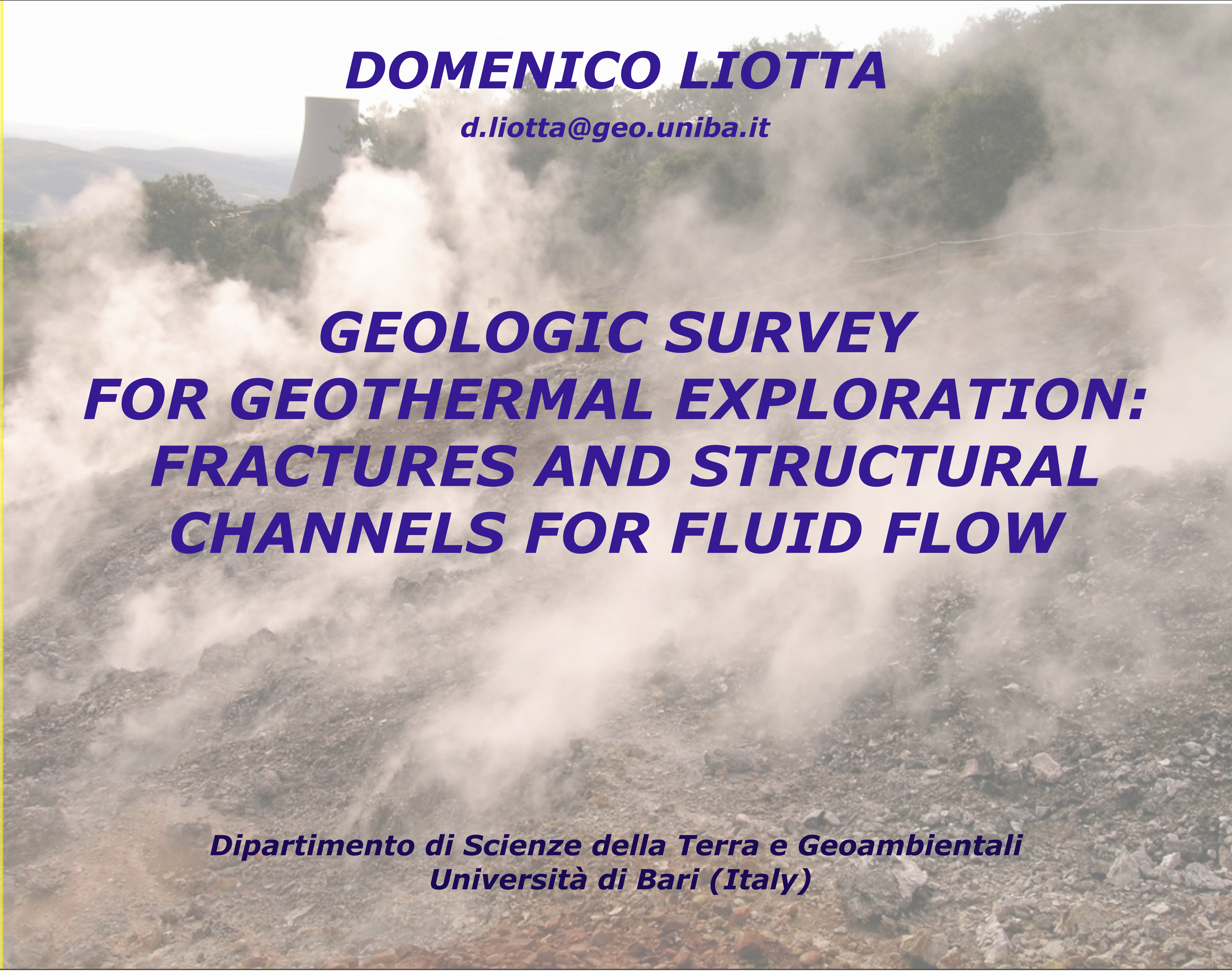


DOMENICO LIOTTA

d.liotta@geo.uniba.it

GEOLOGIC SURVEY FOR GEOTHERMAL EXPLORATION: FRACTURES AND STRUCTURAL CHANNELS FOR FLUID FLOW

Dipartimento di Scienze della Terra e Geoambientali
Università di Bari (Italy)

FIELD GEOLOGY

methodology

integration of data

1

GEOLOGIC SURVEY FOR GEOTHERMAL EXPLORATION: FRACTURES AND STRUCTURAL CHANNELS FOR FLUID FLOW

2

THE CONTRIBUTE OF REGIONAL GEOLOGY: FOSSIL VS. ACTIVE GEOTHERMAL SYSTEMS IN SOUTHERN TUSCANY

conceptual model on the relationships between geothermal resources and geological structures

HOW CHOOSING A GEOTHERMAL AREA TO BE INVESTIGATED ?

which is the most favorable tectonic setting and why?

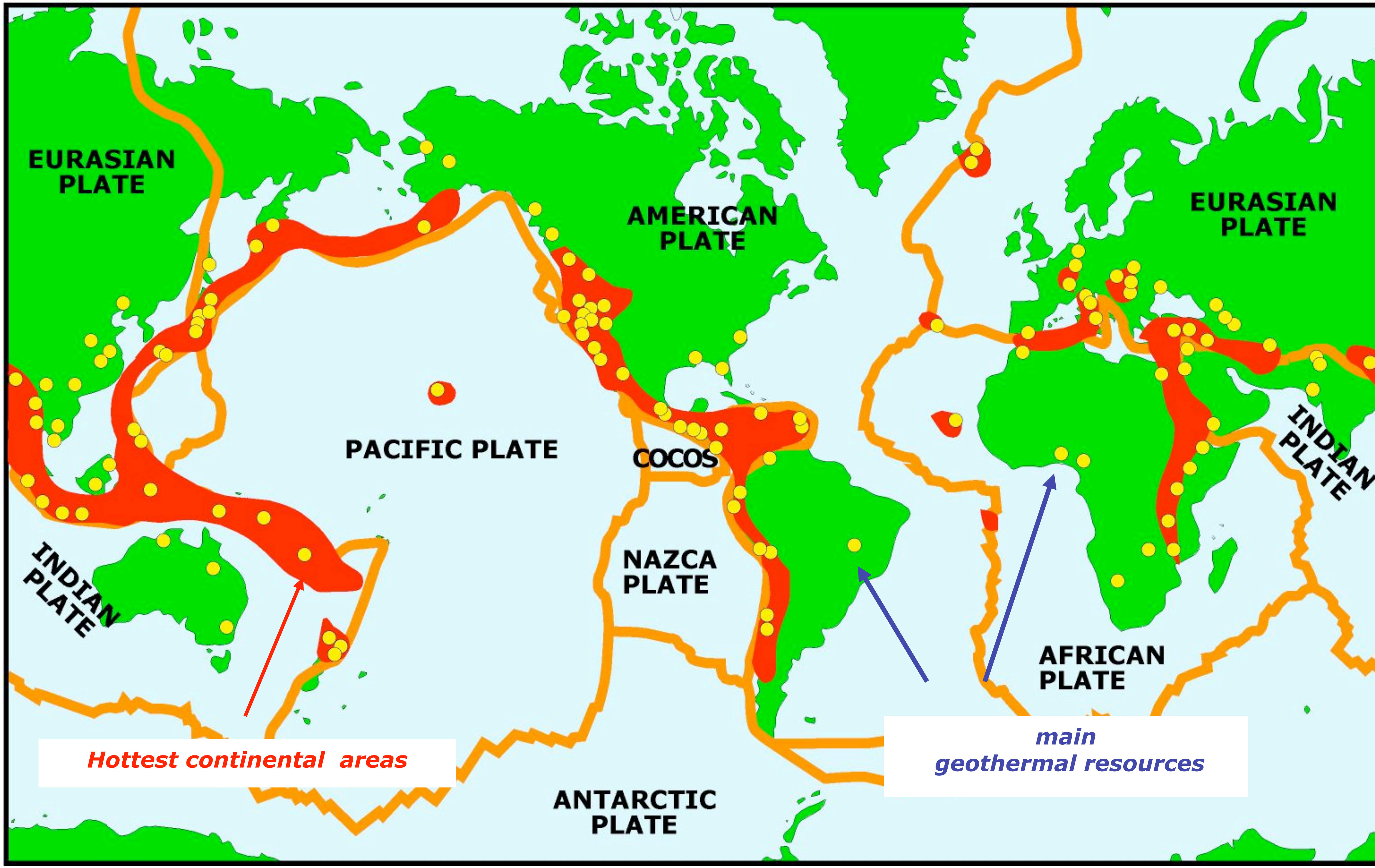
how to identify the field area?

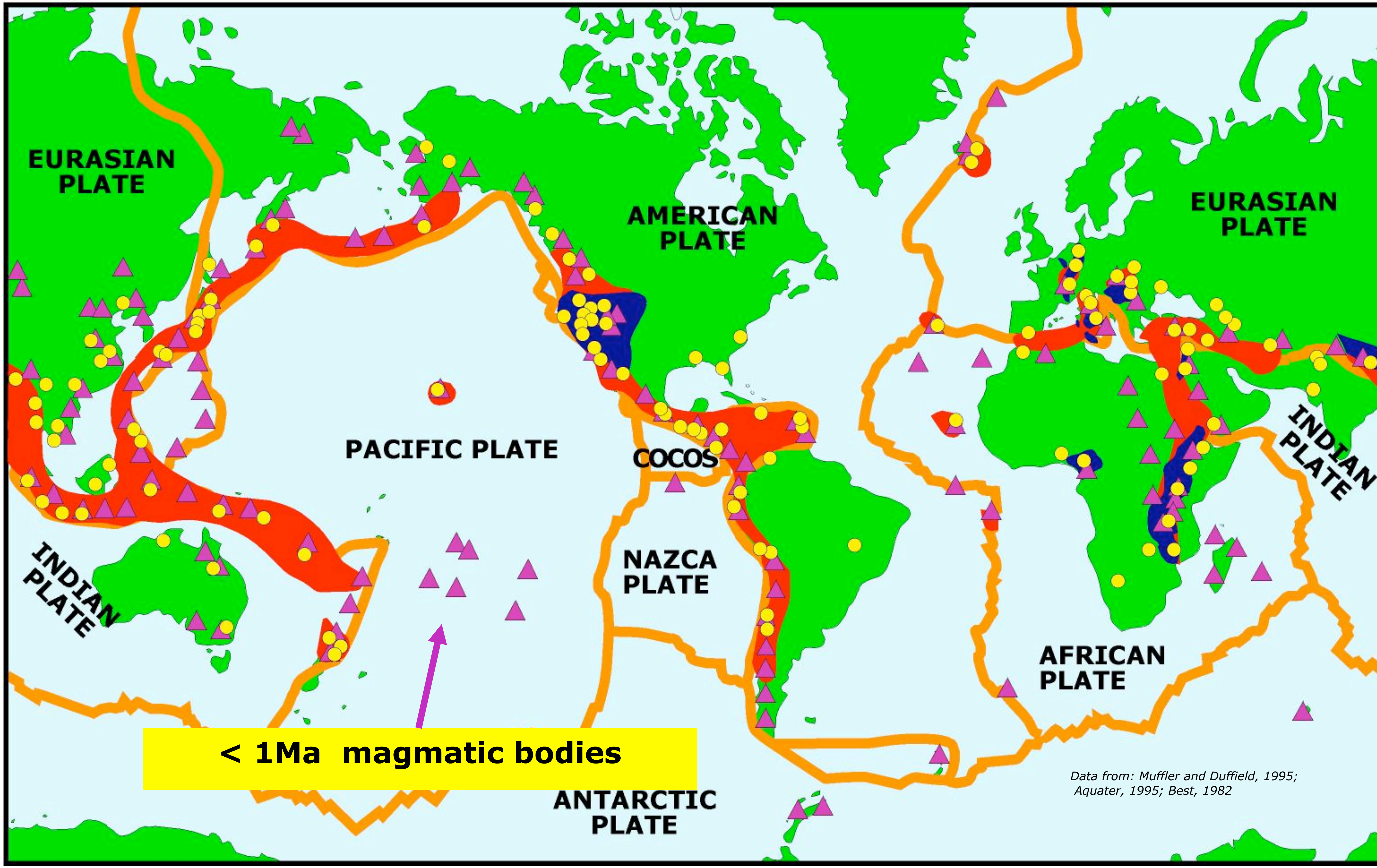
which structures to be studied and how?

INDEX

- generalities: favorable tectonic environments
  - fluids and fractures
- structural geology: faults
  - kinematic indicators
  - associated fractures
  - relationships with the fluid flow
  - parameters

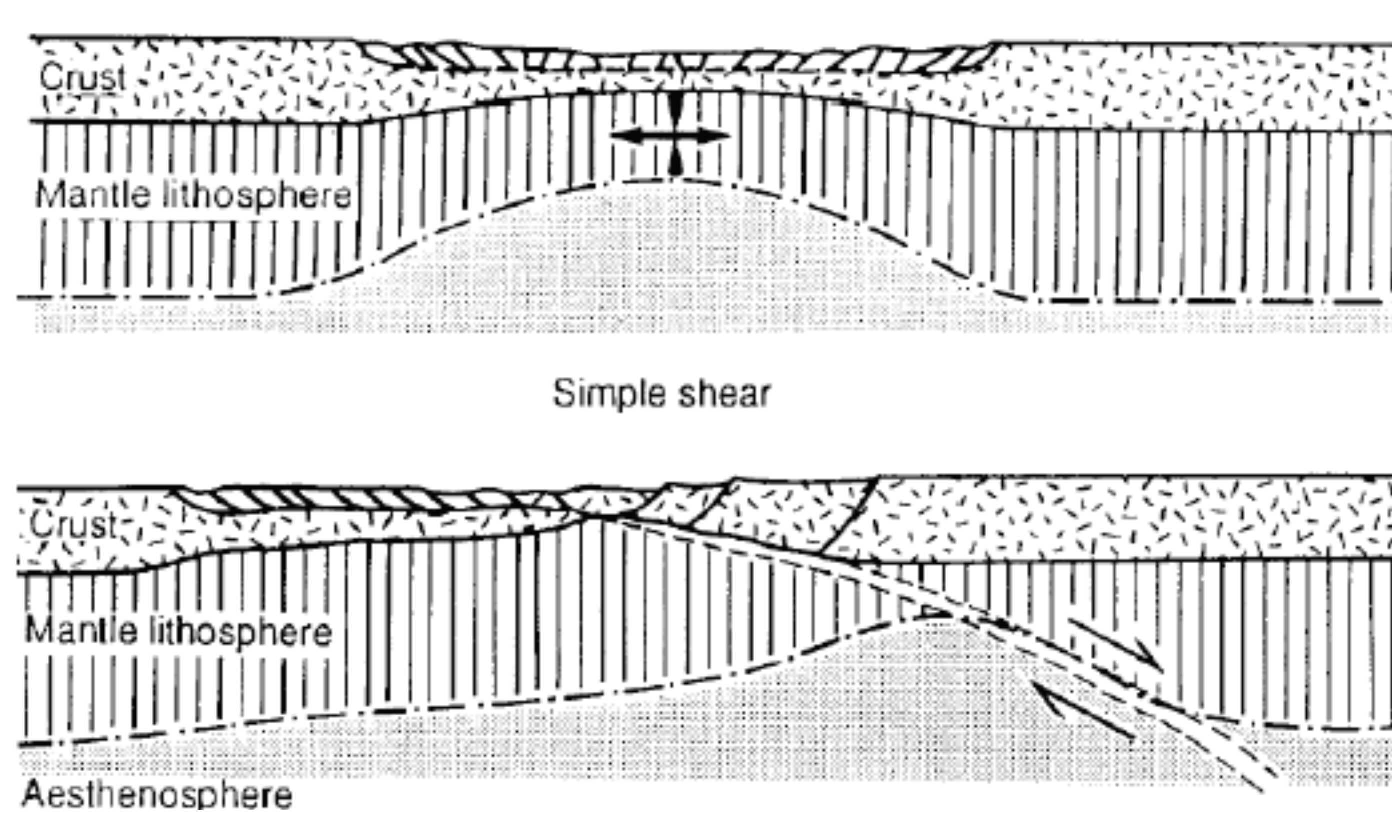
A geothermal area needs heat flow > ≈45-50 mW/m²



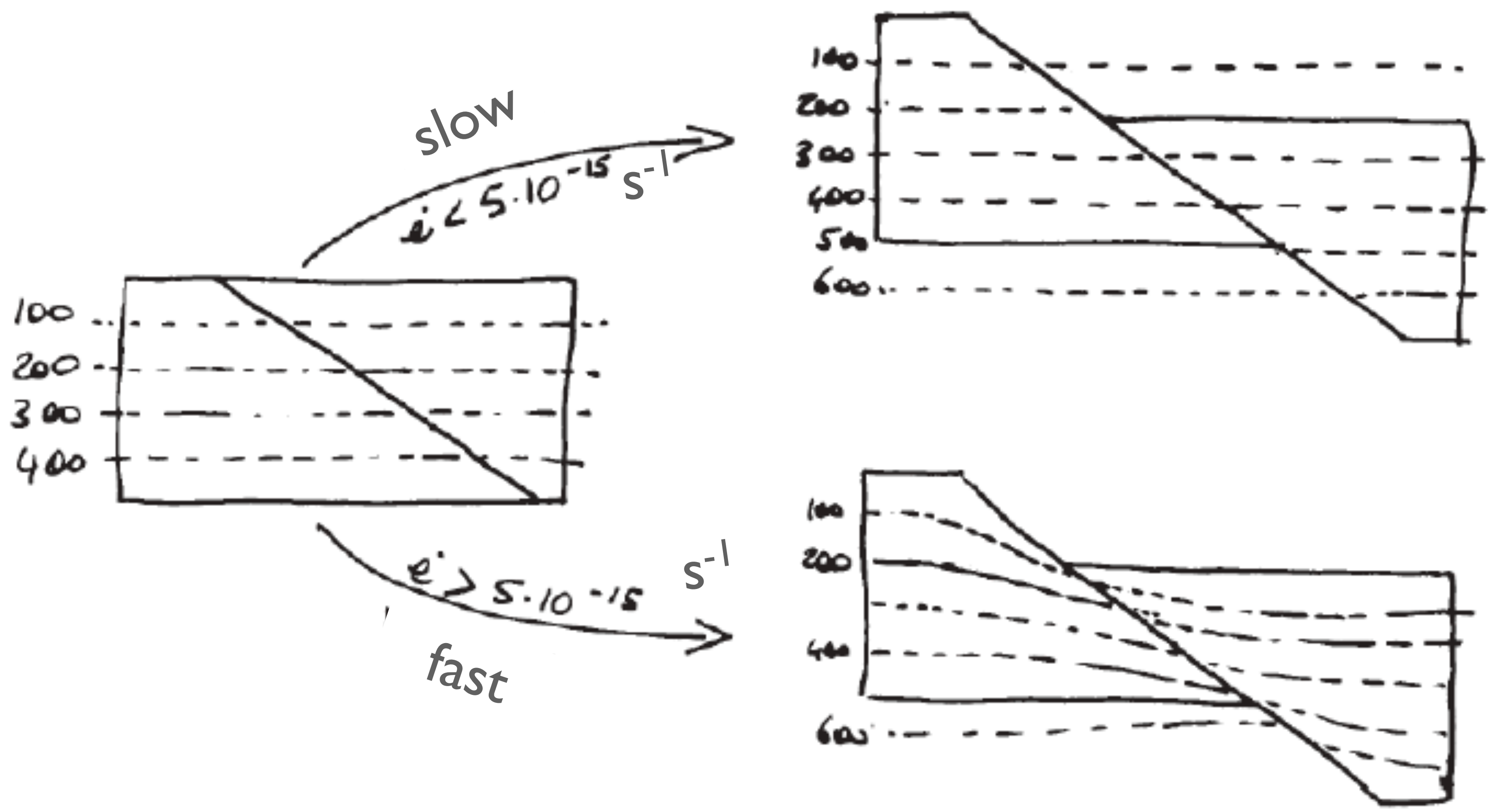

EURASIAN PLATE
AMERICAN PLATE
EURASIAN PLATE
PACIFIC PLATE
COCOS
INDIAN PLATE
INDIAN PLATE
NAZCA PLATE
AFRICAN PLATE
ANTARCTIC PLATE
< 1Ma magmatic bodies
Data from: Muffler and Duffield, 1995; Aquater, 1995; Best, 1982

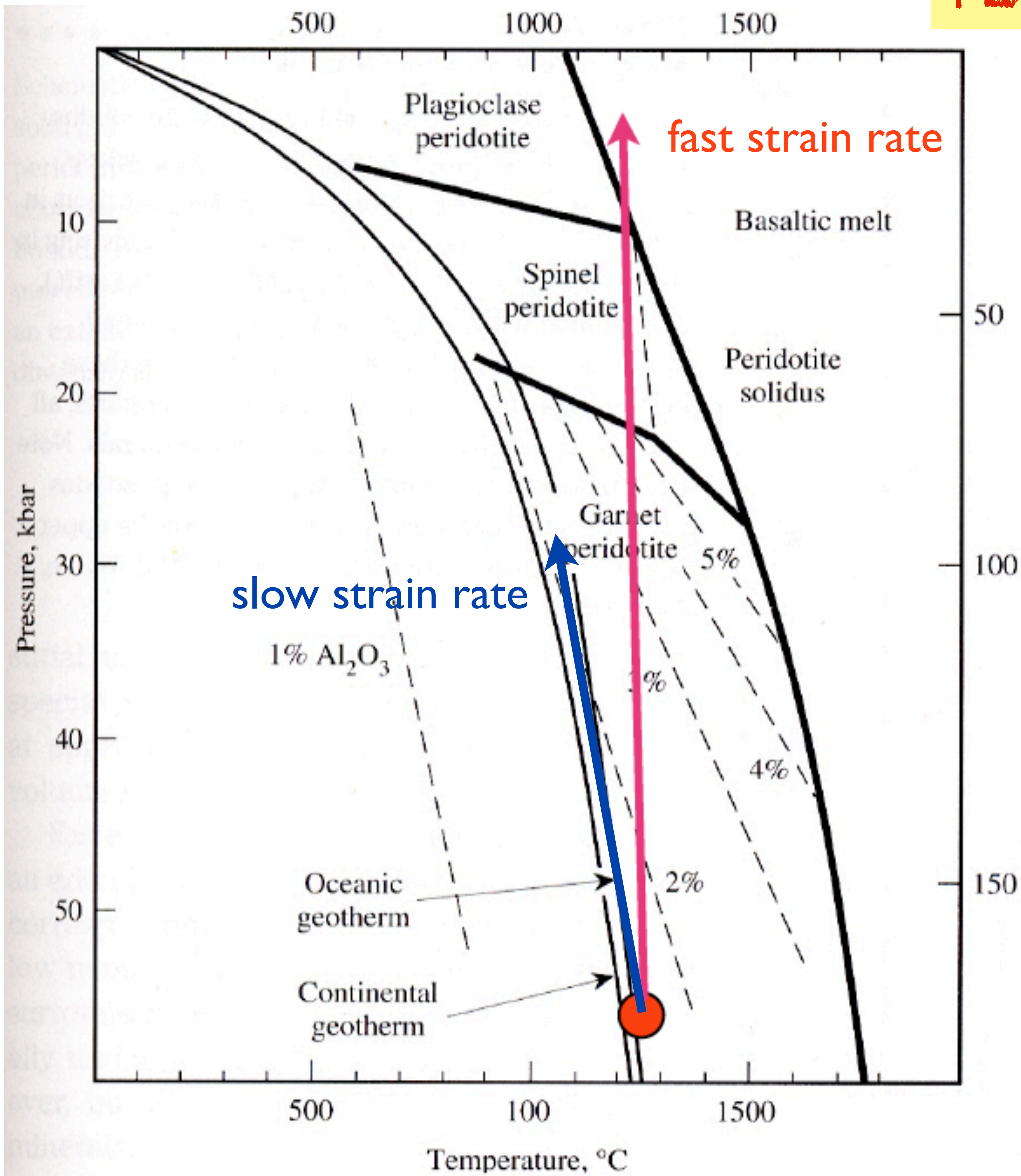
EXTENSIONAL TECTONICS

Extensional tectonics favor the uprising of the astenosphere, that is a necessary but not sufficient condition to gain high geothermal gradient....



...STRAIN RATE...



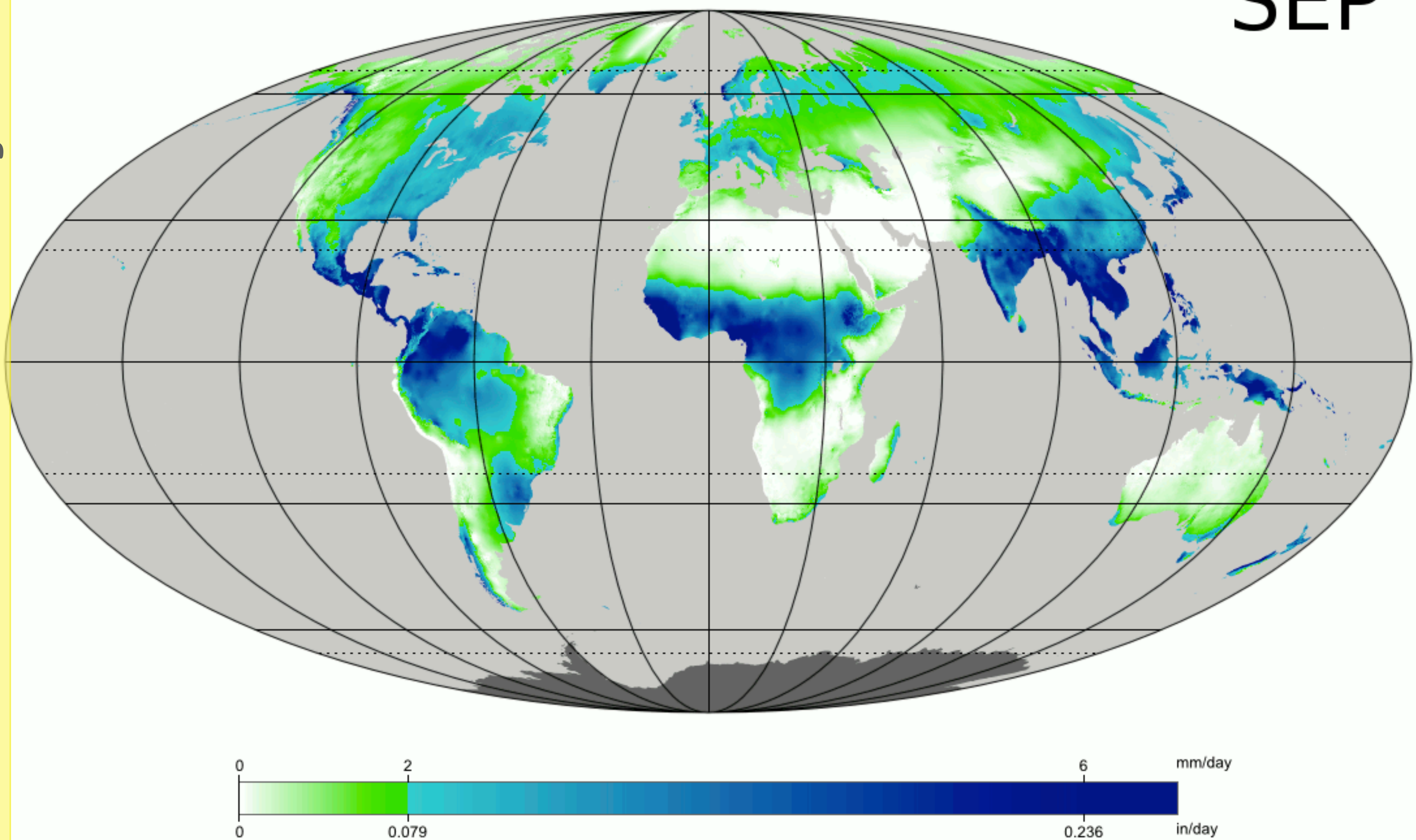


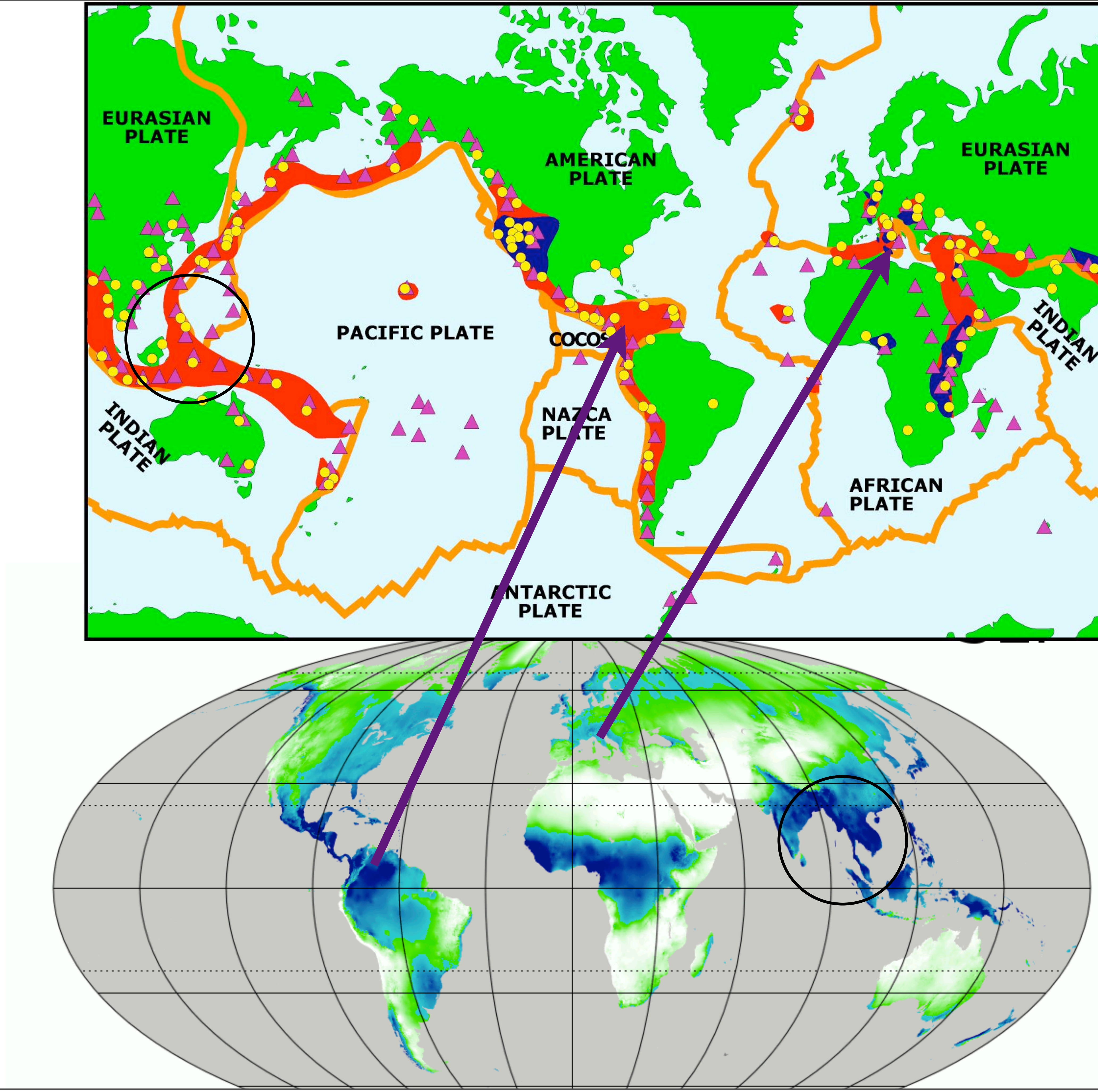
heat flow and magmatism are favored

extension, heat flow, fast strain rate and ....

ANNUAL RAINFALL

SEP



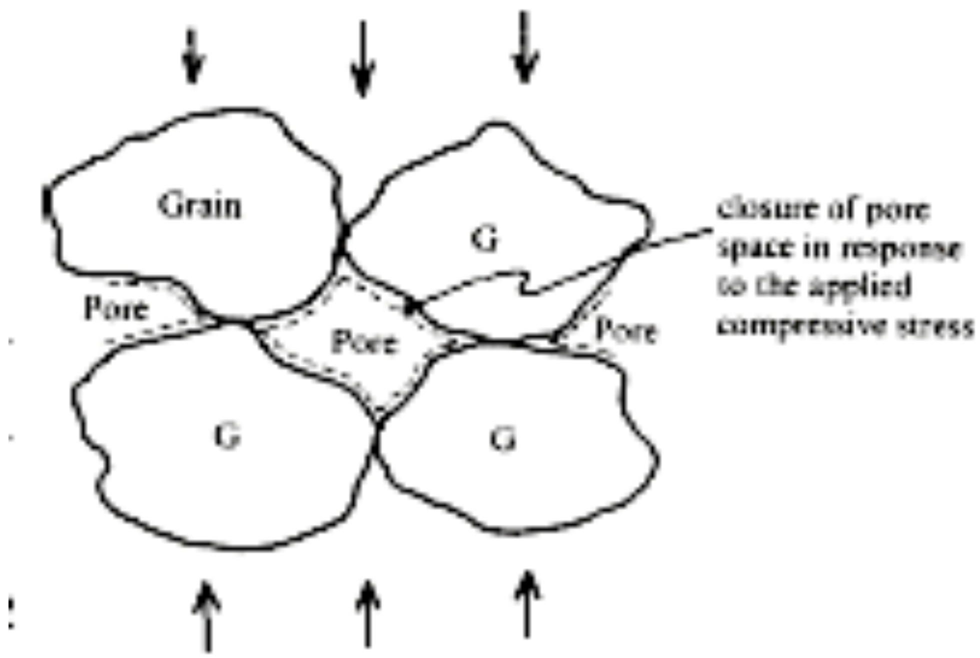

EURASIAN PLATE
AMERICAN PLATE
EURASIAN PLATE
PACIFIC PLATE
COCOS
INDIAN PLATE
INDIAN PLATE
NAZCA PLATE
AFRICAN PLATE
ANTARCTIC PLATE

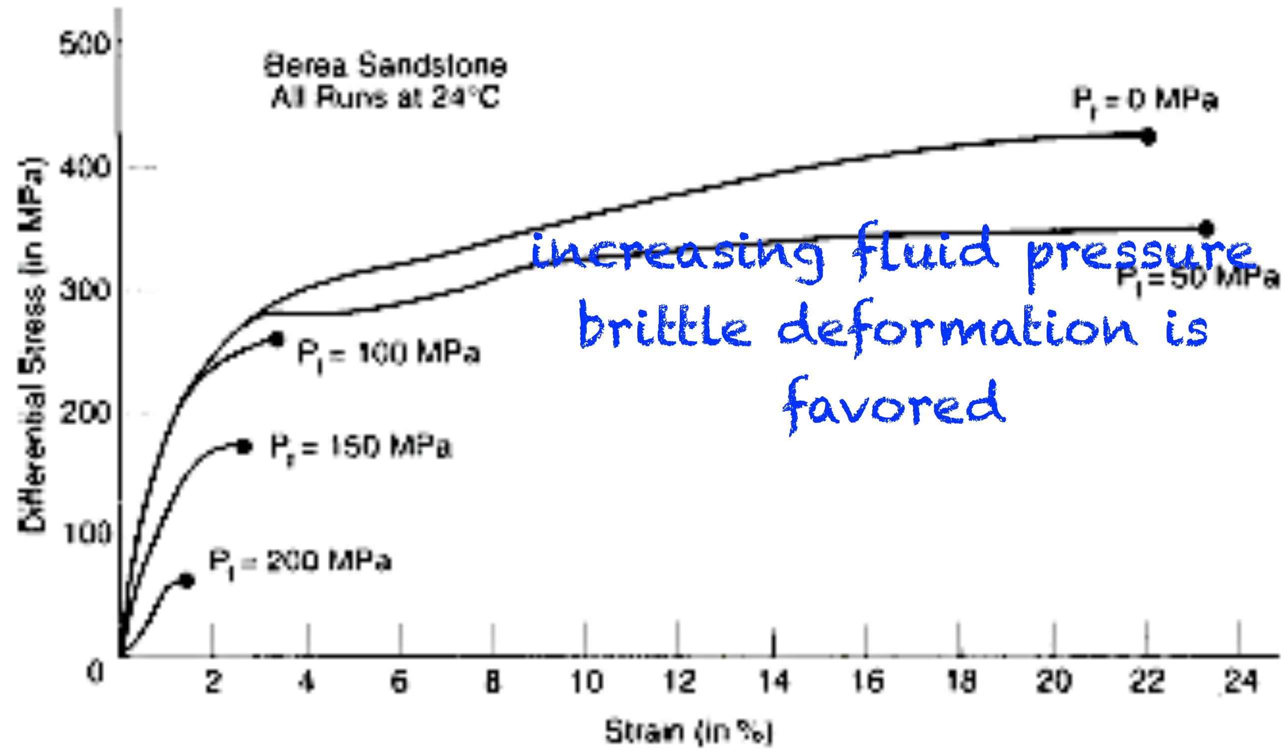
WHY FRACTURES AND FLUID FLOW ARE EACH OTHER RELATED?

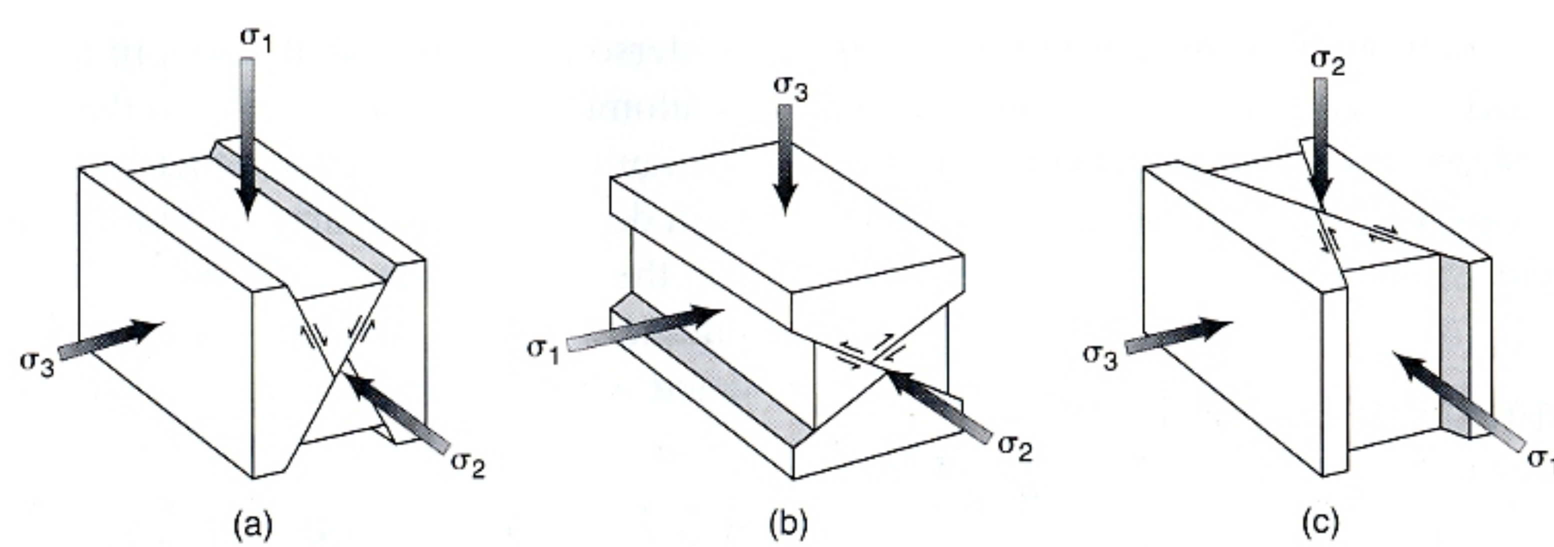
effects of pore fluid pressure

tensile strength of rocks

(I) PORE FLUID PRESSURE







$$\sigma_1' = (\sigma_1 - P_f) > \sigma_2' = (\sigma_2 - P_f) > \sigma_3' = (\sigma_3 - P_f)$$

Andersonian relation

$\lambda = P_f/\rho g z$

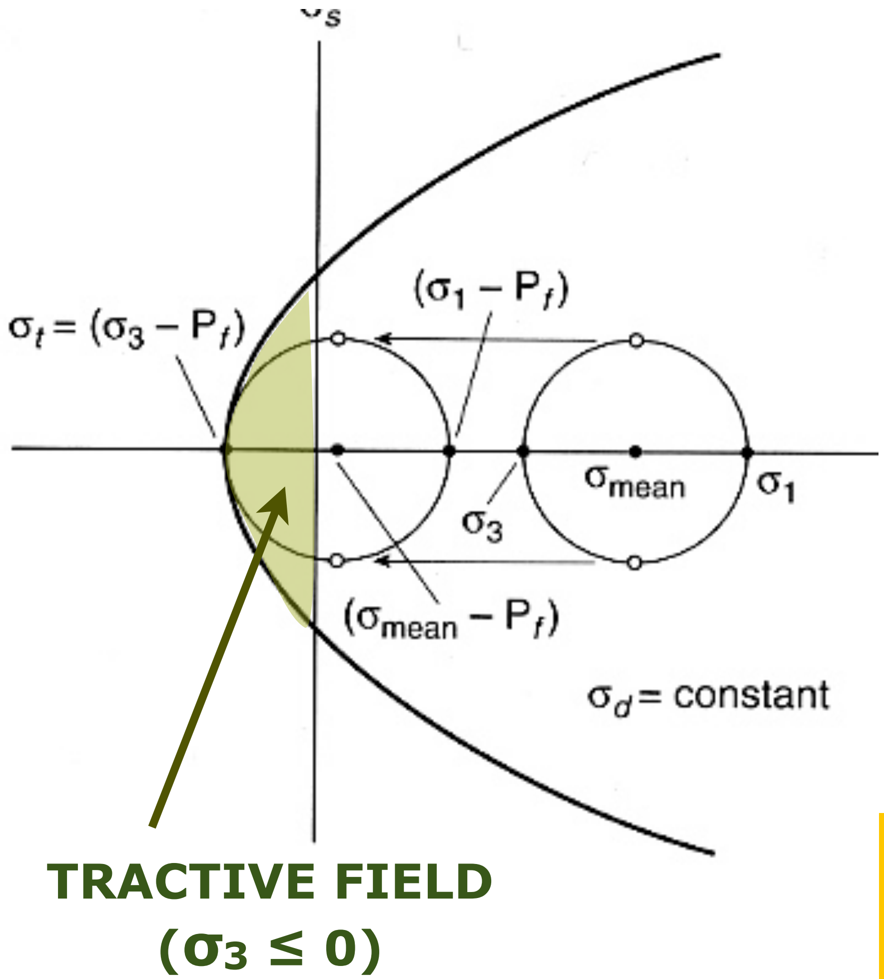
$\lambda \sim 0.4$ hydrostatic

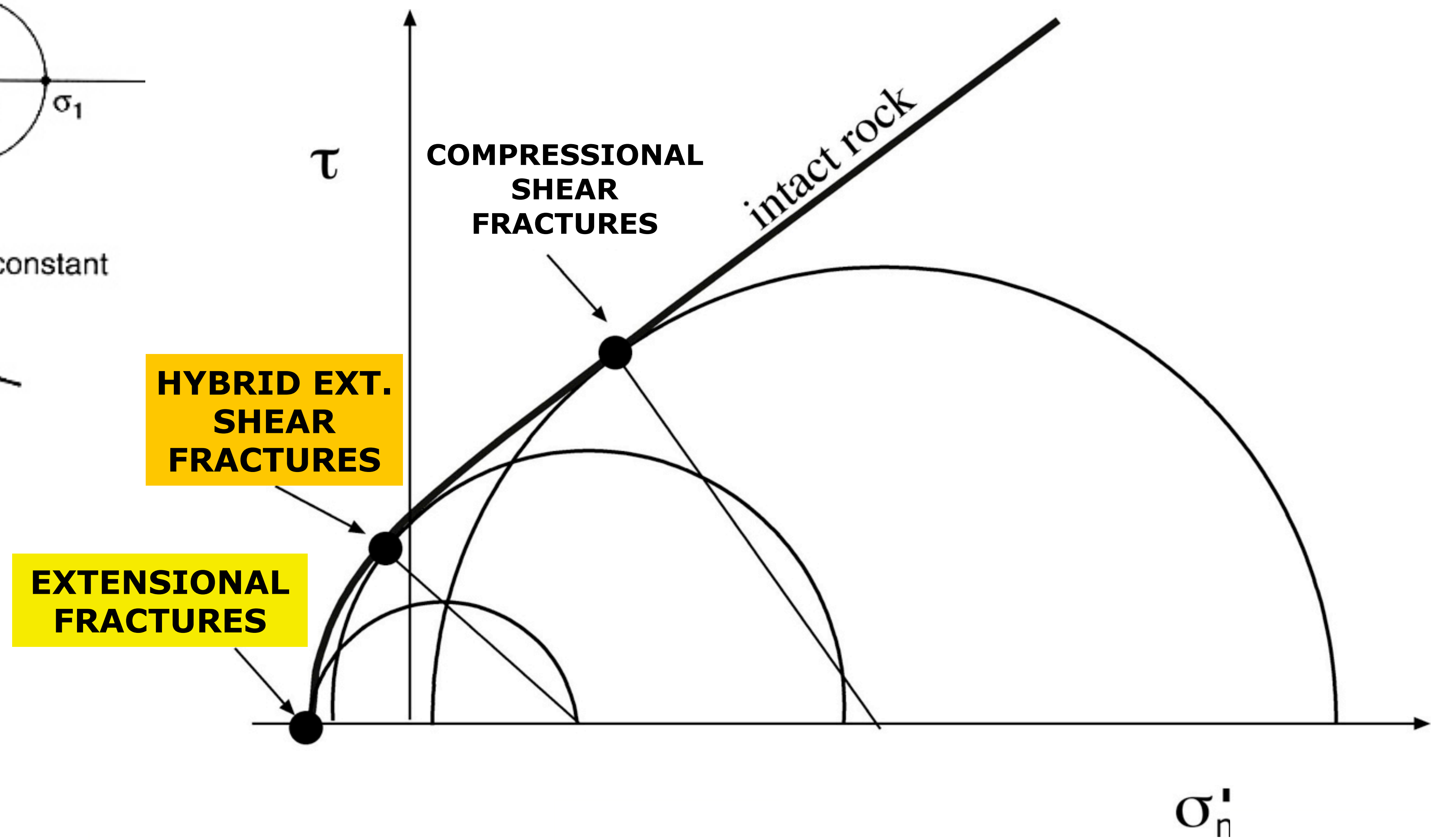
$0.4 < \lambda < 1$ suprahydrostatic

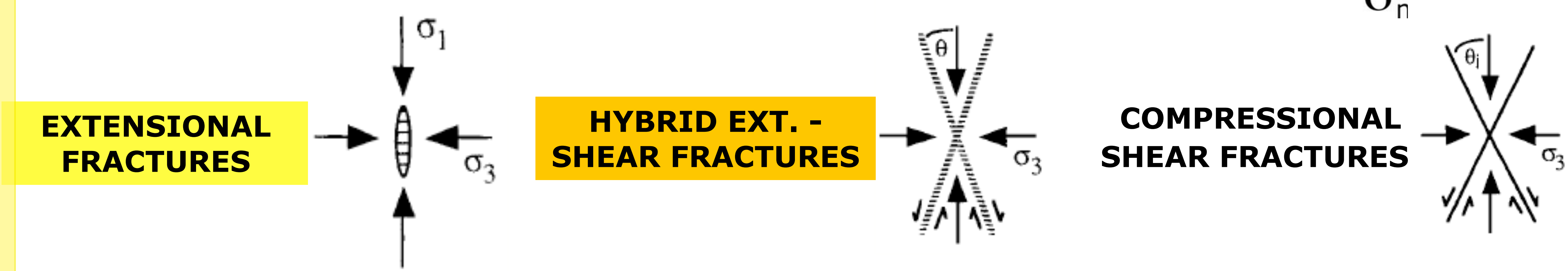
$\lambda = 1$ lithostatic

$\lambda \sim 0,8$ is a reasonable number for the Thyrrenian geothermal provinces

FLUIDS AND FRACTURES







WHY FRACTURES AND FLUID FLOW ARE EACH OTHER RELATED?

effects of pore fluid pressure

tensile strength of rocks

(3) ROCK PROPERTIES

FLUIDS AND FRACTURES

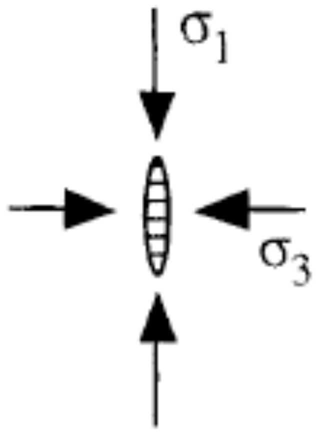
mineralogy, texture, structure and rheological parameters, P and T conditions

T = TENSILE STRENGTH

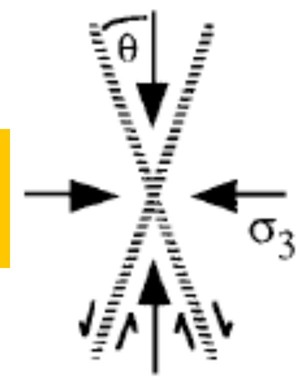
T between 1 and 10 MPa for sedimentary rocks

T between 10 and 20 MPa for crystalline rocks

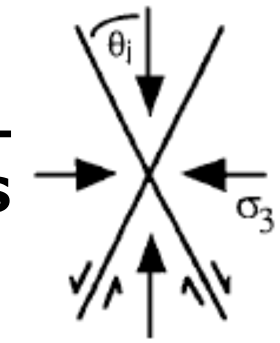
EXTENSIONAL FRACTURES



HYBRID EXT. - SHEAR FRACTURES



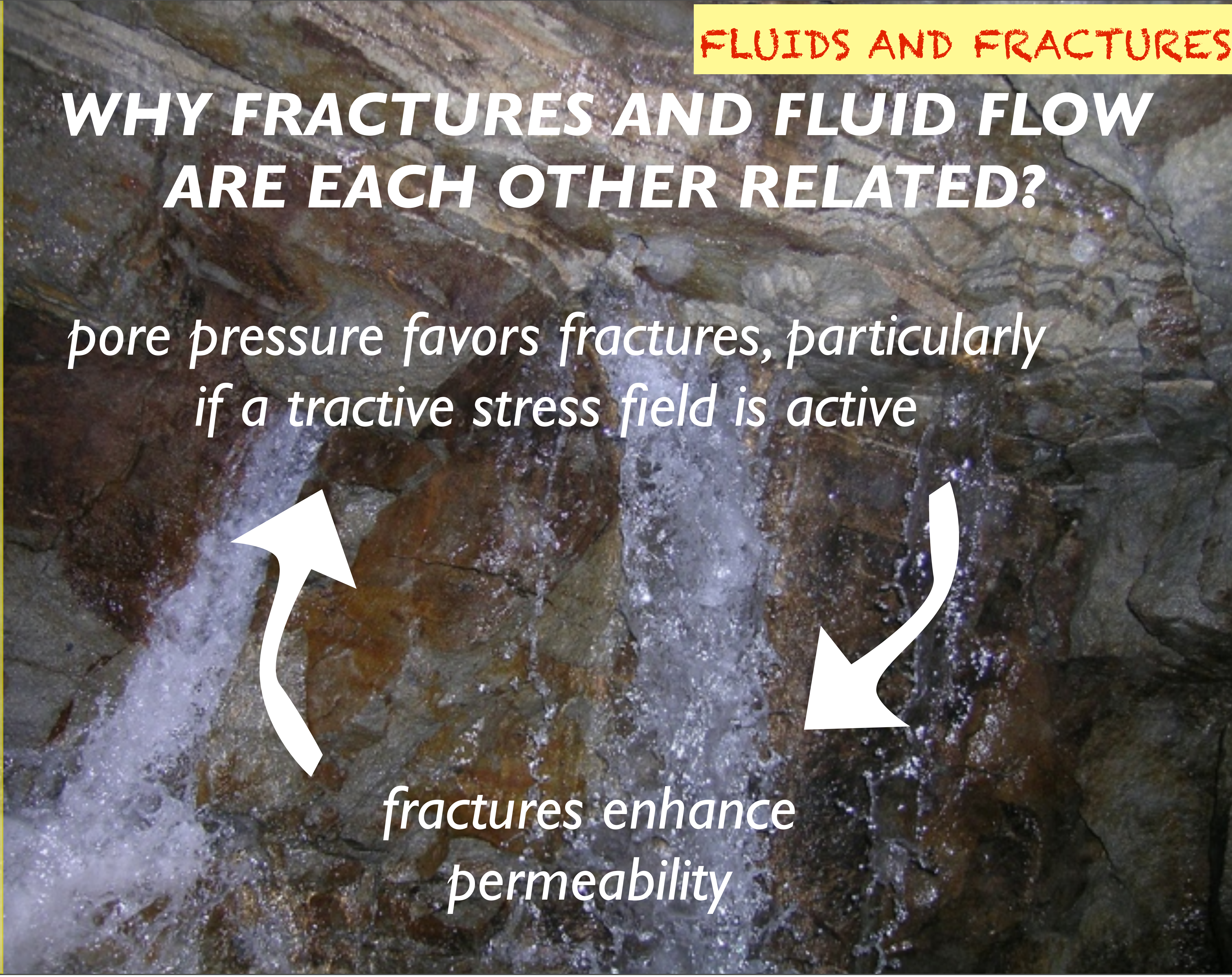
COMPRESSIONAL SHEAR FRACTURES



$(\sigma_1 - \sigma_3) < 4T$ $4T < (\sigma_1 - \sigma_3) < 5.66T$ $(\sigma_1 - \sigma_3) > 5.66T$

from Sibson, 2000

WHY FRACTURES AND FLUID FLOW ARE EACH OTHER RELATED?



pore pressure favors fractures, particularly if a tractive stress field is active

fractures enhance permeability

WHICH IS THE FALLOUT ON THE RELATIONSHIPS BETWEEN GEOLOGICAL STRUCTURES AND GEOTHERMAL RESOURCES?

extensional and ext.shear fractures are the most suitable to develop

↓ ↓ ↓

extensional and transtensional tectonic environments are the most suitable to gain permeability

pore pressure favors fracturing

↓

rain falling environments

pore pressure, if gas is present, increases with temperature

↓

heat flow and magmatism

OUR FIELD AREA

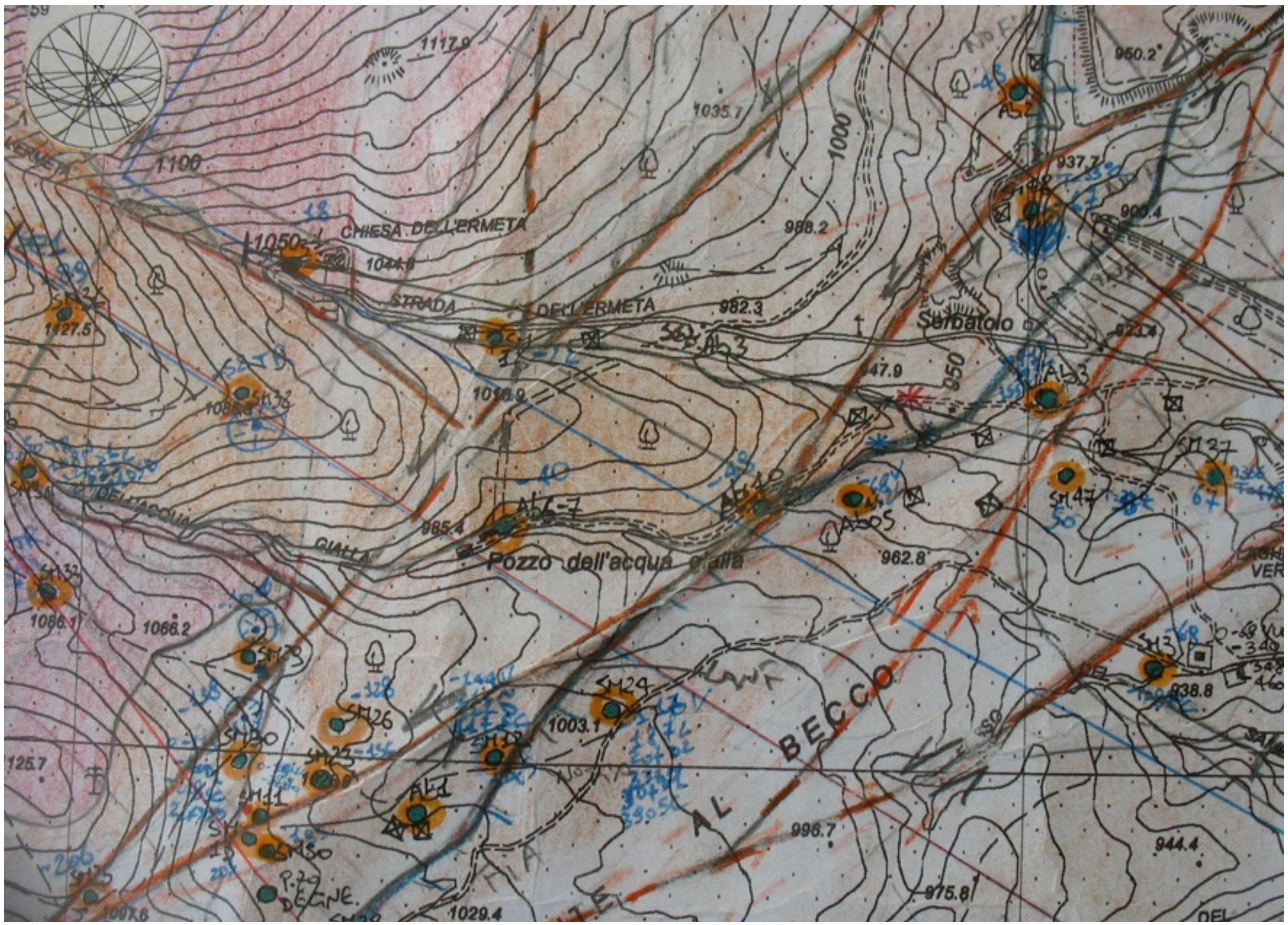
we need geothermal manifestation, such as

gas emission in the forest ....

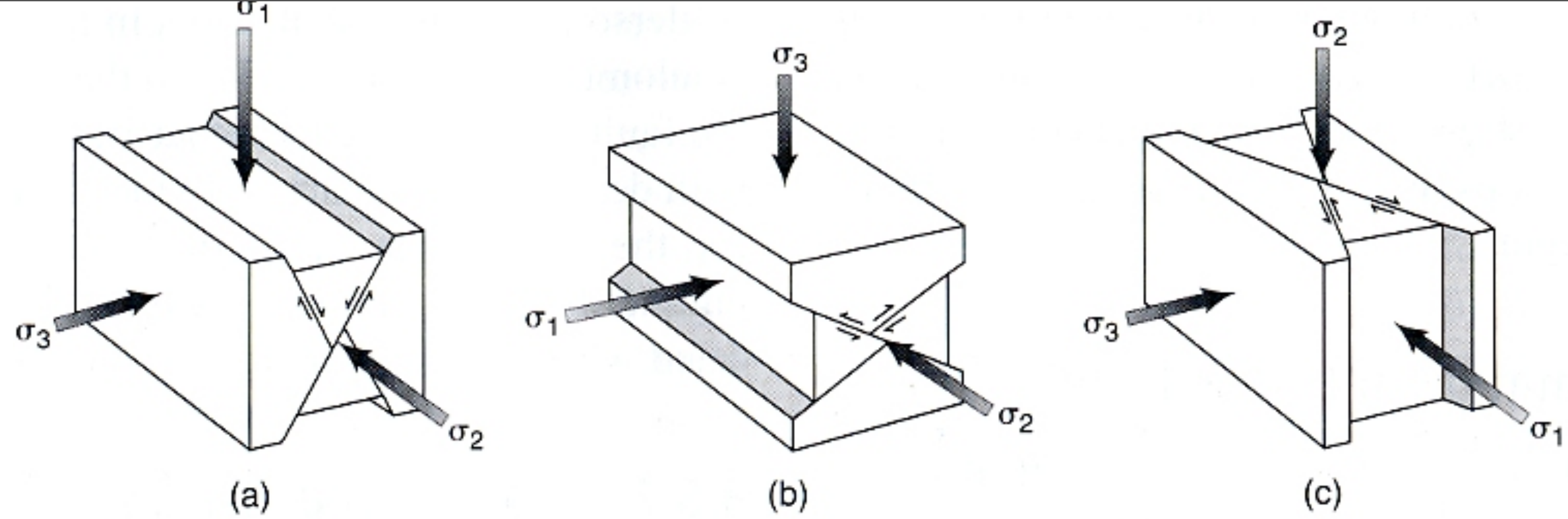
OUR FIELD AREA

CHOOSING THE AREA

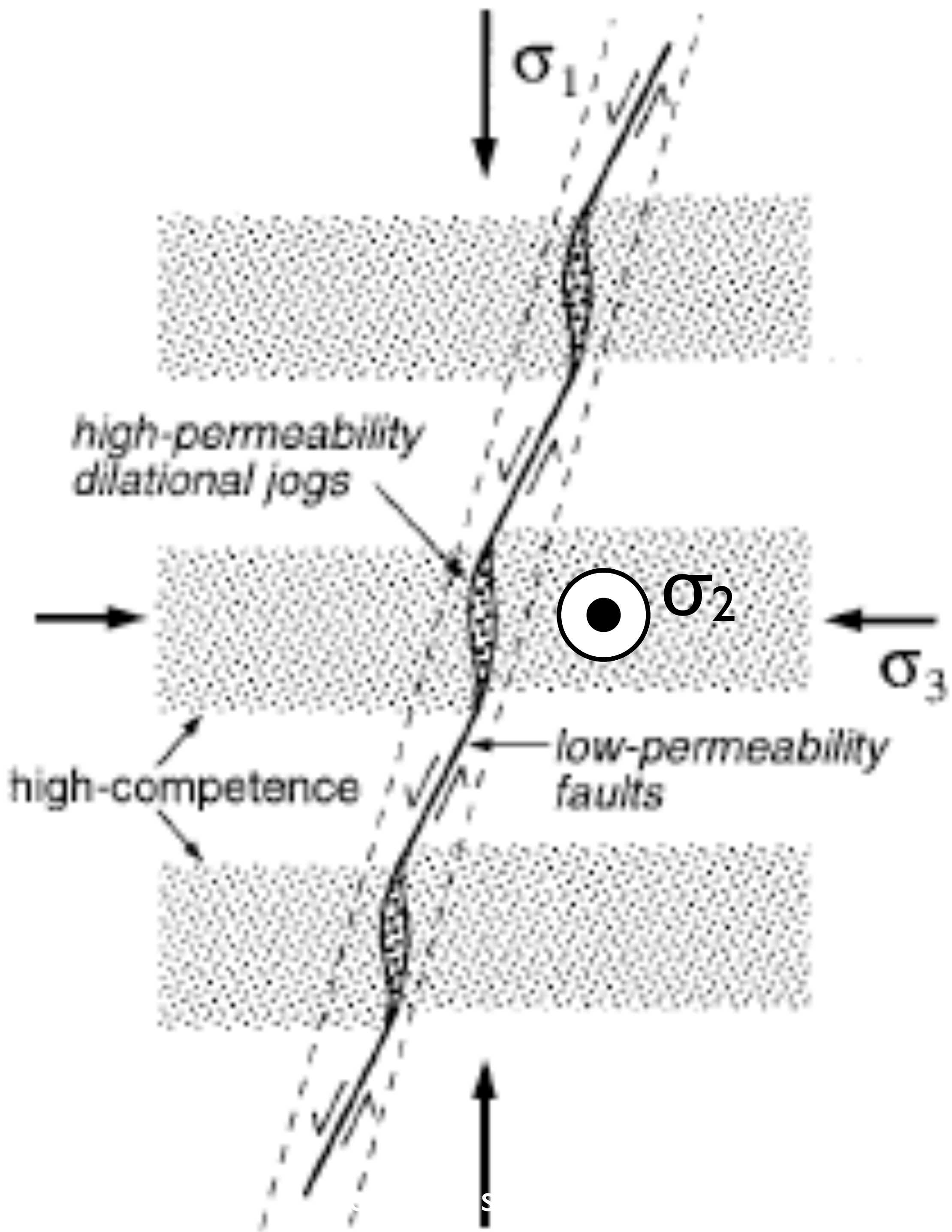
field mapping and structural stations along the main fault systems



FAULTS

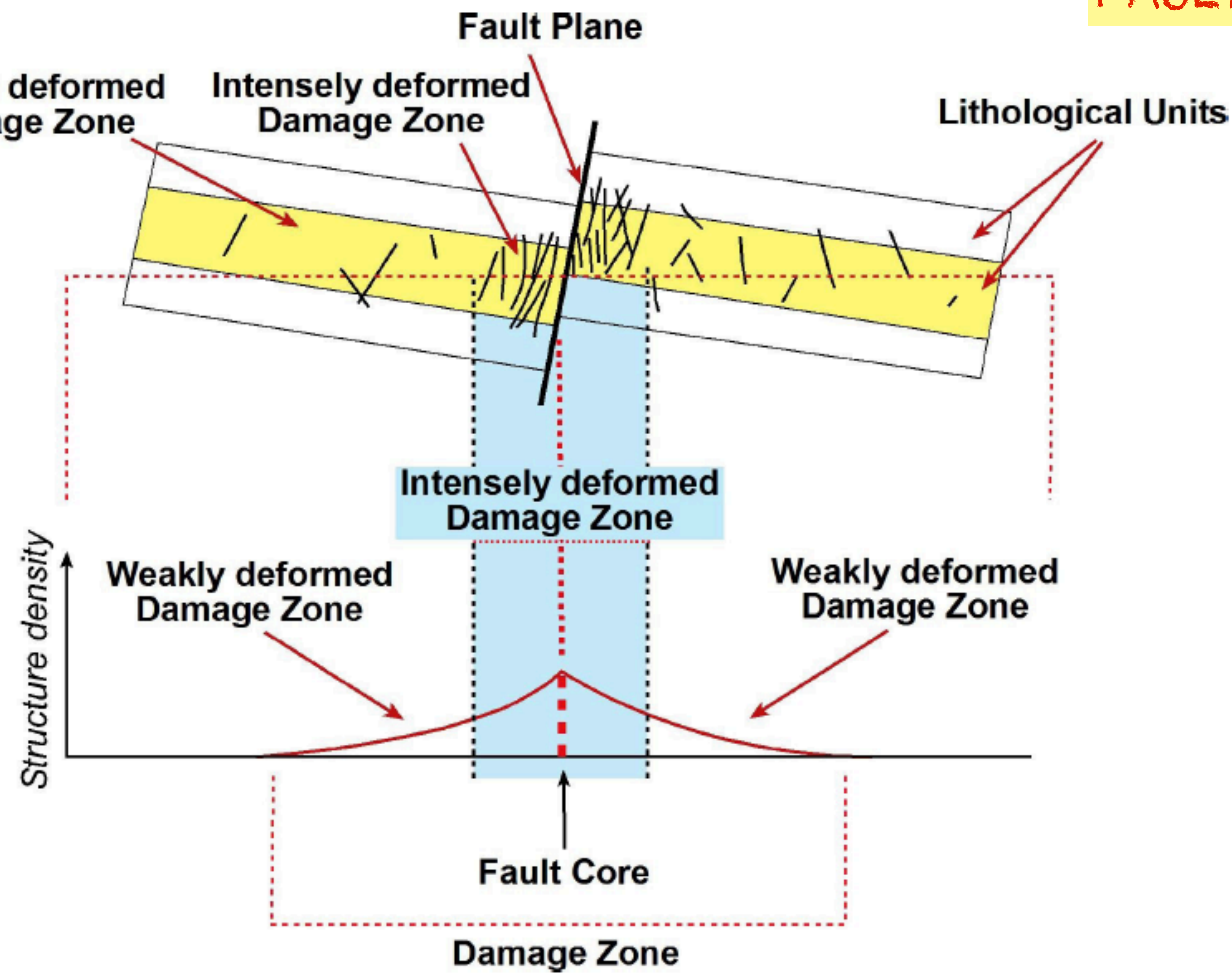


σ1
σ3
σ2
(a)
σ3
σ1
σ2
(b)
σ2
σ3
σ1
(c)



σ1
high-permeability
dilational jogs
σ2
σ3
high-competence
low-permeability
faults

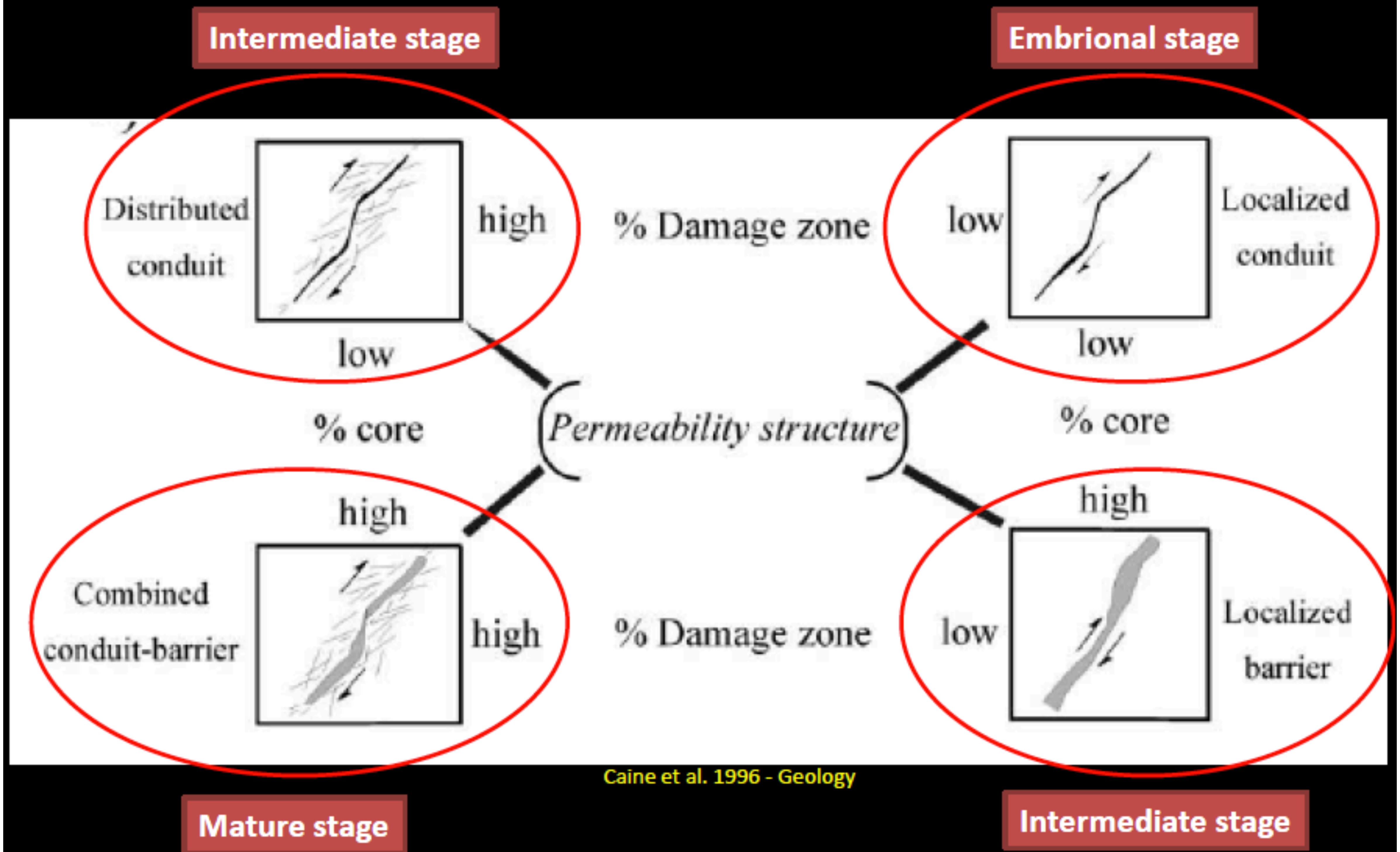
FAULTS



by courtesy A.Brogi, 2011

Fault Zone Permeability structure

Qualitative evaluation by *Caine et al.*



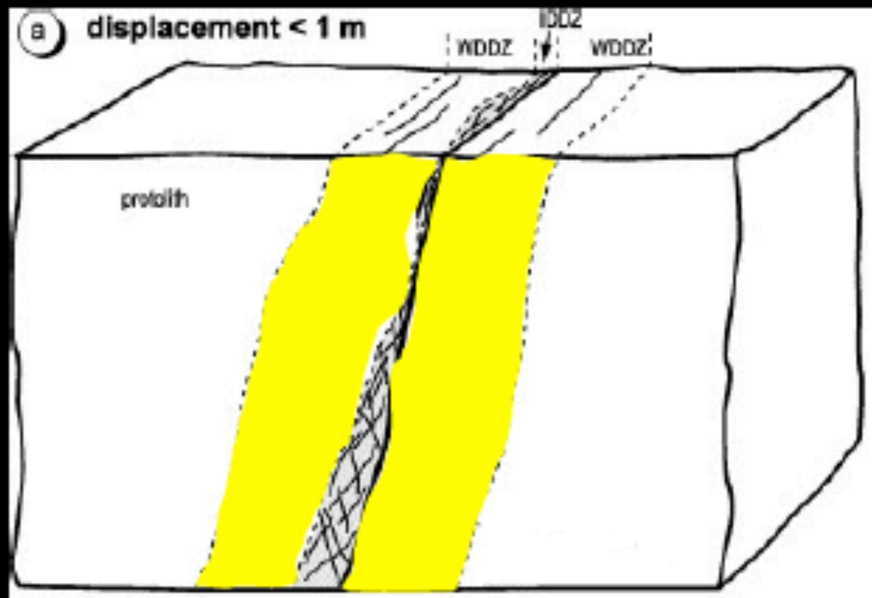
by courtesy A.Brogi, 2011

Fault Zone Anatomy - dynamic evolution

The progressive development of a fault implies :

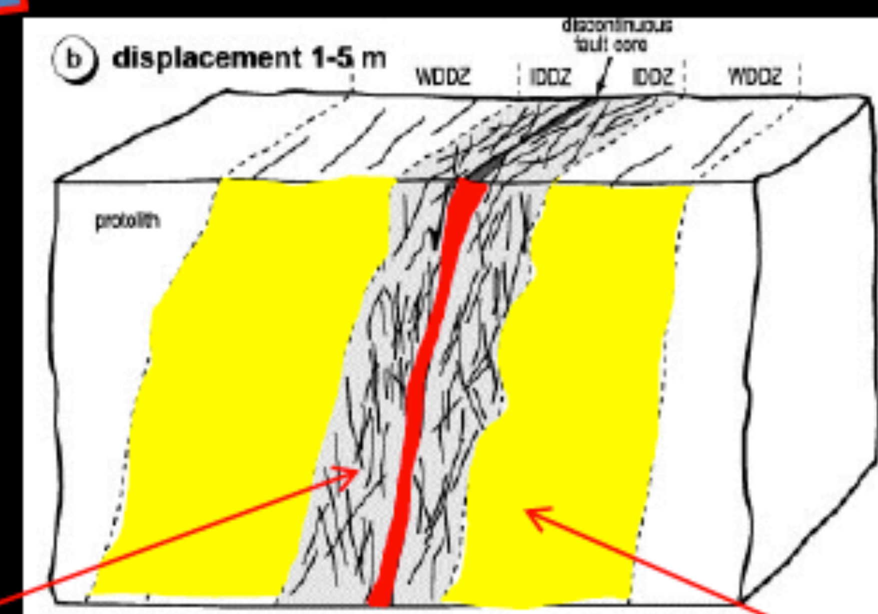
1) The enlargment of the damage zone;
2) The increase of the fractures density;
3) The thickening of the fault core;

Step 1 – Embrional stage



Micarelli et al., 2006 – J. Struct. Geol.

Step 2 – Intermediate stage

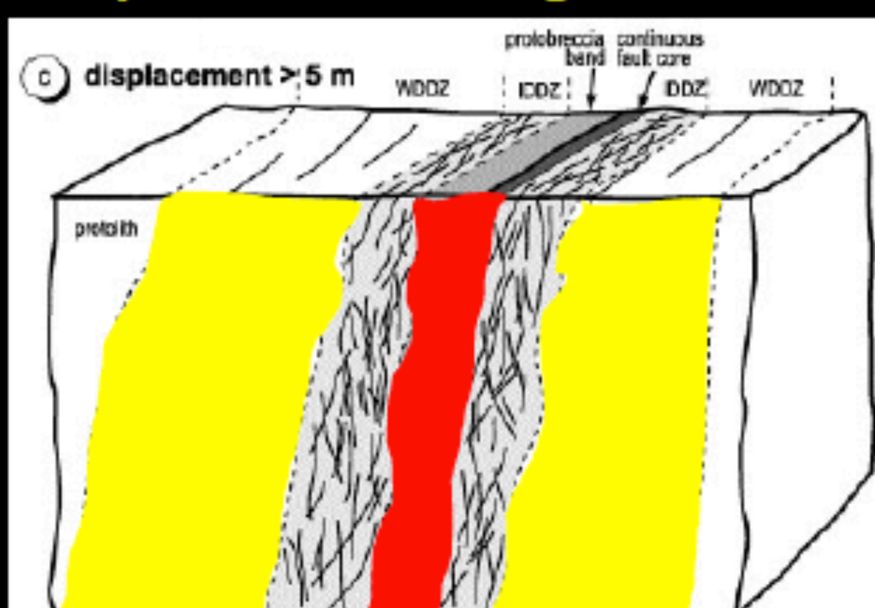


Intensely deformed Damage zone

Fault core

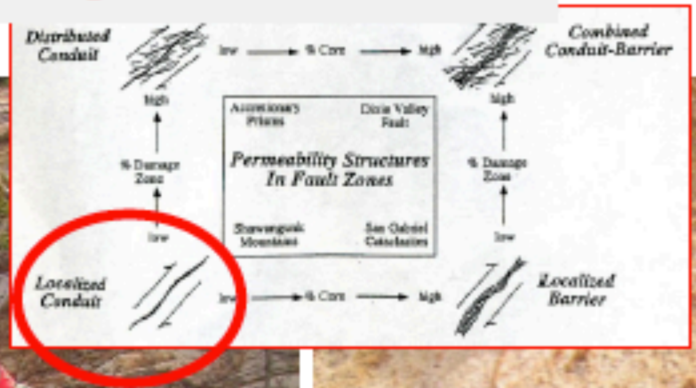
Weakly deformed Damage zone

Step 3 – Mature stage

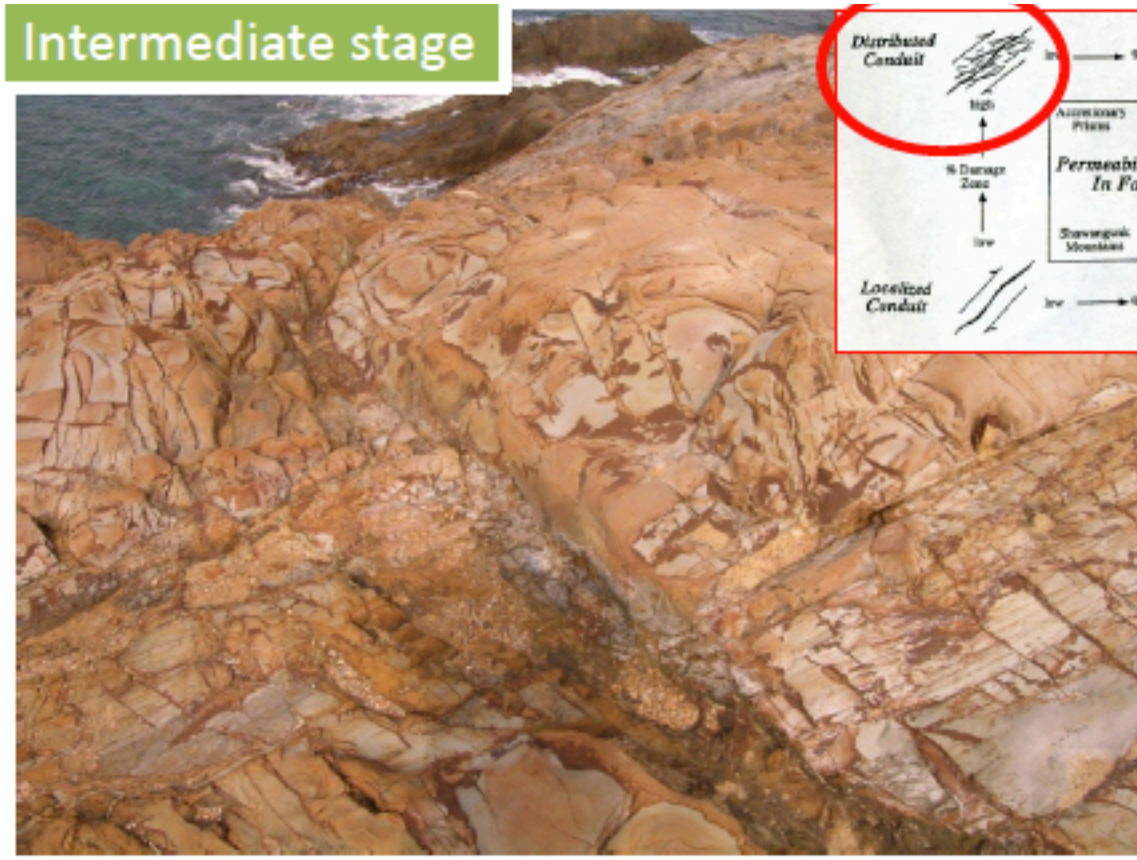


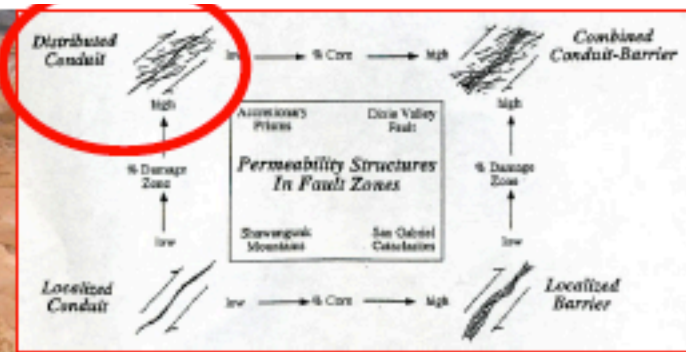
by courtesy A.Brogi, 2011

Fault Zone Permeability structure

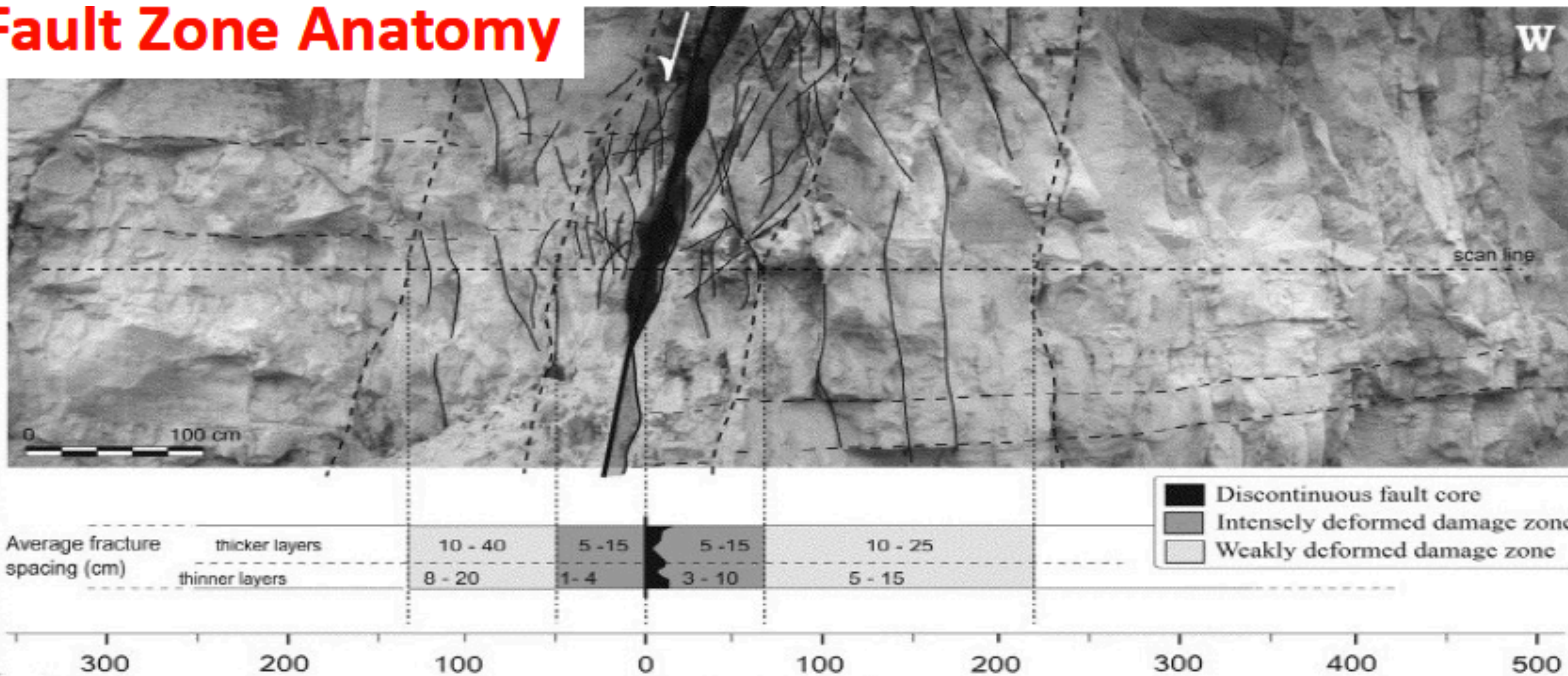


by courtesy A.Brogi, 2011





Fault Zone Anatomy

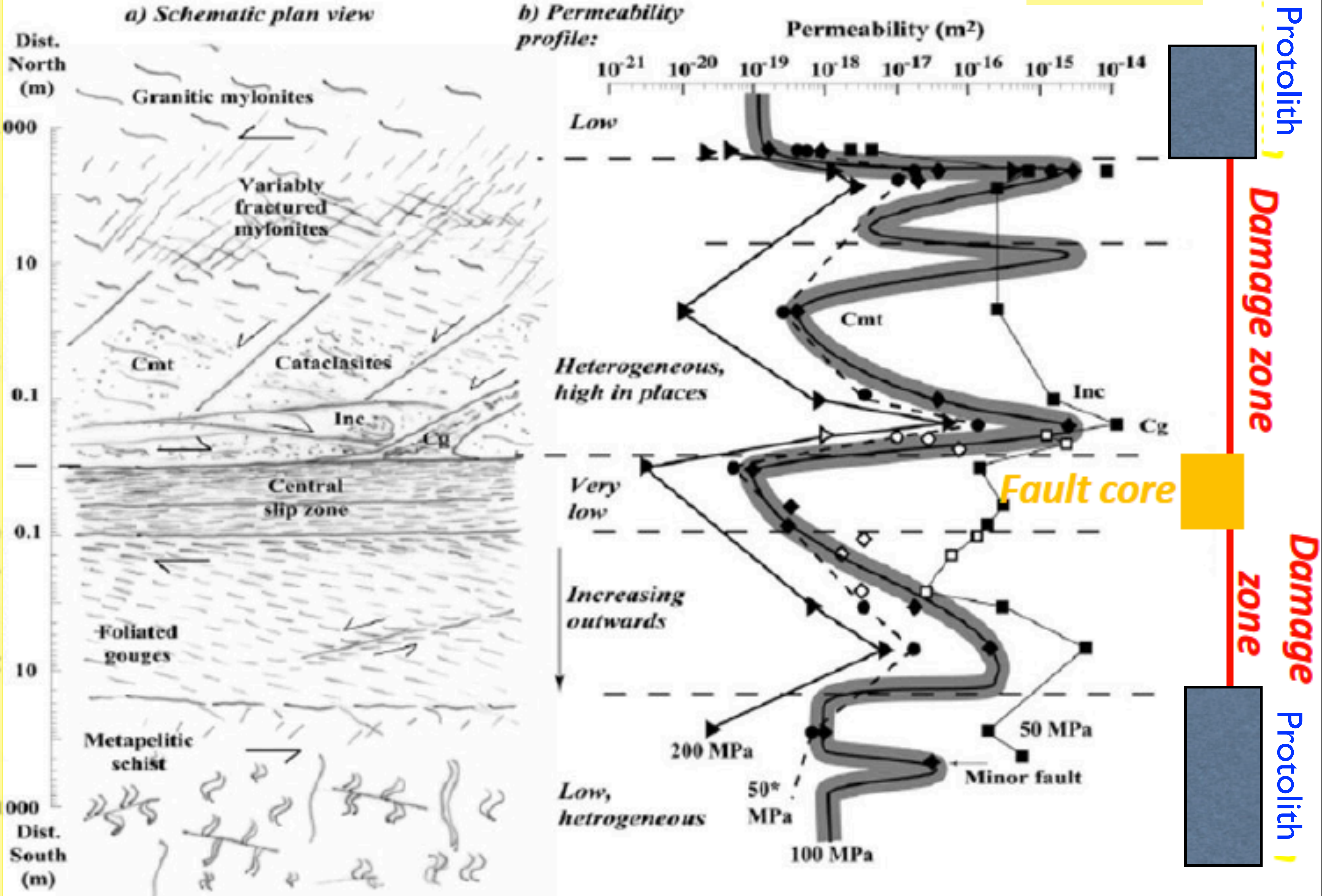


Micarelli et al. 2006 - J. Struct. Geol.

by courtesy A.Brogi, 2011

C.A.J. Wibberley, T. Shimamoto / Journal of Structural Geology 25 (2003) 59–78

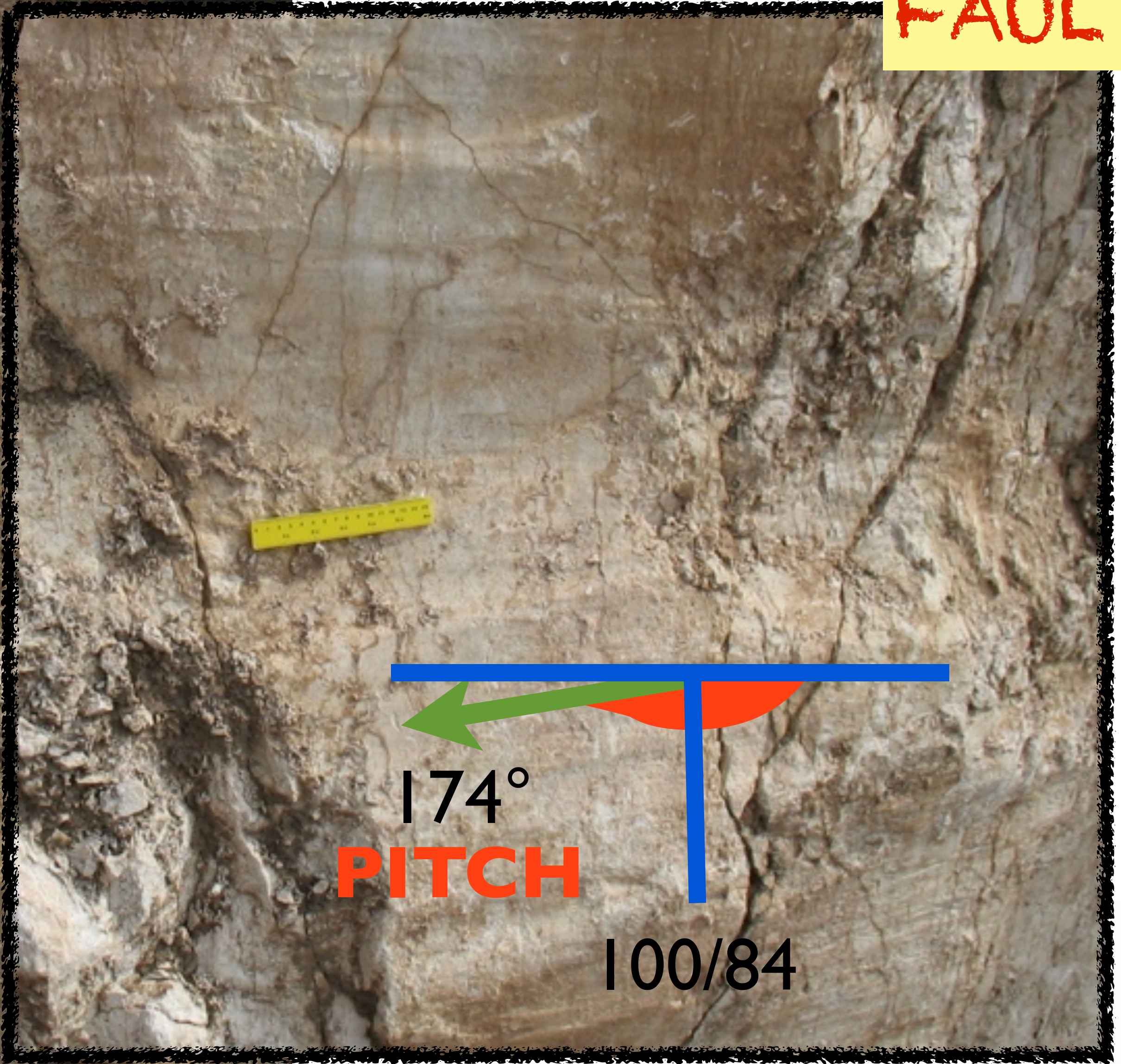
FAULTS



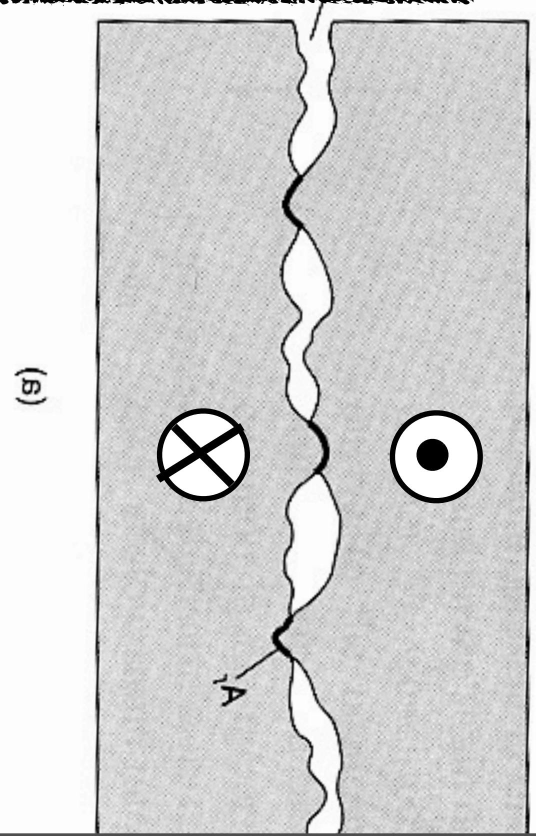
by courtesy A.Brogi, 2011

D. Liotta - international school on geothermal exploration

FAULTS

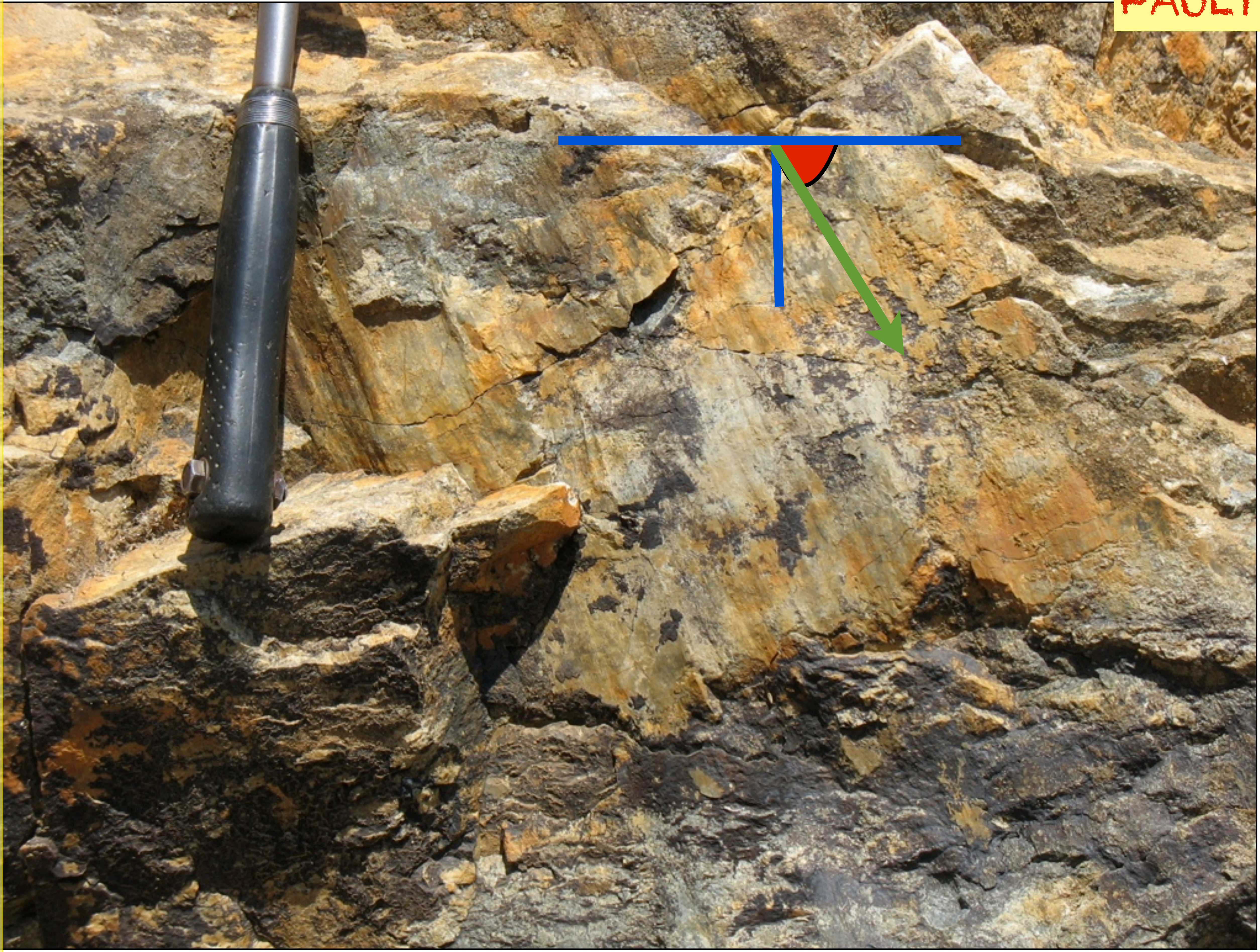


slickenline
on rock

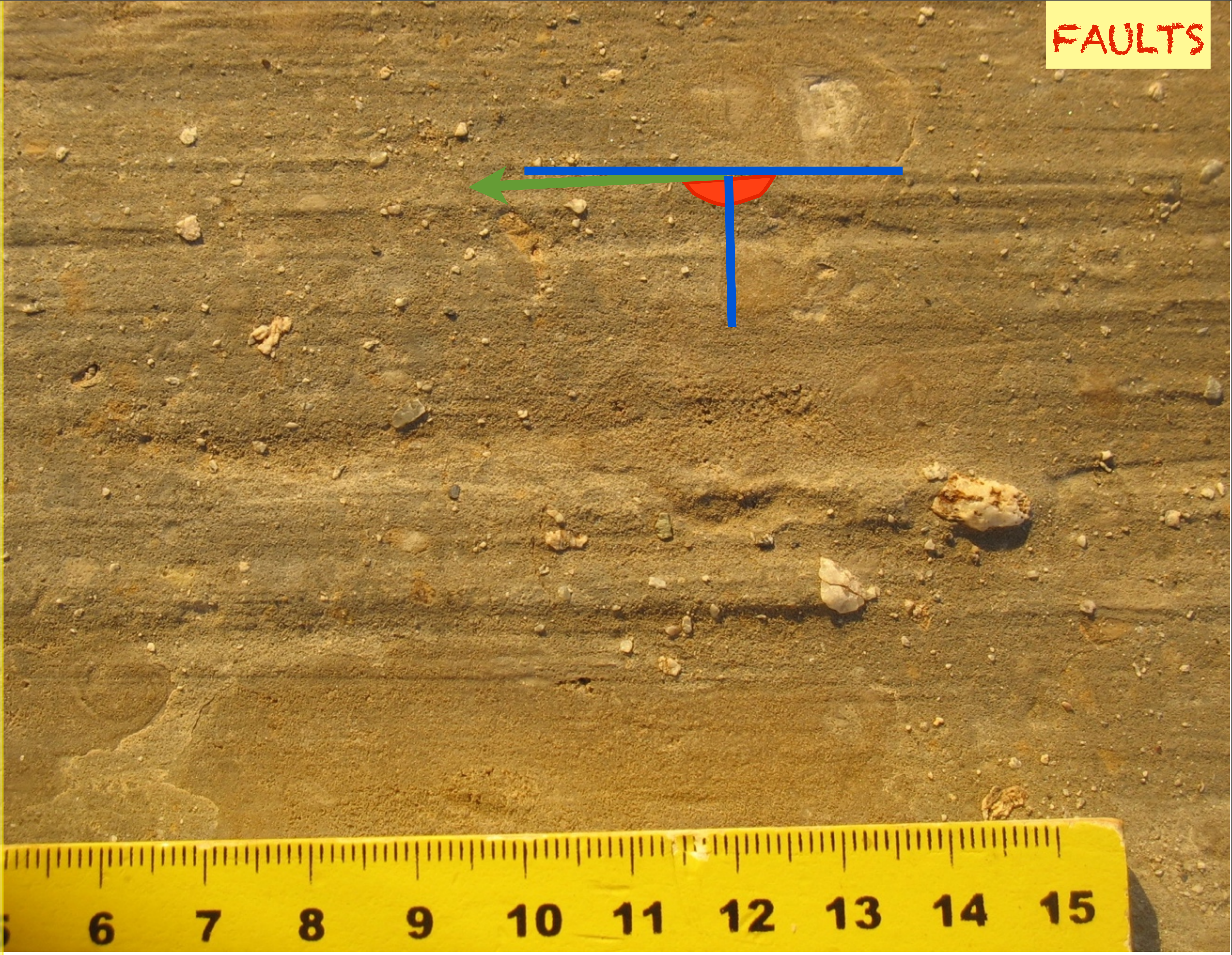



PITCH

FAULTS

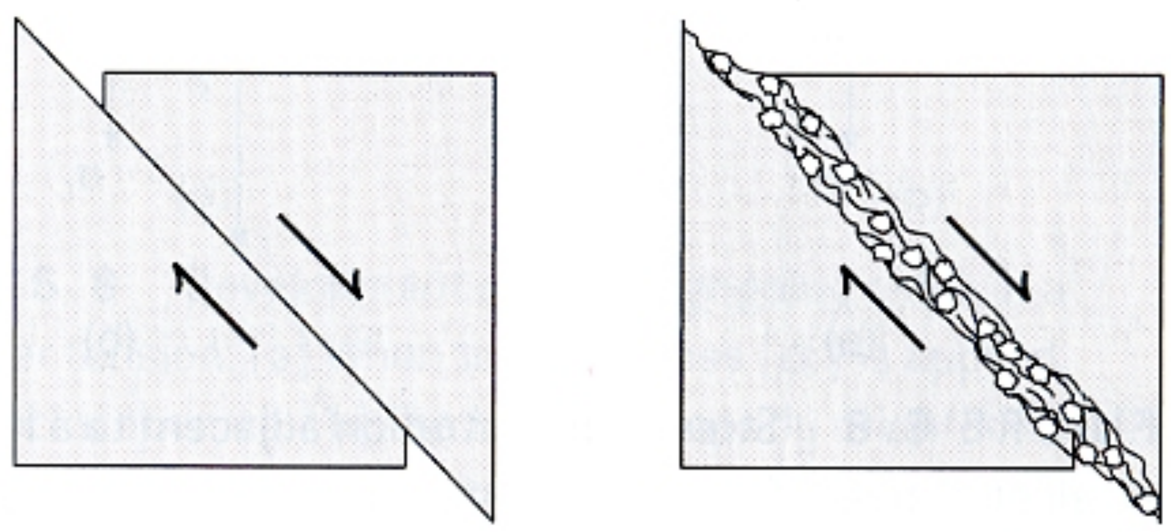


FAULTS

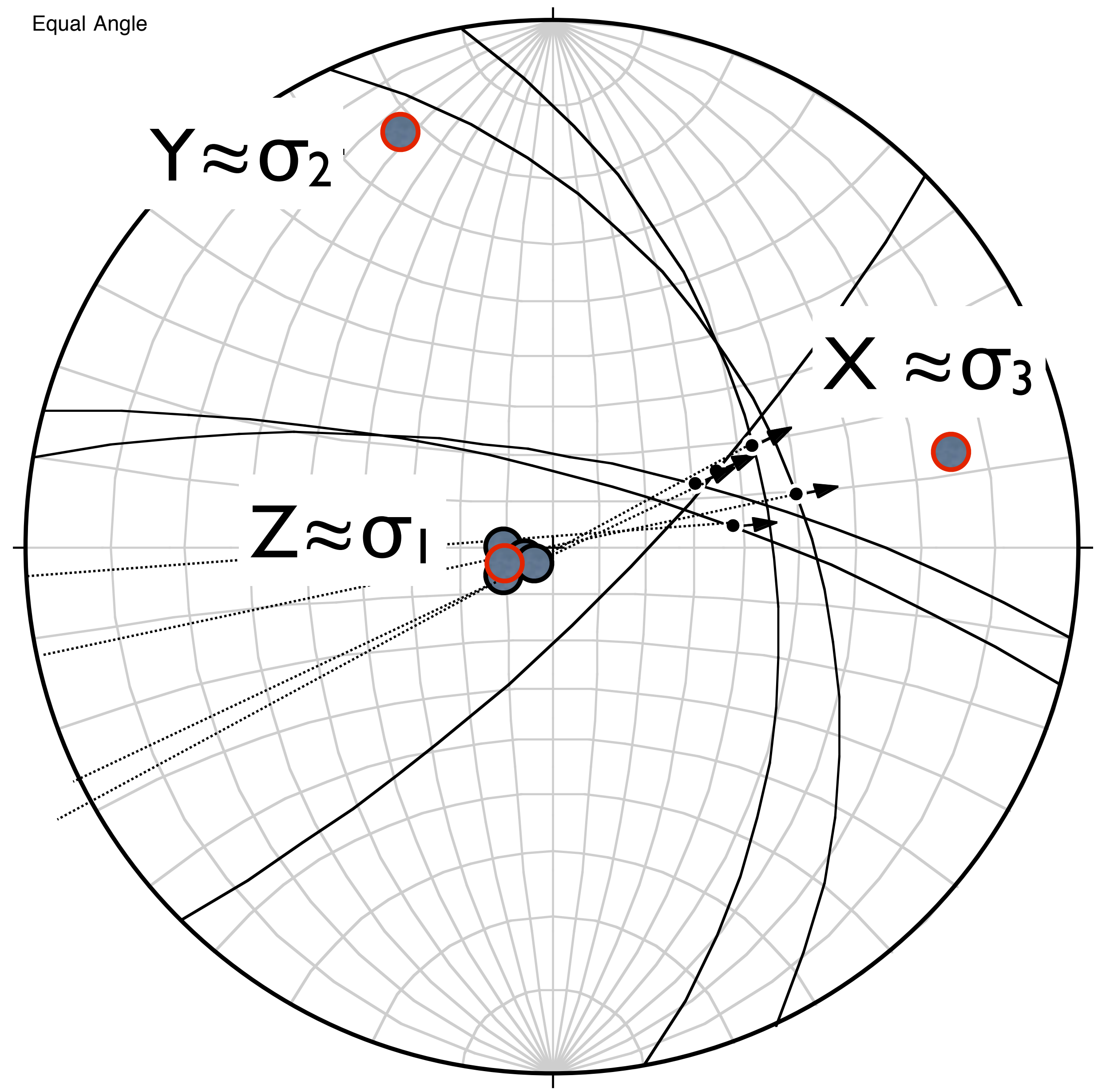


DIP AZIMUTH	DIP	PITCH
65	40	100
135	75	55
15	74	125
10	70	117
80	45	78

EXAMPLE



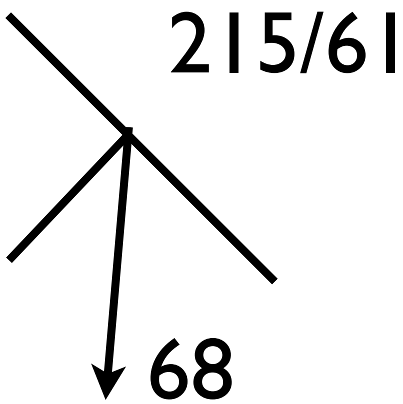
cataclastic flow and kinematic compatibility



http://www.geo.cornell.edu/geology/faculty/RWA/

Rick Allmendinger's home page

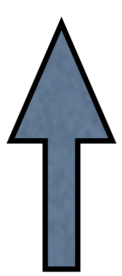
ORIENTATION OF THE INTERMEDIATE AXIS: ≈348/22 *check in the field "your" kinematic compatibility*

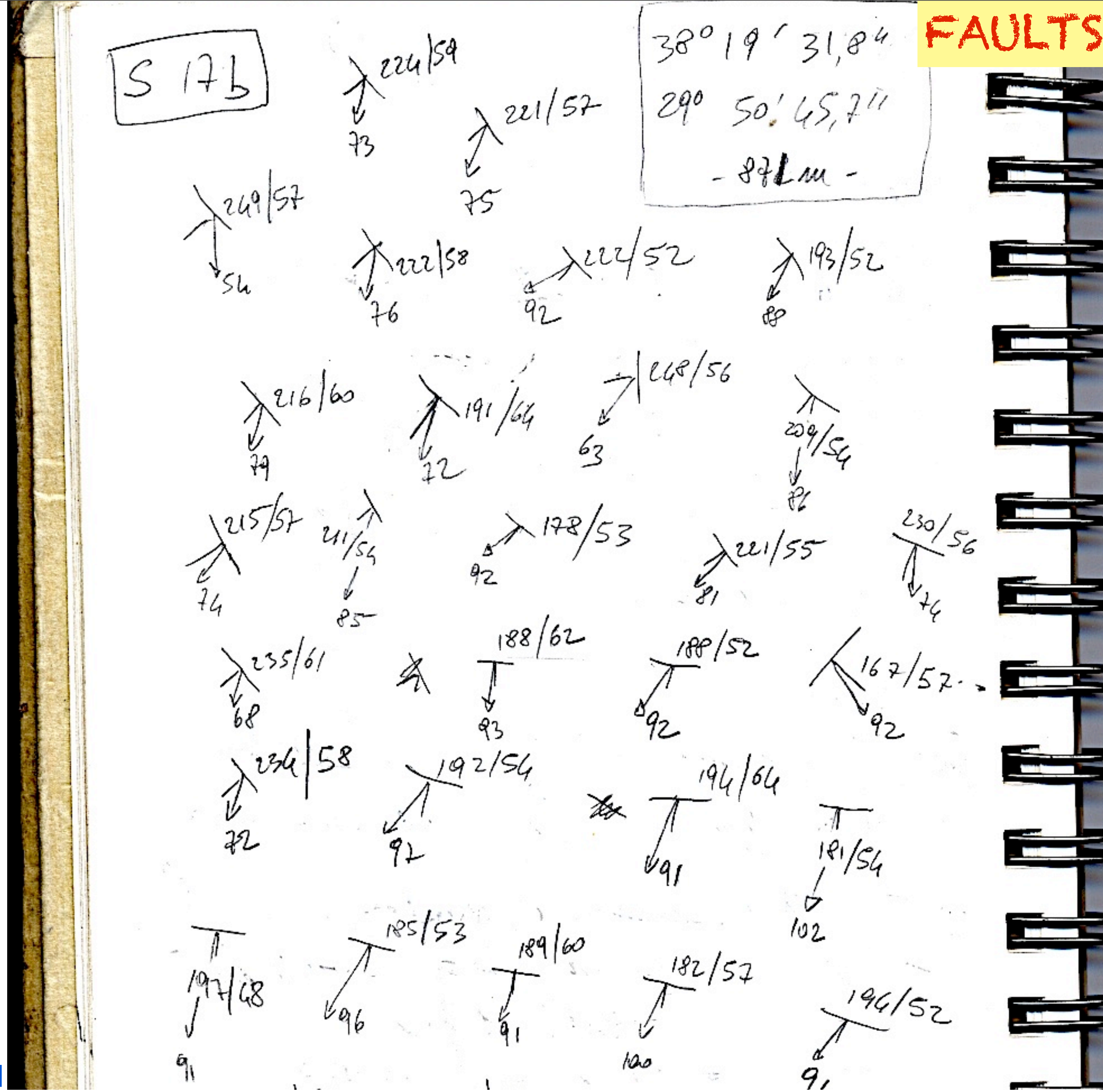


YES!

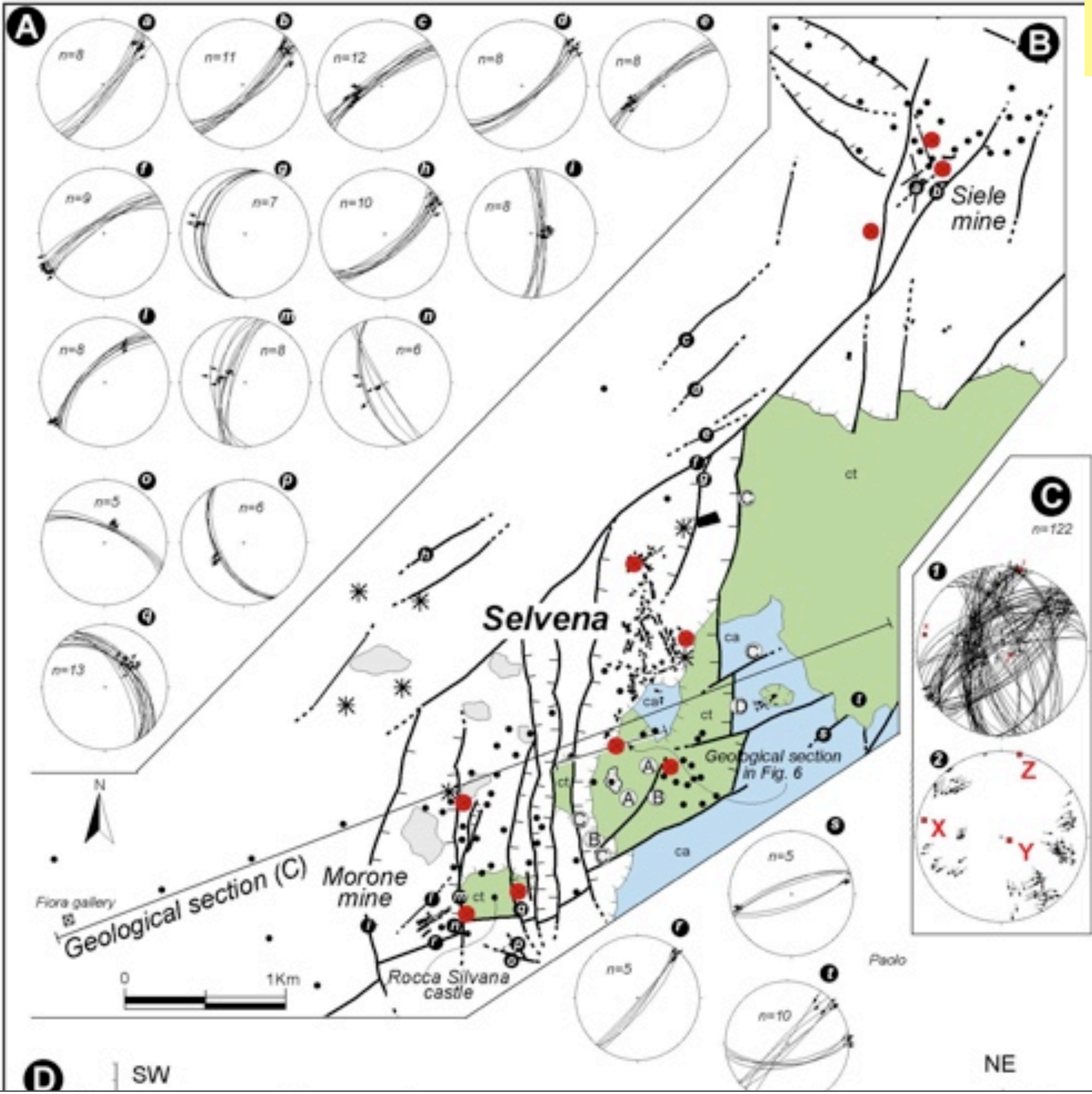
224/59/73
221/57/75
249/57/54
....

NO!



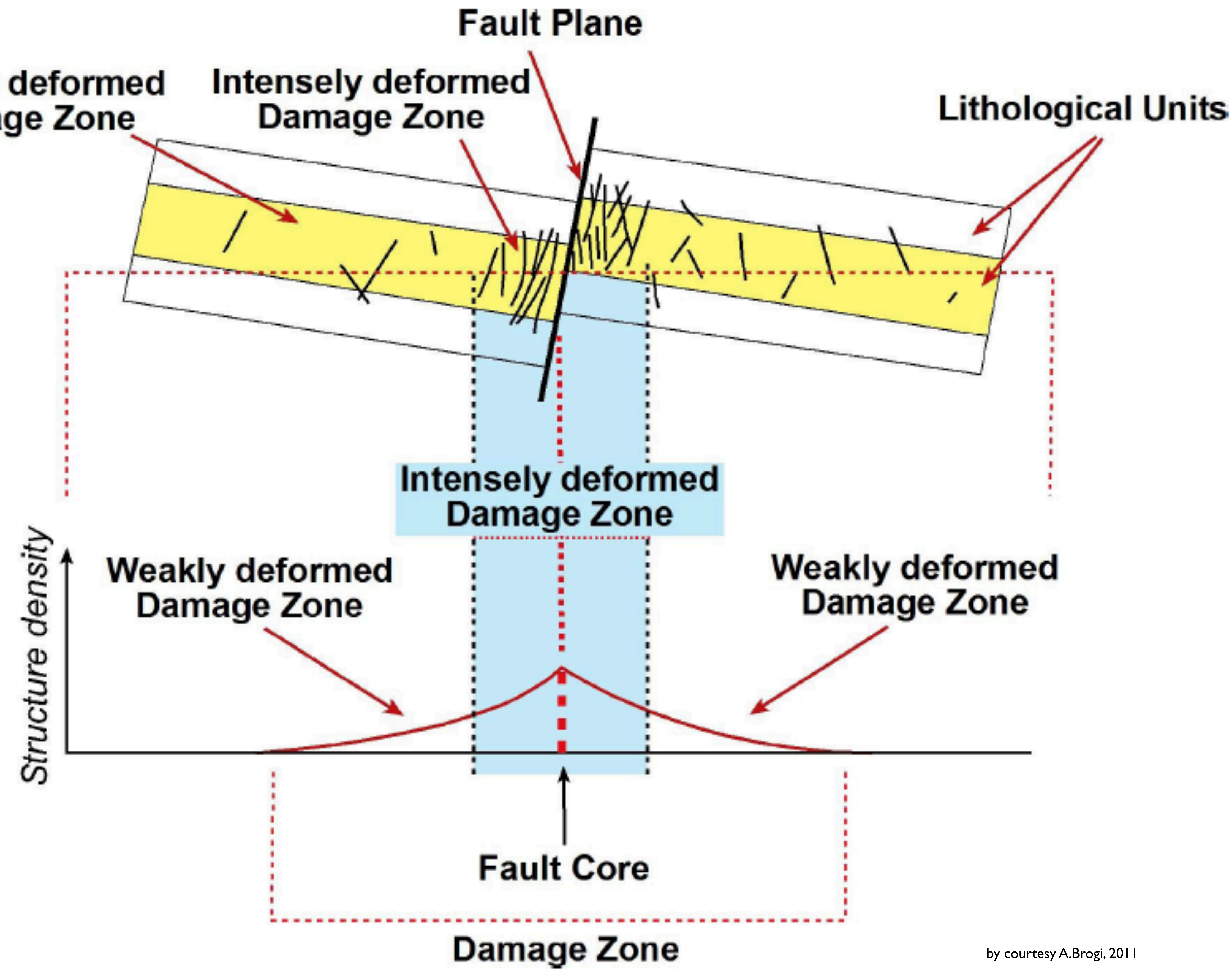


FAULTS


A
B
C
D
n=8
n=11
n=12
n=10
n=9
n=7
n=6
n=5
n=13
n=122
Siele mine
Selvena
Morone mine
Rocca Silvana castle
Fiora gallery
Geological section (C)
Geological section in Fig. 6
ct
ca
cat
0
1Km
N
Paolo
X
Y
Z
SW
NE

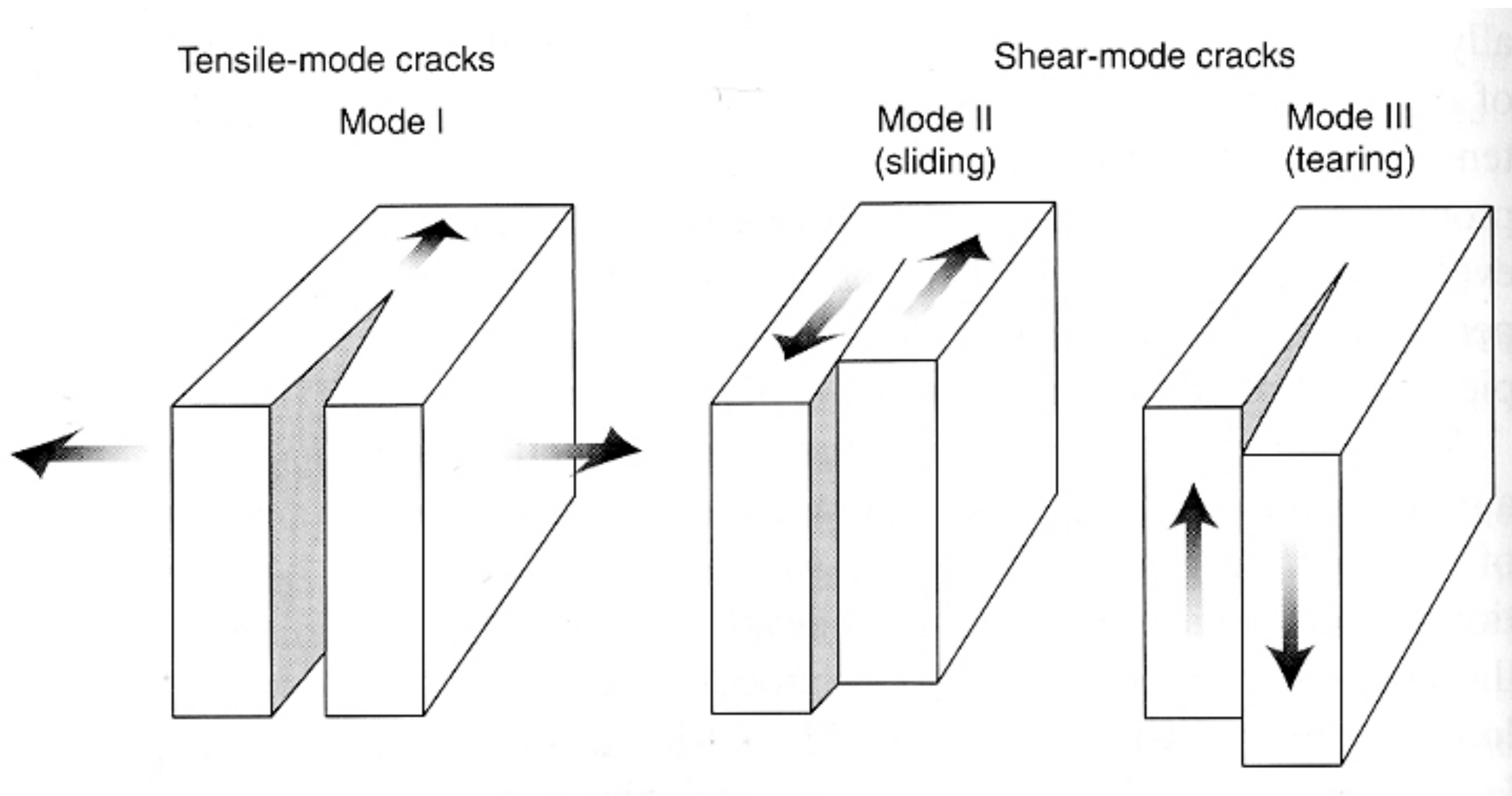
joint fabrics

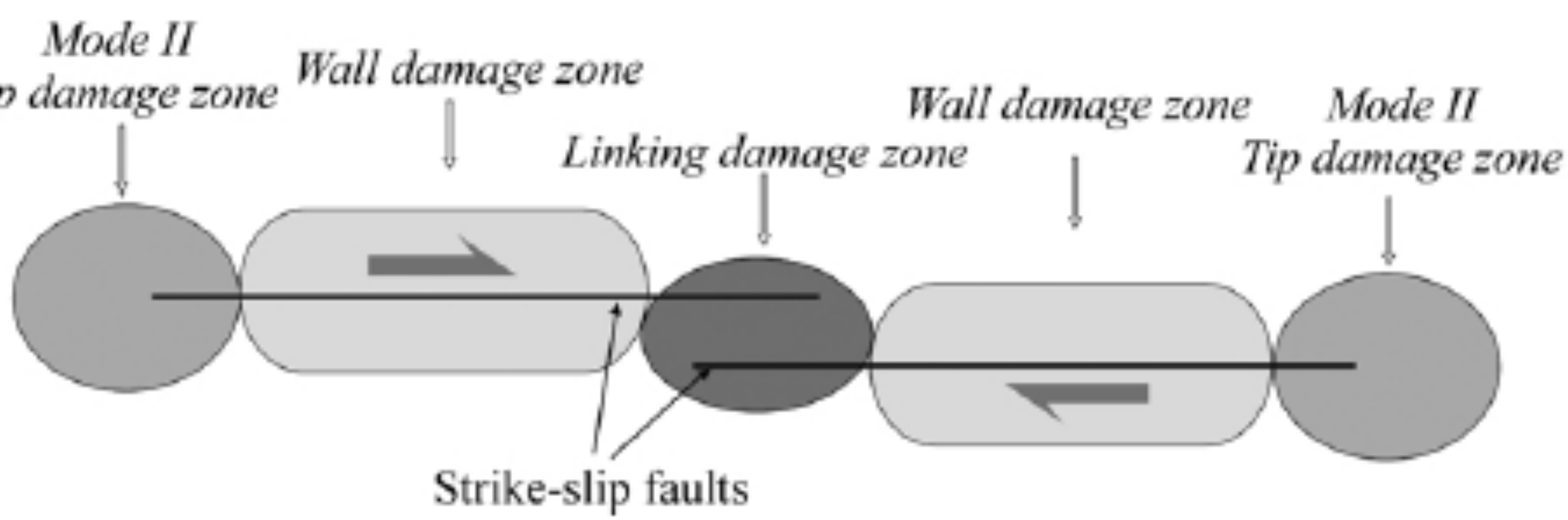
associated fractures



by courtesy A.Brogi, 2011

ASSOCIATED FRACTURES

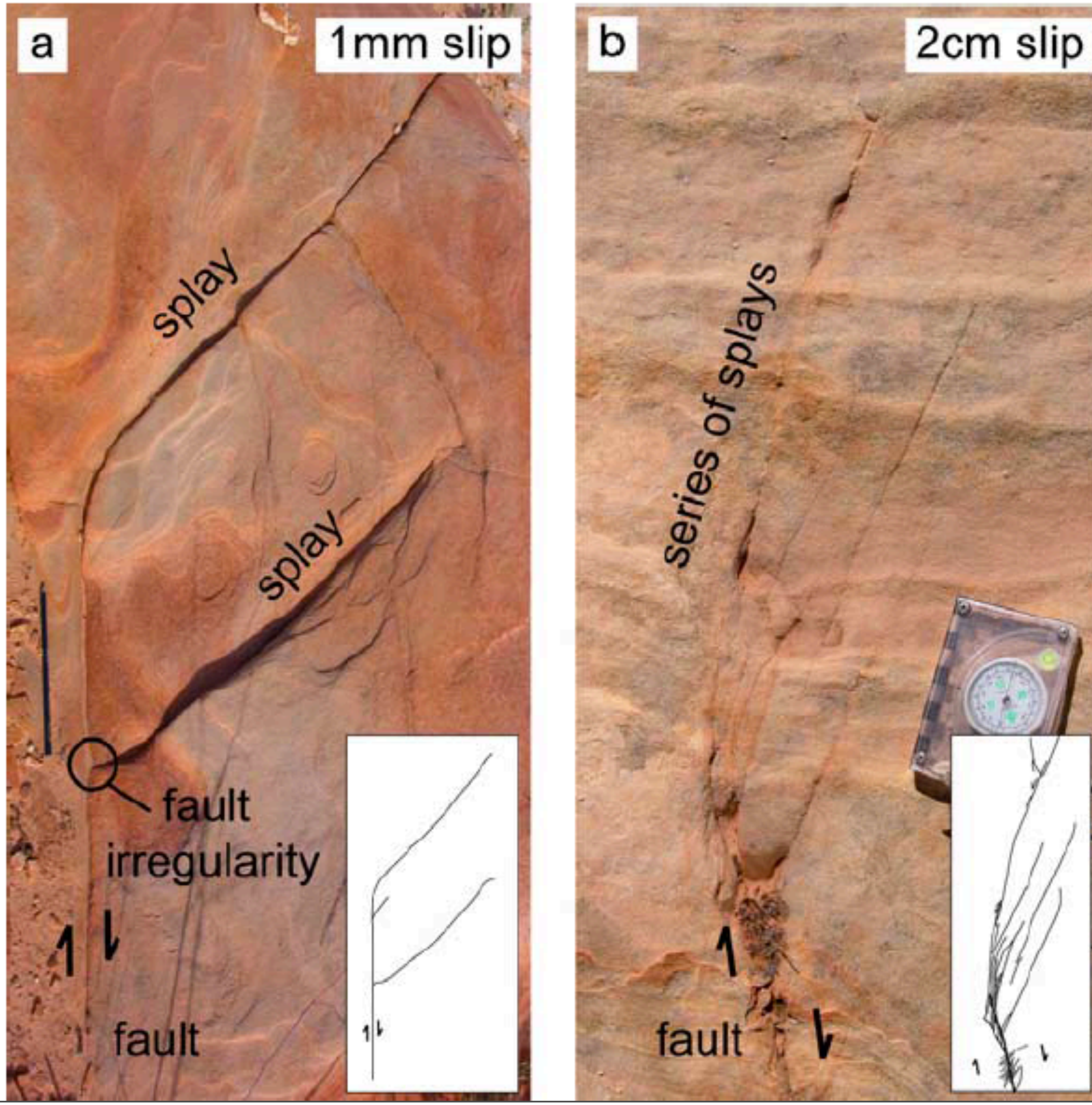




joint fabrics at tip zone (Mode II)

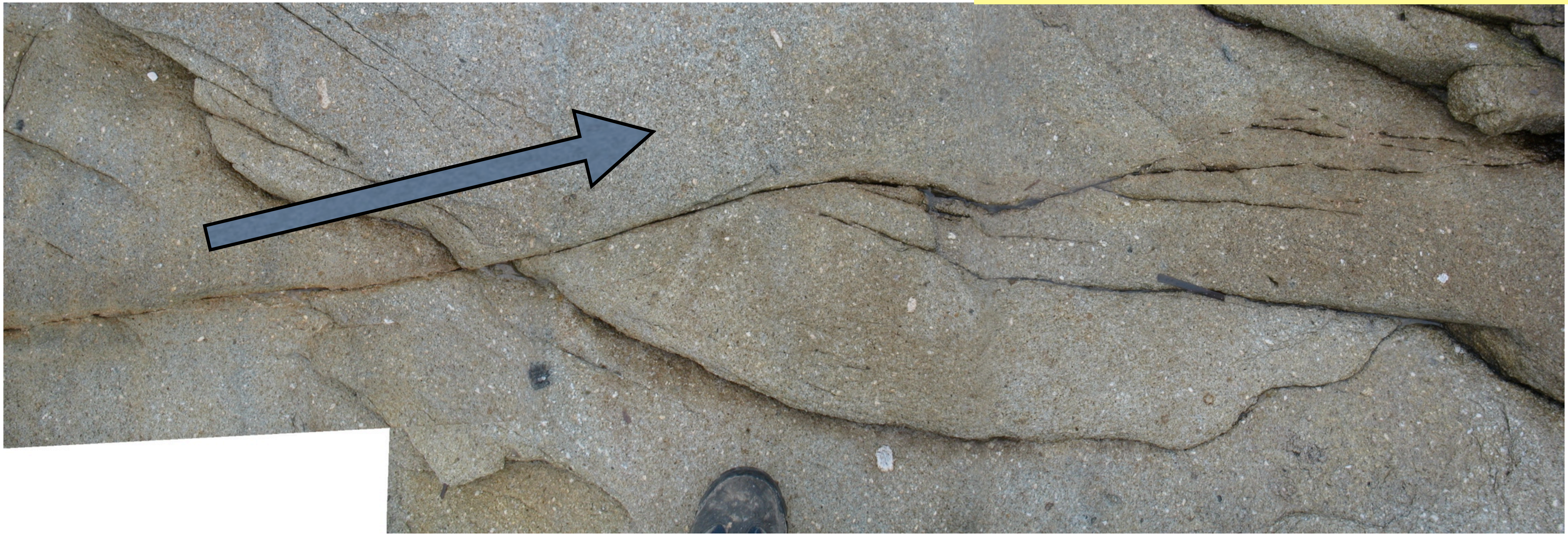
ASSOCIATED FRACTURES

DE JOUSSINEAU AND AYDIN: DAMAGE ZONE EVOLUTION WITH FAULT GROWTH



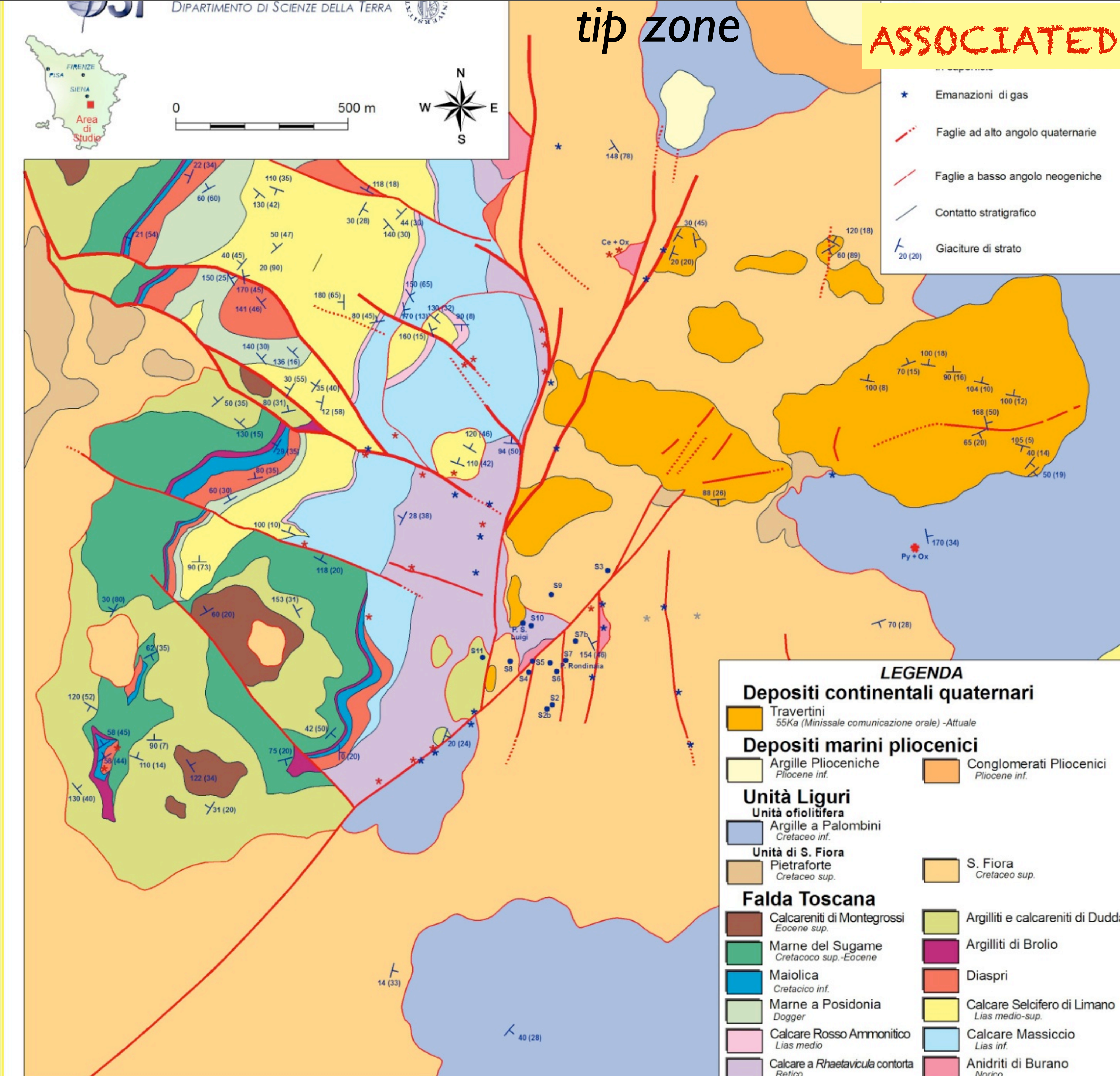
tip zone

ASSOCIATED FRACTURES



ASSOCIATED FRACTURES

tip zone



Brogi and Fabbrini, 2010

ASSOCIATED FRACTURES

tip zone

Mode I

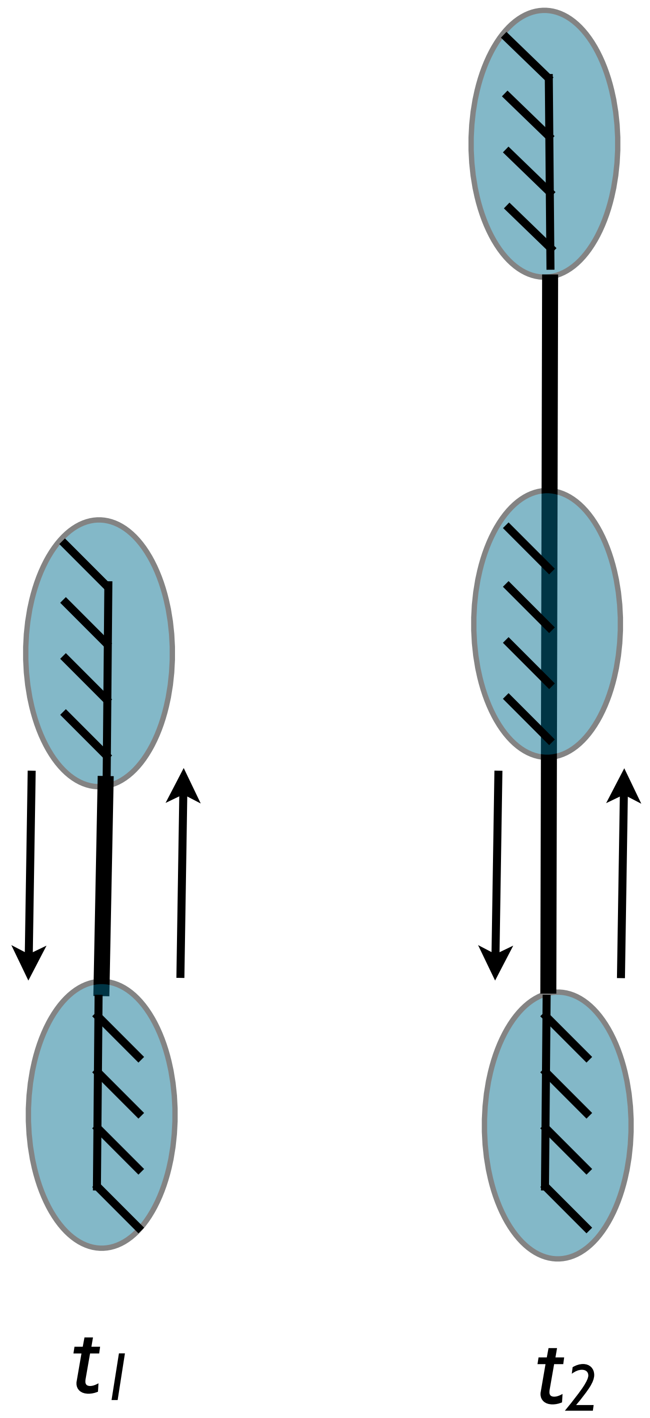
wing structure

Mode II

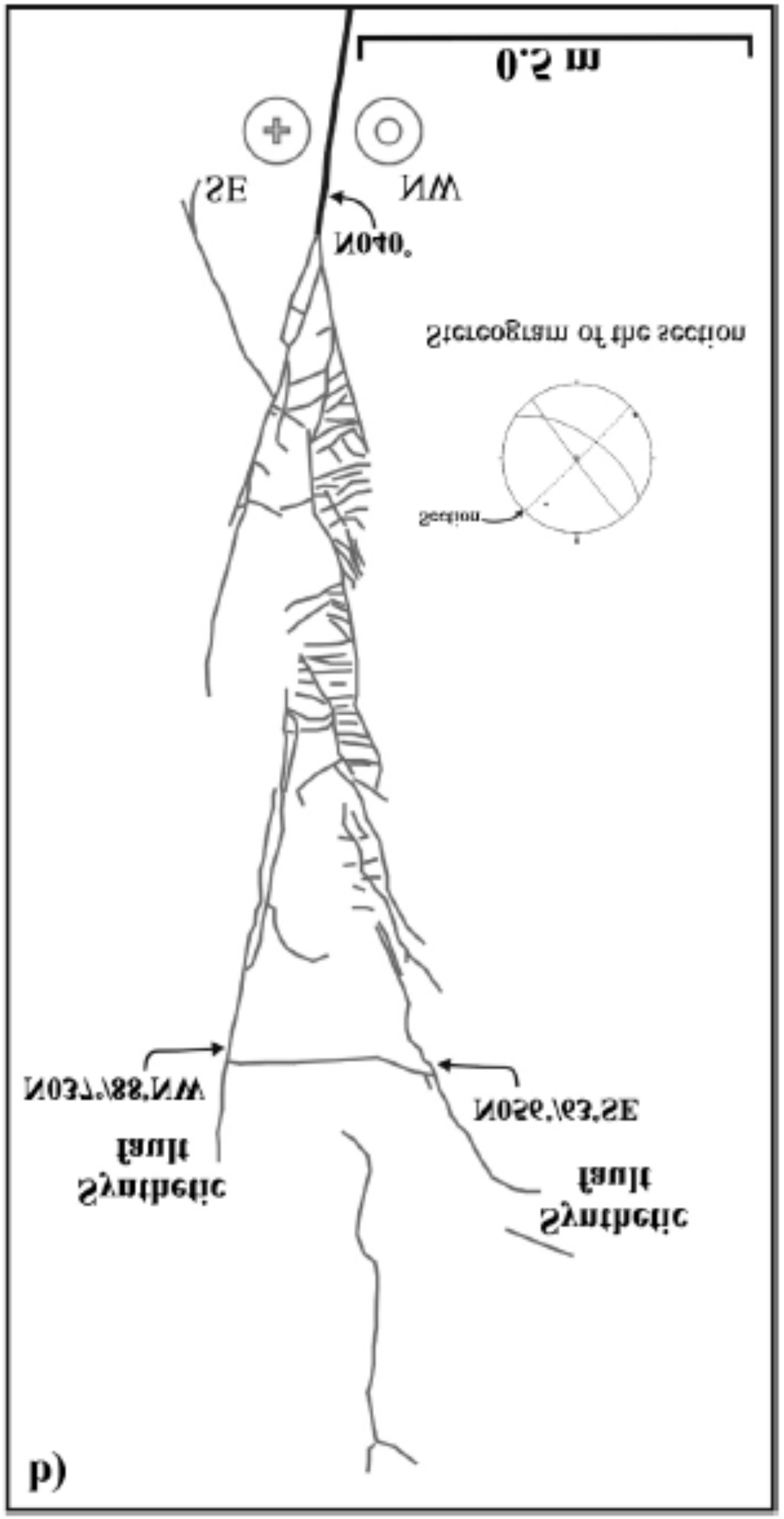
synthetic branch faults

damage zone

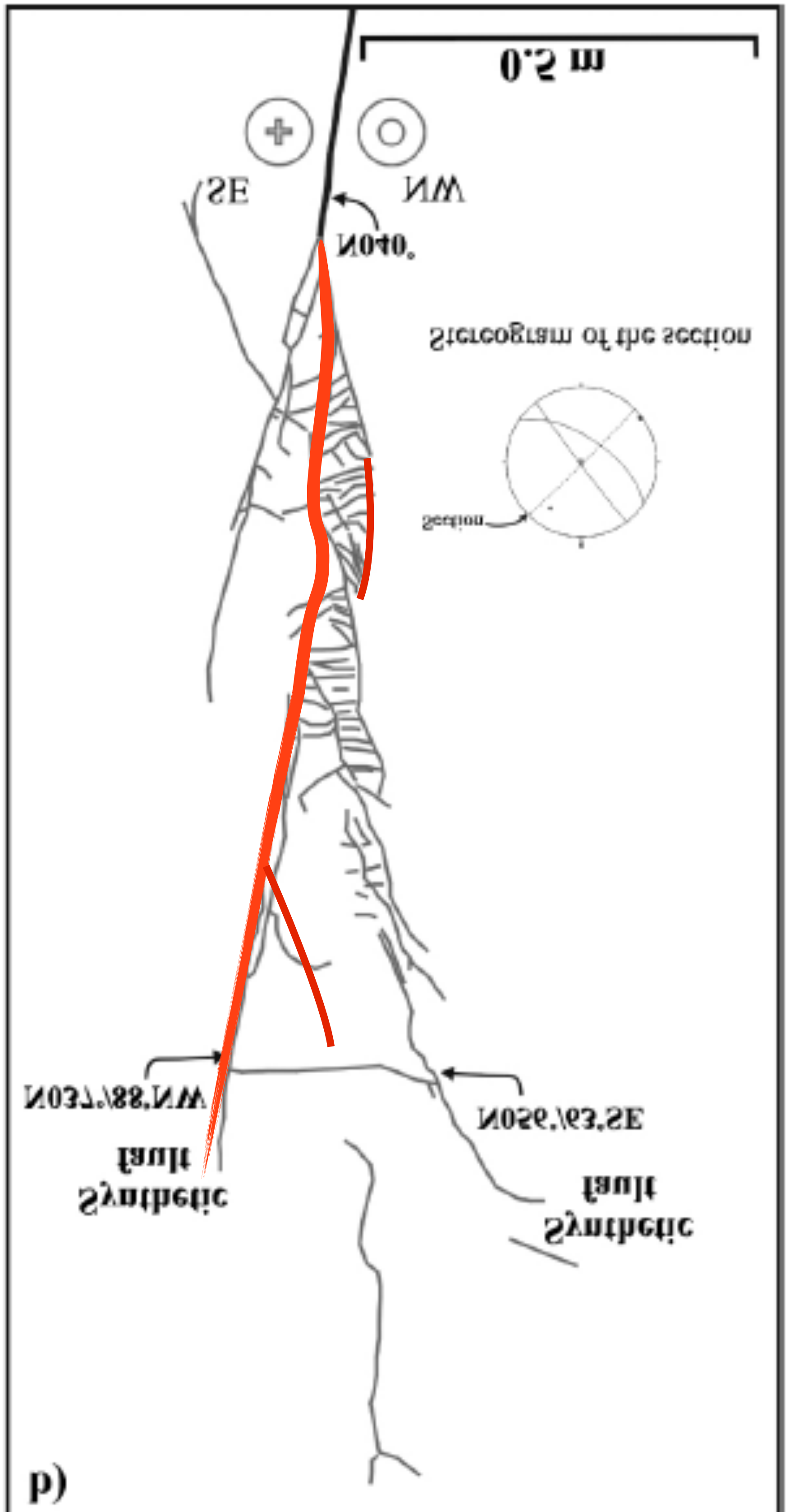
ASSOCIATED FRACTURES



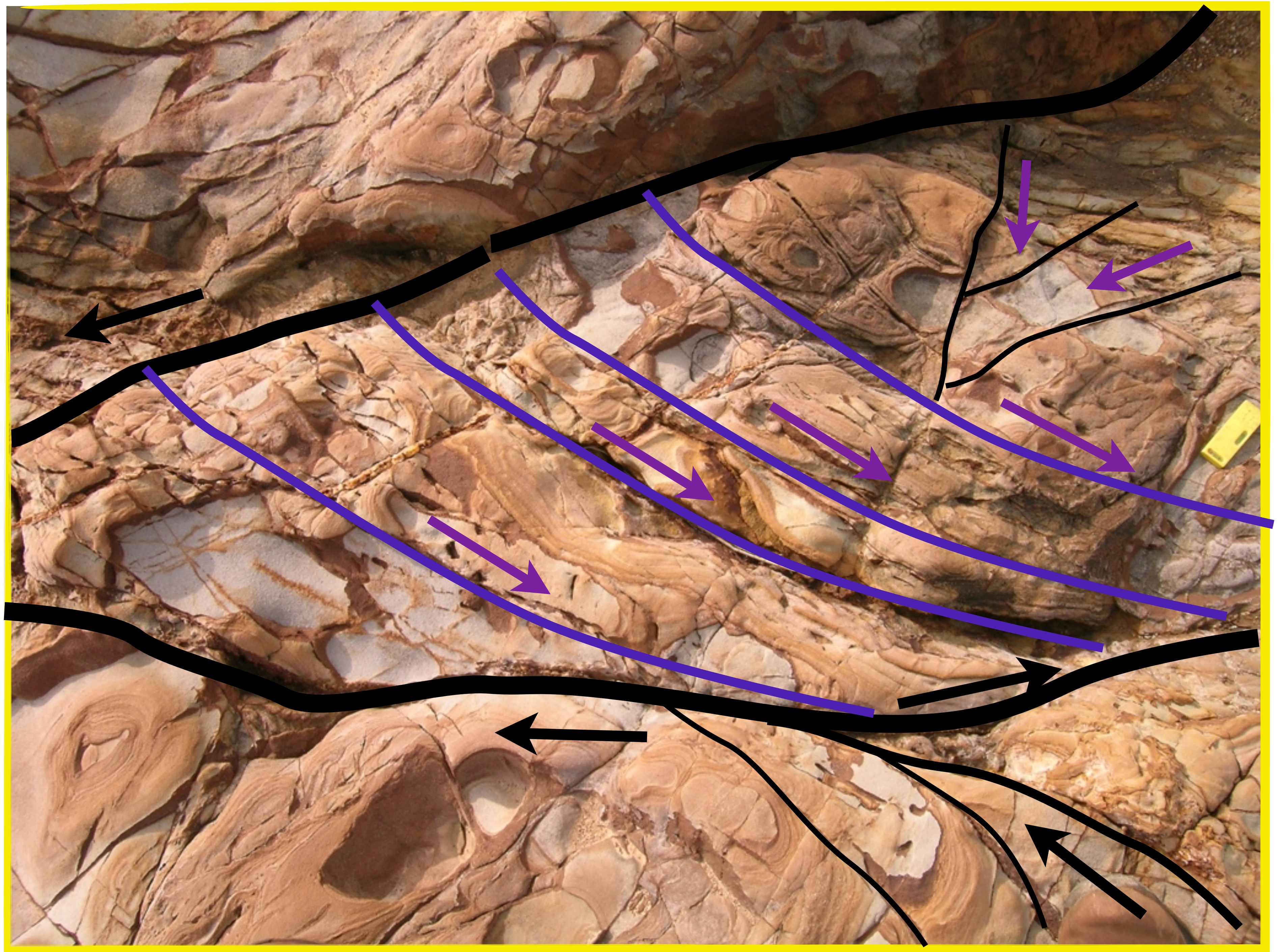
tip zone

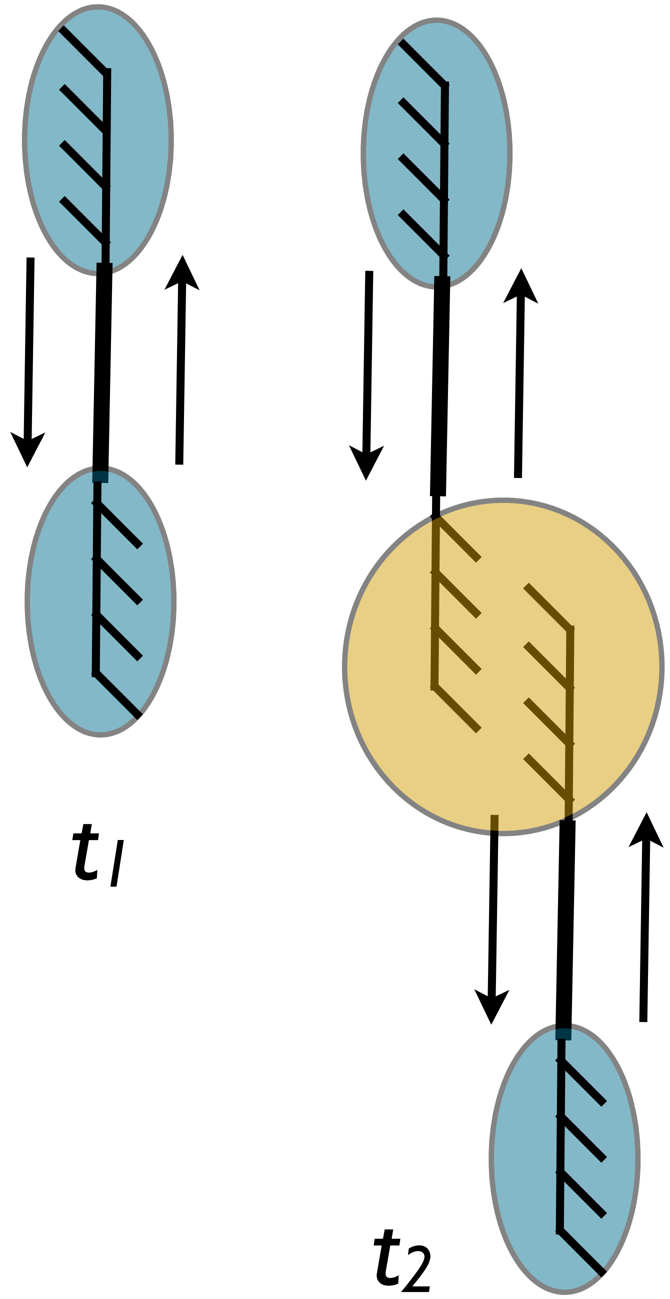

0.5 m
SE
NW
N040°
Stereogram of the section
Section
N037/88NW
Synthetic fault
N056/63SE
Synthetic fault
p)

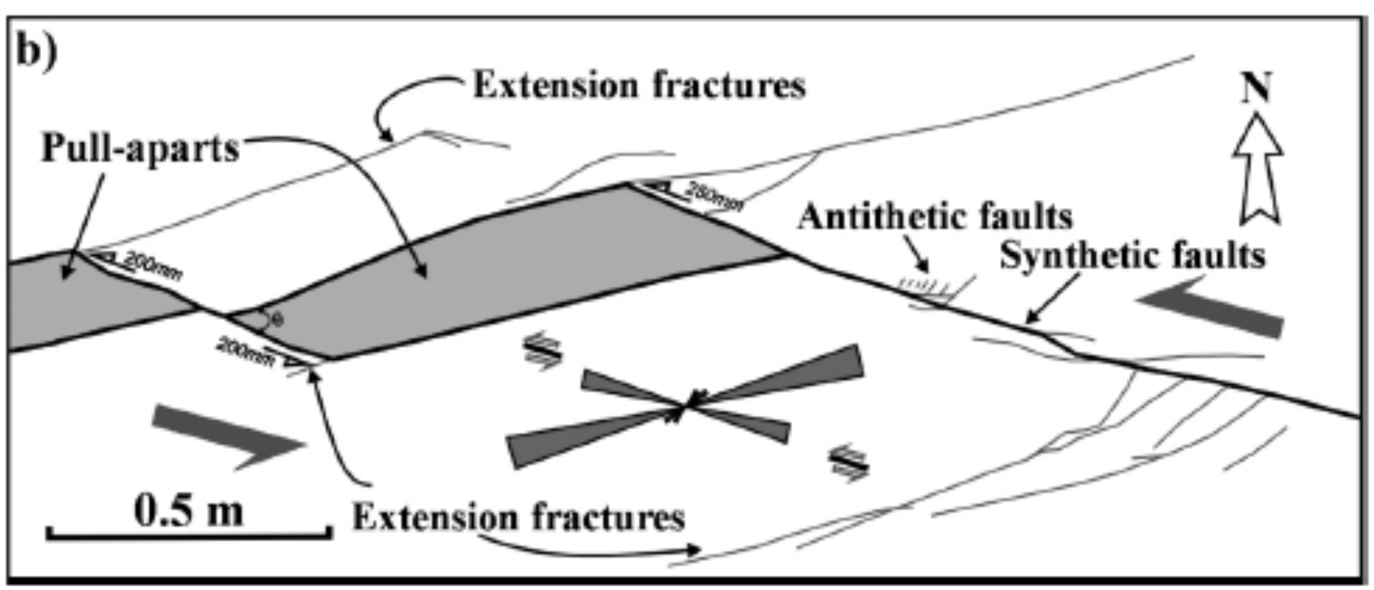
“old” tip zone



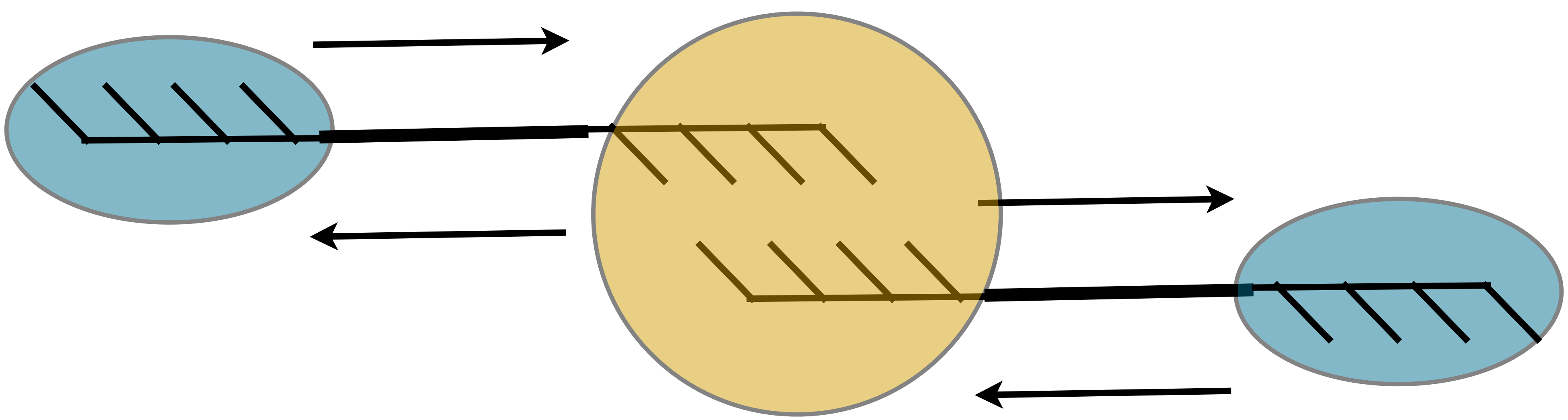
ASSOCIATED FRACTURES

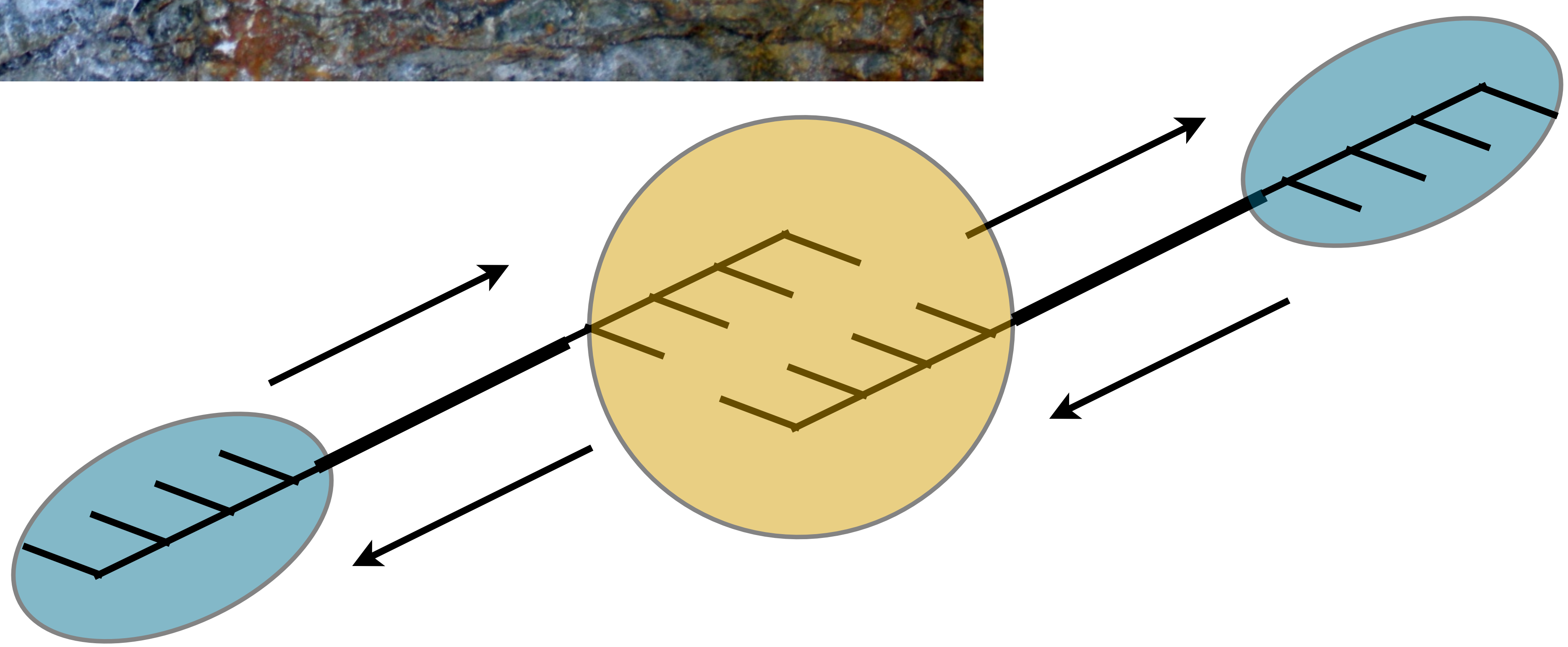



t1
t2


b)
Extension fractures
Pull-aparts
280mm
200mm
200mm
Antithetic faults
Synthetic faults
N
0.5 m
Extension fractures

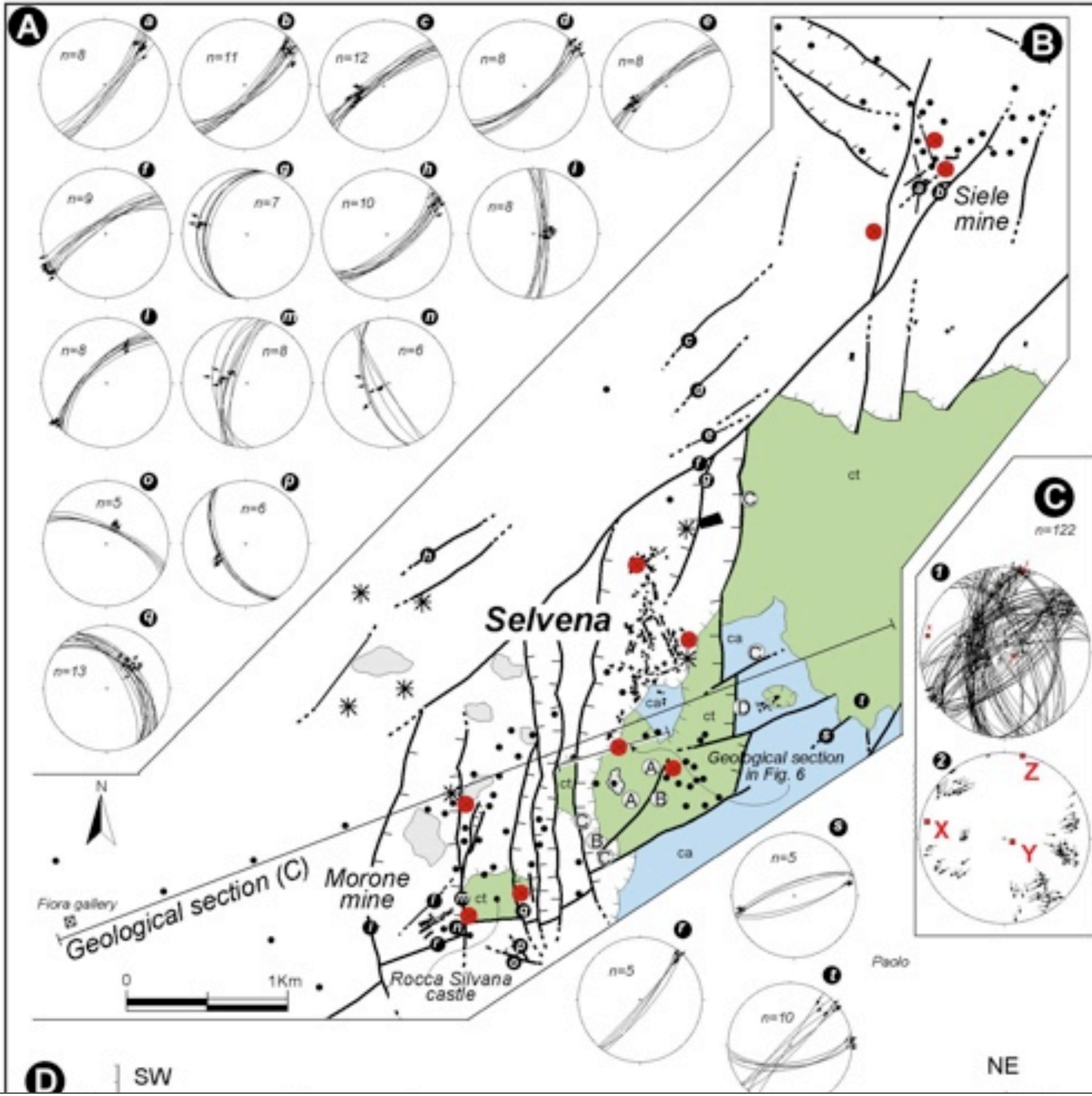

3 cm



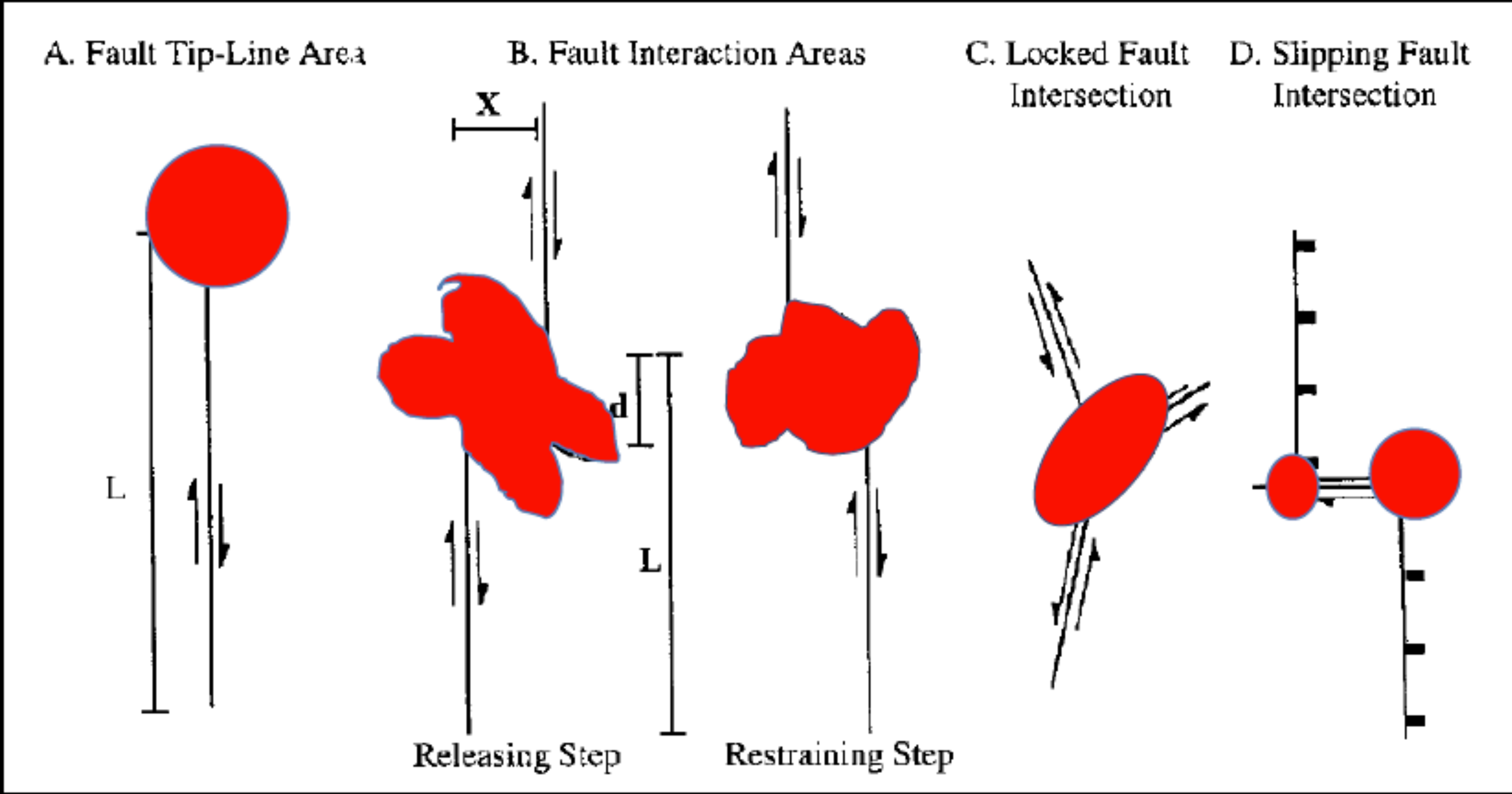


extensional jogs

wing crack

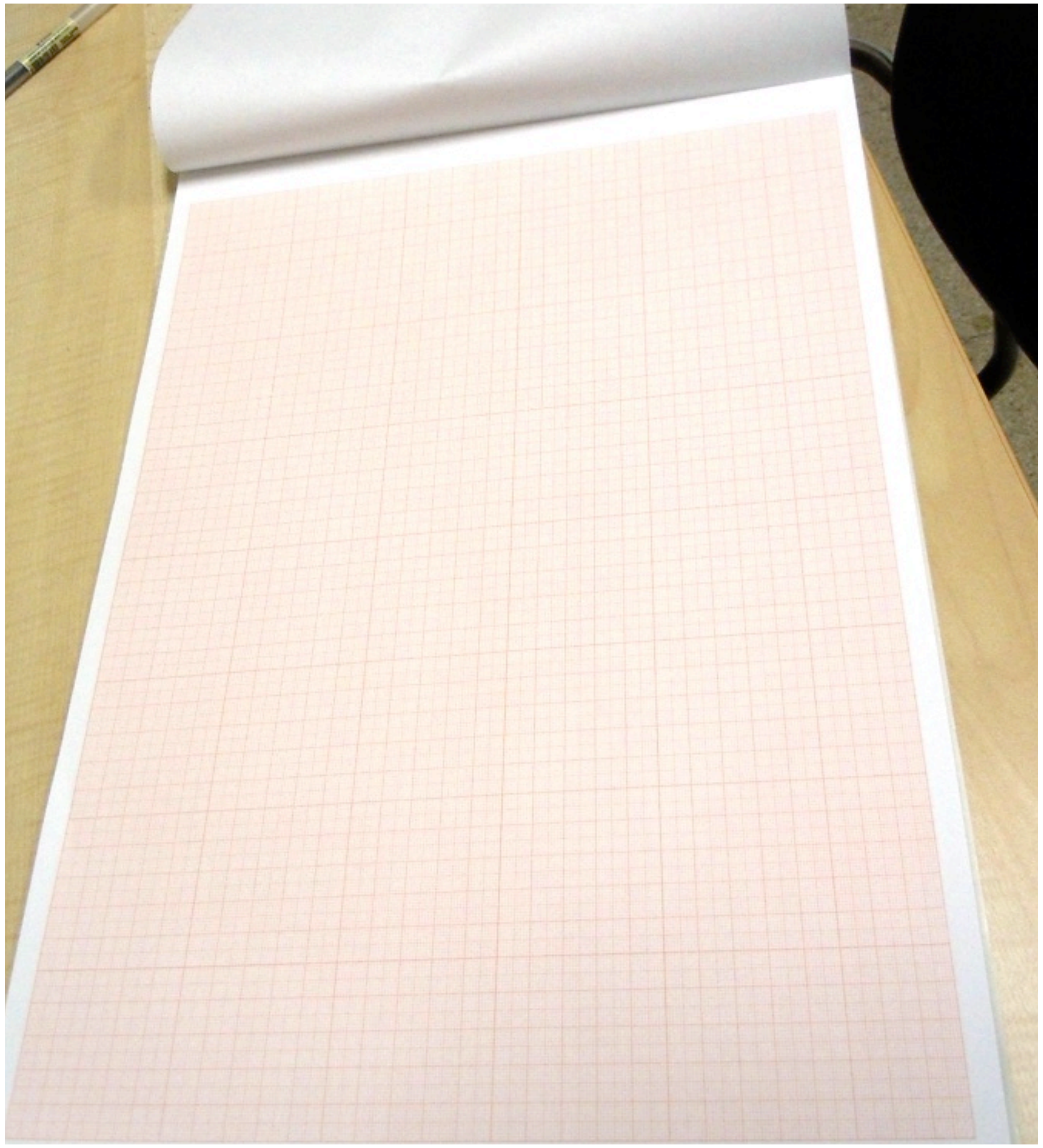

A
B
C
D
Siele mine
Selvena
Morone mine
Rocca Silvana castle
Fiora gallery
Geological section (C)
Geological section in Fig. 6
0
1Km
N
SW
NE
Paolo
ct
ca
n=122
Z
X
Y

Relationships between thermal spring(s) and brittle structures



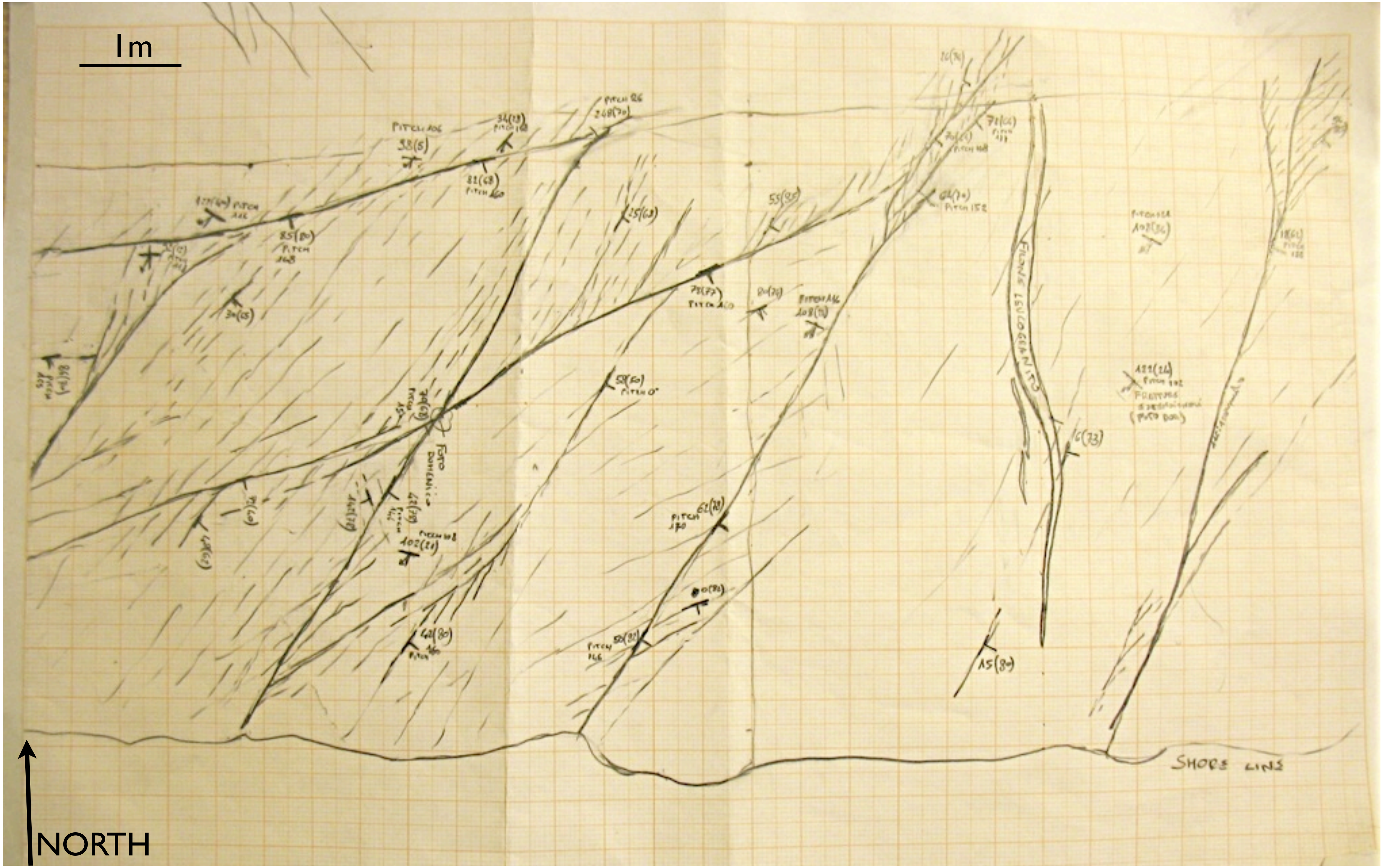
Curewitz and Karson, 1997 - J. Volc. Geoth. Res.

How to represent the fracture network?



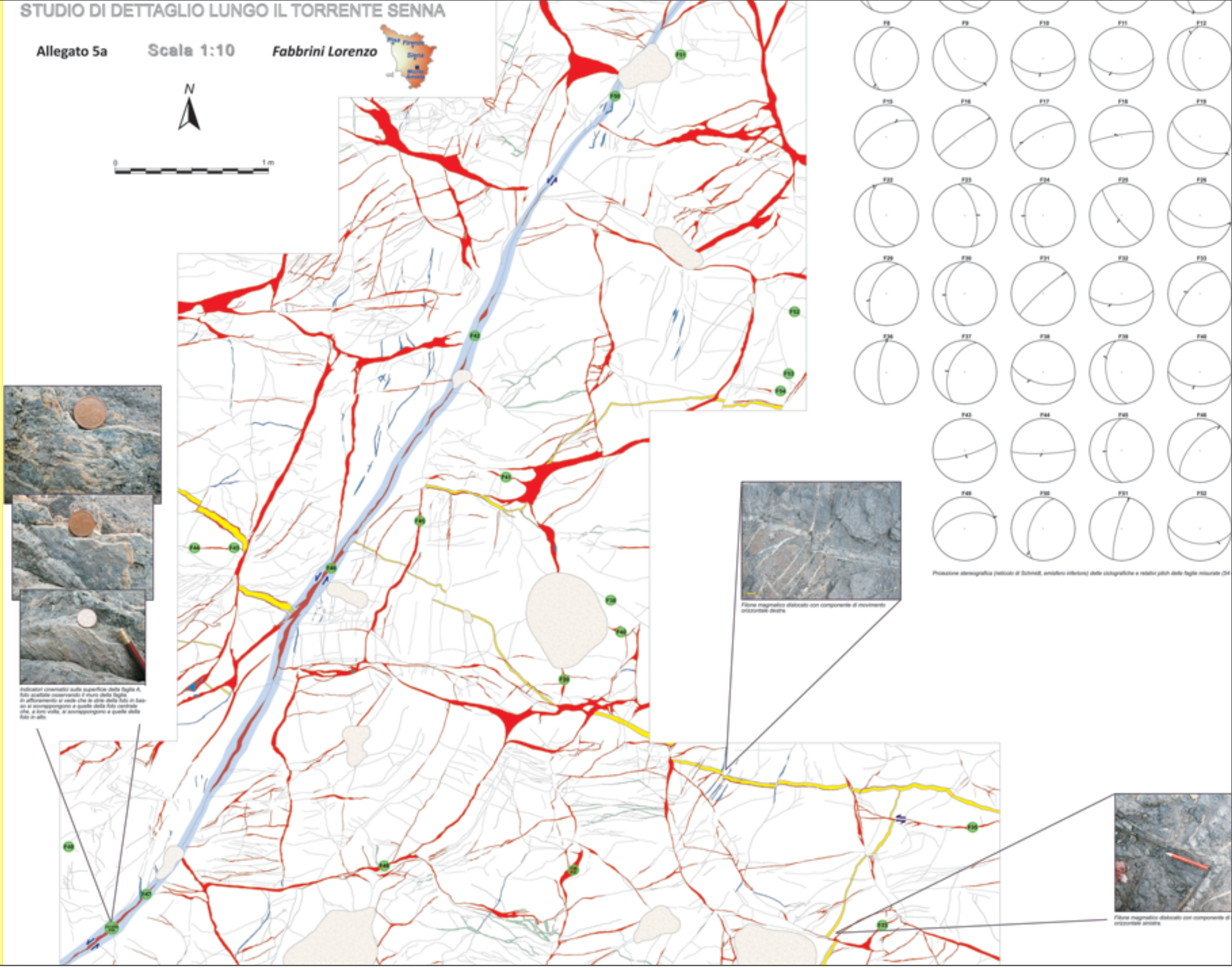

length and orientation
length and orientation


length and orientation

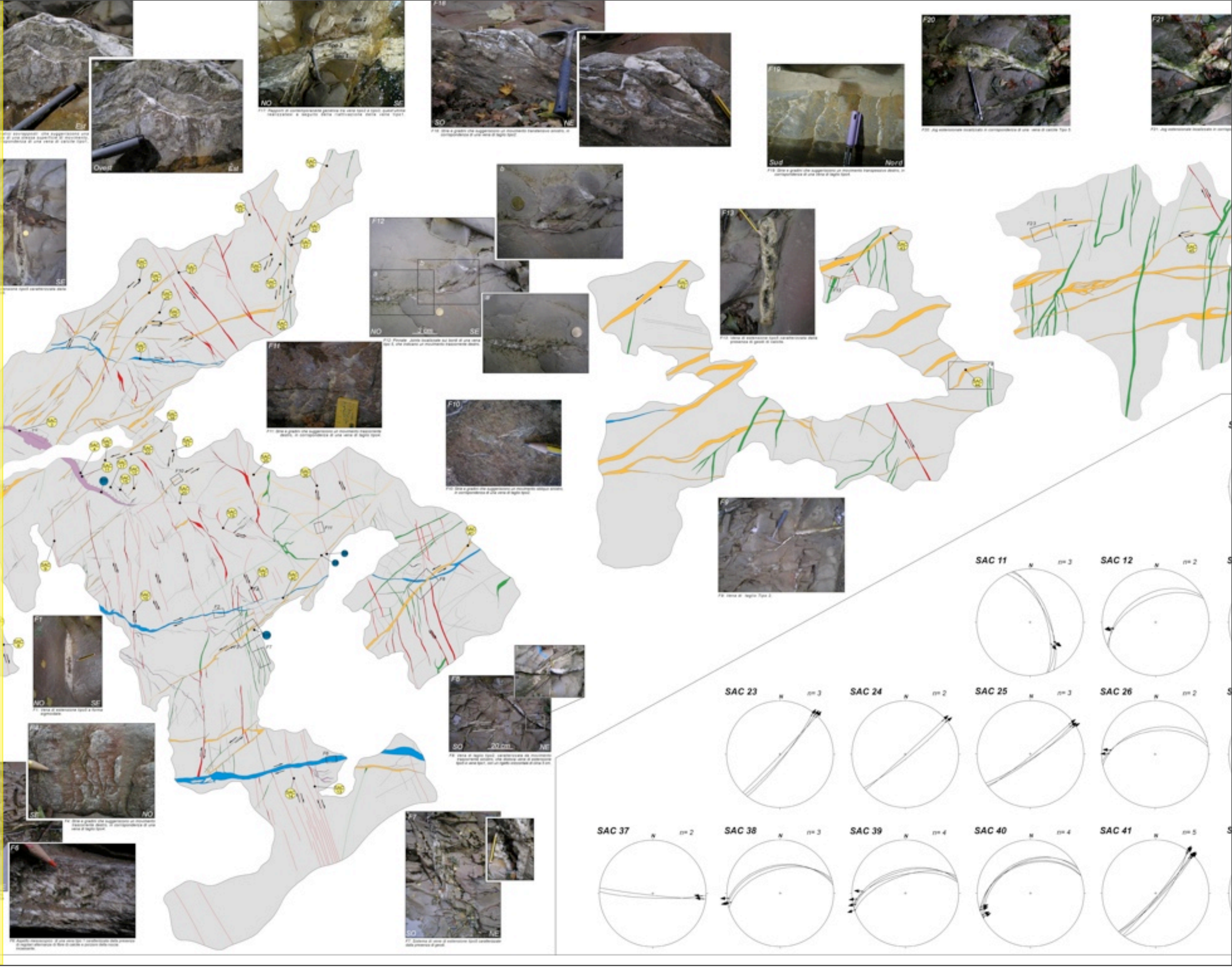

1m
NORTH
SHORE LINE

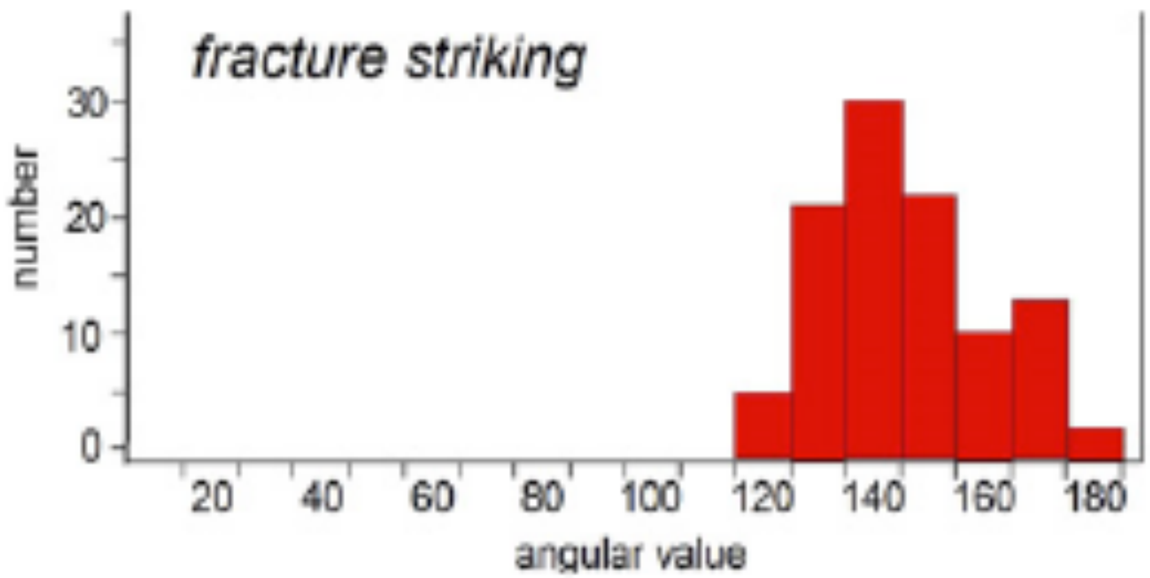
scan - box method

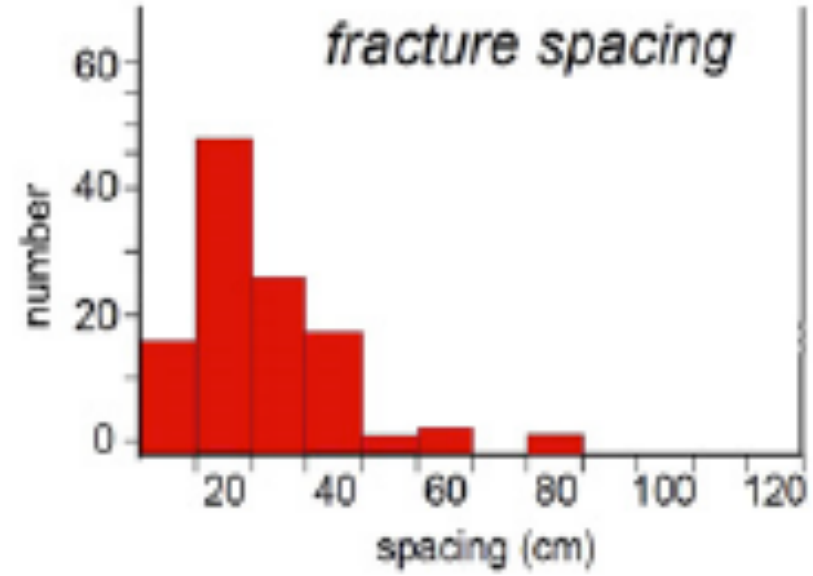
D. Liotta - international school on geothermal exploration



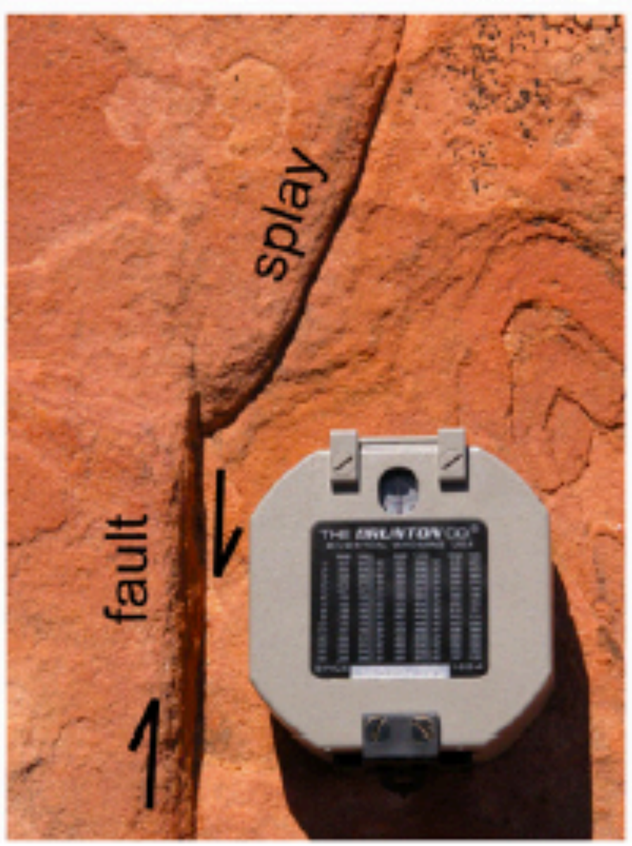
D. Liotta - international school on geothermal exploration



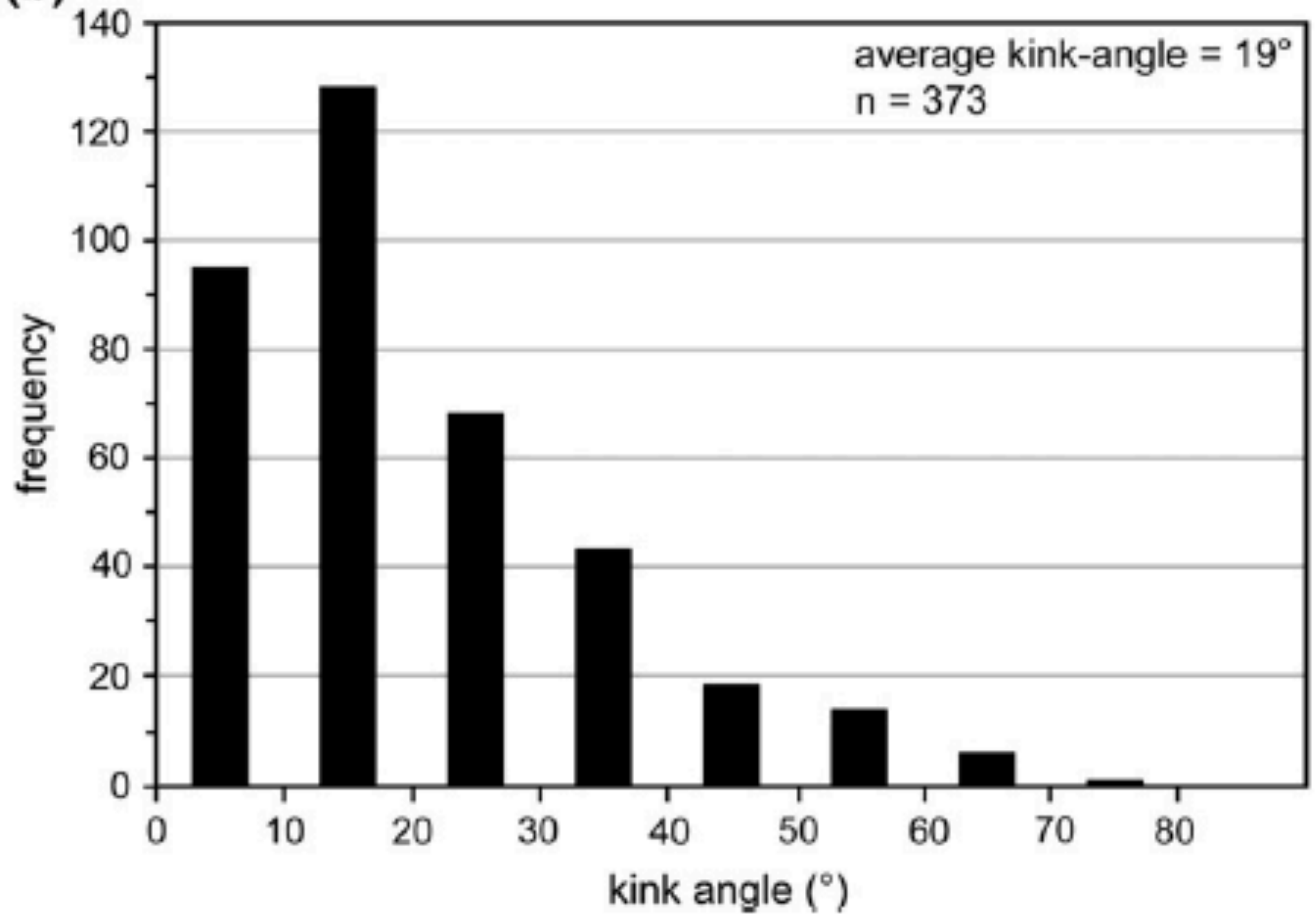

fracture striking
number
0
10
20
30
20
40
60
80
100
120
140
160
180
angular value

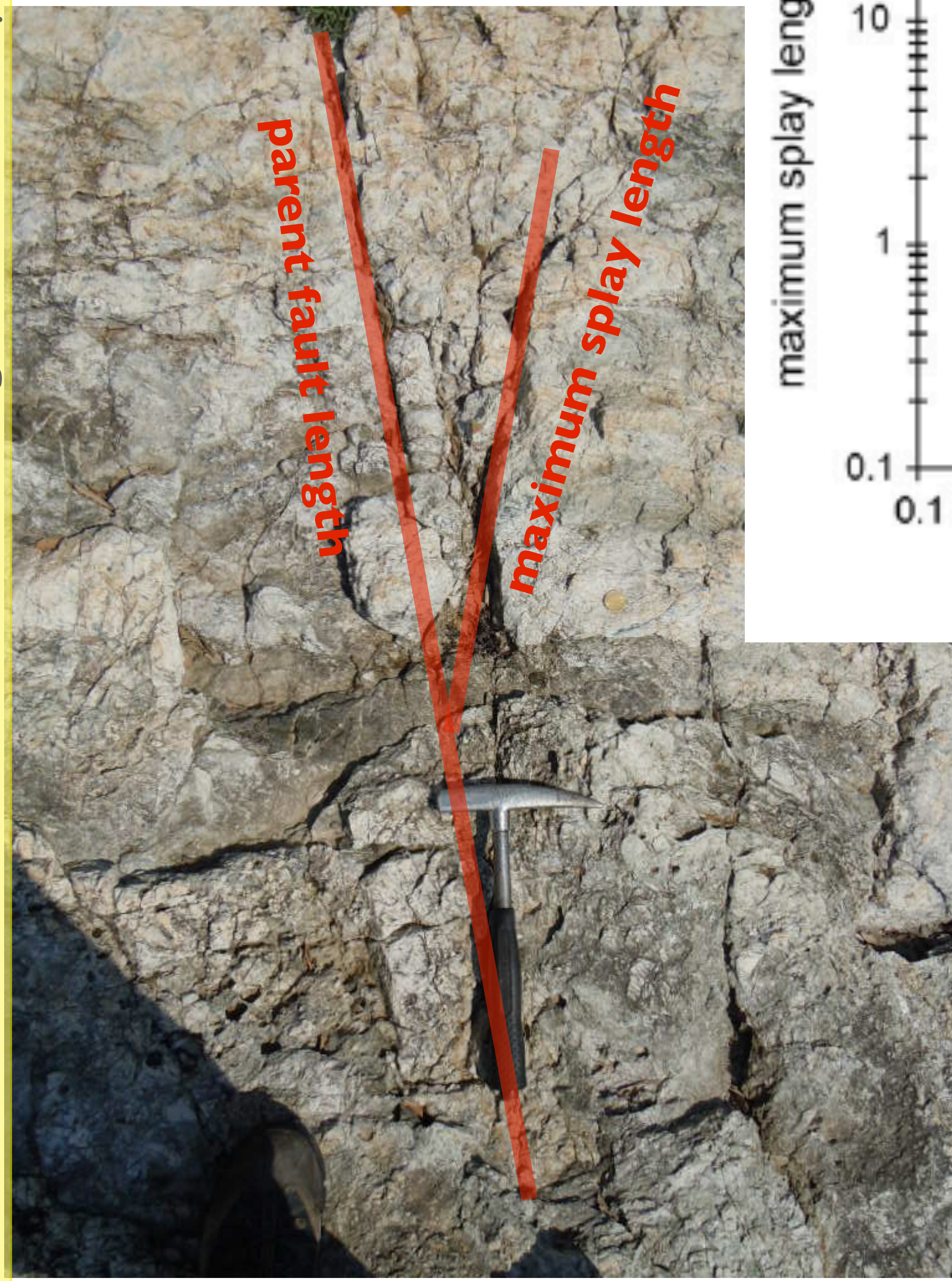

fracture spacing
number
0
20
40
60
20
40
60
80
100
120
spacing (cm)

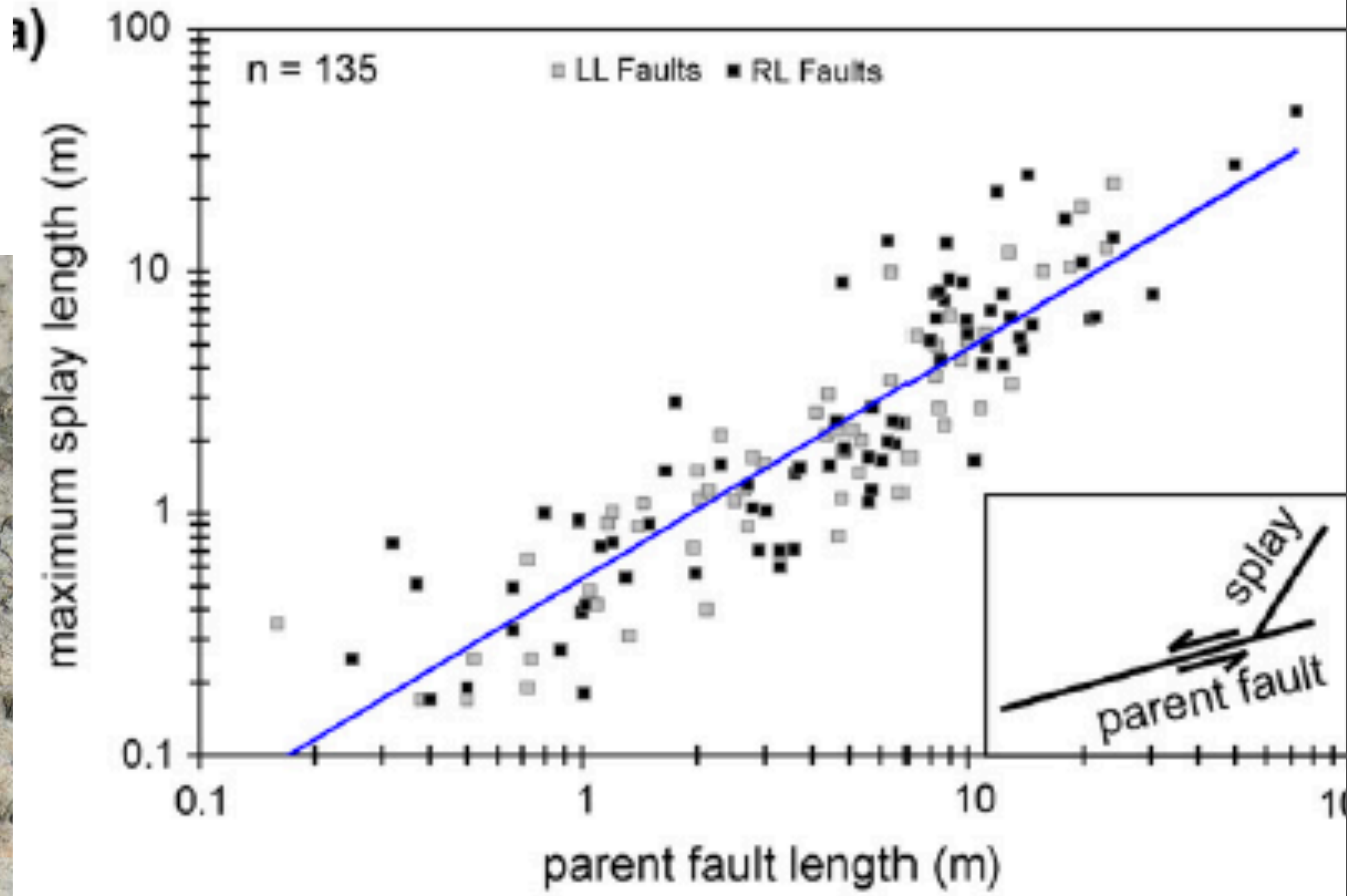
(a)


splay
fault

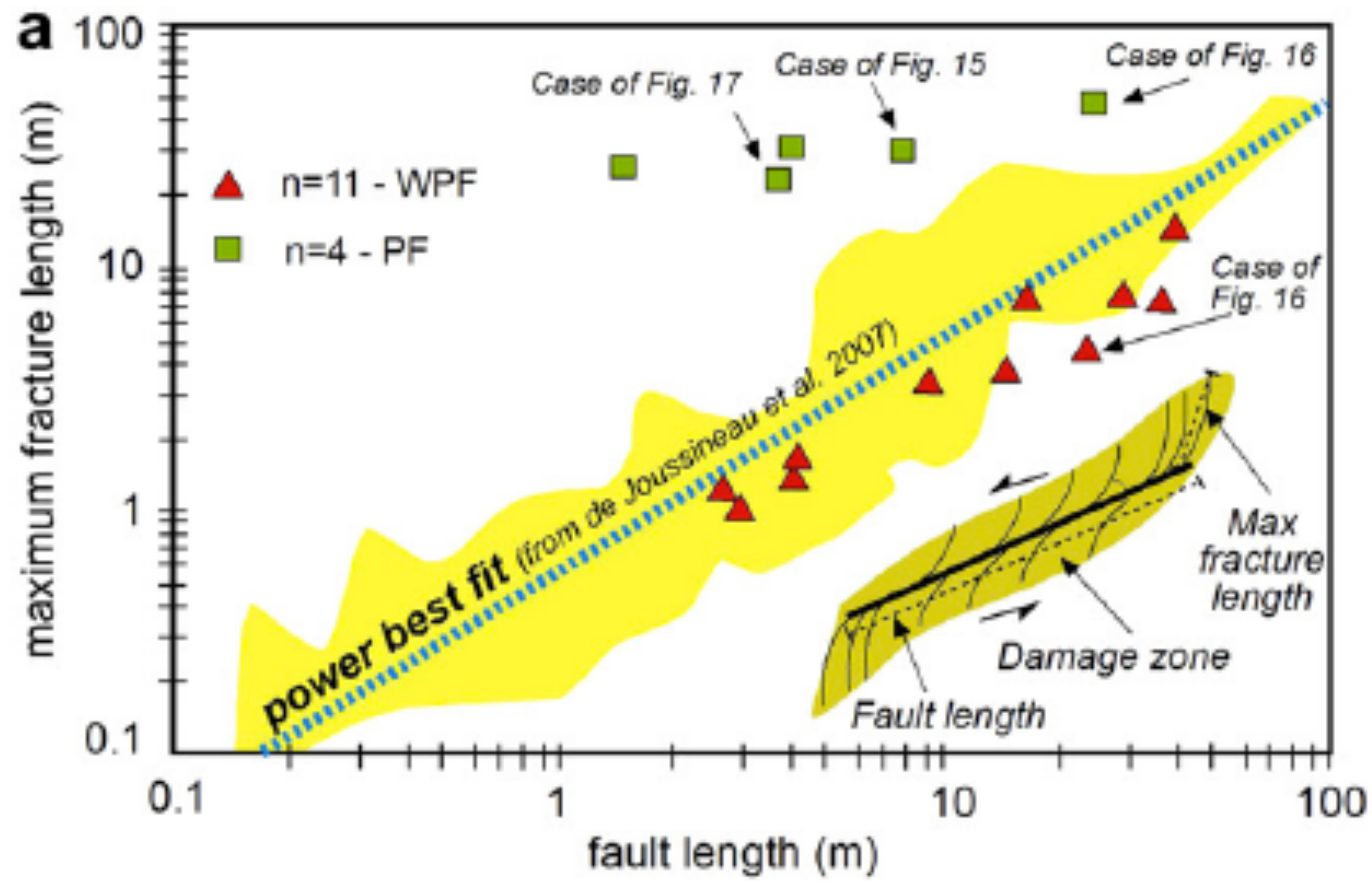
(b)

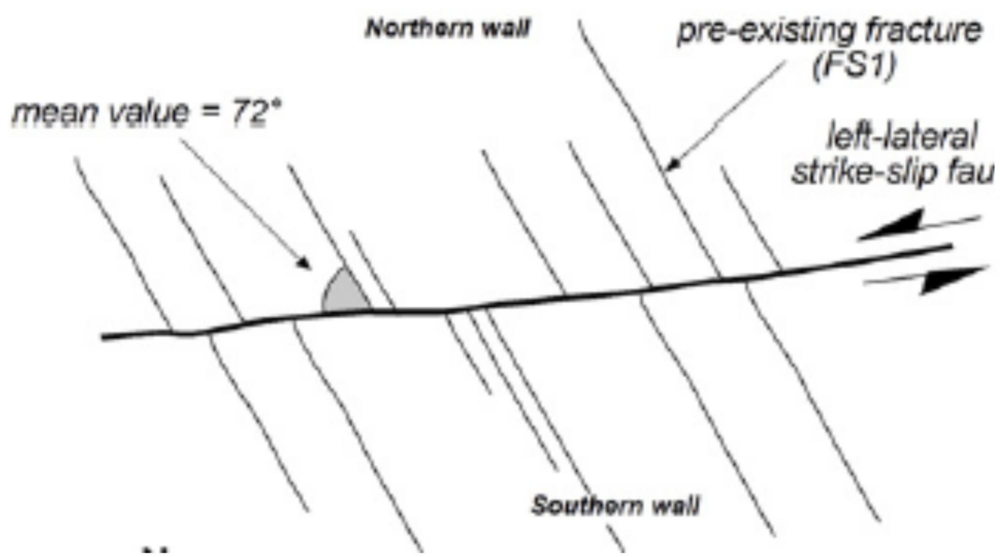

average kink-angle = 19°
n = 373
frequency
0
20
40
60
80
100
120
140
0
10
20
30
40
50
60
70
80
kink angle (°)

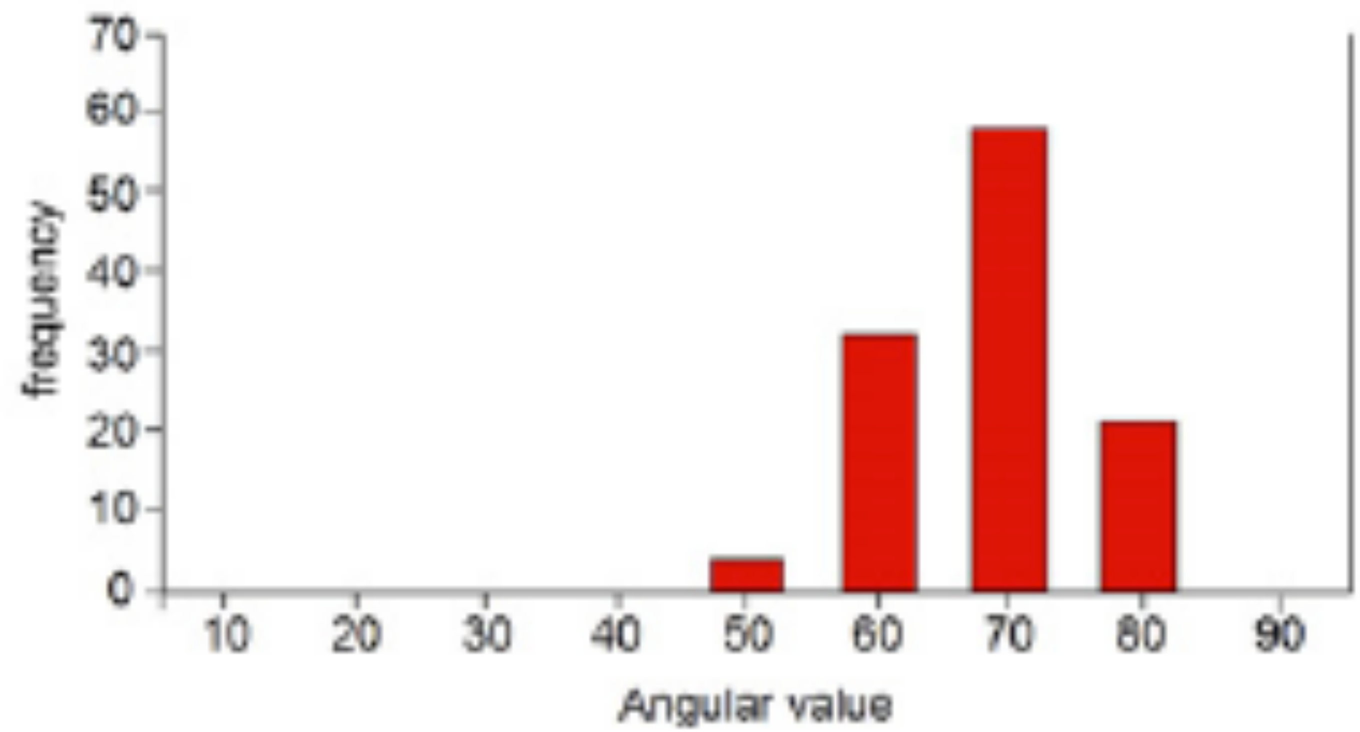

parent fault length
maximum splay length


a)
n = 135
LL Faults
RL Faults
maximum splay length (m)
100
10
1
0.1
0.1
1
10
parent fault length (m)
splay
parent fault

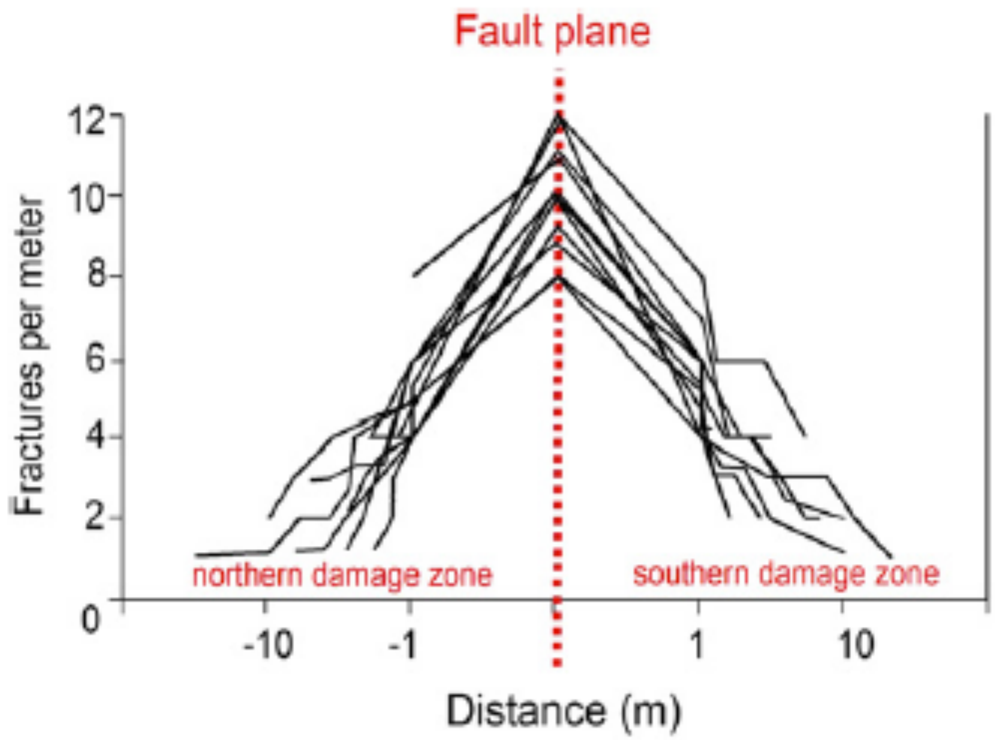
pre-existing fractures

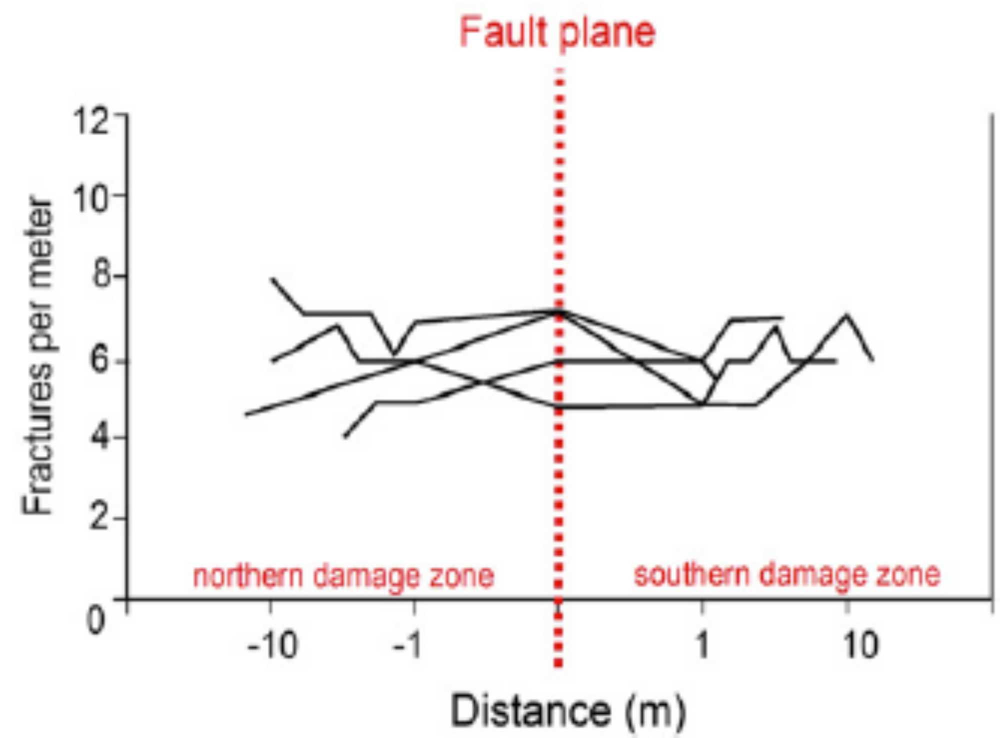






interference with pre-existing fracture network

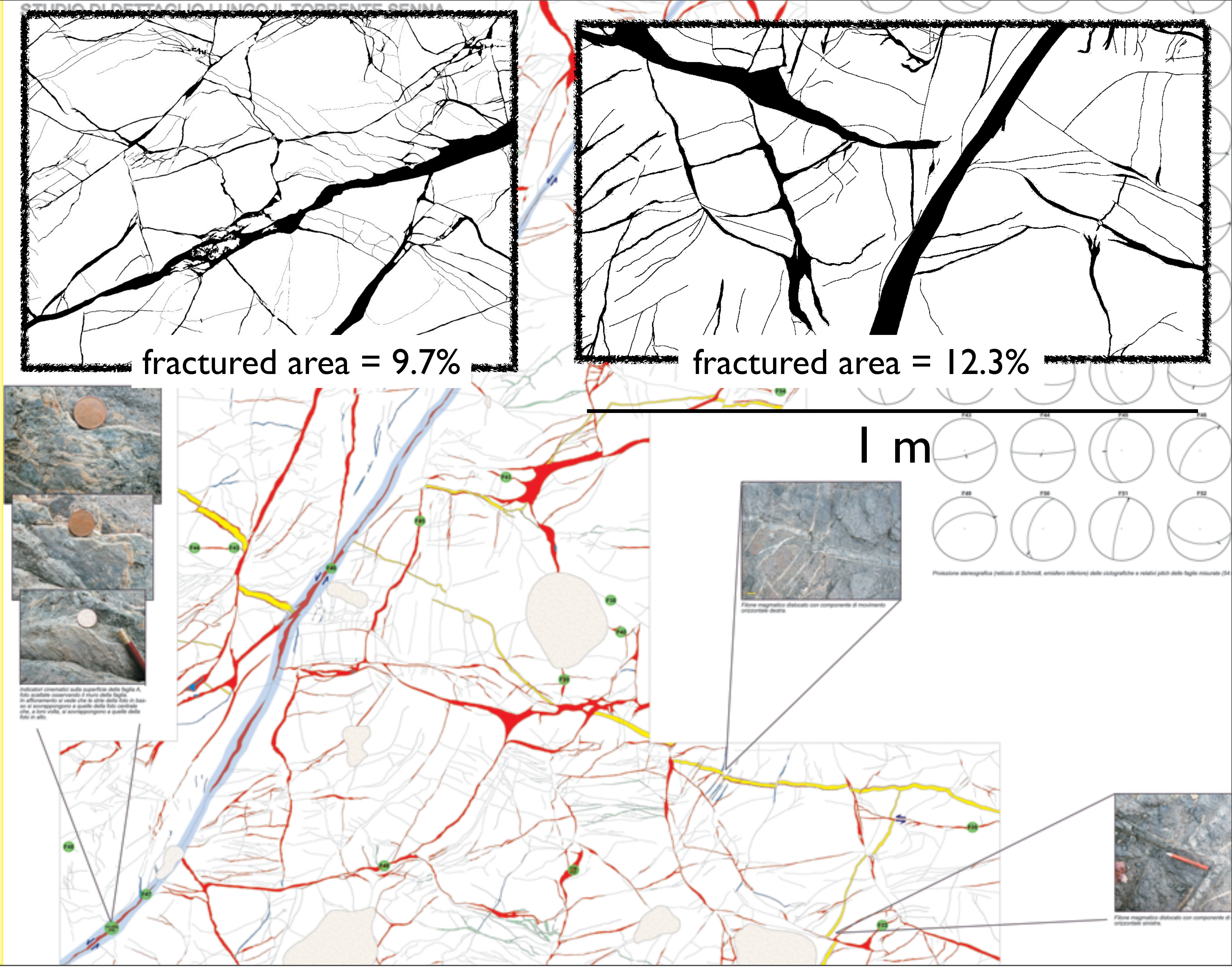


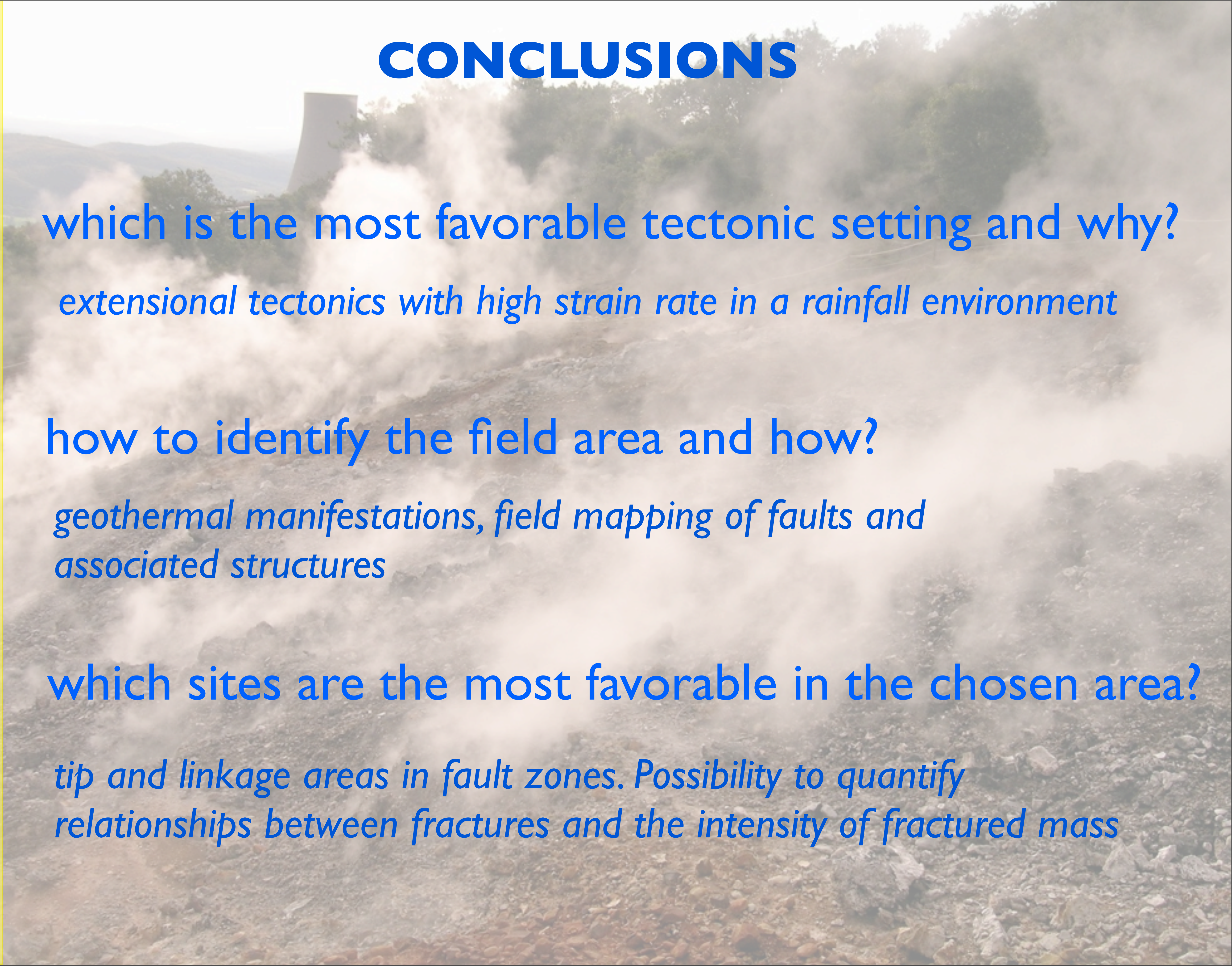


undeformed bedrock — deformed bedrock

new fractures — reactivation of old fractures

D. Liotta - international school on geothermal exploration





CONCLUSIONS

which is the most favorable tectonic setting and why?

extensional tectonics with high strain rate in a rainfall environment

how to identify the field area and how?

geothermal manifestations, field mapping of faults and associated structures

which sites are the most favorable in the chosen area?

tip and linkage areas in fault zones. Possibility to quantify relationships between fractures and the intensity of fractured mass

source list for the figures

Caine et al.(1996) - Fault zone architecture and permeability structure. Geology

Curewitz and Karson (1997) - Structural setting of hydrothermal flow: .... J. Volc.Geth.Res.

Sibson (2000) - Fluid involvement in normal faulting. Journal of Geodynamics

Kim et al.(2004) - Fault damage zones. J. Structural Geology

Fabbrini (2010) - Relazioni fra strutture e circolazioni di fluidi idrotermali:...... PhD thesis, Siena Univ.

Brogi (2011) - Variation in fracture patterns in damage zones. J.Struct. Geol.

Brogi et al. (2011) - Sb–Hg ore deposit distribution controlled by brittle structures: ..... Ore Geology Review