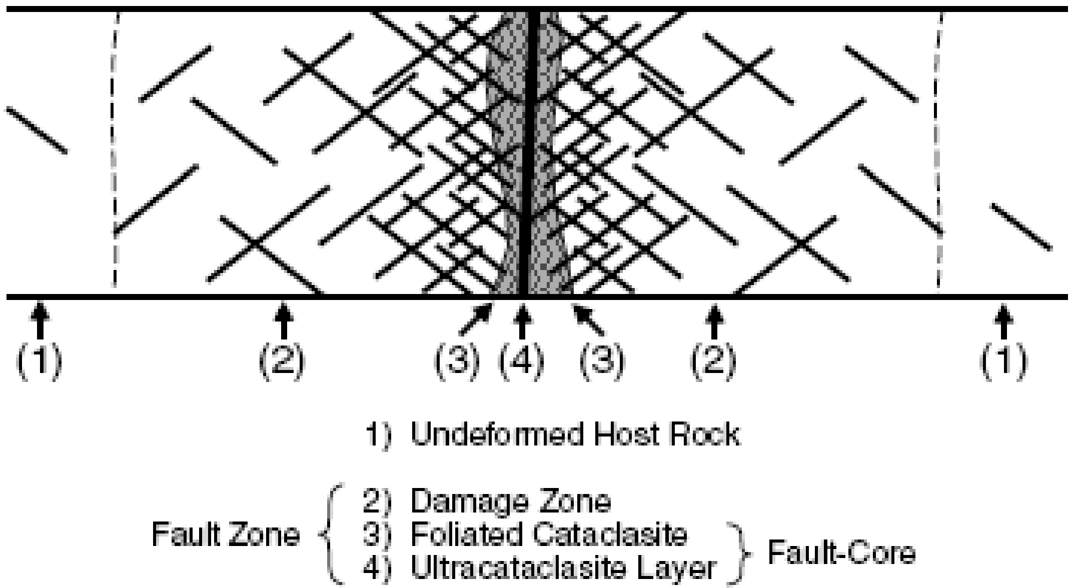
3) Fault structure and slip localization in carbonate-bearing normal faults

Future directions

Experiments on the role of fluid pressure in fault stability

Heterogeneous faults in the lab

Fault zone structure



Chester et al., JGR, 93;

Fault core:
Is the structural, lithologic, morphologic portion of the fault zone where most of the displacement is accumulated

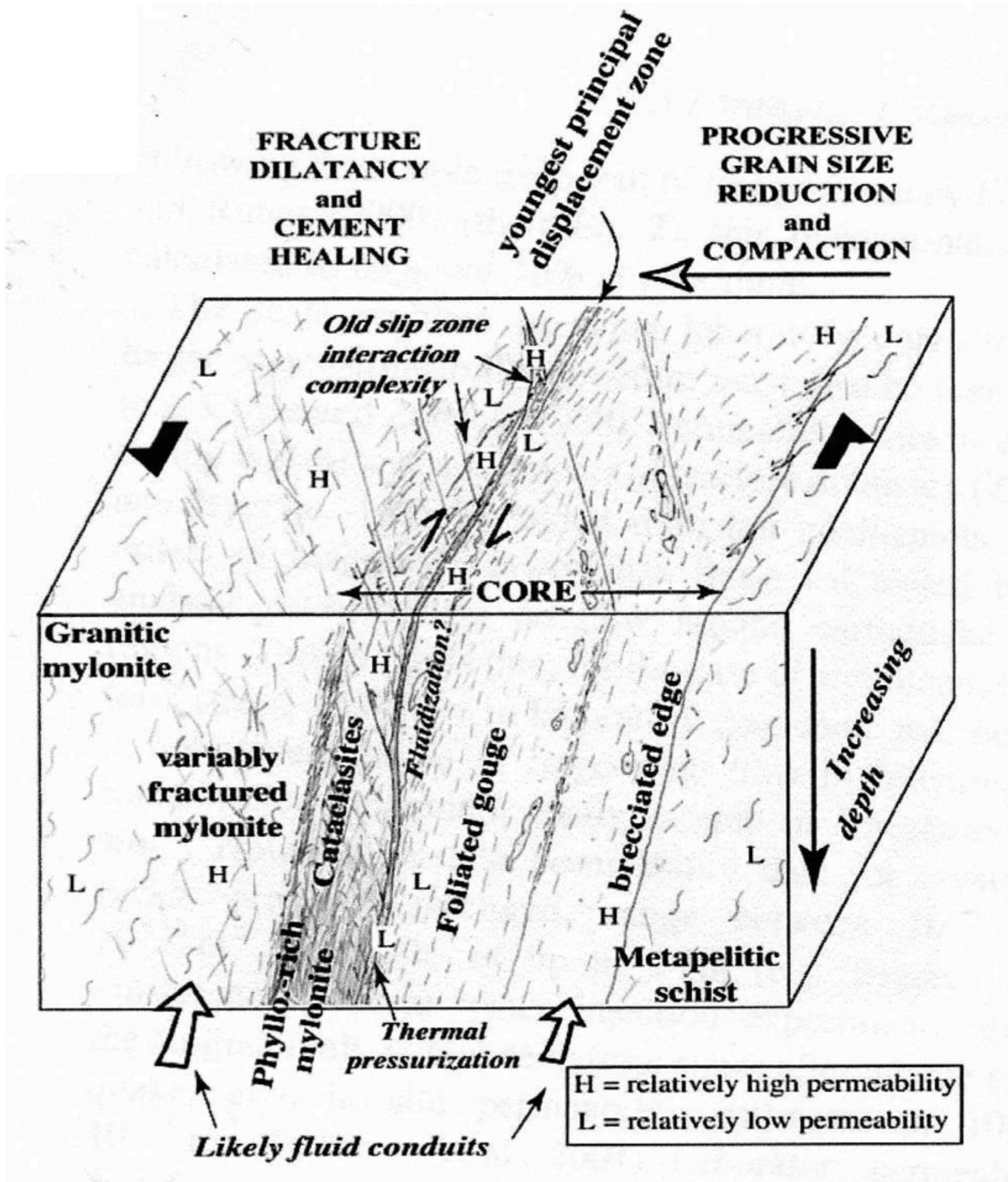
Damage zone:
Is the network of subsidiary structures that bound the fault core

Median Tectonic Line, Japan

(Wibberley & Shimamoto JSG 03

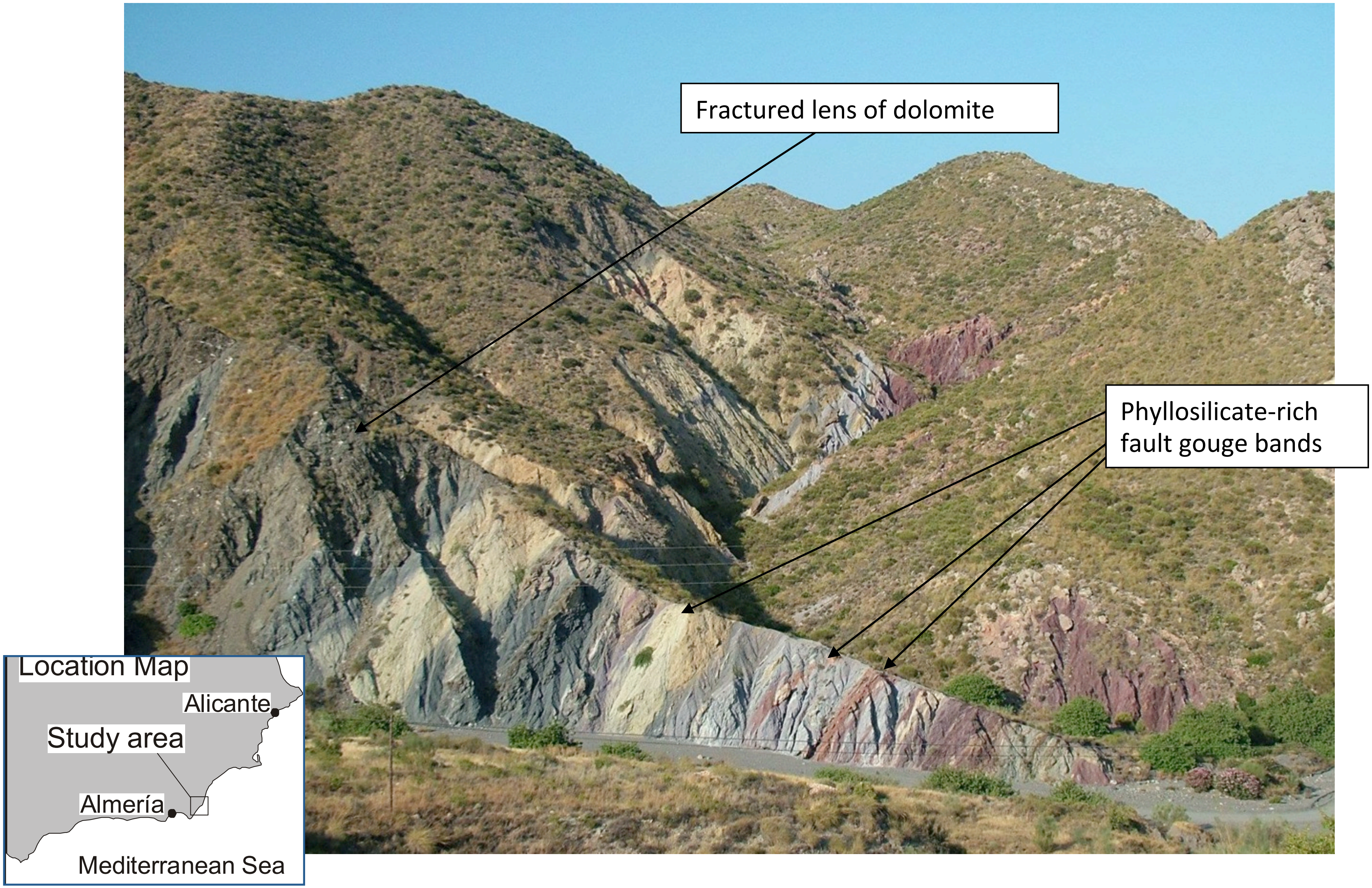
Median Tectonic Line, Japan

(Wibberley & Shimamoto JSG 03



Carboneras fault, Spain

Faulkner & Rutter 01, Geology
Faulkner et al., 03, Tectonophysics



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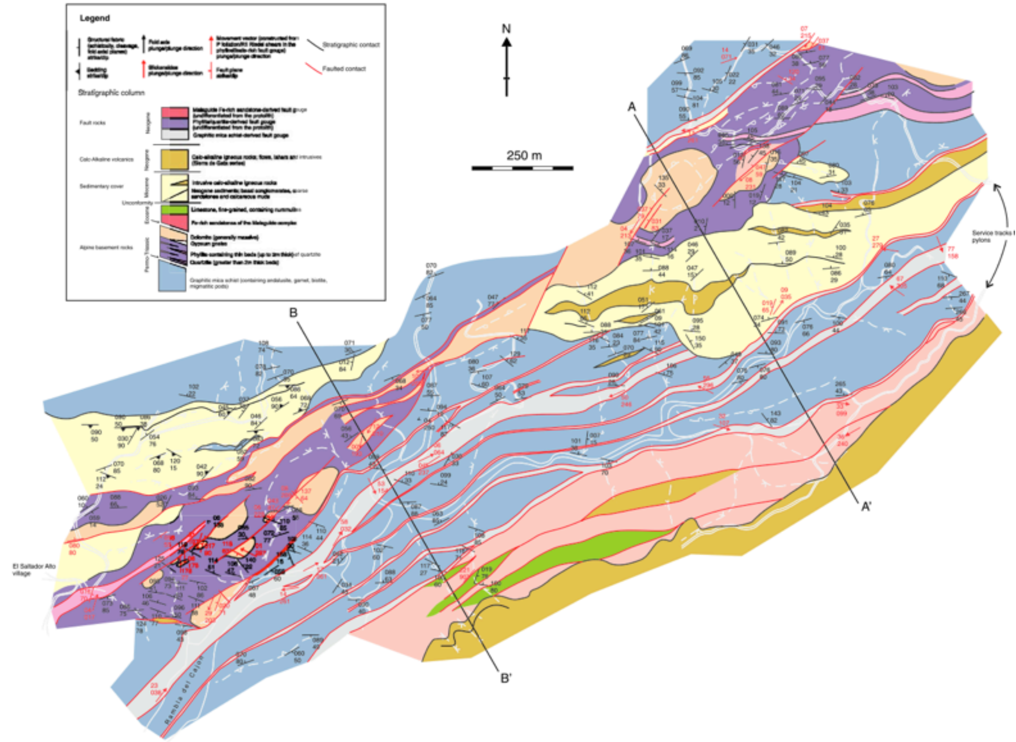
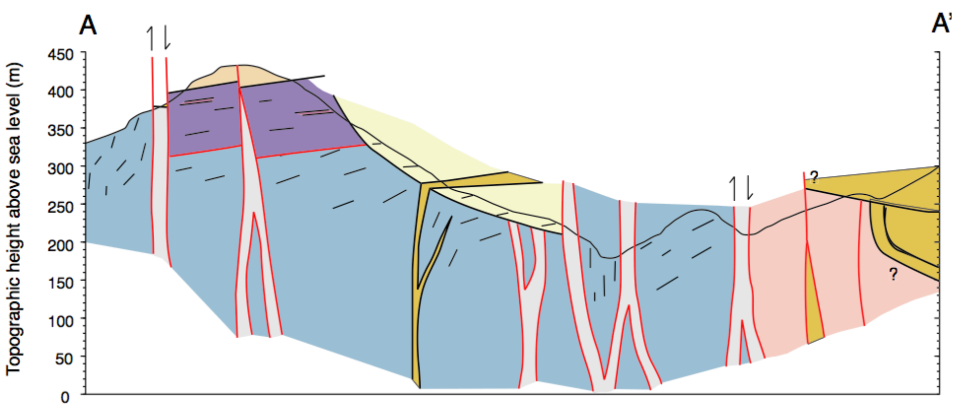
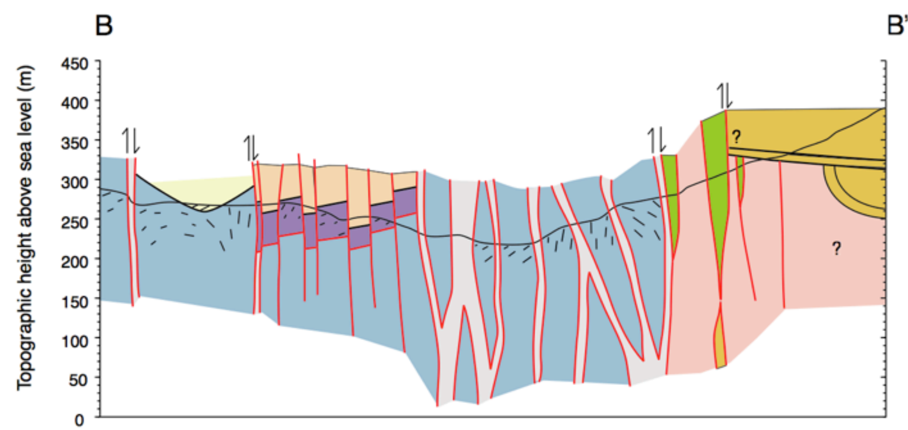
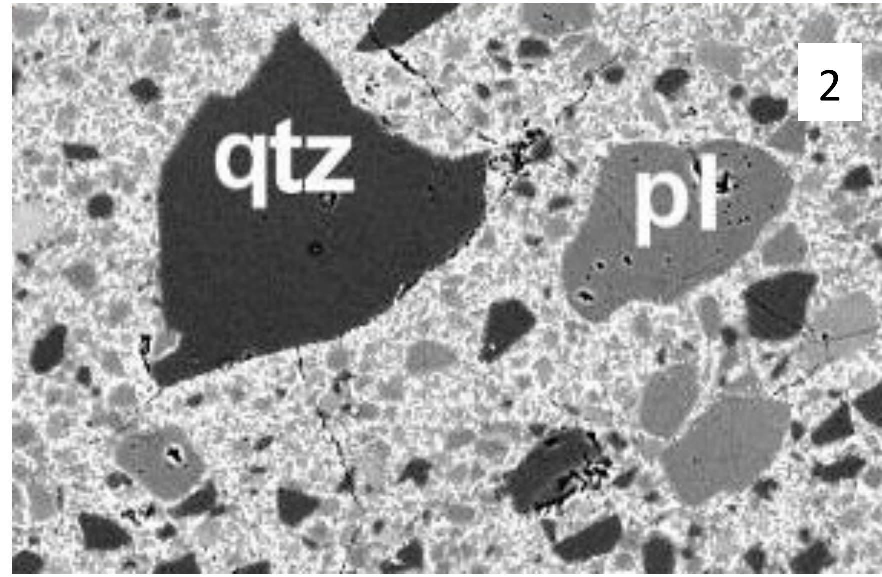
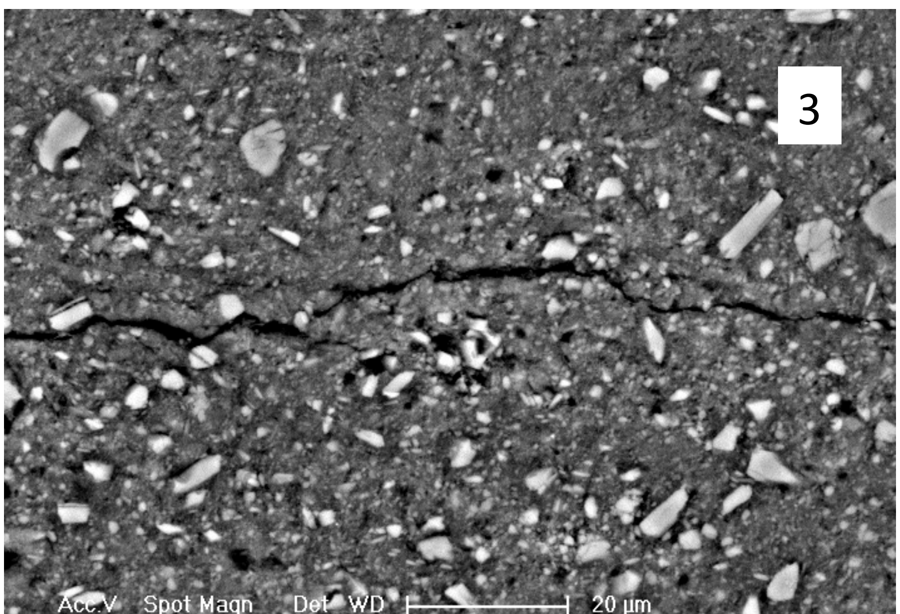


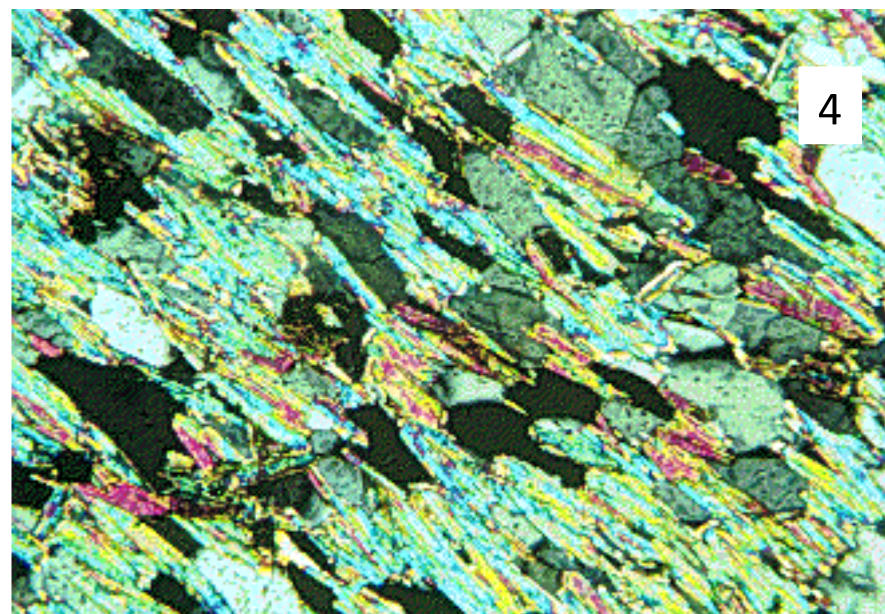




Along the fault zones, fault rocks are the result of different deformation processes







Fault rocks and Fault Mechanisms

R.H. Sibson

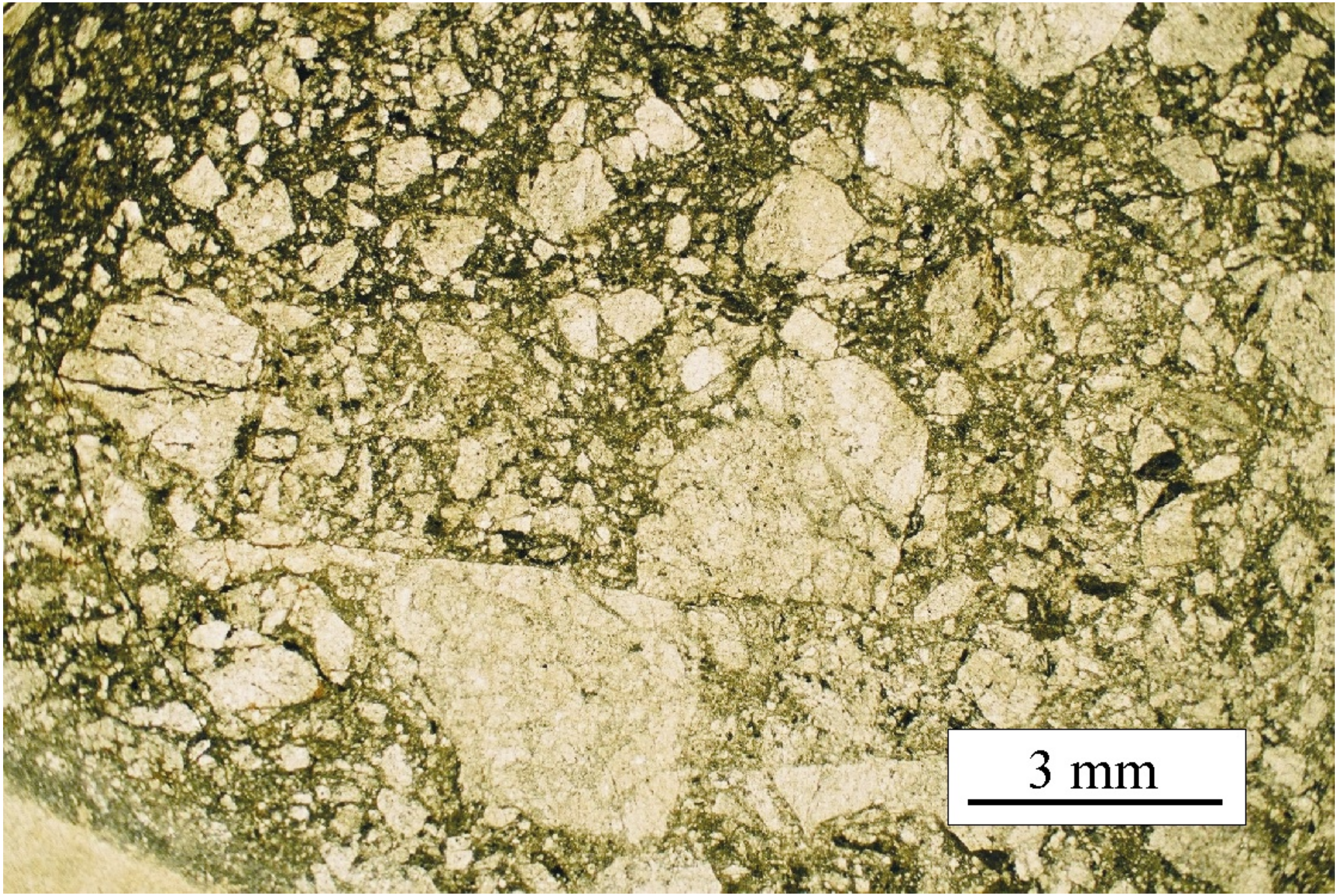
1977

Geol. Soc. Lond. vol 133, 1977, p.191-213 1480 citations

	Random fabric		Foliated	
Incohesive	Fault breccia (visible fragments > 30% of rock mass)			
	Fault gouge (visible fragments < 30% of rock mass)			
Cohesive	Pseudotachylyte (glass, frictional melting)			
	Breccia	0-10 % Matrix		
	Proto cataclasite	10-50% Matrix	Protomylonite	10-50% Matrix
	Cataclasite	50-90% Matrice	Mylonite	50-90% Matrix
	Ultra cataclasite	90-100 % Matrix	Ultramylonite	90-100 % Matrix

Fault gouge formed at 3 km of depth along the Bosman fault (South Africa) during a M=3.7 earthquake in 1997.

Cataclasite formed by grain size reduction, grain rotation and translation + cementation.



Pseudotachylyte: solidified frictional melt (amorphous material, no crystalline structure) formed by temperature rise during fast slip.

Mylonites: foliated rocks produced by “plastic” processes

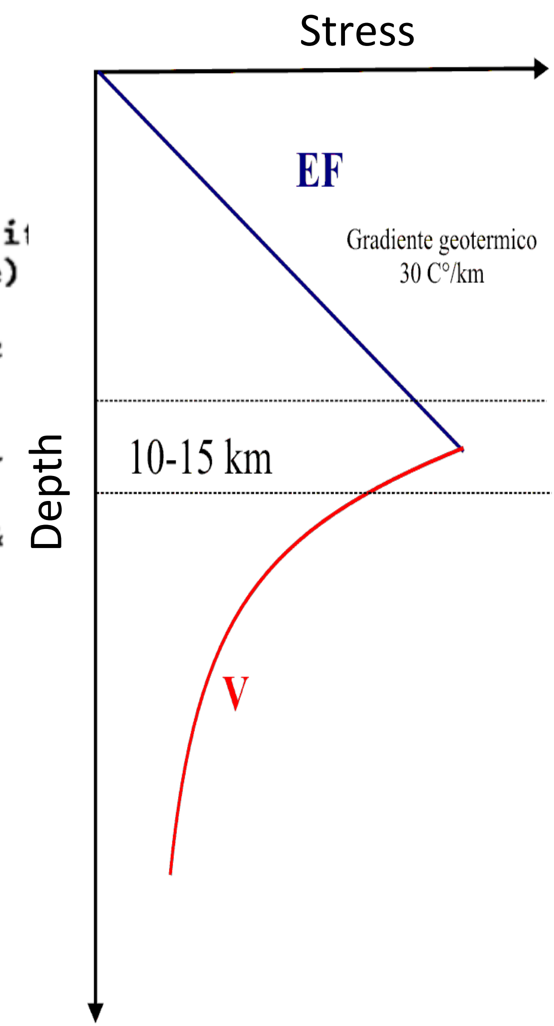
Berthé et al., 1979, JSG
Lister and Snoke, 1984, JGG

1977

R. H. Sibson

2 : *Fault rocks and style of faulting in the Outer Hebrides Thrust zone*

		Style of Faulting	Fault Rocks
random fabric	ELASTICO-FRICTIONAL	Brittle shearing of intact rock Sliding on existing planes	Pseudotachylyte
		Cataclastic crush zones	Cataclasite-Ultracataclasit (& some pseudotachylyte)
		Crush Melange	Crush breccias, microbrec & protocataclasite
foliated	QUASI-PLASTIC	Quasi-plastic shear zones	Phyllonitic mylonites & ultramylonites
		Crush Melange with crude mylonitic foliation	Protomylonites



Fault rocks and Fault Mechanisms

R.H. Sibson

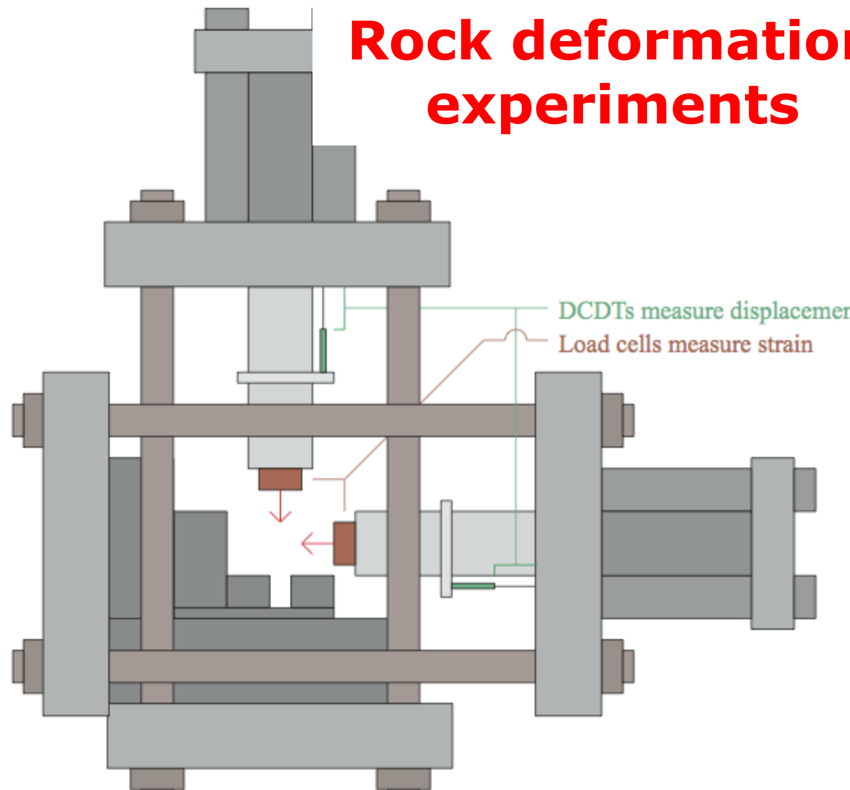
Geol. Soc. Lond. vol 133, 1977, p.191-213 1480 citations

From 1977 we have improved our understanding of fault rocks and deformation mechanisms

Methods

Laboratory analyses: MO, SEM, TEM, XRD.

Rock deformation experiments



Tectonophysics, 111 (1985) 139—146
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

1985

Letter Section

Foliated Cataclasites

F.M. CHESTER, M. FRIEDMAN and J.M. LOGAN

Center for Tectonophysics and Departments of Geology and Geophysics, Texas A&M University, College Station, TX 77843 (U.S.A.)

(Received September 28, 1984)

ABSTRACT

Chester, F.M., Friedman, M. and Logan, J.M., 1985. Foliated cataclasites. *Tectonophysics*, 111: 139—146.

Contrary to recently proposed classifications of fault-related rocks (esp. Wise et al., 1984), cataclasis associated with brittle faulting can produce well-foliated fault gouge. Naturally foliated gouge associated with the Punchbowl fault, Los Angeles Co., California is reproduced in experiments in which only brittle conditions and cataclastic deformation mechanisms prevailed. Moreover, only a brittle regime of physical conditions is inferred for the Punchbowl faulting. Classifications of fault-related rocks must accommodate foliated cataclasites.

Tectonophysics, 111 (1985) 139—146
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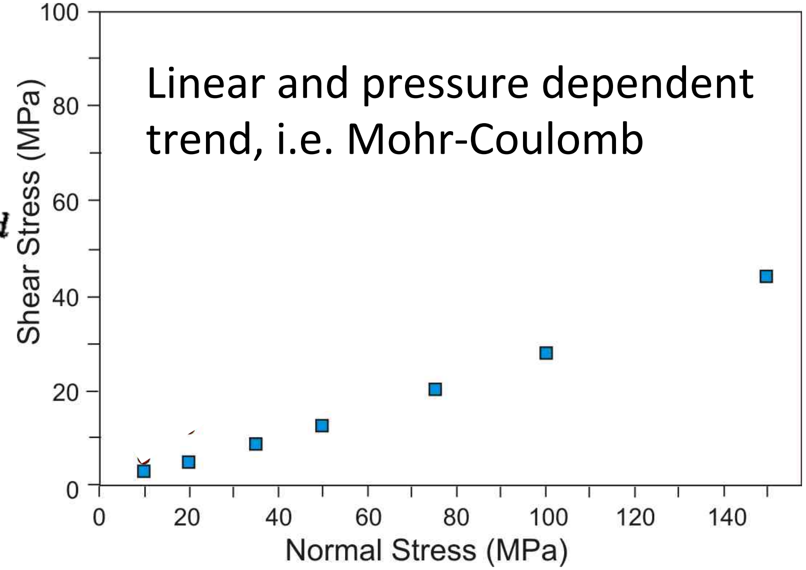
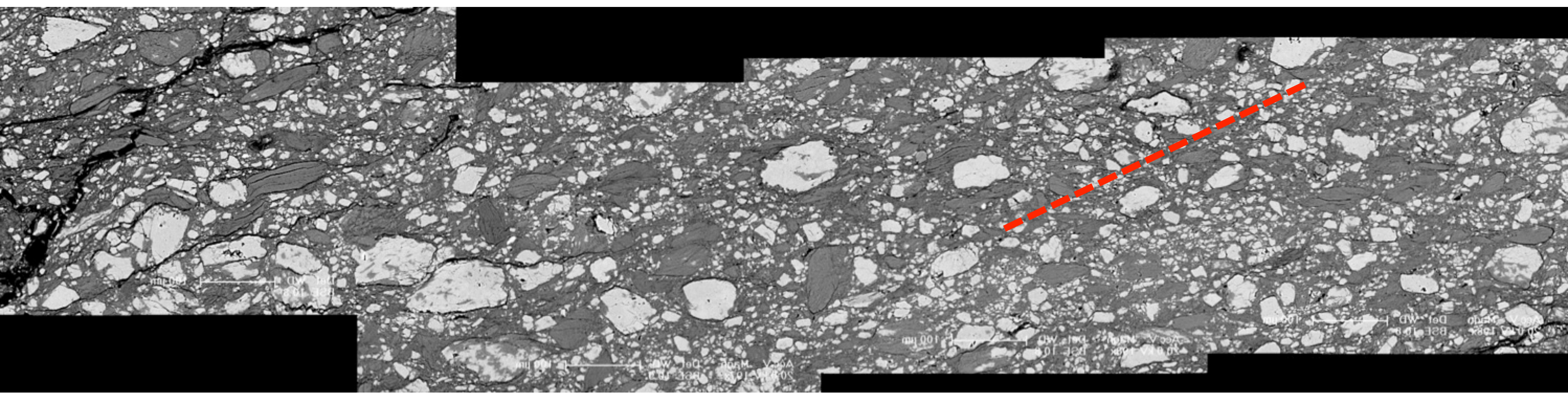




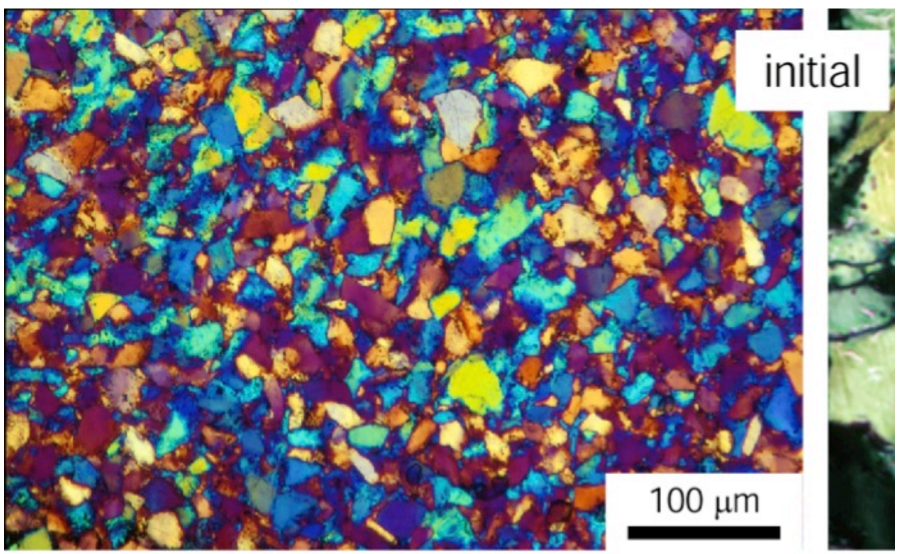
Science 24 November 2000:
Vol. 290 no. 5496 pp. 1564-1567
DOI: 10.1126/science.290.5496.1564

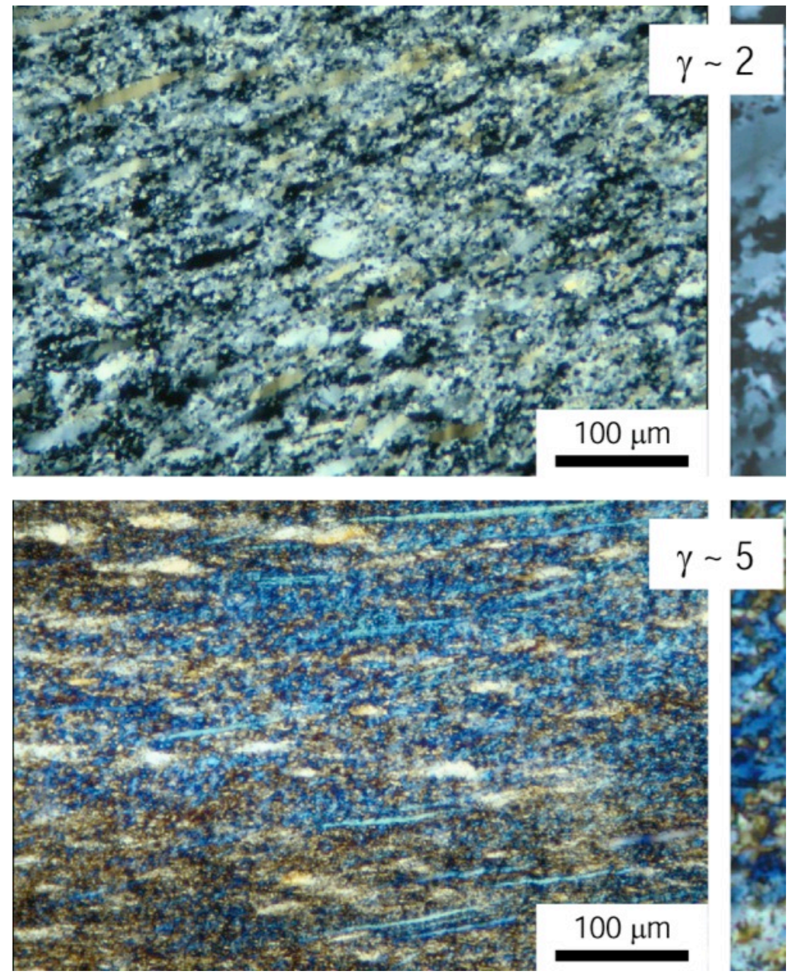
‹ Prev | Table of 2000 ›

REPORT

High Shear Strain of Olivine Aggregates: Rheological and Seismic Consequences

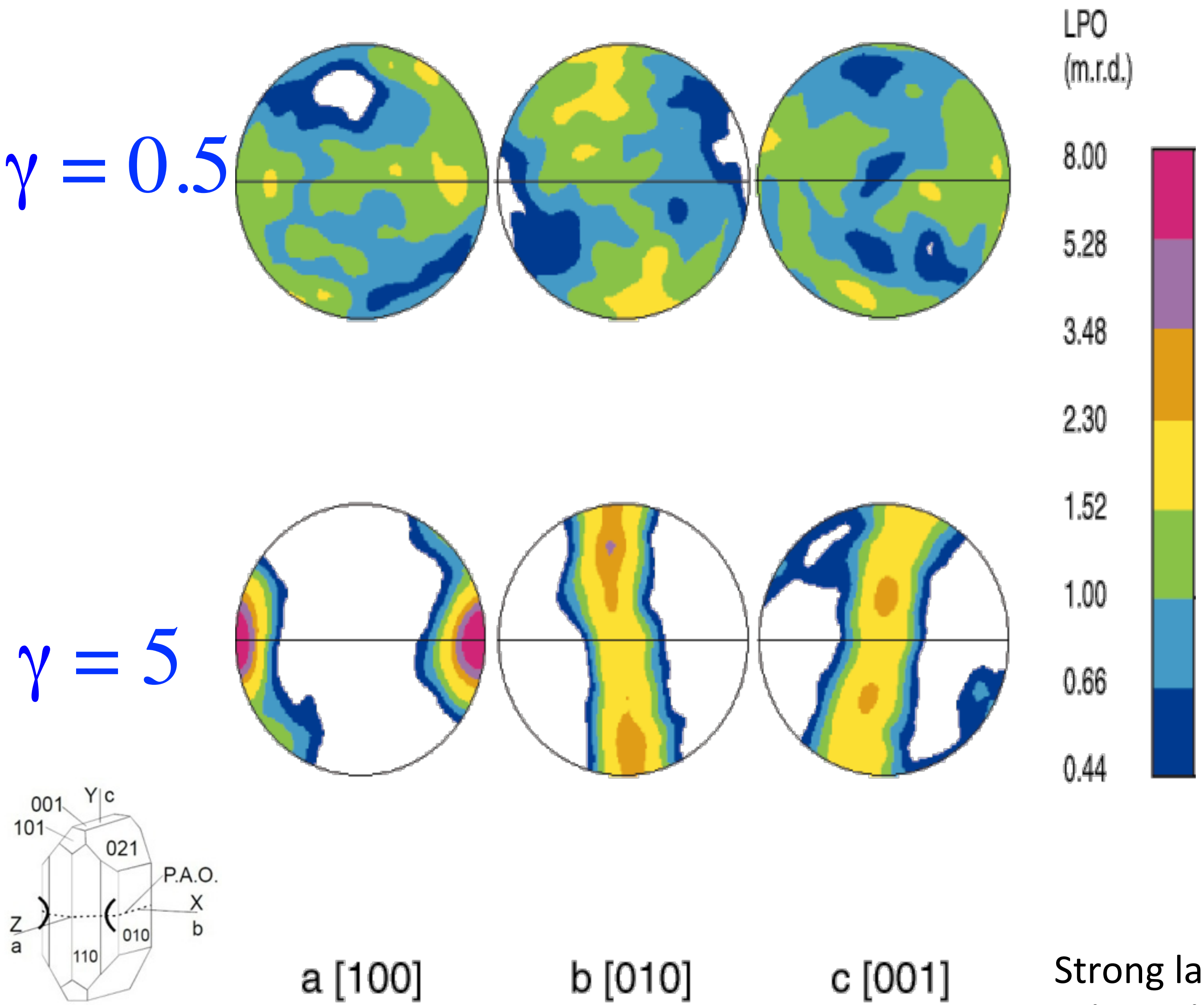
M. Bystricky*, K. Kunze, L. Burlini, J. -P. Burg





Olivine deformed at 1200 C

2000



Strong lattice preferred orientation with deformation

2001

PERGAMON

Journal of Structural Geology 23 (2001) 1187–1202

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Experimental investigation into the microstructural and mechanical evolution of phyllosilicate-bearing fault rock under conditions favouring pressure solution

B. Bos*, C.J. Spiers

HPT Laboratory, Institute of Earth Sciences, Utrecht University, PO Box 80021, 3508 TA Utrecht, the Netherlands

Received 1 June 2000; accepted 21 November 2000

Abstract

Mature crustal fault zones are known to be zones of persistent weakness. This weakness is believed to result from microstructural modifications during deformation, such as grain-size reduction and foliation development. Around the brittle–ductile transition, phyllosilicates are expected to have a significant effect on fault strength, in particular under conditions favouring pressure solution. To study such effects, we performed rotary shear experiments on brine-saturated halite/kaolinite mixtures, aimed at investigating the relation between microstructural and mechanical evolution in a system where pressure solution and cataclasis dominate. The results show significant strain weakening, and a transition with progressive strain towards more rate-sensitive and less normal stress-sensitive behaviour. This was accompanied by a microstructural evolution from a purely cataclastic microstructure to a mylonitic microstructure consisting of elongate, asymmetric clasts in a fine-grained, foliated matrix. The results demonstrate that strain weakening and the development of a typical 'mylonitic' microstructure can occur as a consequence of grain-size reduction by cataclasis, and a transition to pressure solution accommodated deformation, even in the absence of dislocation creep. The data raise questions regarding the reliability of microstructures as rheology indicators, as well as on the use of low strain, monomineralic flow laws for modelling crustal dynamics.

PERGAMON

Journal of Structural Geology 23 (2001) 1187–1202

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

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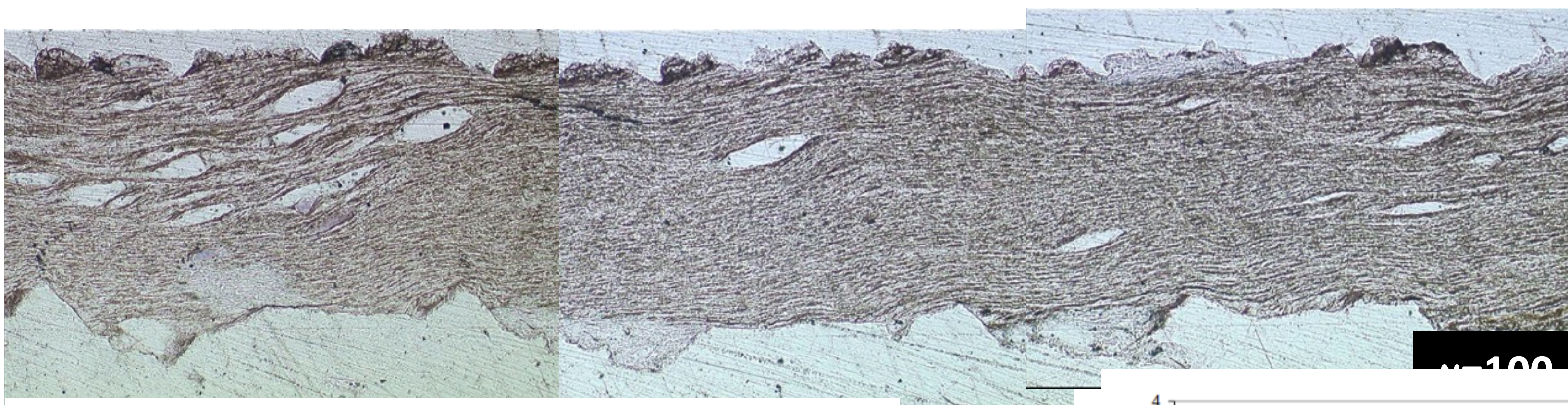

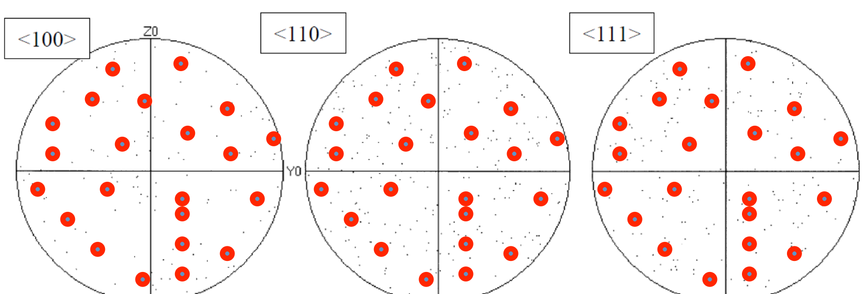

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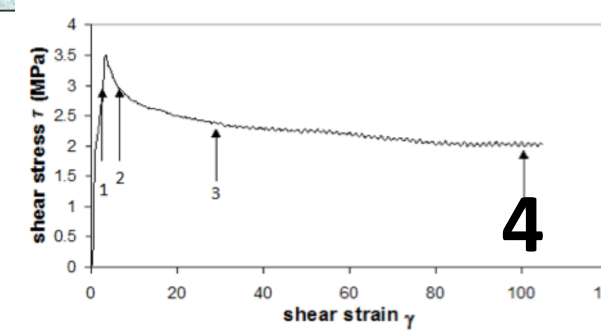
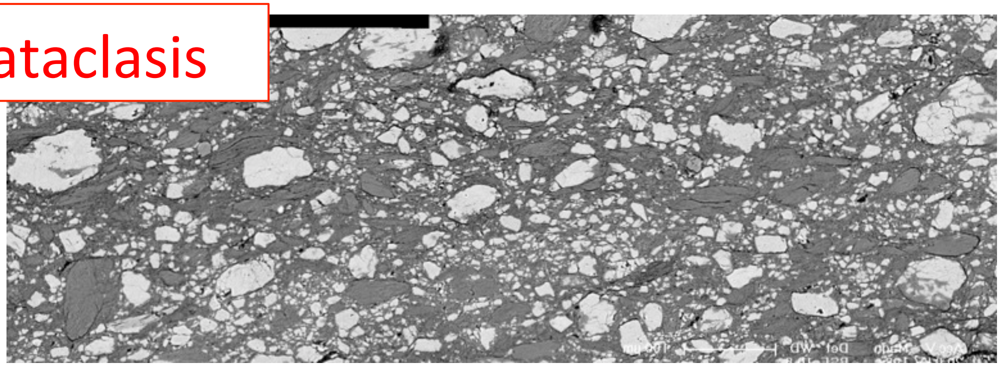
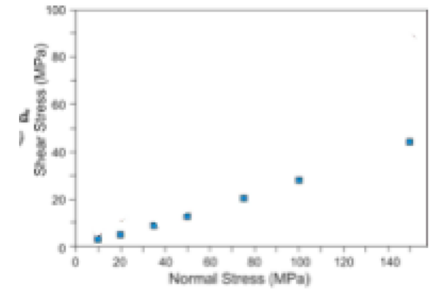


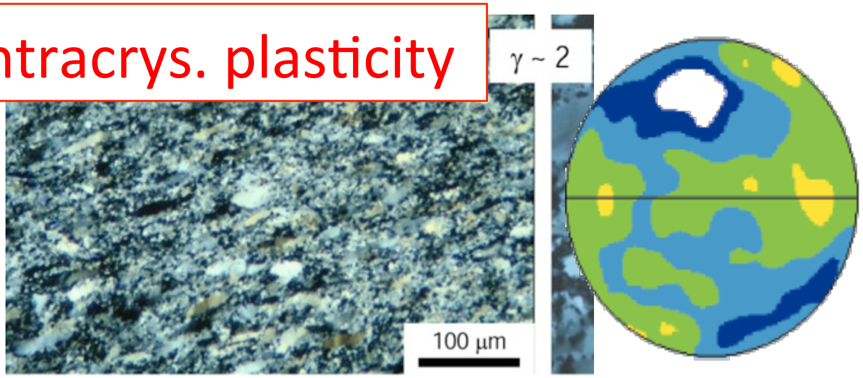
Foliated Fault rocks formed by:

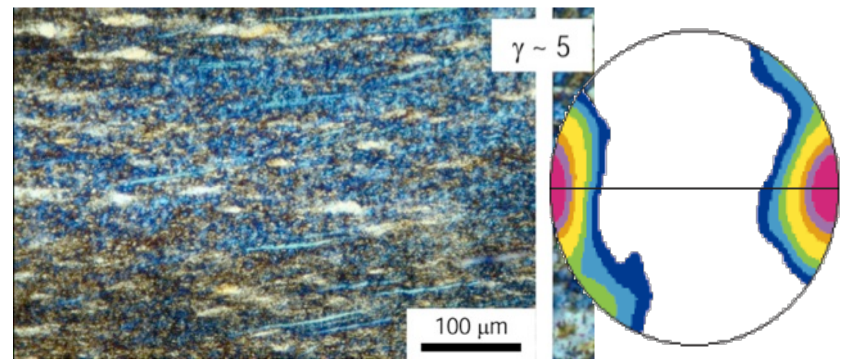
Cataclasis



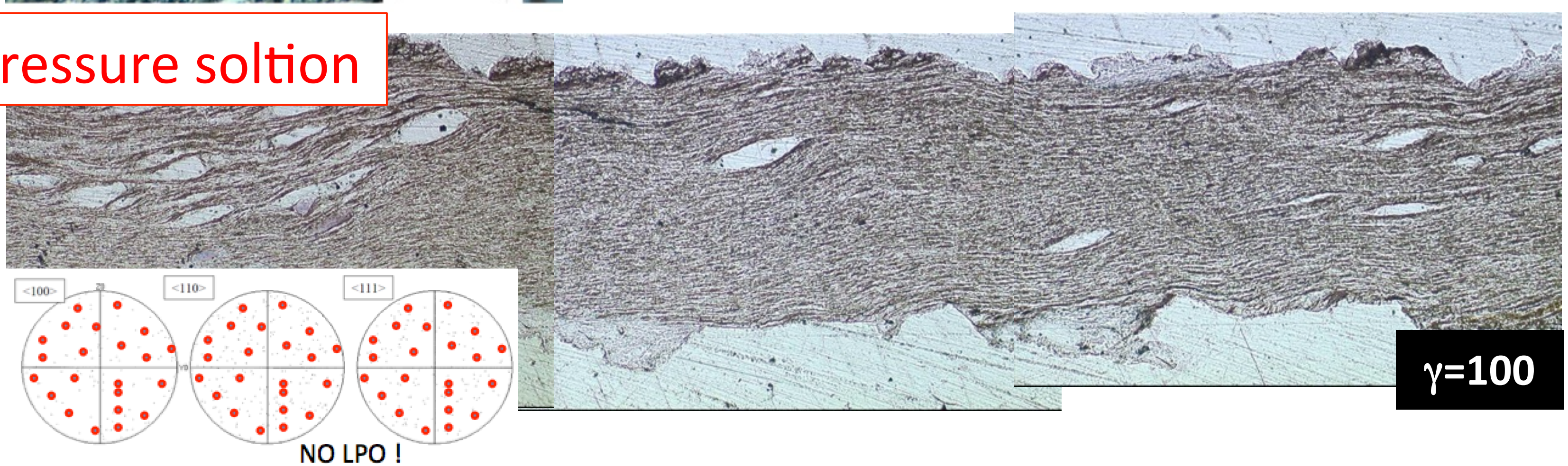


Intracrys. plasticity





Pressure soltion



Fault rock classification & deformation mechanisms

Random fabric				Foliated		
Incohesive	Fault breccia (visible fragments > 30% of rock mass)		Cataclasi	Foliated gouge		cataclasis
	Fault gouge (visible fragments < 30% of rock mass)		Cataclasi			
Cohesive	Pseudotachylyte (galss, frictional melting)		Frictional melting	SCC' tectonites		Dissolution-precipitation
	Breccia	0-10 % Matrice	Cataclasis	Mylonites		
	Proto cataclasite	10-50% Matrix	Cataclasis	Protomylonite	10-50% Matrix	Intracryst. Plastic
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Future directions

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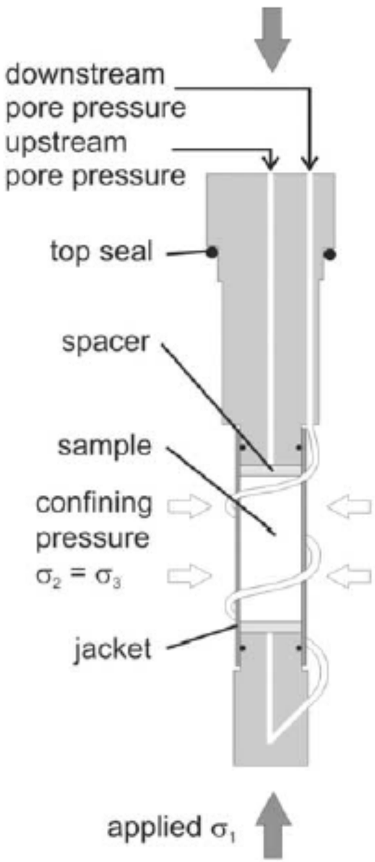
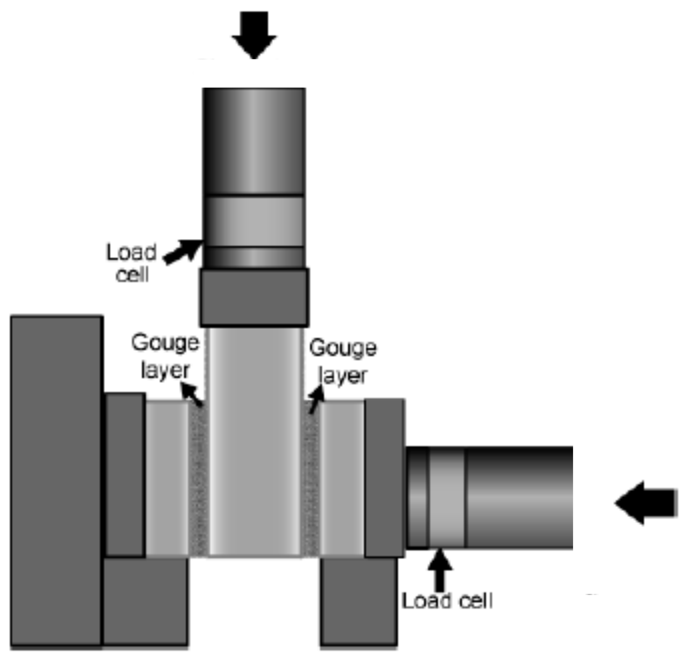
Heterogeneous faults in the lab

Frictional properties

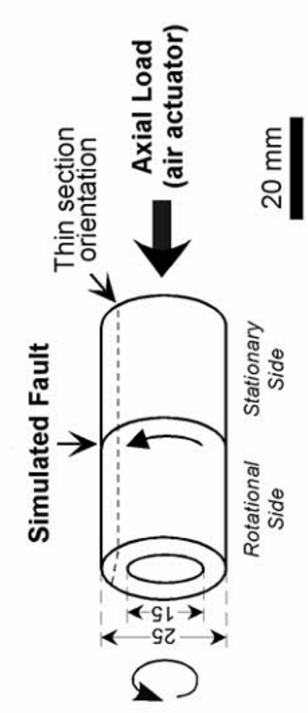
Triaxial



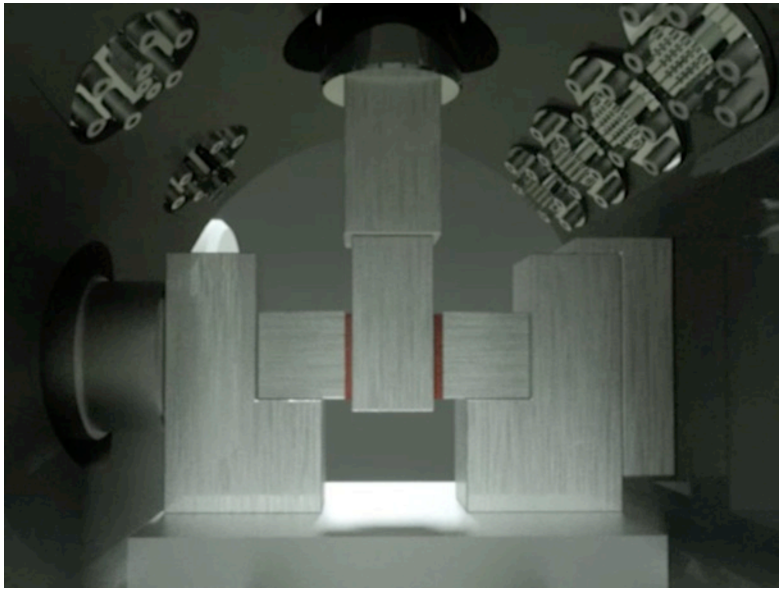
Biaxial

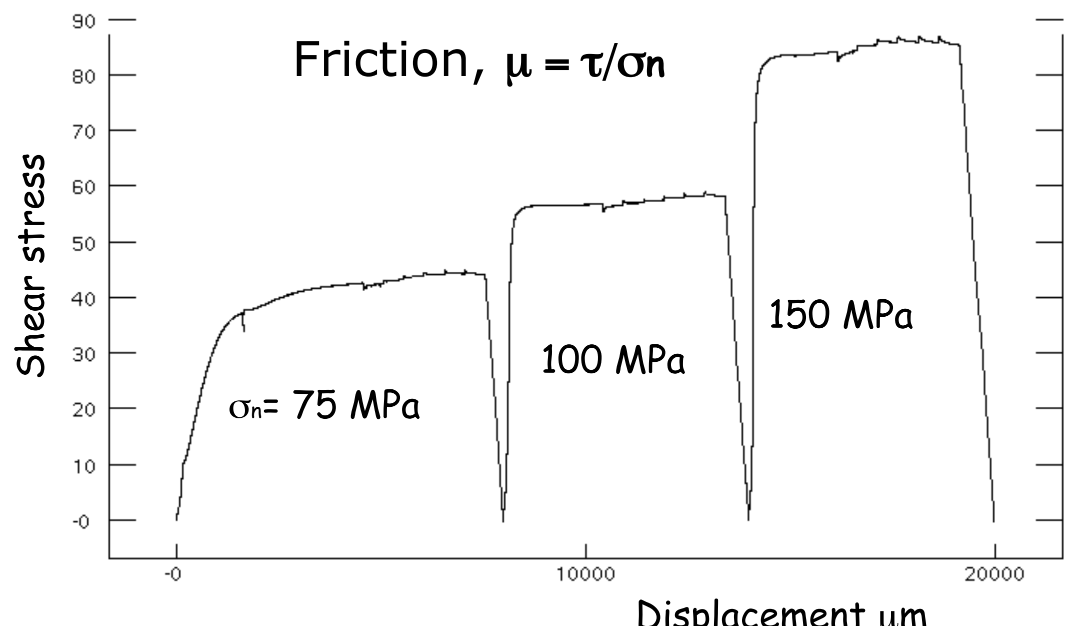


Rotary-shear



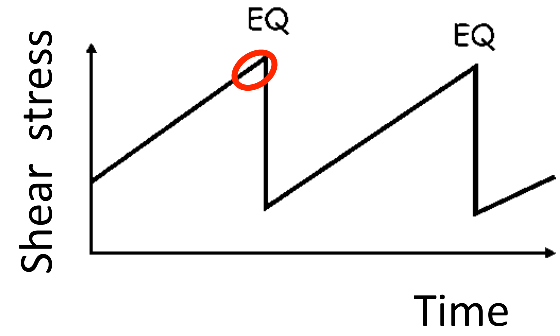
Frictional properties

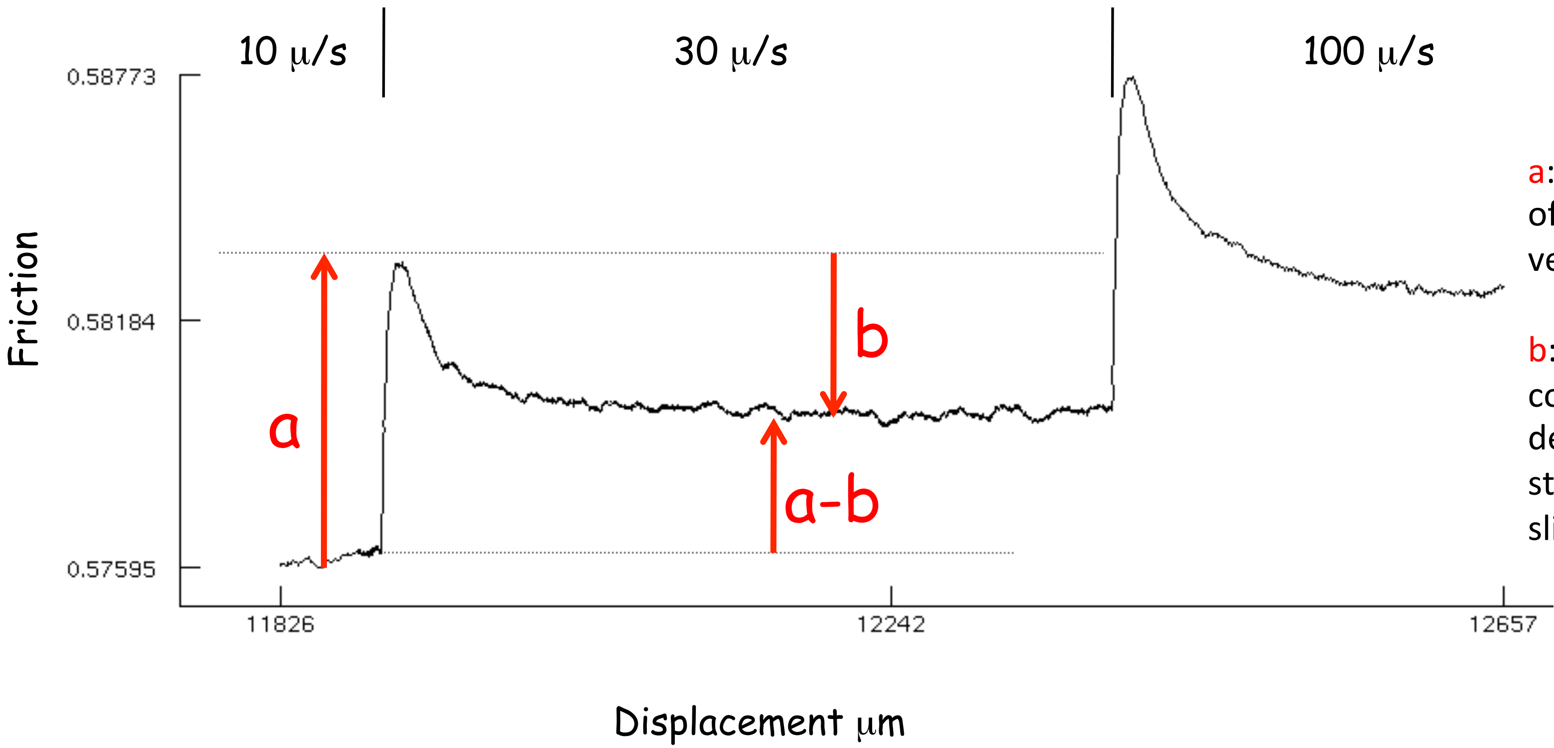




EQ nucleation phase

Velocity dependence of friction





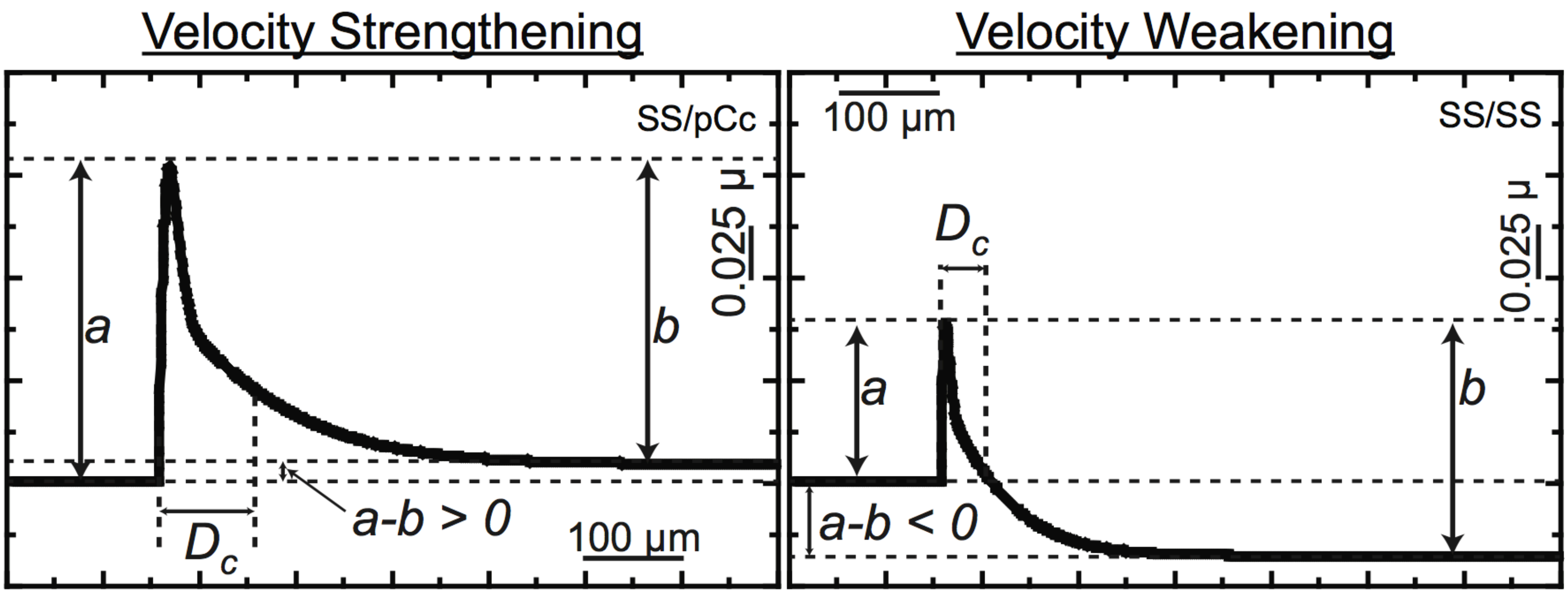
a: direct effect always of the same sign of the velocity change.

b: evolution effect, the coefficient of friction decay to a steady state for the new sliding velocity.

The velocity dependence of sliding friction is given by (a-b) = $\Delta u / \Delta \ln V$

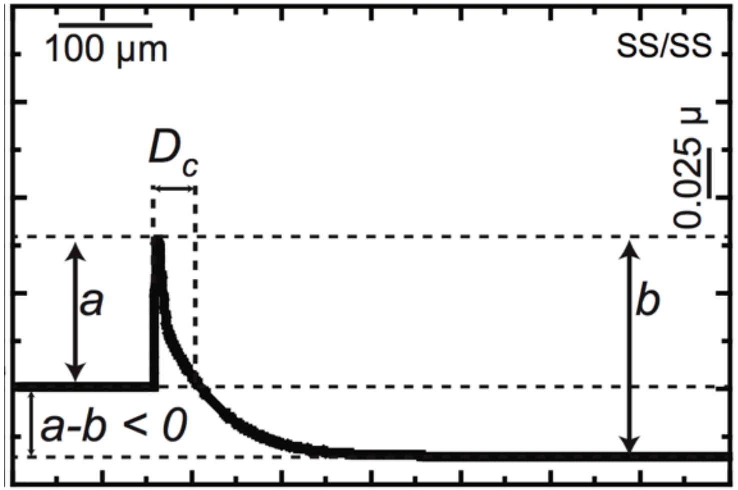
EQ nucleation phase

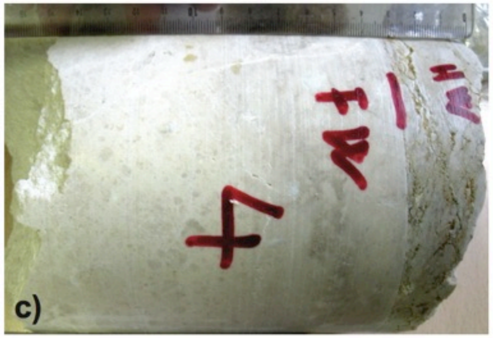
Velocity dependence of friction

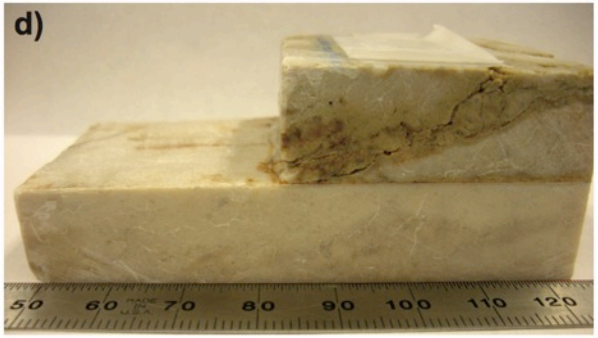


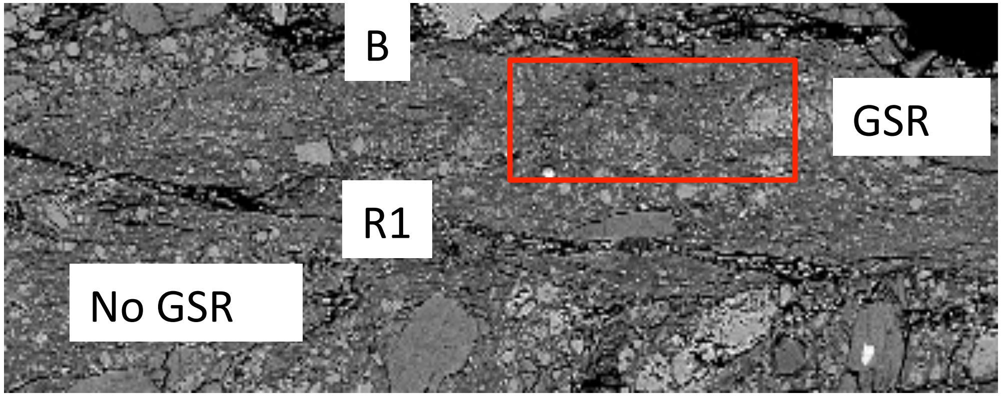
EQ nucleation phase

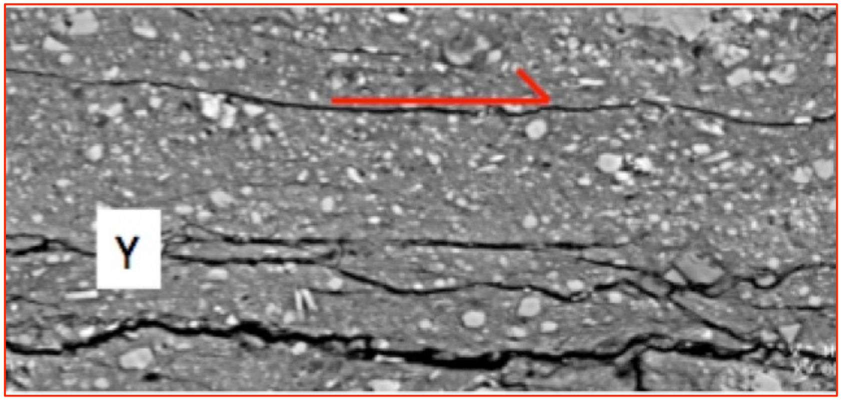
Velocity weakening behavior seems to occur along sharp slip surfaces promoted by grain-size reduction and localization.





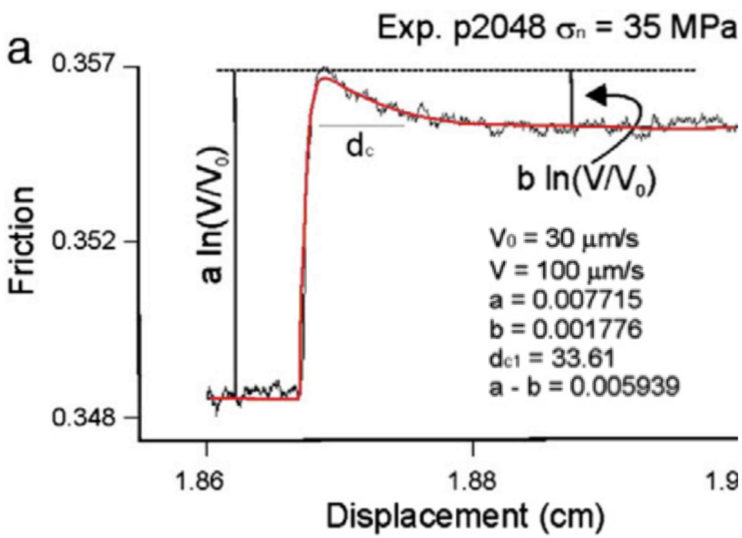


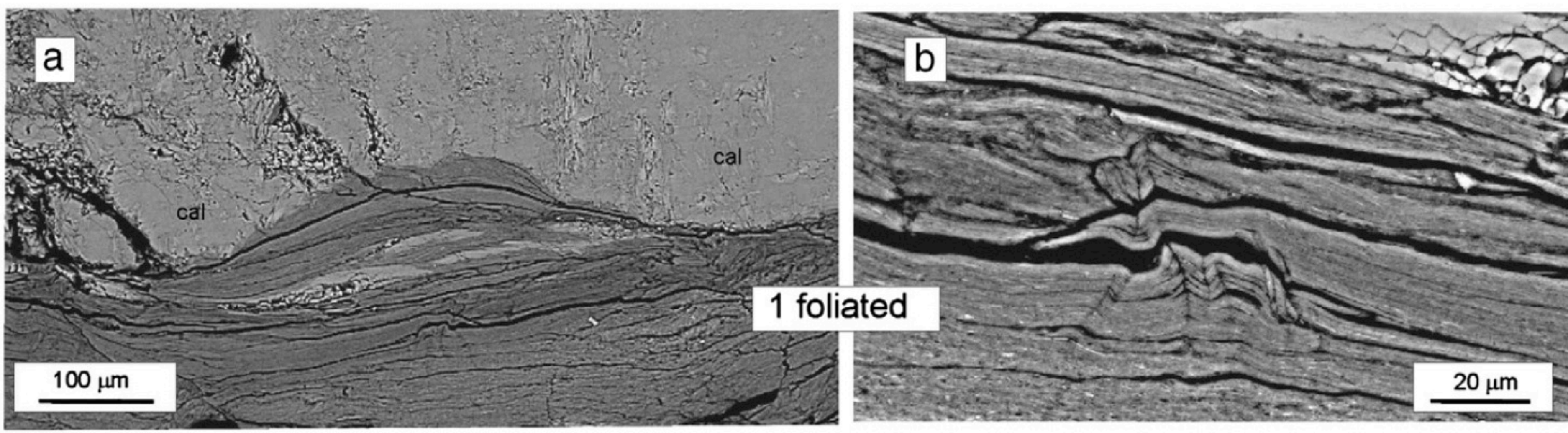




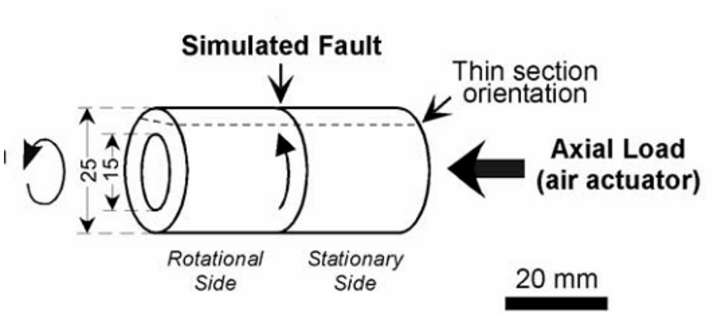
EQ nucleation phase

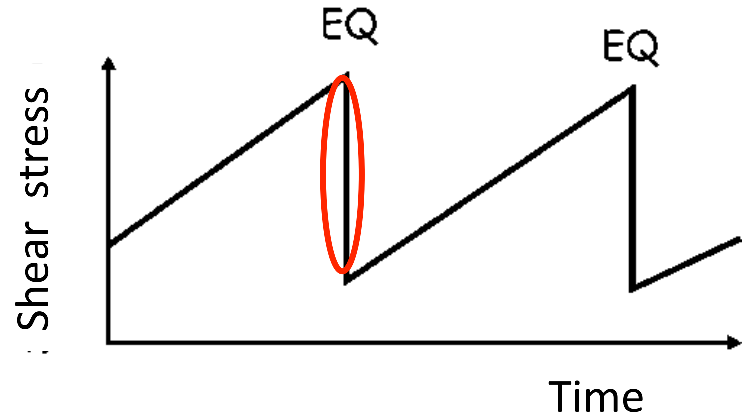
Distributed deformation within cataclasites & phyllosilicate-rich fault rocks seem to favor velocity strengthening behavior.

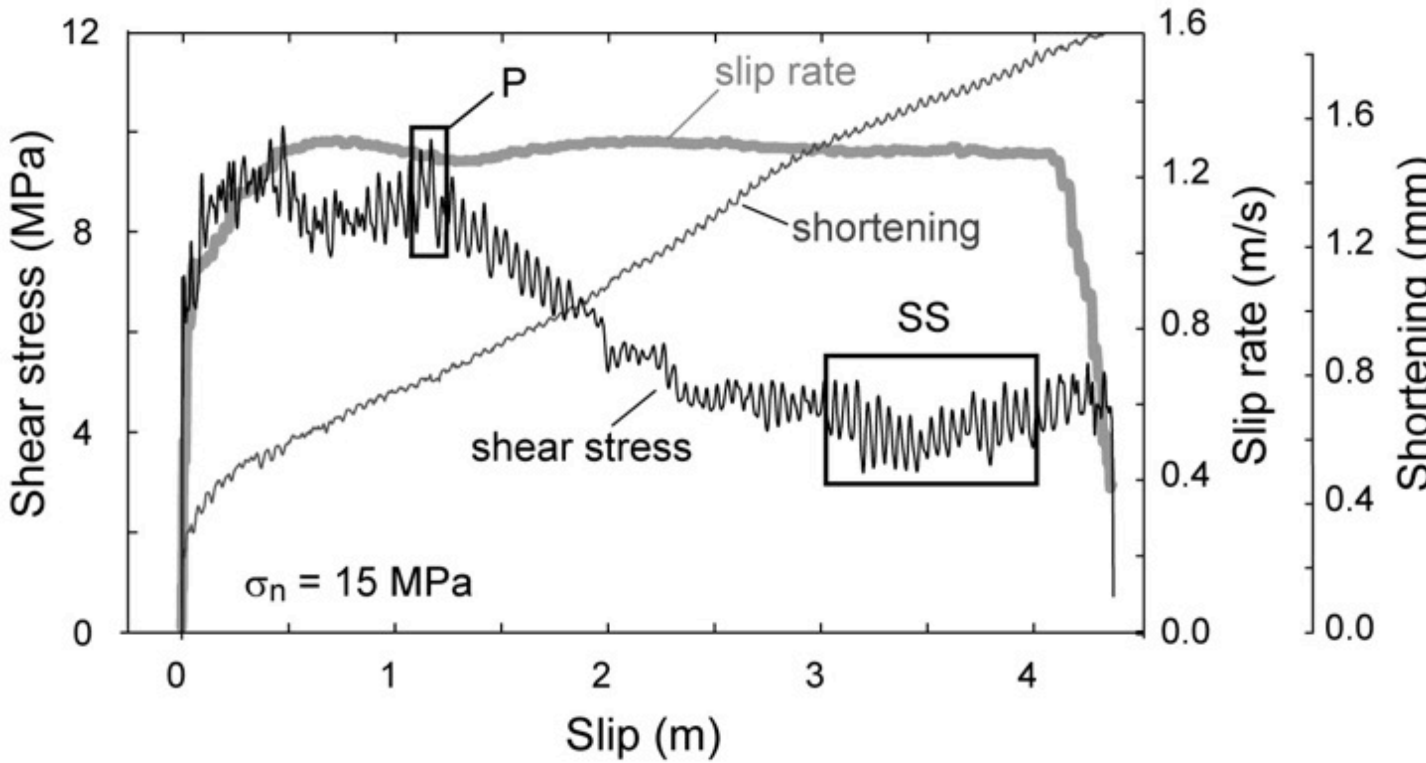




Dynamic weakening in High-Velocity Friction Experiments, HVFE

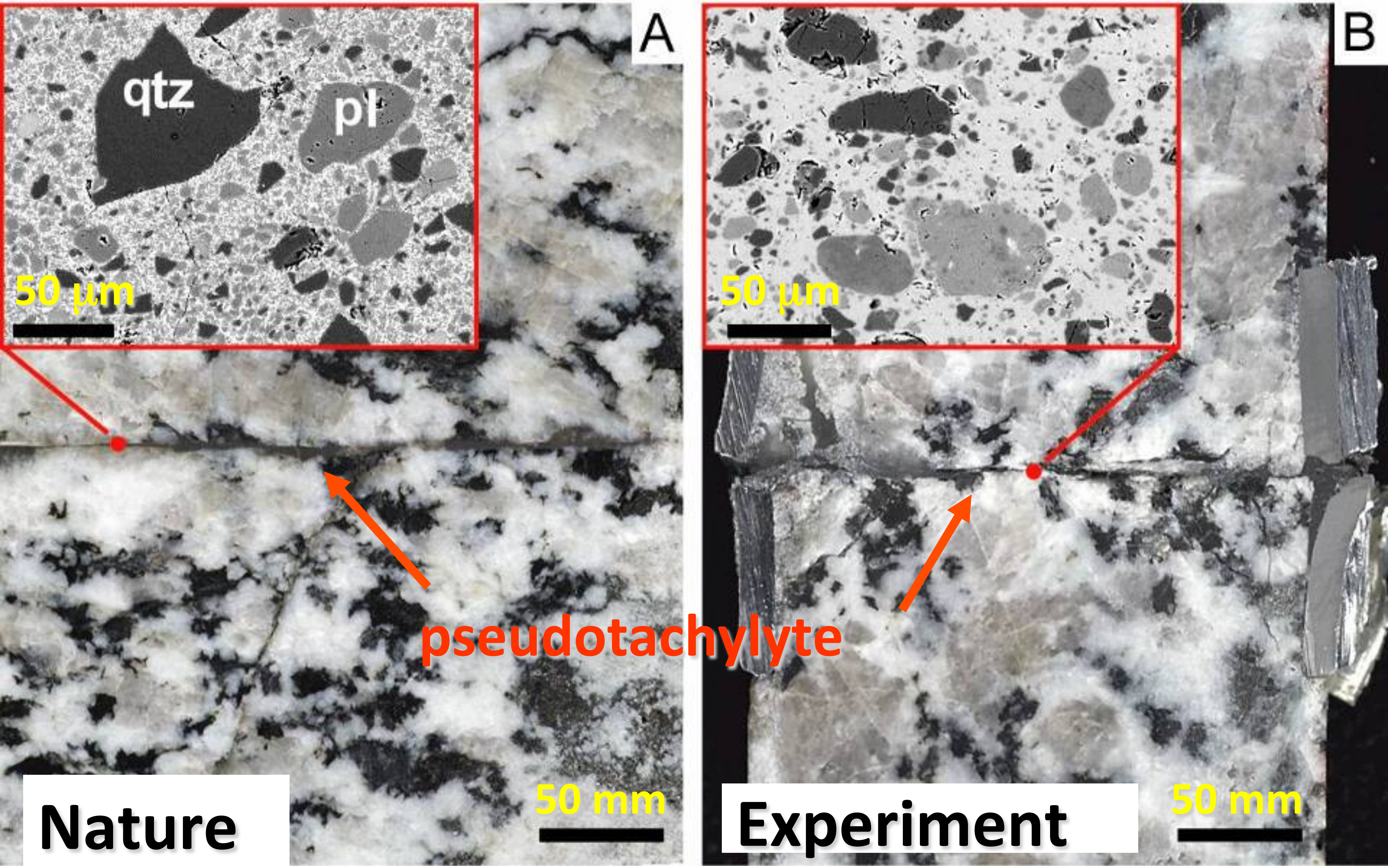




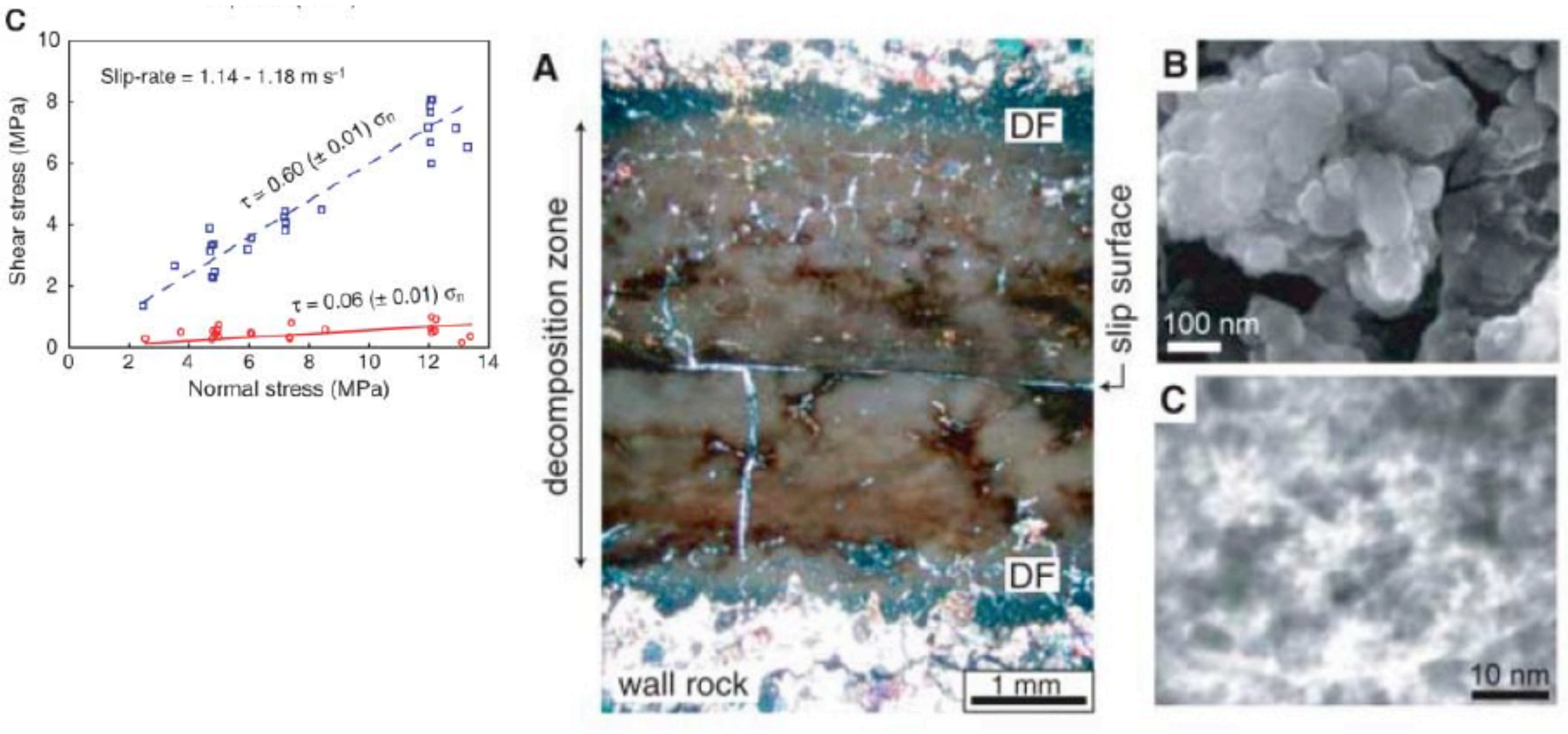


In granites and in the absence of water it has been shown that friction-induced melts can lubricate faults

Di Toro et al., Science 2006



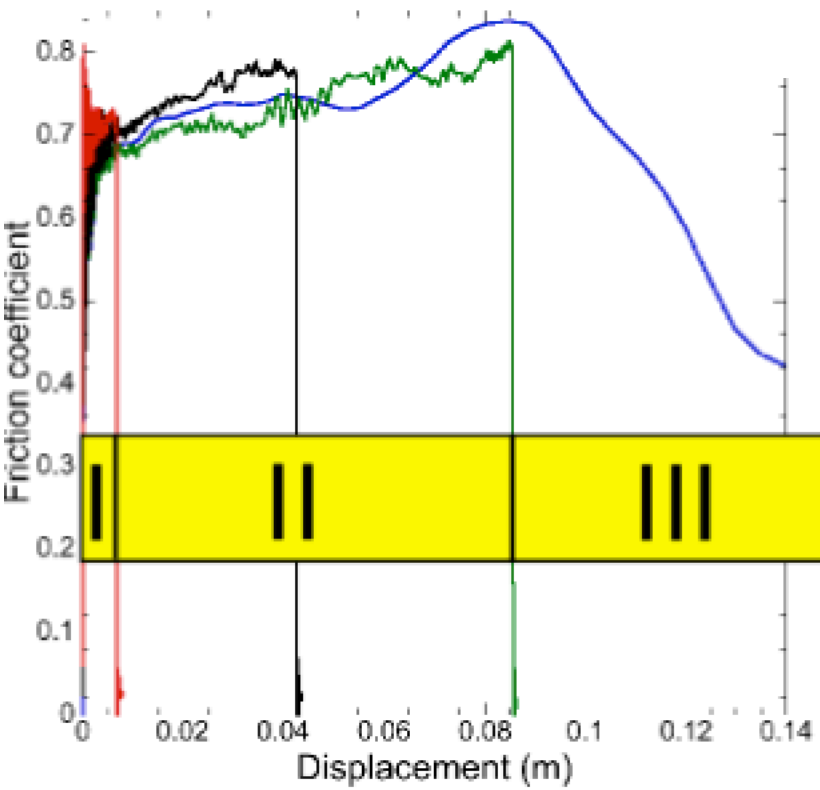
In calcite-rich fault rocks thermal decomposition produces nanoparticles of calcite and lime that cause ultralow friction.



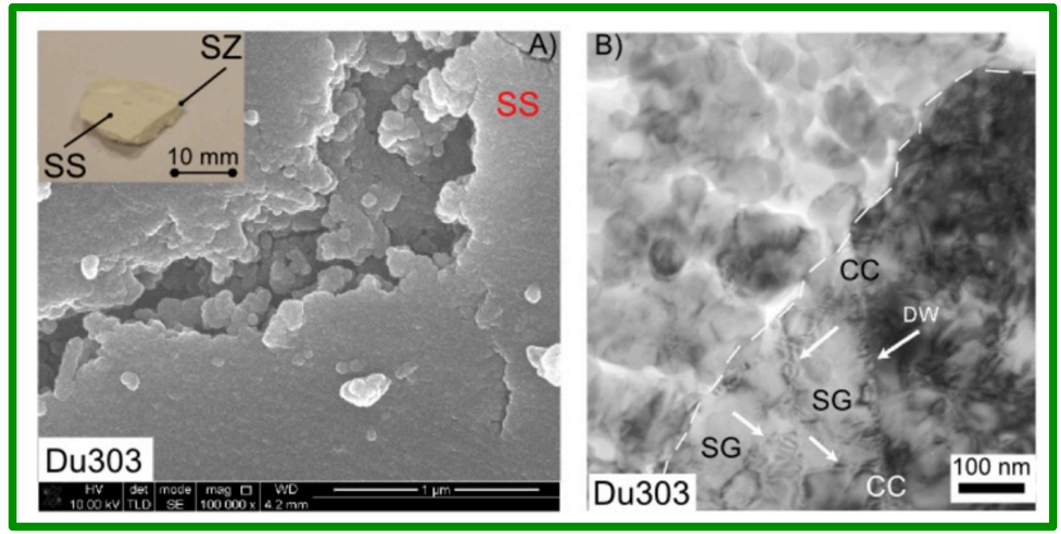
Han et al., Science 2007

In calcite-rich fault rocks the on-set of dynamic weakening seems to be associated with the development of plastic deformations.

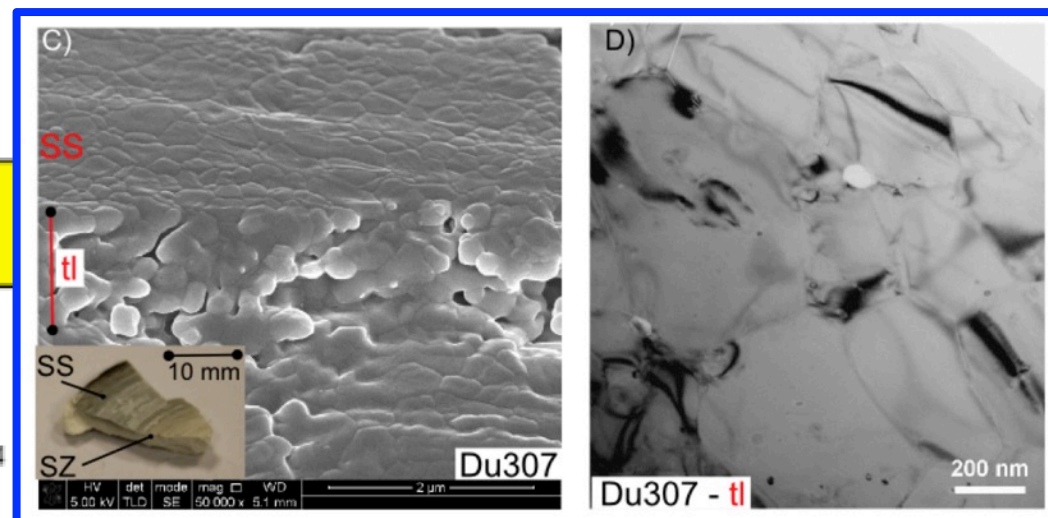
HVFE halted at different displacement:
green: at peak stress before weakening
blue: soon after dynamic weakening



De Paola et al., in prep.

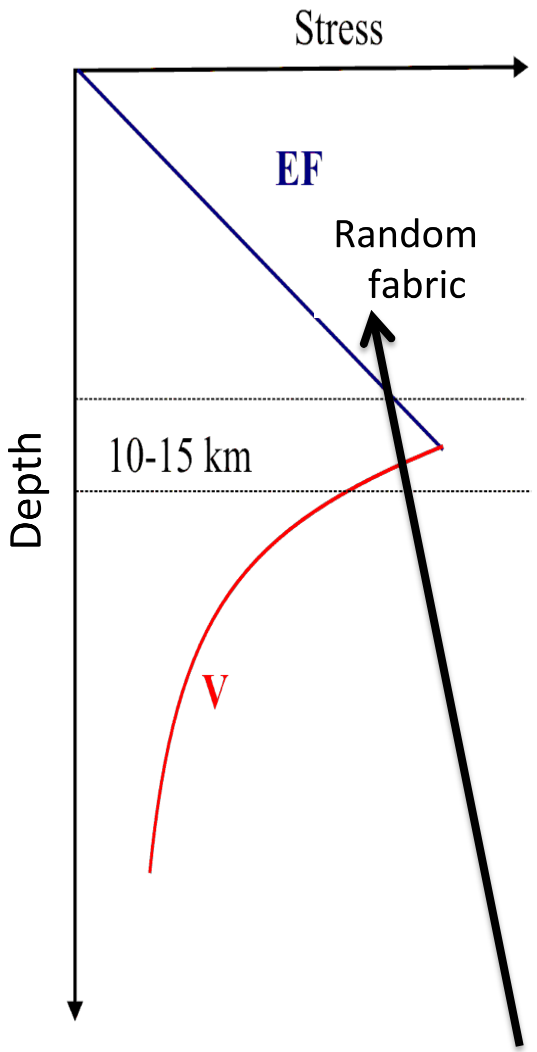


Dislocations and dislocation walls (DW) separate subgrains



Stacked & striated slip surfaces composed of compact polygonal nanostructures suggesting SP deformation

Fault rock classification & deformation mechanisms



Random fabric				Foliated		
Incohesive	Fault breccia (visible fragments > 30% of rock mass)		Cataclasi	Foliated gouge		cataclasis
	Fault gouge (visible fragments < 30% of rock mass)		Cataclasi			
Cohesive	Pseudotachylyte (galss, frictional melting)		Frictional melting	SCC' tectonites		Dissolution-precipitation
	Breccia	0-10 % Matrice	Cataclasis	Mylonites		
	Proto cataclasite	10-50% Matrix	Cataclasis	Protomylonite	10-50% Matrix	Intracryst. Plastic
	Cataclasite	50-90% Matrix	Cataclasis	Mylonite	50-90% Matrix	Intracryst. Plastic
	Ultra cataclasite	90-100 % Matrix	Cataclasis	Ultramylonite	90-100 % Matrix	Intracryst. Plastic

From HVFE (and also from some natural faults) it seems that plastic deformation plays a key-role in the dynamic weakening of some faults. Plastic deformation is present also within the elastico-frictional regime (random fabric) .

Introduction

Natural fault rocks and microstructures
Lab. experiments for slip behavior and microstructures

1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

3) Fault structure and slip localization in carbonate-bearing normal faults

Future directions

Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab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Marco Scuderi
Bret Carpenter
Telemaco Tesei
erc
2007-2013
SEVENTH FRAMEWORK PROGRAMME
Luisa Valoroso
Lauro Chiaraluce
Cecilia Viti
Chris Marone

Introduction

- **Natural fault rocks and microstructures**
- **Lab. experiments for slip behavior and microstructures**

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Future directions

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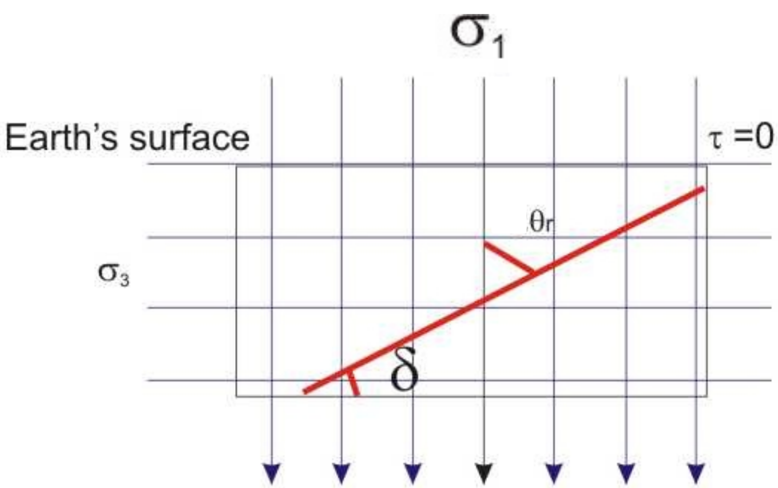
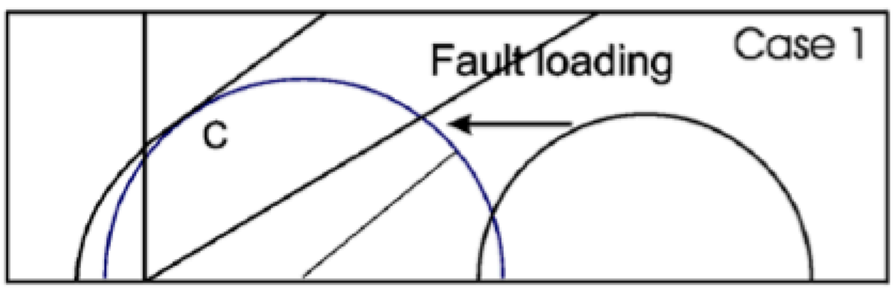
- **Heterogeneous faults in the lab**

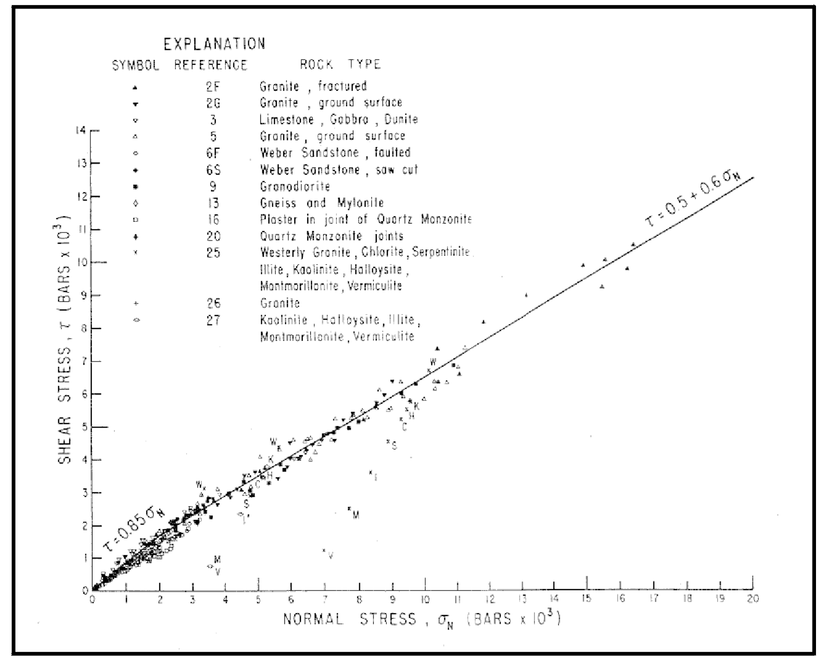
The LANF mechanical paradox

Frictional Fault Mechanics under Byerlee's friction predicts no-slip on normal faults dipping less than 30°.





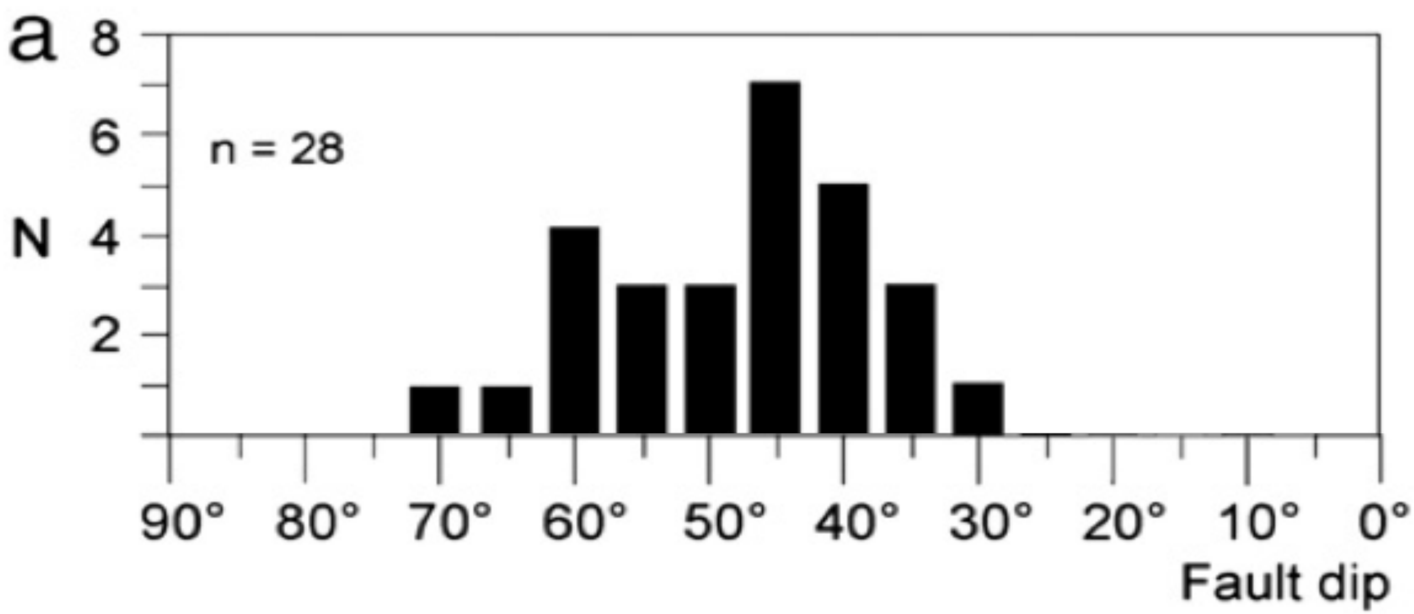
Byerlee, PAGEOPH, 1978



$0.6 < \mu_s < 0.85$

The LANF mechanical paradox

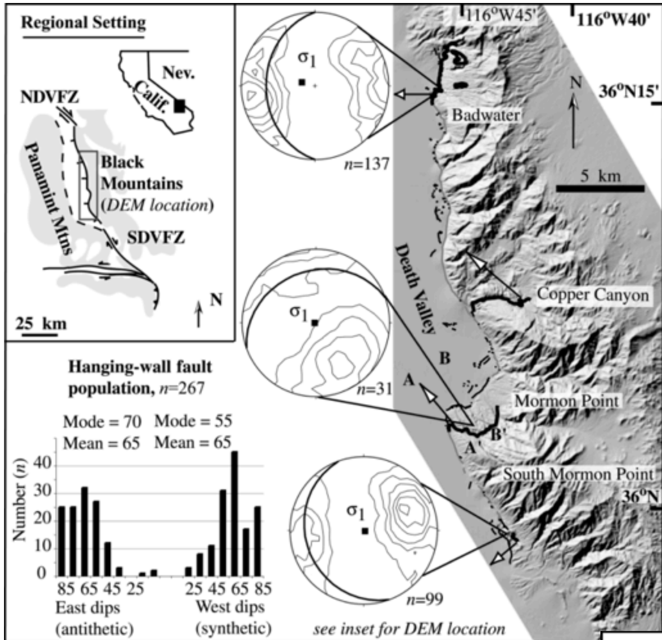
Frictional Fault Mechanics prediction is consistent with the absence of moderate-to-large earthquakes occurring on normal faults dipping less then 30° worldwide.

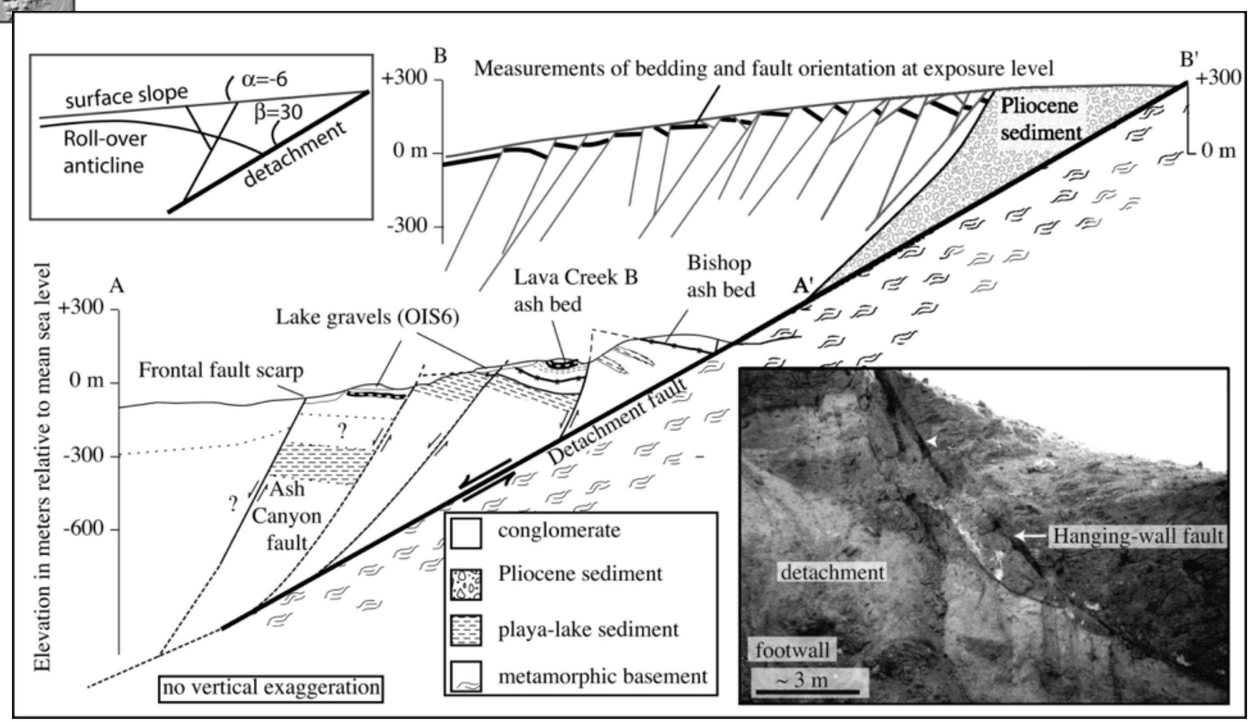


No M > 5.5 on LANF on positively discriminated rupture planes worldwide

Collettini & Sibson, Geology, 2001

However geological records show that LANF seem to be important structures for accommodating crustal extension.

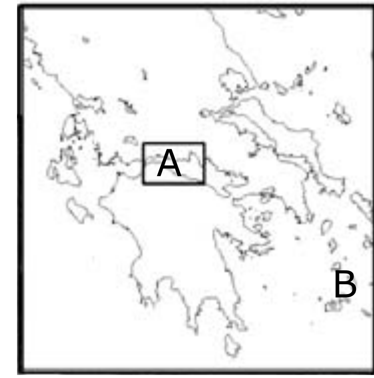


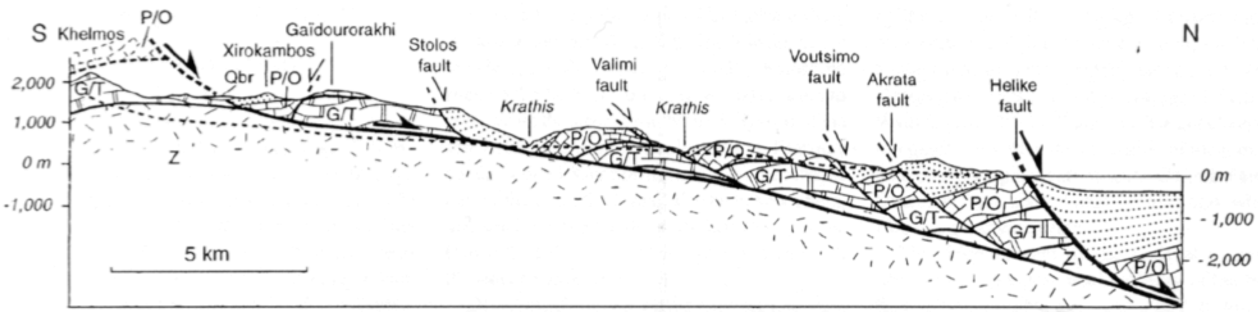


Death valley detachment
(Hayman et al., Geology, 2003)

However geological records show that LANF seem to be important structures for accommodating crustal extension.

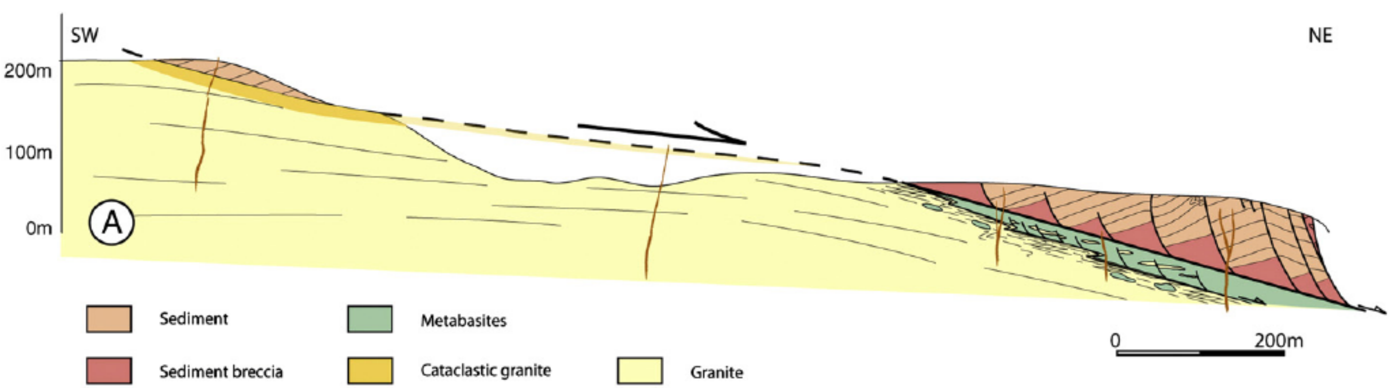
A: Gulf of Corinth



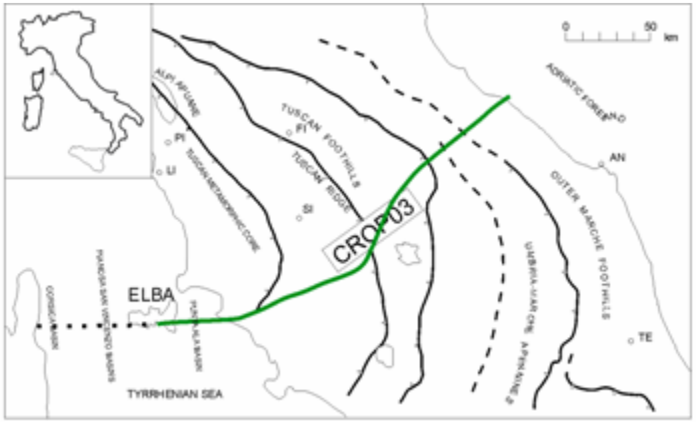


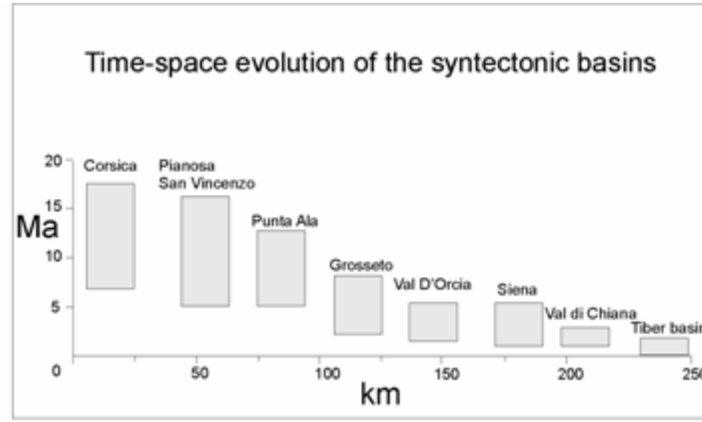
Detachemnts in the Gulf of Corinth and Cyclades (Sorel, Geology 2000; Jolivet et al., EPSL, 2010).

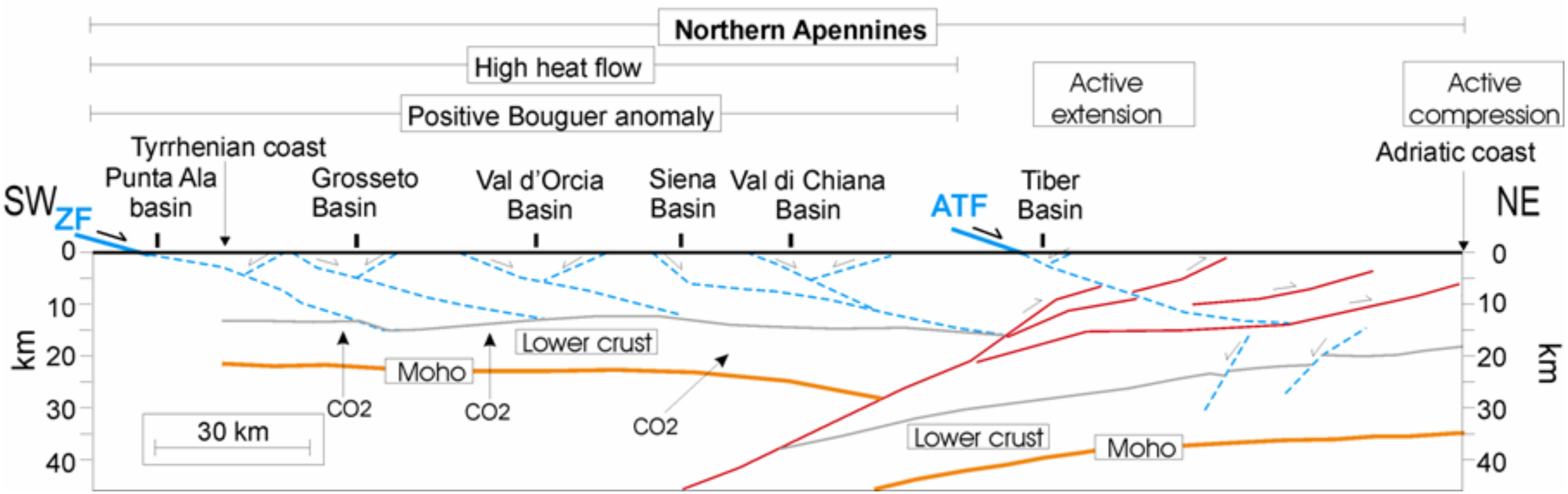
B: Mykonos detachment



The CROP03 deep seismic reflection profile showed that significant extension in the Northern Apennines occurs on LANFs





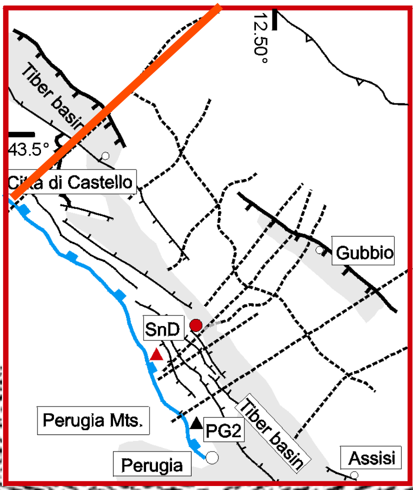


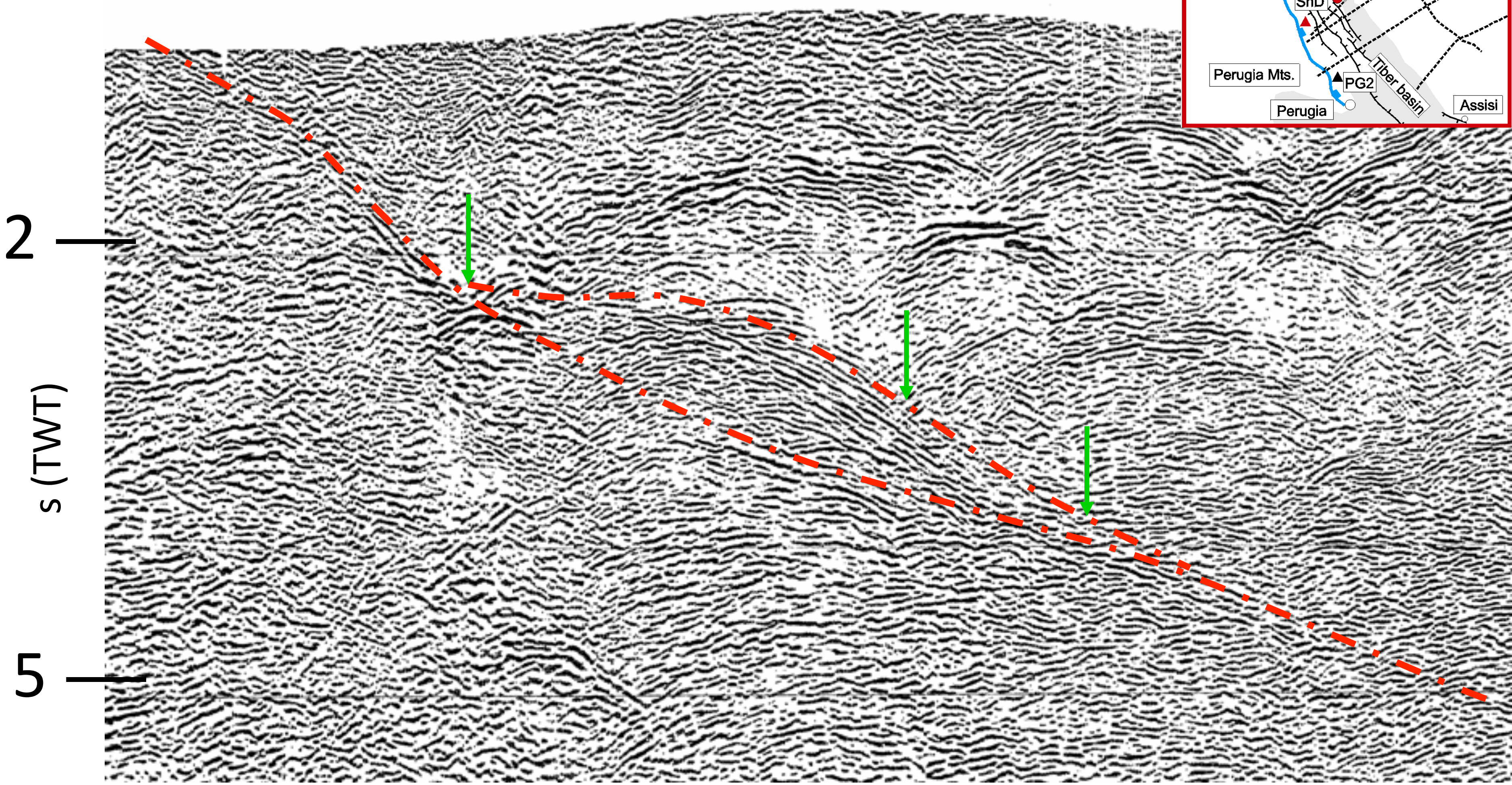
Barchi et al., 1998 MSGI

CROP03 Seismic Profiles + commercial seismic profiles

Barchi et al., 1998, MSGI;
Boncio et al., 2000, Tectonics;
Collettini and Barchi 2002, Tectonophysics;

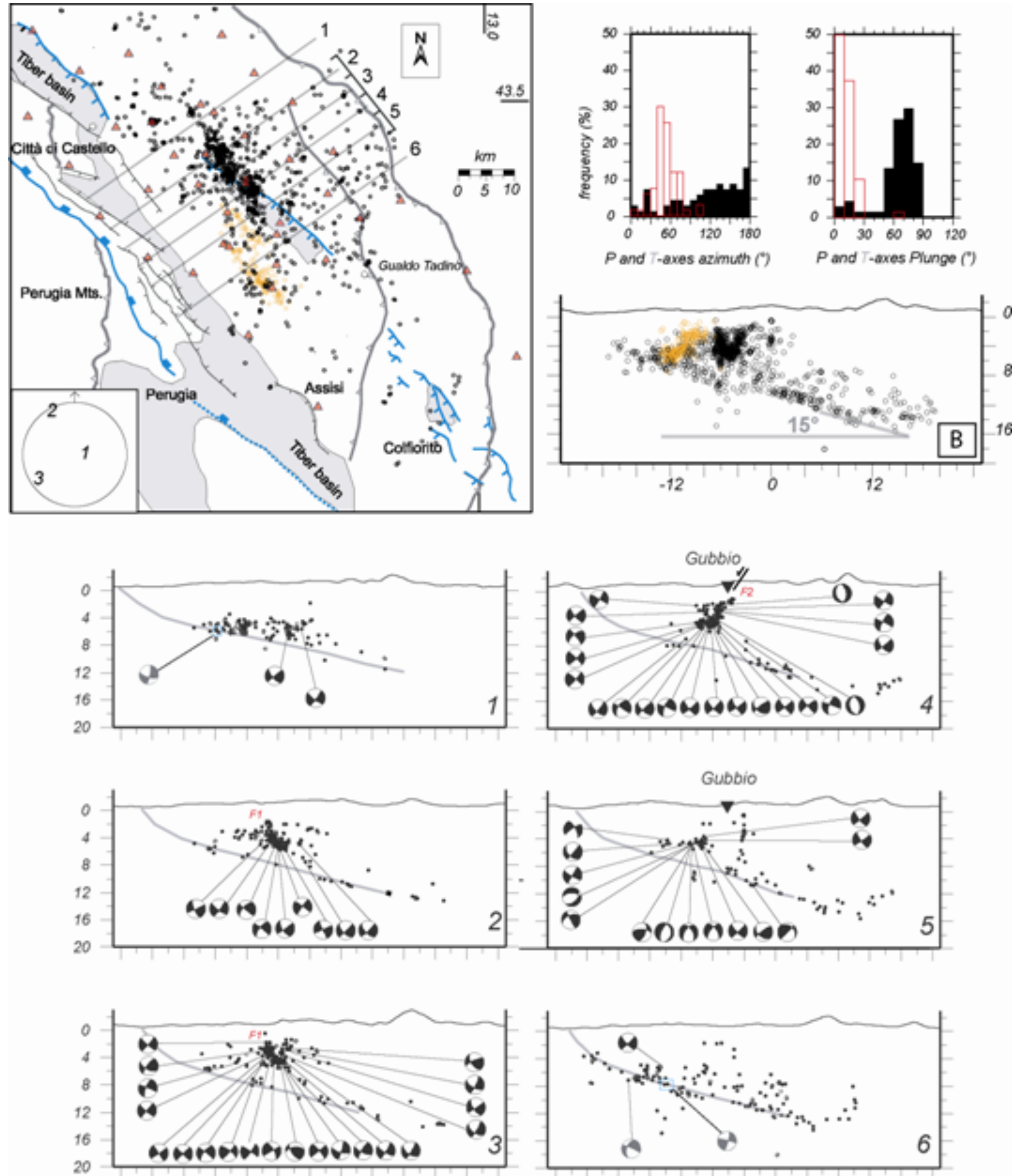
displacement 6-8 km
slip-rate 1-2 mm/a





In 2000-2001, during 8 months, more than 2,000 earthquakes with ML<3.2 have been recorded by a dense temporary seismic network.

Chiaraluce et al. JGR 2007



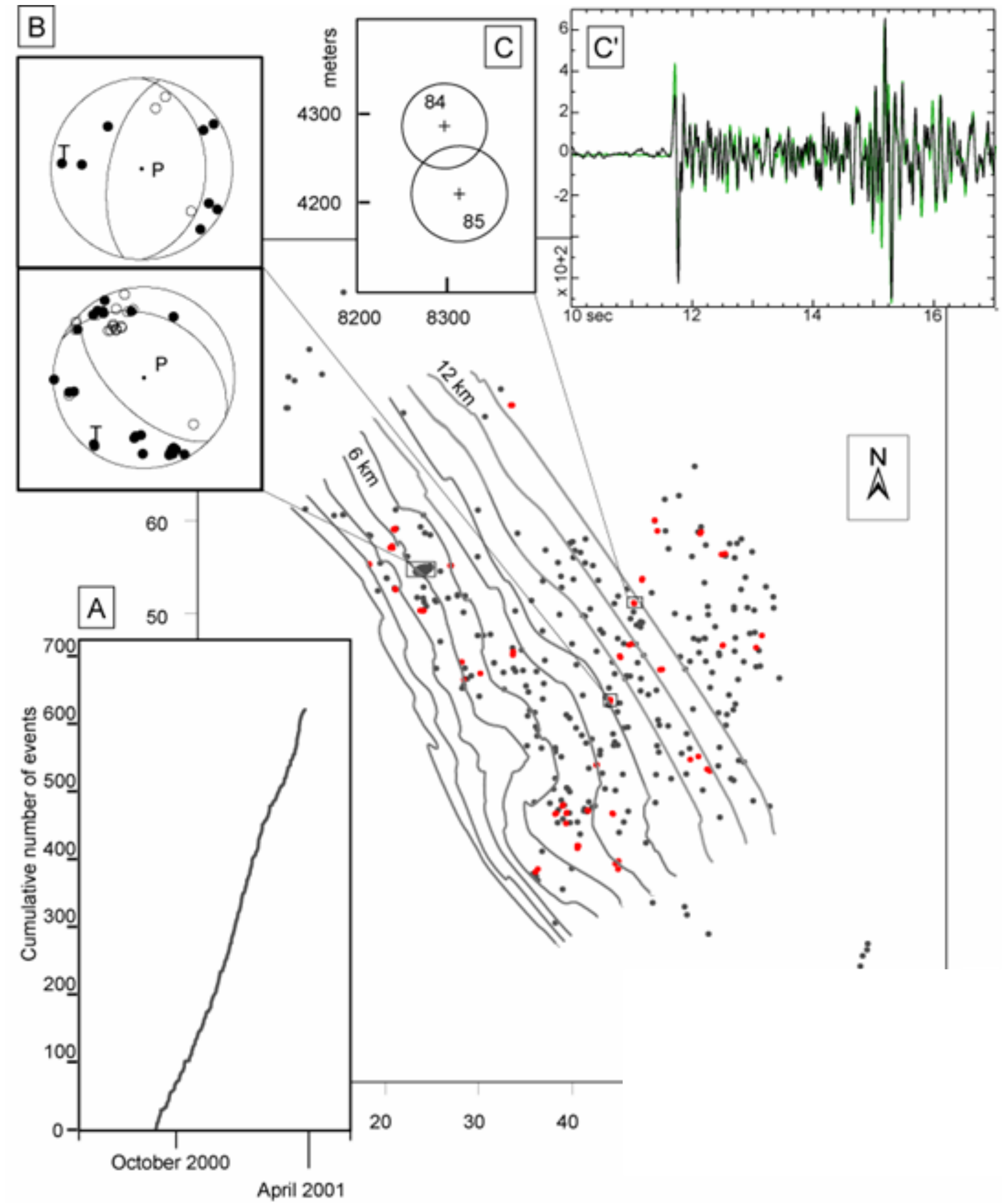
F1 & F2 hangingwall normal faults that sole into the detachment

Map view of the 621 events located at <500 m from the detachment

A) A constant seismicity rate 3.5 event/d, M_L<2.3, that cannot explain 1-2 mm/yr

B) Composite focal mechanisms with a gently E-dipping plane

C) Multiple events with highly correlated waveforms



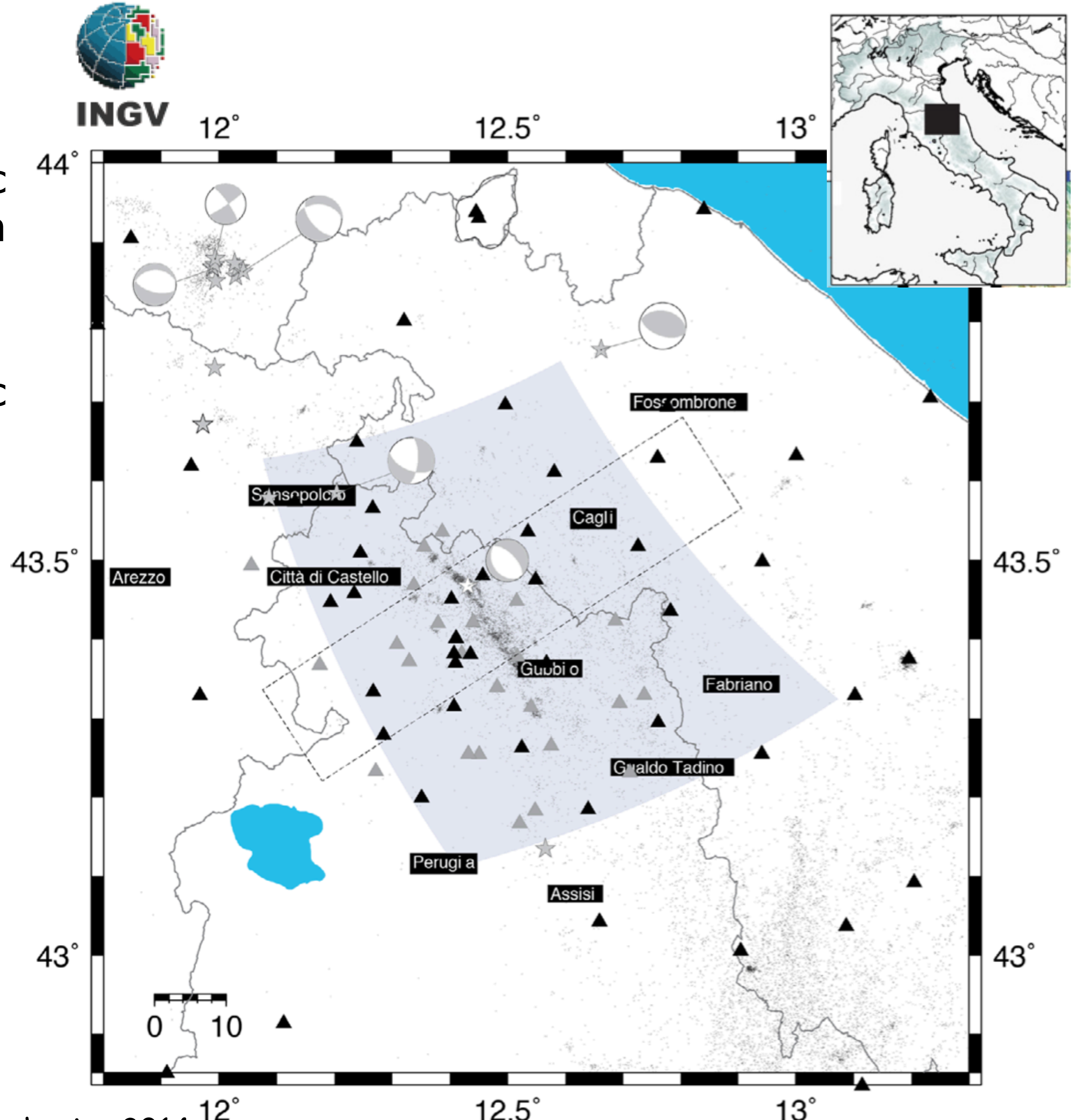
Chiaraluce et al. JGR 2007

From 2010
TABOO infrastructure

50 permanent seismic stations covering an area of 120 × 120 km^2

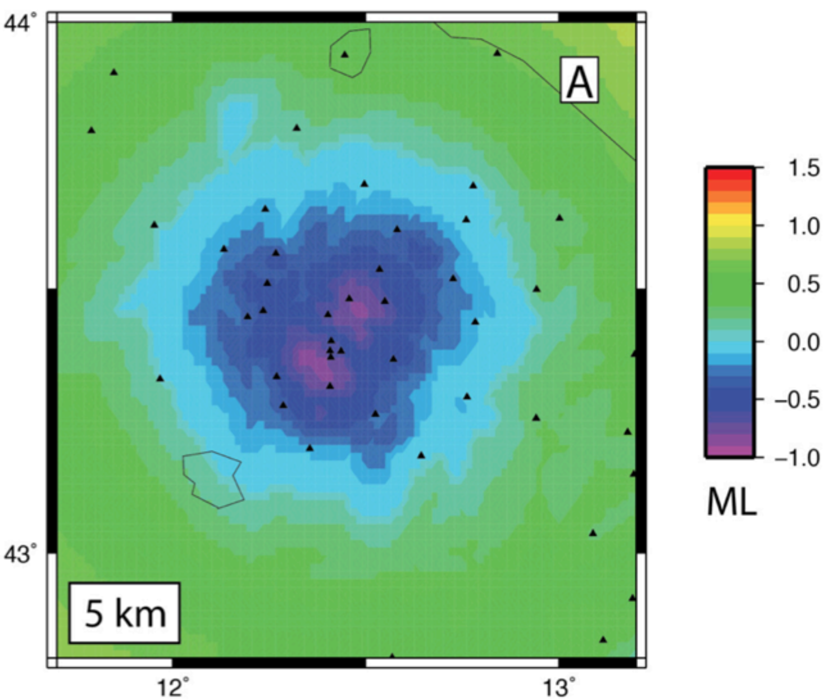
24 continuous geodetic GPS stations

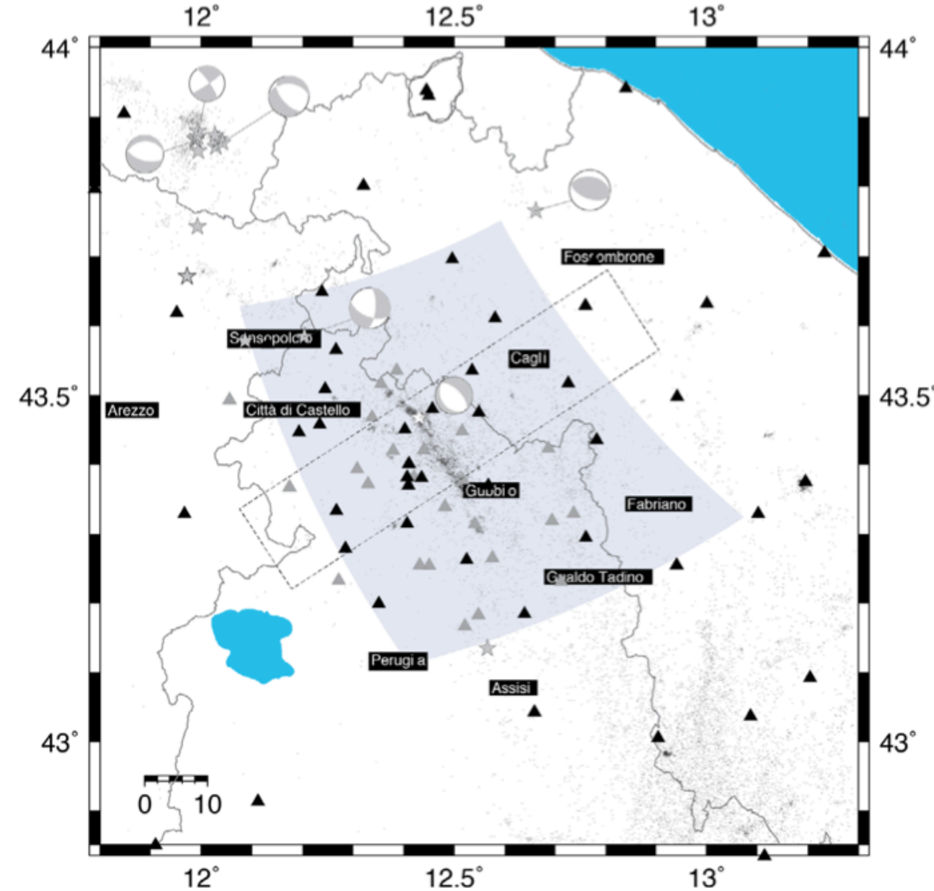
3 down-hole seismometers (GLASS ERC)

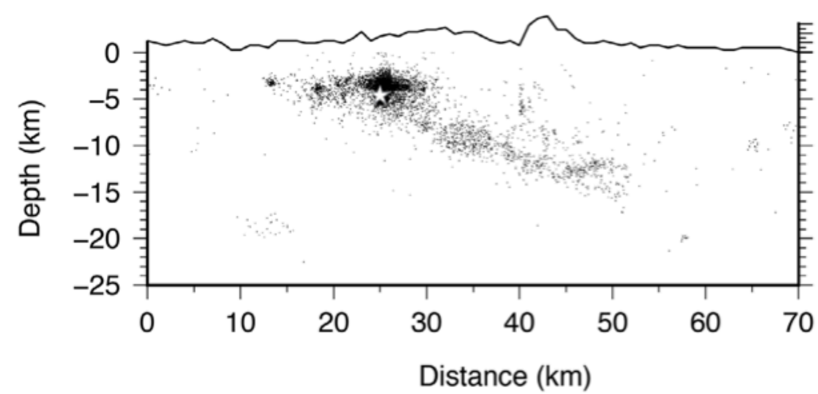


Chiaraluce et al. Annals of Geophysics 2014

In 36 months TABOO recorded 19,422 events with ML ≤ 3.8







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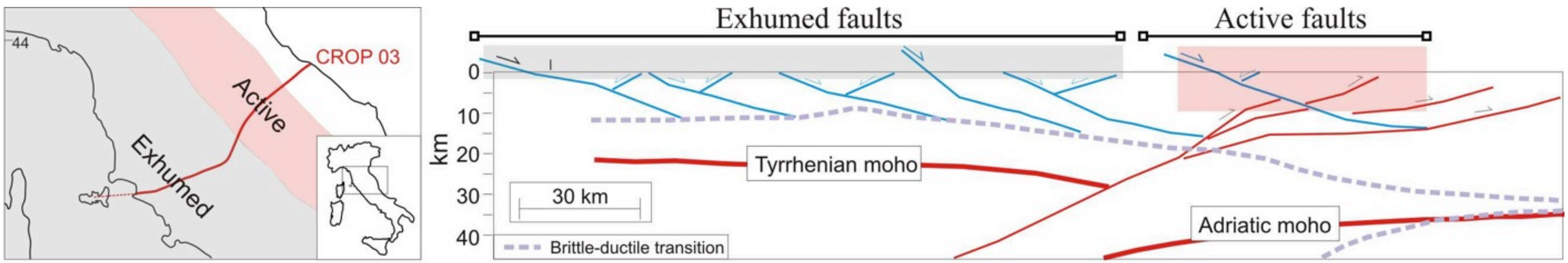
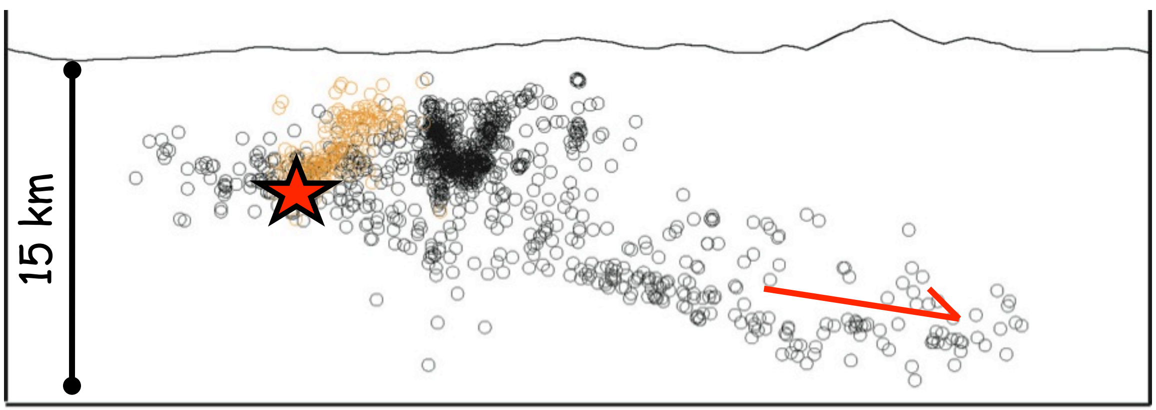
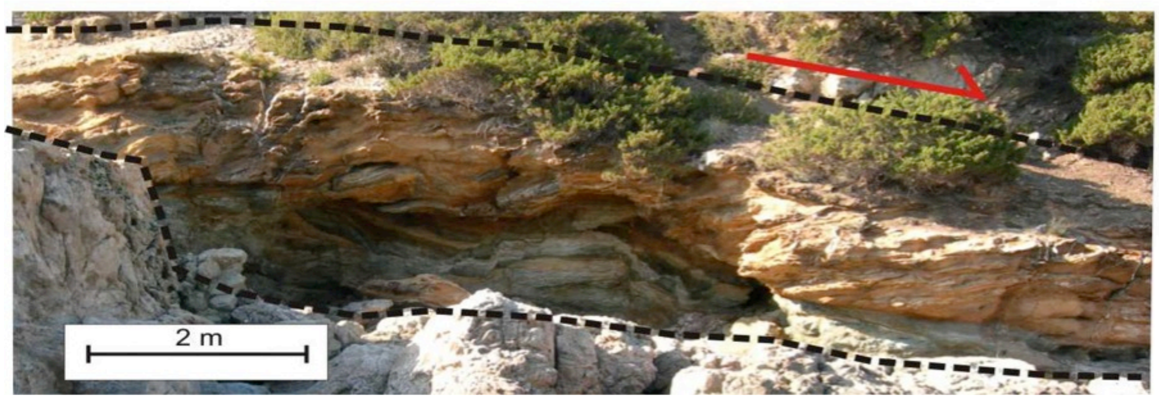


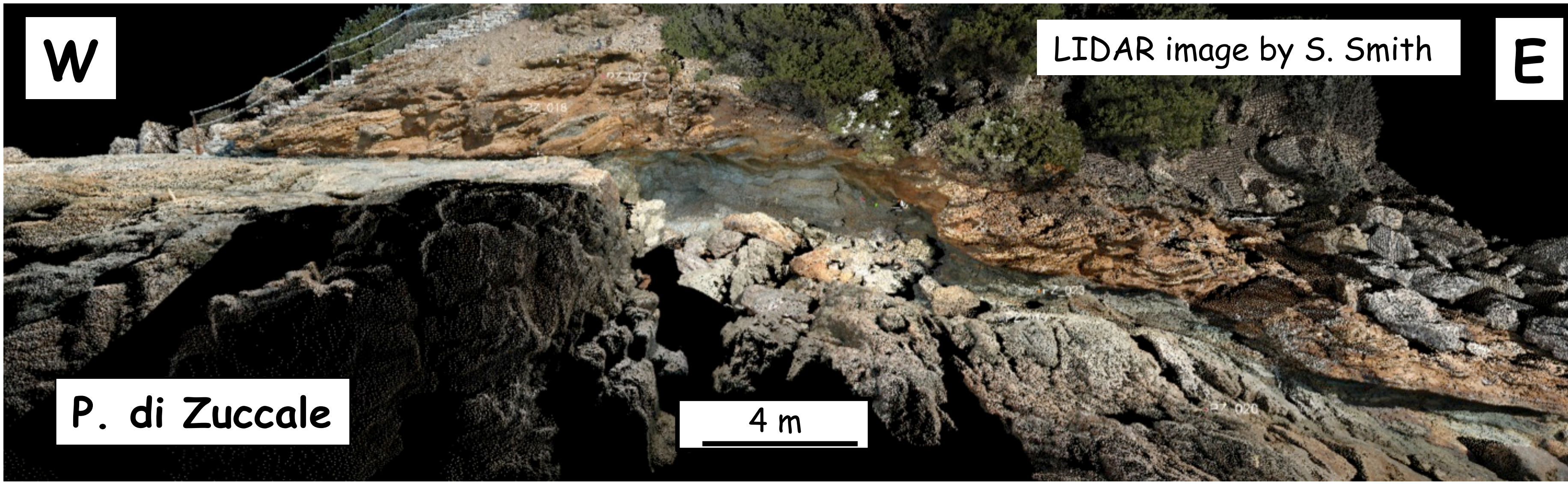


Seismic images of an Active LANF.



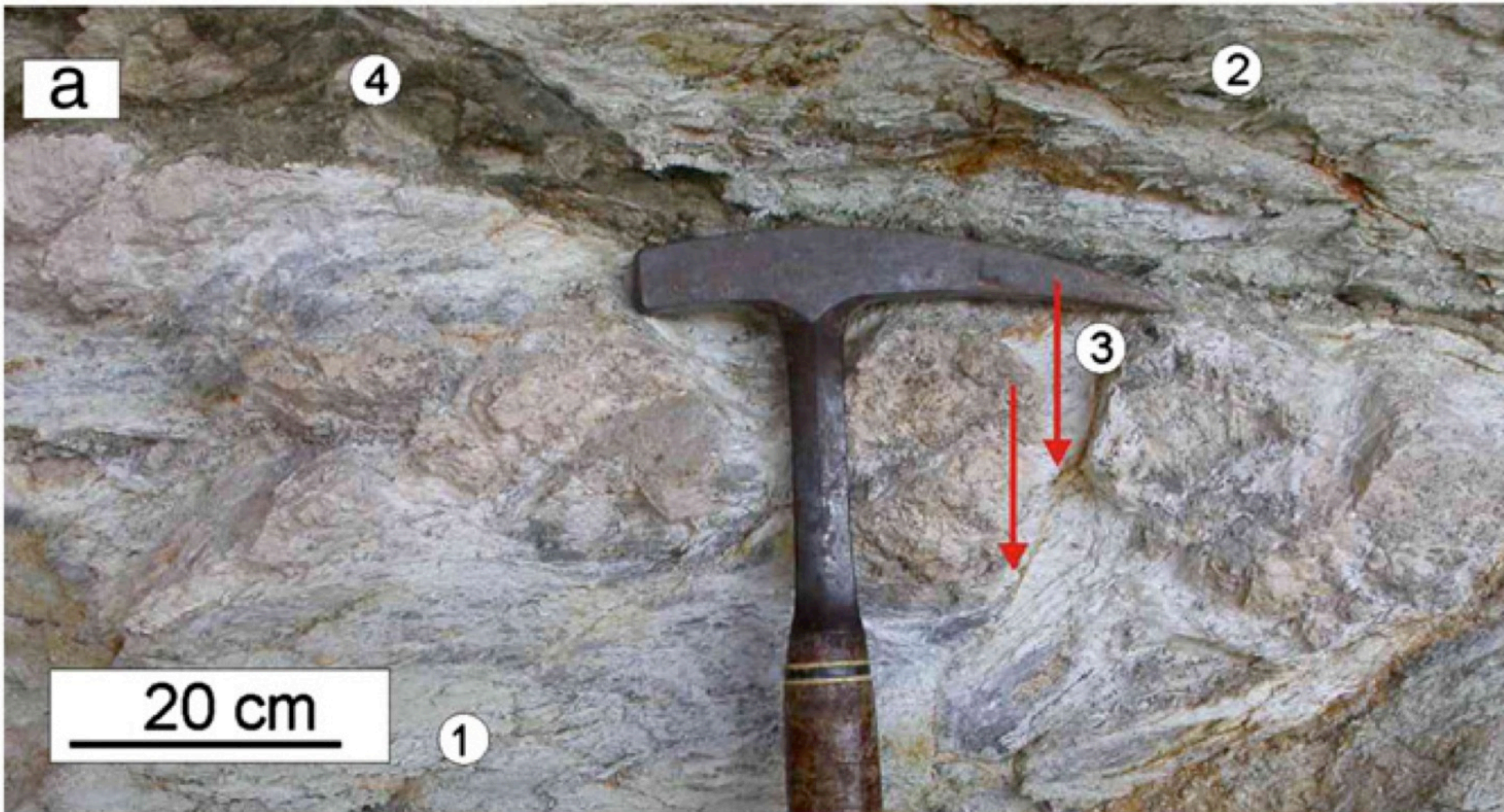
Ancient exhumed faults to study fault zone structure and collect fault rocks for laboratory studies & rock deformation exp.

The Zuccale Fault:
displacement 6-8 km
fault exhumation 3-6 km

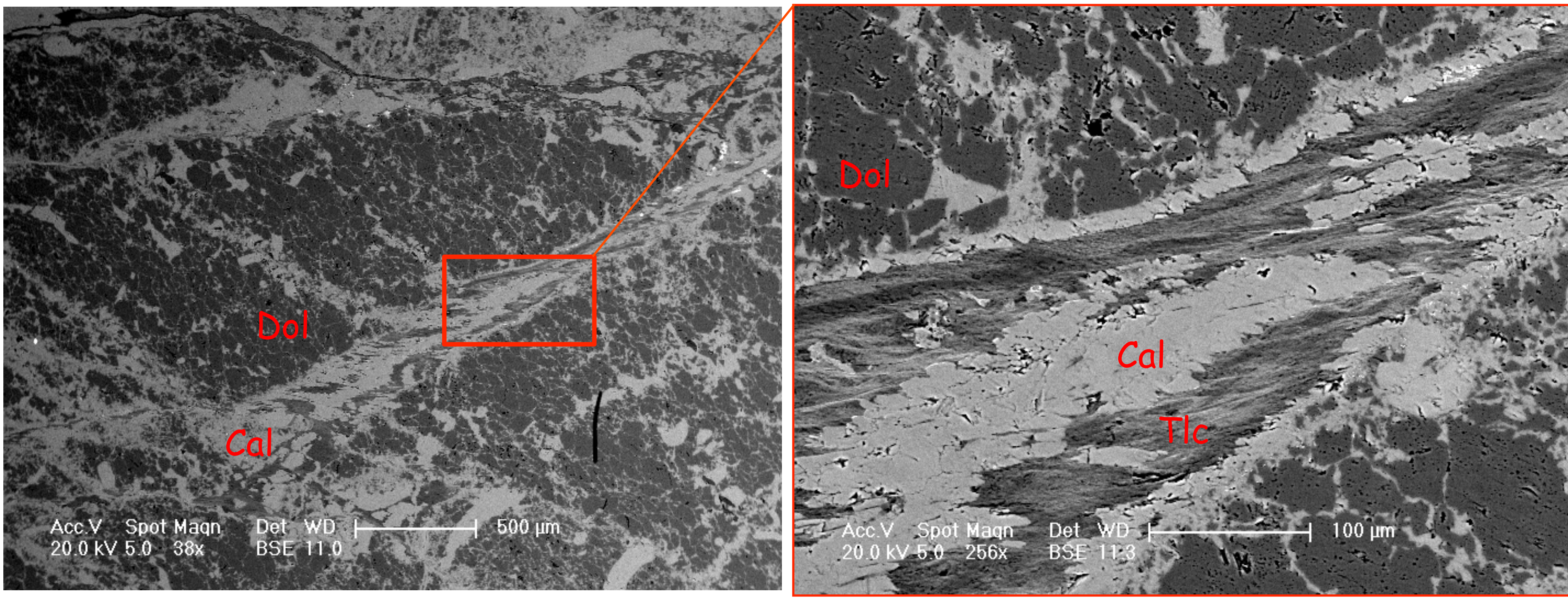


Collettini & Holdsworth, GSL, 2004.
Smith et al., JSG, 2008.
Collettini et al., Geology 2009.

Low-strain domains

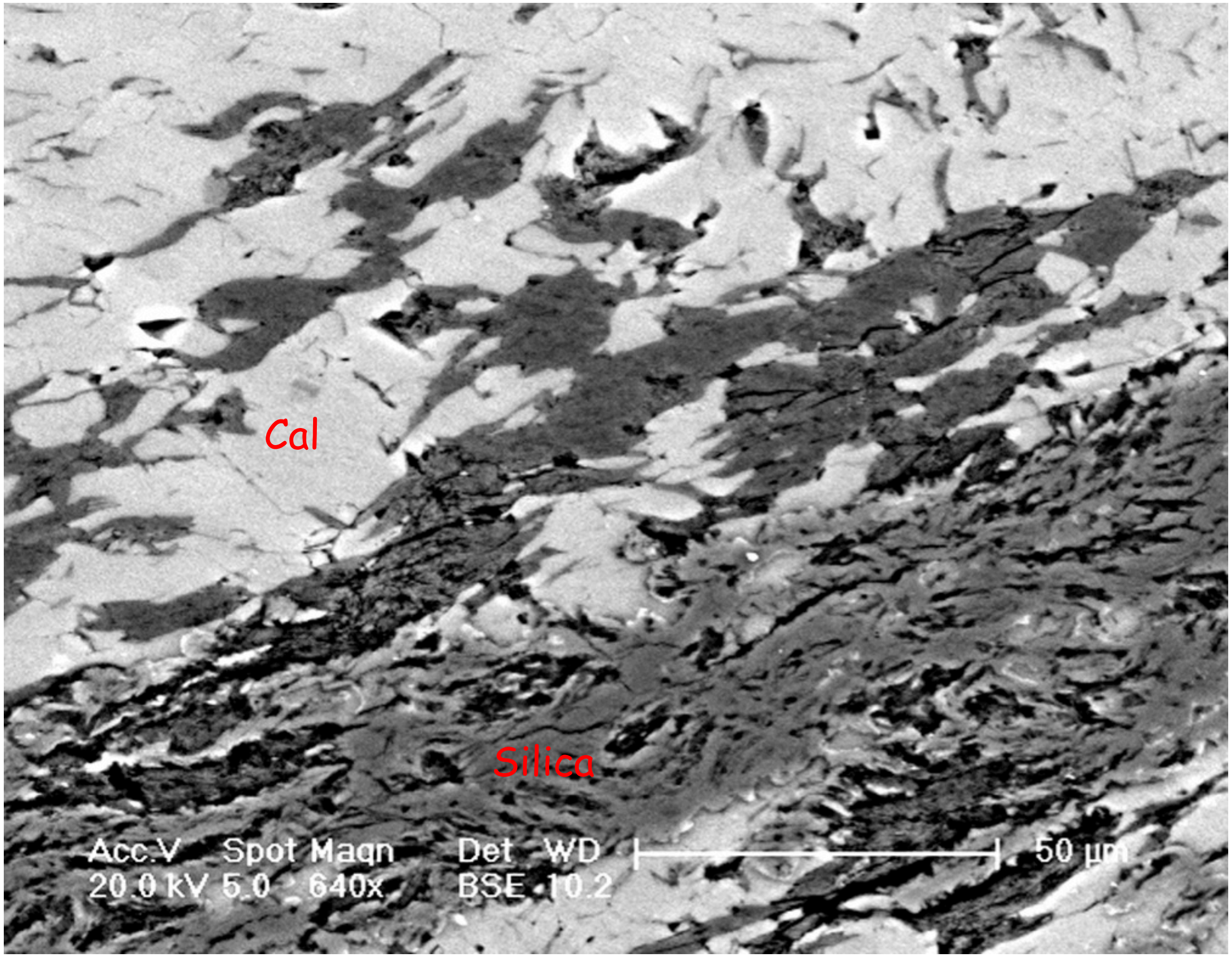


Low-strain domains



Calcite concentration along major fractures and syn-tectonic precipitation of calcite and talc along veins

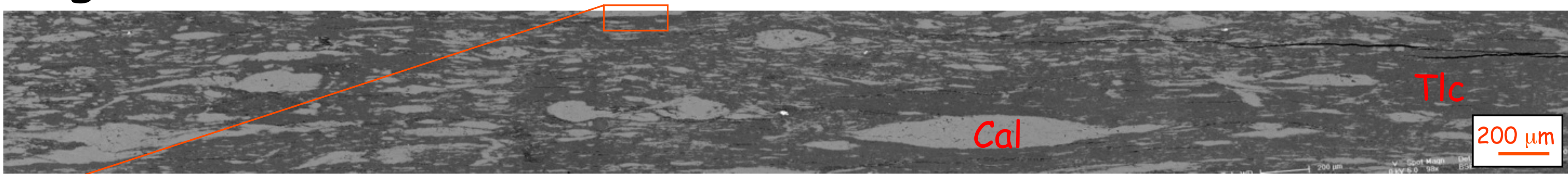
Low-strain domains

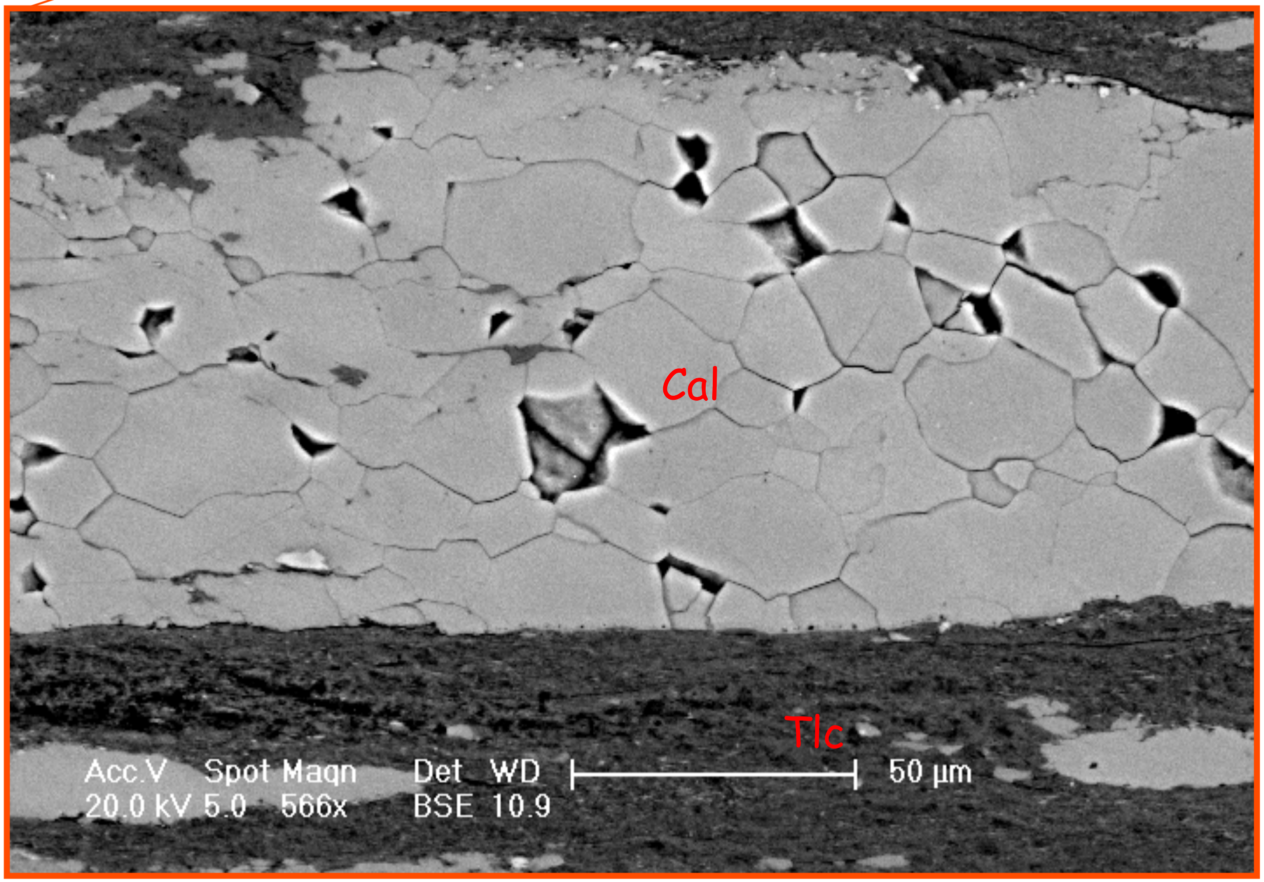


Silica-rich fluid circulation

High-strain domains: interconnected talc rich network

High-strain domains: interconnected talc rich network



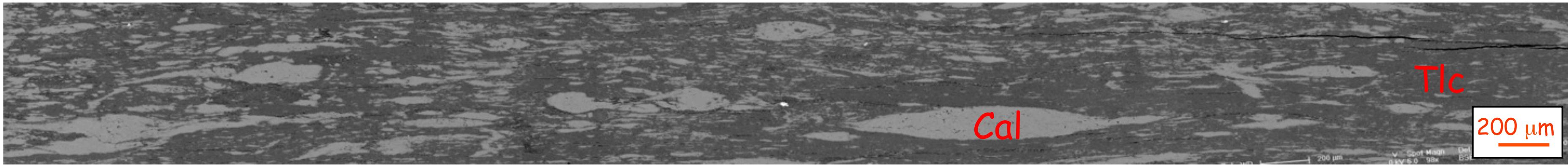


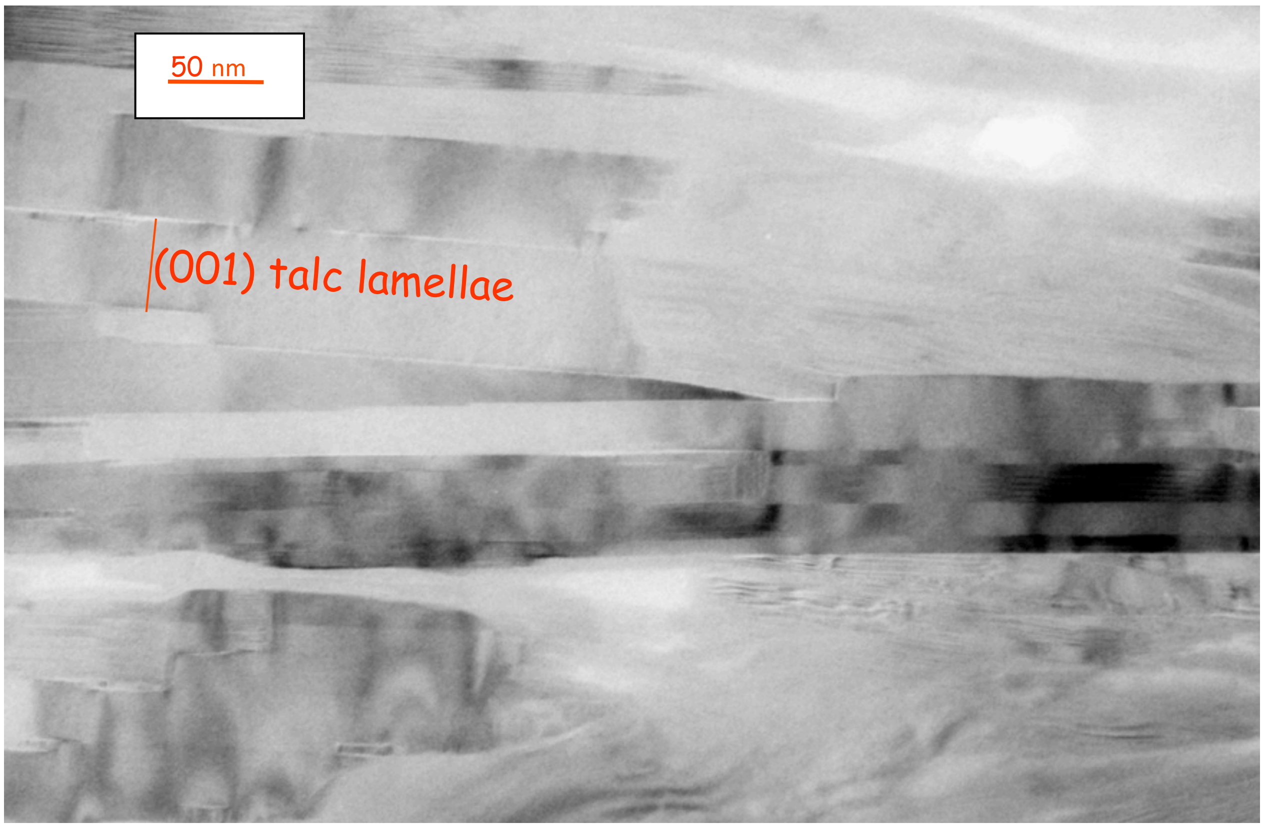
Fluid assisted dissolution and precipitation processes

DOLOMITE + SILICA + H_2O = TALC + CALCITE + CO_2

$3\ MgCa(CO_3)_2 + 4\ SiO_2 + H_2O = Mg_3Si_4O_{10}(OH)_2 + 3\ CaCO_3 + 3\ CO_2$

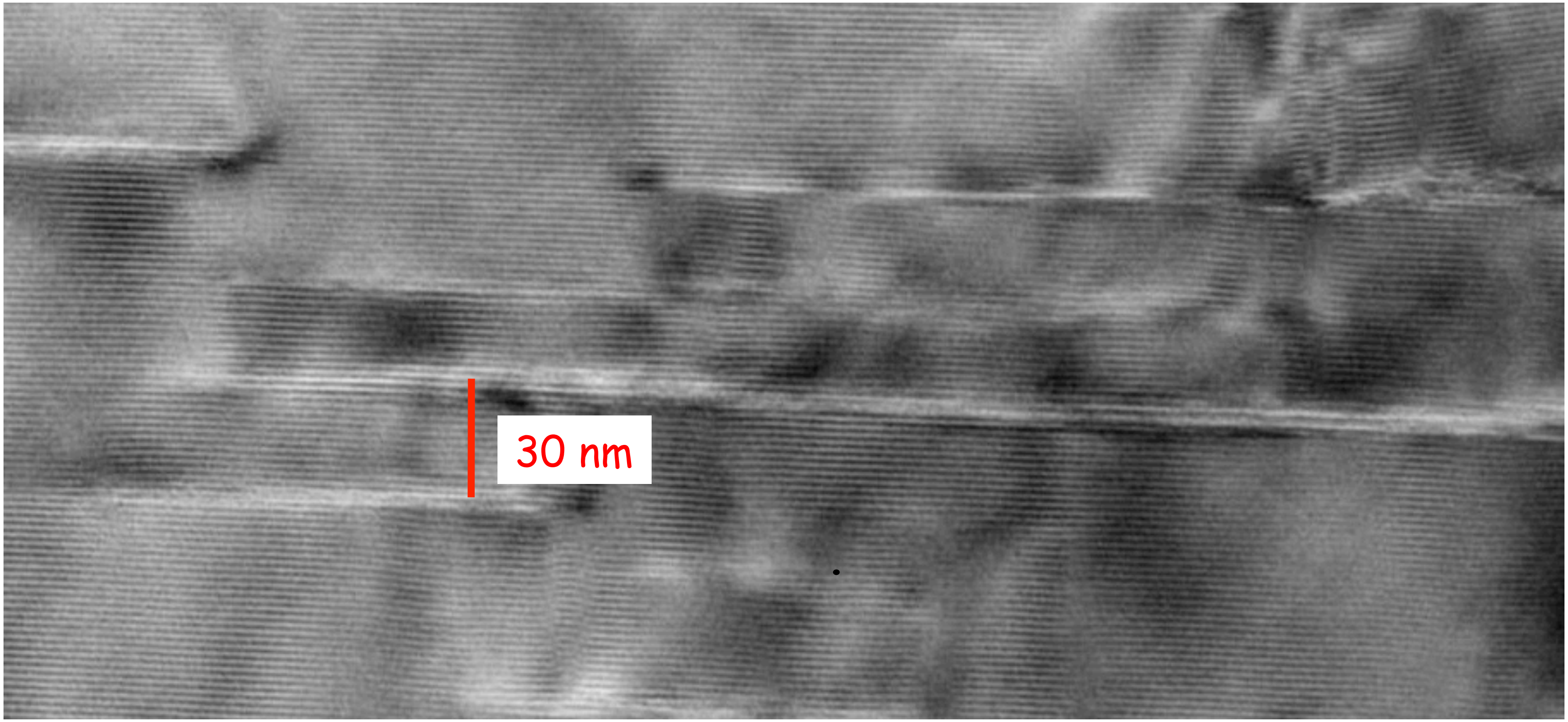
High-strain domains: interconnected talc rich network





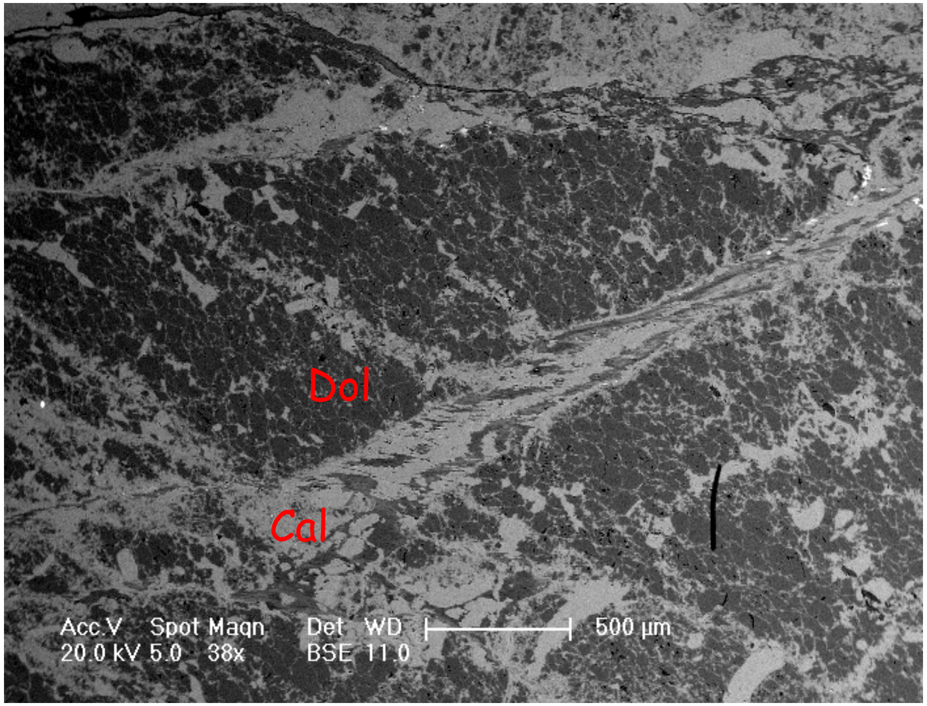
Talc lamellae are oriented parallel to the foliation and are affected by rotation of the (001) talc layers.

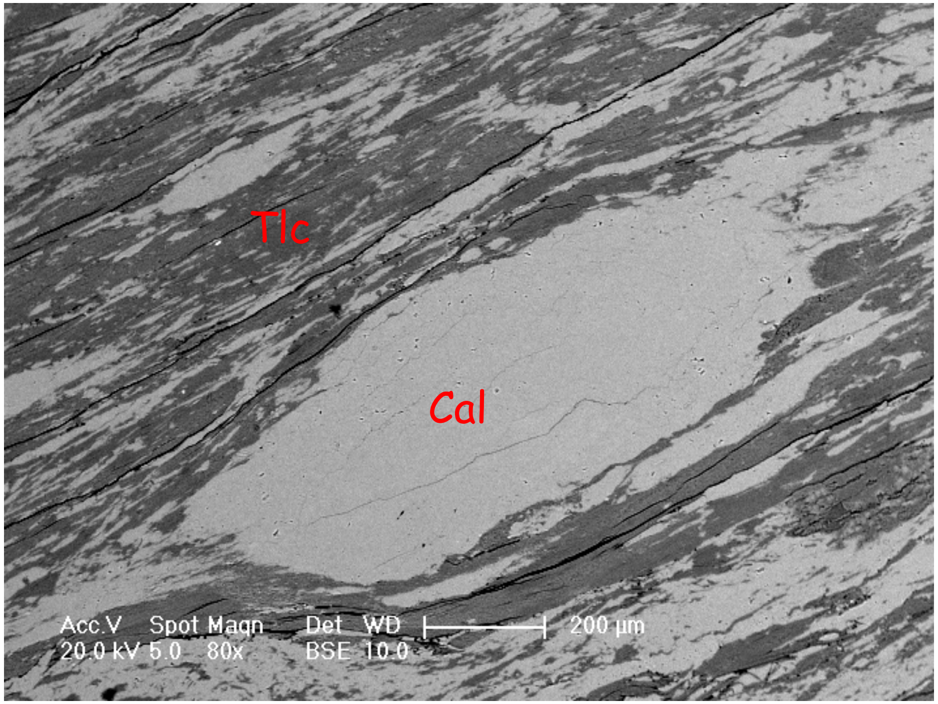
High-strain domains: interconnected talc rich network



Interlayer delaminations widespread resulting in talc grain-size reduction, down to 30 nm, and providing an infinite number of possible slipping planes.

Collettini et al., Geology, 2009
Viti & Collettini, CMP, 2009

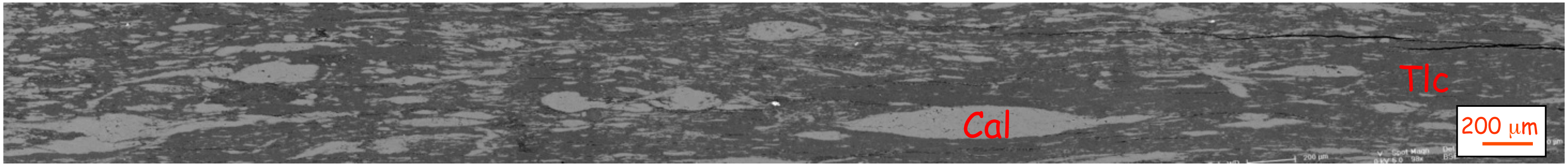


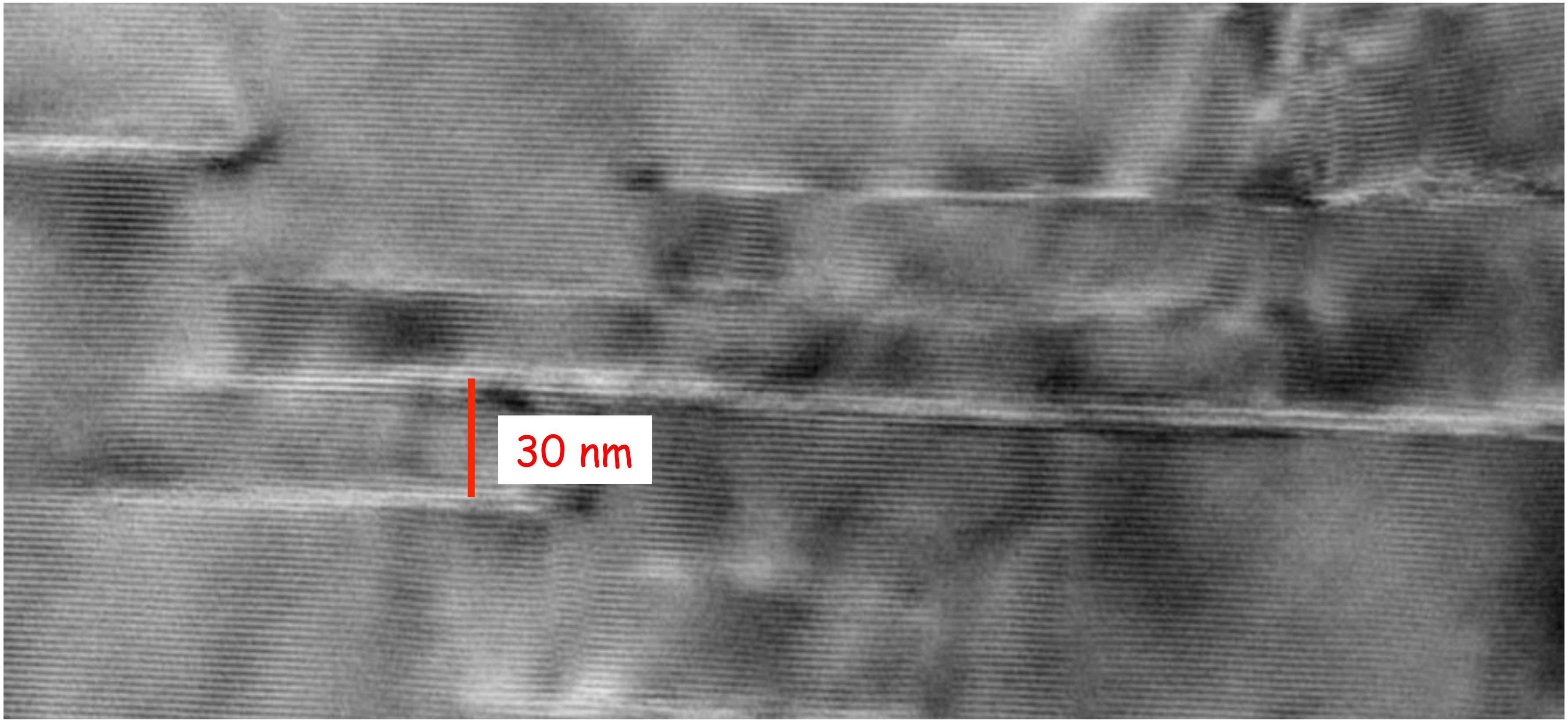


Low strain → **High strain**

Cataclasis	Brittle dilatancy & increase of permeability	Influx of silica-rich fluids	Diss.of Dol ppt. of cal and tlc	Interconnected talc-rich foliation affected by frictional slip

Which are the frictional properties of these fault rocks?





Talc grain-size reduction, down to 30 nm providing infinite number of possible slipping planes.

2008 ICDP workshop to drill across the active LANF in the Apennines

MOLE drilling project

Multidisciplinary Observatory and
Laboratory of Experiments
in Central Italy

Let's rock on !

NSF: discoveries

Faults Family and Friction

by Marone & Collettini, 2010

http://www.nsf.gov/discoveries/

Let’s rock on !

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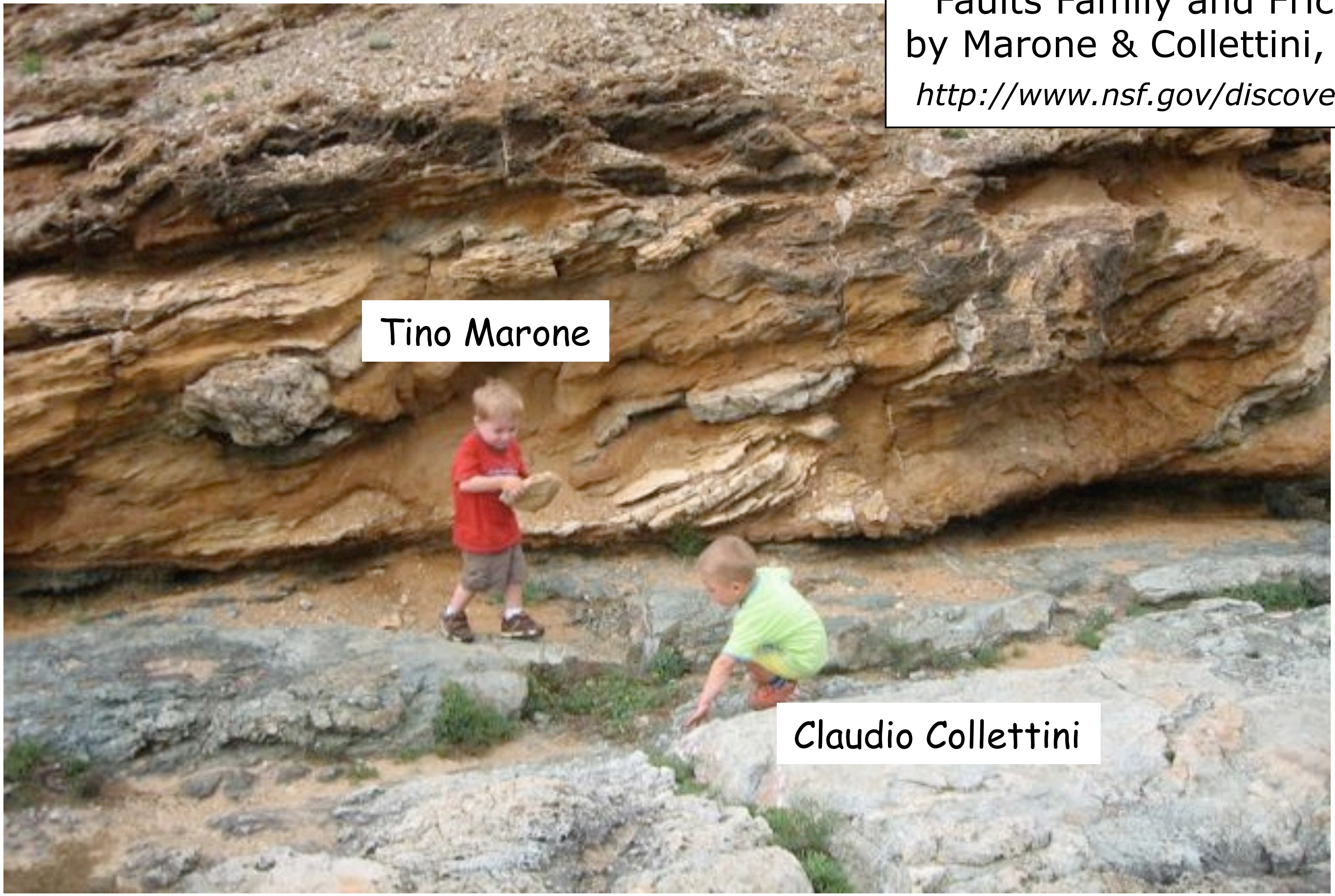
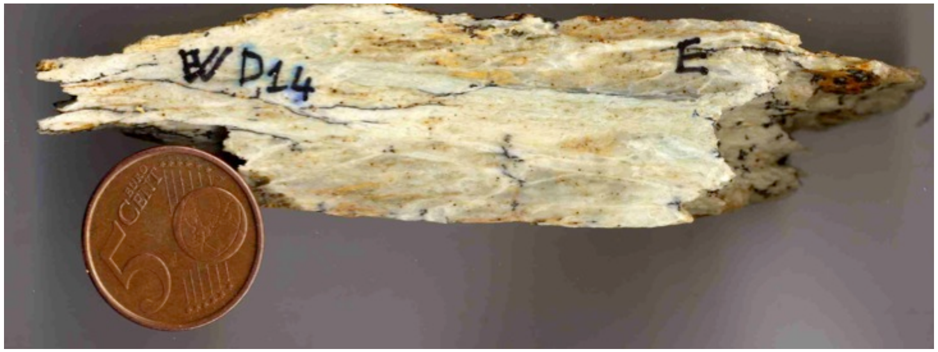
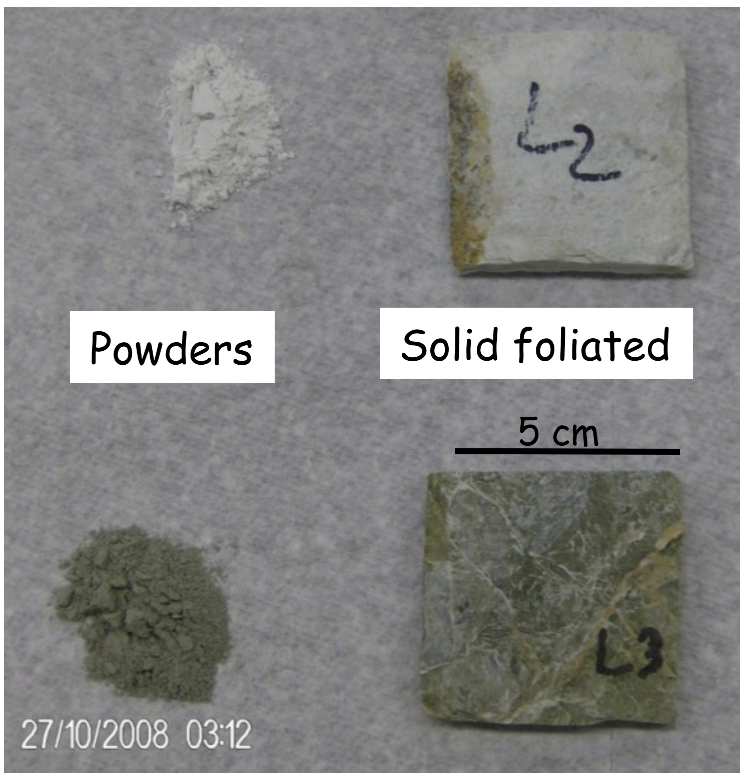


Let’s rock on !

NSF: discoveries
Faults Family and Friction
by Marone & Collettini, 2010
http://www.nsf.gov/discoveries/

…..6 years later





	L2	L3
calcite	43%	39%
tremolite	36%	26%
talc	6%	15%
smectite	15%	20%
phyllosilicates	21%	35%

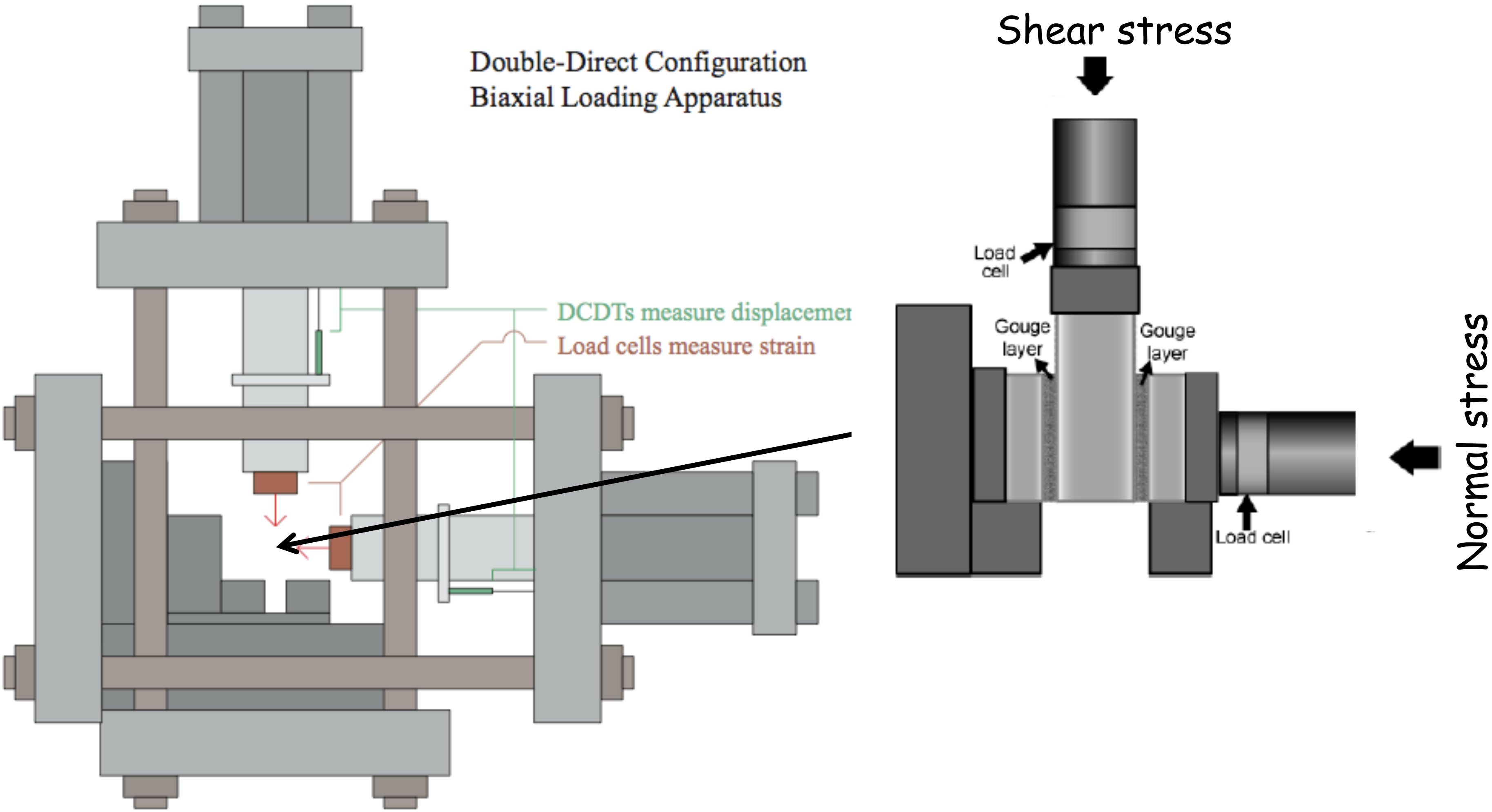
Differential thermal analysis coupled with mass spectrometer;

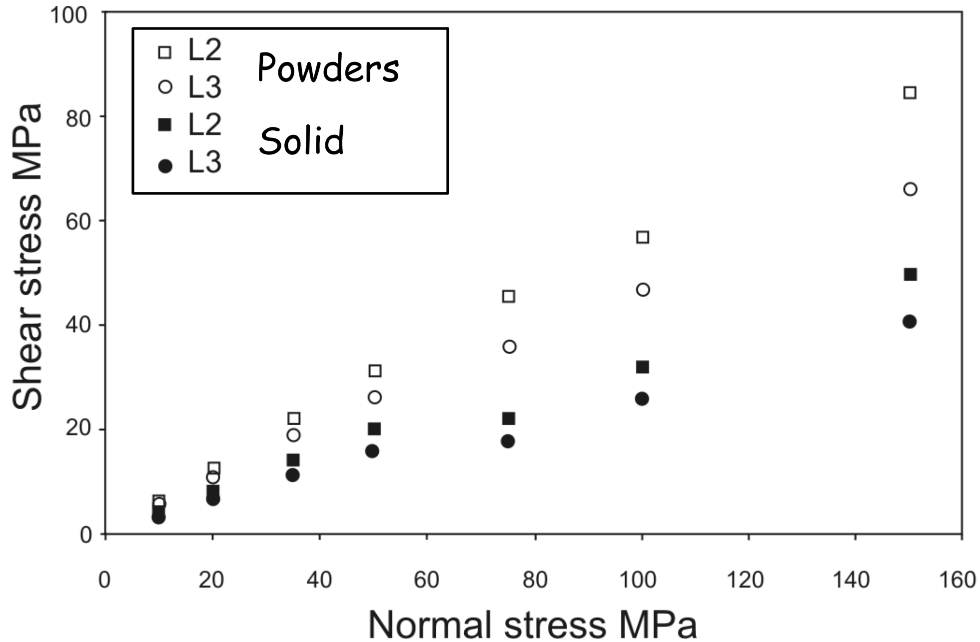
XRPD on bulk starting sample;

XRPD on the fine fraction (< 2 μm).

Collettini, Niemeijer, Viti, Marone, Nature 2009

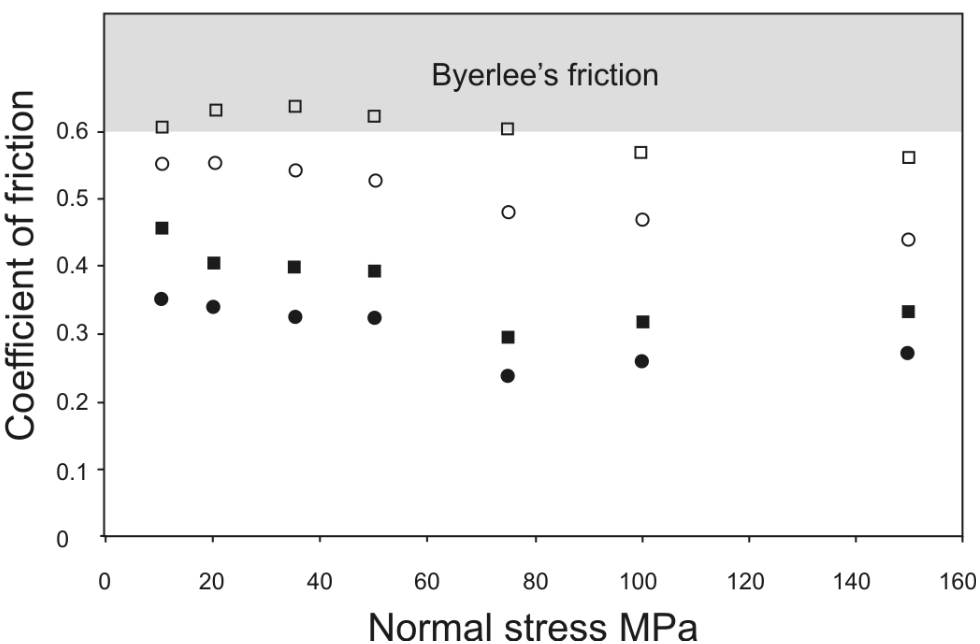
Double direct biaxial loading apparatus at Penn State University





Frictional properties: solid-foliated vs. powdered

Each rock-type plots along a line consistent with a brittle failure envelope, BUT the foliated solid wafers are much weaker than their powdered analogues.

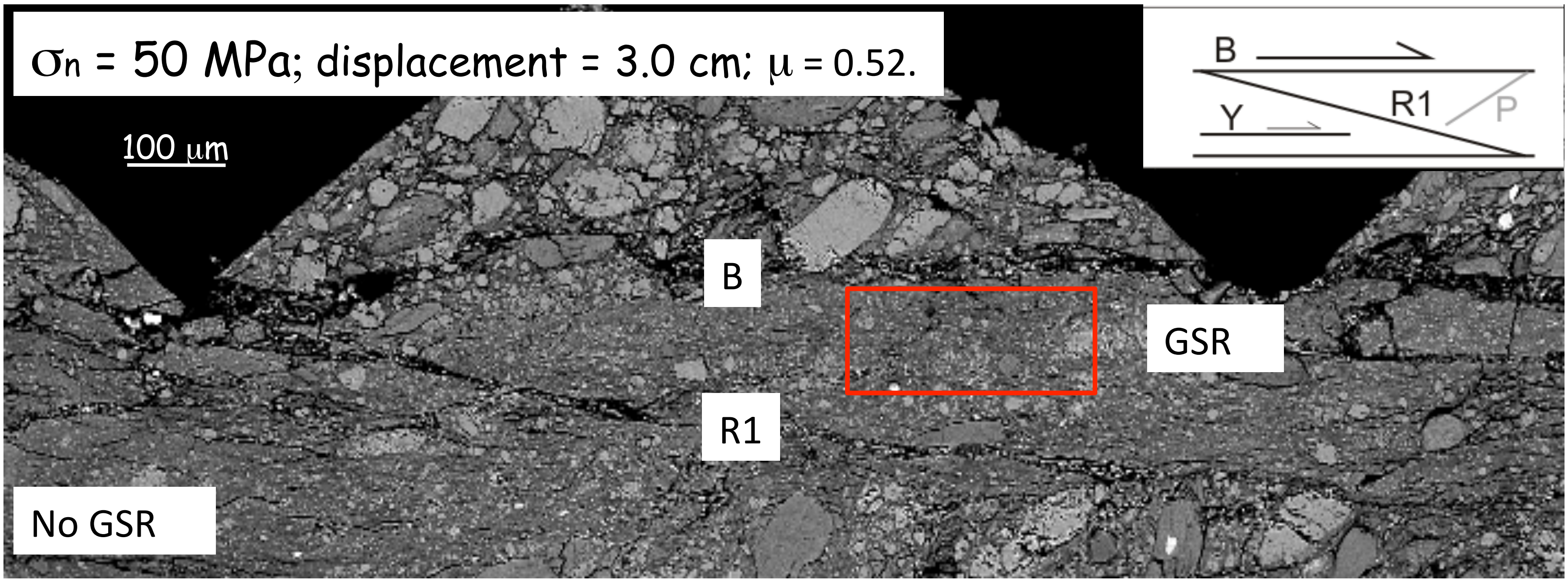


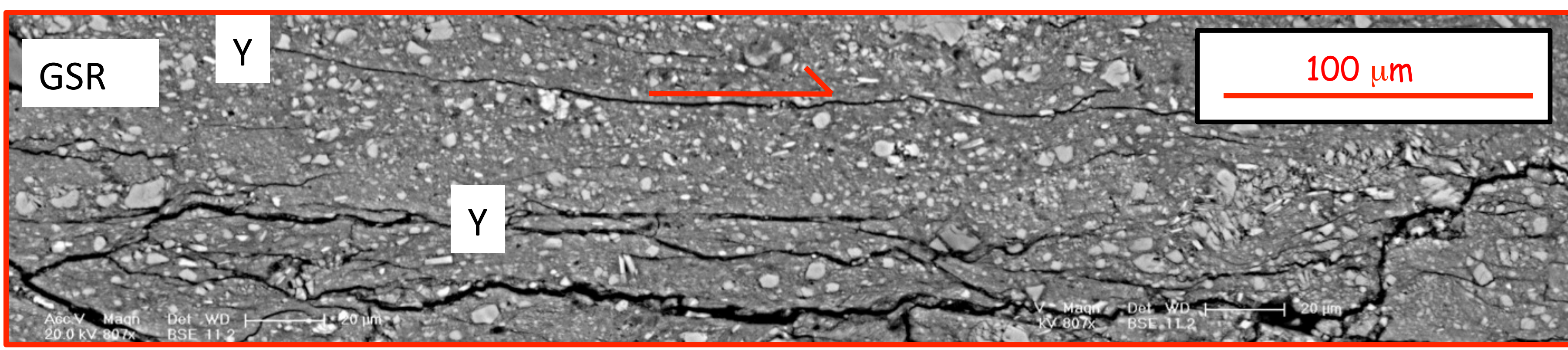
Powders show a friction close to Byerlee's values whereas the foliated rocks posses values significantly lower, 0.45-0.23, and for each normal stress solid rocks have a friction coefficient 0.2-0.3 lower than powders

Collettini, Niemeijer, Viti, Marone, Nature 2009

Microstructures
solid-foliated vs. powdered

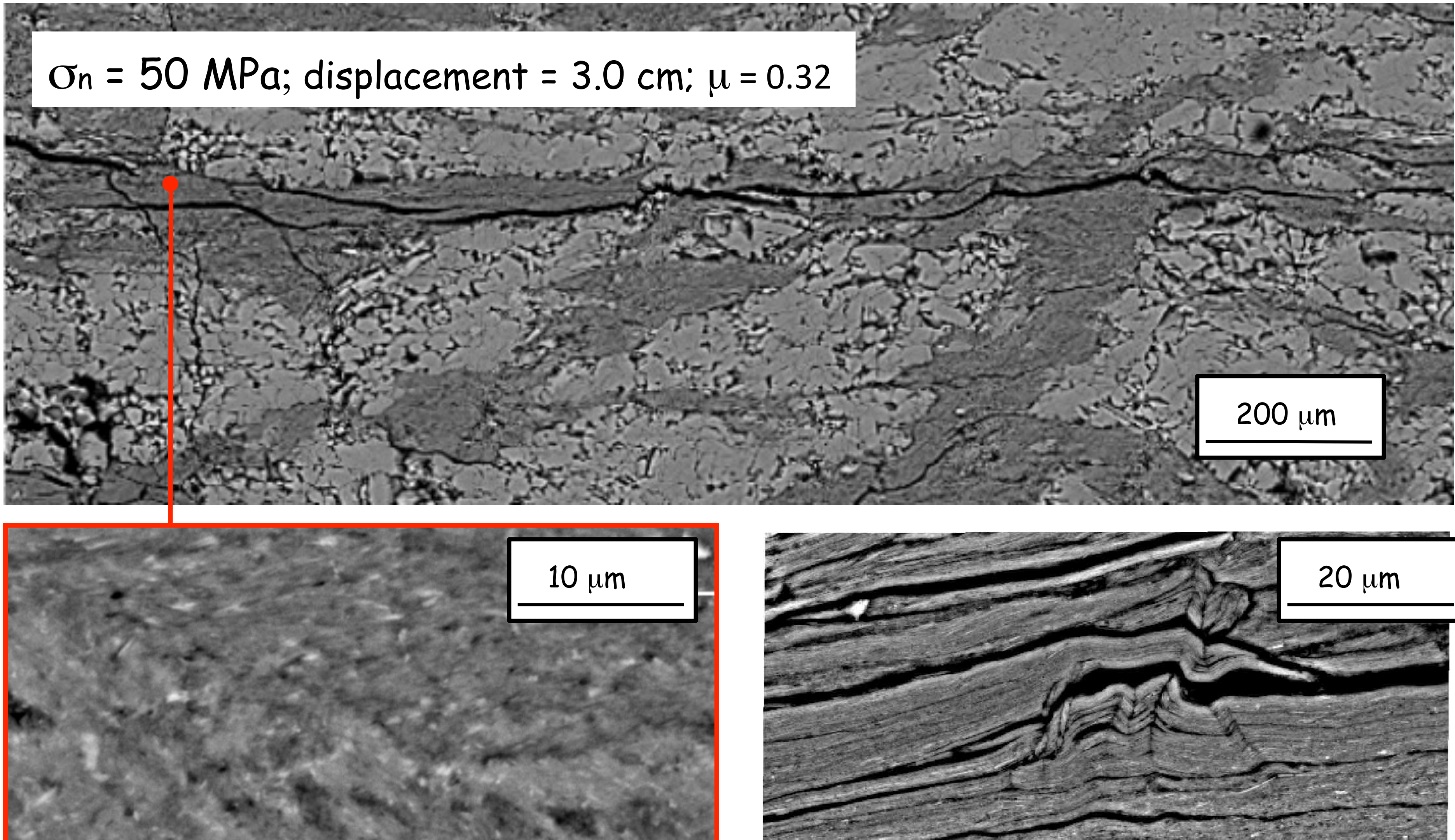
Powders: deformation occurs along a zone characterised by cataclasis with grain-size reduction and affected by shear localization along R1, Y, B shears (e.g. Logan, 1978; Beeler et al., 1996; Marone et al., 1998).



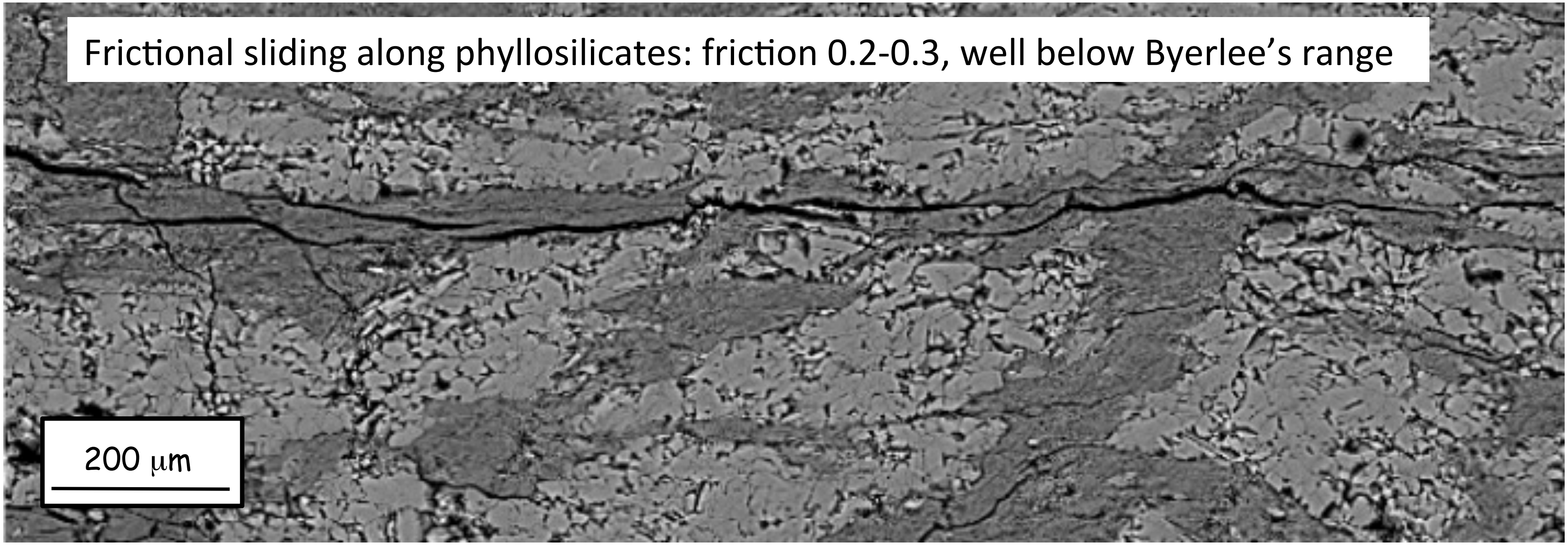


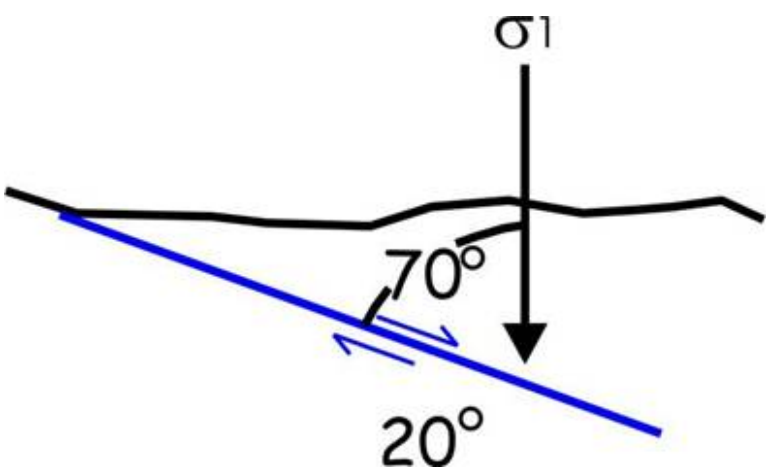
Solid-foliated sliding surfaces located along the pre-existing very fine grained, <2mm.

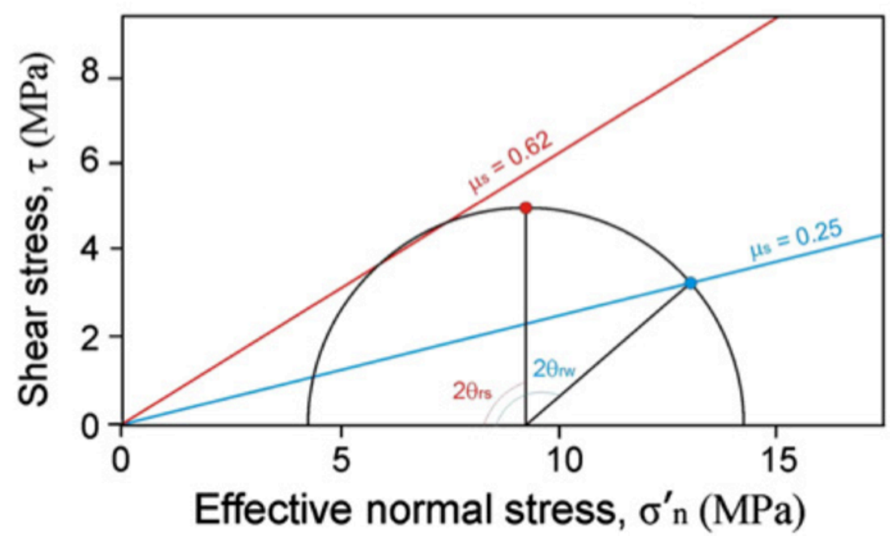
Microstructures solid-foliated vs. powdered



Frictional sliding along phyllosilicates: friction 0.2-0.3, well below Byerlee's range

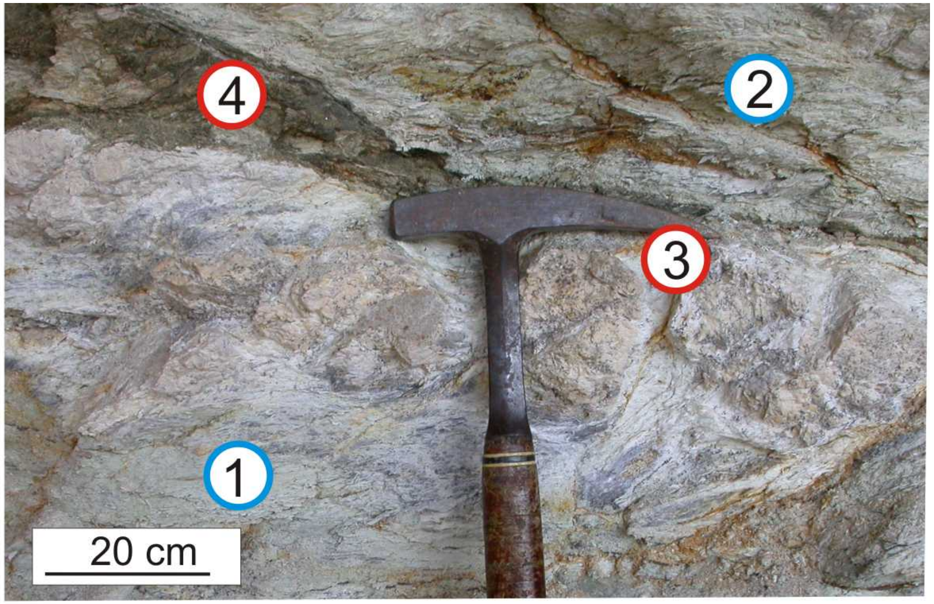


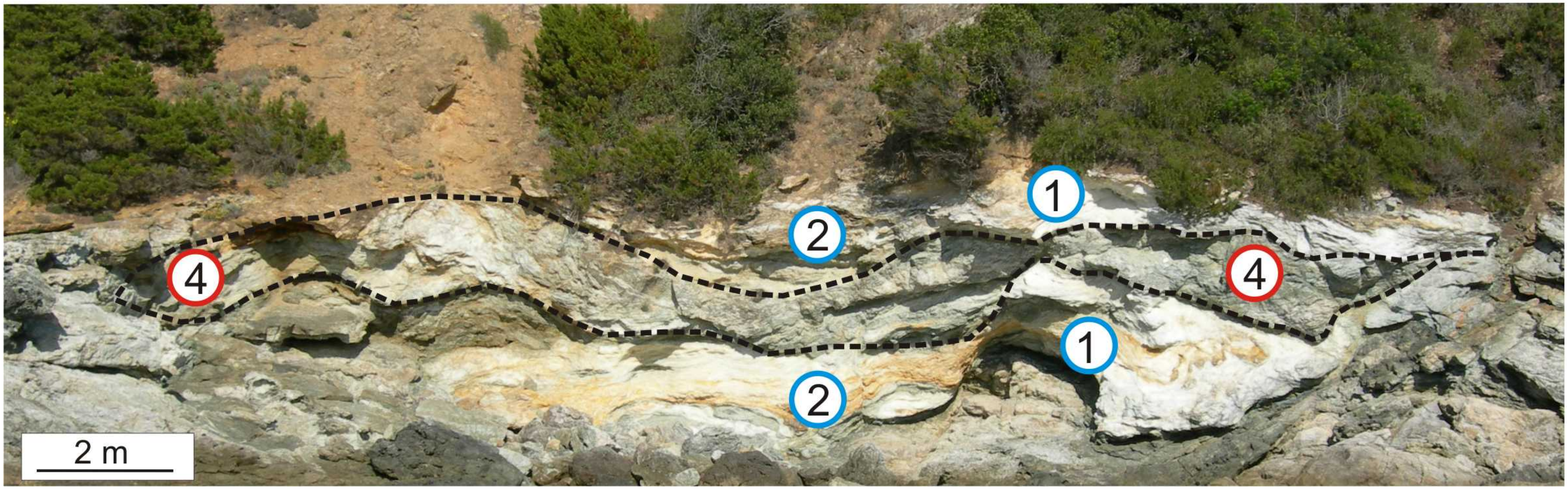




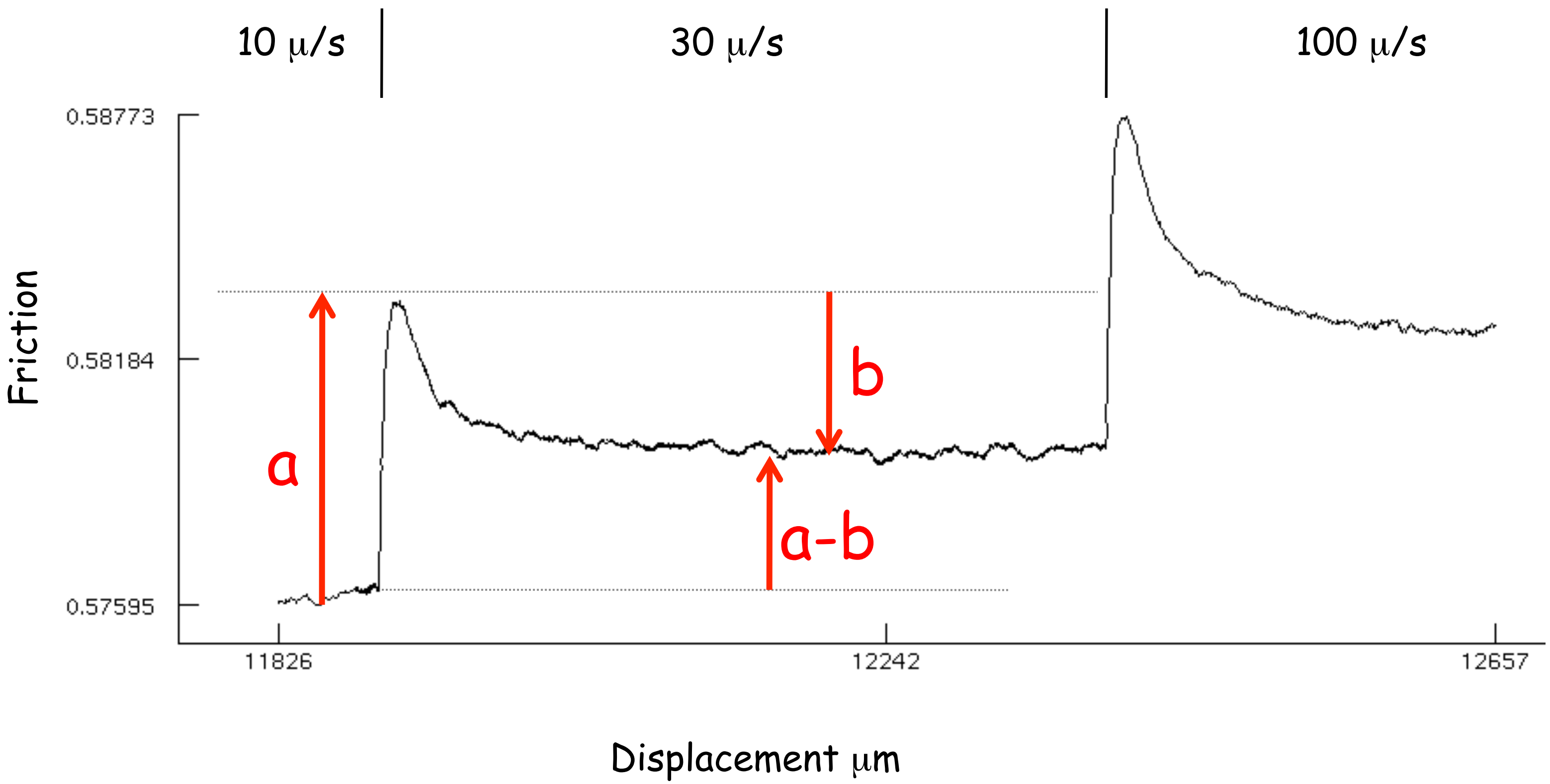
Heterogeneous fault zone structure and frictional properties

	Rock-Type	Friction
1	Foliated Phyll.	0.3
2	Foliated Phyll.	0.25
3	Dolostone	0.7
4	Mafic	0.7





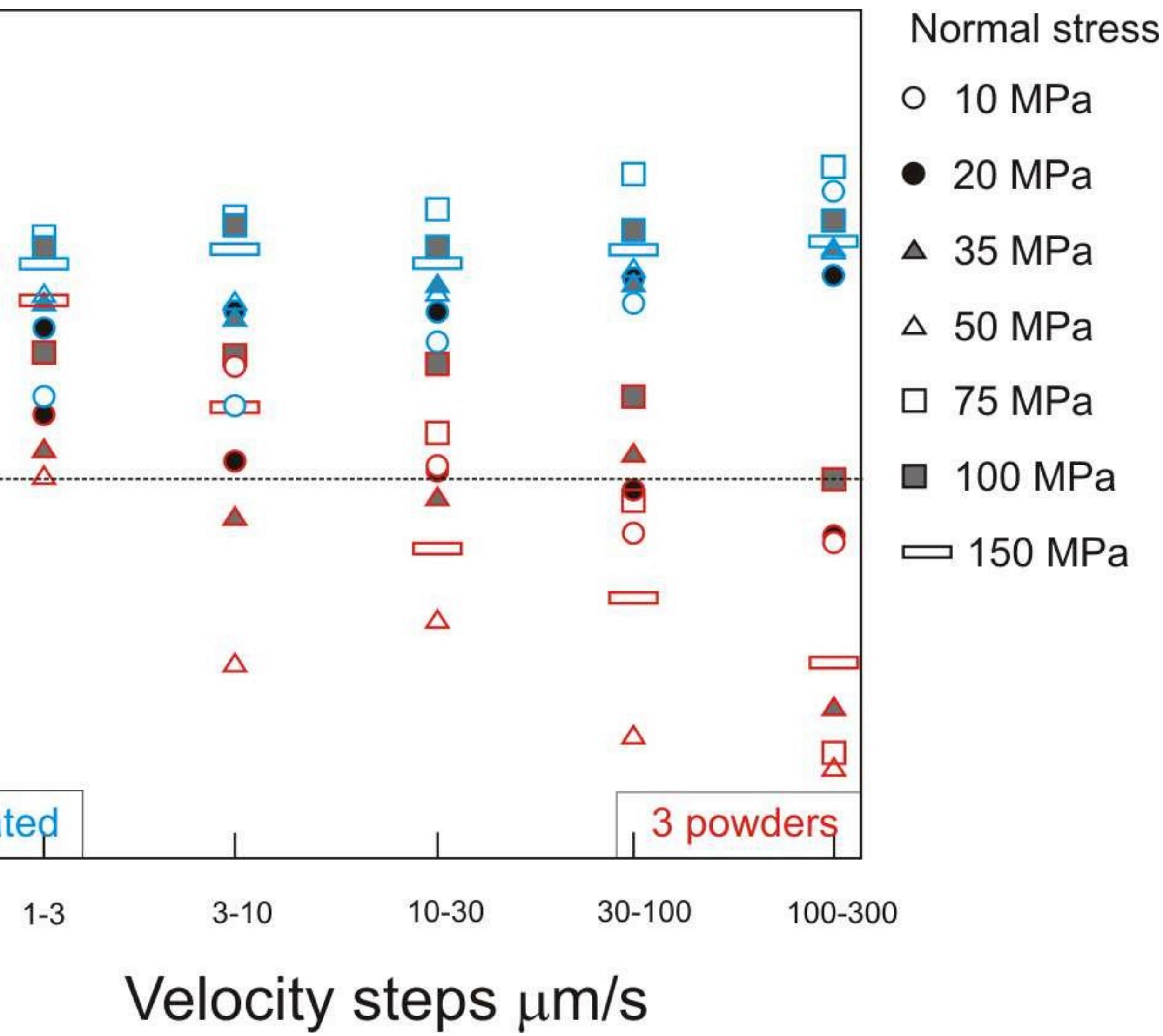
Velocity dependence of sliding friction solid-foliated vs. powdered

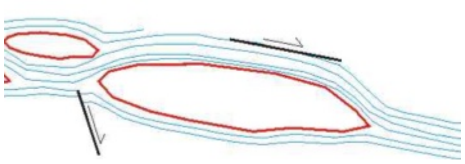


The velocity dependence of sliding friction is given by (a-b) = $\Delta u / \Delta \ln V$

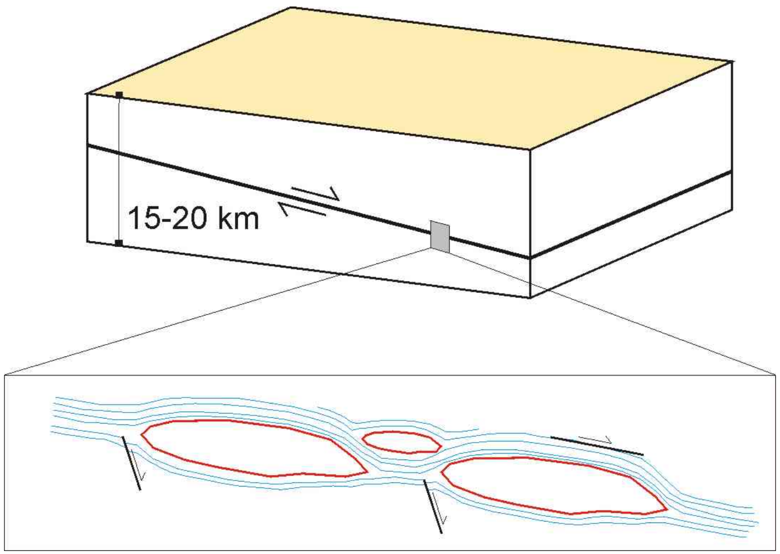
Negative values of (a-b) reflect velocity weakening behaviour, positive (a-b) reflect velocity strengthening, which results in stable sliding.

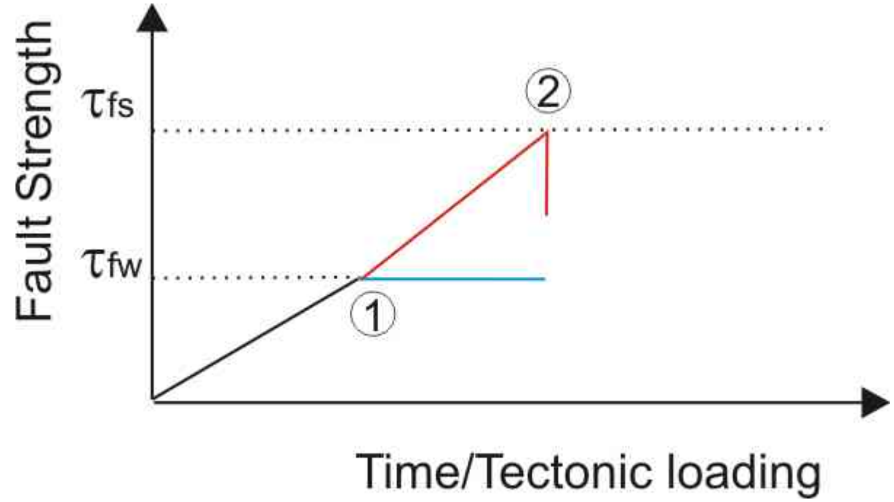
Heterogeneous fault zone structure and frictional properties

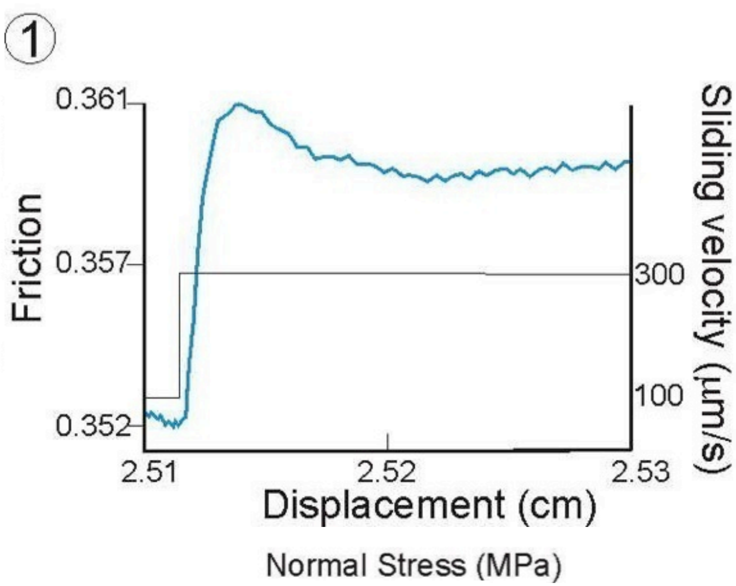


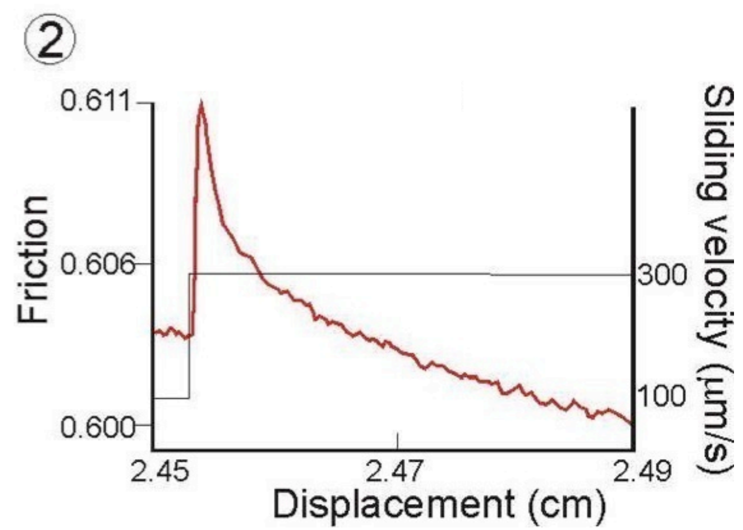


Mixed-mode slip behaviour: creep + microseismicity



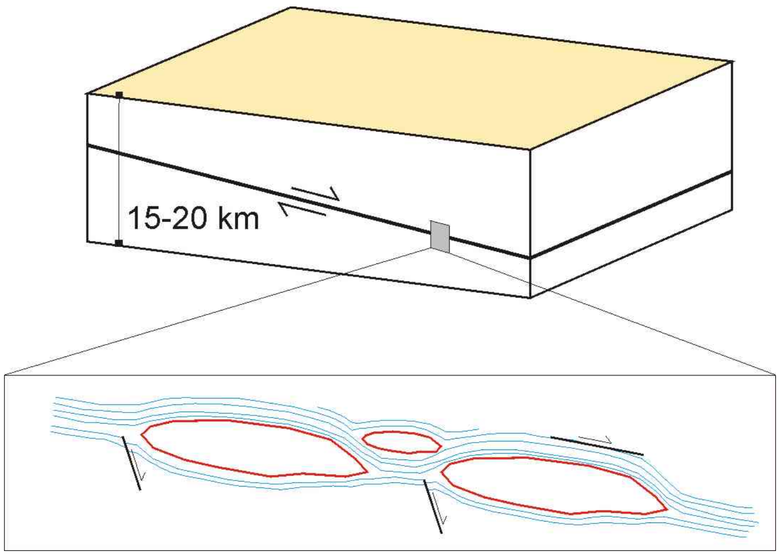


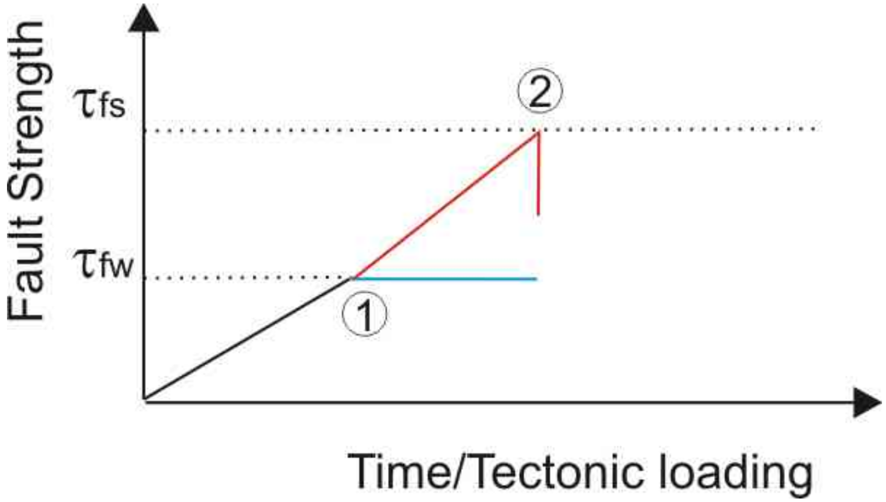


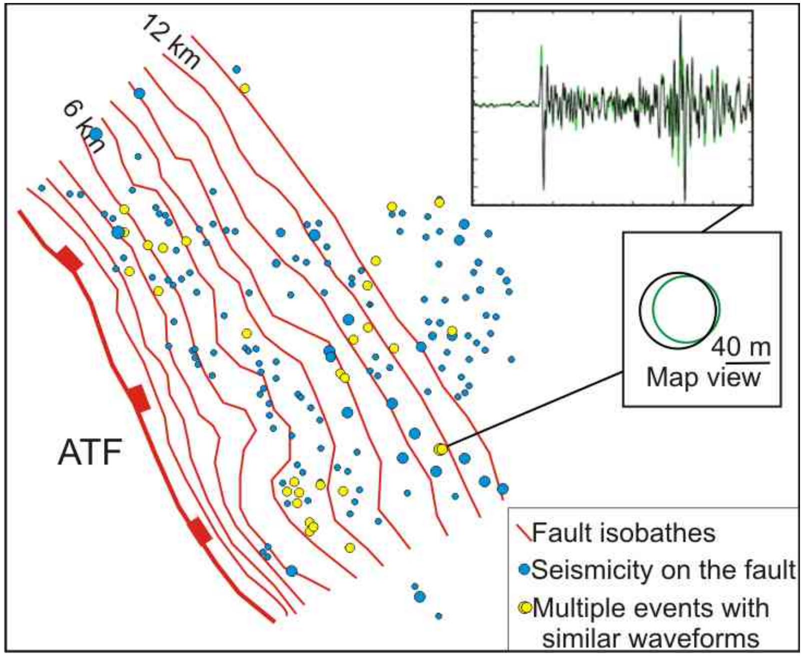


Collettini et al., EPSL, 2011.

Mixed-mode slip behaviour: creep + microseismicity







Introduction

Natural fault rocks and microstructures
Lab. experiments for slip behavior and microstructures

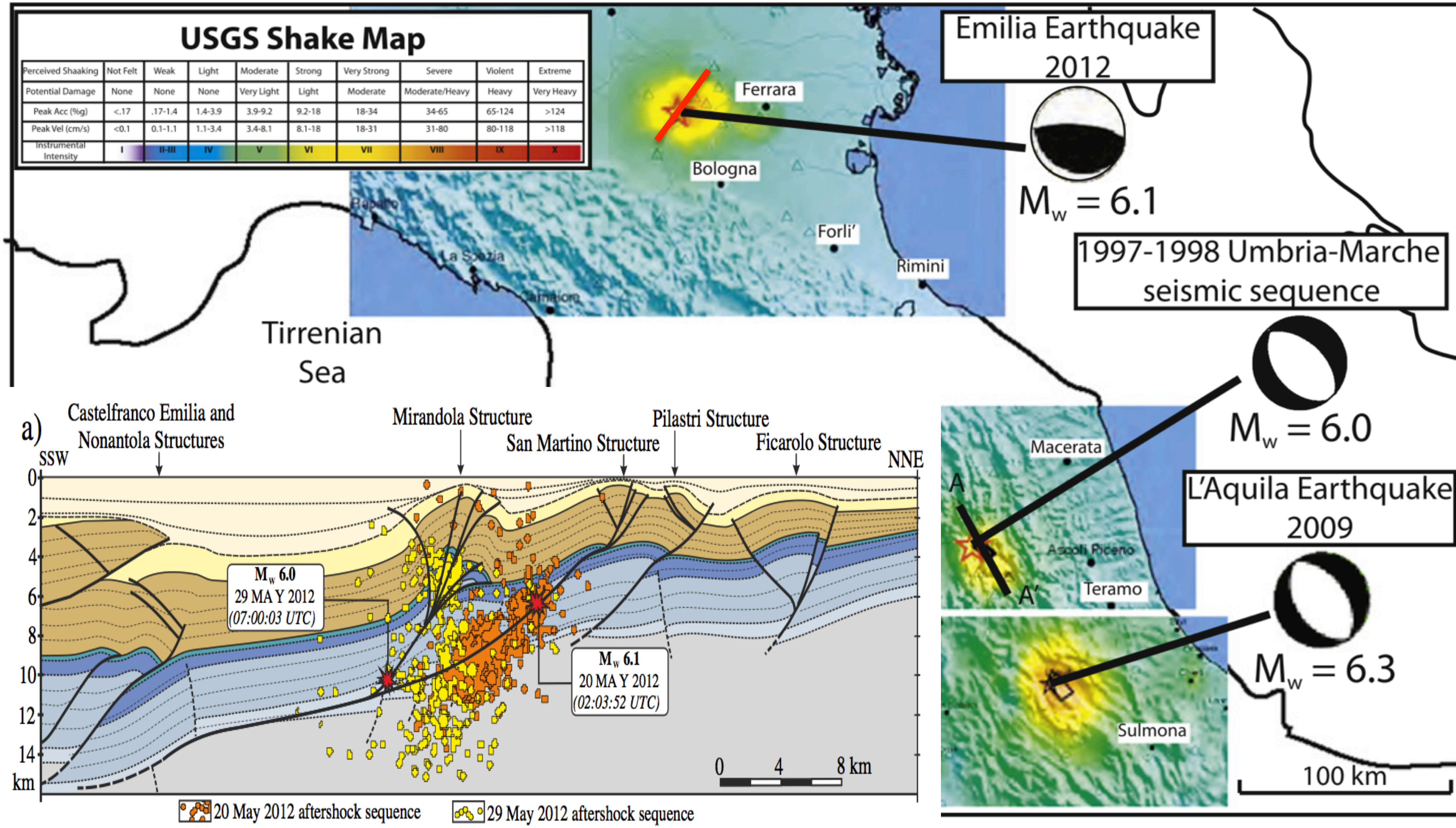
1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

3) Fault structure and slip localization in carbonate-bearing normal faults

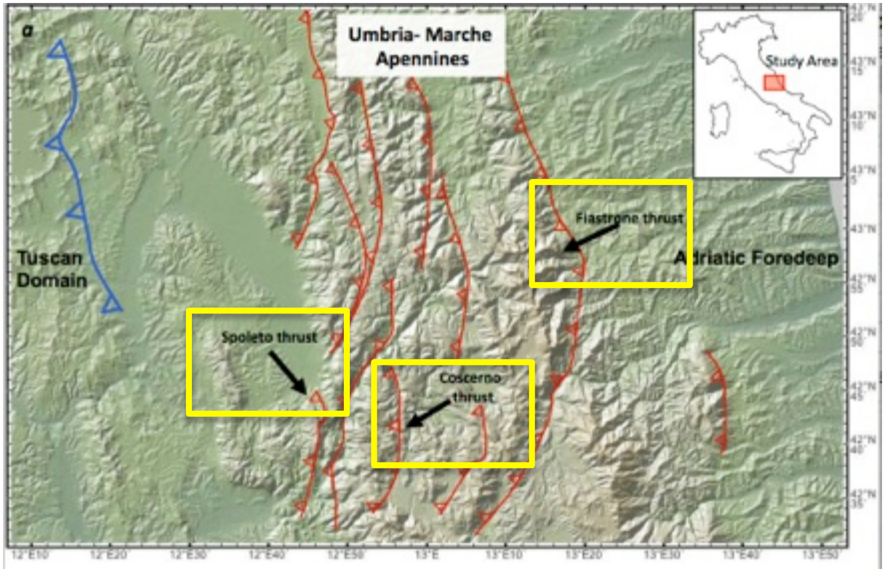
Future directions

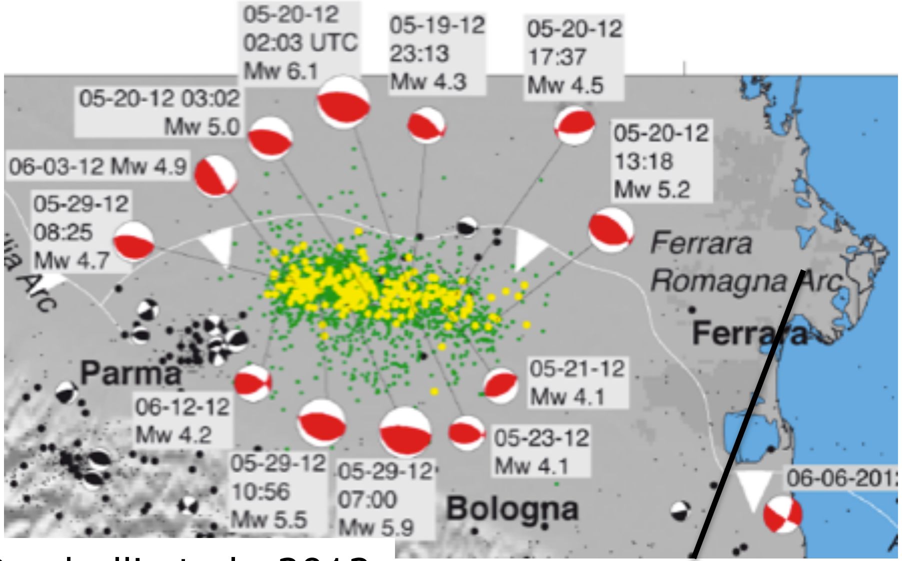
Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab



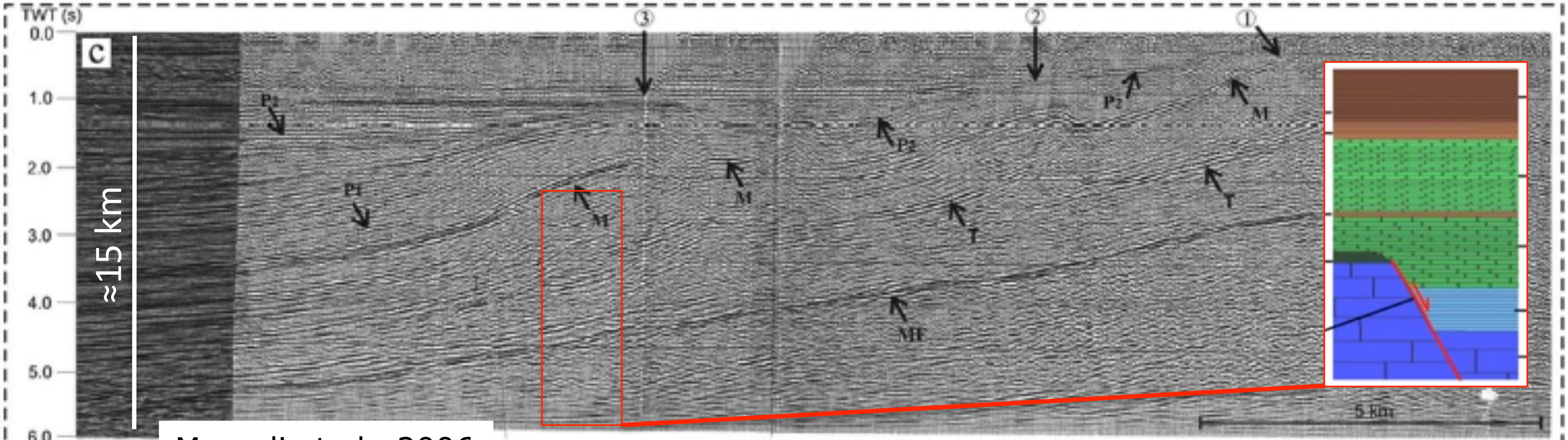
Bonini et al., 2014

Field studies of regional thrusts that represent exhumed analogues of the active faults responsible for the seismicity in the Emilia region.



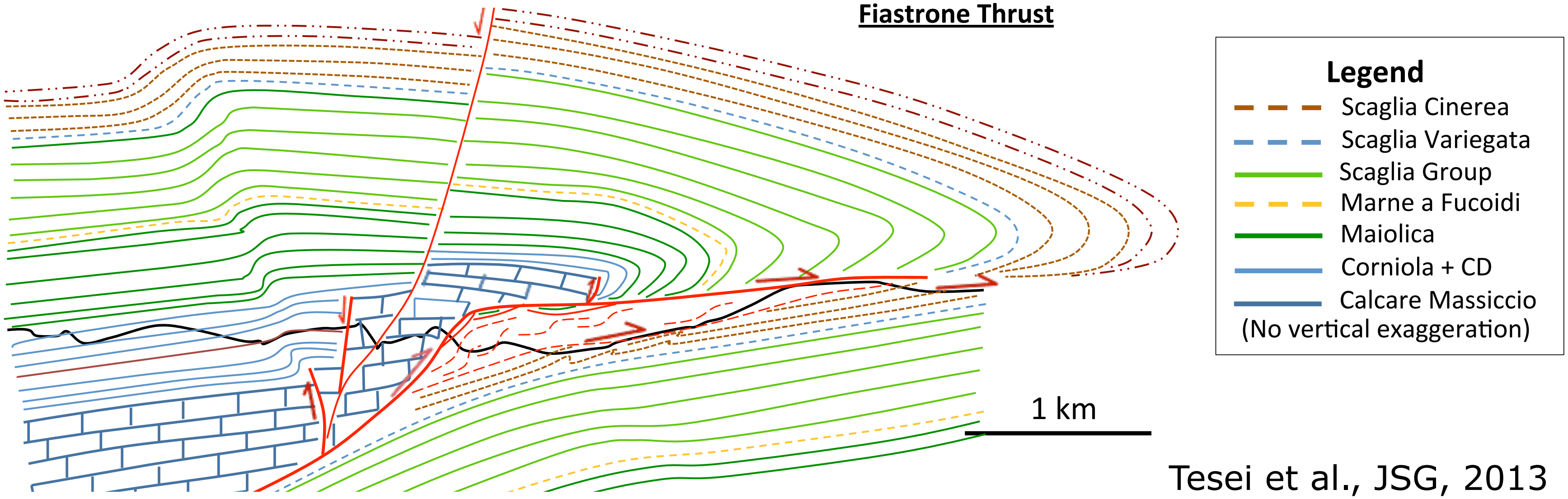


Pondrelli et al., 2012

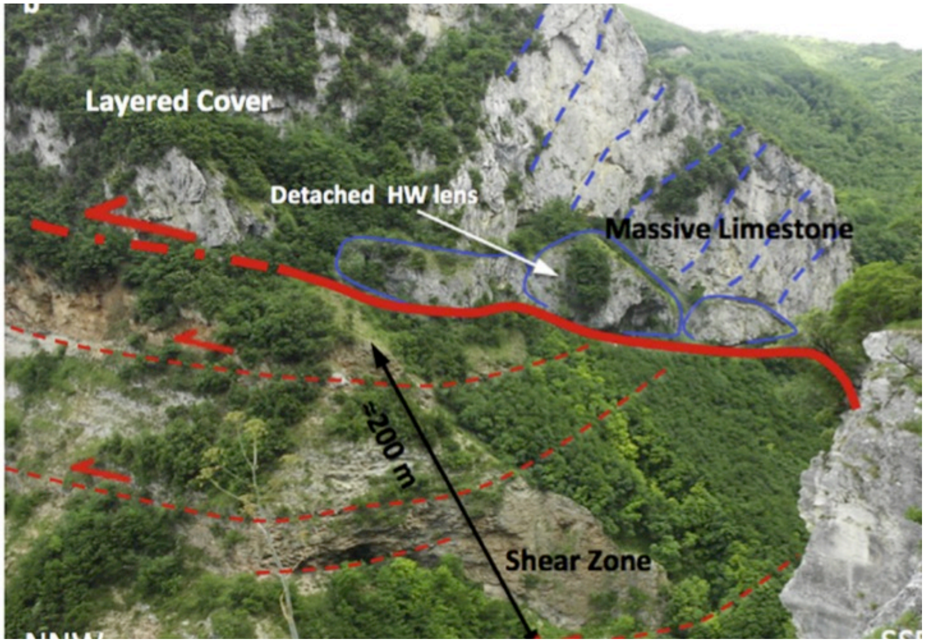


Massoli et al., 2006

Distributed deformation in marly limestones

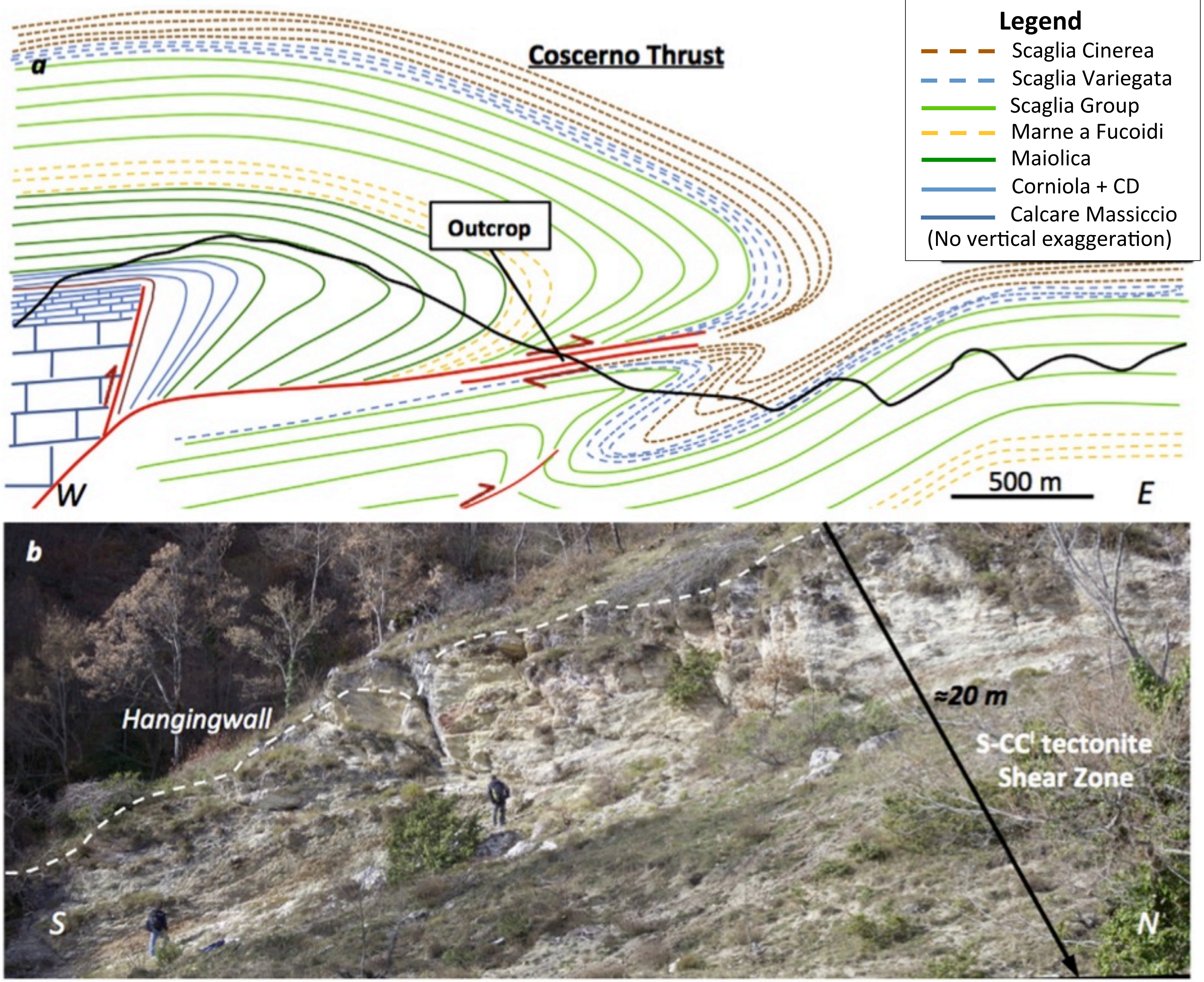


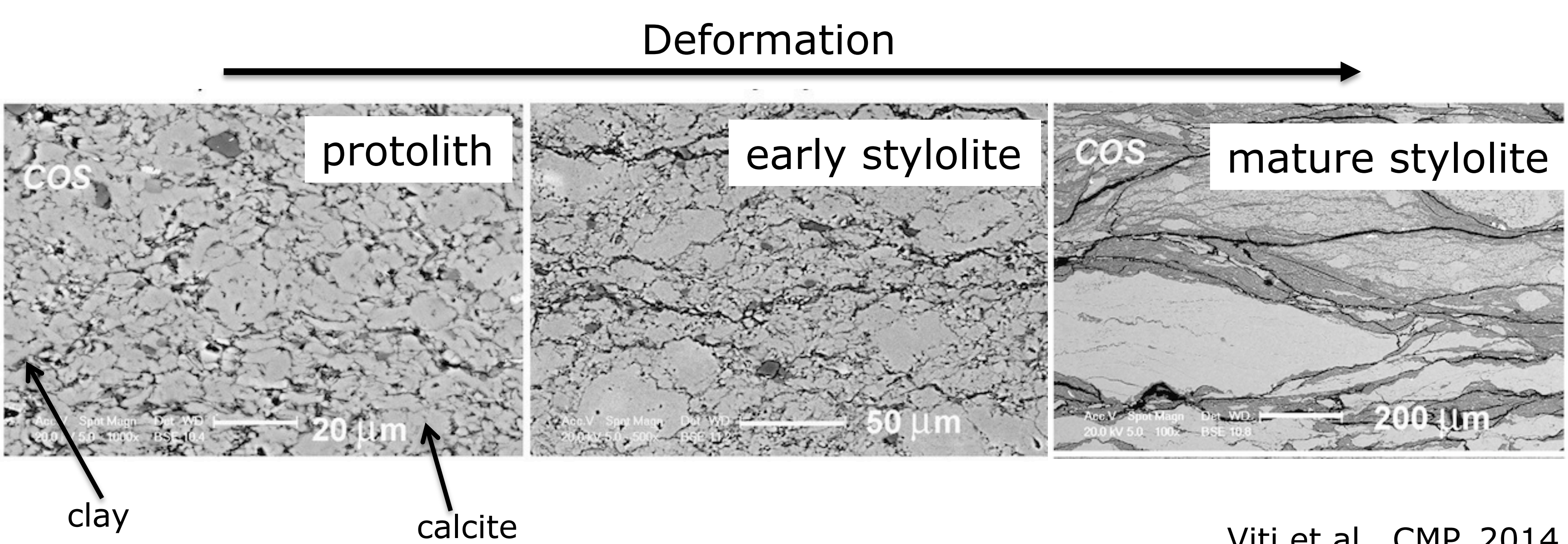
Tesei et al., JSG, 2013



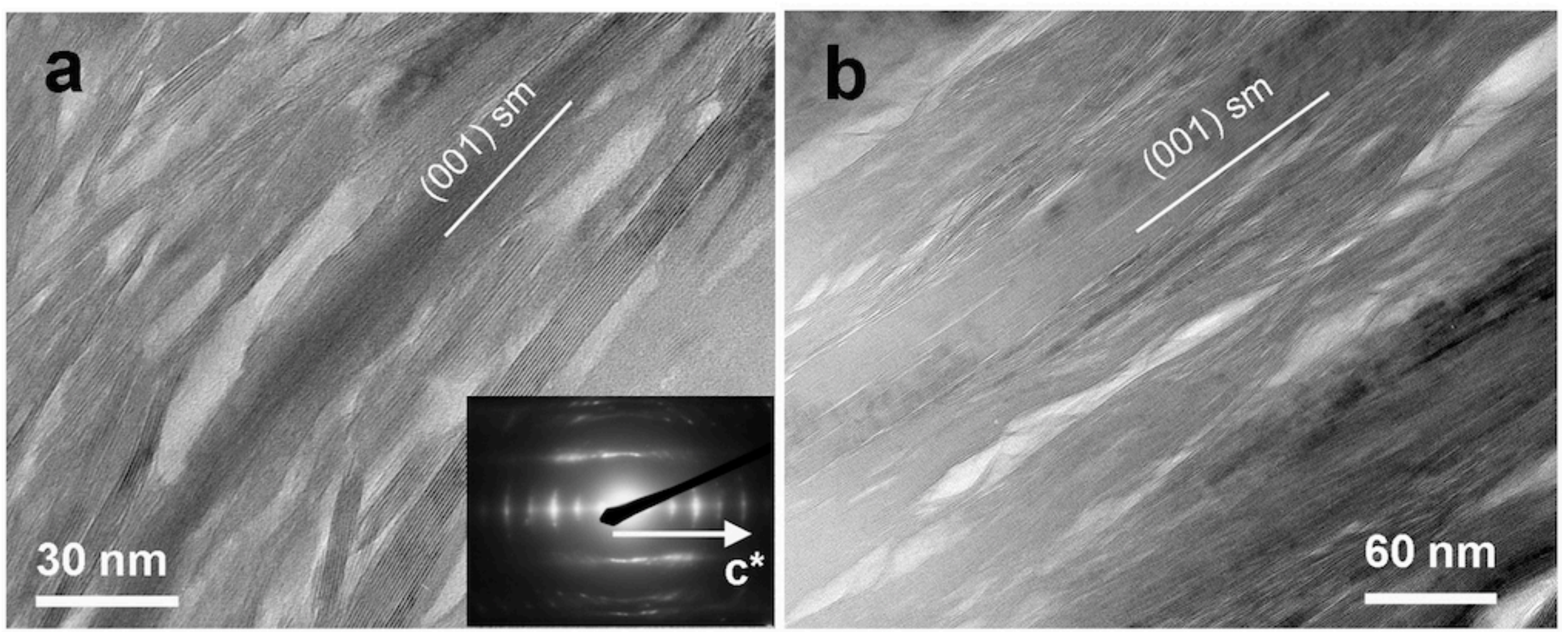
Distributed deformation in marly limestones

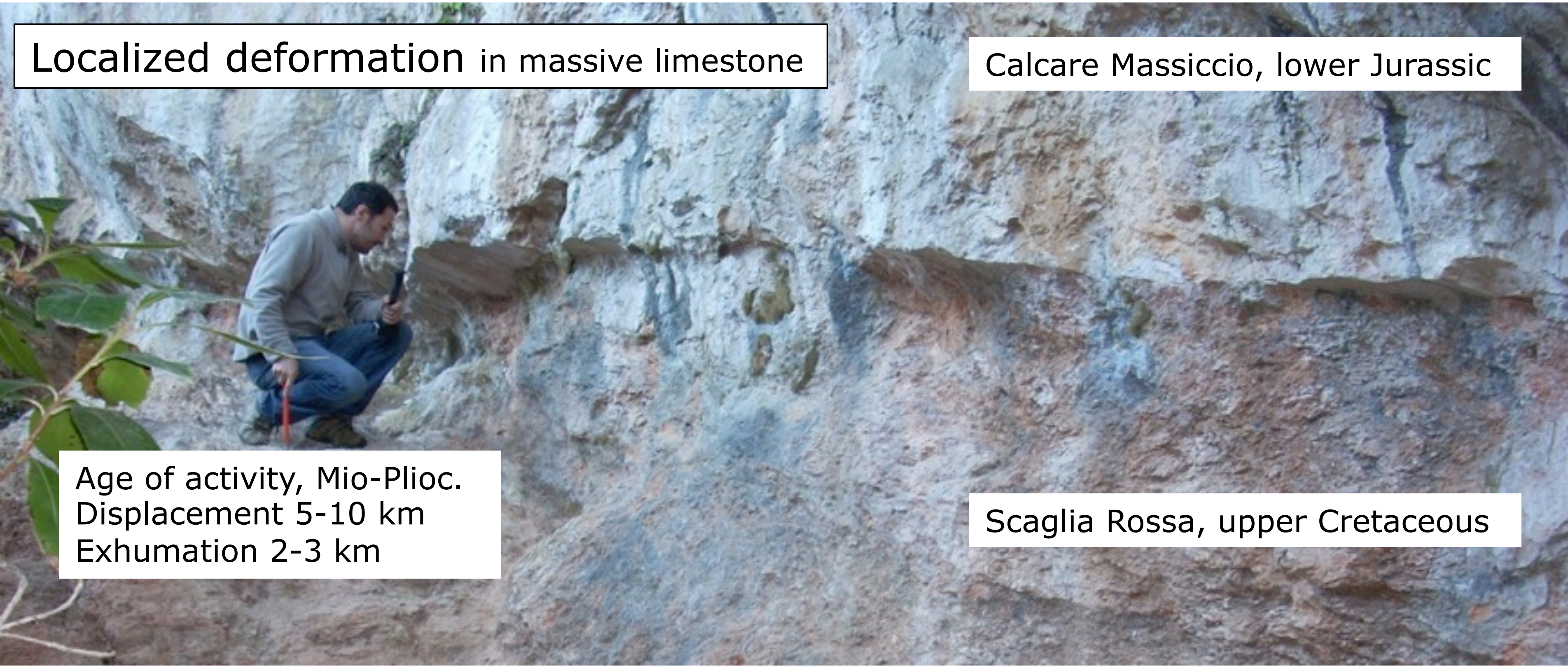
Tesei et al., JSG, 2013



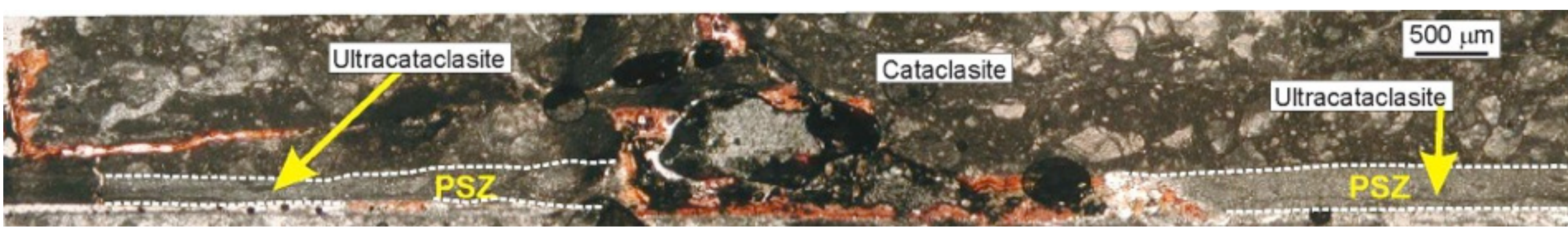


Viti et al., CMP, 2014

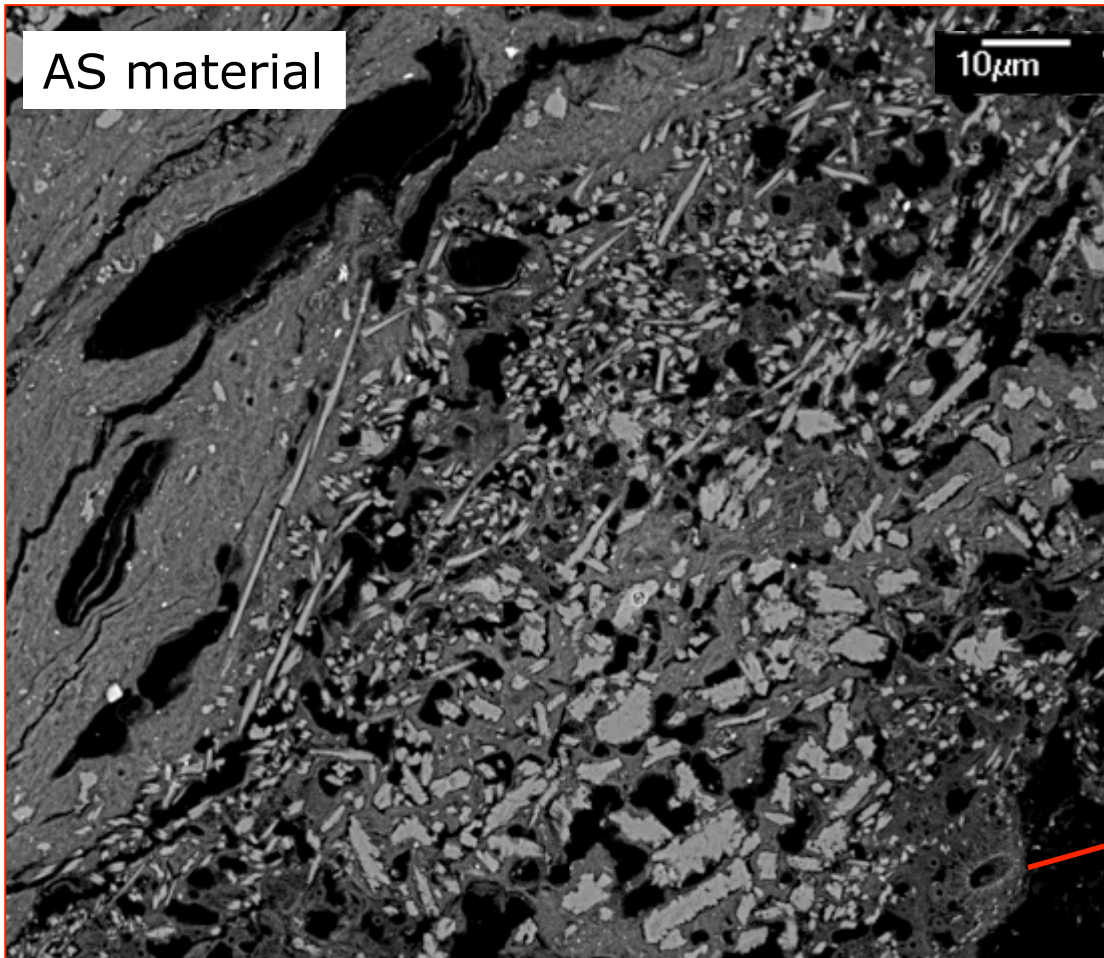


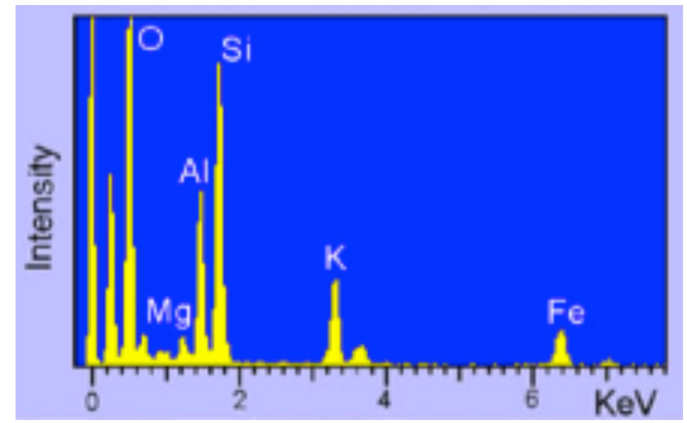


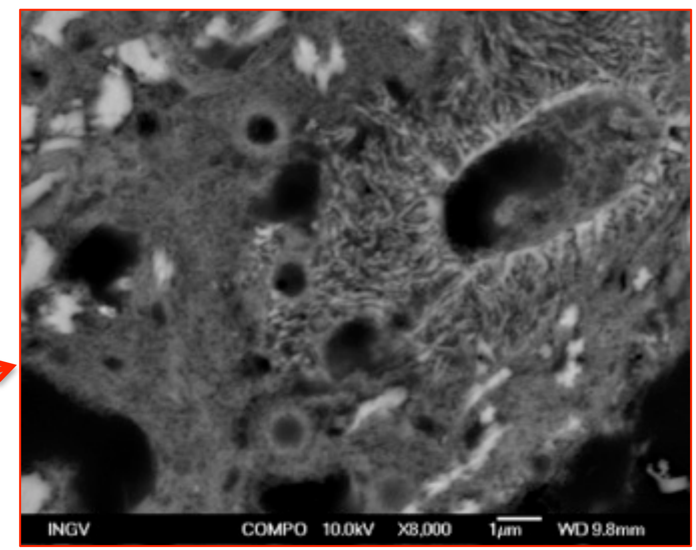
Collettini et al., Geology 2013

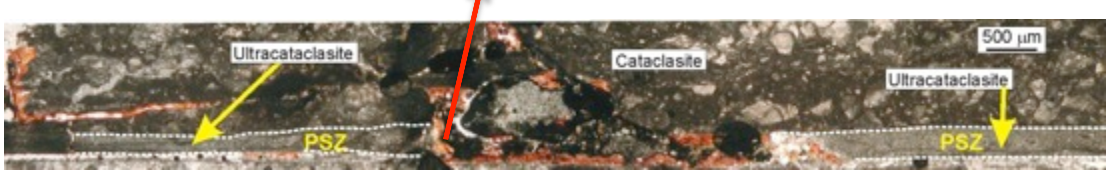


Amorphous-silicate material made of: relict calcite and clay, numerous vesicles, poorly crystalline/ amorphous phases, and newly formed calcite skeletal.

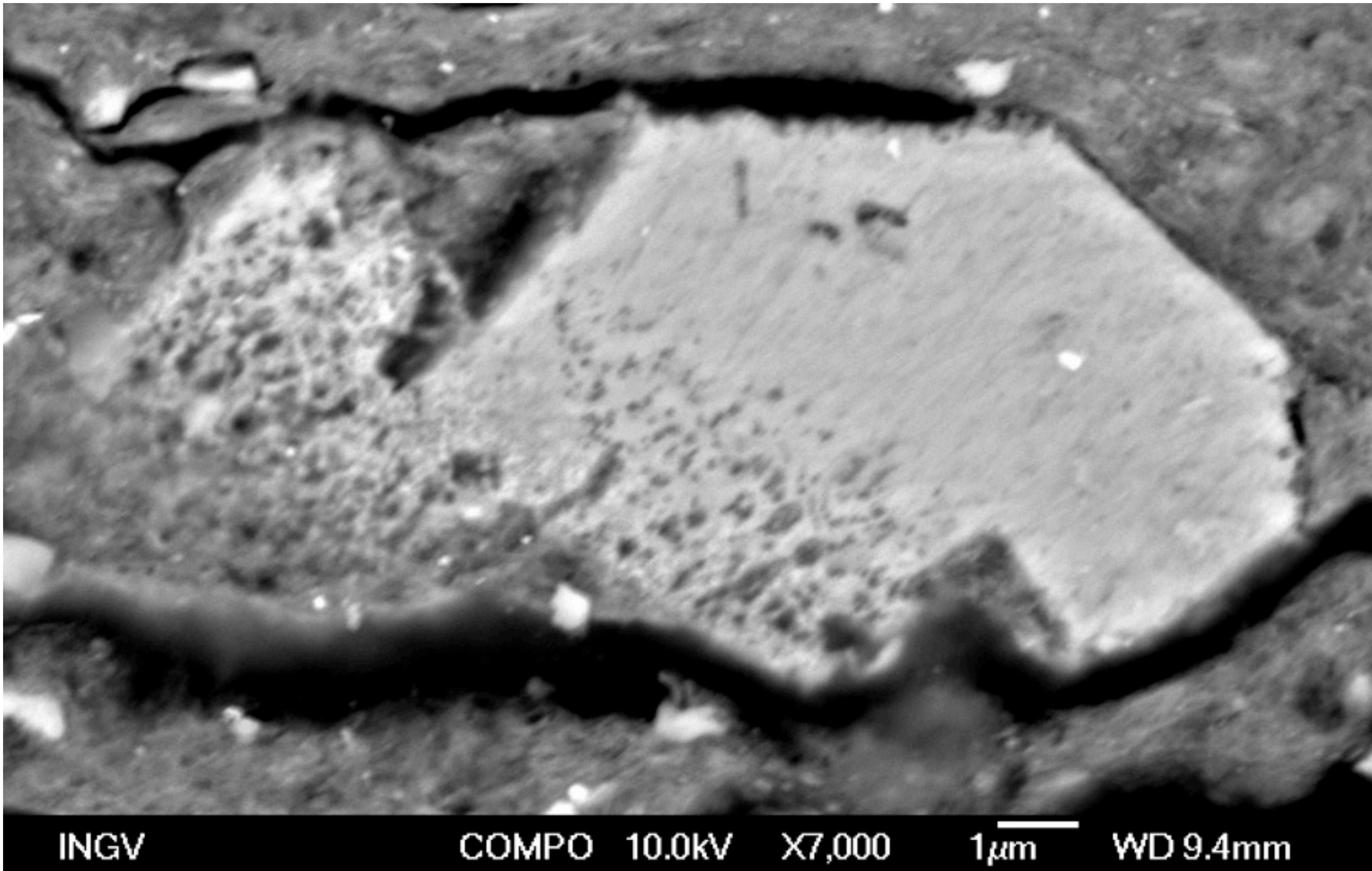




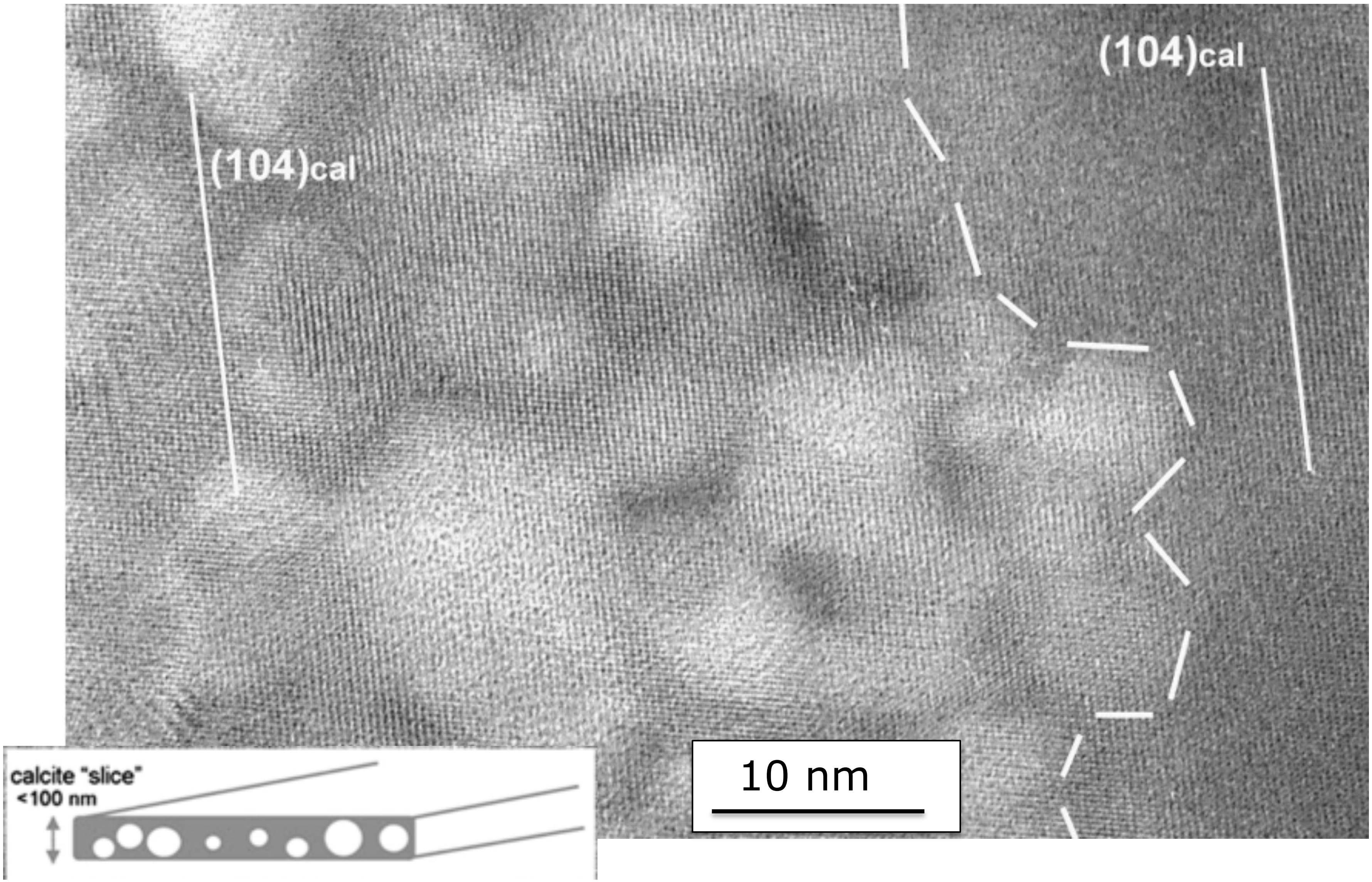




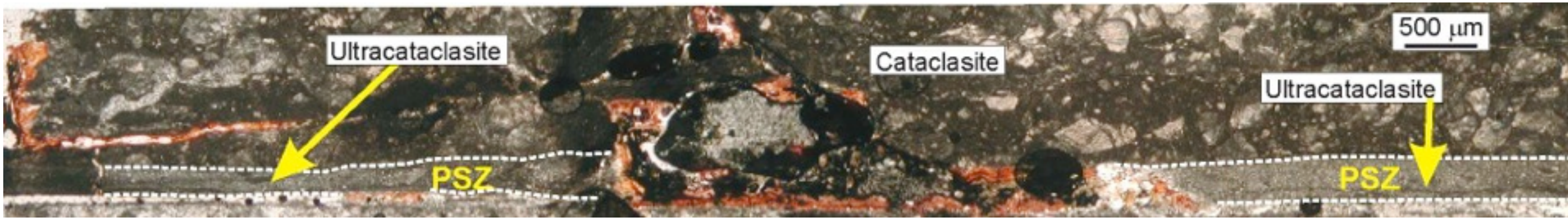
Calcite crystal showing decarbonation.



Calcite crystal showing decarbonation.



Thermal decomposition of calcite initiates at about 600 °C, BUT the fault rock of the thrust formed at 2-3 km of depth, at temperature below 70° C.



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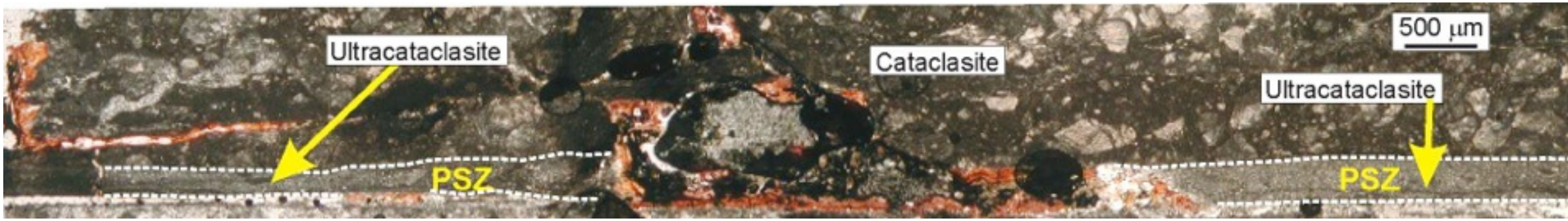
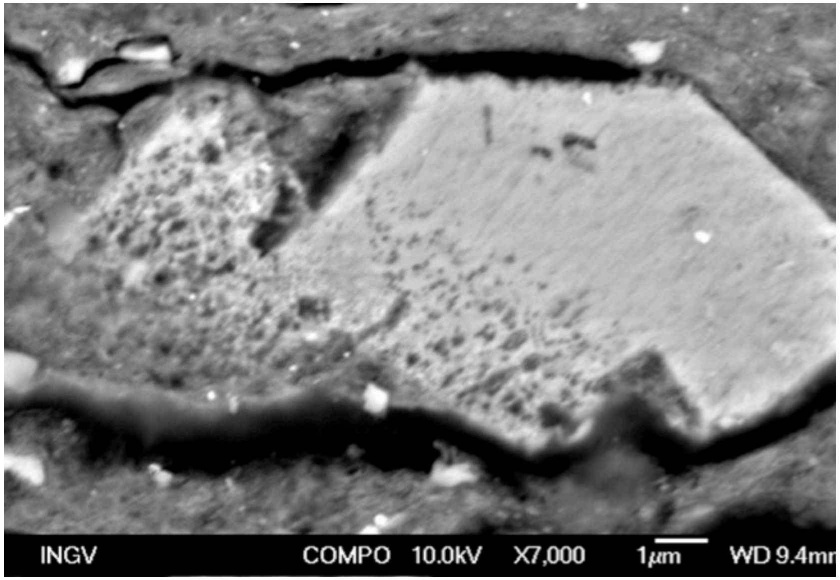
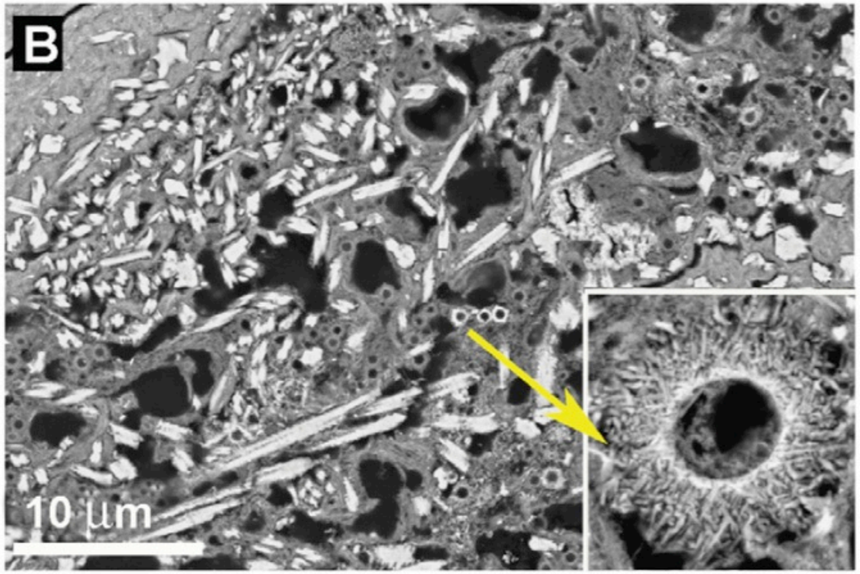


EQ slip localized on a thin slip surface
Temperature increase with Decarb + Dehyd.



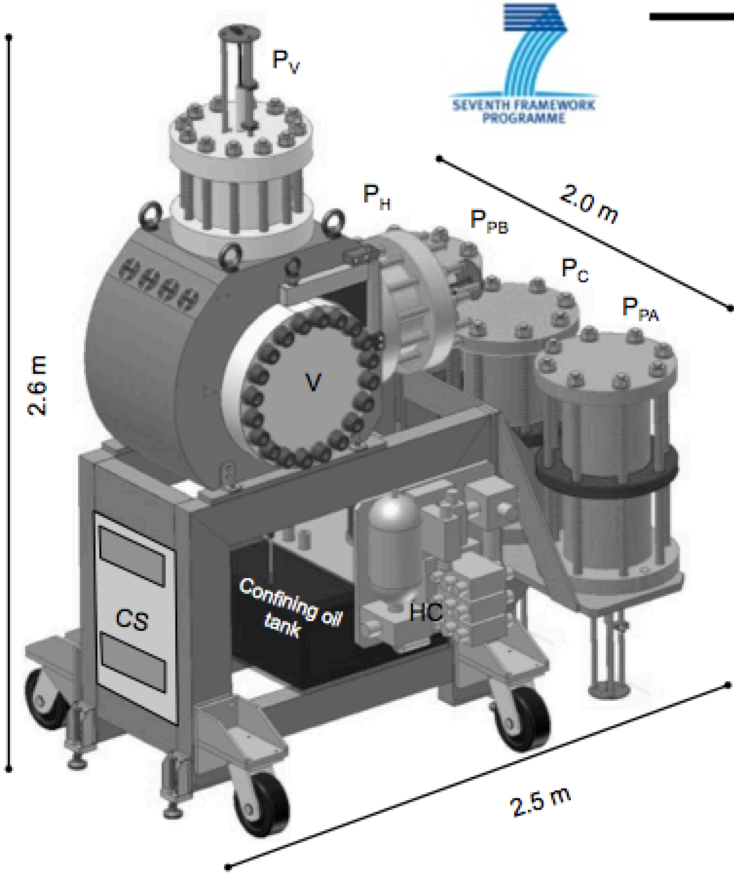
....and the production of
vesiculated material with skeletal crys.

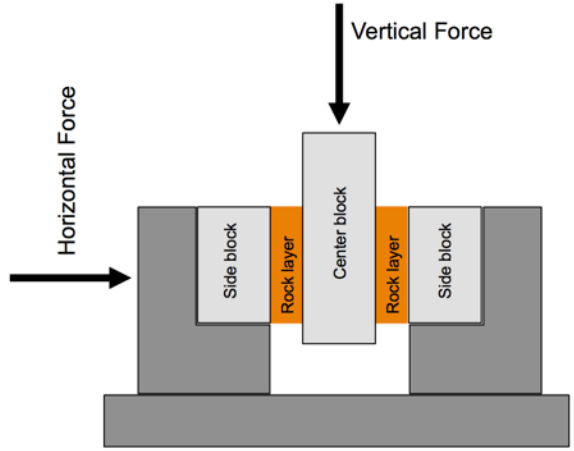


Collettini et al., Geology 2013

Reproduce the heterogeneous fault rocks in the lab.

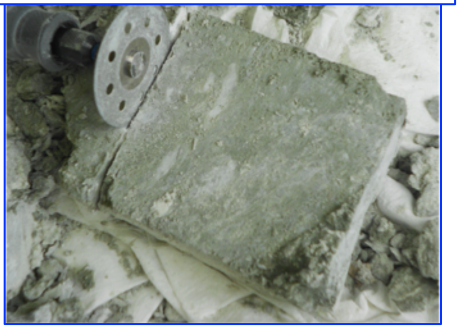
BRAVA @ INGV



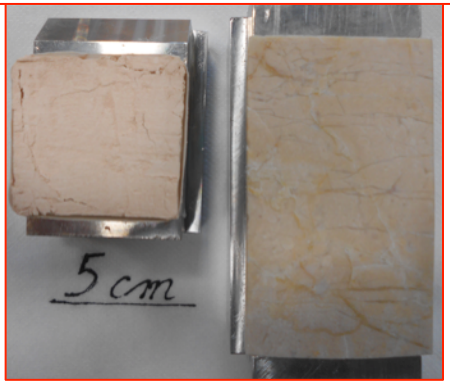


Collettini et al., IJRMMS, 2014

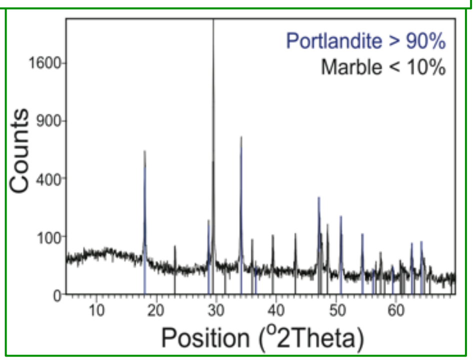
Clay-rich shear zones

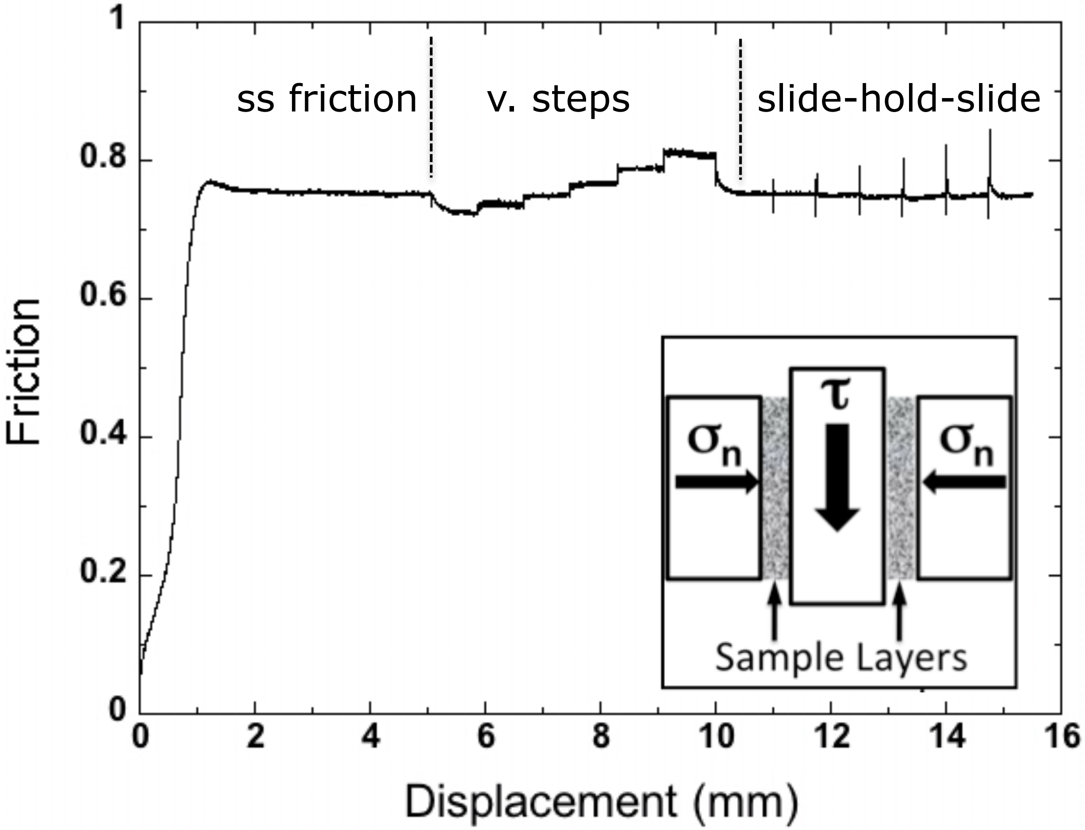


Localiz. on massive carb.

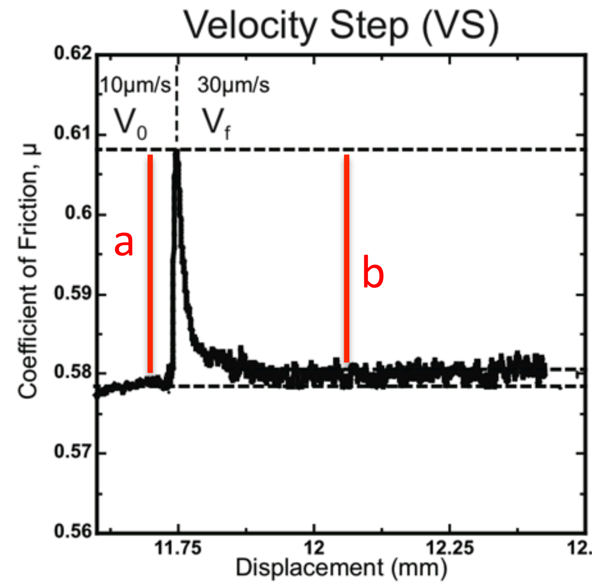


Decarbonated material

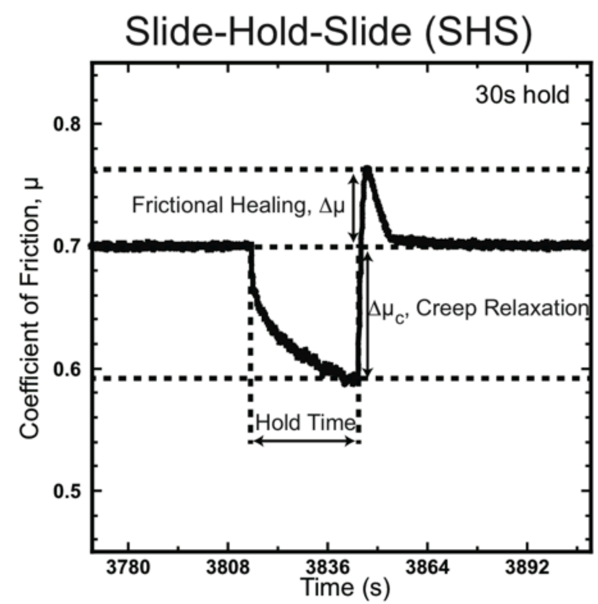




Friction
Displacement (mm)
ss friction
v. steps
slide-hold-slide
Sample Layers

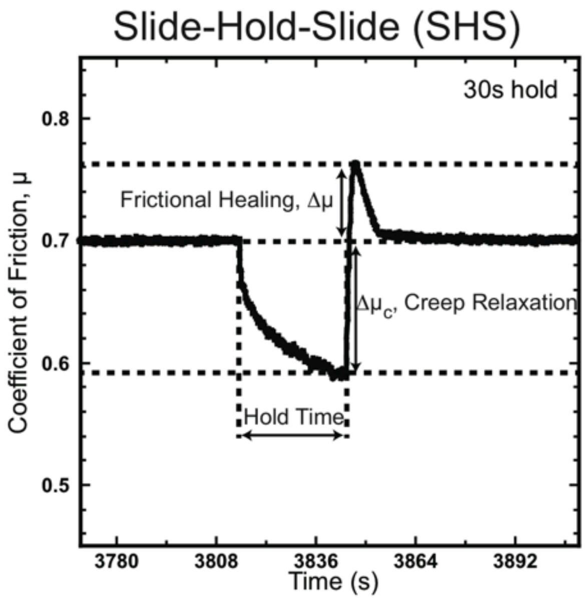


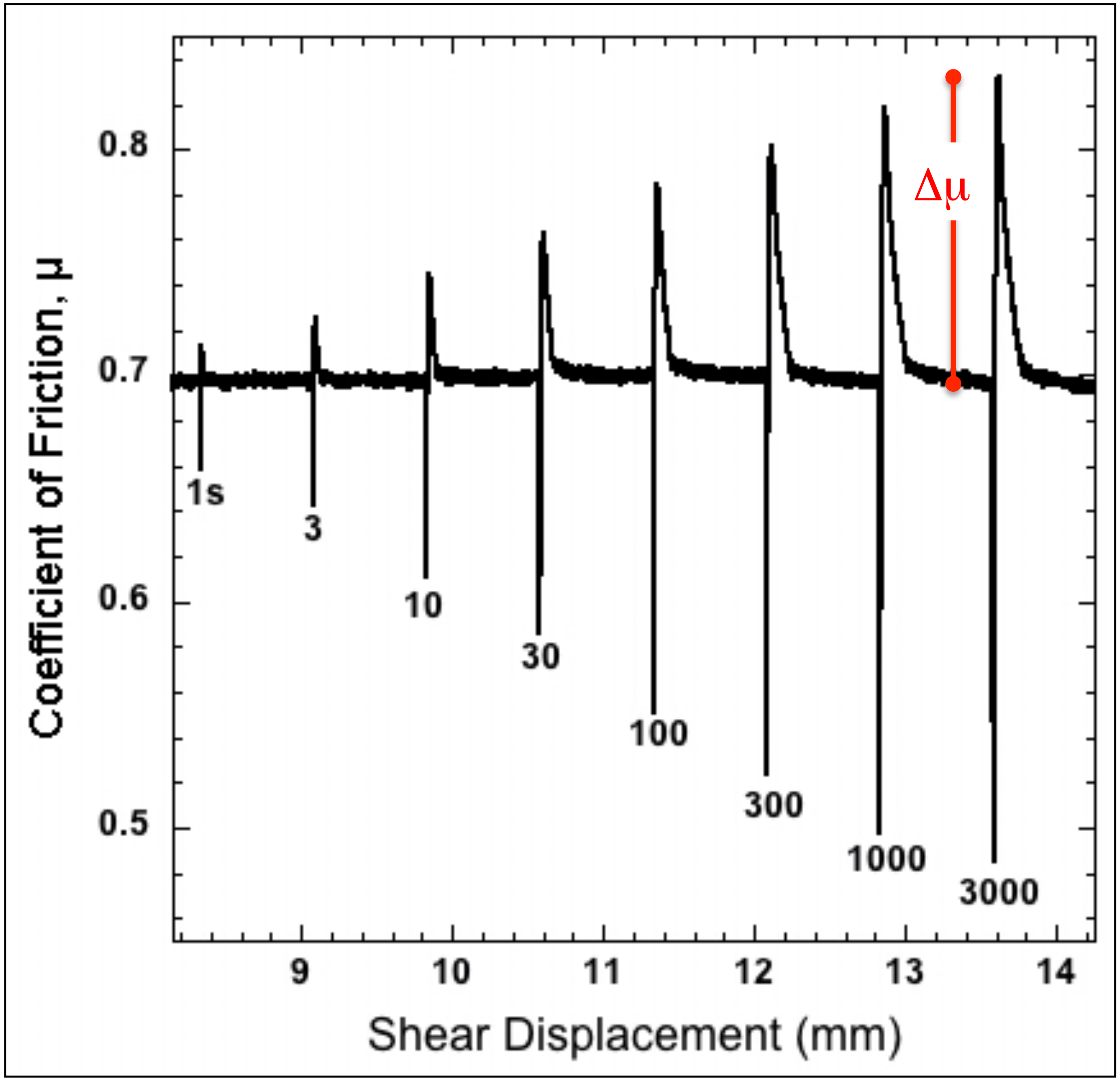
Velocity Step (VS)
10µm/s
30µm/s
V0
Vf
a
b
Coefficient of Friction, µ
Displacement (mm)



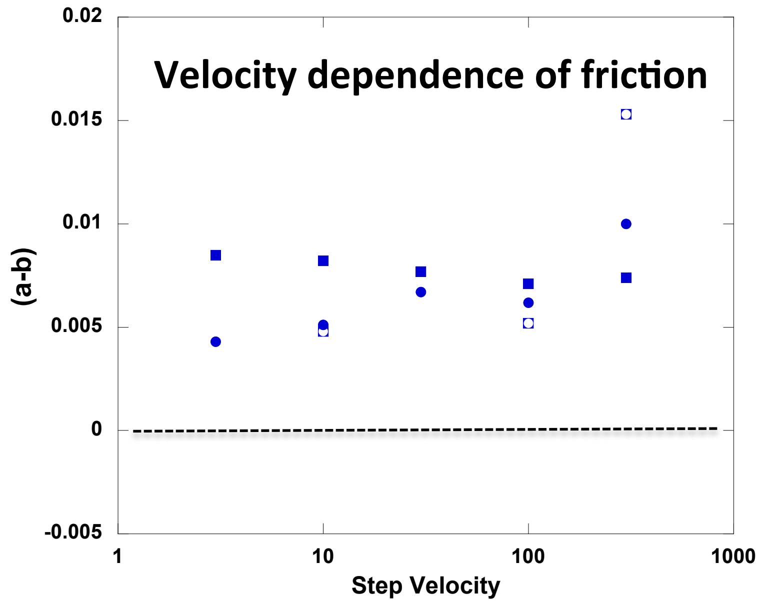
Slide-Hold-Slide (SHS)
30s hold
Frictional Healing, Δµ
Δµc, Creep Relaxation
Hold Time
Coefficient of Friction, µ
Time (s)

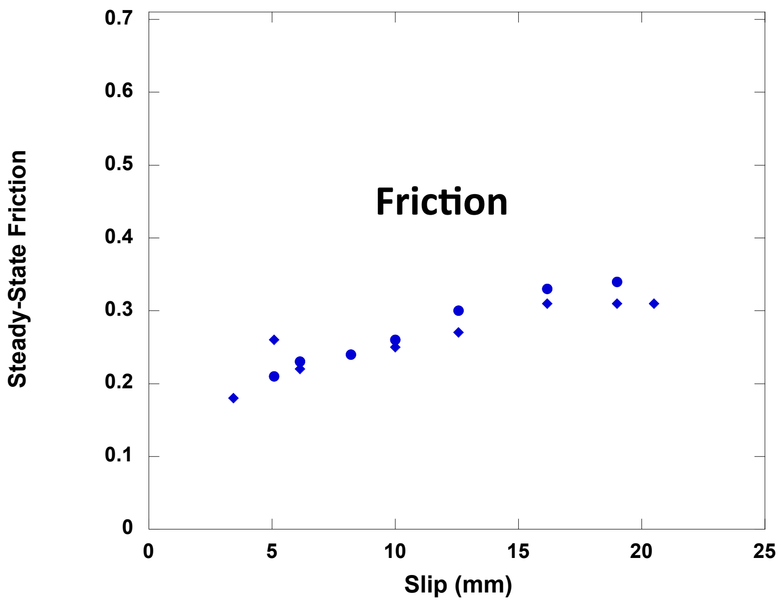
Slide-hold-slide experiments: frictional healing $\Delta\mu$

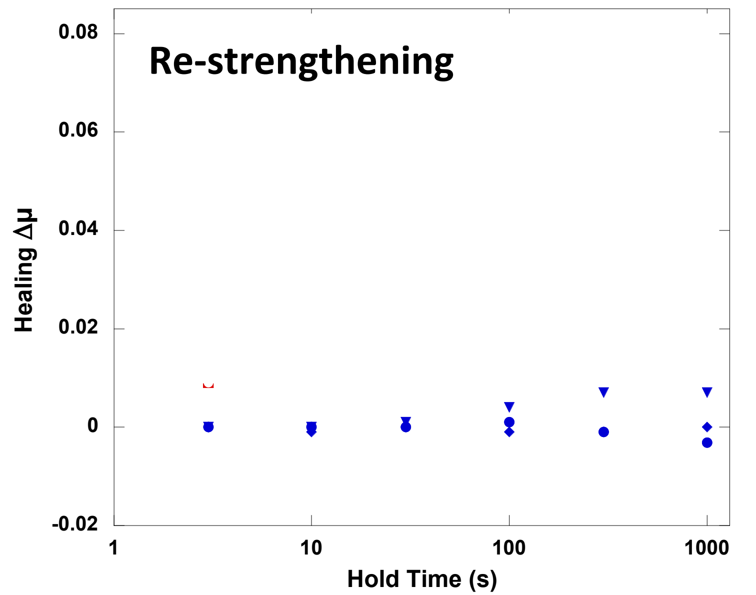




Shear zones are weak, v. strengthening with no re-strengthening.







Tesei et al., EPSL, 2014

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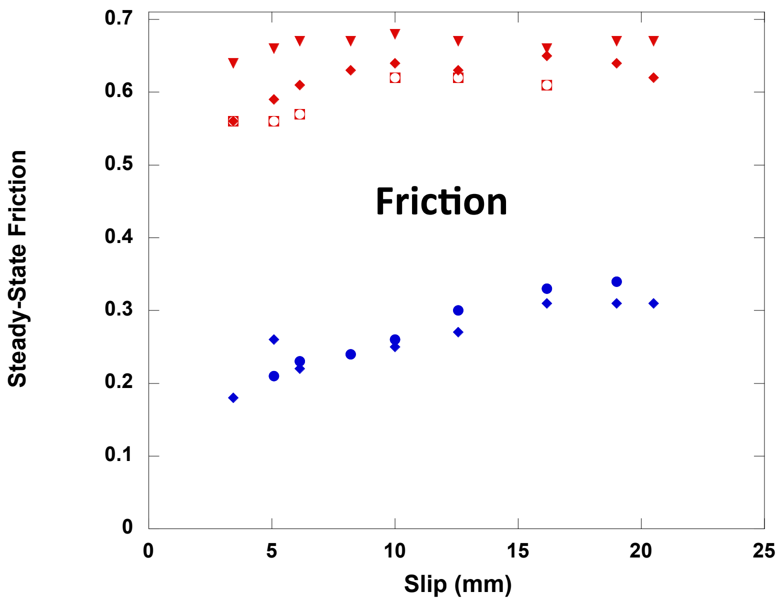
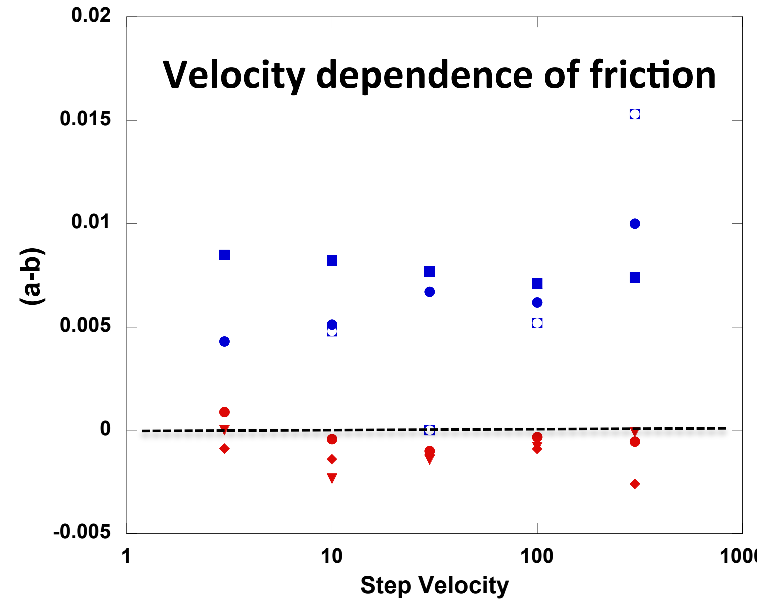
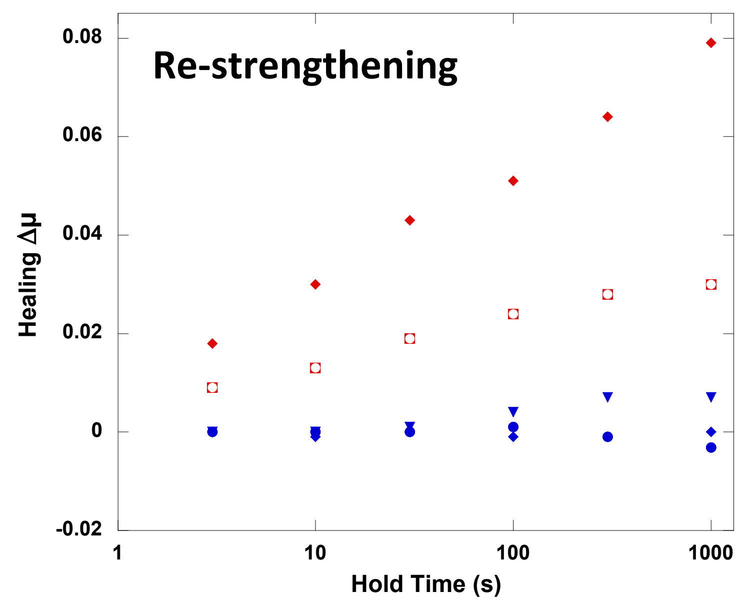
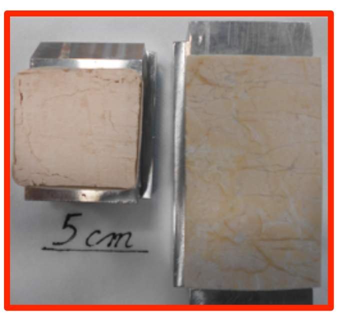






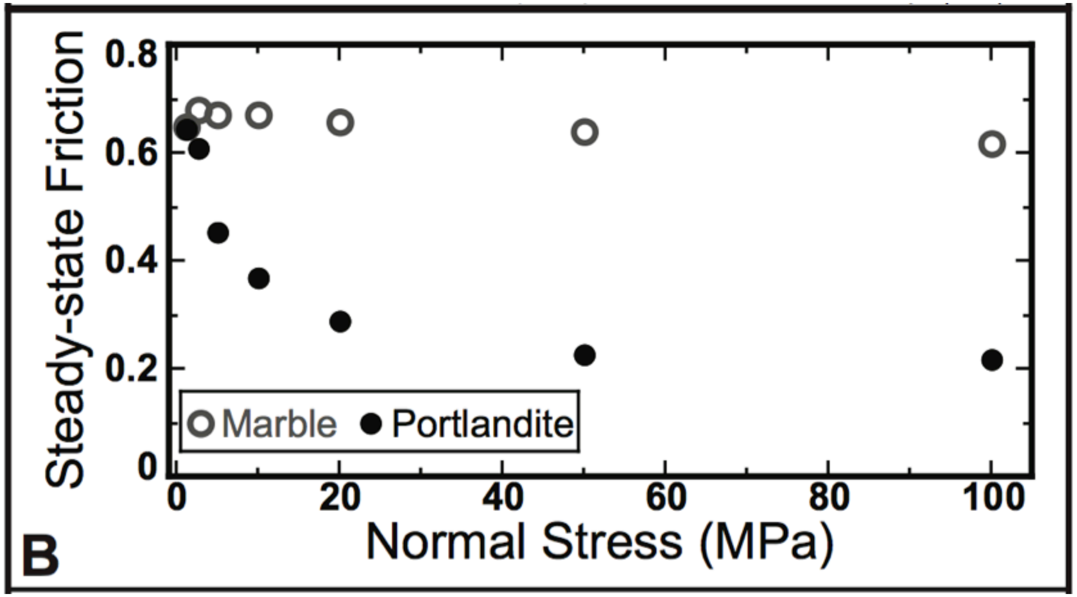


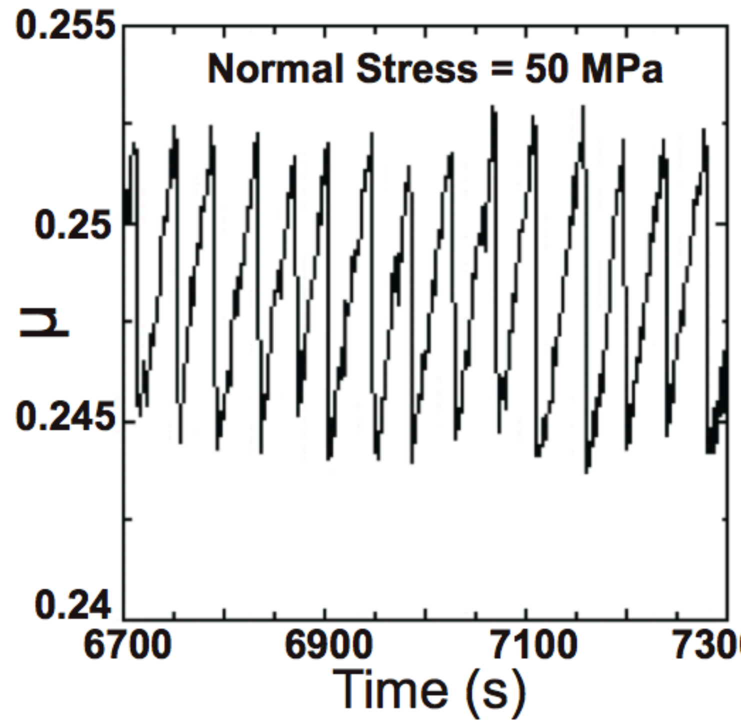
Sharp slipping zones are strong, v. weakening with re-strengthening.

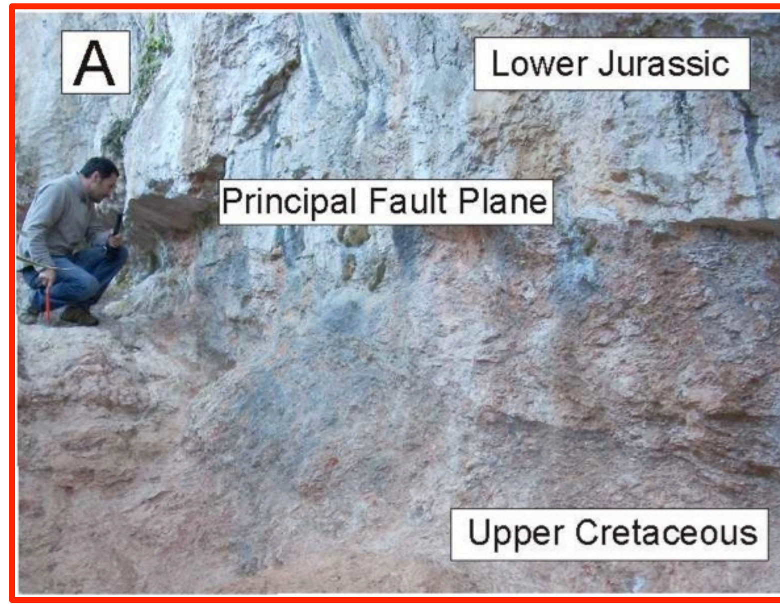
Tesei et al., EPSL, 2014

Decarbonated material is weaker then calcite and very velocity weakening in particular at low sliding velocities.

Carpenter et al., in review







Shear zones with pressure solution and sliding along phyllosilicates

Weak, μ = 0.2-0.3

Velocity strengthening

No-healing

Long term creep

Localization with cataclasis and thermal decomposition

Strong, μ = 0.6-0.7

Velocity neutral/weakening

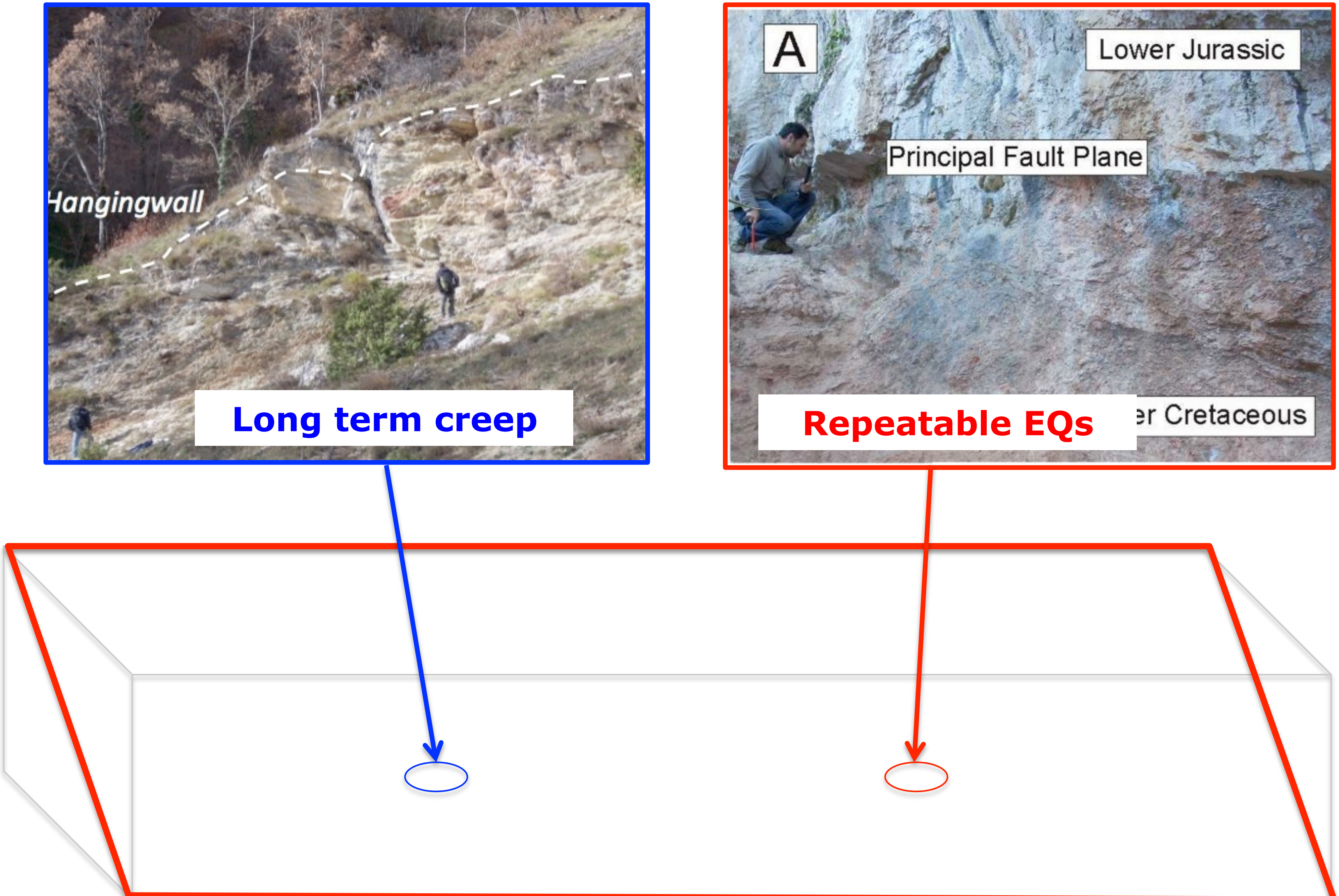
Re-strengthening

Repeatable seismic slip

DC weak

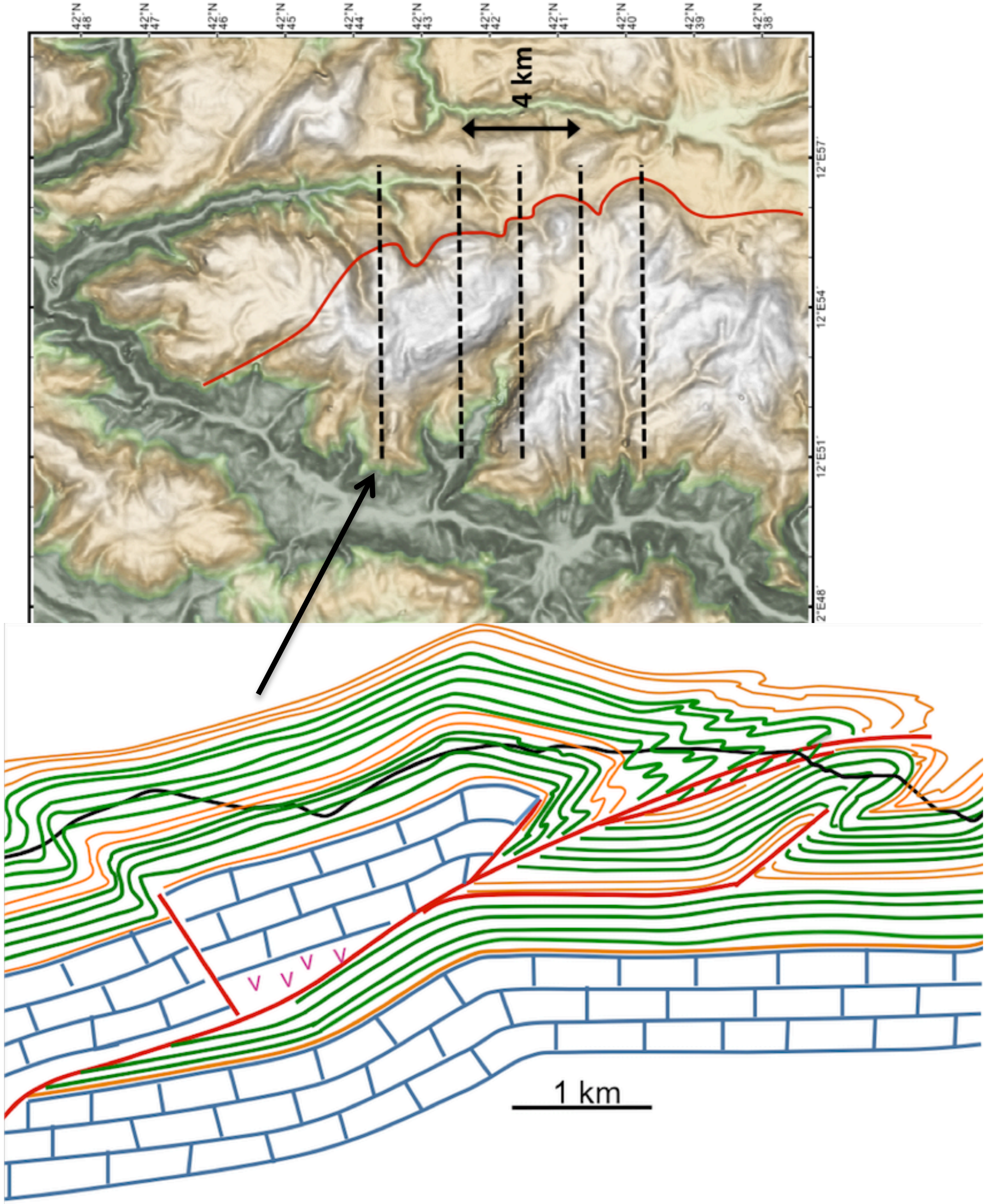
Very velocity weakening

How can we extrapolate these two characterization to an entire fault plane?



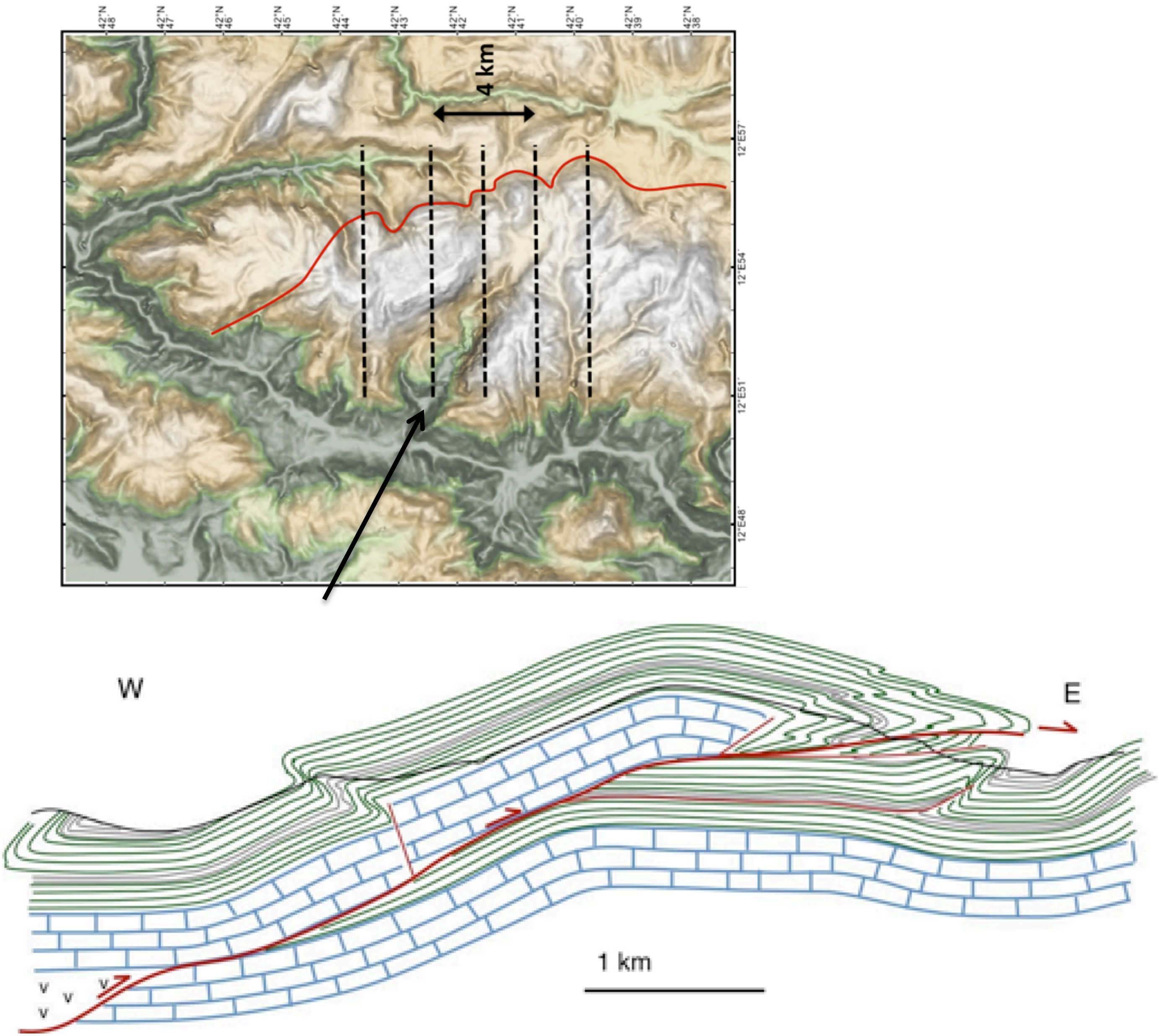
Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014



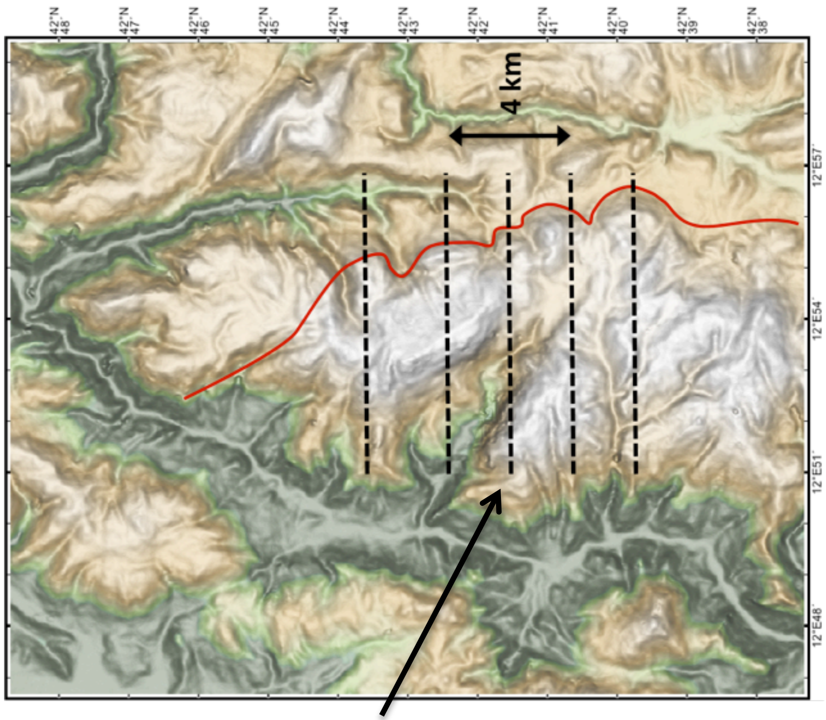
Series of geological cross sections across the fault plane

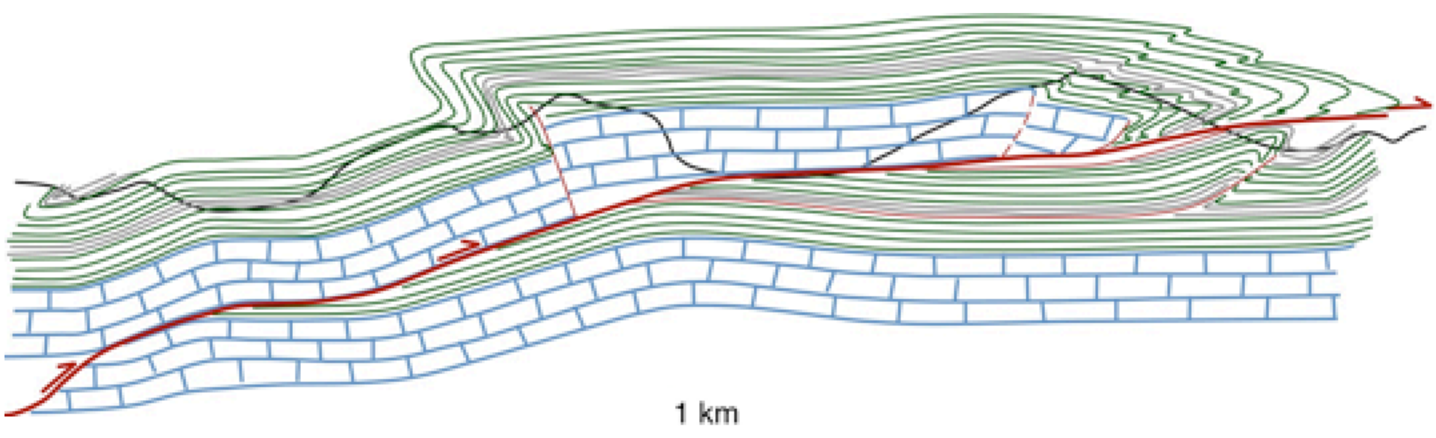
Tesei et al., EPSL, 2014



Series of geological cross sections across the fault plane

Tesei et al., EPSL, 2014





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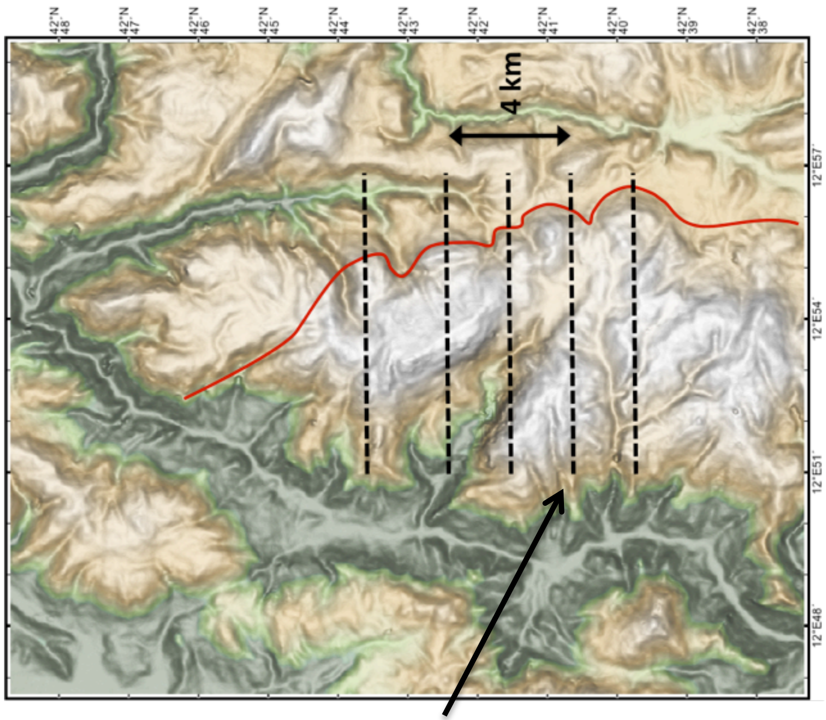
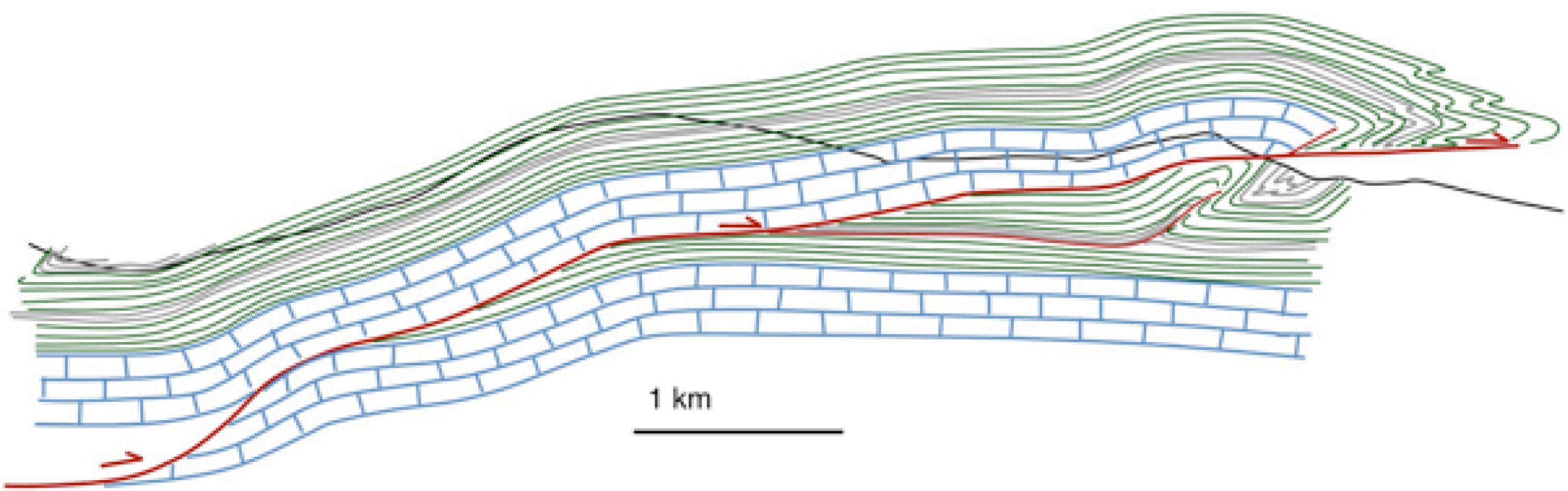
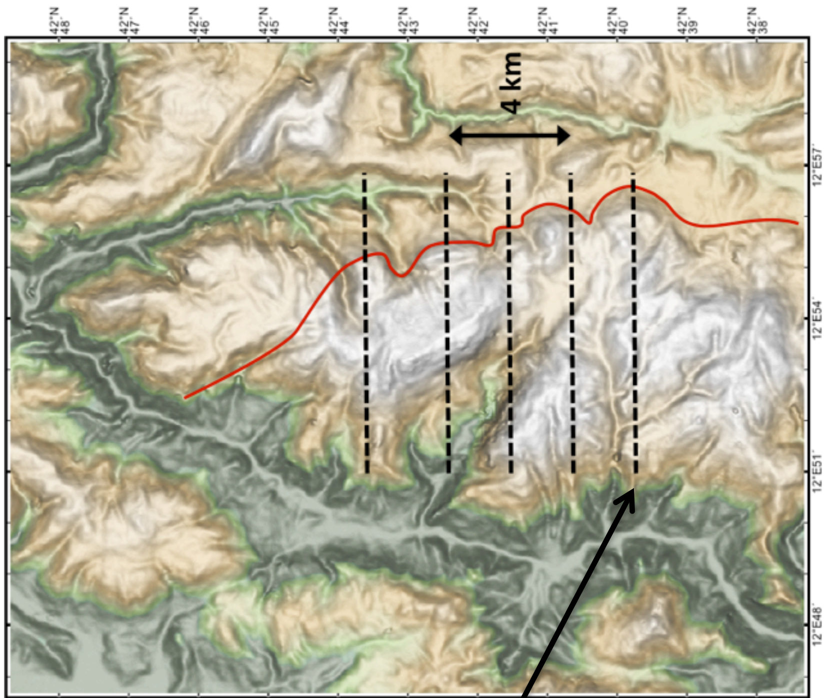
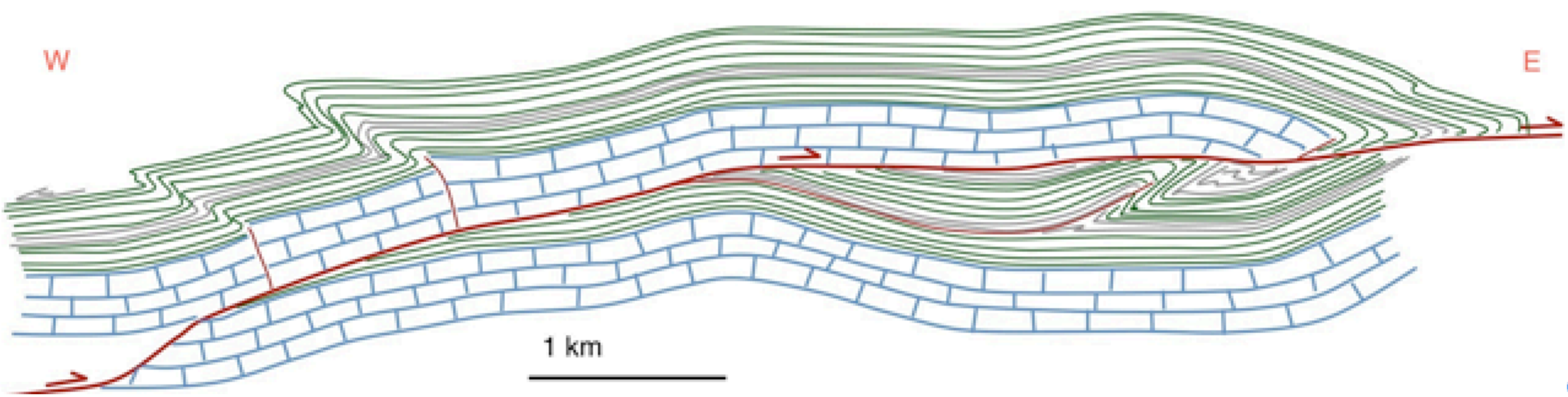




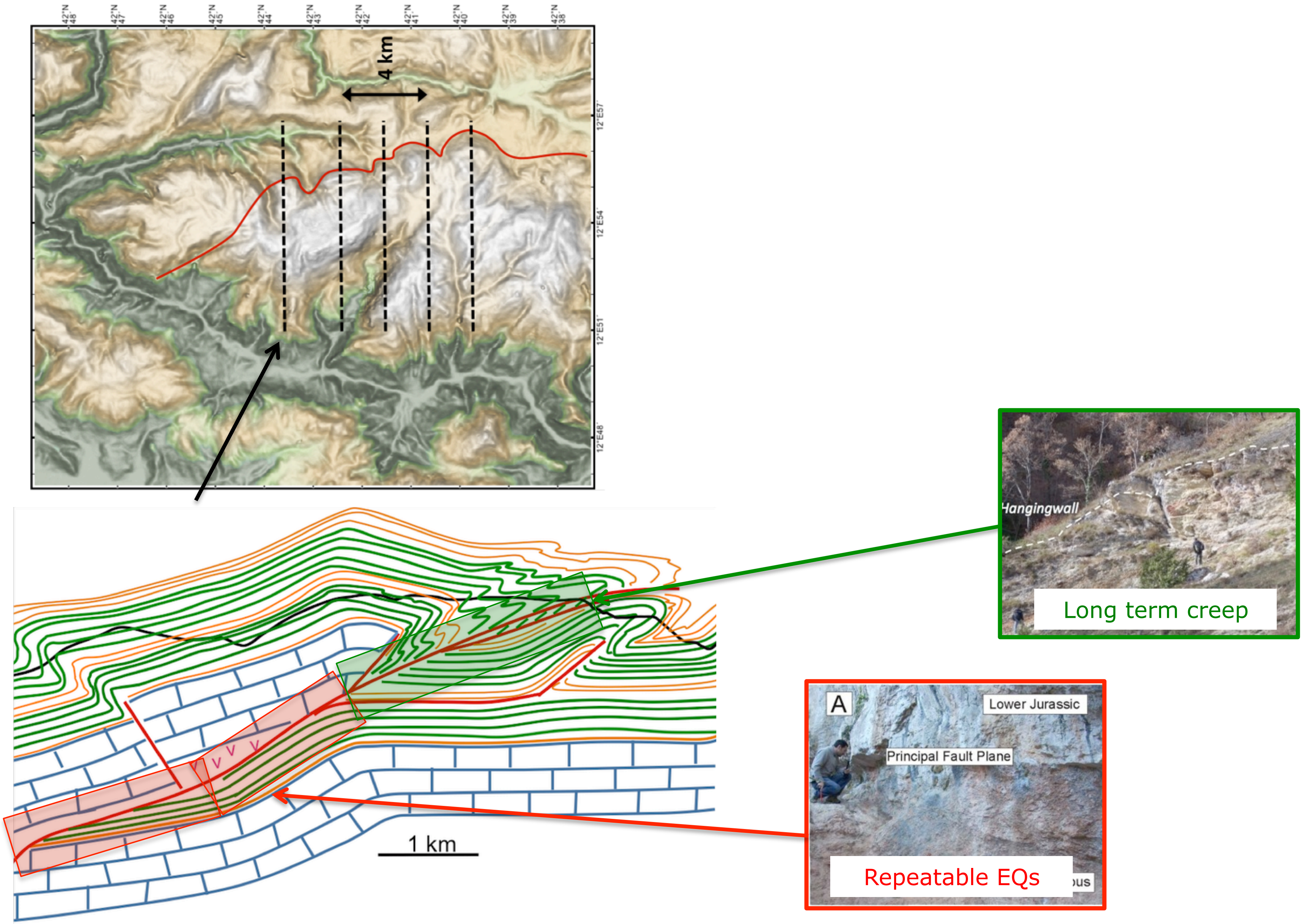
Series of geological cross sections across the fault plane

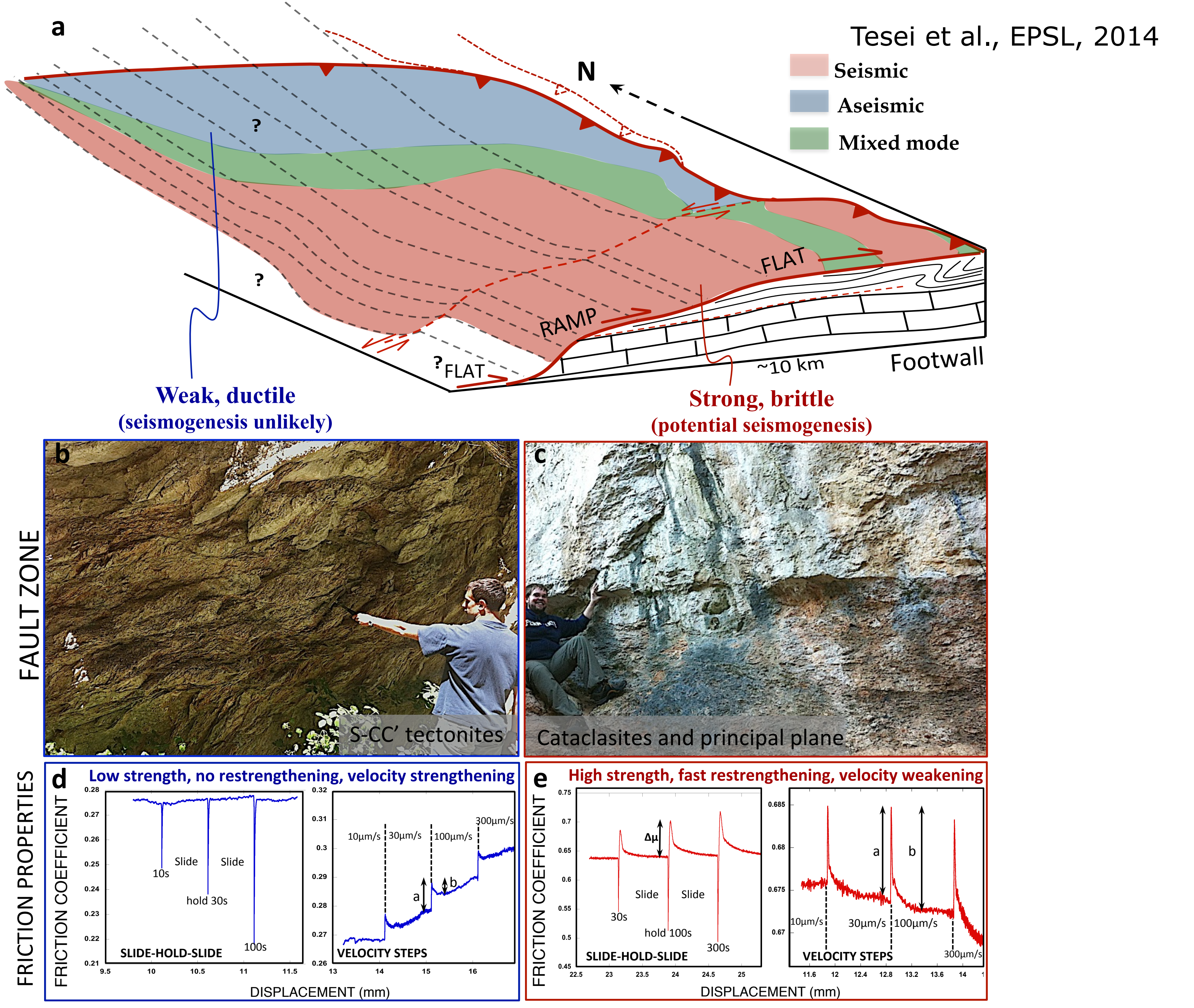
Tesei et al., EPSL, 2014





Fault plane heterogeneities





a
Tesei et al., EPSL, 2014
Seismic
Aseismic
Mixed mode
N
?
?
FLAT
RAMP
?FLAT
~10 km
Footwall
Weak, ductile
(seismogenesis unlikely)
Strong, brittle
(potential seismogenesis)
FAULT ZONE
b
S-CC' tectonites
c
Cataclasites and principal plane
FRICTION PROPERTIES
d
Low strength, no restrengthening, velocity strengthening
FRICTION COEFFICIENT
10s
Slide
Slide
hold 30s
100s
SLIDE-HOLD-SLIDE
10µm/s
30µm/s
100µm/s
300µm/s
a
b
VELOCITY STEPS
DISPLACEMENT (mm)
e
High strength, fast restrengthening, velocity weakening
FRICTION COEFFICIENT
Δμ
30s
Slide
Slide
hold 100s
300s
SLIDE-HOLD-SLIDE
a
b
10µm/s
30µm/s
100µm/s
300µm/s
VELOCITY STEPS
DISPLACEMENT (mm)

Introduction

Natural fault rocks and microstructures
Lab. experiments for slip behavior and microstructures

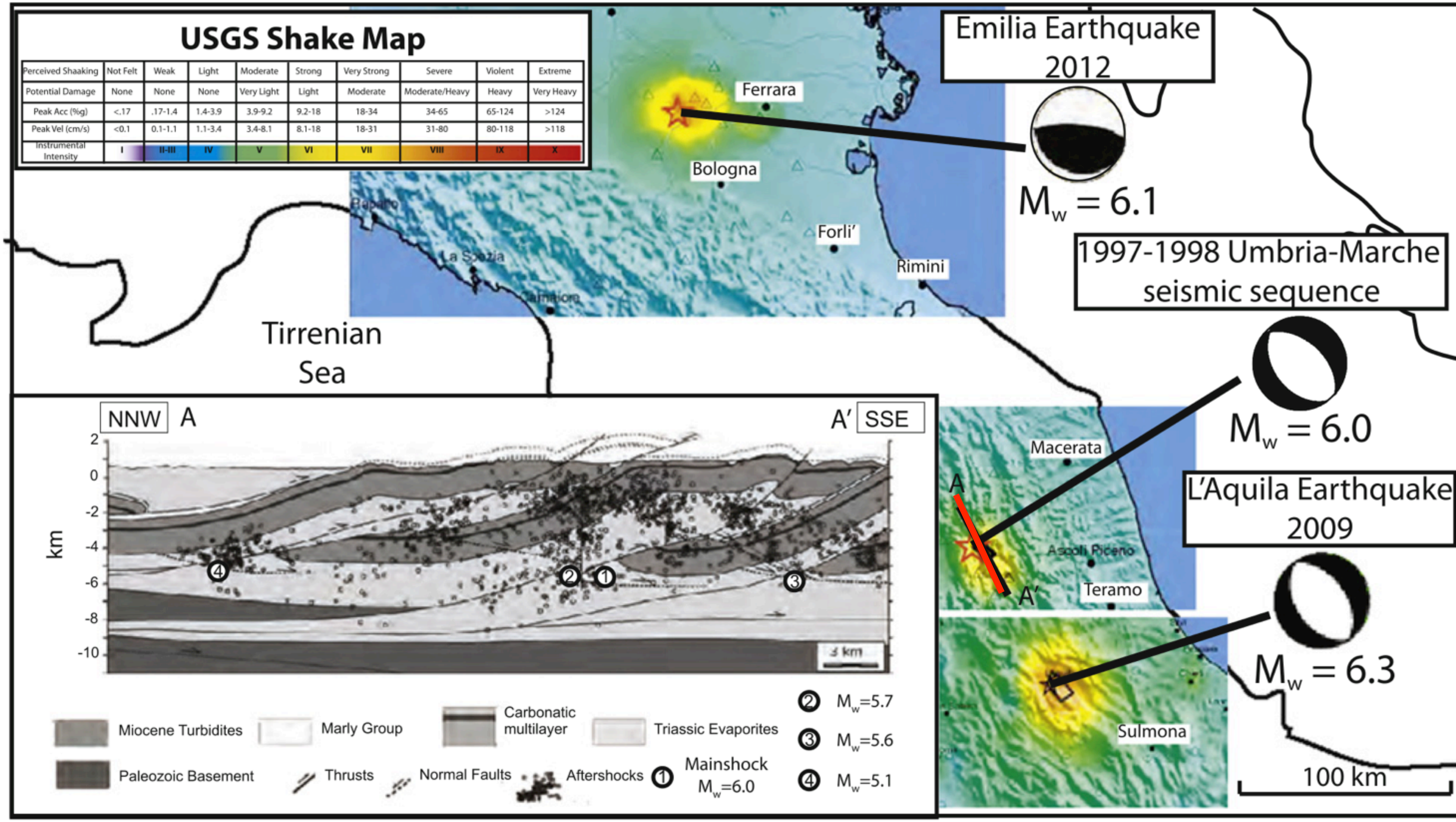
1) Fault structure, frictional properties and mixed-mode fault slip behavior of LANF

2) Heterogeneous strength and fault zone complexity of carbonate-bearing thrusts

3) Fault structure and slip localization in carbonate-bearing normal faults

Future directions

Experiments on the role of fluid pressure in fault stability
Heterogeneous faults in the lab

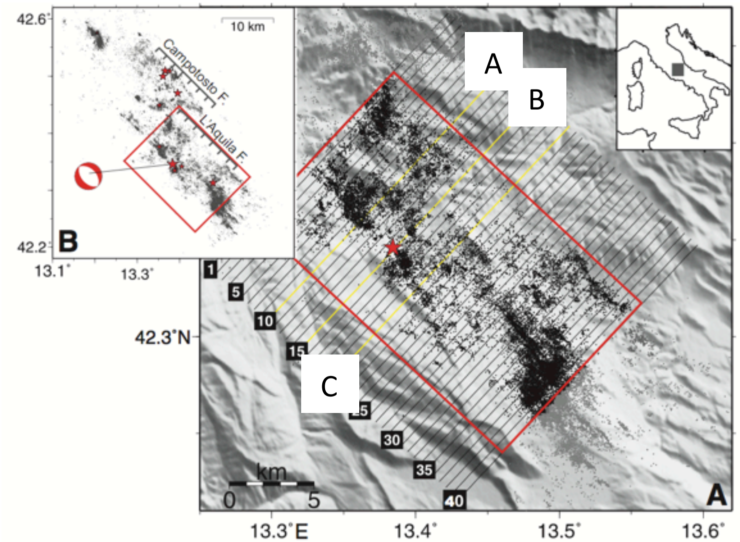


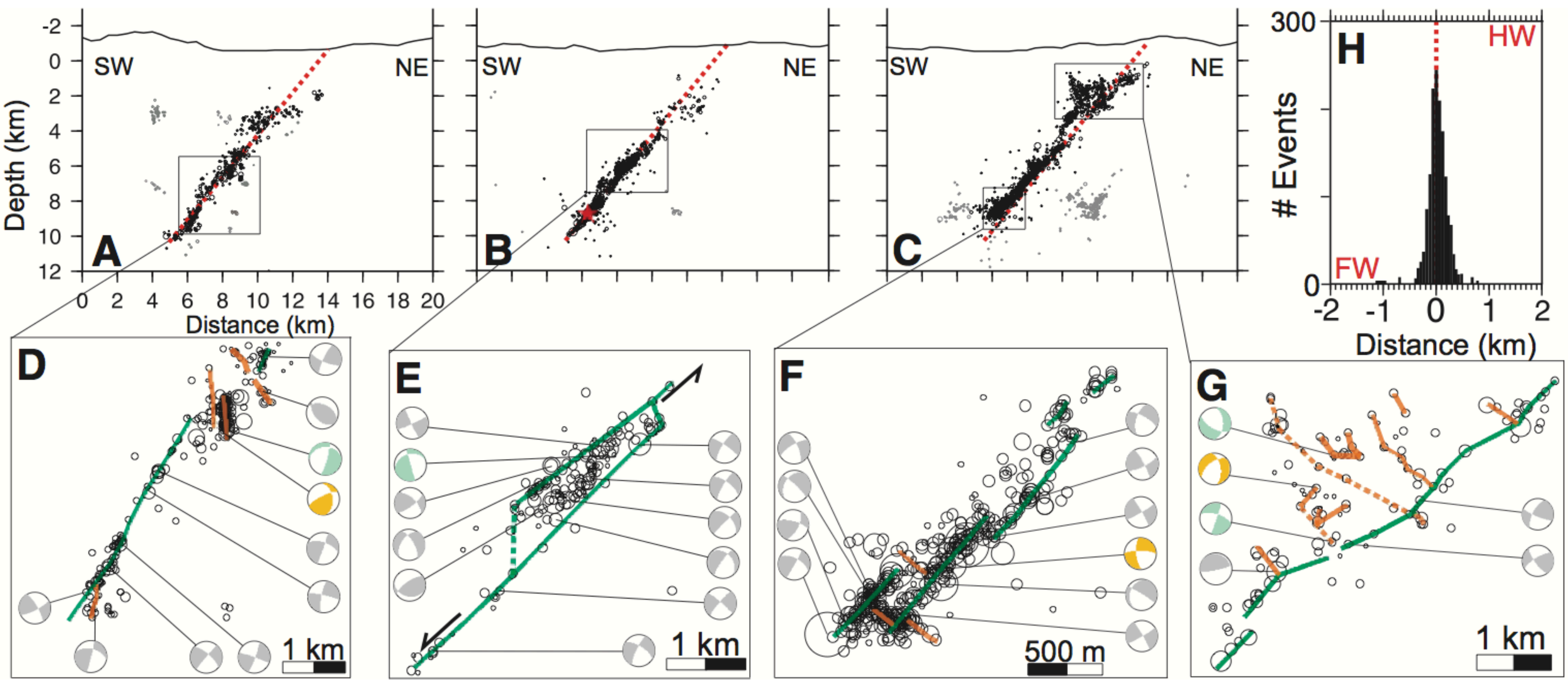
USGS Shake Map
Perceived Shaking | Not Felt | Weak | Light | Moderate | Strong | Very Strong | Severe | Violent | Extreme
Potential Damage | None | None | None | Very Light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy
Peak Acc (%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124
Peak Vel (cm/s) | <0.1 | 0.1-1.1 | 1.1-3.4 | 3.4-8.1 | 8.1-18 | 18-31 | 31-80 | 80-118 | >118
Instrumental Intensity | I | II-III | IV | V | VI | VII | VIII | IX | X
Emilia Earthquake 2012
Ferrara
Bologna
Forli'
Rimini
La Spezia
$M_w = 6.1$
1997-1998 Umbria-Marche seismic sequence
$M_w = 6.0$
L'Aquila Earthquake 2009
$M_w = 6.3$
Tirrenian Sea
Macerata
Ascoli Piceno
Teramo
Sulmona
A
A'
100 km
NNW
A
A'
SSE
km
2
0
-2
-4
-6
-8
-10
Miocene Turbidites
Marly Group
Carbonatic multilayer
Triassic Evaporites
Paleozoic Basement
Thrusts
Normal Faults
Aftershocks
① Mainshock M_w=6.0
② M_w=5.7
③ M_w=5.6
④ M_w=5.1

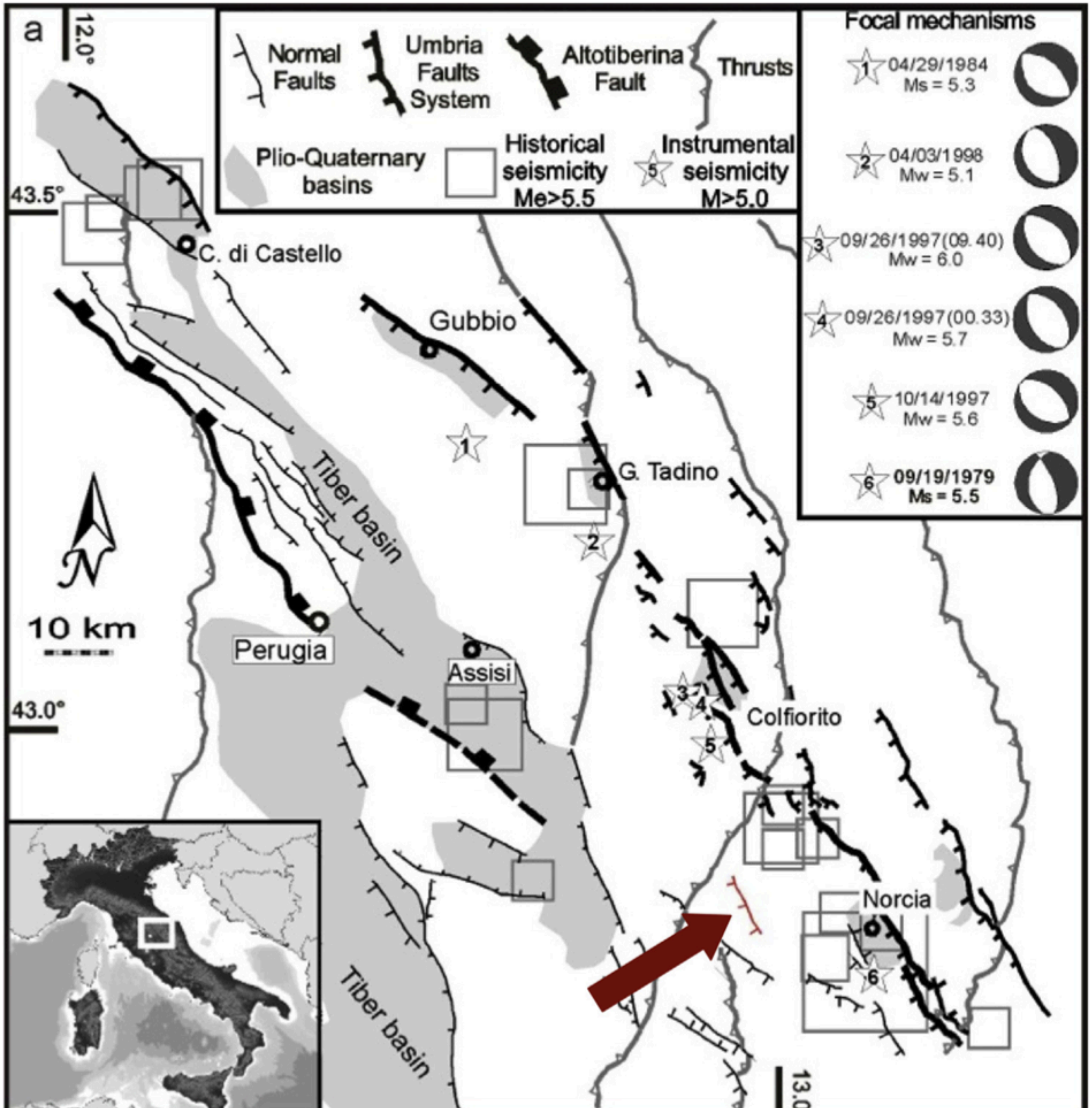
~19,000 high-resolution aftershock locations nucleated along causative fault of MW=6.1, 2009 L'Aquila earthquake.

Seismological fault zone structure characterization

Valoroso et al., Geology 2014





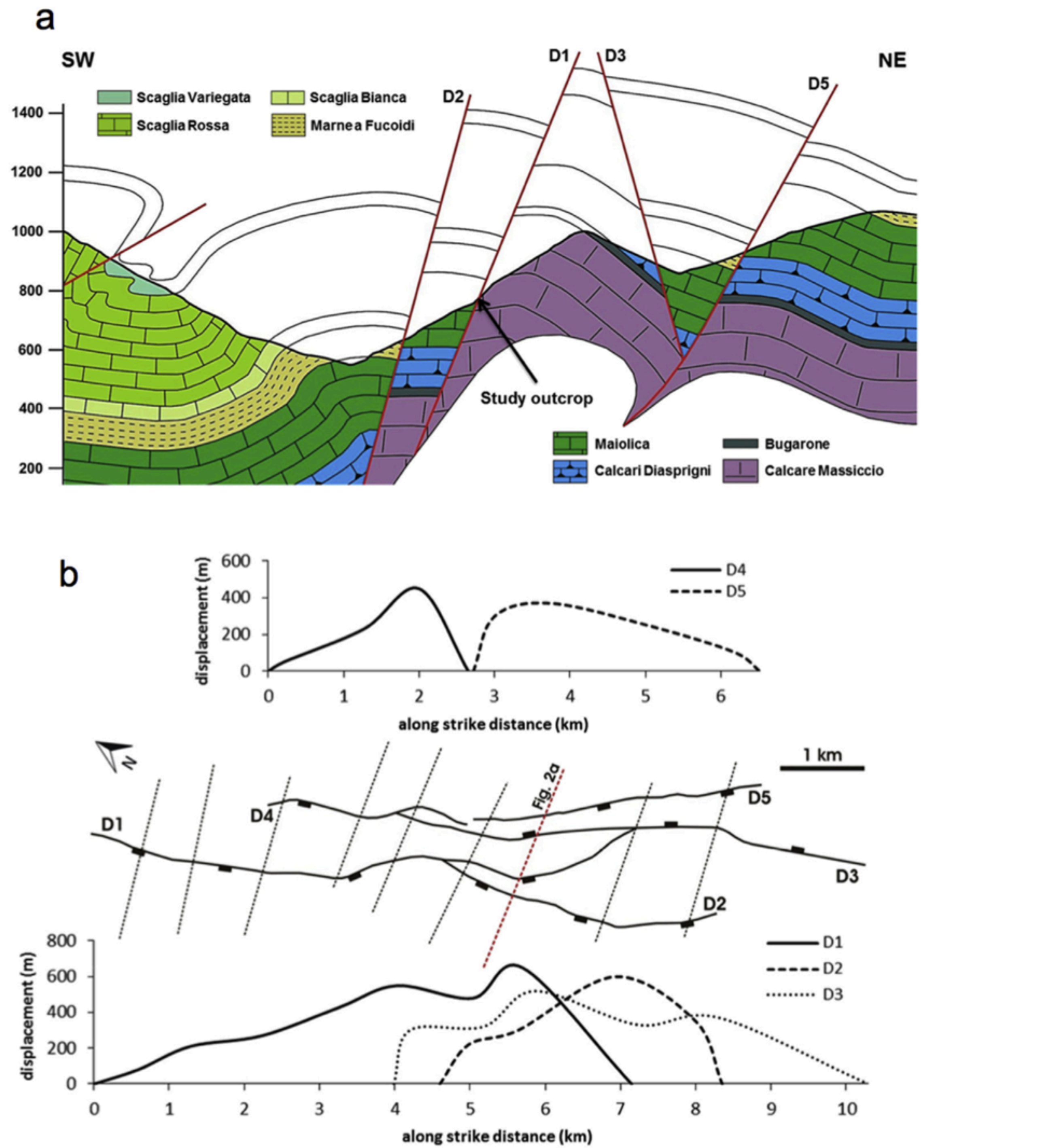


a
12.0°
Normal Faults
Umbria Faults System
Altotiberina Fault
Thrusts
Plio-Quaternary basins
Historical seismicity Me>5.5
Instrumental seismicity M>5.0
Focal mechanisms
1 04/29/1984 Ms = 5.3
2 04/03/1998 Mw = 5.1
3 09/26/1997(09.40) Mw = 6.0
4 09/26/1997(00.33) Mw = 5.7
5 10/14/1997 Mw = 5.6
6 09/19/1979 Ms = 5.5
43.5°
C. di Castello
Gubbio
G. Tadino
Tiber basin
10 km
Perugia
Assisi
43.0°
Colfiorito
Norcia
Tiber basin
13.0°

At the km scale

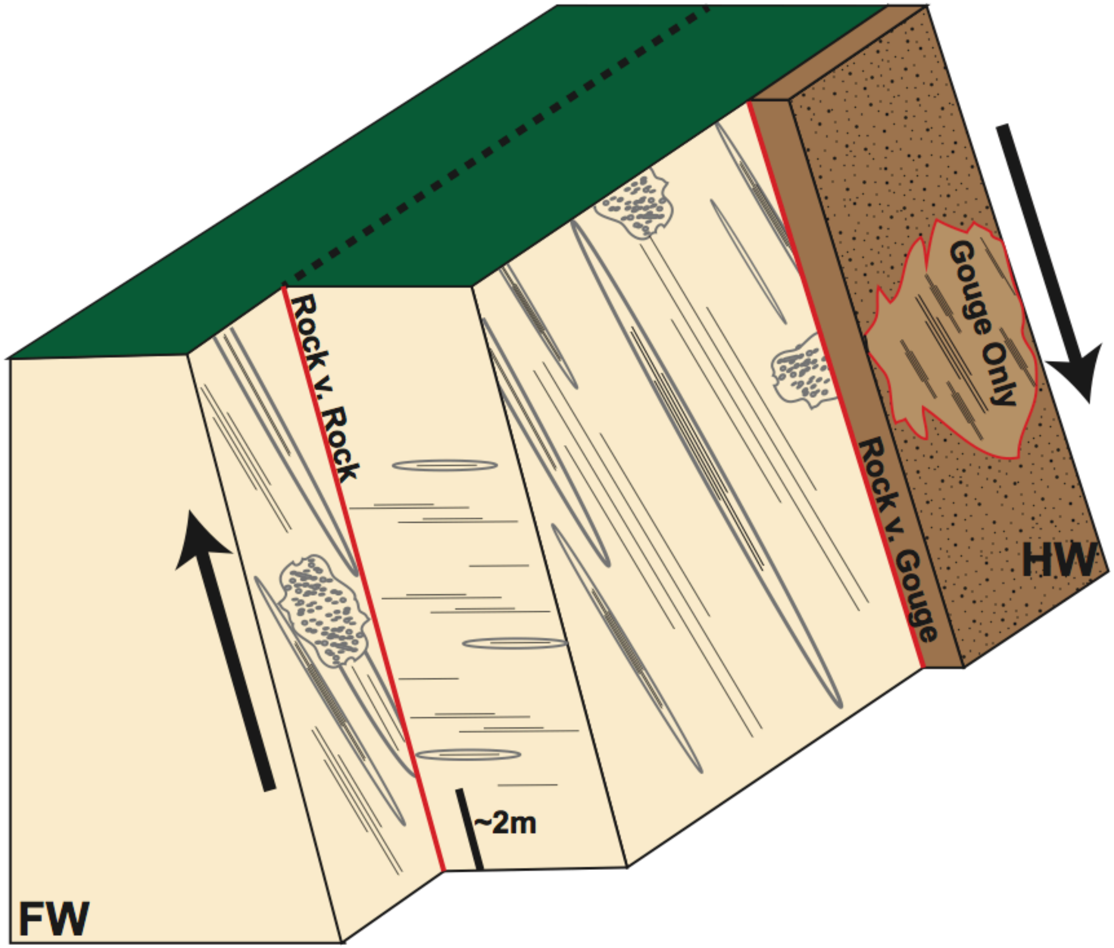
Along strike, fault length is ~10 km and the maximum width of the fault is ~1.5 km.

Some displacements are distorted and denote a degree of interaction.

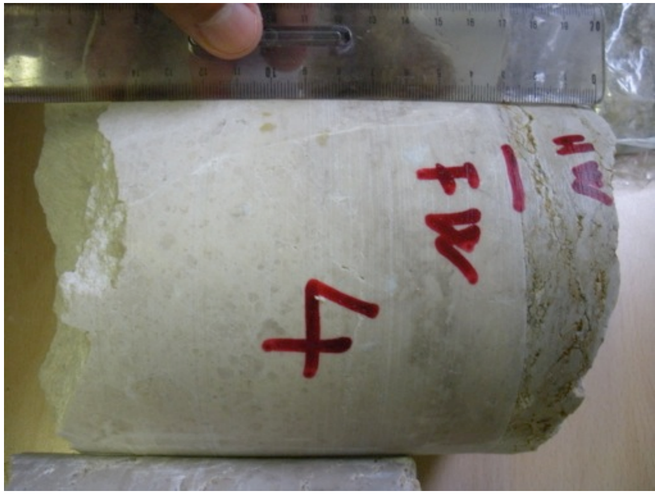


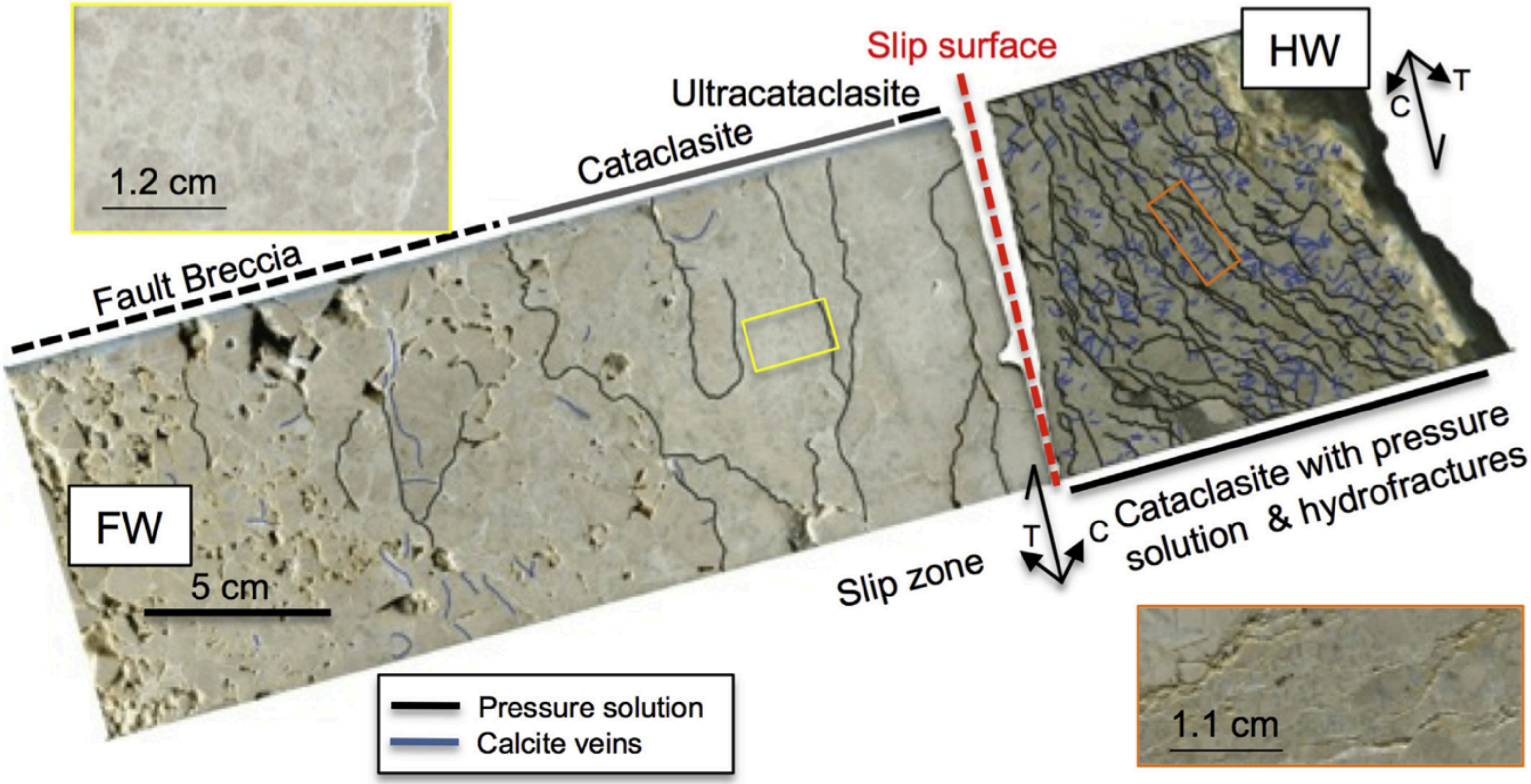
At the outcrop scale

parallel slipping zones distributed over a width of about 50 m

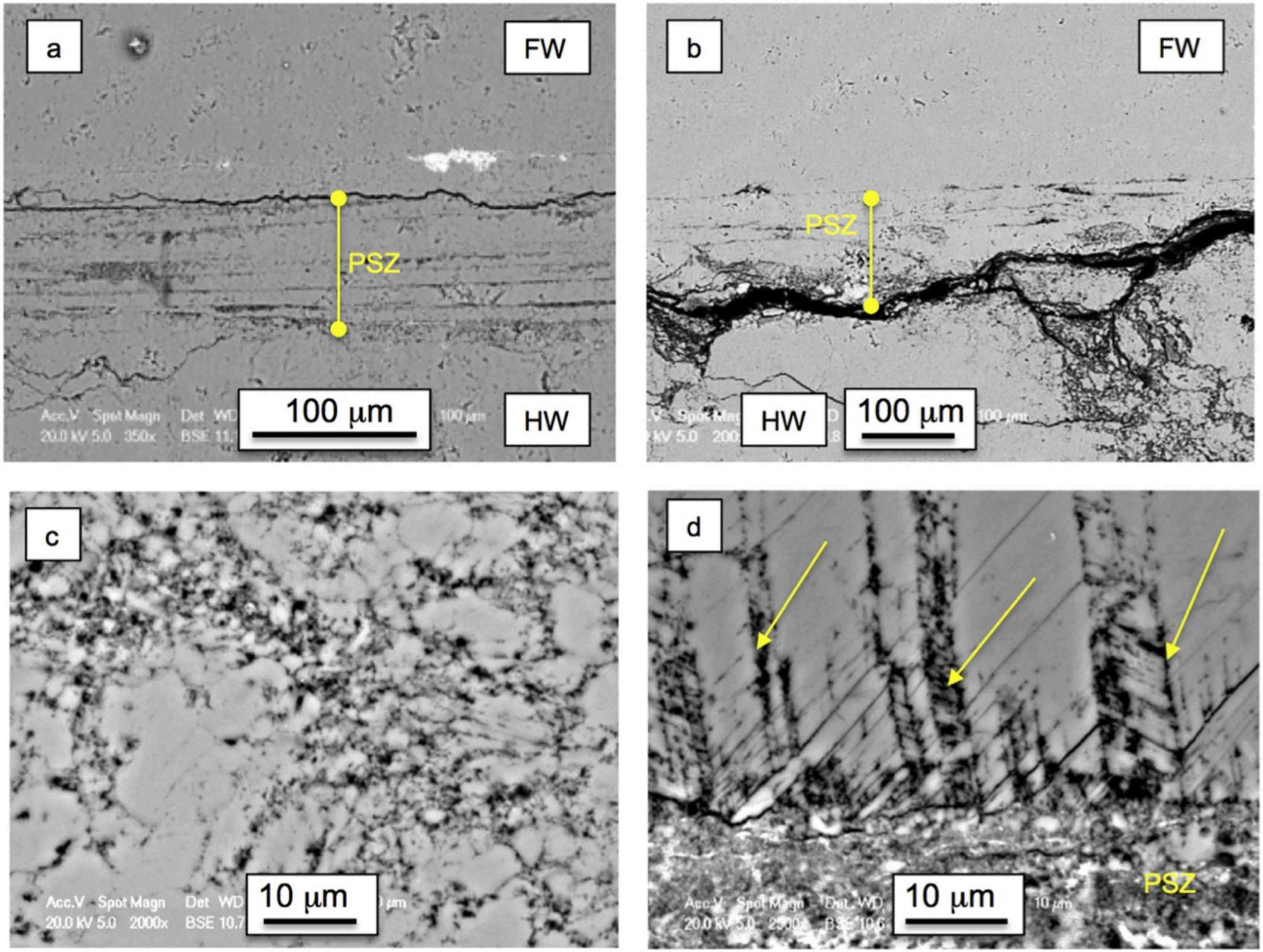


Collecting rock samples for microstructural studies & experiments

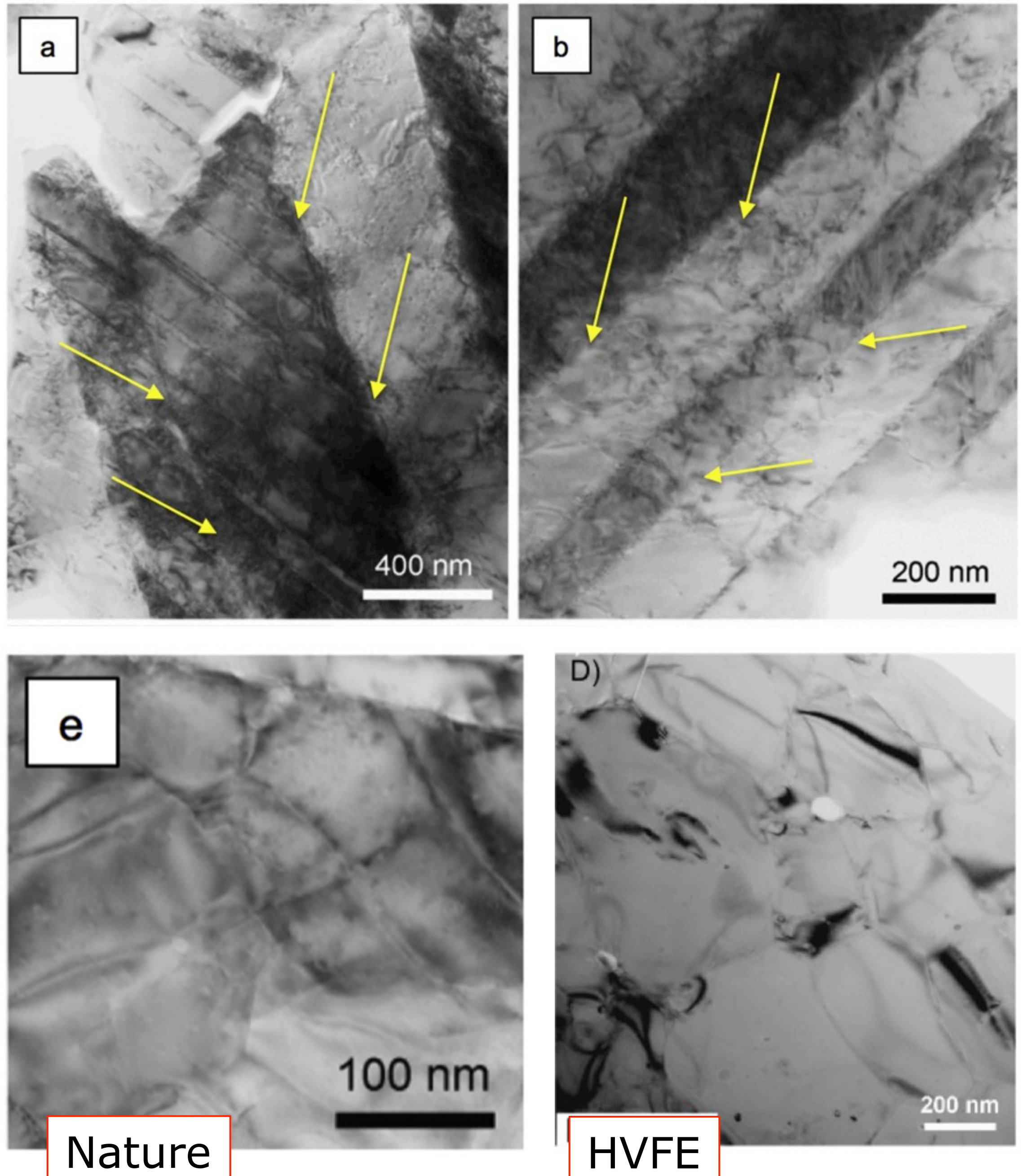




At micron scale: thin Principal Slipping Zone with parallel slipping planes + disaggregation features pointing to decarbonation

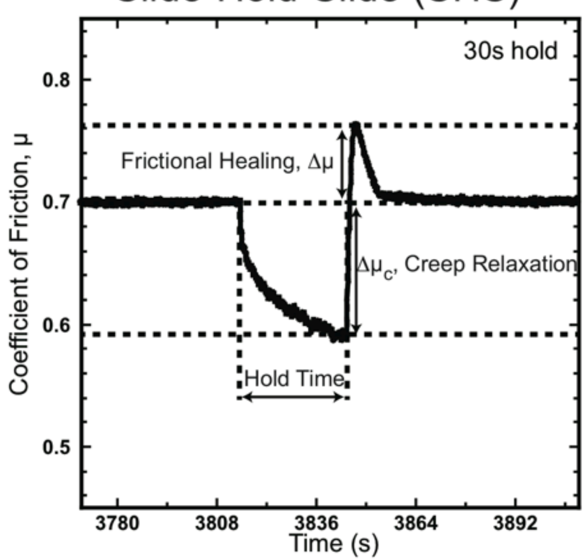


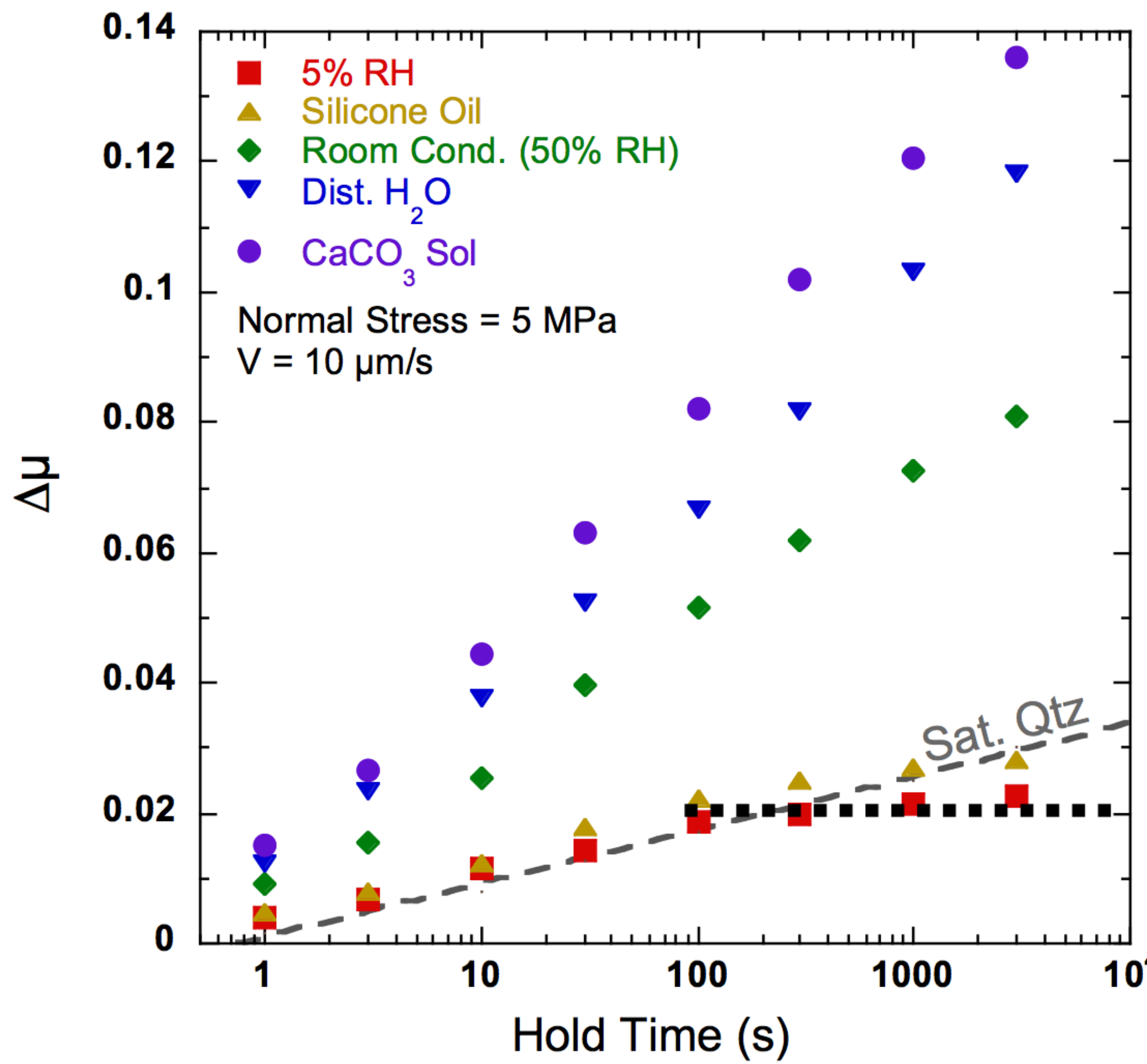
At the nanoscale: plastic deformation with twinning, nanograins & polygonal structures (with strain-free calcite crystals) similar to the one documented in HVFE at the early stage of dynamic weakening (De Paola et al., in prep.)



Very high healing rates in particular for $CaCo_3$ solutions

Slide-Hold-Slide (SHS)

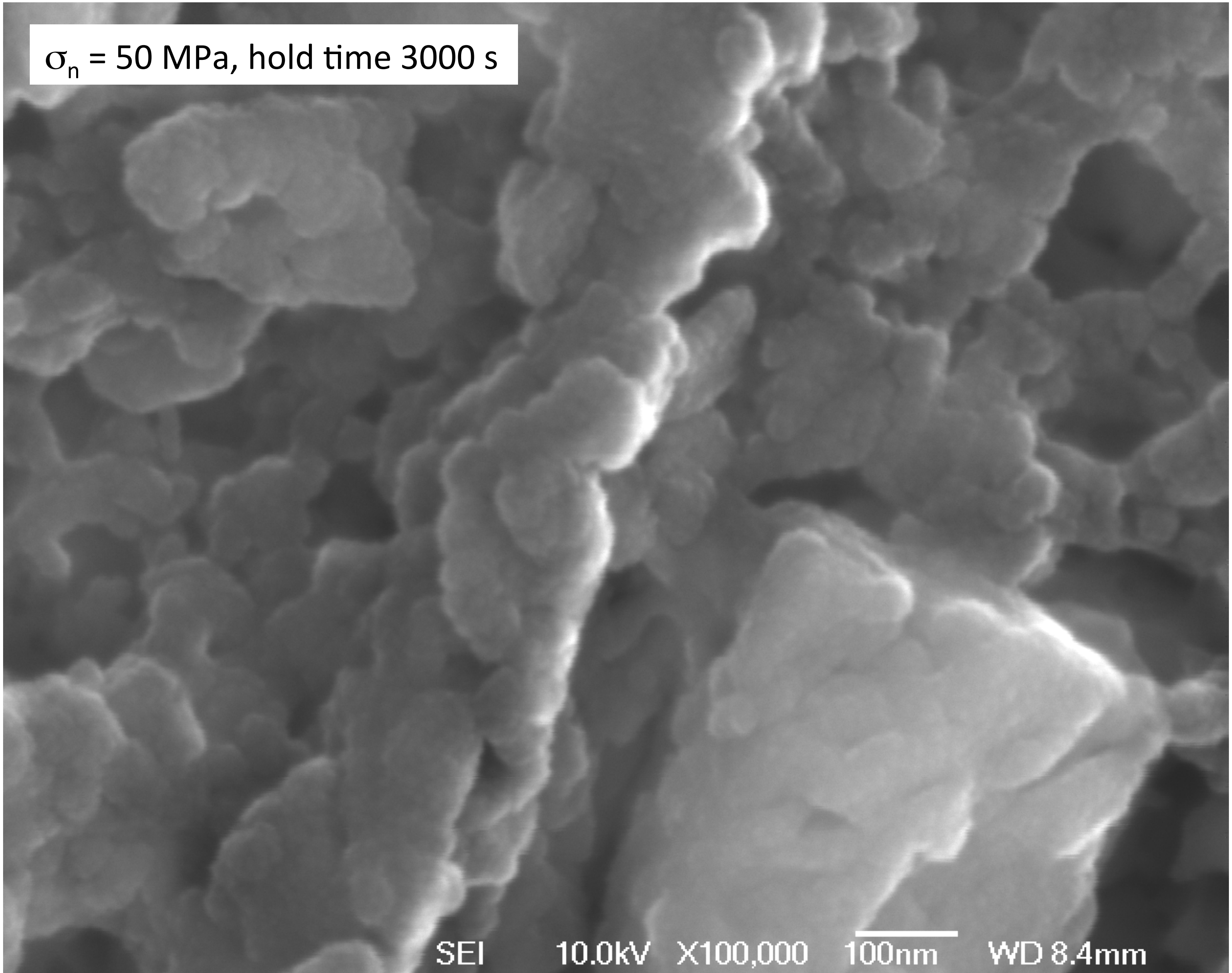




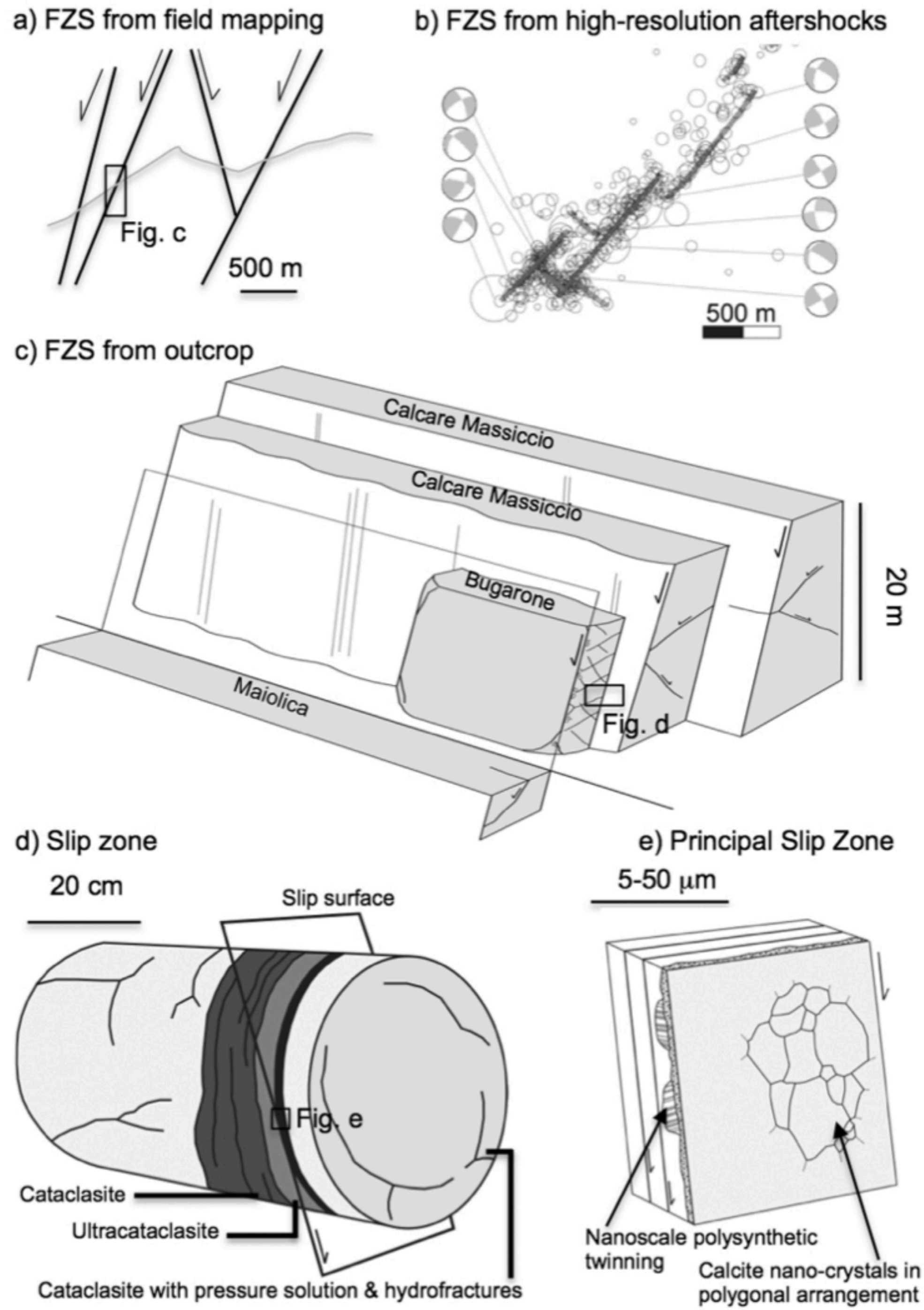
Carpenter et al., in prep.

Very high healing rates favored by dissolution and precipitation processes during hold periods.

Carpenter et al., in prep.



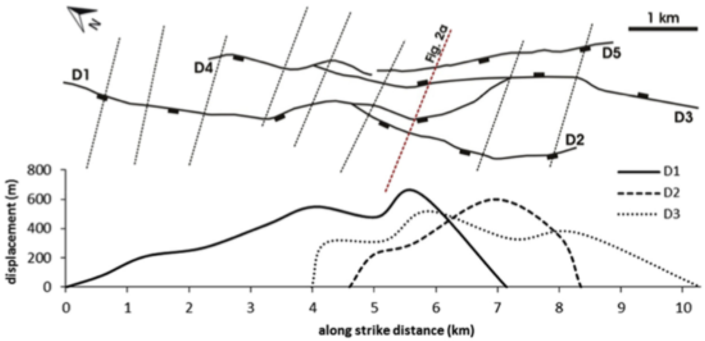
The common theme linking multiscale observations is the presence of multiple slipping planes.

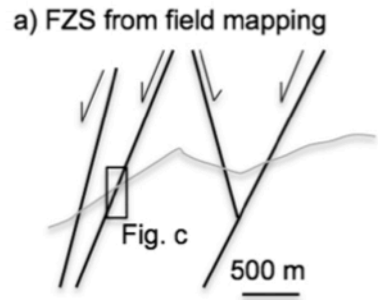


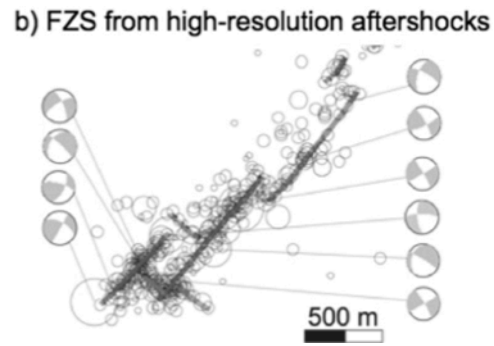
Collettini et al., JSG, 2014

These multiple slipping planes are the result of different deformation mechanisms including:

Fault growth & interaction







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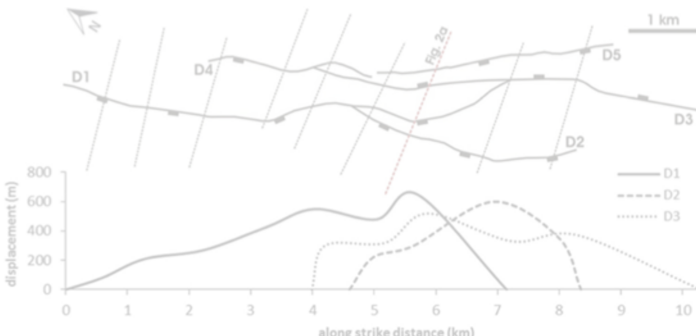
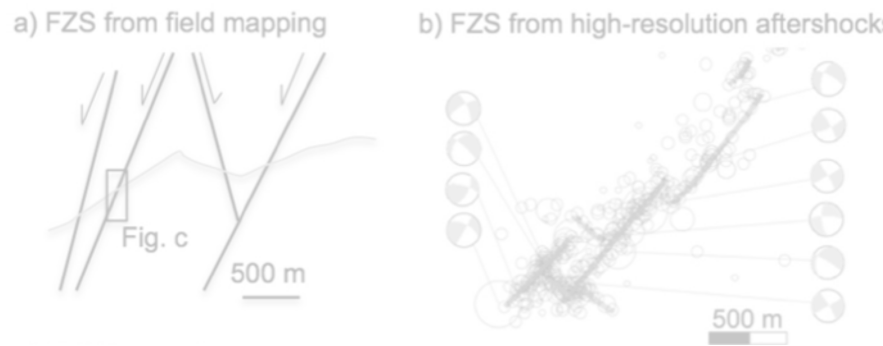
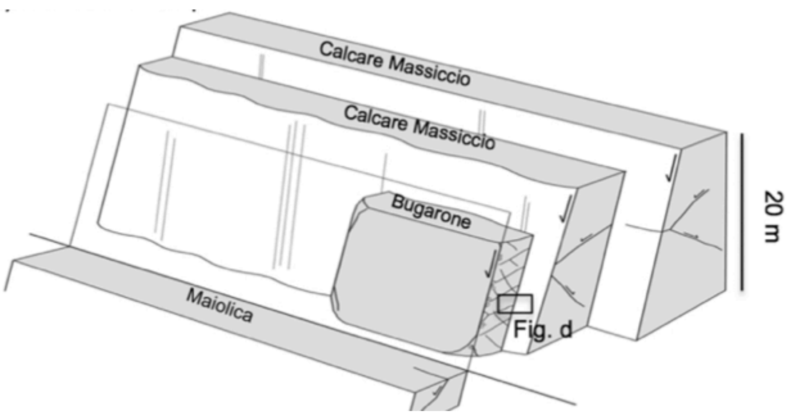
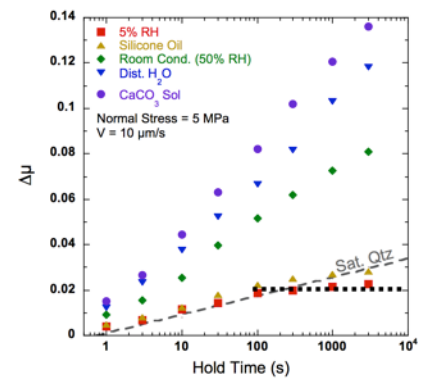




Strength evolution with cementation and healing





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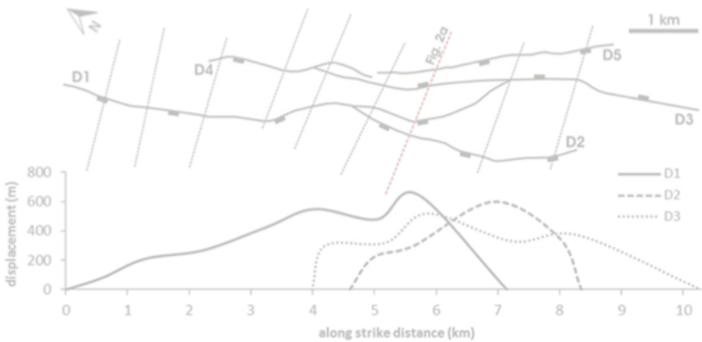

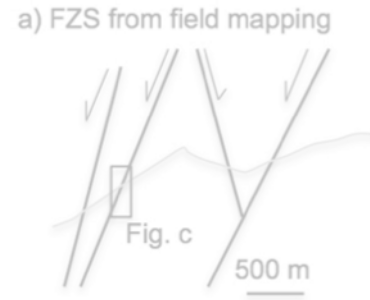

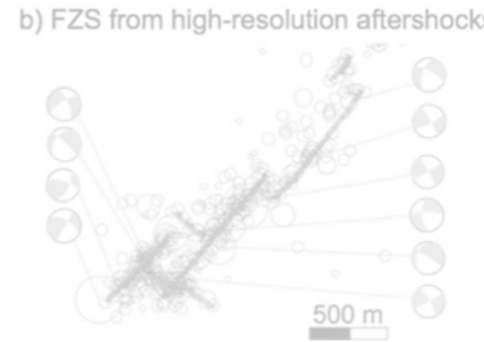

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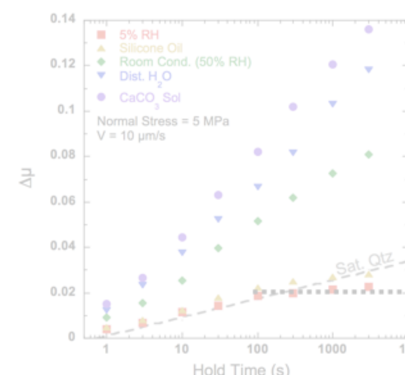
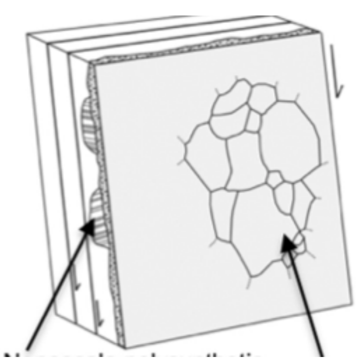
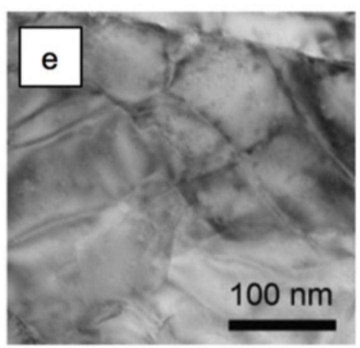
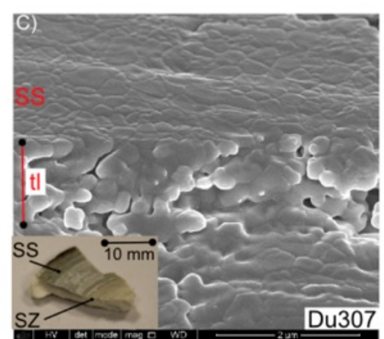
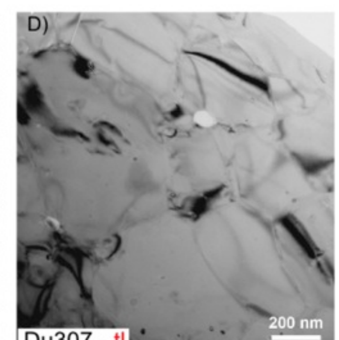


Plastic deformation and decarbonation during co-seismic slip









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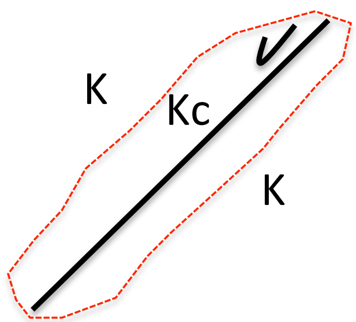
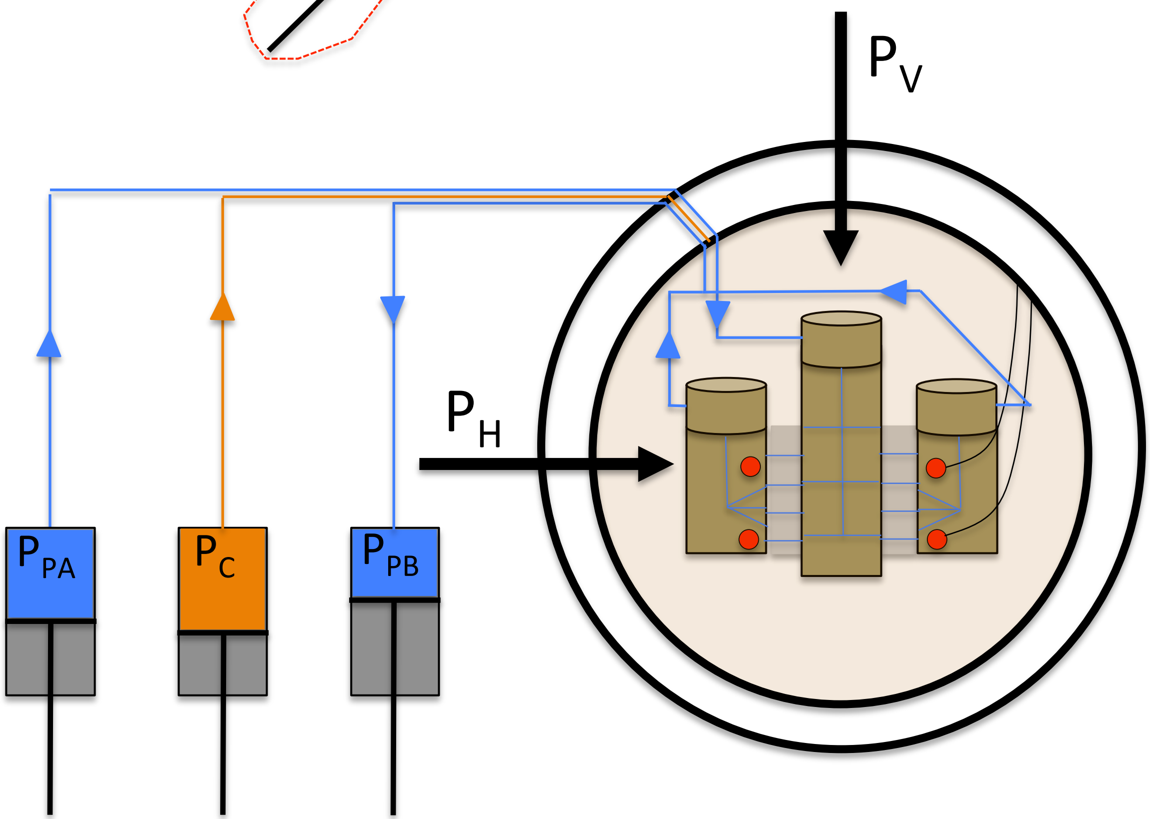
Heterogeneous faults in the lab

Experiments on the role of fluid pressure in fault stability

R&S friction predicts a frictional instability when the stiffness of the fault (Kc) is greater than the stiffness of the loading system (K)



$$k < k_c = \frac{(\sigma_n - P_f)(b-a)}{D_c}$$



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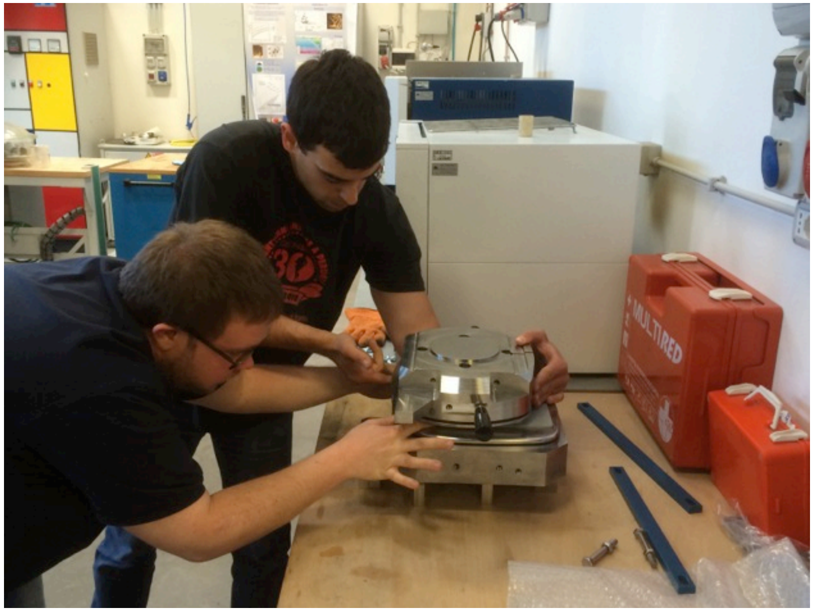
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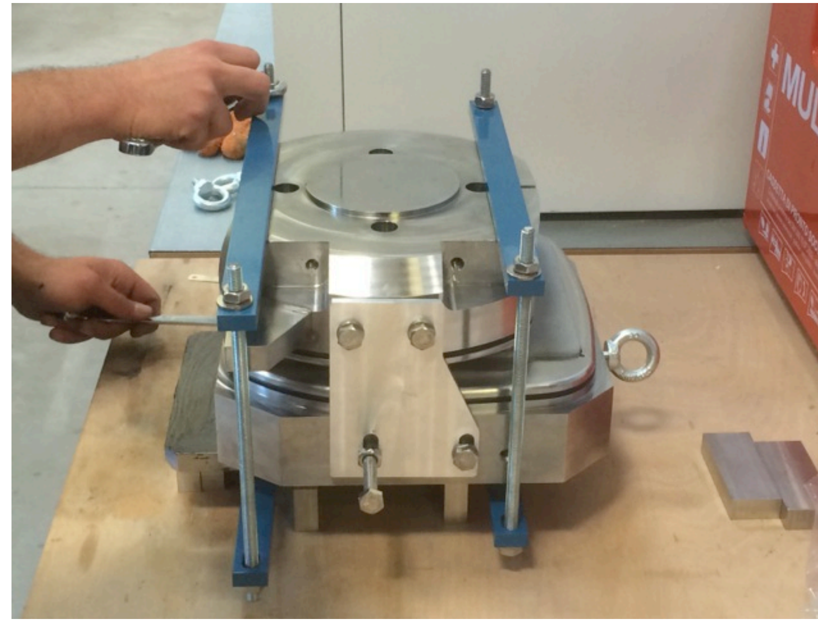
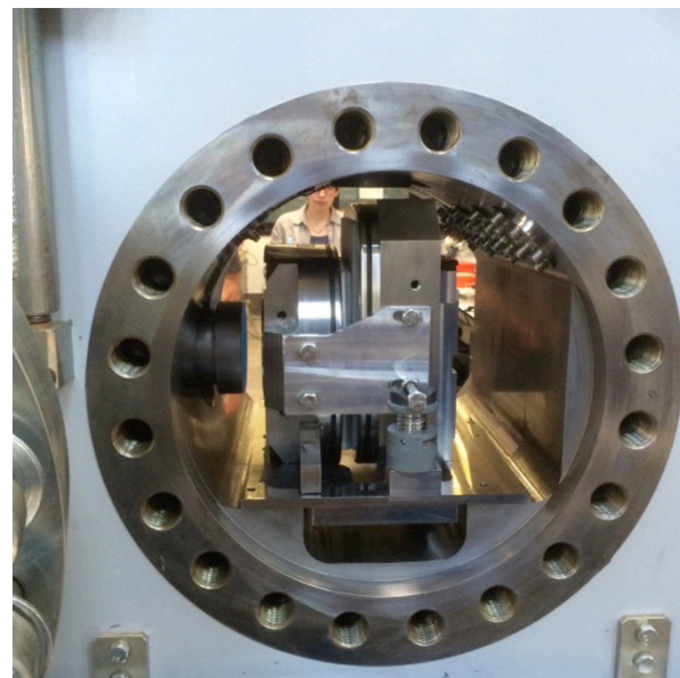
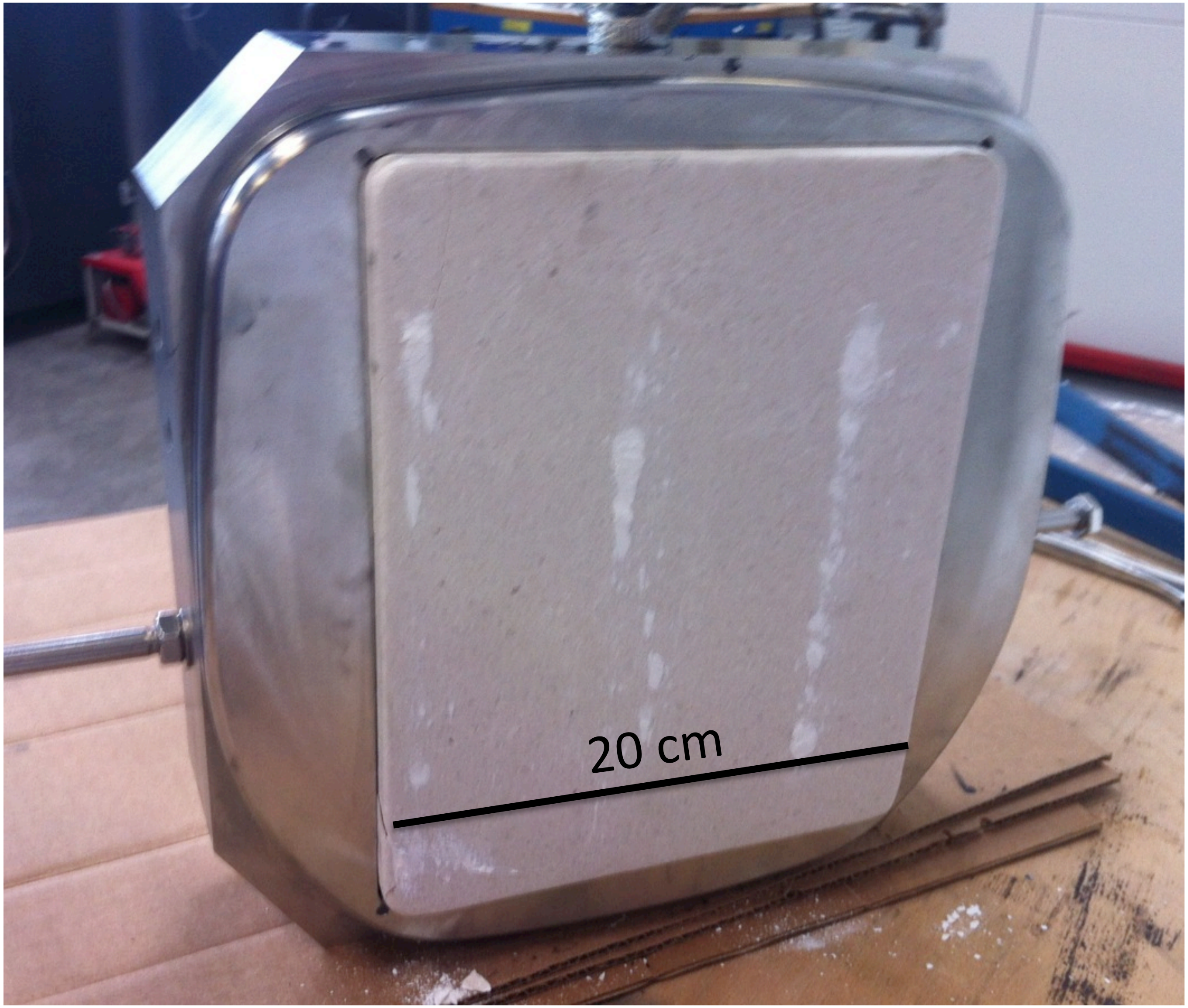


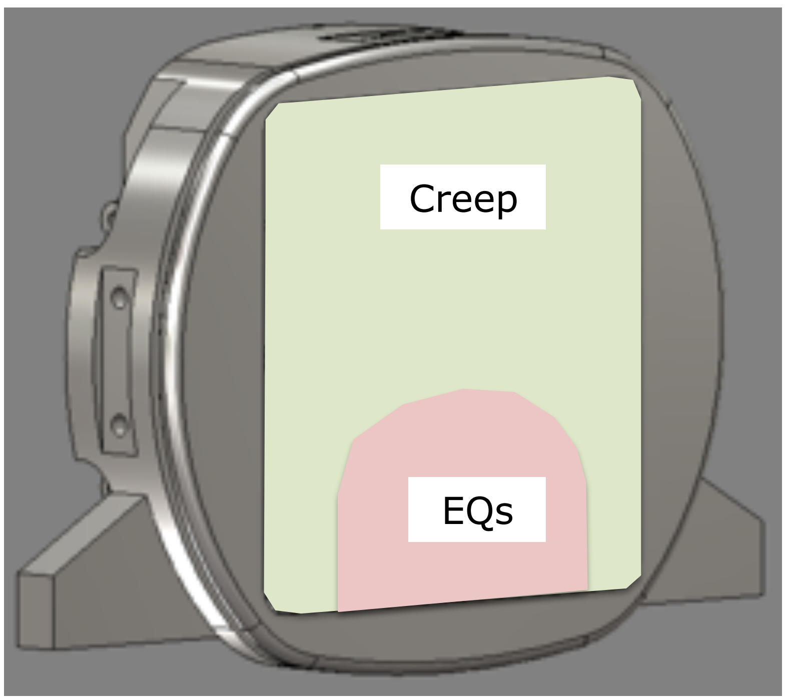
Heterogeneous experimental faults



Tesei et al., in progress

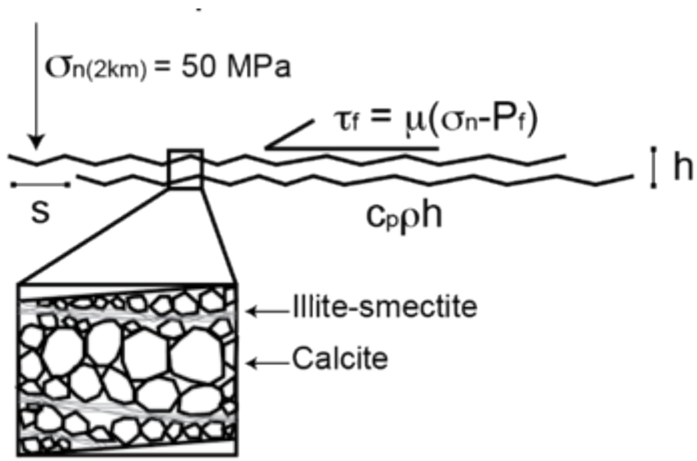
Heterogeneous experimental faults

Interaction between EQ-like and creep like fault patches along a large (20 x 20 cm), fluid rich experimental fault.



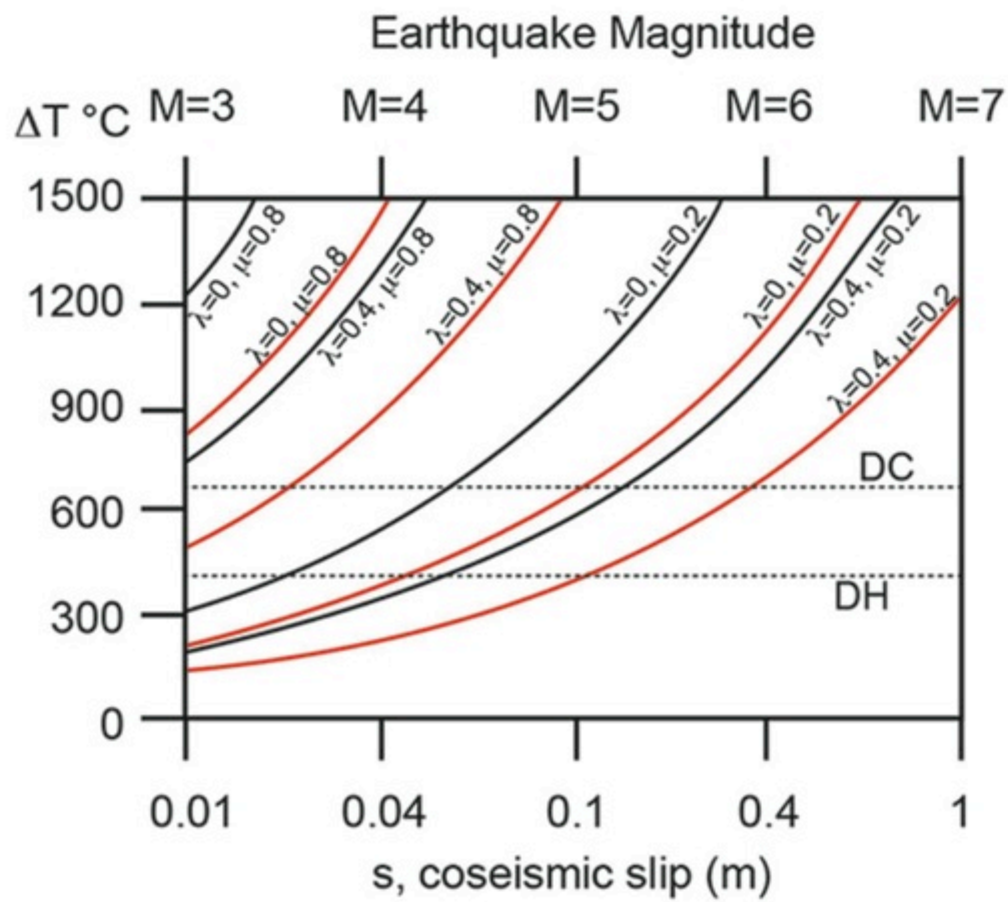
Tesei et al., in progress


Thank you



Slipping zone of no thickness (Rice, 2006):

$$\Delta T = \frac{\tau_f}{\rho C_p} \sqrt{\frac{V\, s}{\pi\, \kappa}}$$



τ_f is the shear resistance of the fault;
ρ = 2710 kg/m^3;
Cp is the heat capacity (962 J/kgK);
V = 1 ms^{-1} is the constant slip velocity;
s is the mean co-seismic slip;
k is the thermal diffusivity.