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# Seismic Melts and Earthquake Mechanics Part 1

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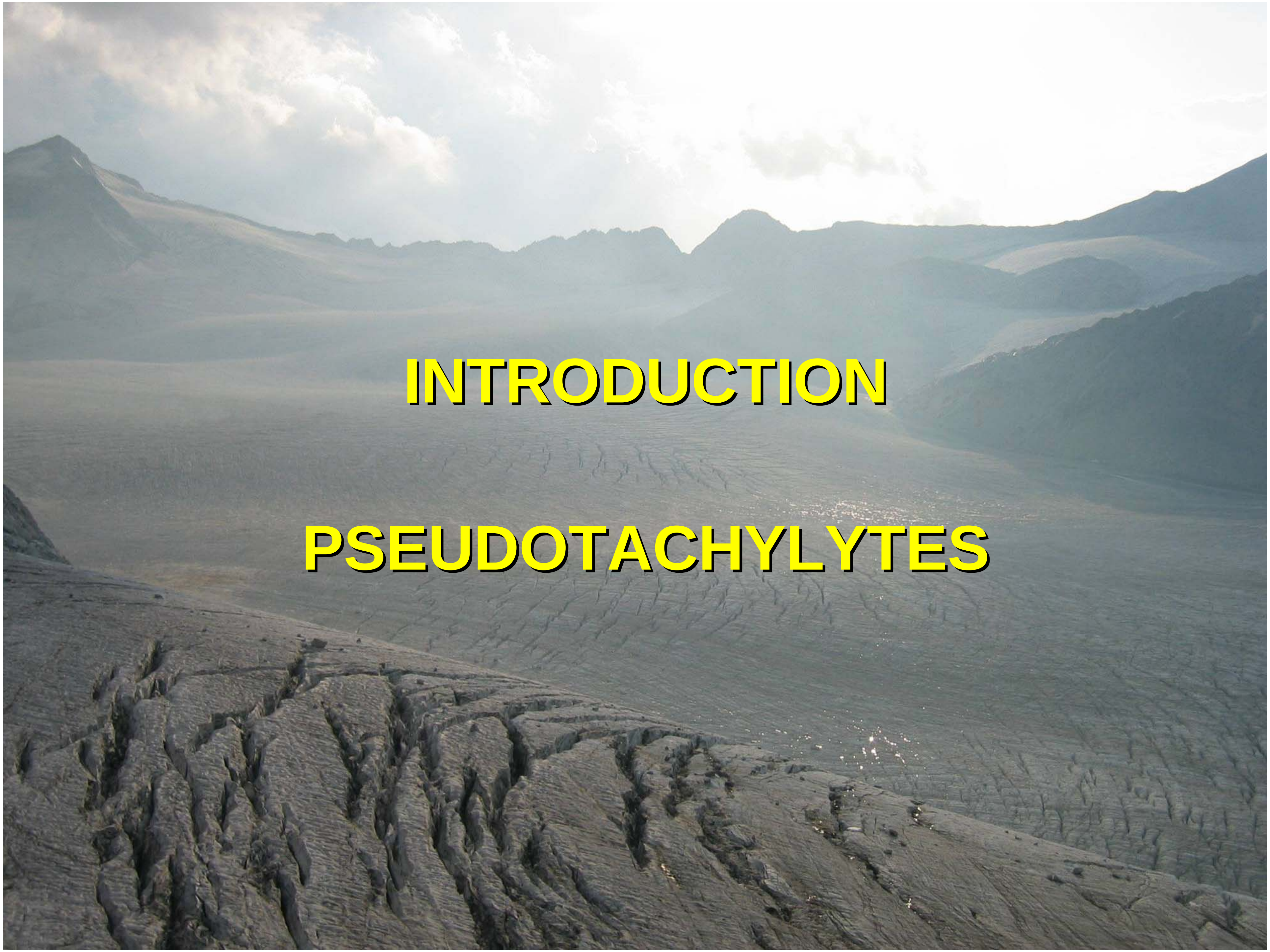
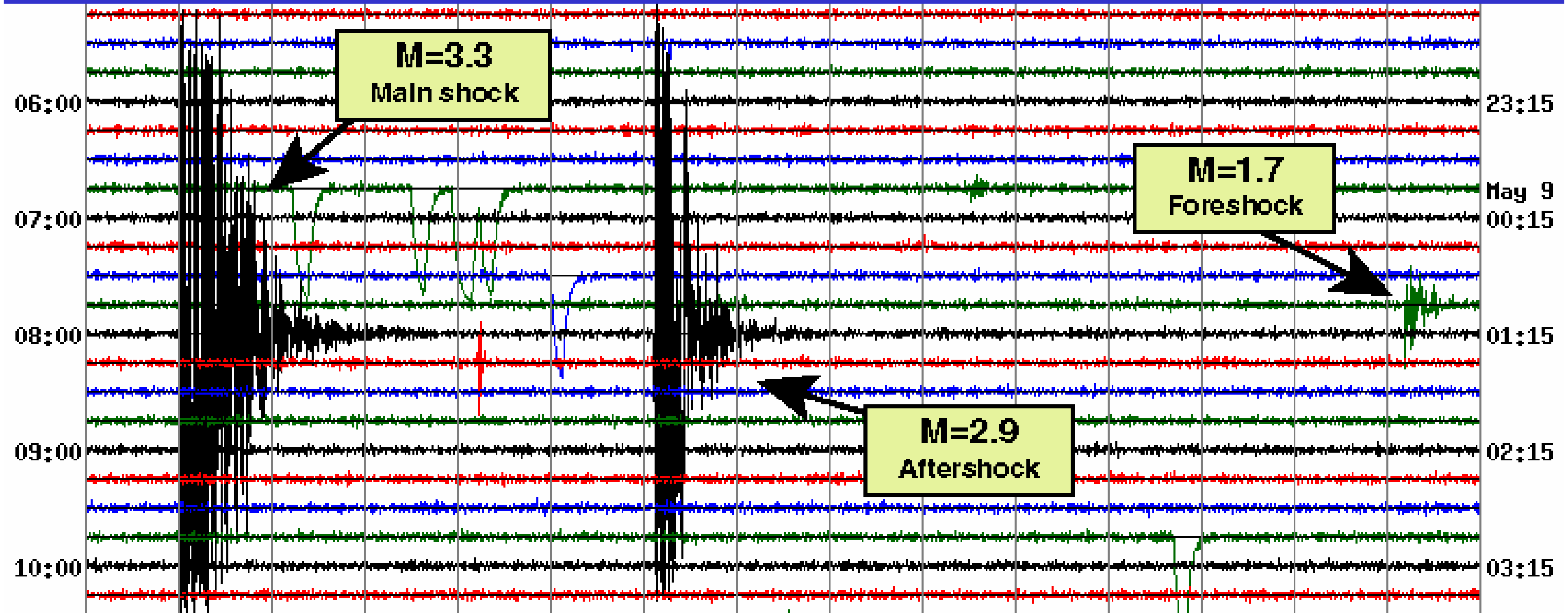

INTRODUCTION
PSEUDOTACHYLYTES

# Earthquake Mechanics….

Kobe Earthquake (JPN) 1995

# ….is mainly investigated by seismologists and geophysicists… and they get the money…



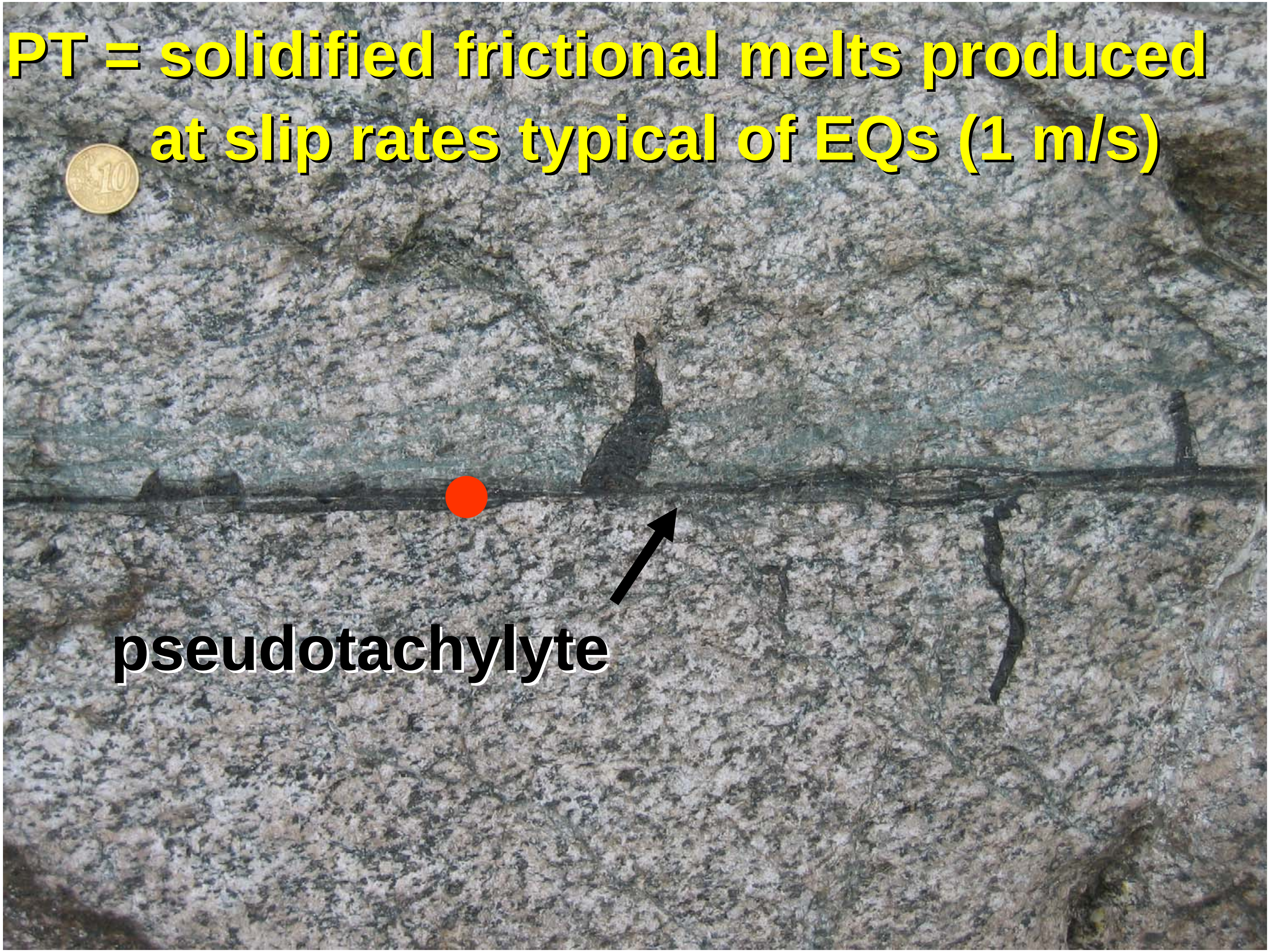

http://quake.usgs.gov/recent/helicorders/Examples/Fore_main_after.html

…but, inferring EQ mechanics from seismograms is like trying to understand how the engine of a car works by listening to its noise from far away (deadly EQs nucleate at 10-15 km depth).

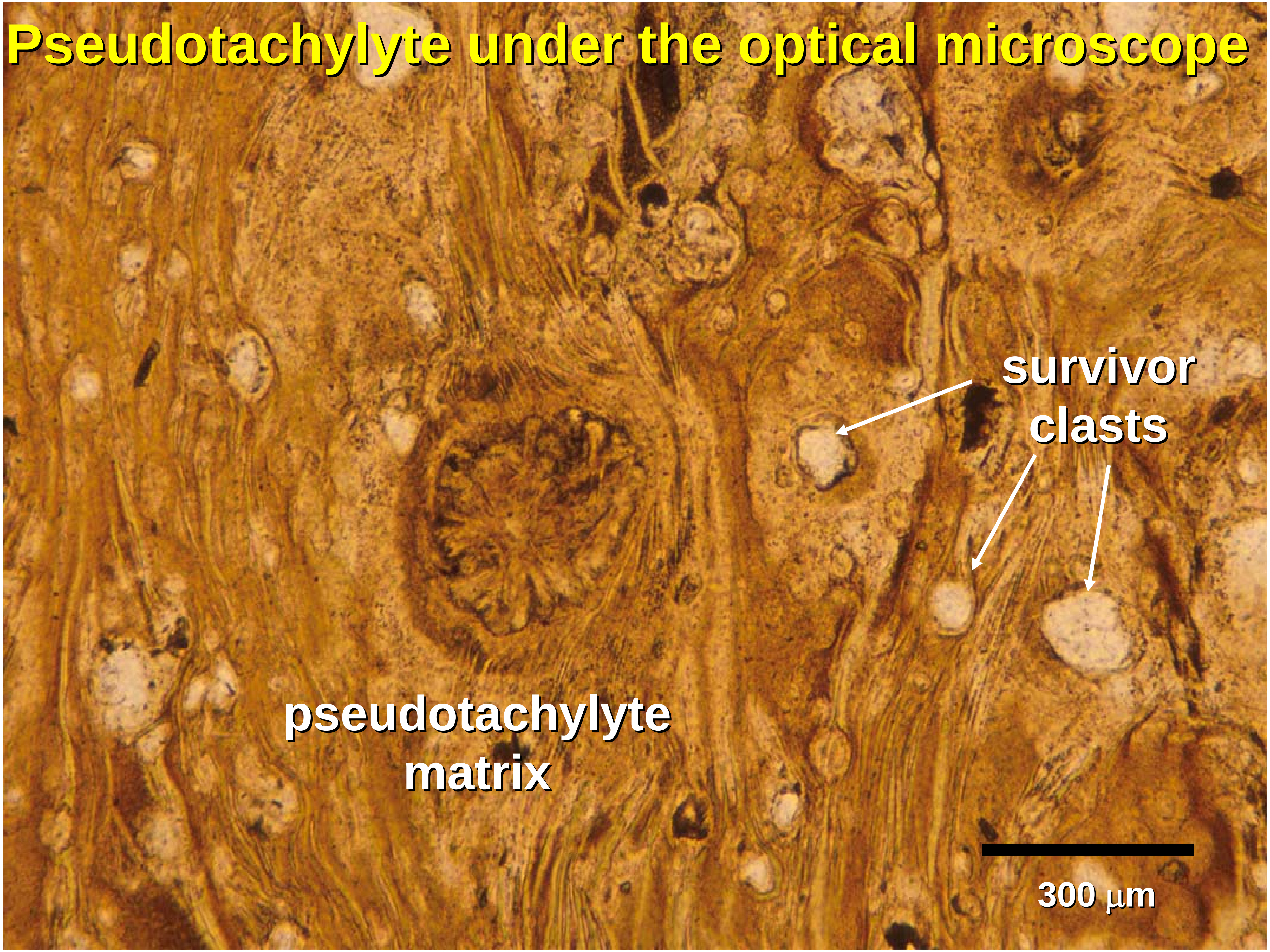
In the next 90’, let’s lift the bonnet of the EQ engine.

The EQ engine: an **exhumed fault.** However it’s an old and rusted engine.

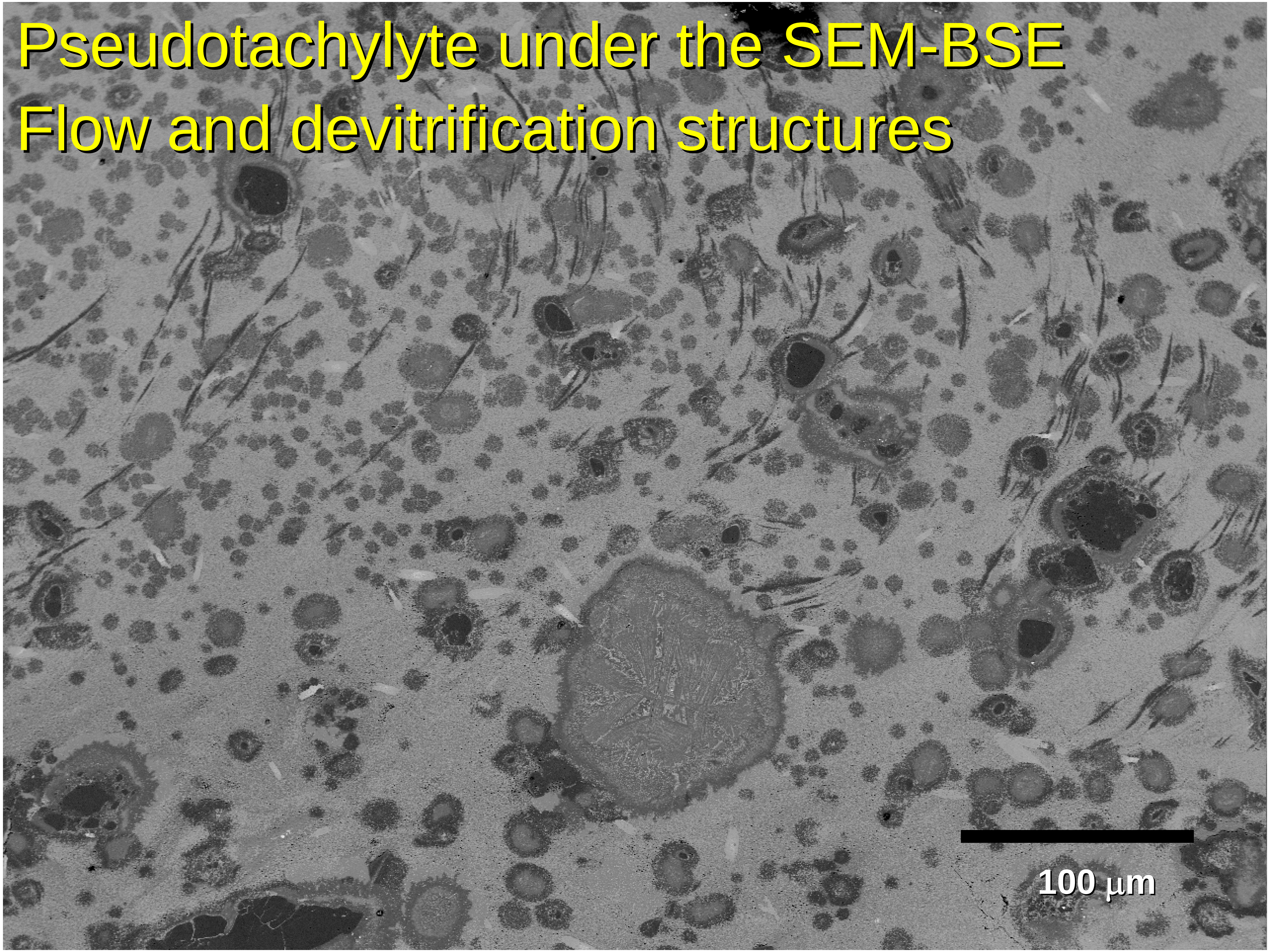
How do we know that the fault was seismic?


PT = solidified frictional melts produced
at slip rates typical of EQs (1 m/s)
pseudotachylyte

# Pseudotachylyte under the optical microscope



# Pseudotachylyte under the SEM-BSE
# Flow and devitrification structures



# Why faults with pseudotachylytes?

1) **The fault was seismic** (Cowan, JSG, 1999)

2) **One pseudotachylyte layer = one EQ**

3) **Since fractures are filled by PT, fractures were opened/prod. during seismic faulting**

4) **Geological constraints (age, ambient cond.)**

**Problems of using pseudotachylytes… a lot, let’s discuss this later…**

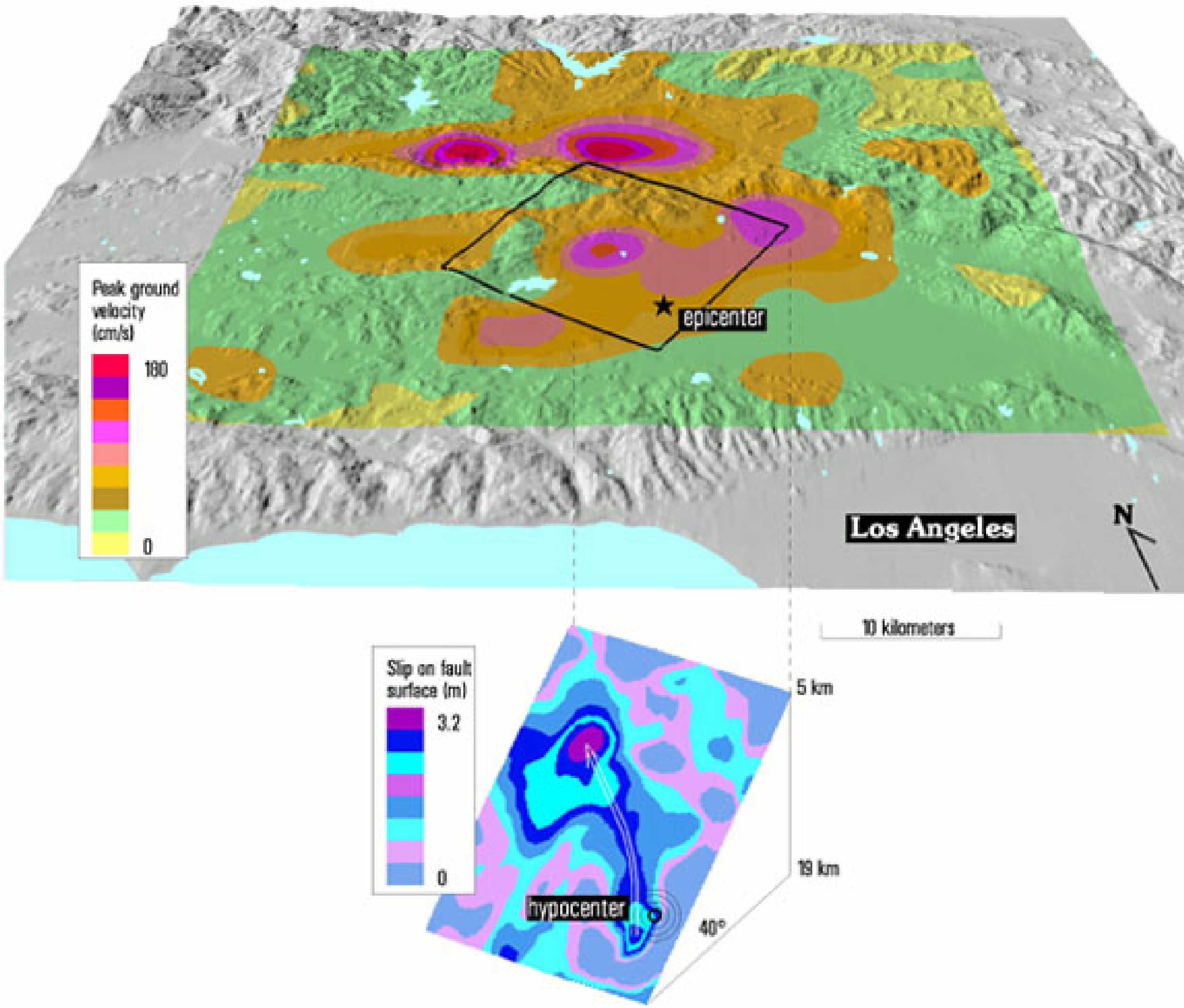
# What happens during an EQ?

Northridge Earthquake (Los Angeles)

M 6.9

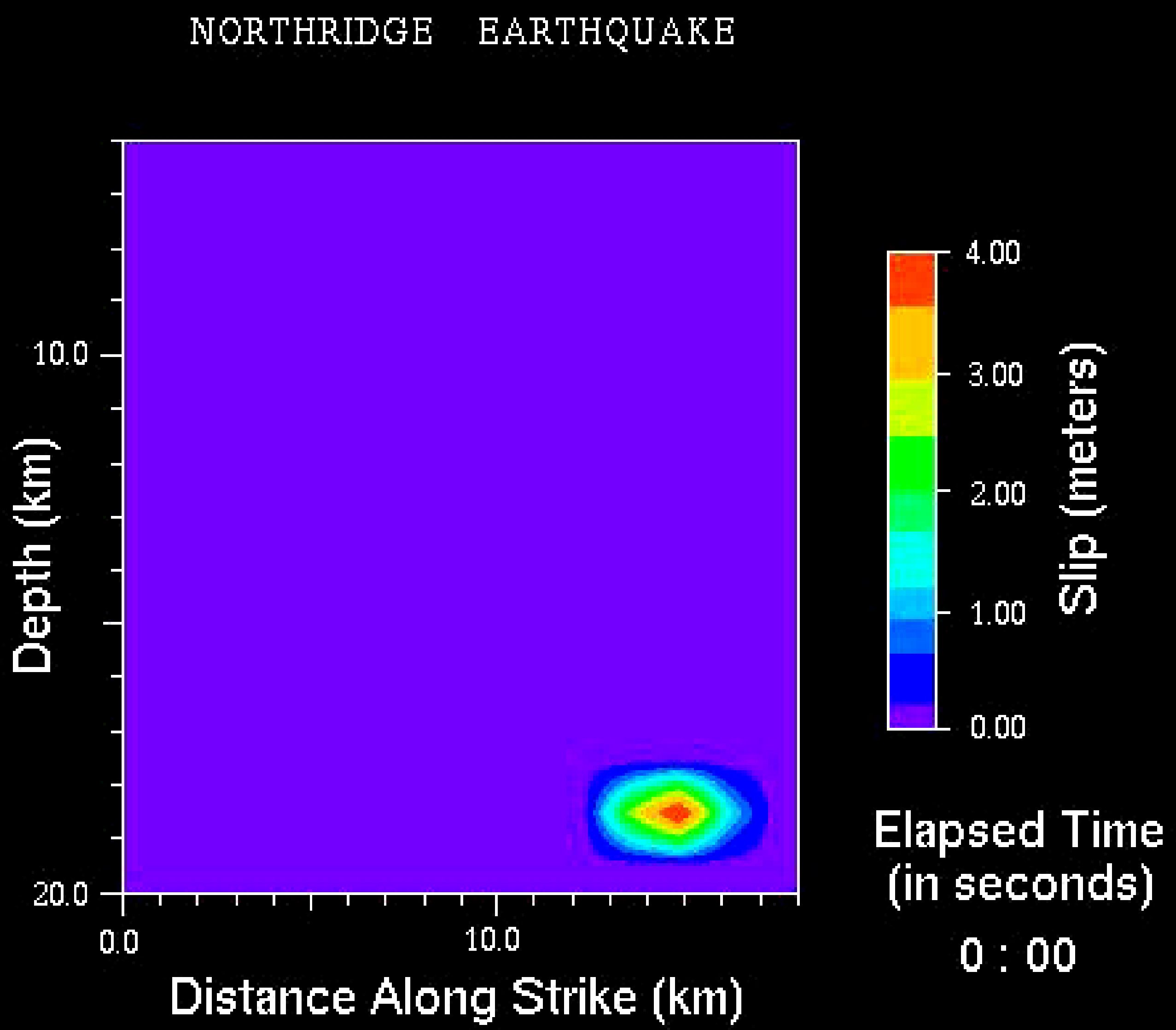
(57 dead and > 9000 wound.)

blind thrust - SAF



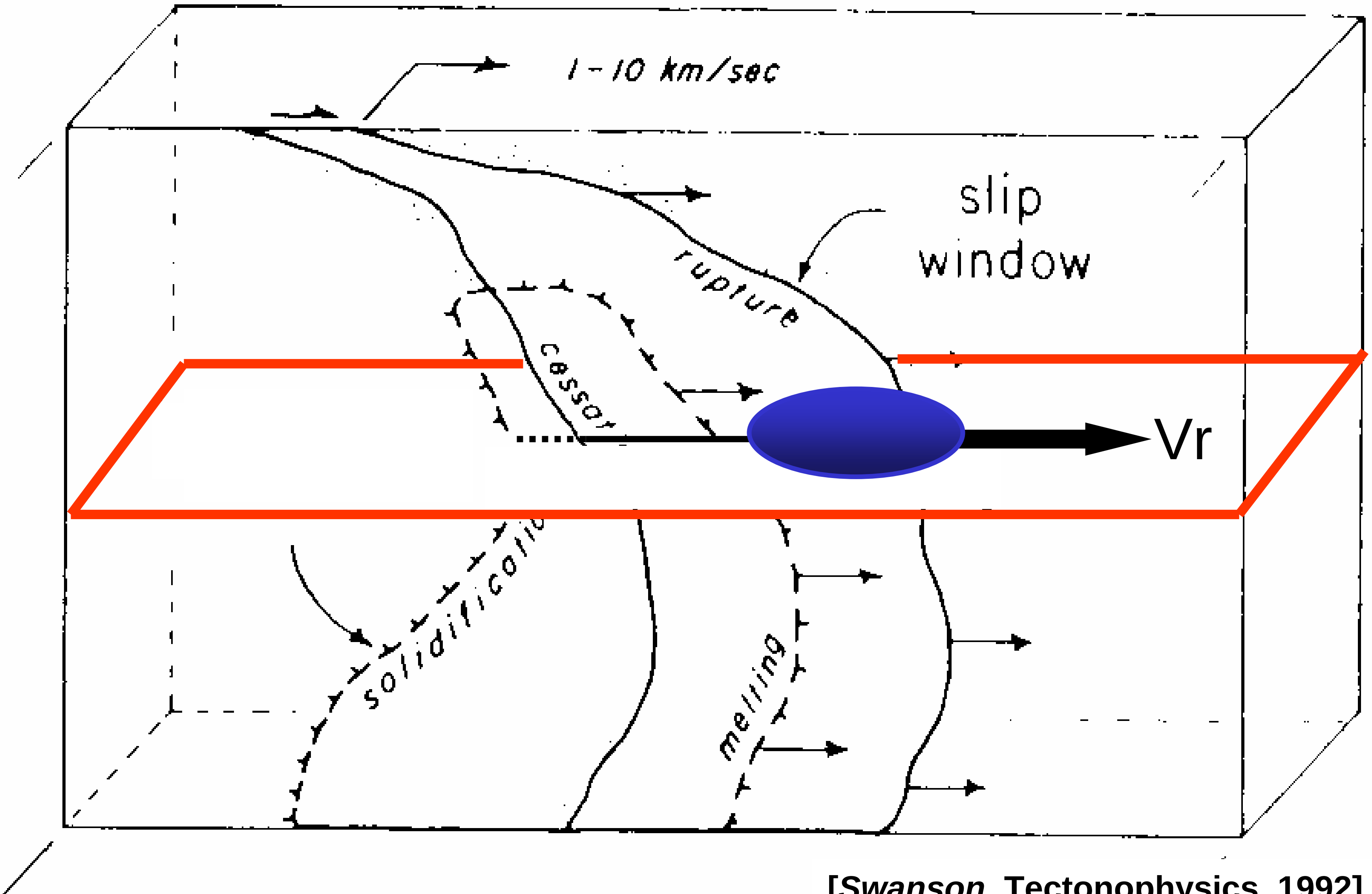

**http://www.data.scec.org/Module/links/northrup.html**

# Looking at the fault surface. Crack propagation as a self-healing pulse




http://www.data.scec.org/Module/links/northrup.html

# Do PST record EQ dynamics?

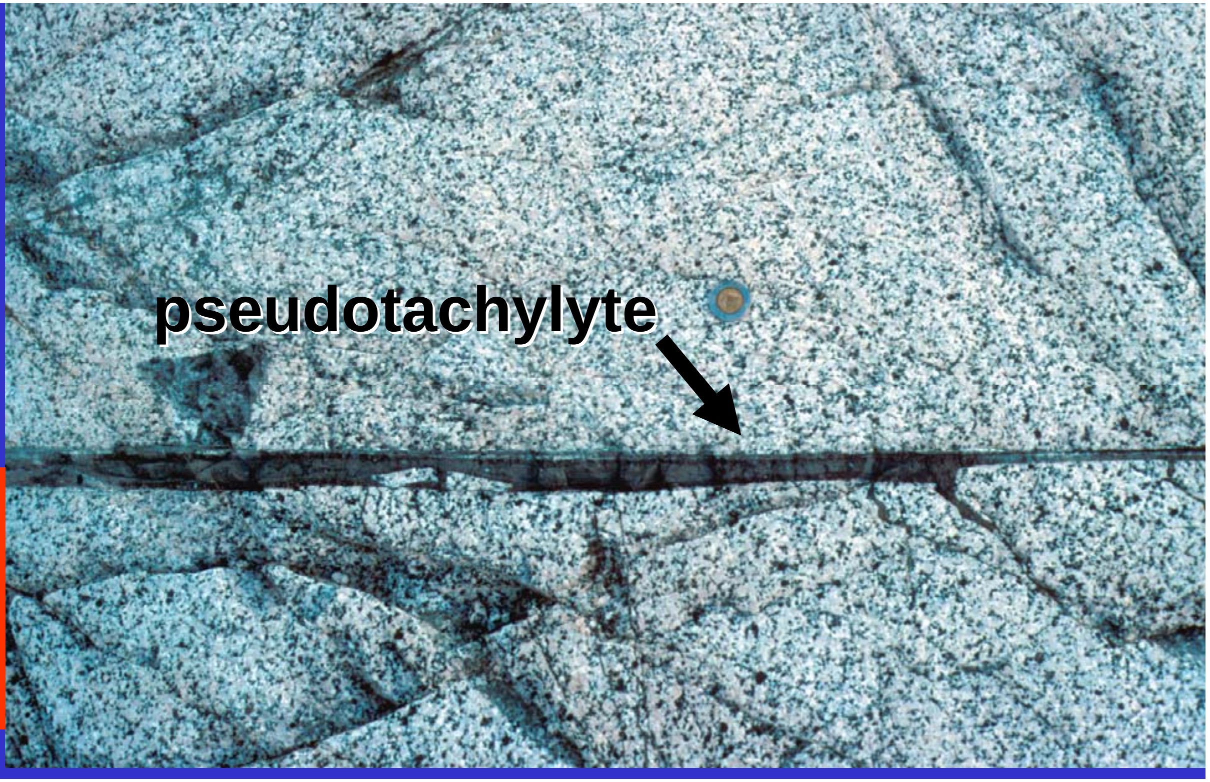


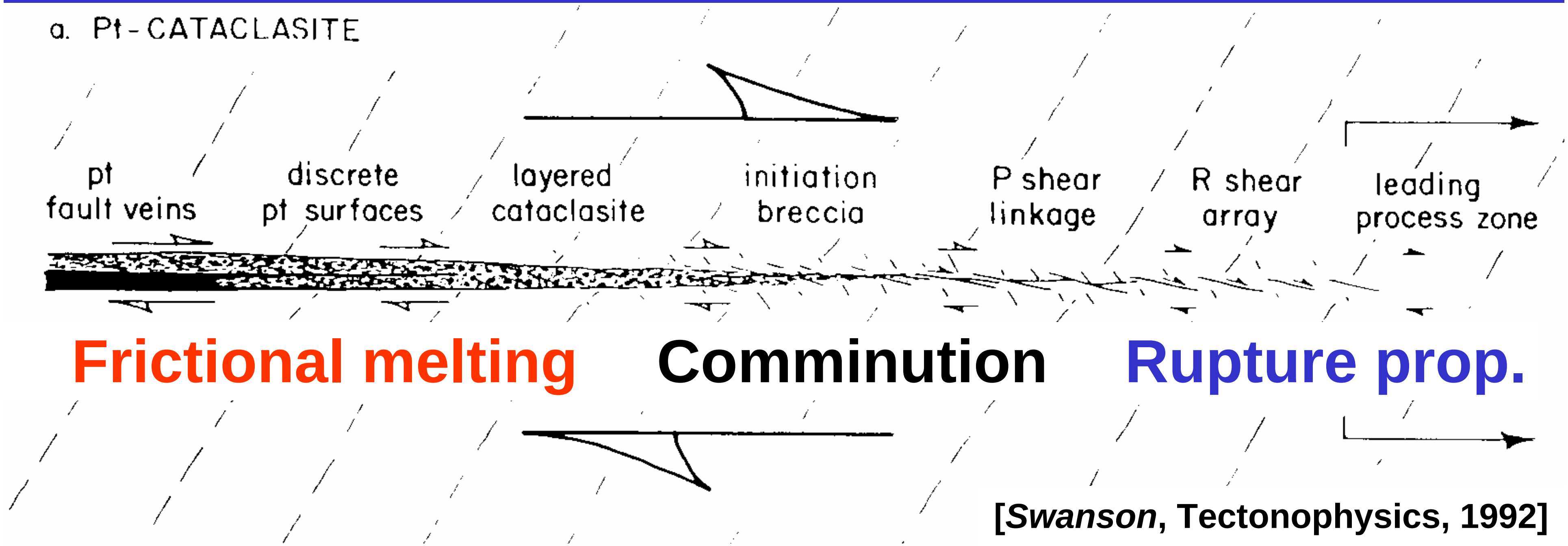

[*Swanson*, Tectonophysics, 1992]

# How do rocks **record** all this?

V rupture ~ 3 km/s

V slip ~ 1 m/s

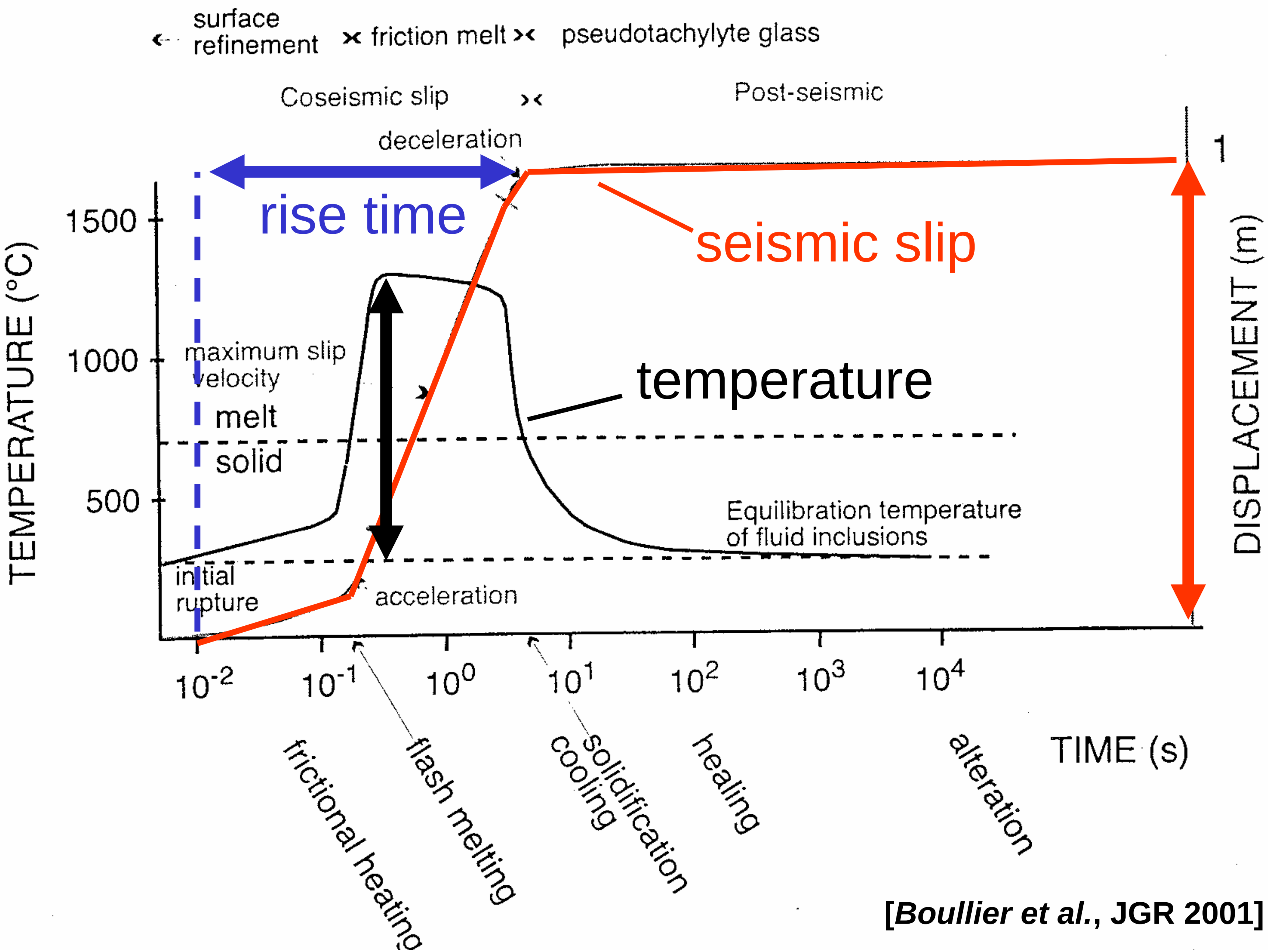



**Frictional melting** **Comminution** **Rupture prop.**

[*Swanson*, Tectonophysics, 1992]

# At a point of a fault




[*Boullier et al.*, JGR 2001]

What I will try to sell today is that PT-bearing faults networks retain information on:

1) EQ rupture dynamics

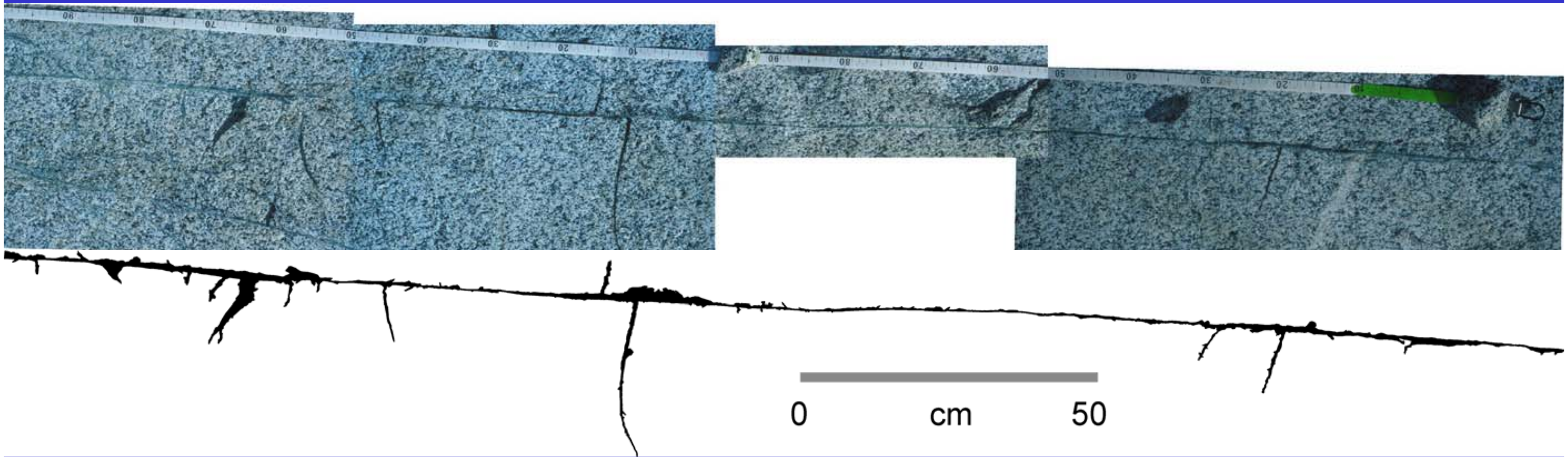
2) Fault strength during an EQ

3) EQ energy budgets

**Points 2 and 3 are out of the range of seismology**

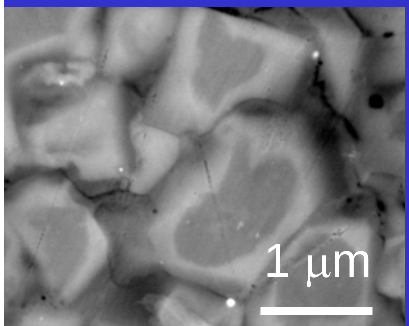
How can I sell you this?

# By linking field obs. of exhumed faults



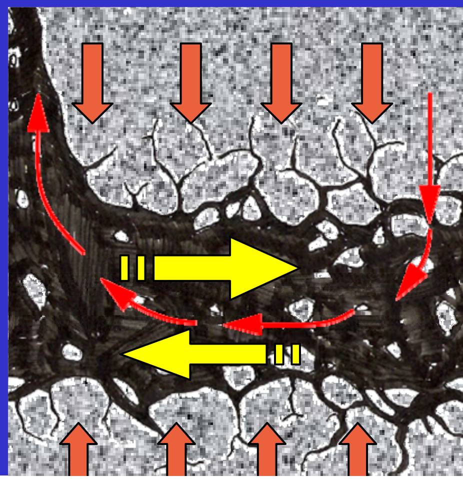

WITH

1) micr. observ.

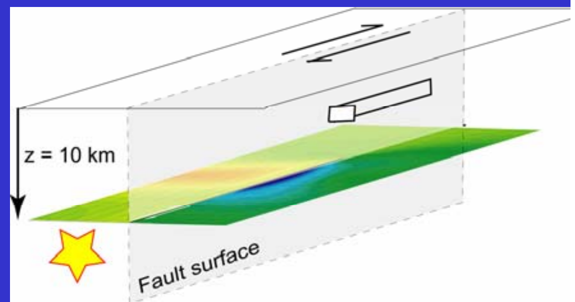


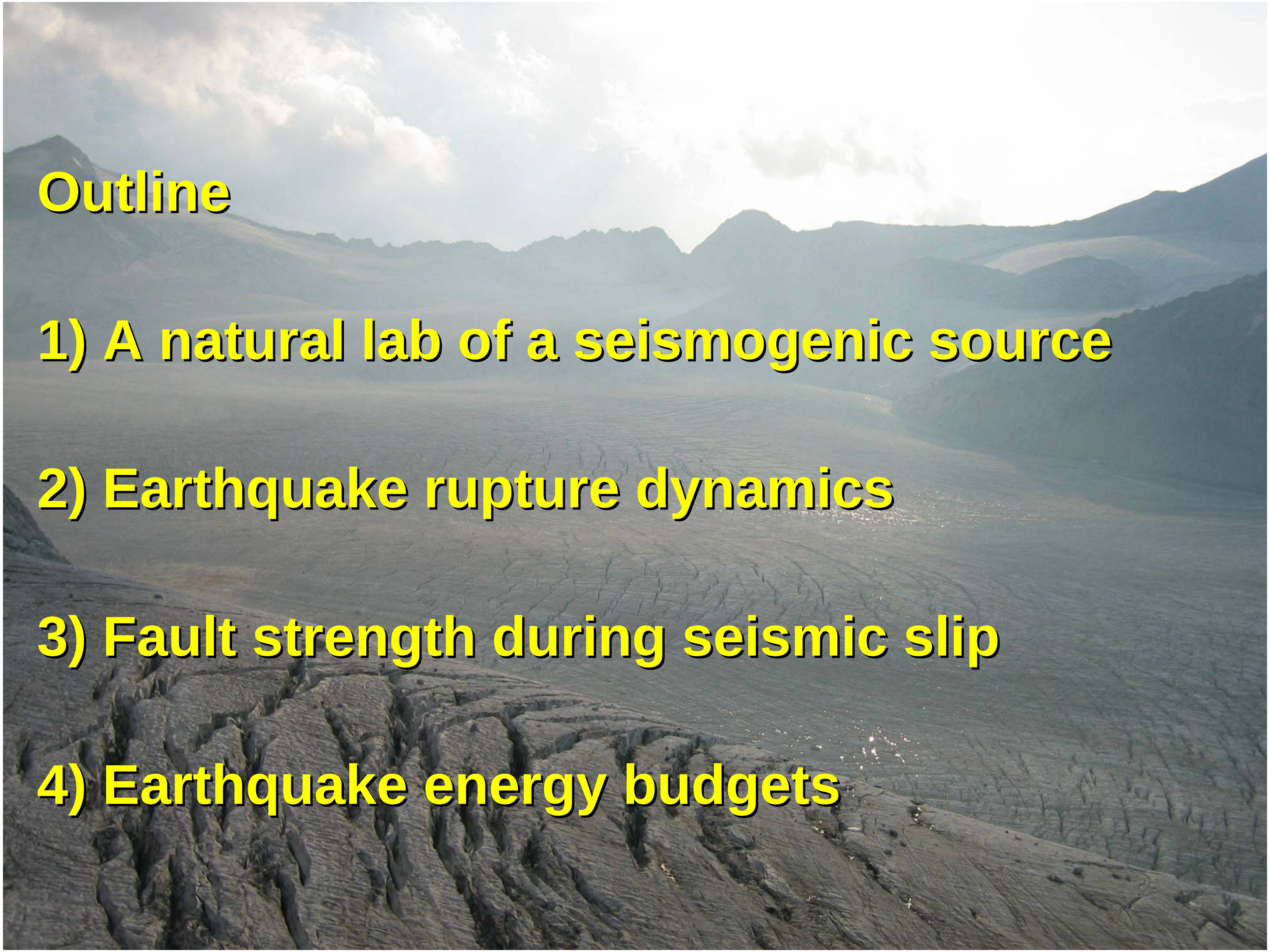

2) HVRFE

3) melt lubr. modeling



4) rupture dynamics modeling





# Outline

1) A natural lab of a seismogenic source

2) Earthquake rupture dynamics

3) Fault strength during seismic slip

4) Earthquake energy budgets


Outline
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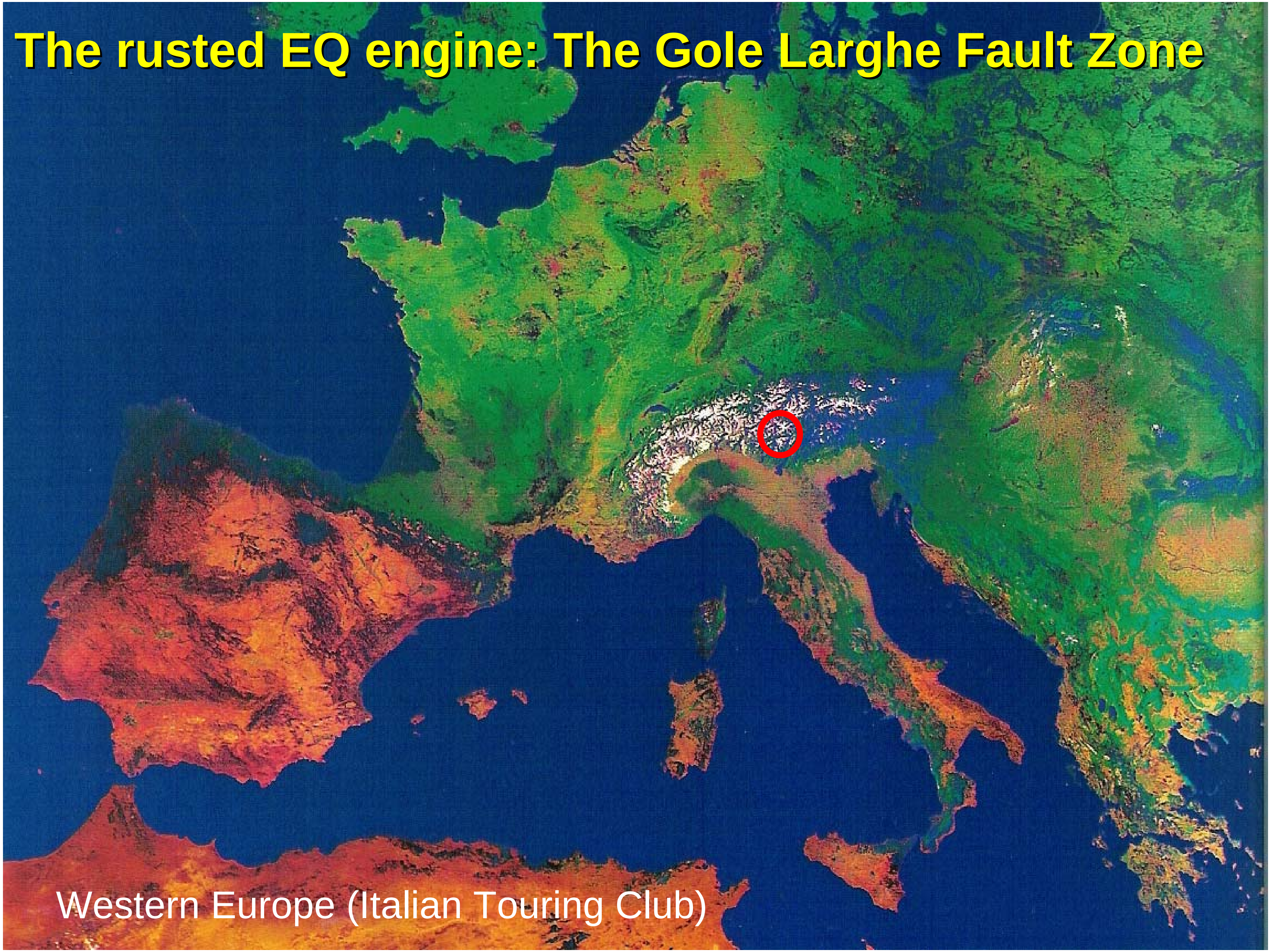
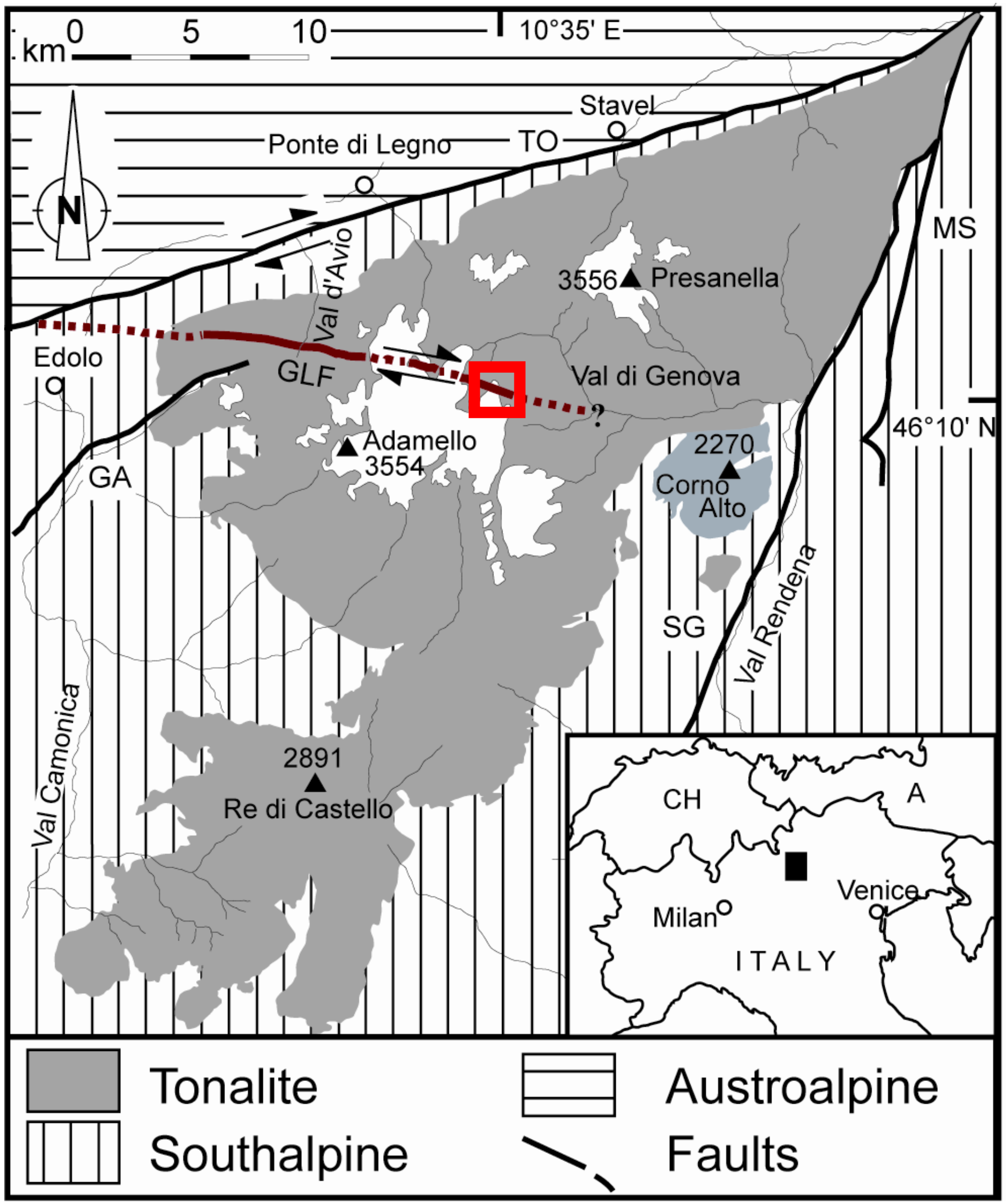
# The rusted EQ engine: The Gole Larghe Fault Zone



Western Europe (Italian Touring Club)

## Geological Setting




# GOLE LARGHE FAULT ZONE

**30 Ma** old (Ar-Ar)

Seismic faulting ambient conditions:

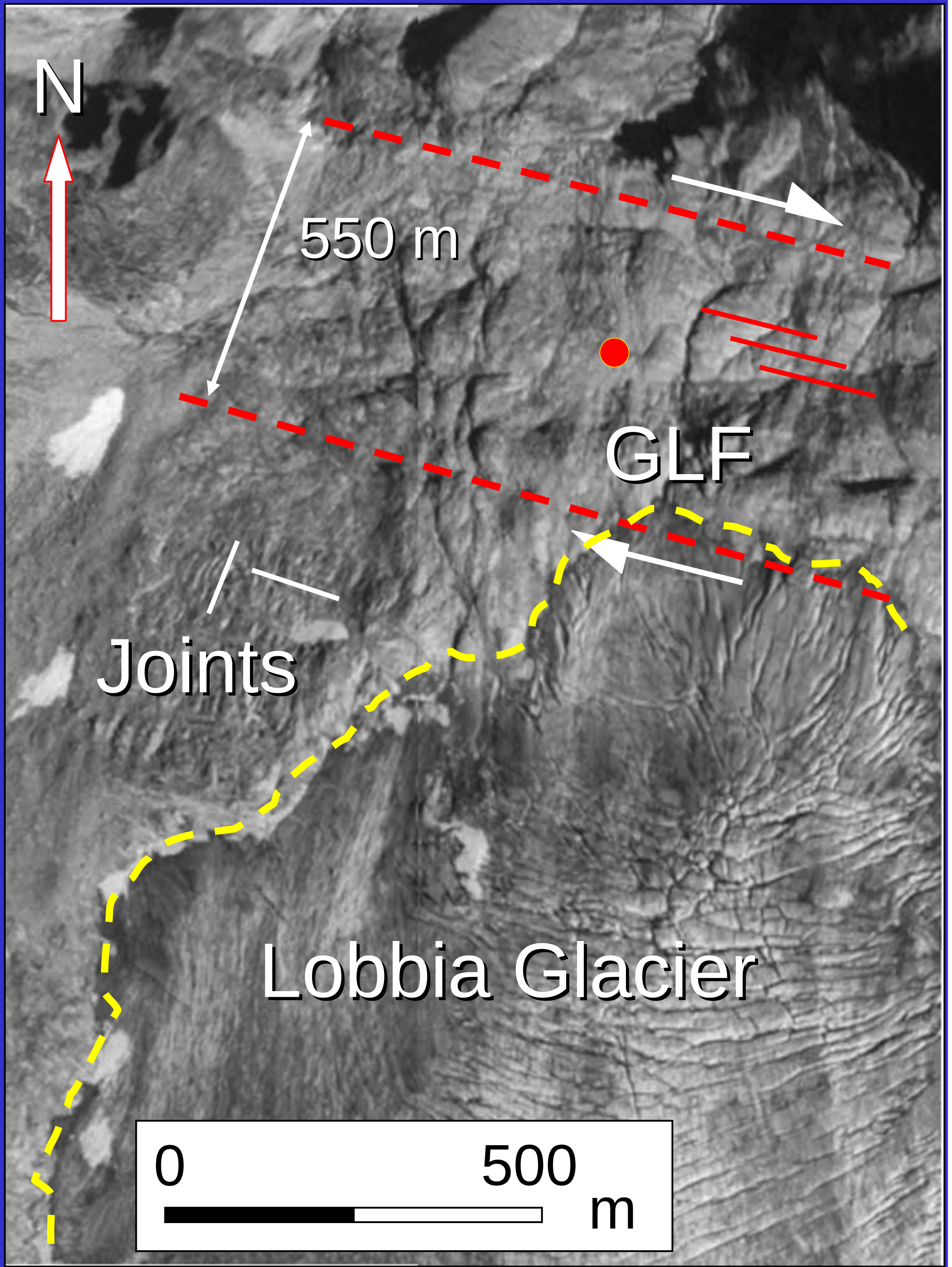
**9-11 km depth**

**250-300 °C**

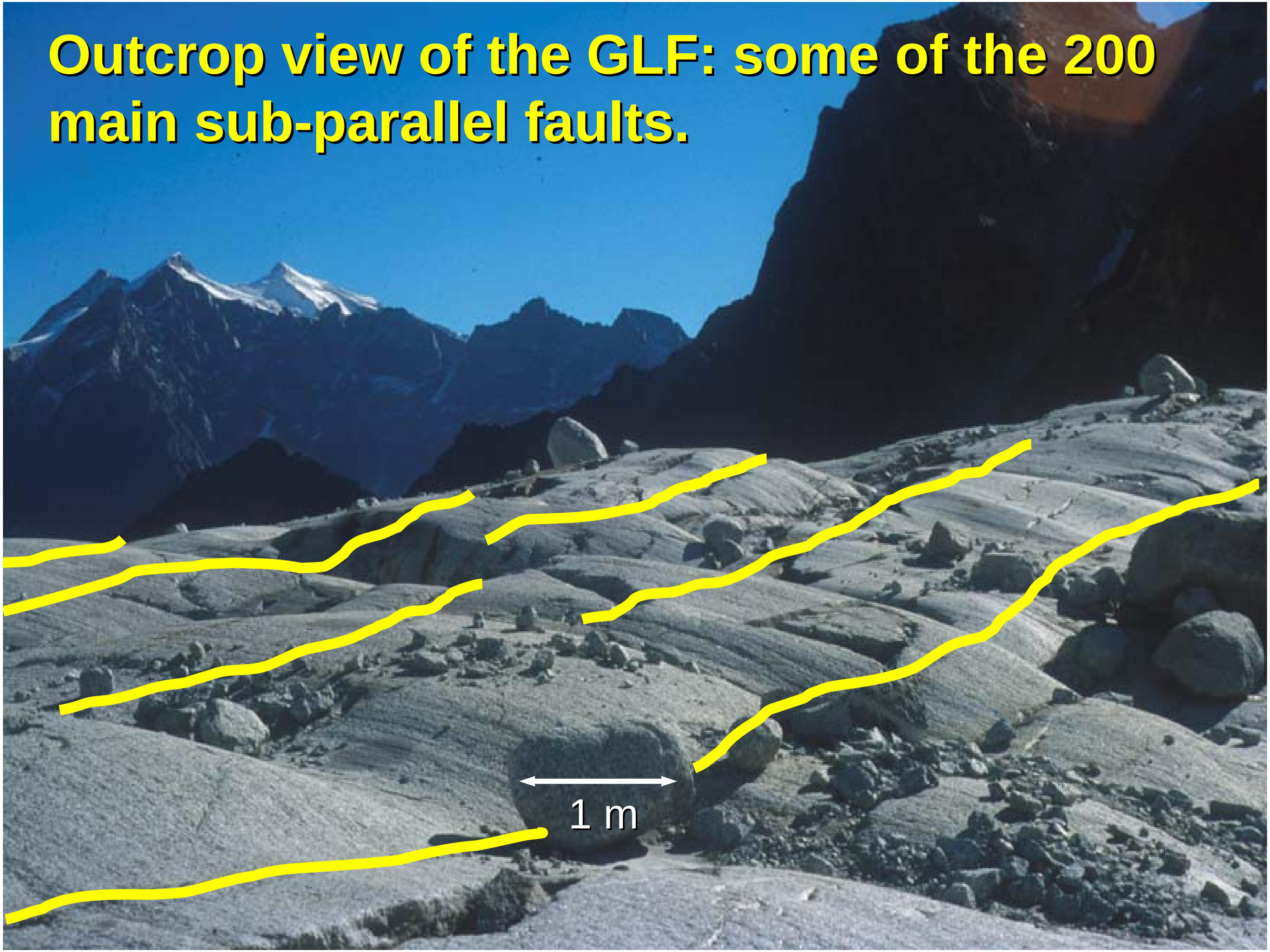
[*Di Toro and Pennacchioni*, JSG, 2004; *Di Toro et al.*, Tectonophysics, 2005; *Pennacchioni et al.*, Tectonophysics, 2006]

# Aerial view of the Gole Larghe Fault

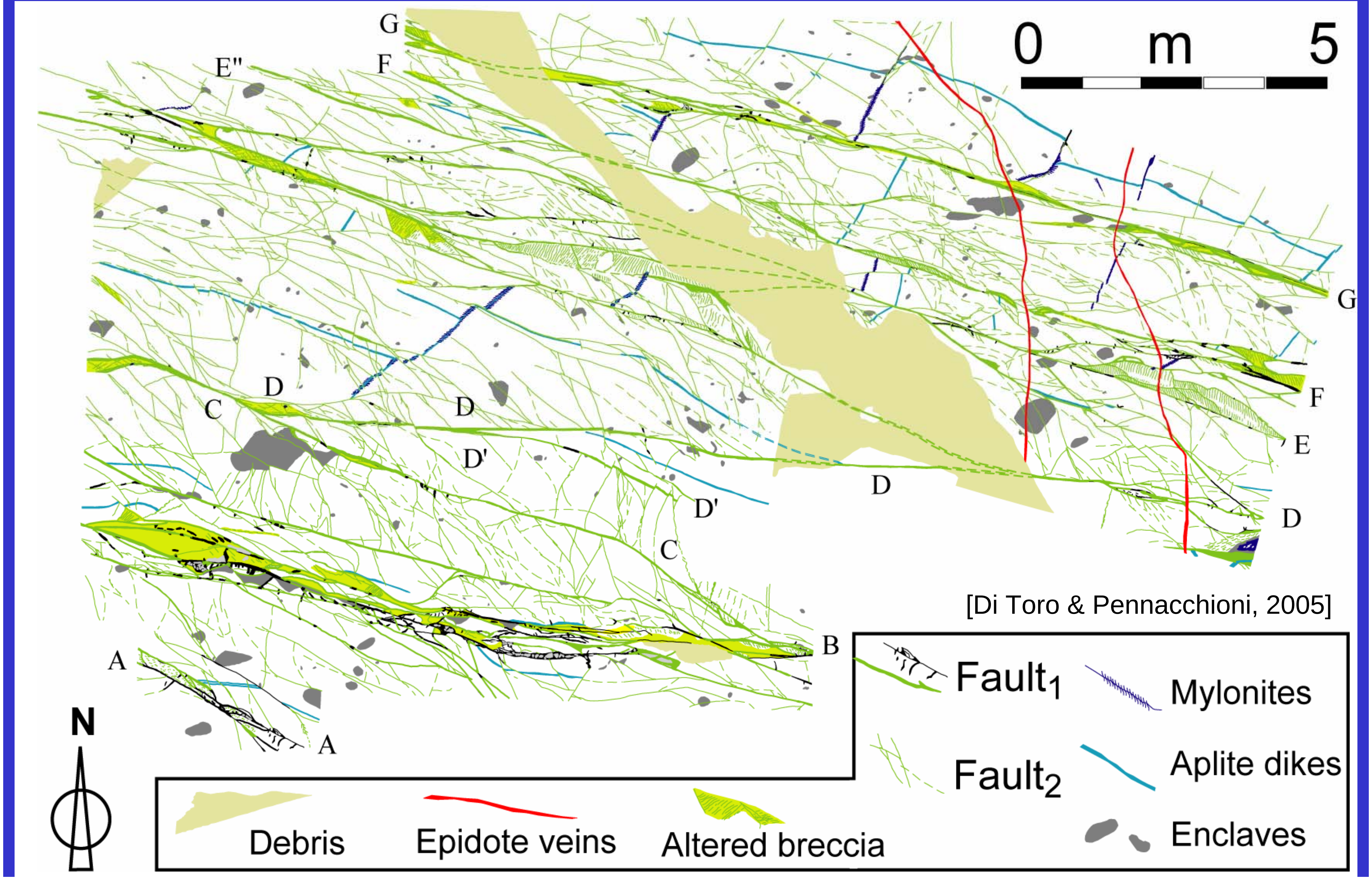
Most faults exploit WNW-ESE striking pre-existing joints.




[Di Toro & Pennacchioni, Tectonophysics, 2005]


Outcrop view of the GLF: some of the 200 main sub-parallel faults.
1 m

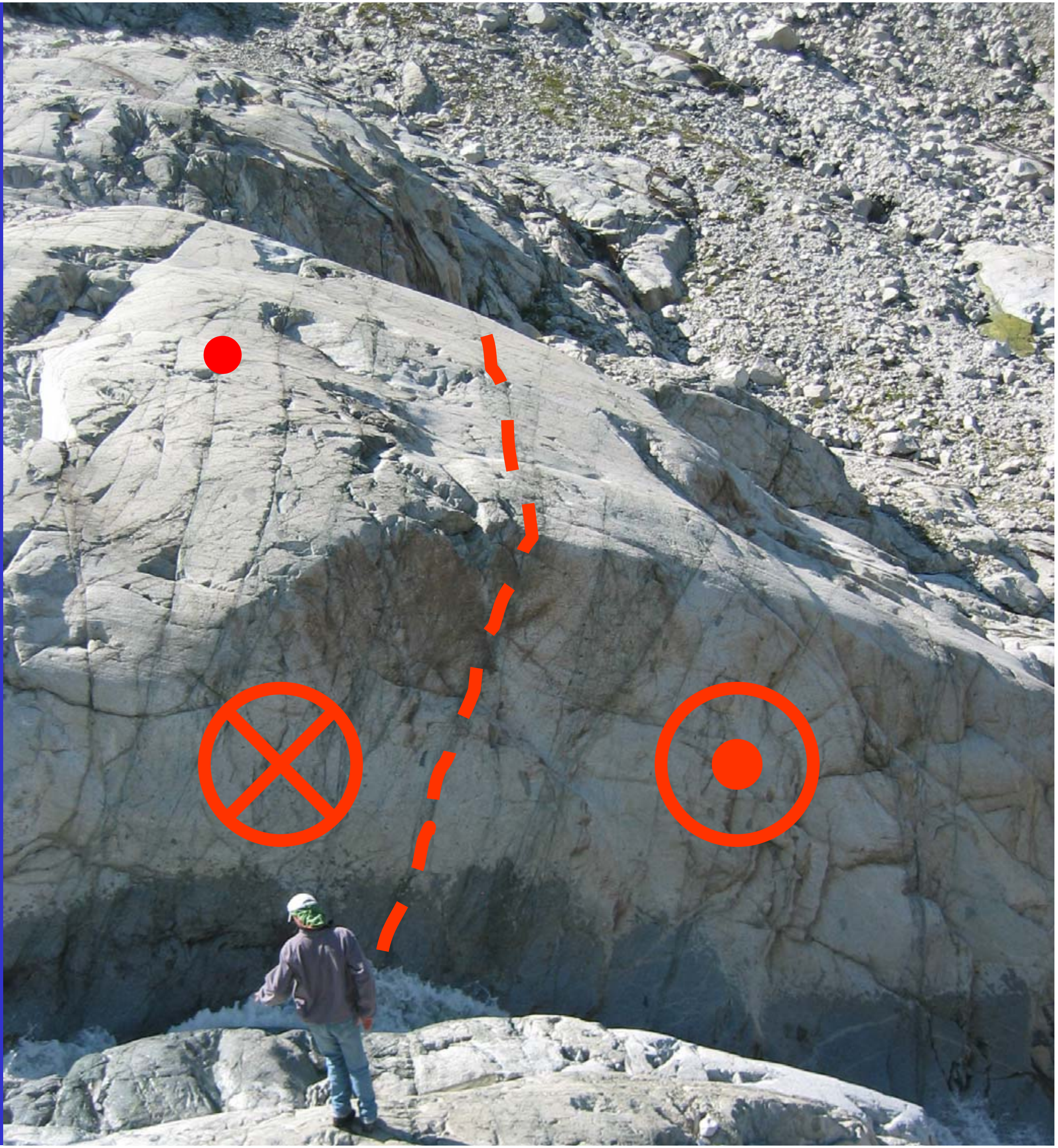
# Detail of the Gole Larghe Fault Zone: main faults are spaced apart every 2-5 m



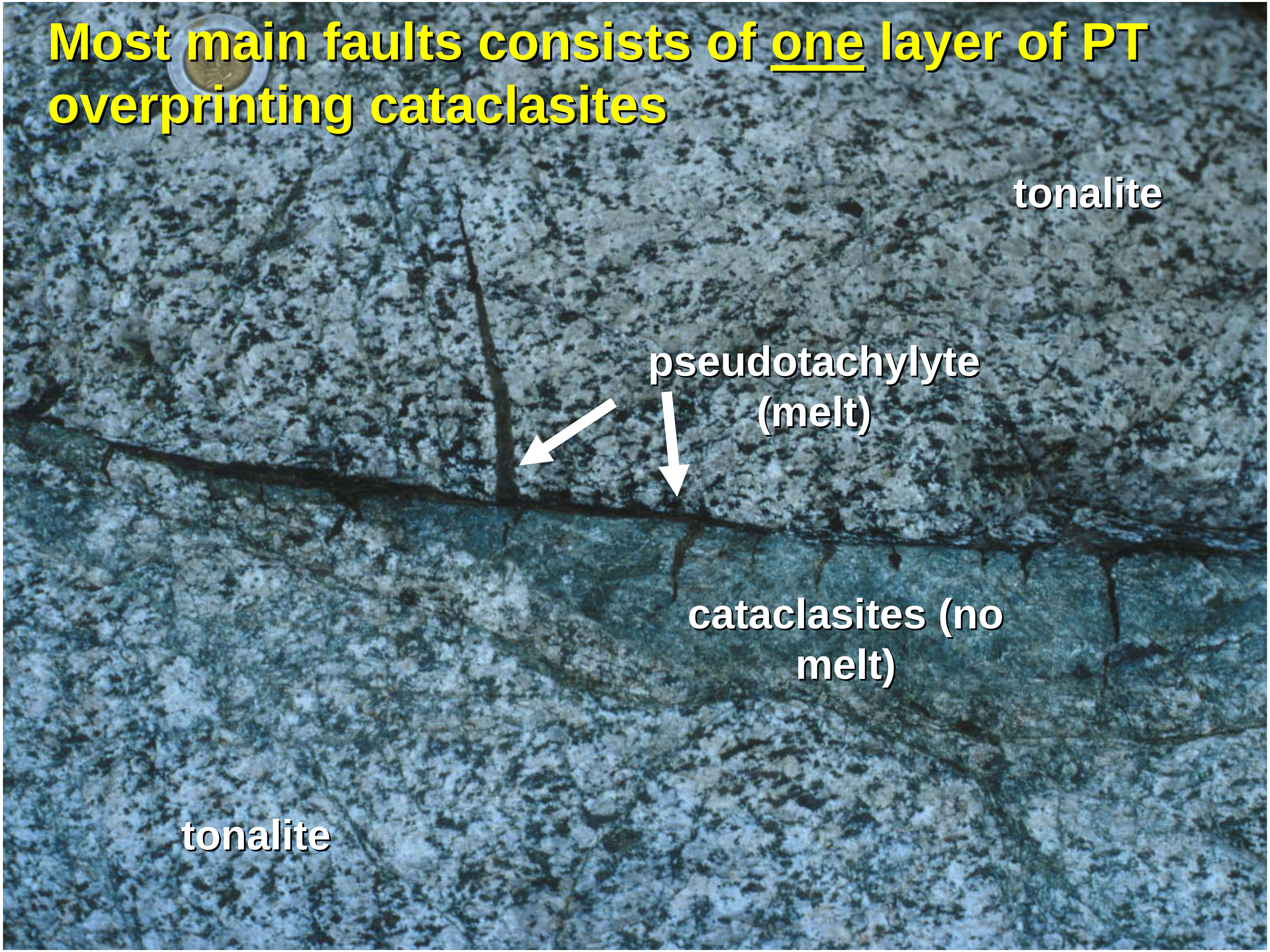
# 3D View

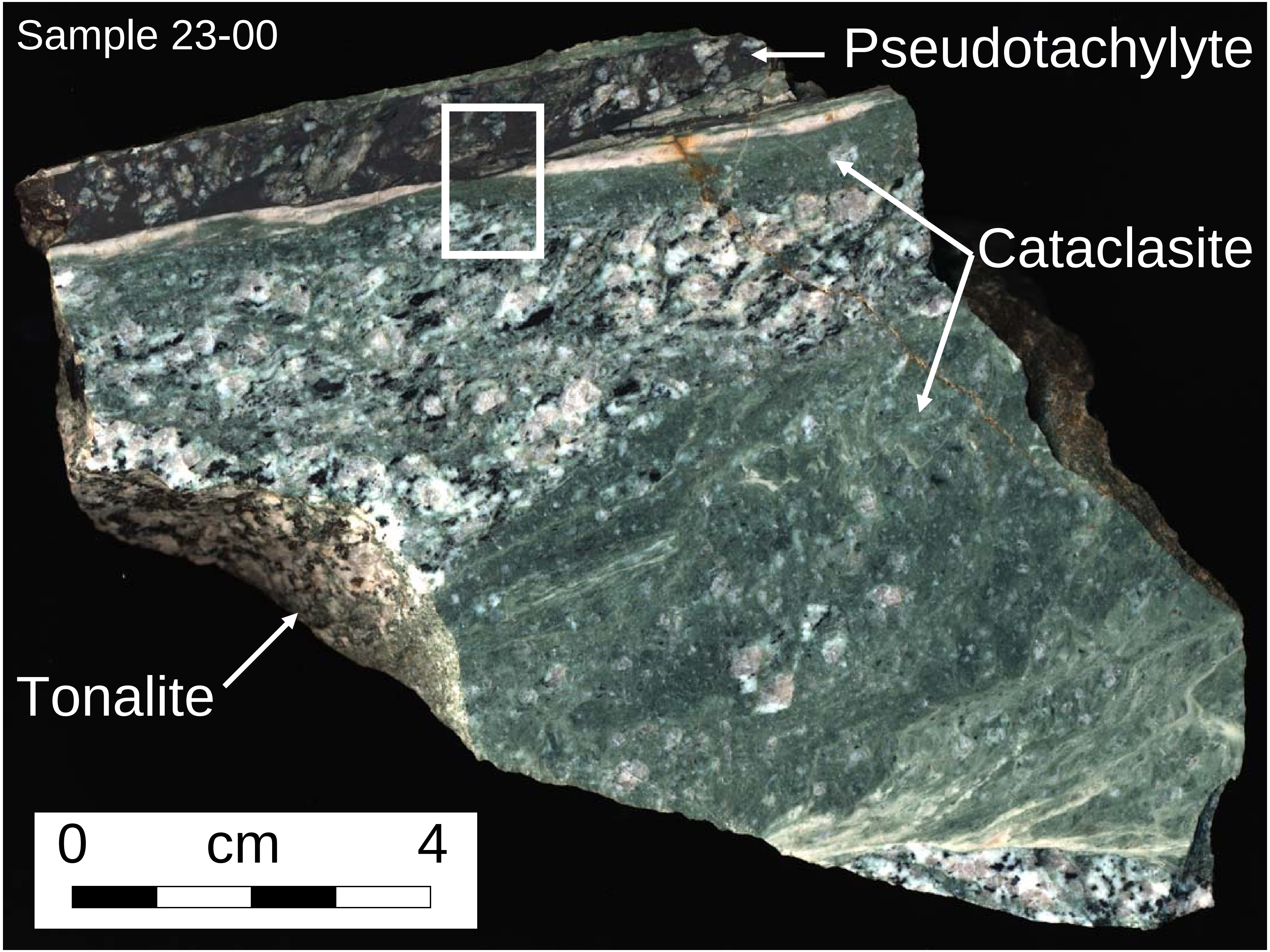
Faults are **sub-vertical** and maintained their original attitude during exhumation

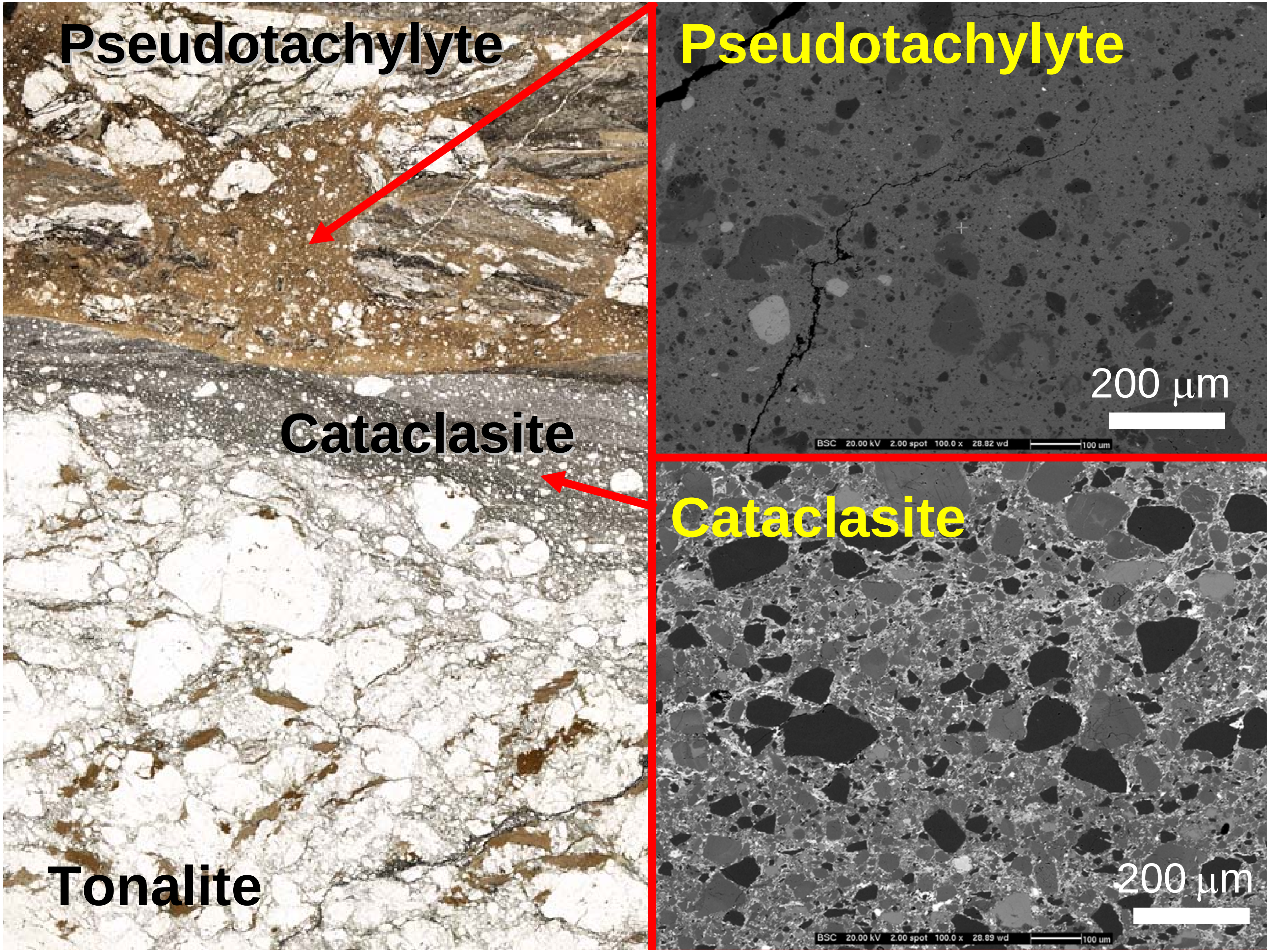
e.g., host rock roof pendants are sub-horizontal inside the batholith



# Most main faults consists of <u>one</u> layer of PT overprinting cataclasites

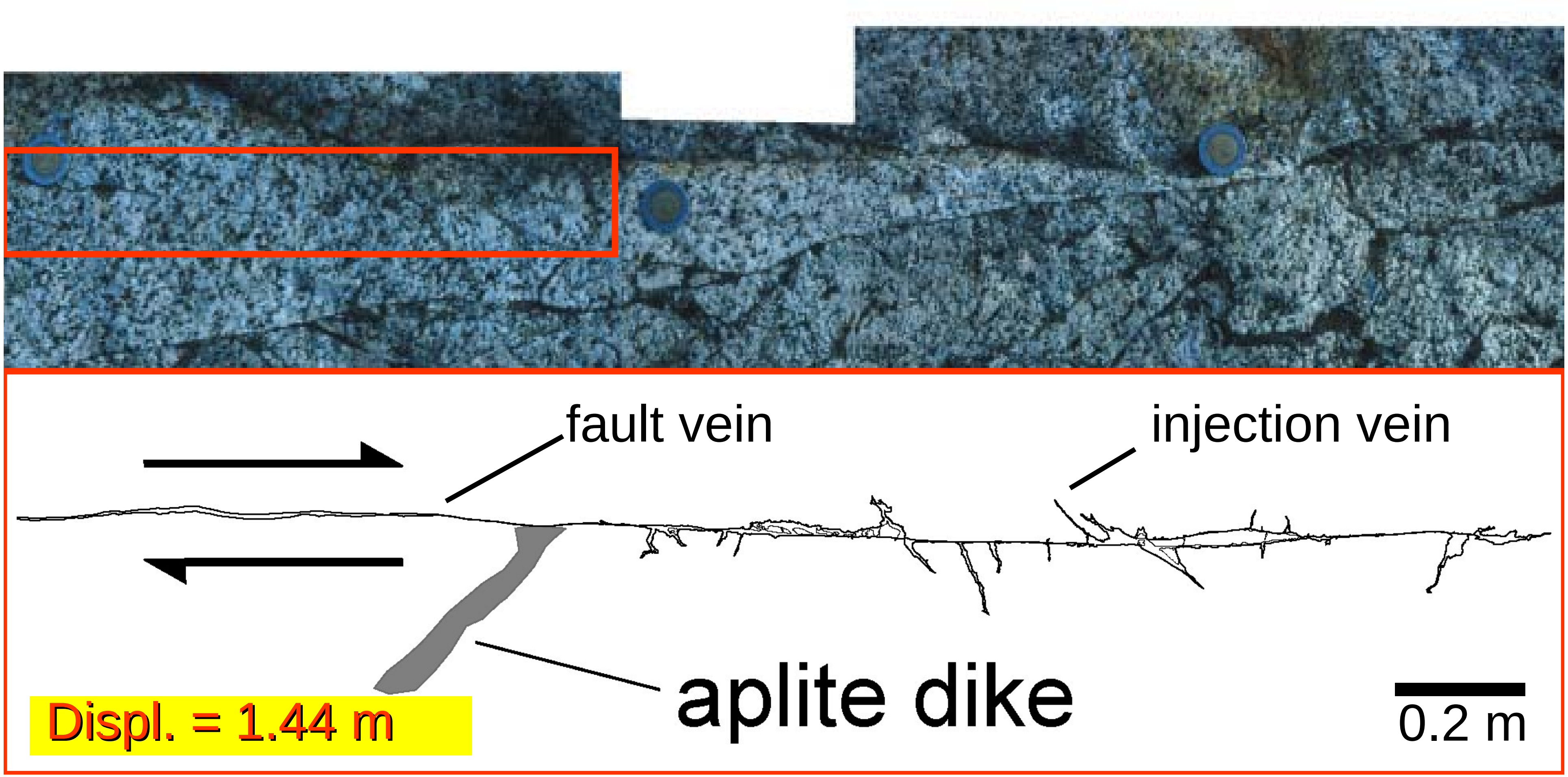



Sample 23-00
Pseudotachylyte
Cataclasite
Tonalite
0
cm
4

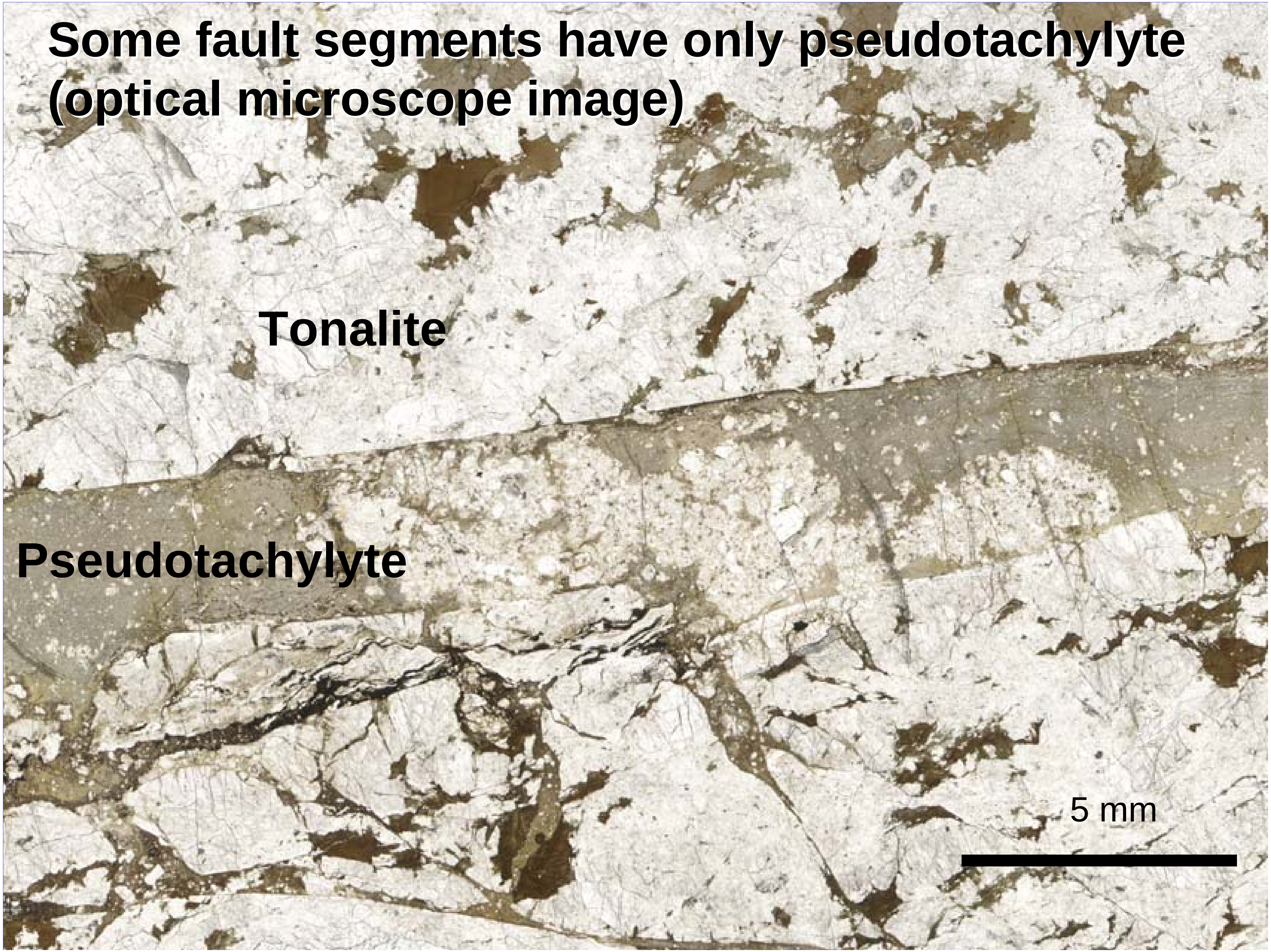


Pseudotachylyte
Cataclasite
Tonalite
Pseudotachylyte
200 μm
Cataclasite
200 μm

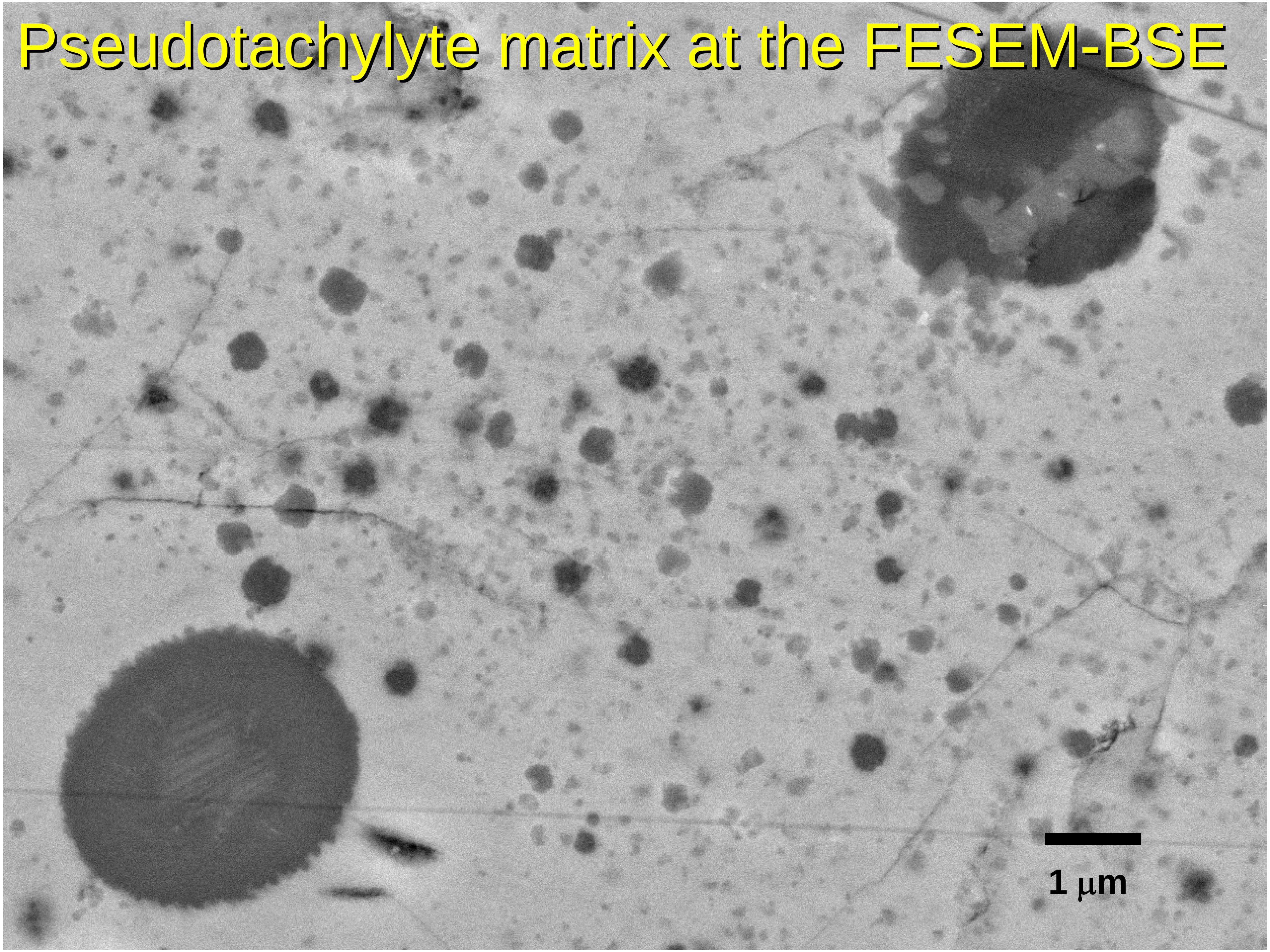
# Some fault segments have only pseudotachylyte



# Some fault segments have only pseudotachylyte (optical microscope image)



# Pseudotachylyte matrix at the FESEM-BSE



The Adamello outcrops are a window over a 10 km depth seismogenic source.

Some faults segments of the GLF have only one continuous layer of PST.

EQs produced up to 1.44 m of slip 30 Ma ago. This slip corresponds to a ~ M6-7 EQ.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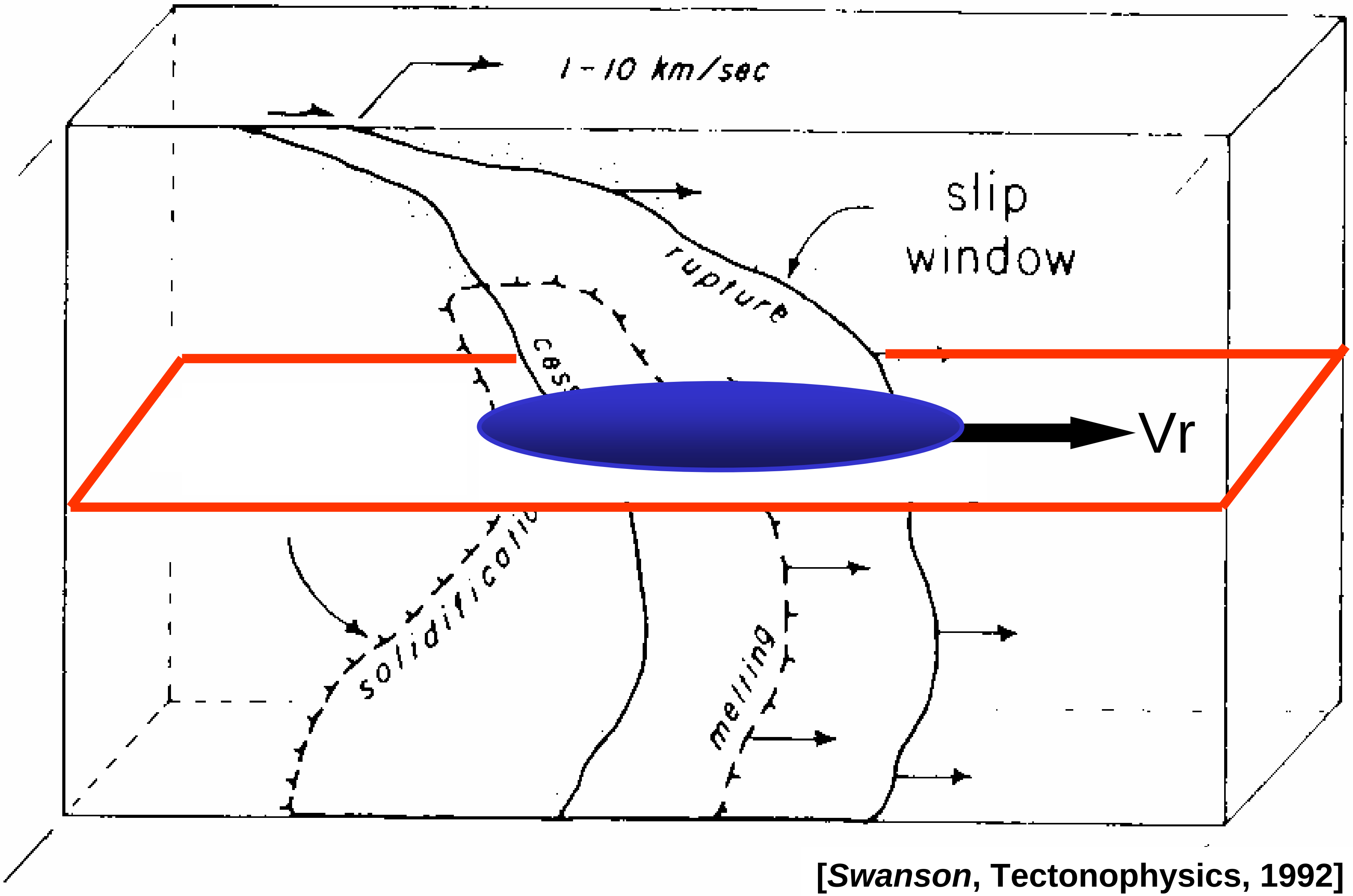
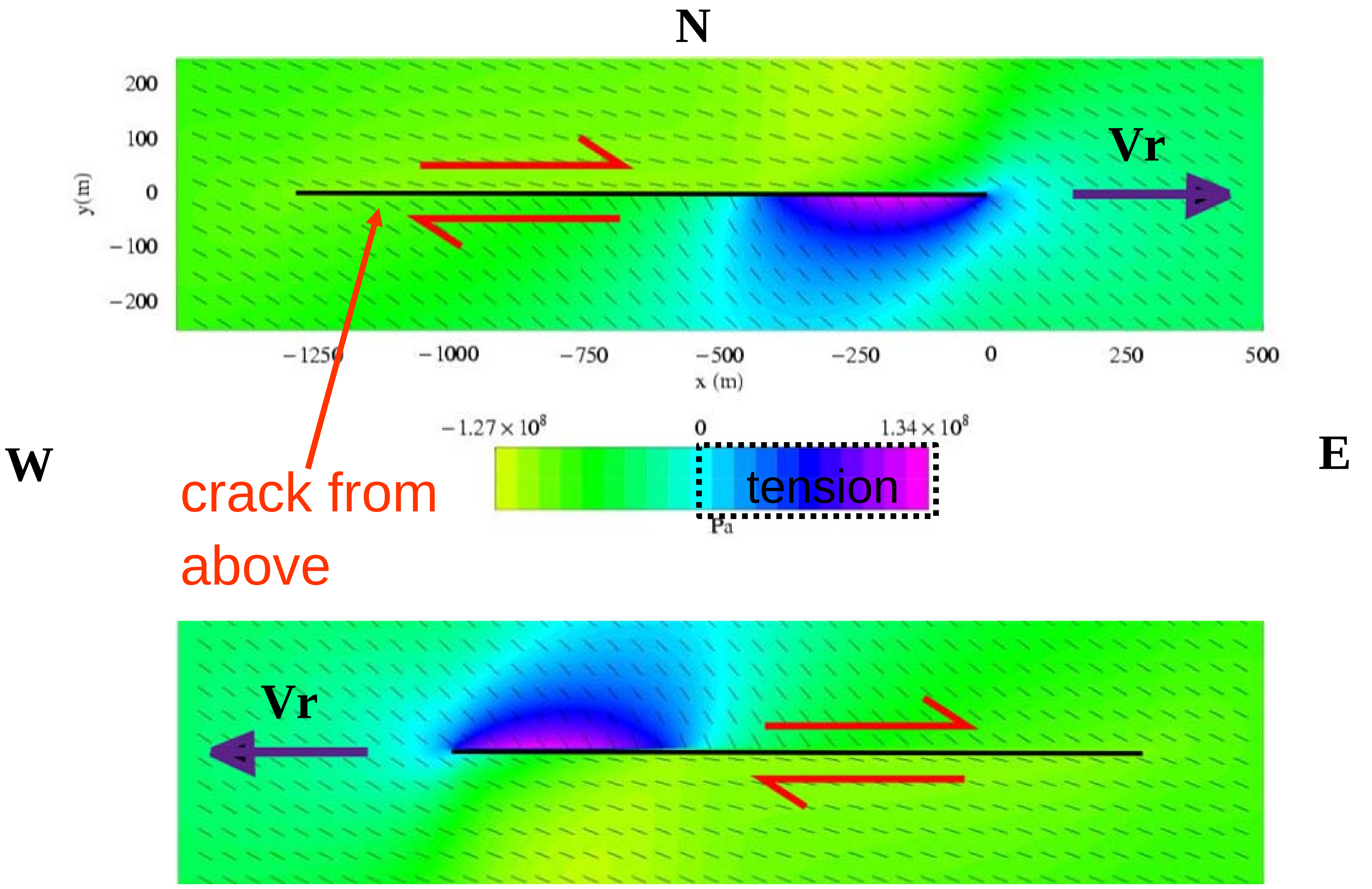
# Do PT record EQ dynamics?




[*Swanson*, Tectonophysics, 1992]

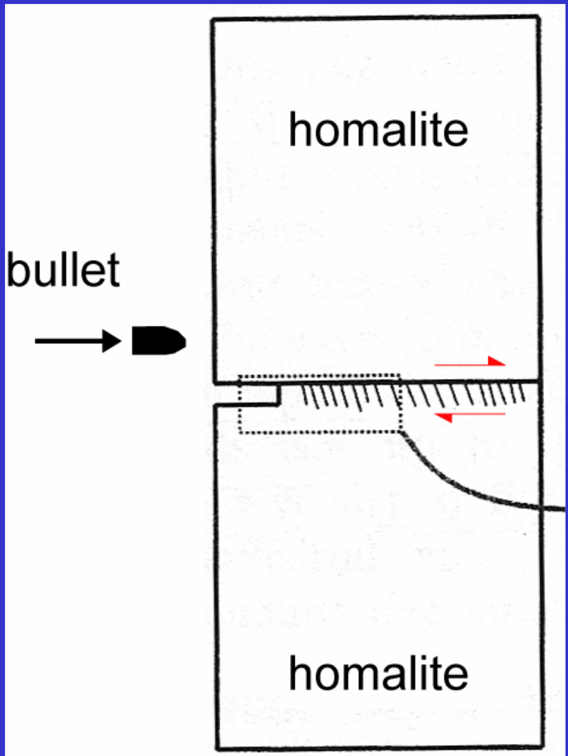
# Stress field around a propagating crack (theory)



# Experiments

# Nature



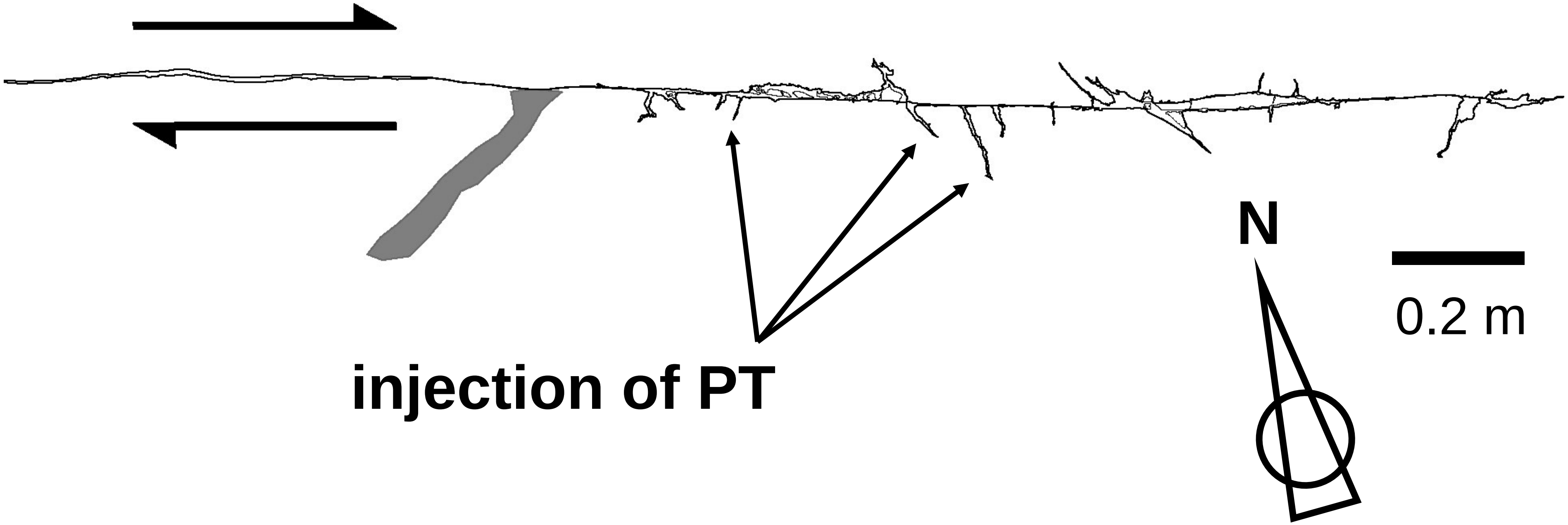



Very similar features, produced by shooting:

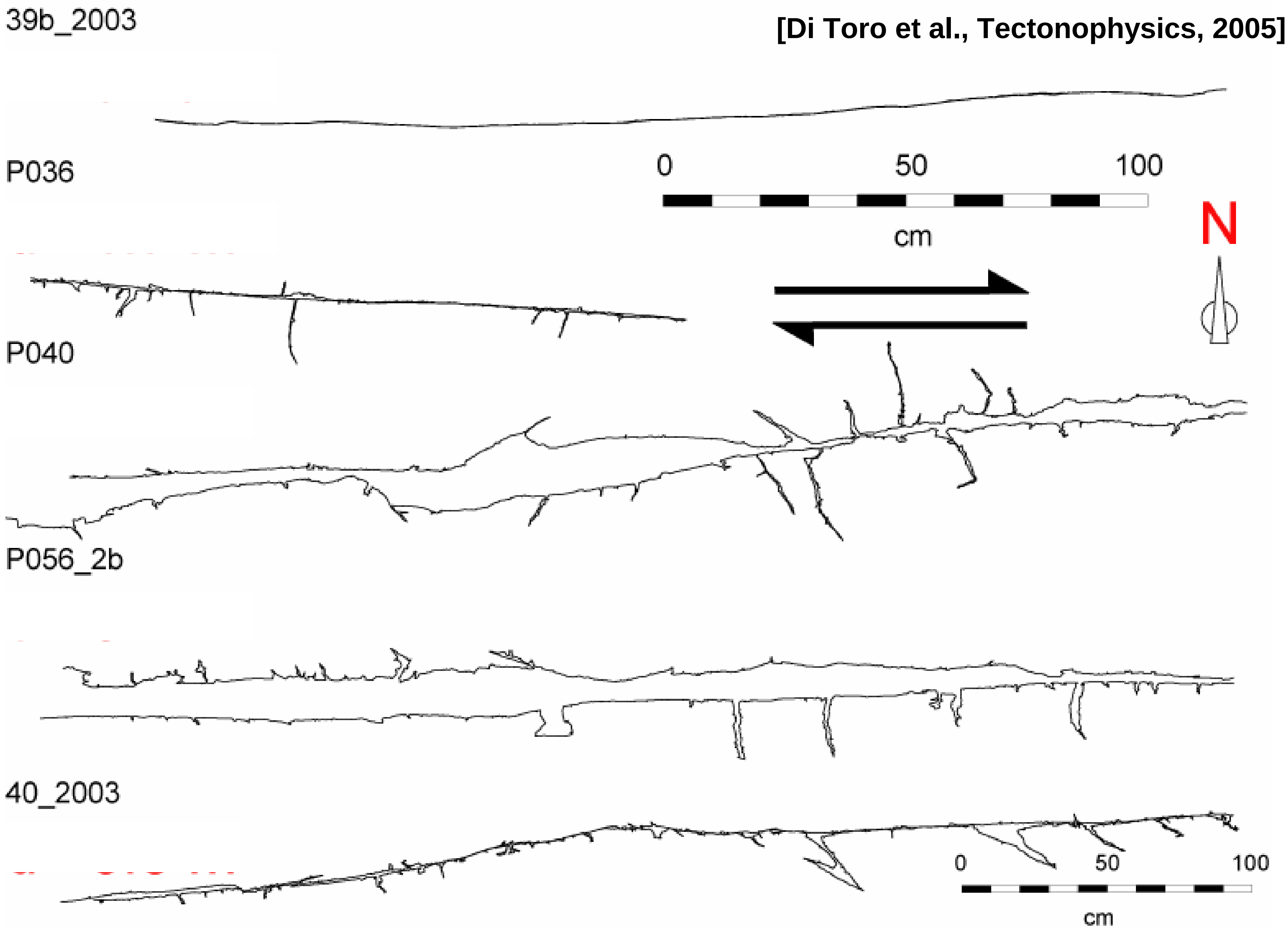
- **EQs** in the Gole Larghe Fault 30.000.000 yrs ago.

- **Bullets** in the lab 7 yrs ago.

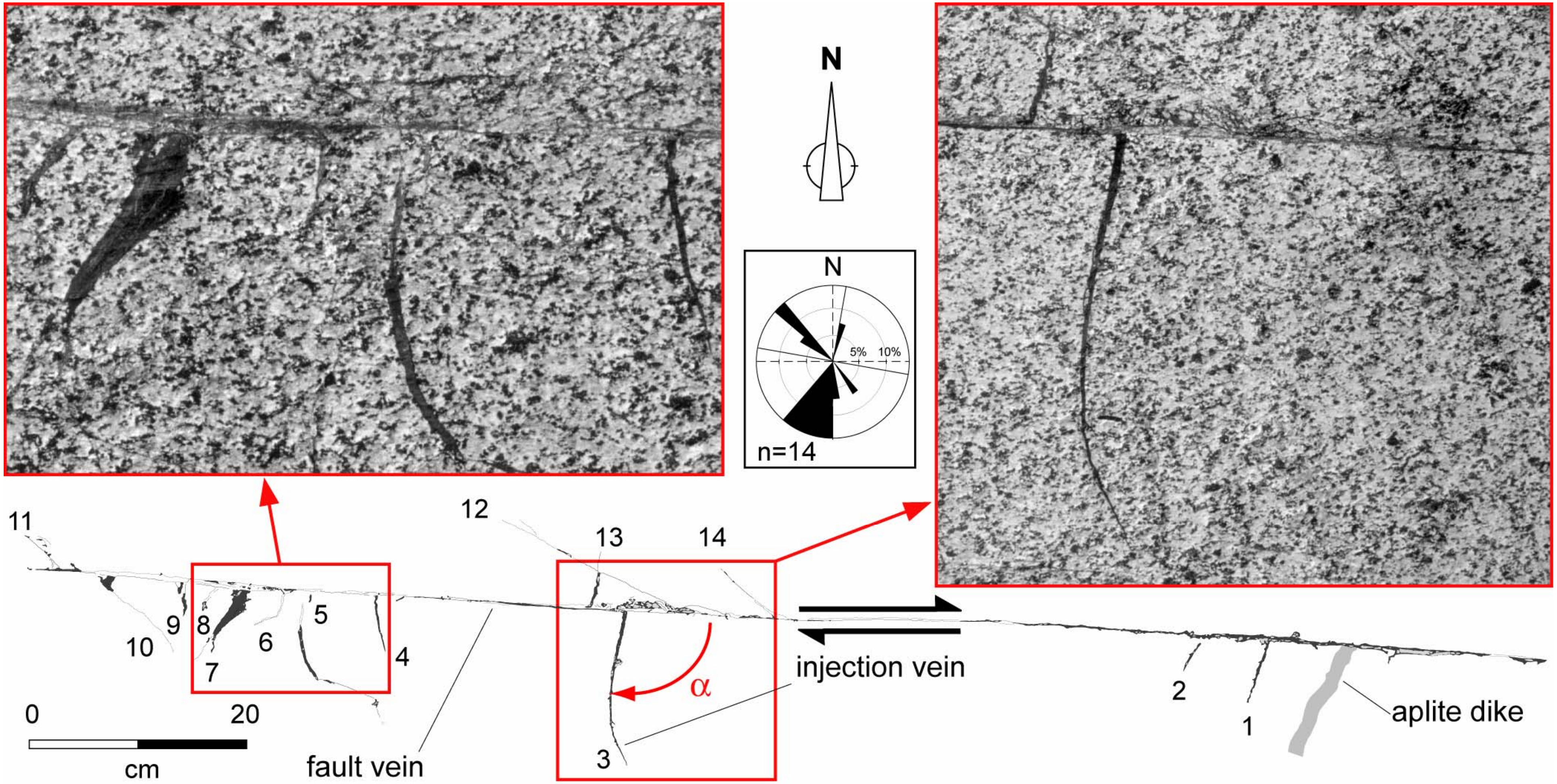
Most fractures (coseismic) injected by melt are **towards the south**.



# This seems a general rule in this fault zone.



# We measured the angle $\alpha$ of PT-bearing fractures with respect of the major faults.

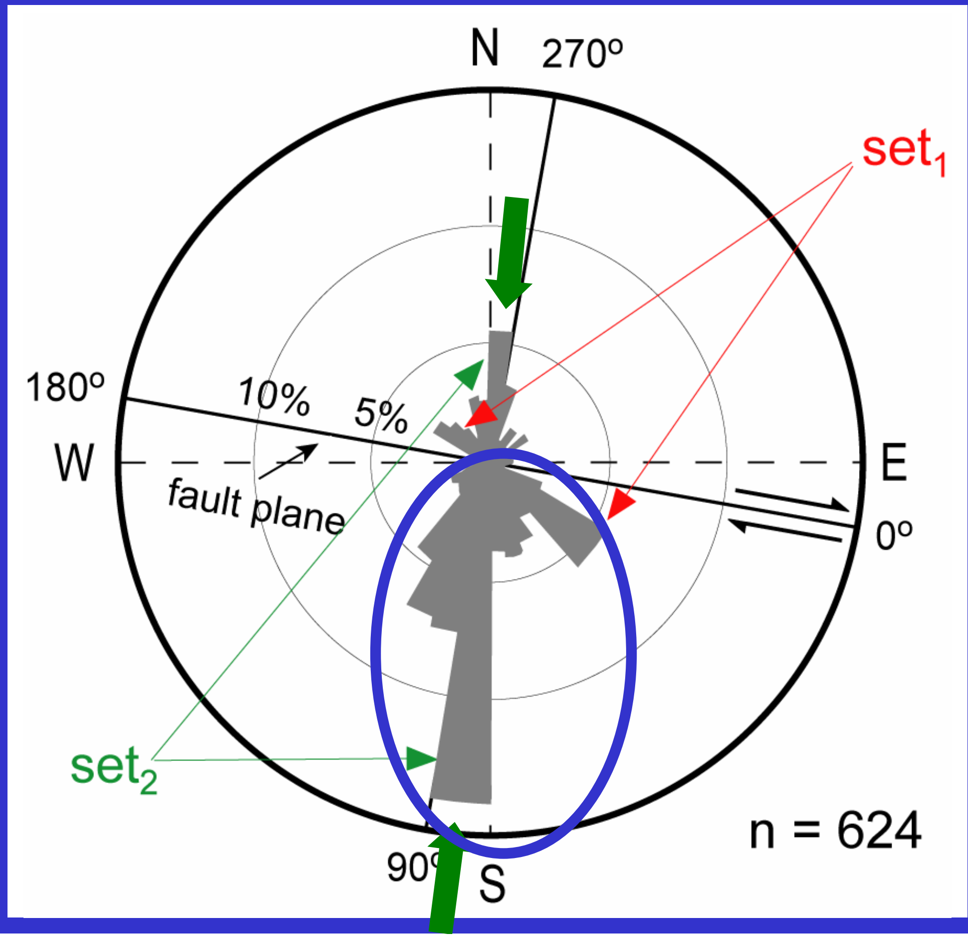



Di Toro et al., Nature 2005

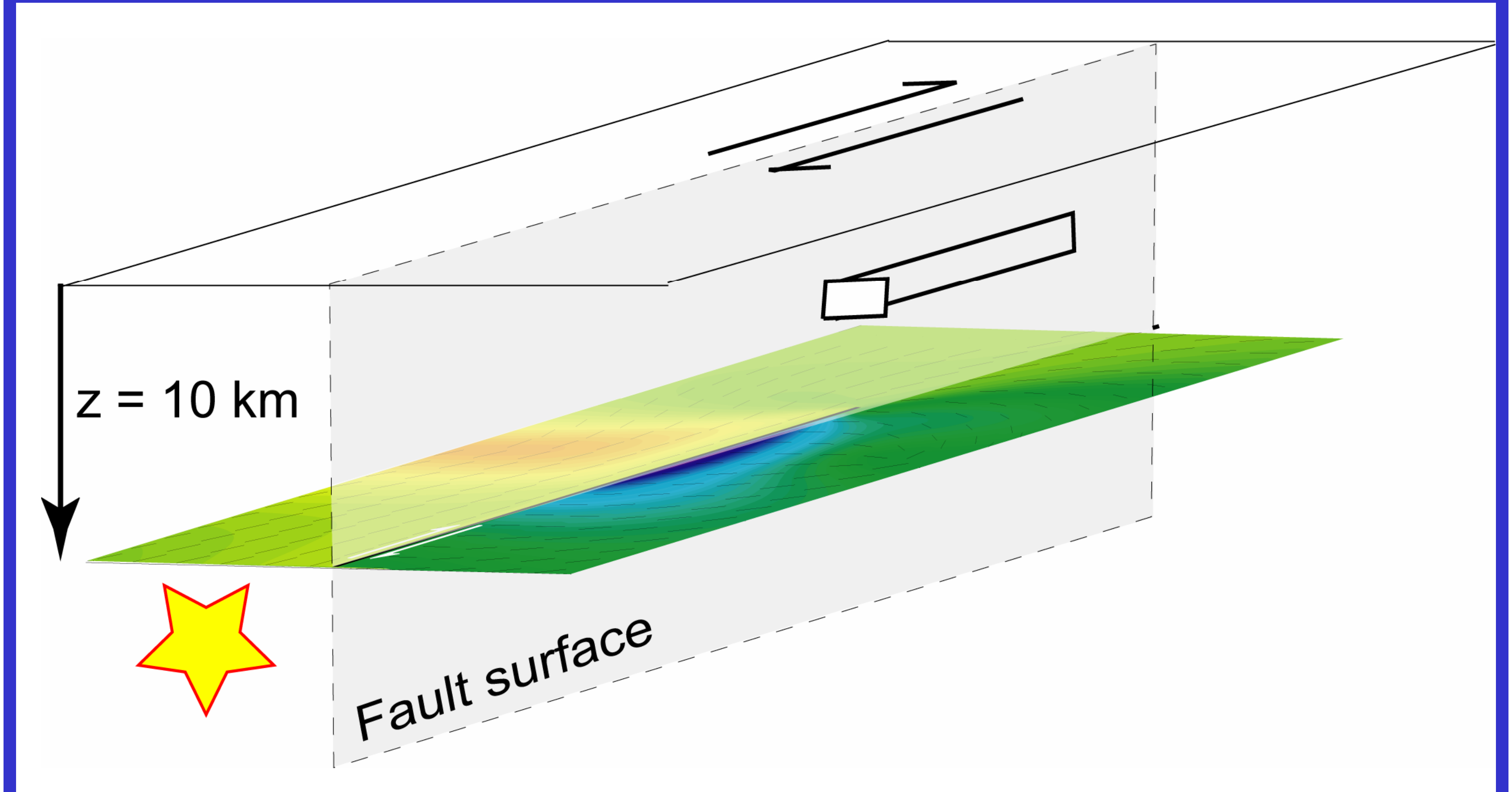
Of 624 PT-filled fractures (29 faults), most are striking:

1) at $90^o$-$270^o$

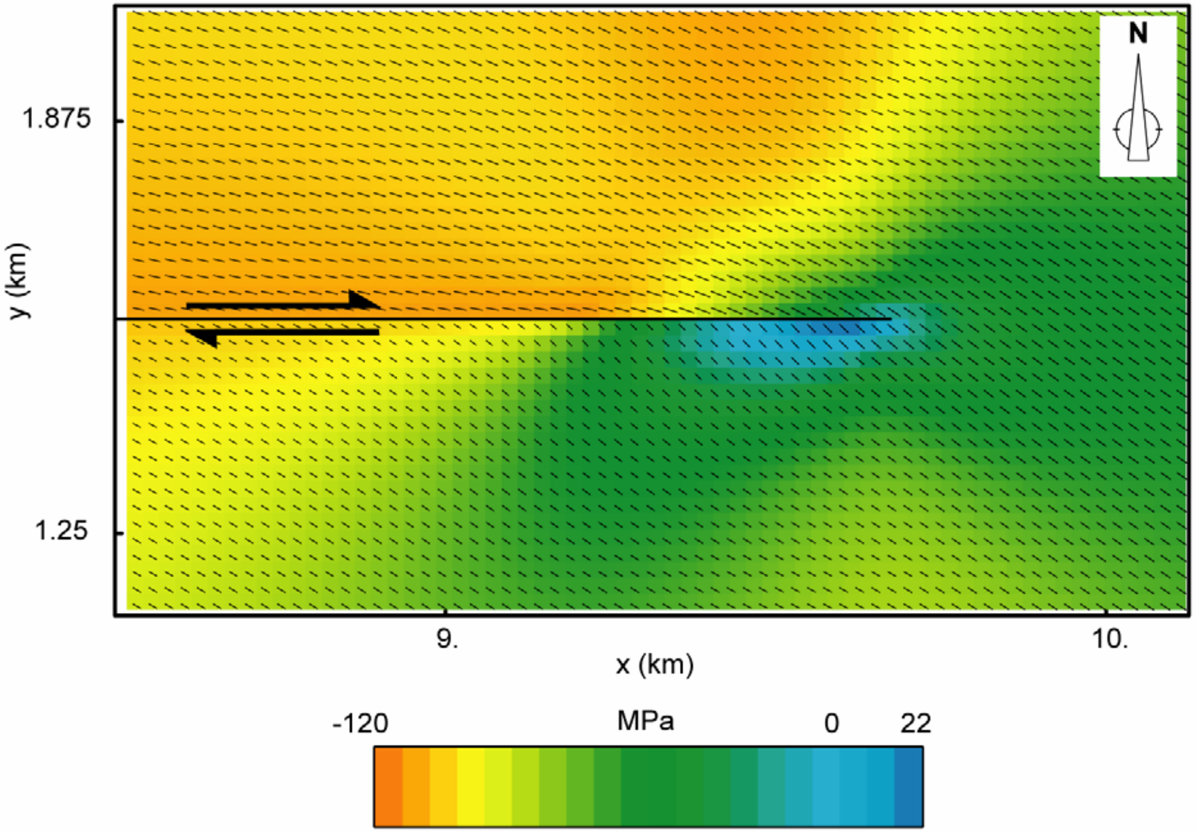
2) towards the **SOUTH** wall rock



We simulated the **dynamical stress field** on a horizontal plane at 10 km depth during rupture propagation for the Gole Larghe Fault EQs.



# Numerical model mechanical parameters




DATA USED IN THE NUMERICAL MODEL

1. GOLE LARGHE FAULT PROPERTIES:

| | |
|---|---|
| Fault length | 10 km |
| Fault depth | 10 km |
| Vertical Stress | 260 MPa |
| Pore pressure | 100 MPa |
| Effective stress normal to the fault | 112 MPa |
| Maximum effective horizontal stress | 256 MPa |
| Minimum effective horizontal stress | 64 MPa |
| Coefficient of friction at rupture | 0.7 |
| Coseismic slip | 1.0 m |

2. GEOMECHANICAL PROPERTIES FOR TONALITE

| | |
|---|---|
| Tonalite density | 2700 kg $m^{-3}$ |
| Fracture toughness | 2 MPa $m^{1/2}$ |
| Shear Modulus | 26 GPa |
| Bulk modulus | 47 GPa |
| Young moduls for tonalite | 60 GPa |
| Poisson's ratio | 0.2 |
| Ultim. compressive strength (unconf.) | 150 MPa |
| Ultimate tensile strength | 15 MPa |
| Ultmate shear strength | 30 MPa |
| Mode II rupture velocity | 4 km $s^{-1}$ |

# Slip pulse model

steady state

slip-weakening

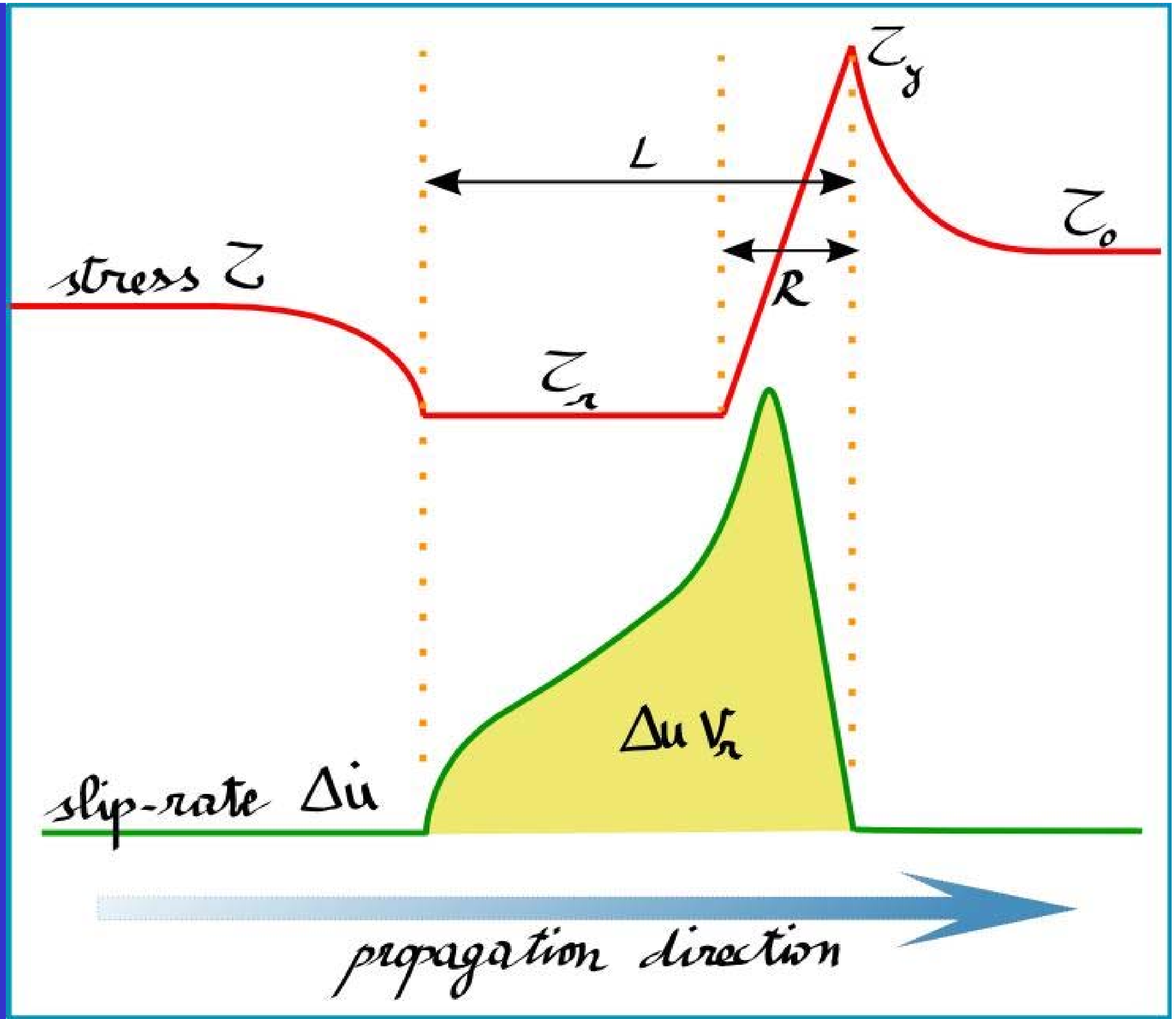
self-healing pulse

$\tau_y$ peak stress

$\tau_r$ residual stress

$R$ cohesion zone length

$L$ slipping zone length




For $V_r < V_{Ral}$ analytical solution (Rice et al., 2005)

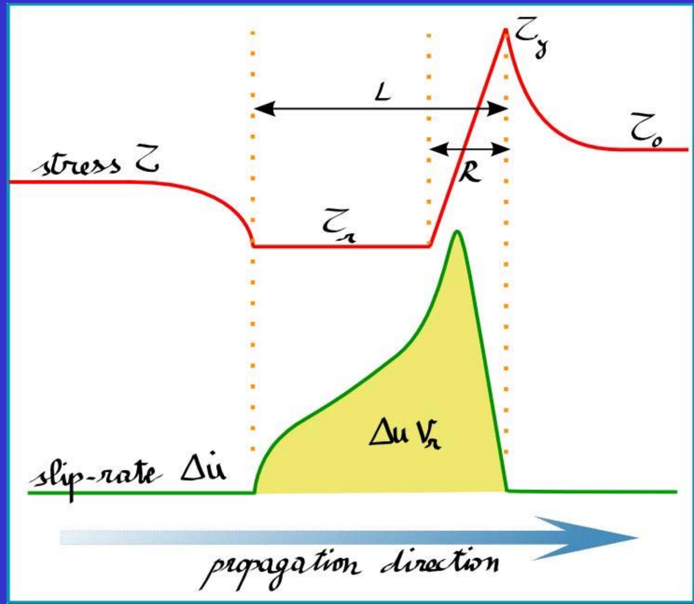
For $V_r > V_{Ral}$ numerical solution

# Elastodynamics gives constraints

$$G = \delta(\tau_0 - \tau_r)$$

$$G = \frac{(\tau_y - \tau_r)^2}{\mu} Rh\left(\frac{R}{L}\right) F(V_r)$$

$$\frac{\tau_0 - \tau_r}{\tau_y - \tau_r} = g\left(\frac{R}{L}\right)$$




| | |
|---|---|
| $G$ | fracture energy |
| $\delta$ | displacement |
| $\mu$ | shear modulus |
| $g, h, F$ | functions |
| $R$ | cohesion zone length |
| $L$ | crack length |

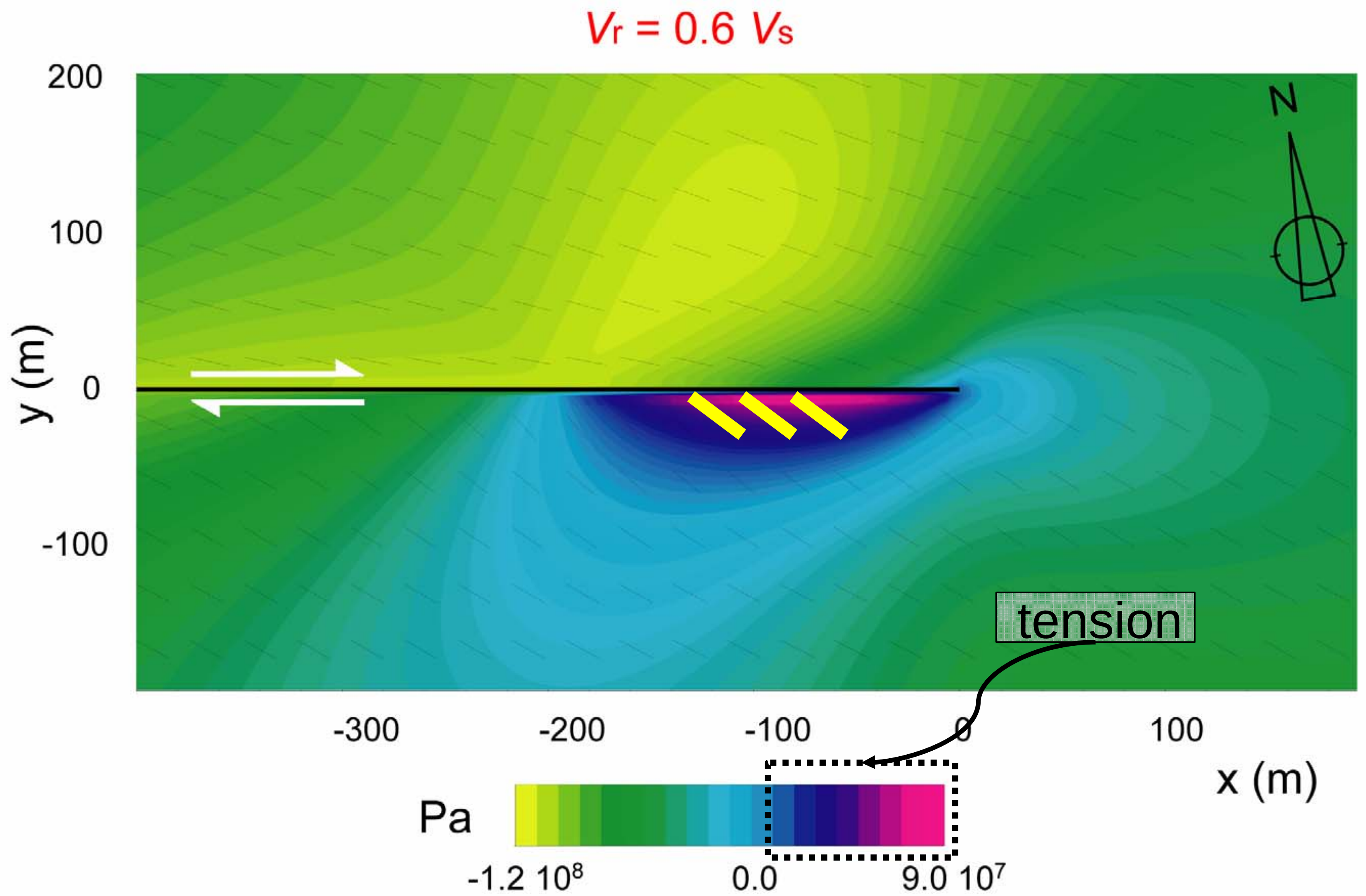
unknown: $\tau_r$, $R$, $L$, $V_r$, $G$

known: $\tau_y$, $\tau_0$, $\mu$, $\delta$

constraints: **Direction of coseismic, tension fractures**

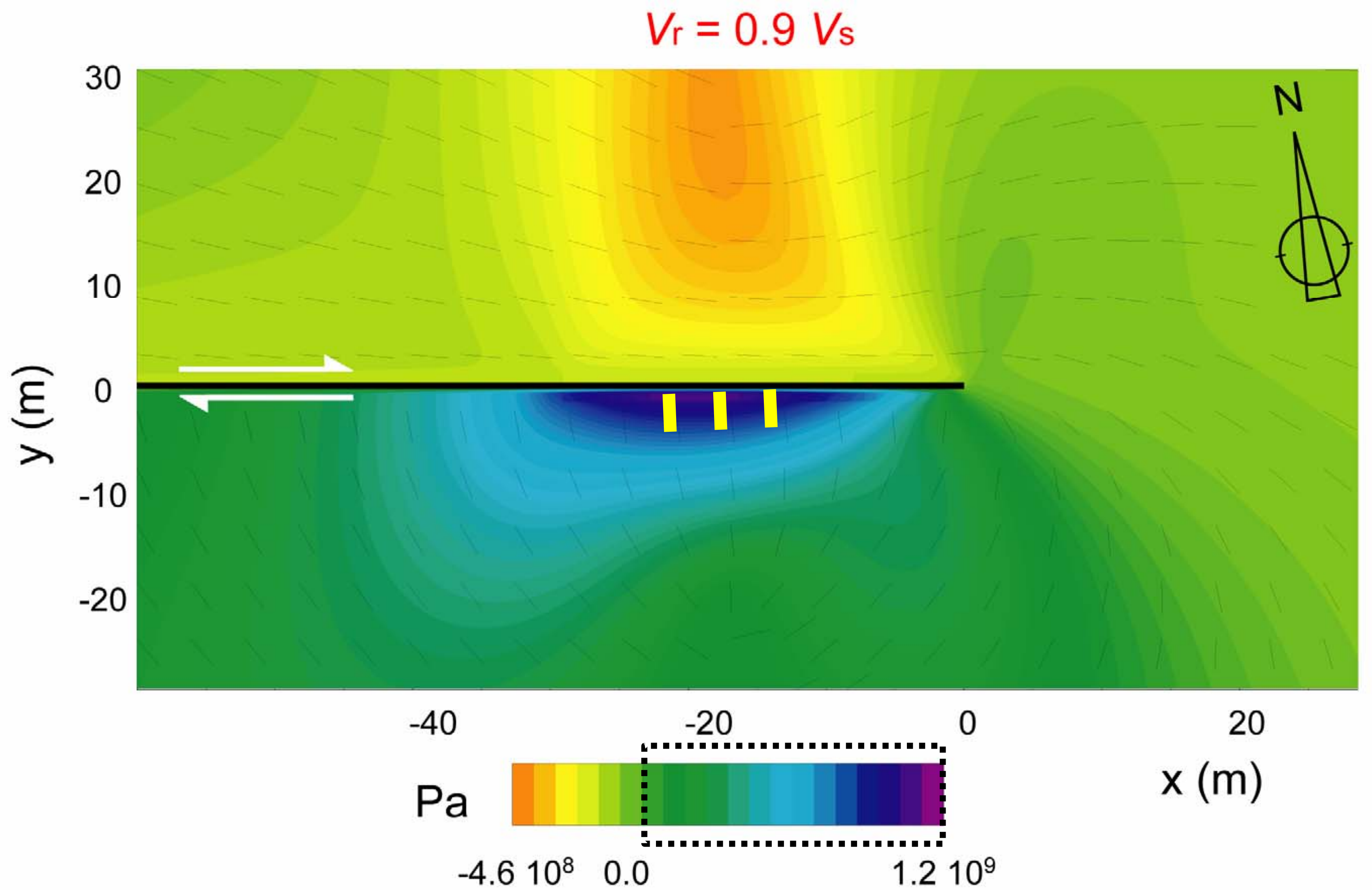
**Minimum level of absolute tension**

# Rupture velocity ***Vr = 0.6 Vs*** (shear wave velocity)



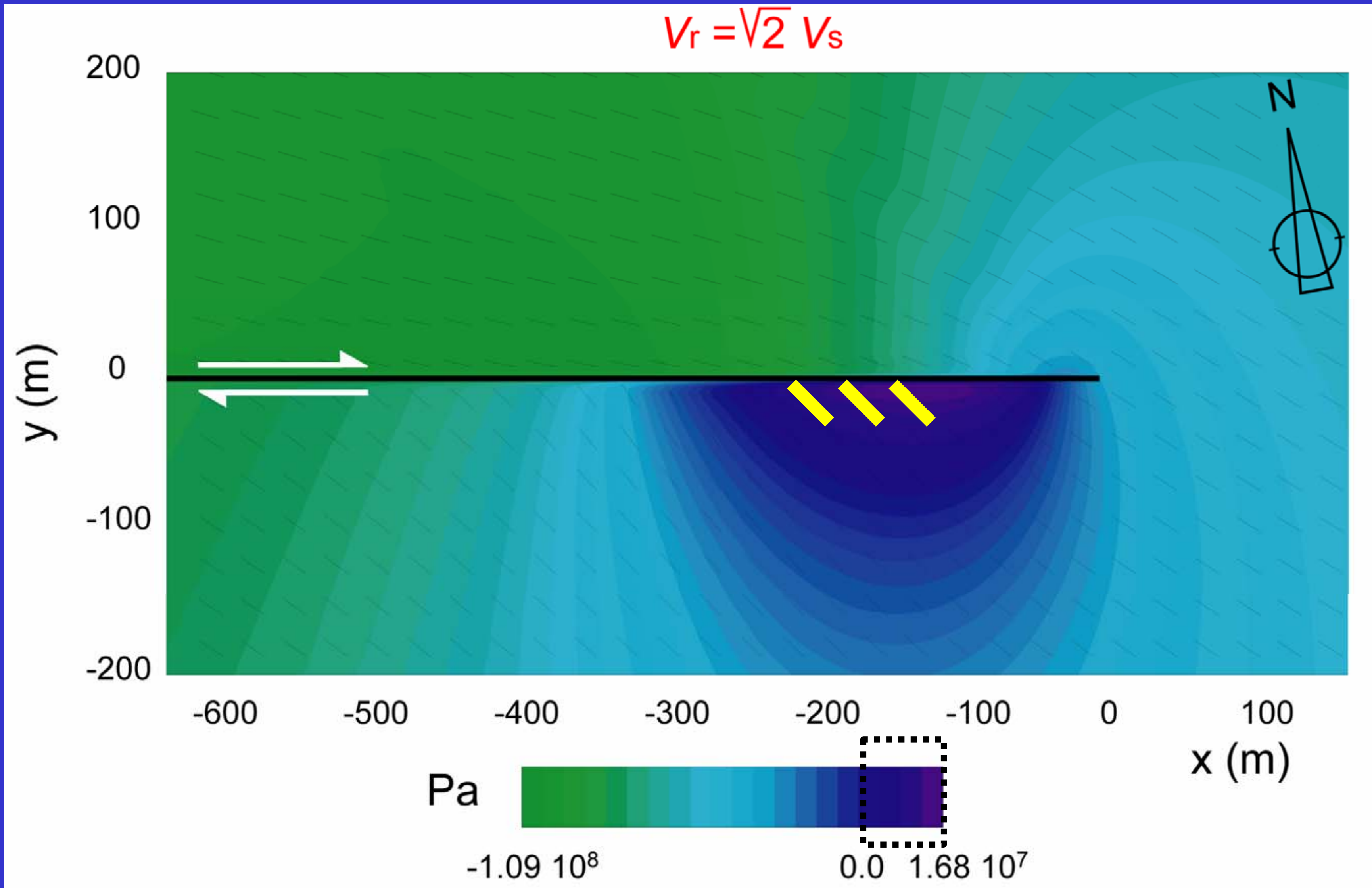

color = stress magnitude (purple=tension; yellow=compression)
thin segments = planes of maximum tension

# Rupture velocity ***Vr* = 0.9 *Vs*** (shear wave velocity)




color = stress magn. (violet = tension; orange= compression)
thin segments = planes of maximum tension

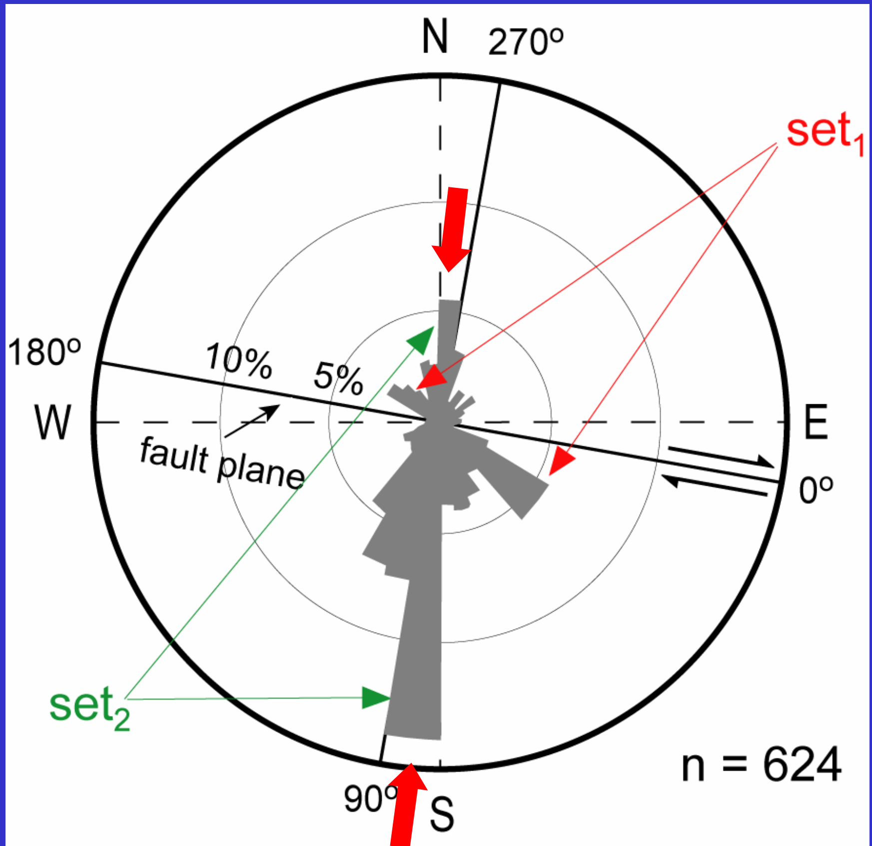
# Rupture velocity **Vr = 1.41 Vs** (shear wave velocity)

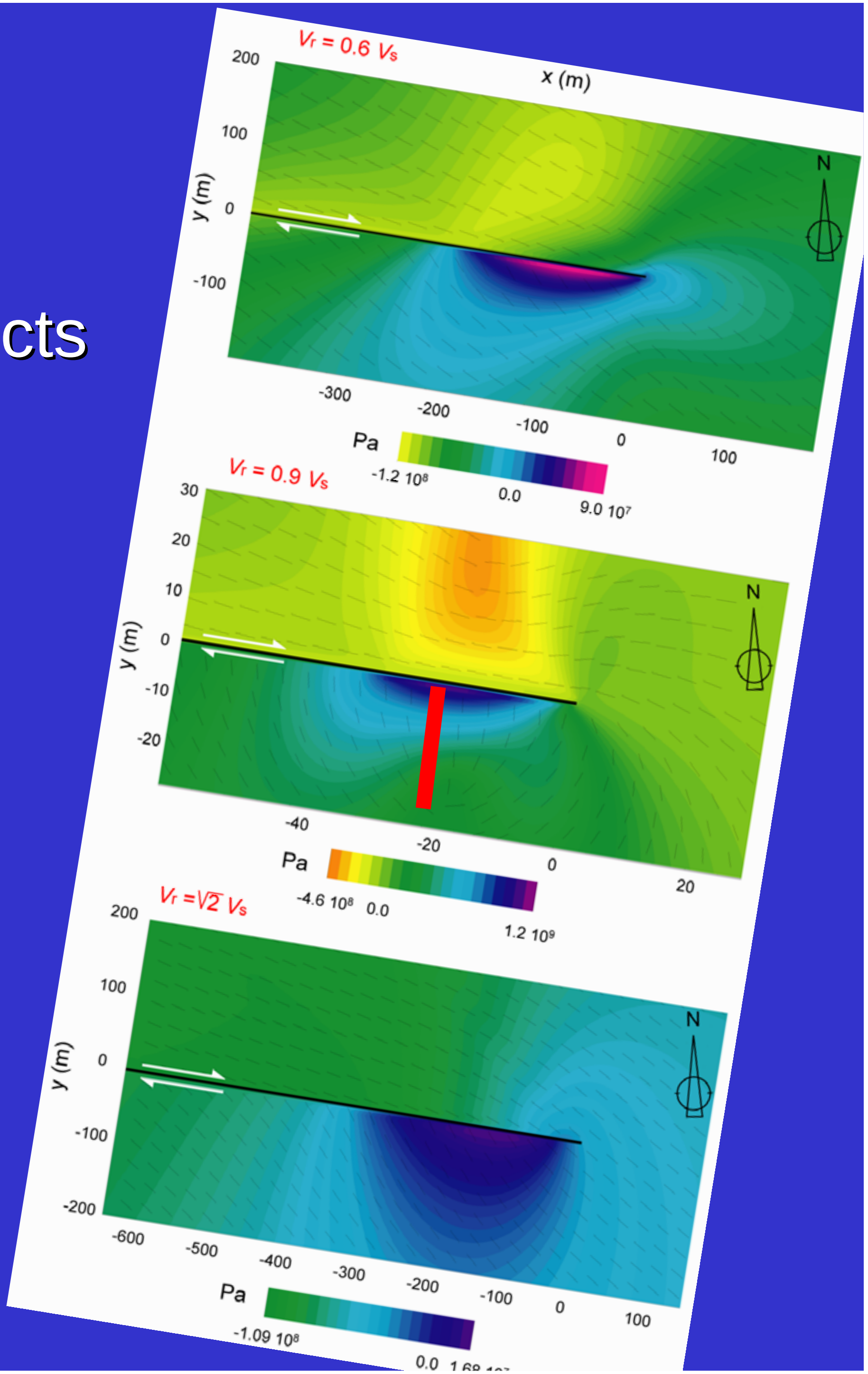



color = stress magn. (purple = tension; green = compression)
thin segments = planes of maximum tension

1) N/S asymmetry reflects **directivity** (rocks are weaker under tension)

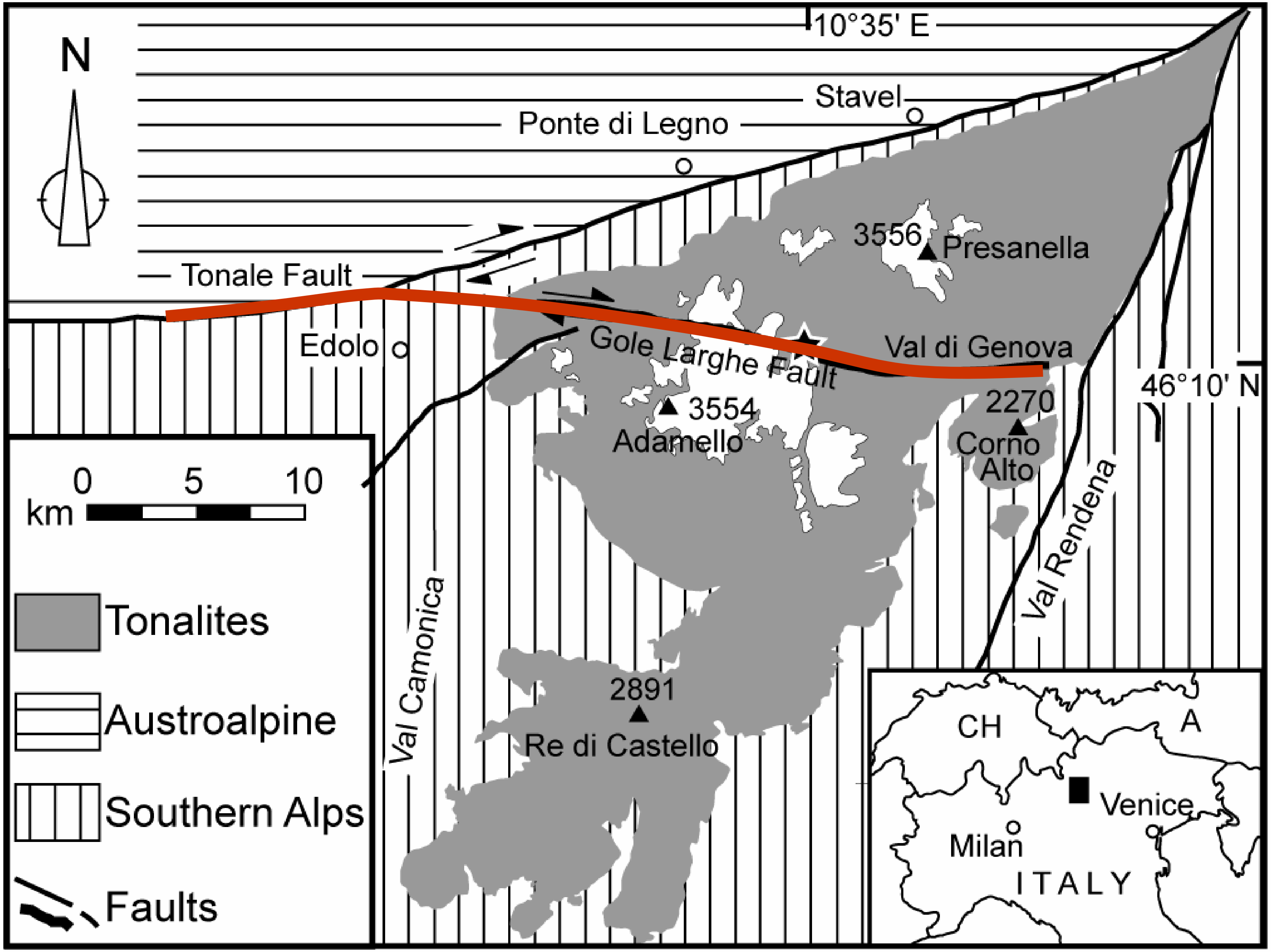
2) Tens. **crack direction** reflects rupture velocity Vr ~ 0.9 Vs




Di Toro et al., Nature 2005

# Earthquakes propagated from West toward the East



# Conclusion

Rupture dynamics is frozen in ancient exhumed pseudotachylyte-bearing faults.

The ancient EQs propagated from the West to the East, probably at $V_r \sim 0.9\ V_s$.