Paleoseismology, methods and examples

Paleoseismology

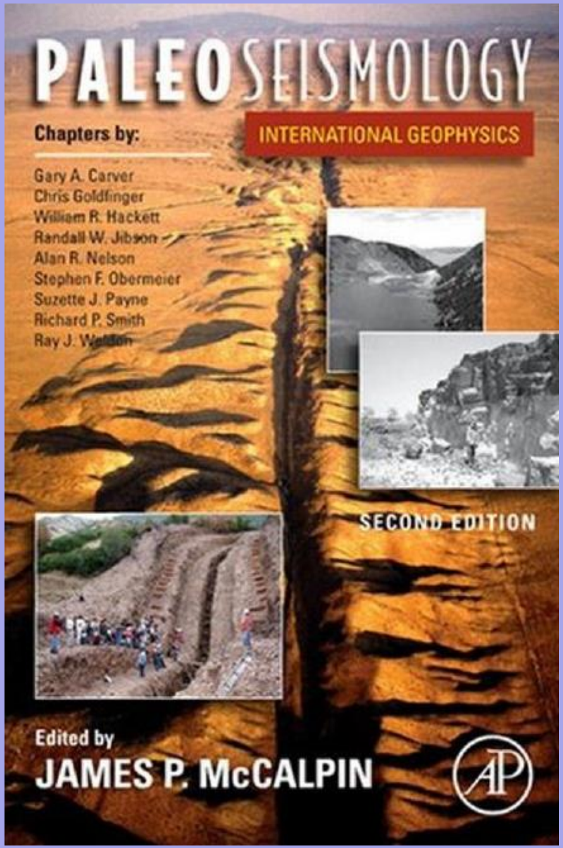
- behaving of seismogenic fault in geological history

Paleoseismology studies **<u>prehistoric</u>** earthquakes from geological record

Seismologists - data measured instrumentally during earthquakes

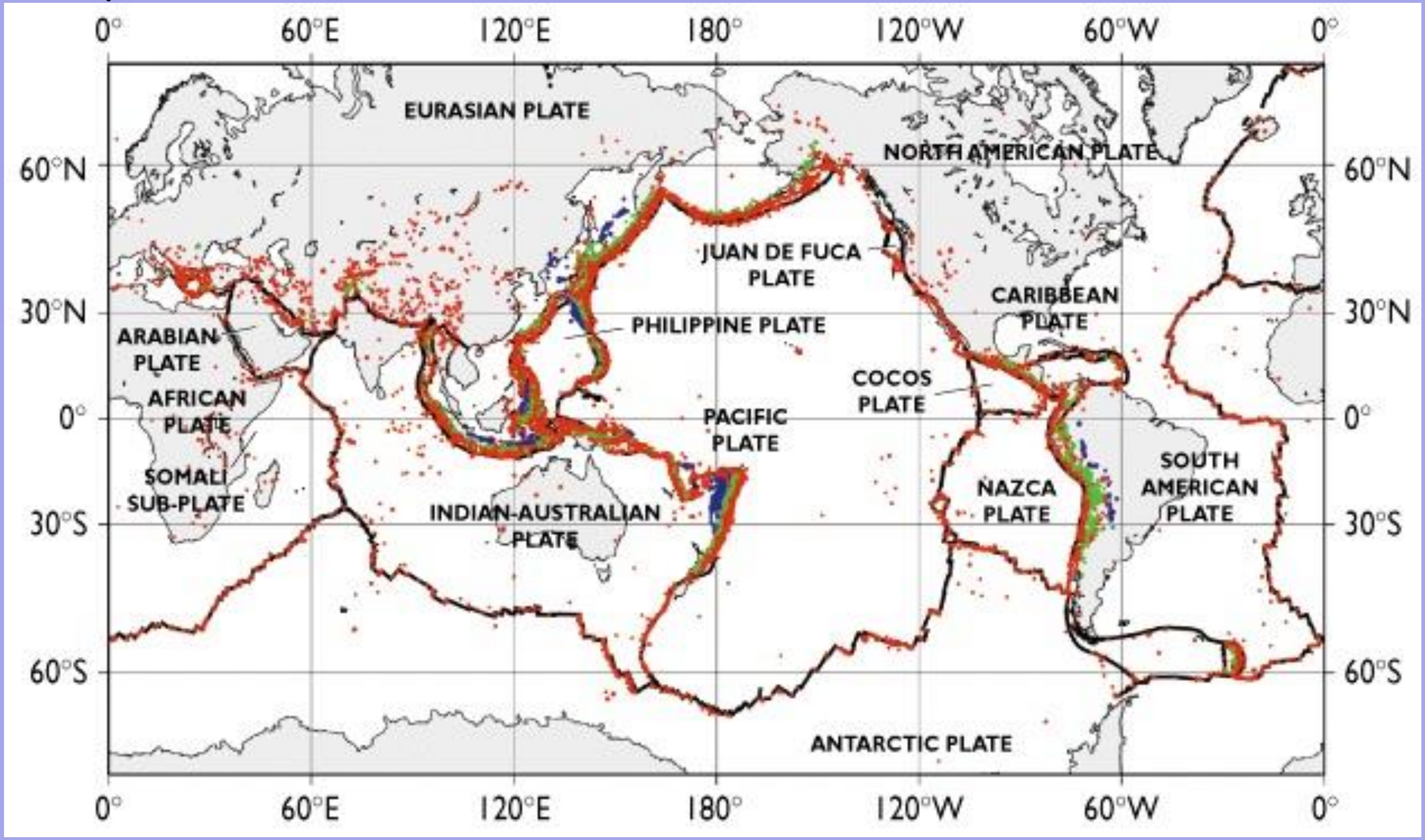
X

Paleoseismologists interpret **geological phenomena** accompanied by individual EQs



McCALPIN, J. (2009). *Paleoseismology.* San Diego: Academic Press.

Why?



Present day seismicity – plate boundaries, intraplate regions
Catastrophic EQs – sometimes in areas with faults with no present day seismicity, - seismic cycle – longer reccurence interval (China, New Zealand)

Most areas – record of historical EQs only several hundred yrs (historical and instrumental seismicity)

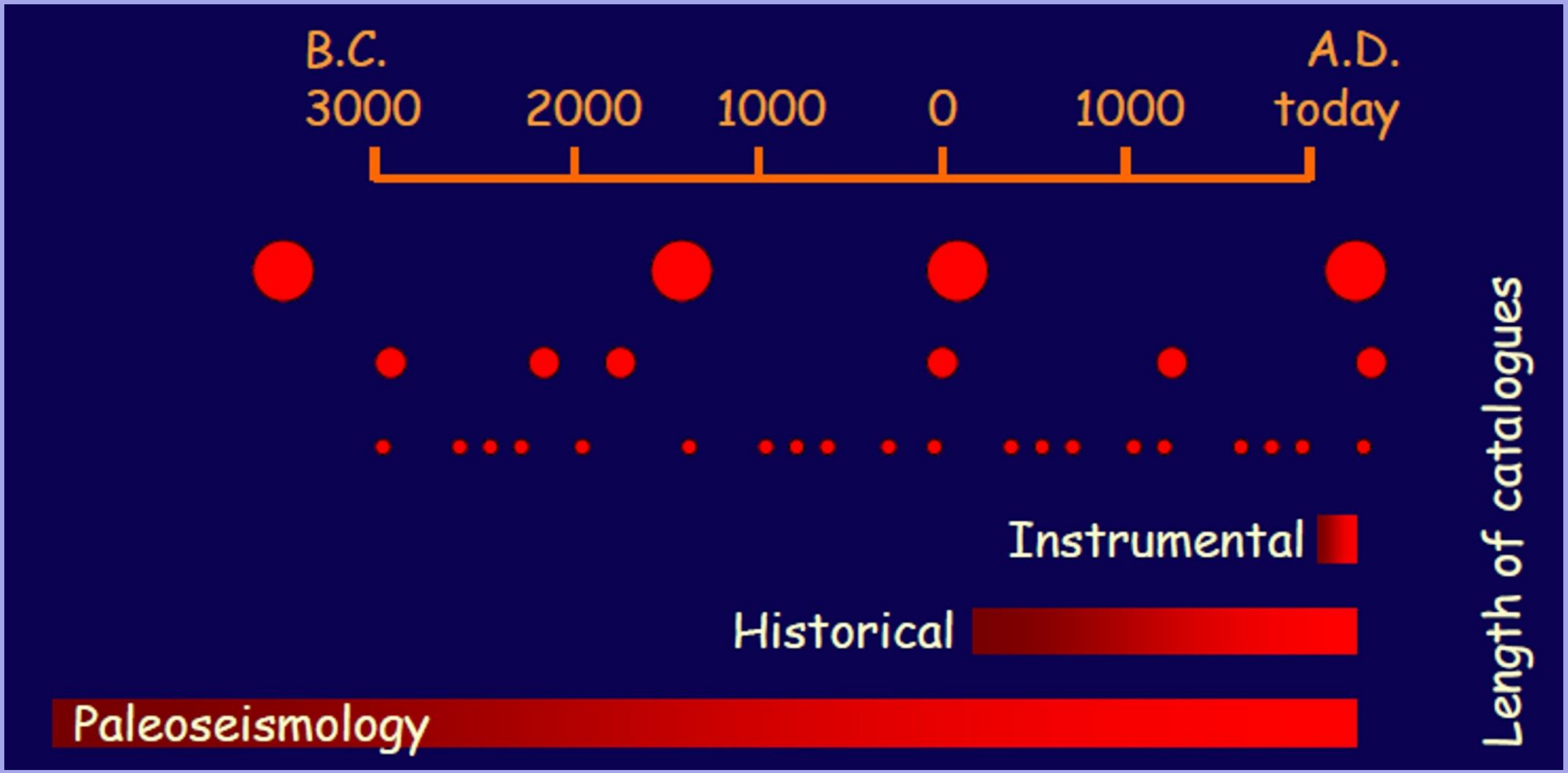
X some active faults expressed in morphology and geology – no historical seismicity or large EQs

China and Middle-East – record thousands yrs and more, still not long enough (fault active millions yrs)
The historical record of 3,000 yrs – covers only little part of faulting history

Seismic hazard assessment – based on very short period of record of historical EQs, it may cause 2 problems:

❖ overestimation of probability of future EQs based on historical large EQs, but with long recurrence interval (seismic energy is released)

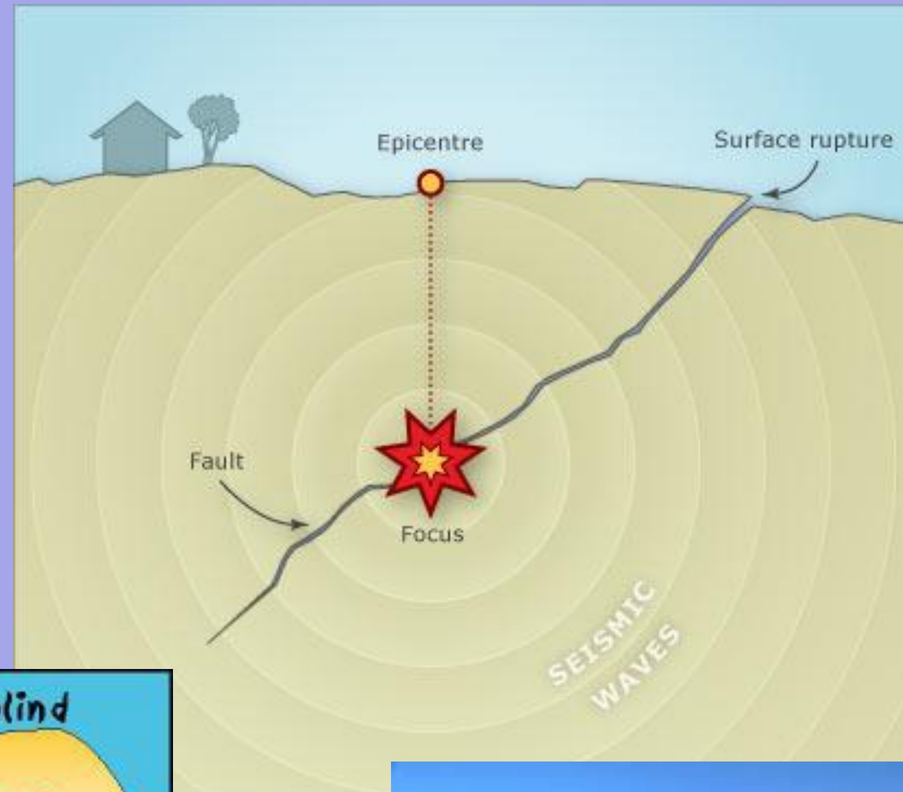
❖ underestimation – in areas with seismogenic faults but no historical record (strain accumulation)

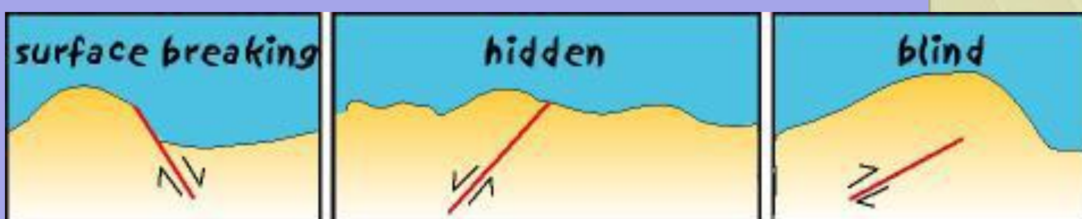


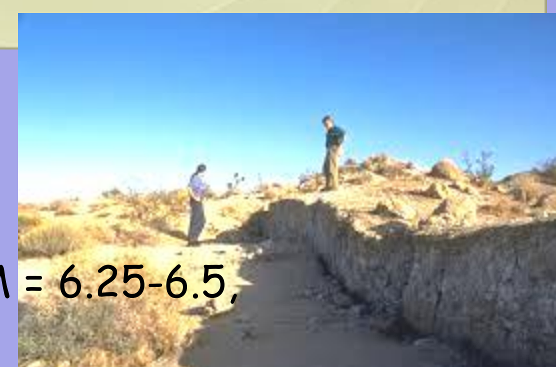
Paleoseismology extends record of EQs into the geological past

Earthquakes catalogues too short

Premise – EQ only larger M > 6 can create permanent deformation on the surface → topographic instability → new processes - erosion and accumulation → new landforms and structures → geological record of EQ

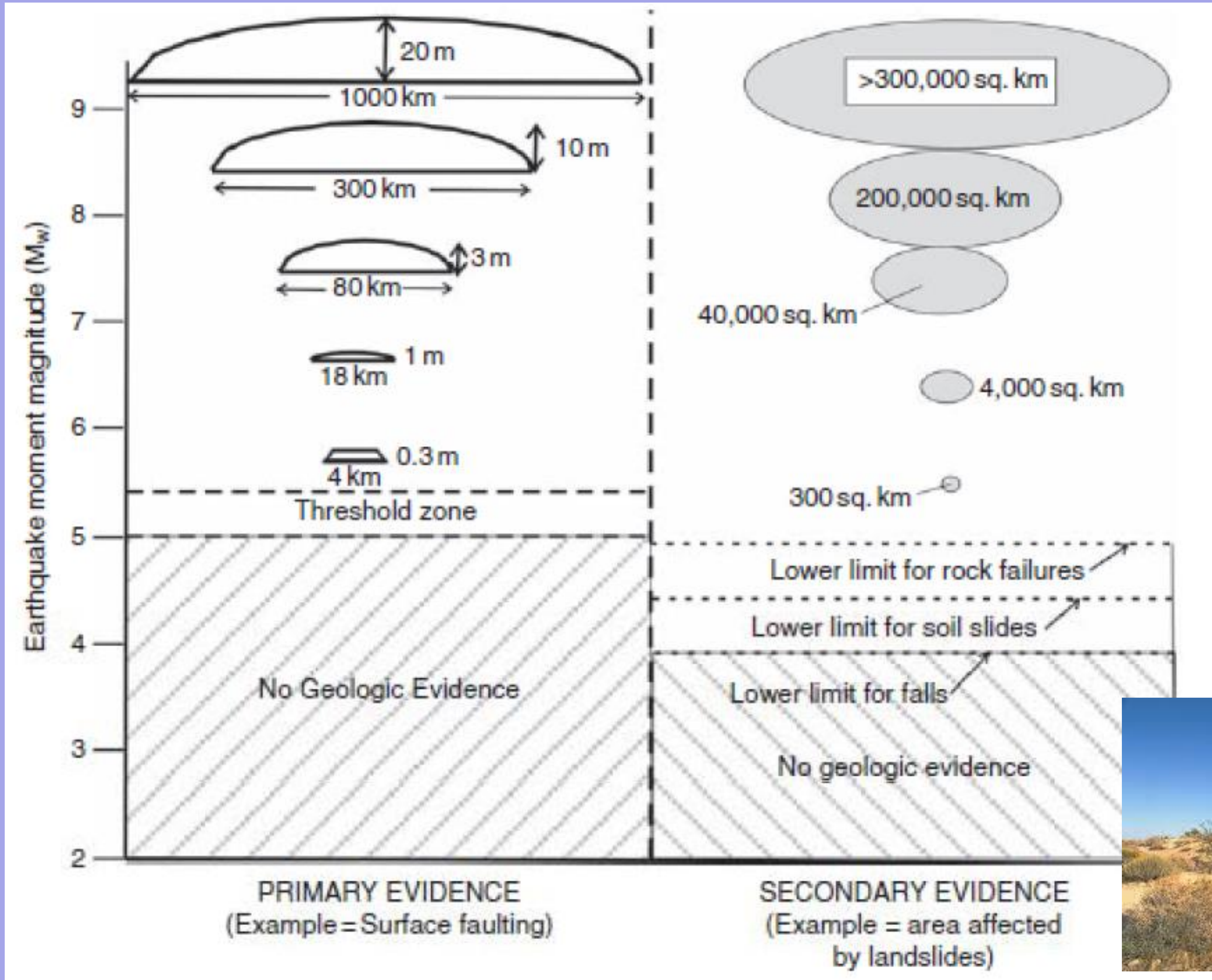






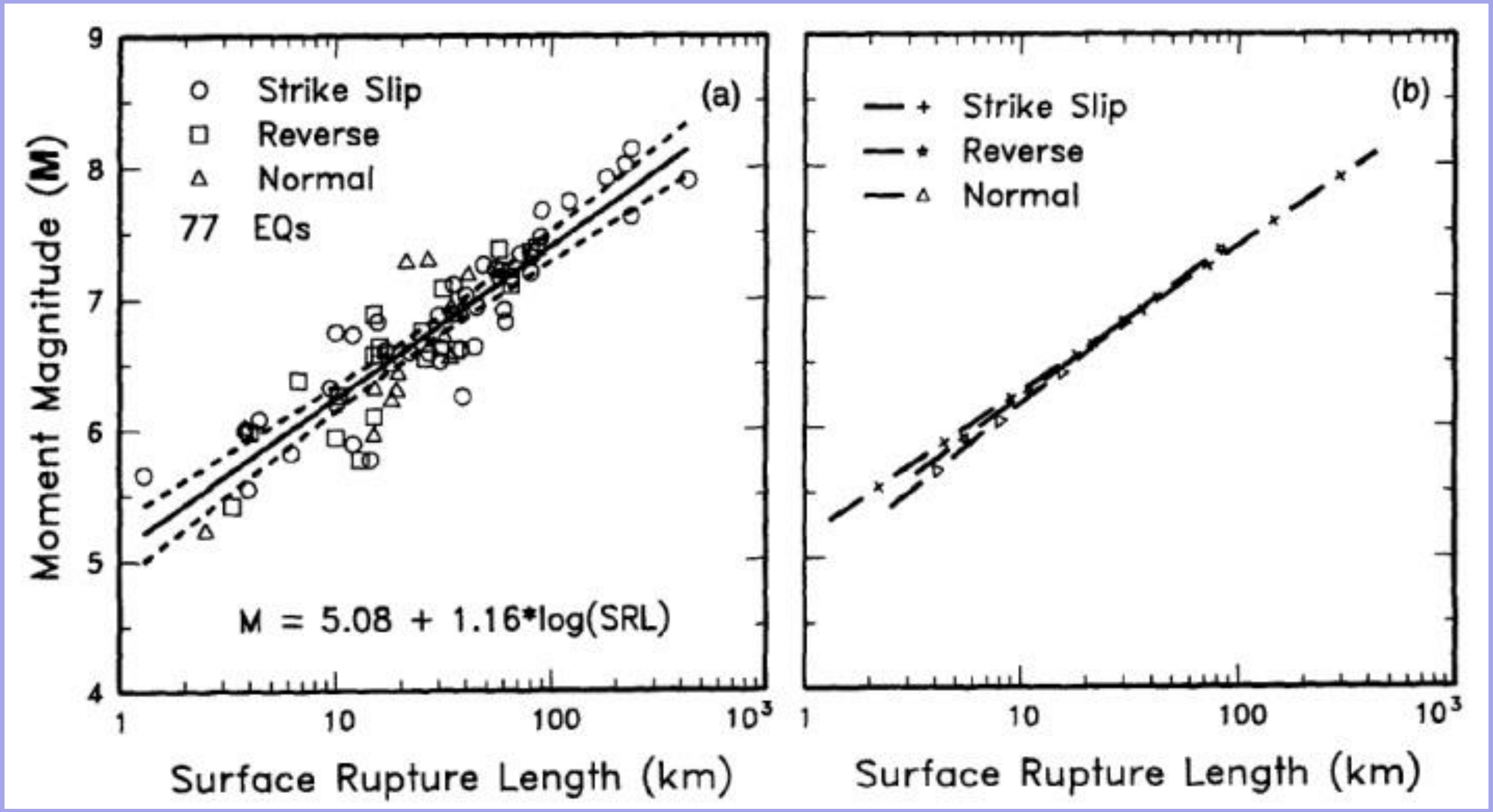
Smaller EQ - rarely geological expression created or survives
Fault type – normal faults M ≥ 6.3; strike-slips – California i – M = 6.25-6.5,
Depth of seismogenic crust – deeper needs higher magnitude

Loma Prieta 1989 M=6.9, 2m slip in depth 3-18km, no surface rupture
Gujarat 2001 M=7.7, blind fault, 1-4m in depth 9-15km,



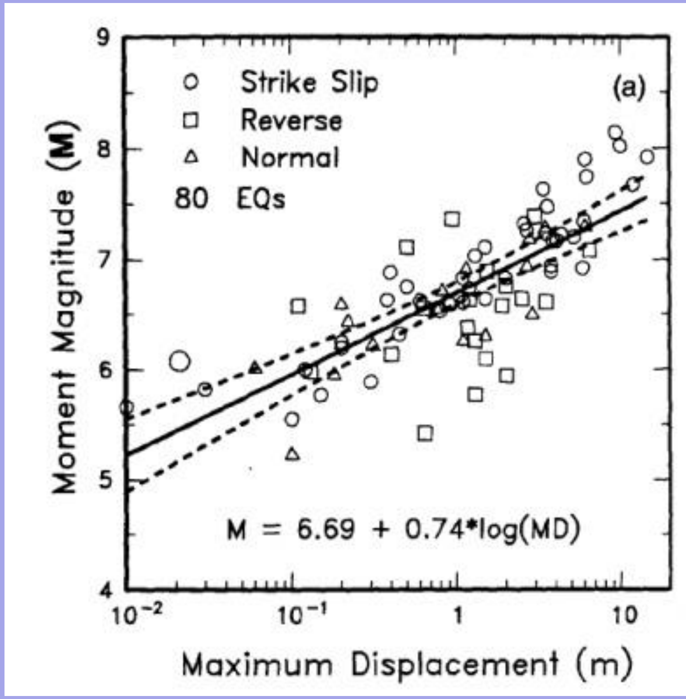
Empirical relationships based on observation from historical EQs

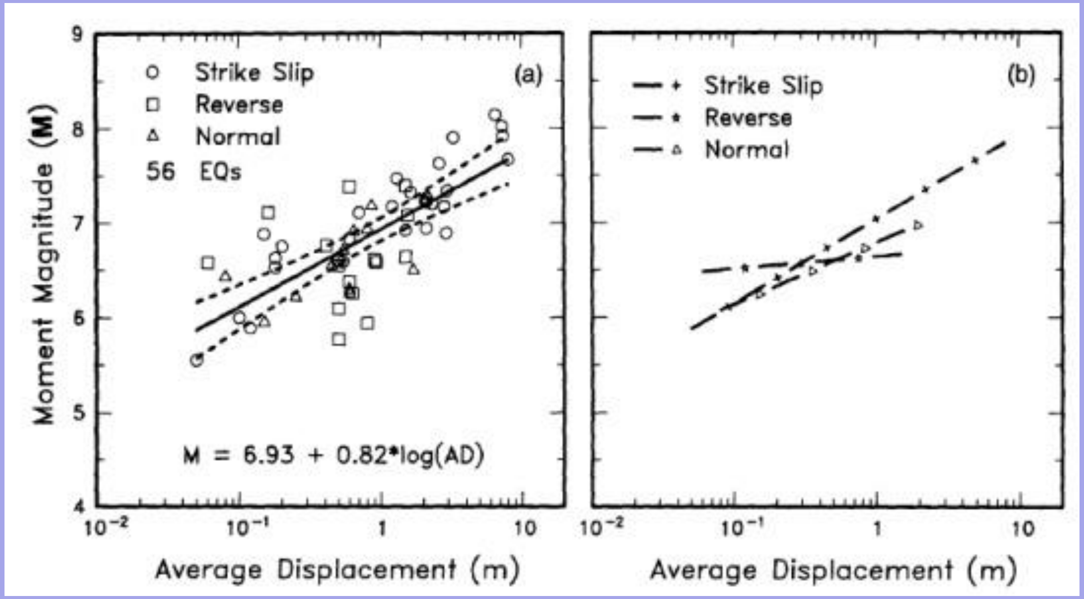
Relationships: fault length, amount of displacements, size of Magnitude
e.g. fault 80km long can generate EQ Mw=7.5 and displacement 3m



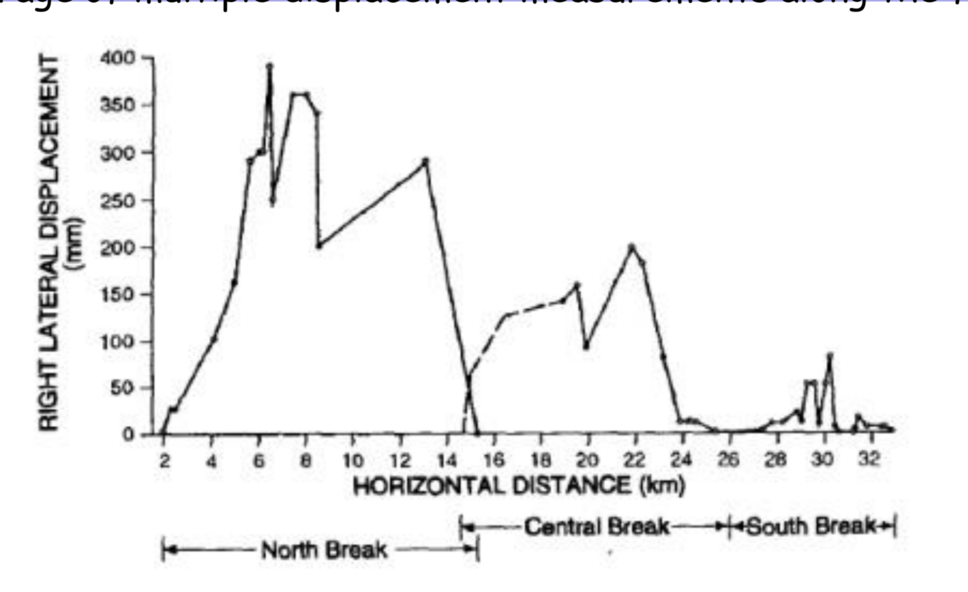
Empirical relationships – historical EQs (421), focis depth <40km, Mw > 4.5

Wells, and Coppersmith 1992



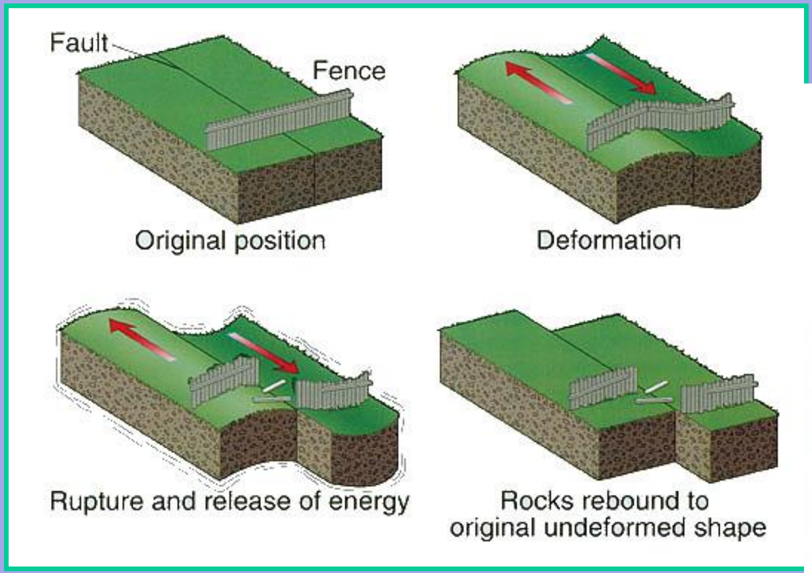


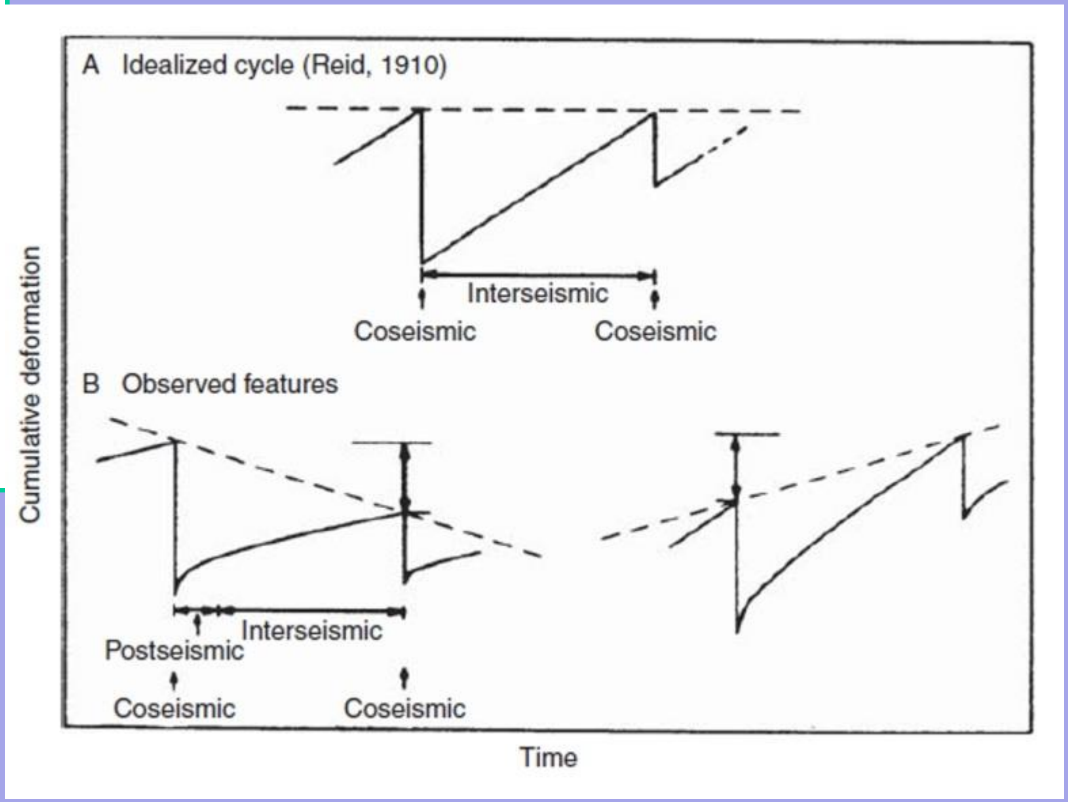
Average of multiple displacement measurements along the fault



9. 4. 1968, Borego Mts, CA

Seismic cycle – elastic model





Idealized cycle -

characteristic earthquake

Earthquake deformation cycle

Paleoseismological study of faults

- Localisation and geometry (geomorphology, geological mapping)
- Slip rate – faulting velocity (= displacement/time)
- Slip per event – characteristic displacement during individual EQs
- Recurrence period – (repeated EQ, frequency EQ)
- Elapsed time – time from the last EQ
- Maximum potential magnitude

Chronological reconstruction of movements

- stratigraphic, structural, geomorphological, biological, archeological evidence
- dating of displaced features or movement indicators

- dating of multiple movements (EQs) - recurrence interval, long-term slip-rate, variability of movements during EQs

→ predict location and magnitude of future EQs

Methods

– direct observations of dislocated objects – on the surface or in **trenches**, outcrops

❖ young sediments, fine grained, stratified - well recognizable displacement of layers, not thick

alluvial fans, lake sediments X debris flow

❖ datable material– chronology of movements

Evidence of earthquakes (EQ) in geological profiles in a trench

A) Difference in cumulative offset

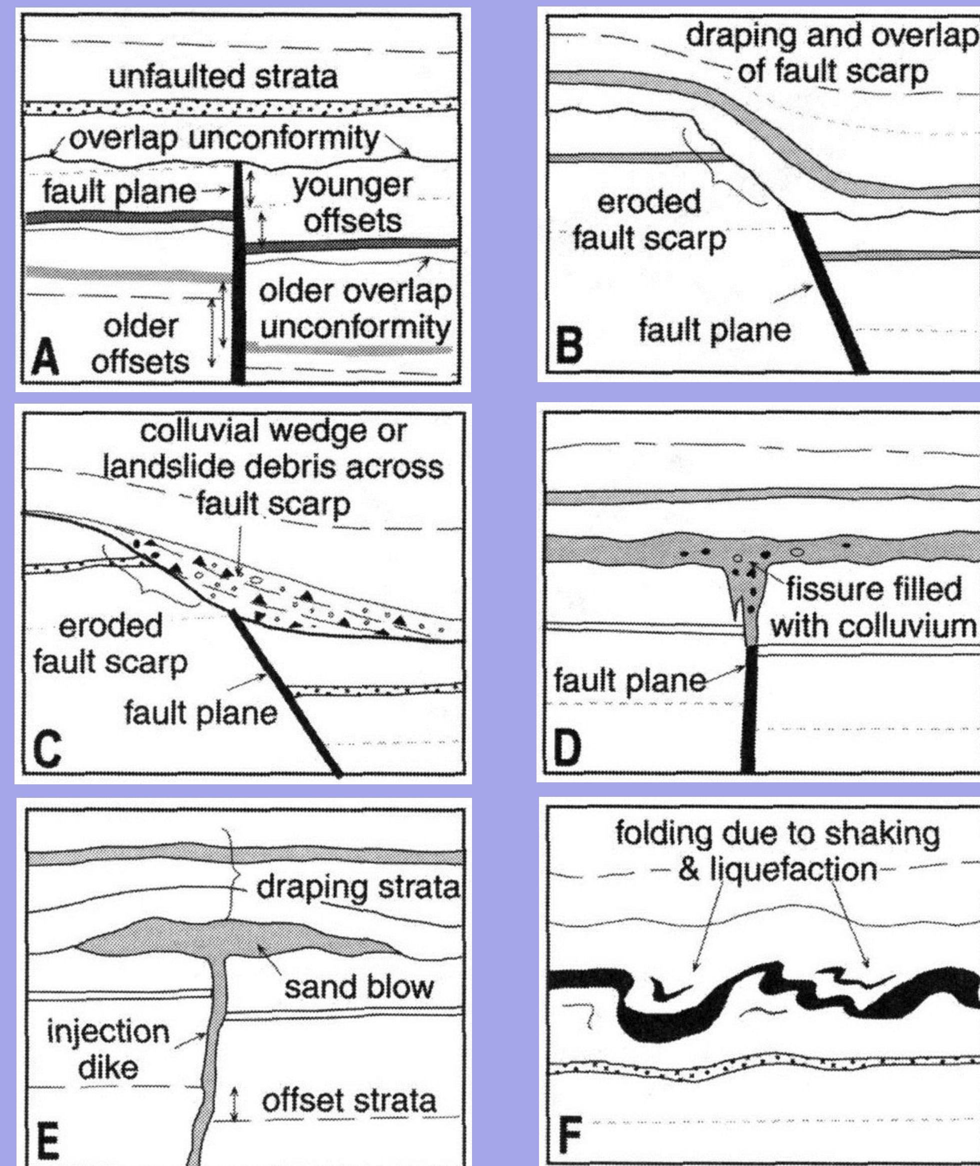
B) Buried fault scarp

C) Coluvial wedge- typical for sudden movement

D) Fissures filled by overlying material

E) Sand dykes

F) Liquefied layers



Allen (1986)

Repated EQs

- Difference in cumulative offset

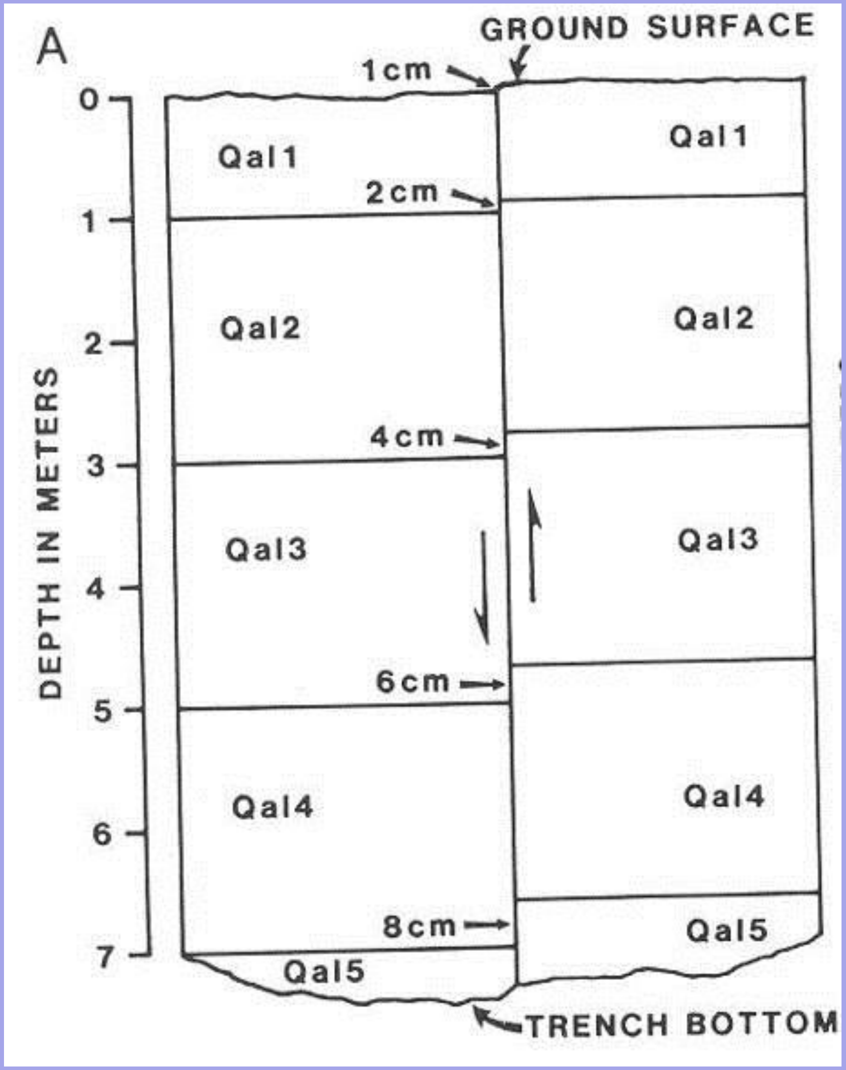
? How many: retrodeformation

4 events – vertical offset 2cm

Oldest layer - (Qal5) all 4 events, cumulative 8cm

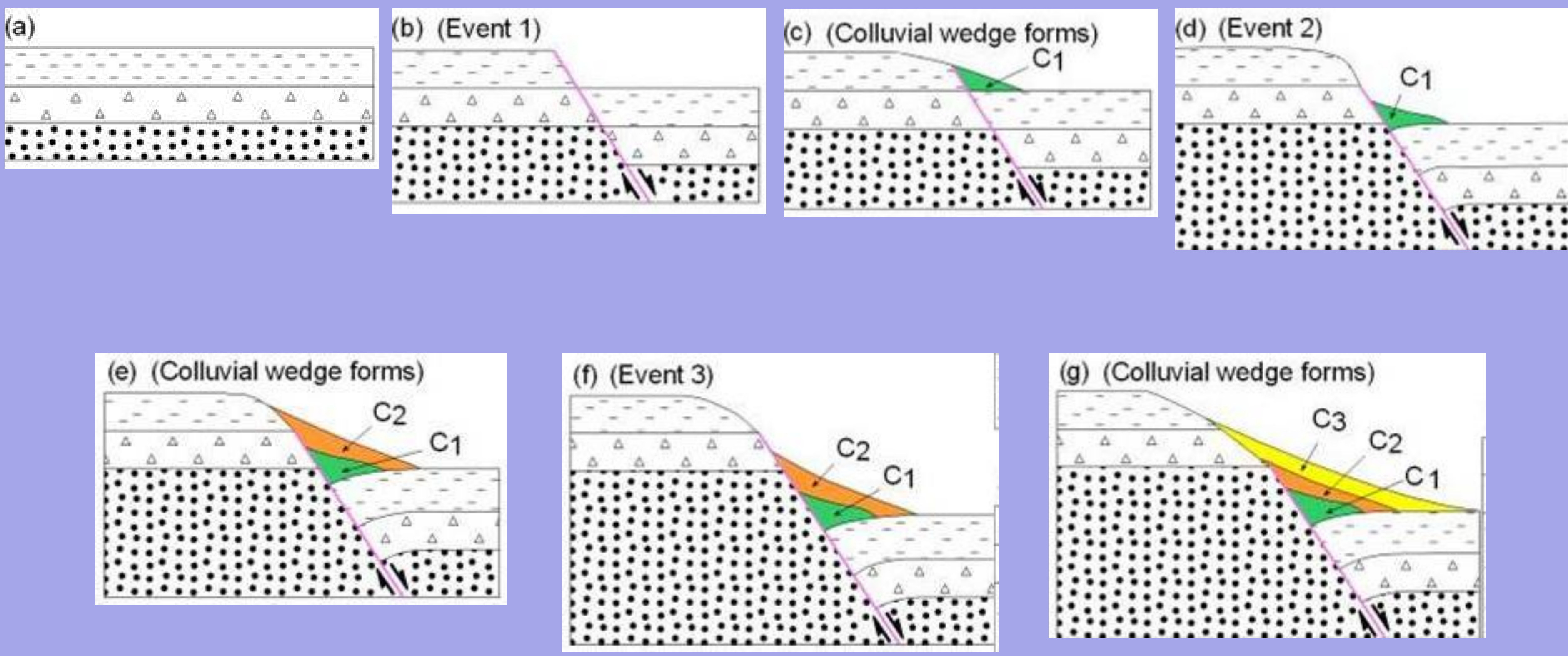
Youngest (Qal1) has experienced only 1 event → 2 cm on the layer base, but 1 cm on the surface!

Surficial erosion



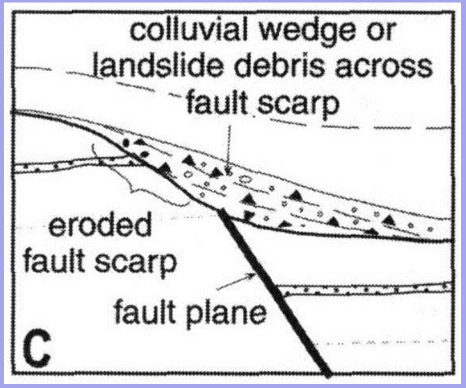
Normal faulting

Colluvial wedge

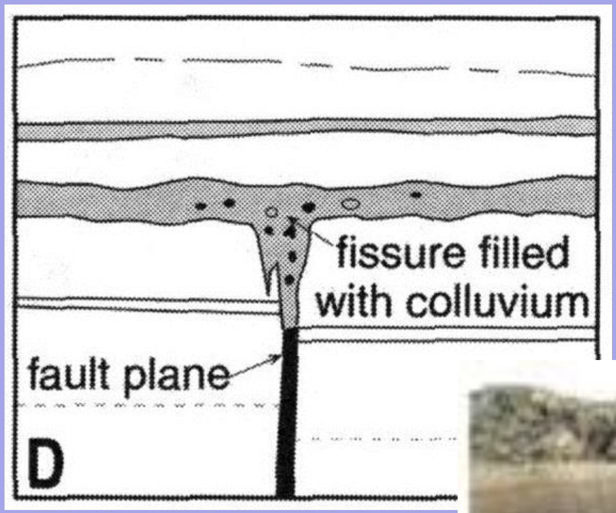


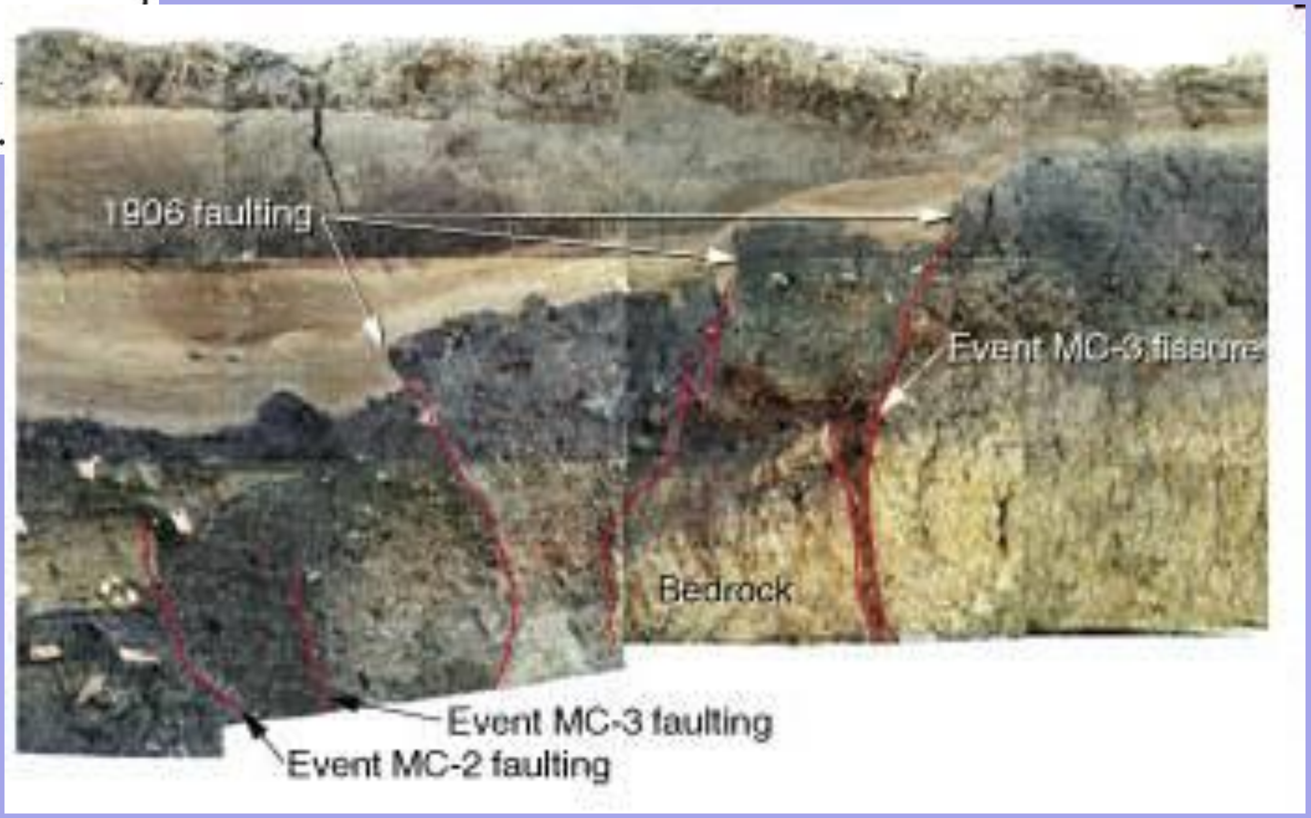
Gravitational instabilty

Fault scarp derived material - wedge



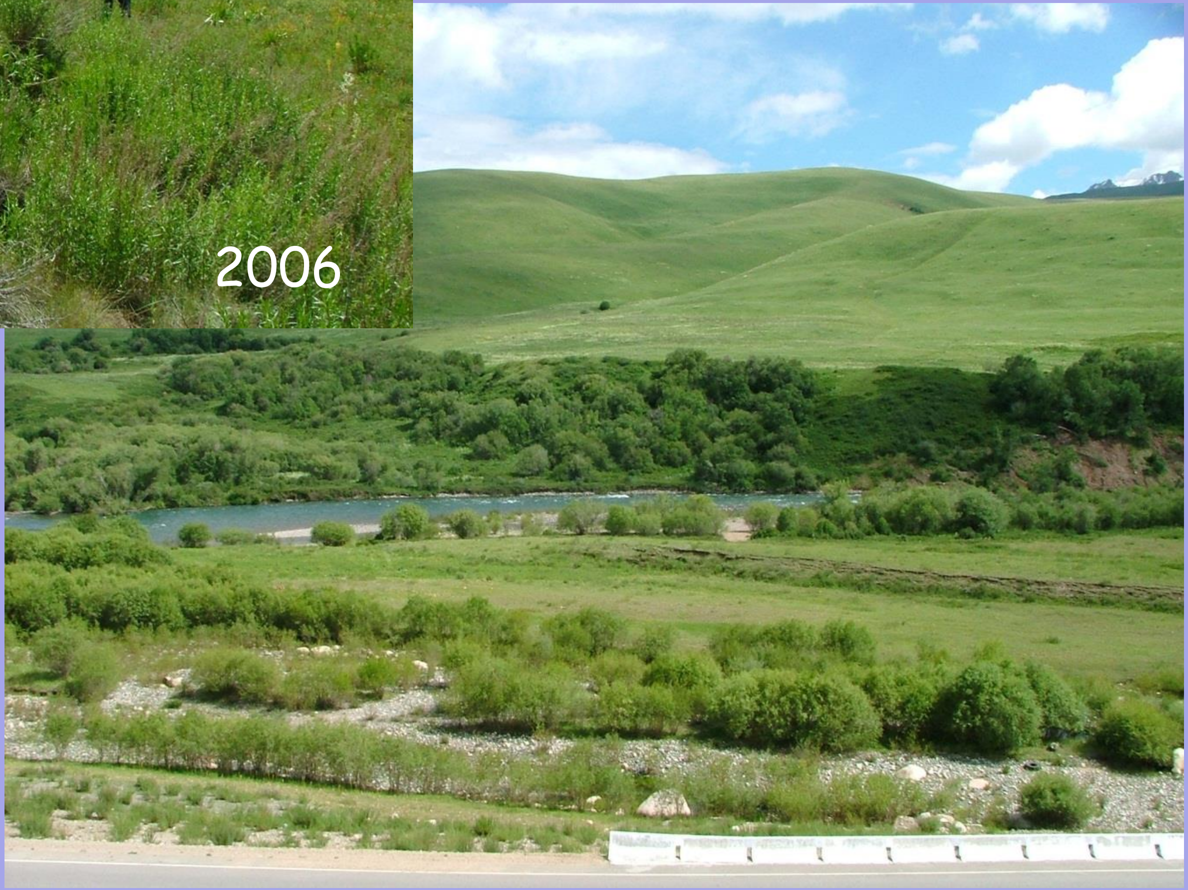
- **Filled fissure**





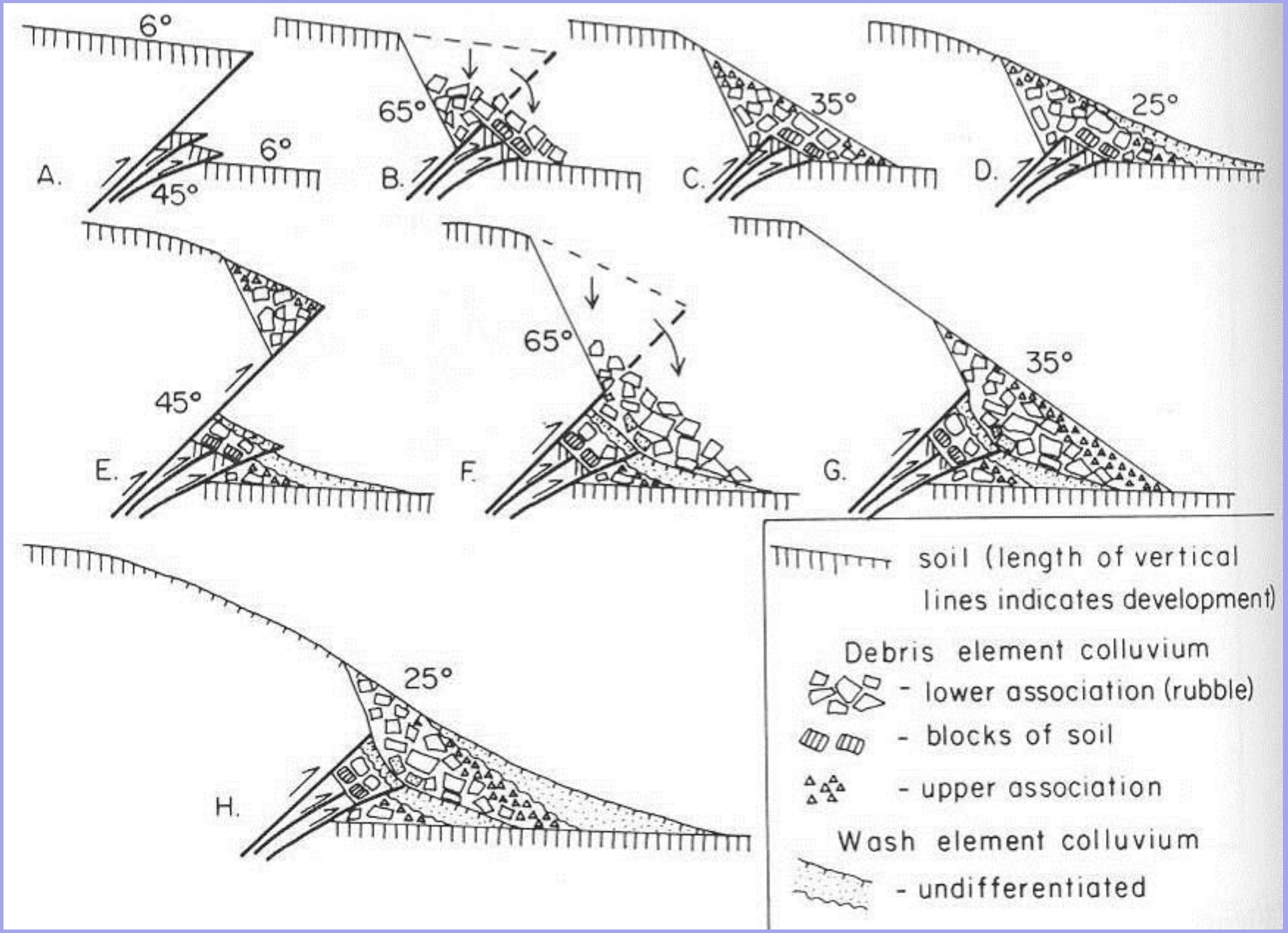
Aremogna-Cinquemiglia fault - Italy

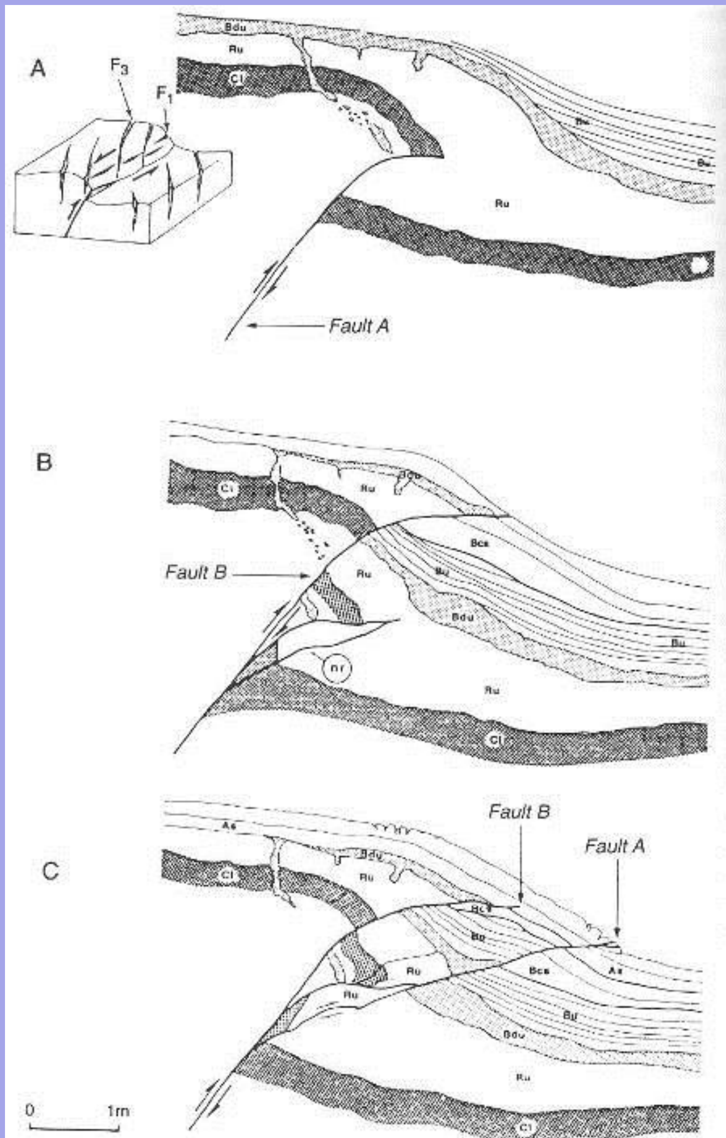
Reverse faulting



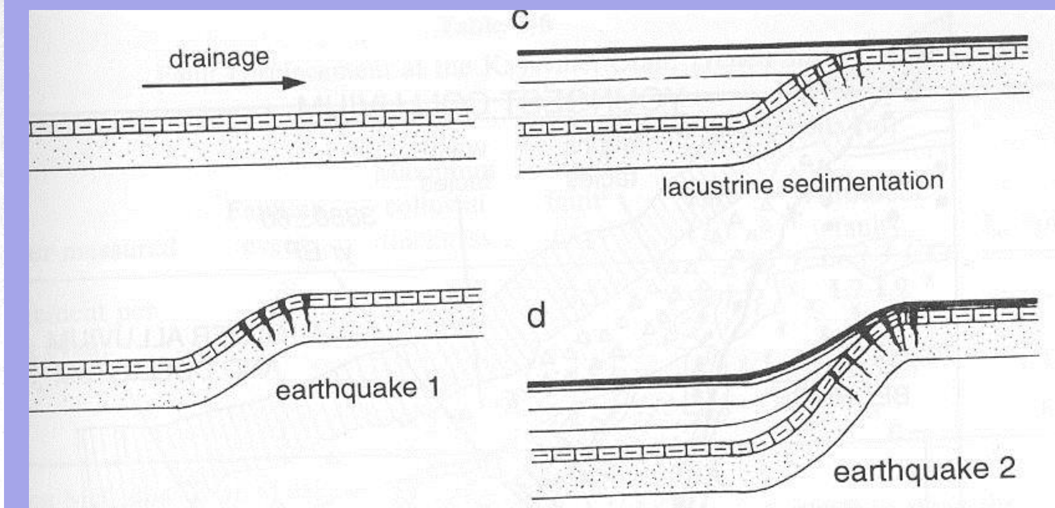
Suusamyr, 1992, M=7,4
Kyrgyzstan

Reverse faults – colluvial wedge

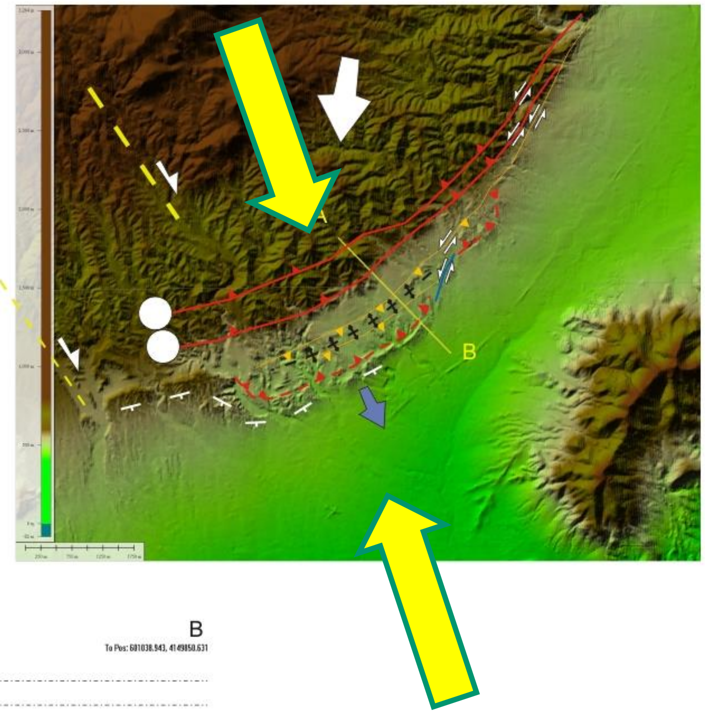


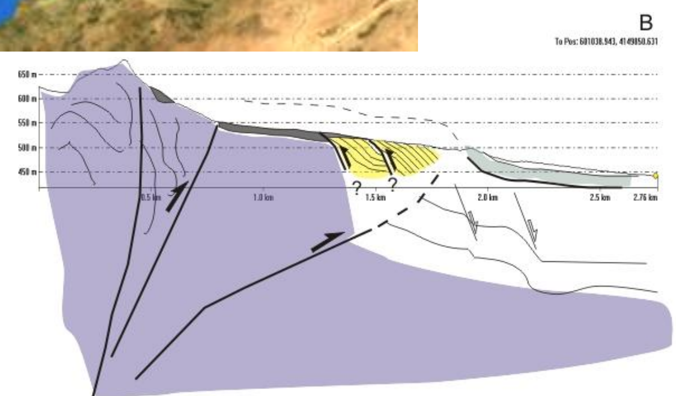


Seismic events reconstruction

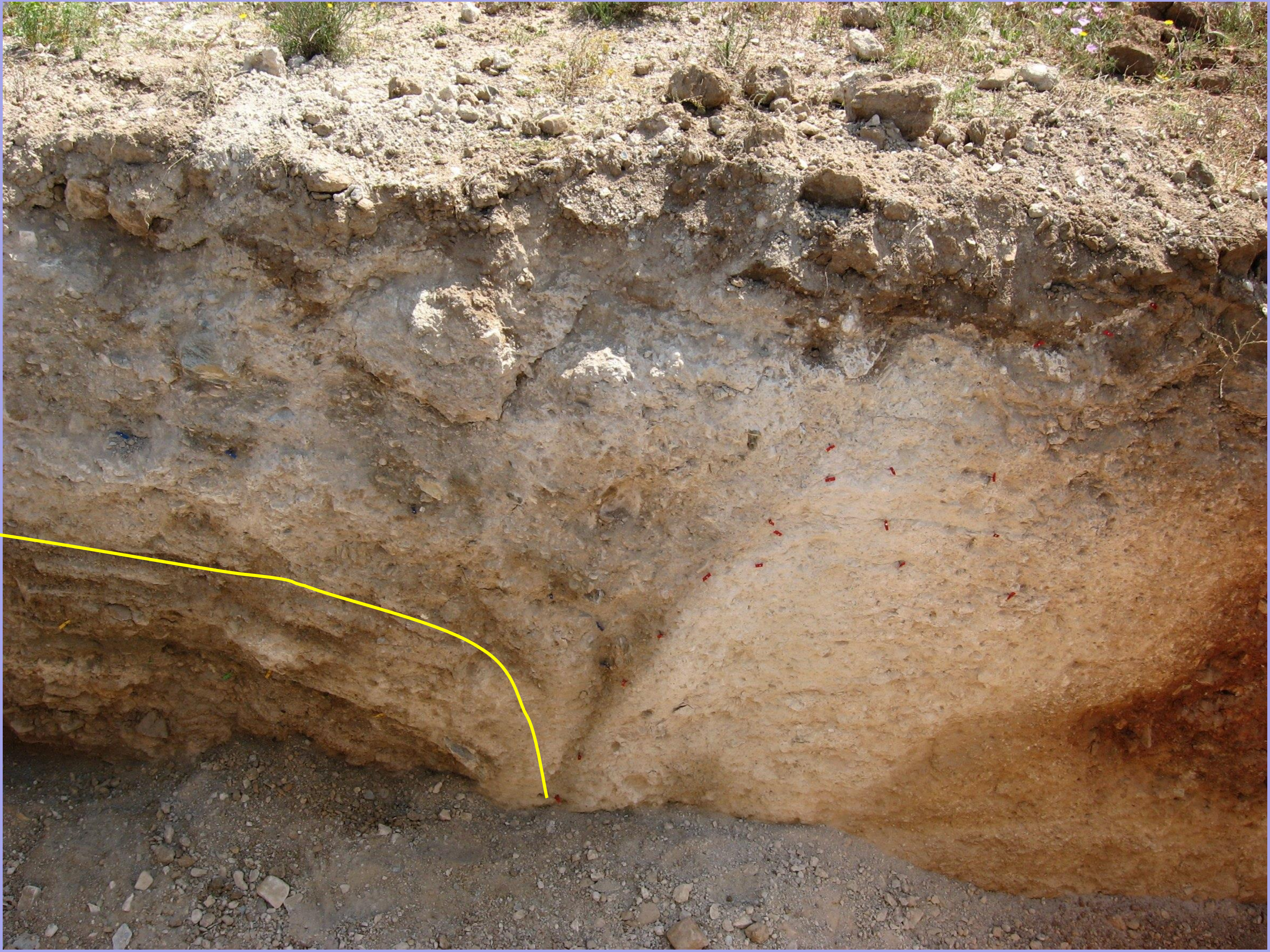


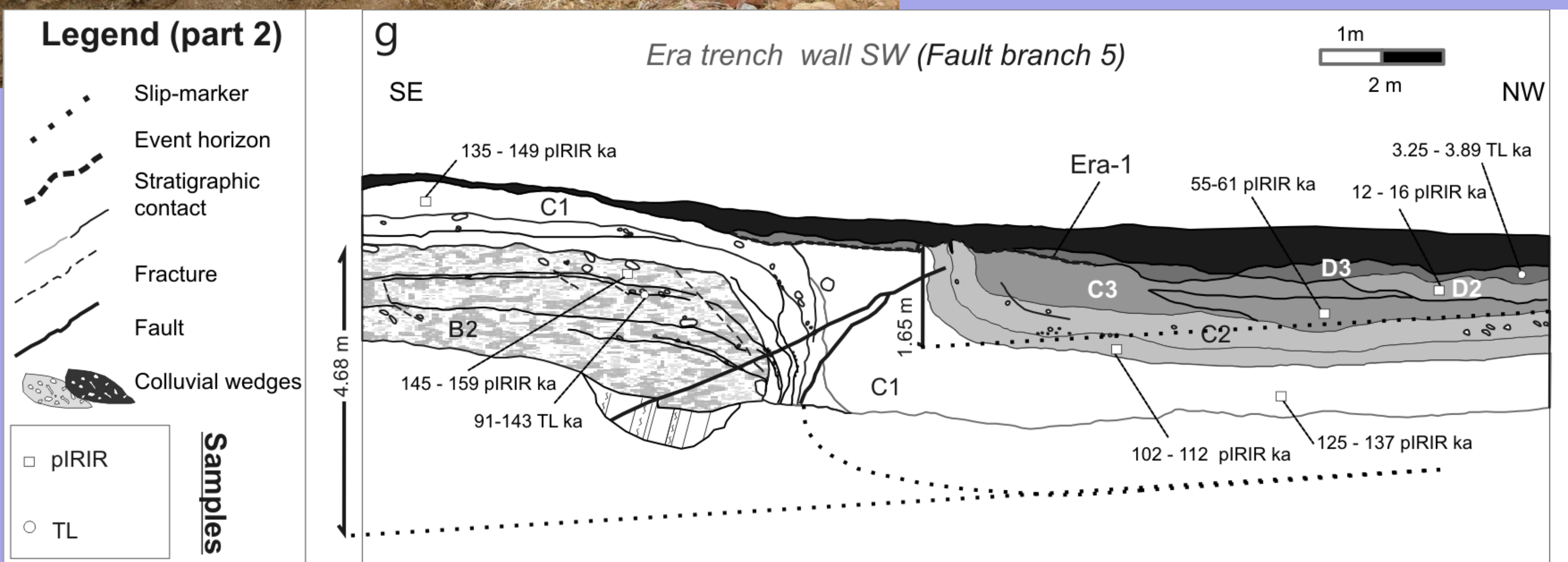
Alhama de Murcía fault (Spain)





Various kinematics related to different stress diection

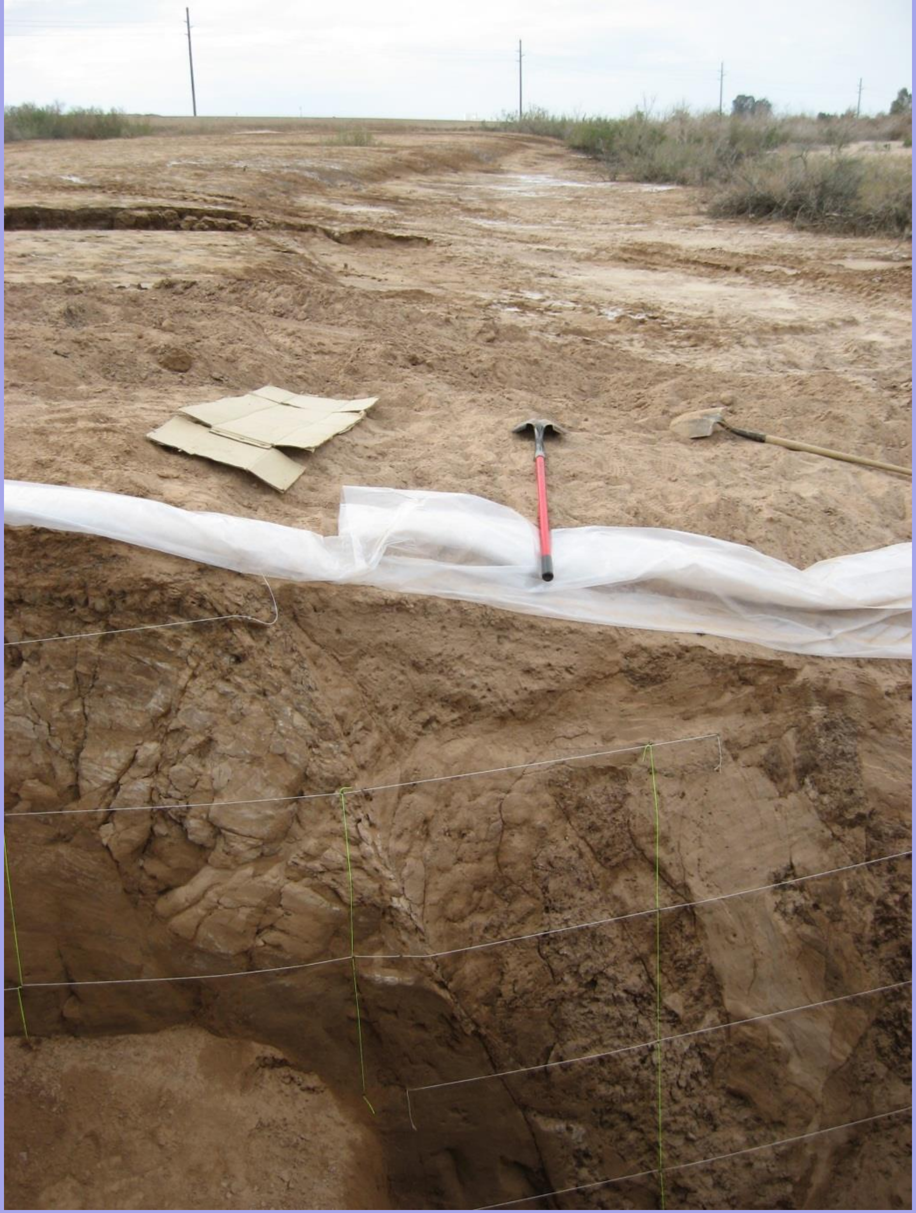





Legend (part 2)
Slip-marker
Event horizon
Stratigraphic contact
Fracture
Fault
Colluvial wedges
pIRIR
TL
Samples
g
Era trench wall SW (Fault branch 5)
1m
2 m
SE
NW
135 - 149 pIRIR ka
Era-1
3.25 - 3.89 TL ka
55-61 pIRIR ka
12 - 16 pIRIR ka
C1
D3
C3
D2
C2
B2
1.65 m
4.68 m
145 - 159 pIRIR ka
91-143 TL ka
C1
102 - 112 pIRIR ka
125 - 137 pIRIR ka

Fault scarp and colluvial wedge on strike-slip fault

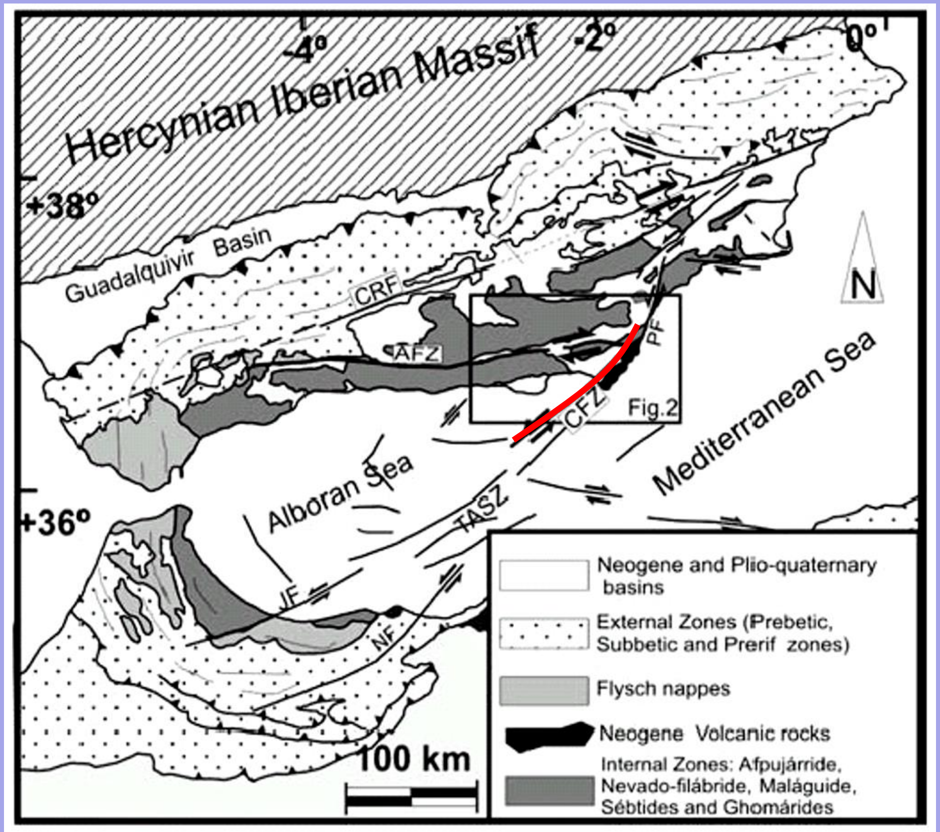
Imperial fault, 1940 M=7.6m offset, 60km



Case study

Carboneras fault zone – Spain

Carboneras

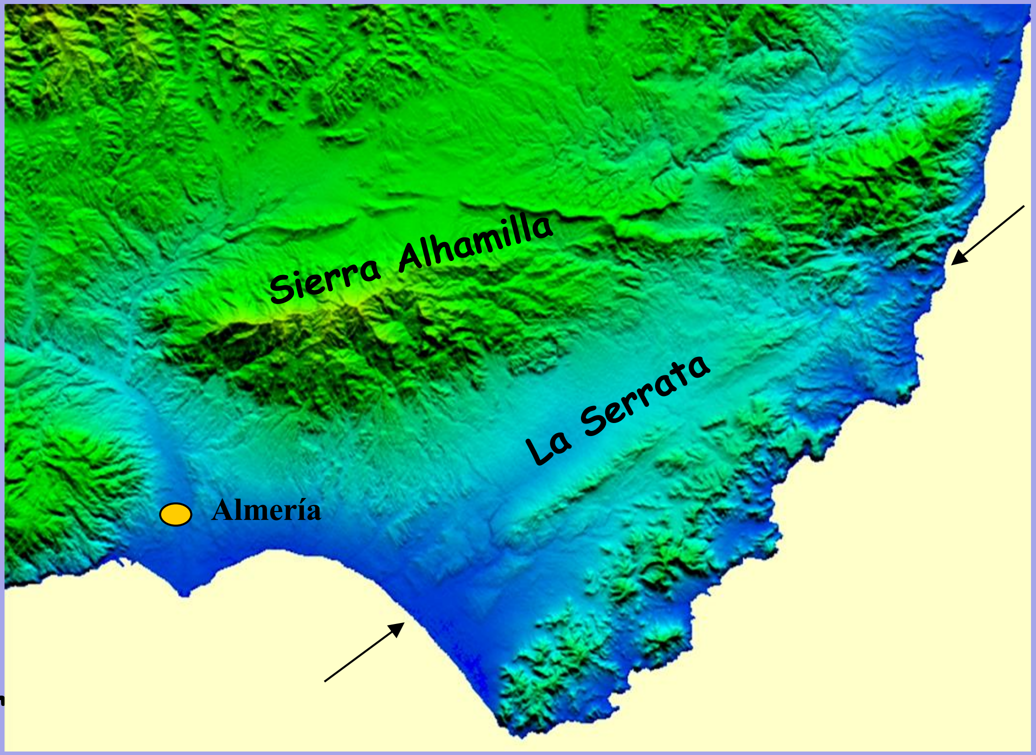


Masana E. et al.

- Collision zone Europe x Africa plate
- Southern margin of Alpine orogen
- Part of Bettic Cordillera

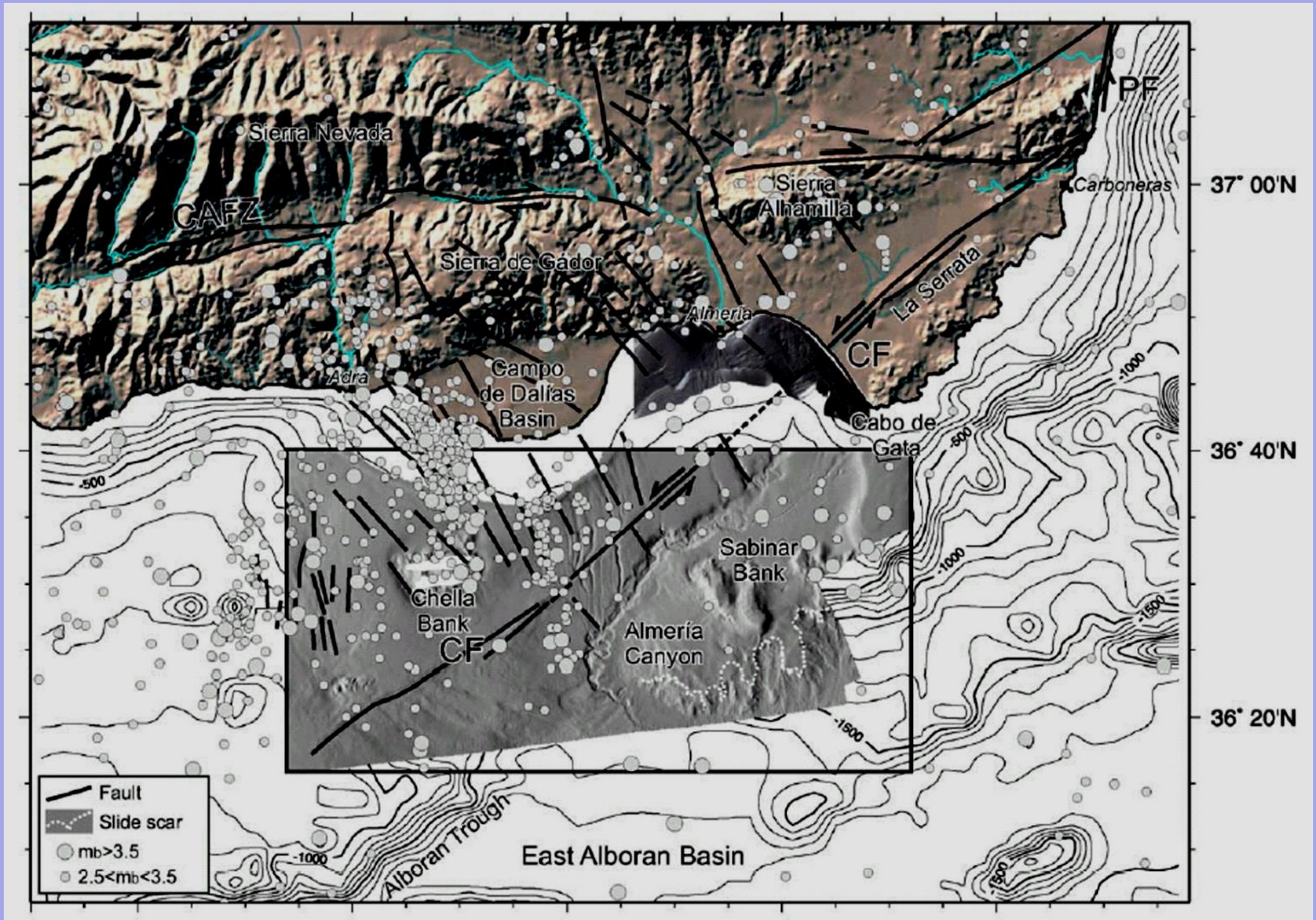
– outer zone (nappe from Mesozoic to Tertiary rocks) paleo-margin of Iberian plate

- inner zone– metamorphic complex + Neogene to Quaternary sediments – intramontane basins bounded by faults NE-SW



Carboneras - formed in the last period of collision of inner and outer zone of Betic cordillera in early Miocene

- Miocene to Quaternary – stress field rotation
  - normal faults - mid-Miocene – part of rifting (volcanism)
  - reverse faults – early Pleistocene (formation of small mountains e.g. La Serrata)
  - strike-slips – left-lateral (up to present-day)

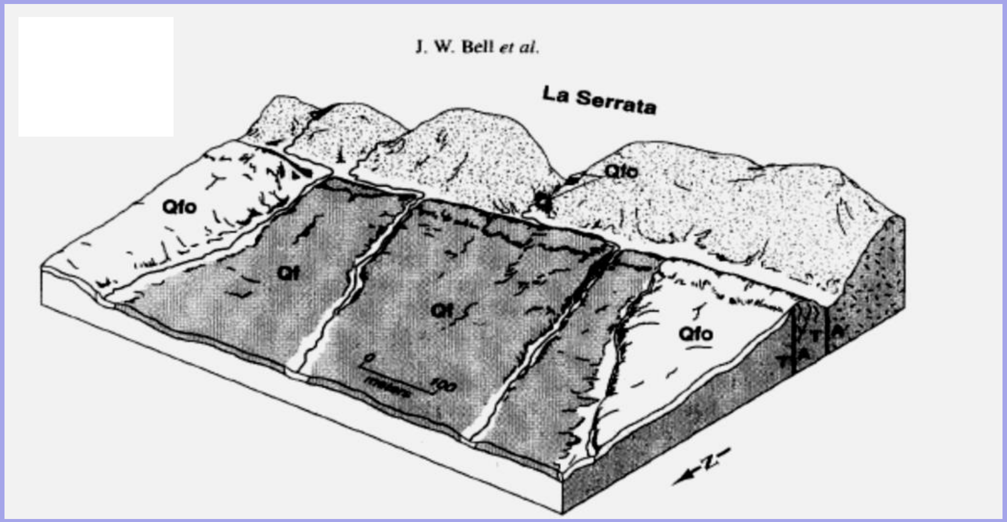


- seismicity – SE margin of Iberian peninsula – permanent shallow earthquakes M < 5.5 (transversal faults now without seismicity – Carboneras)
- last 2.000 years – at least 50 larger earthquakes

Previous studies in 90th of 20th century

1) Study of evidence of left-lateral movements dated by radiometric dating of marine terraces and their recent uplift

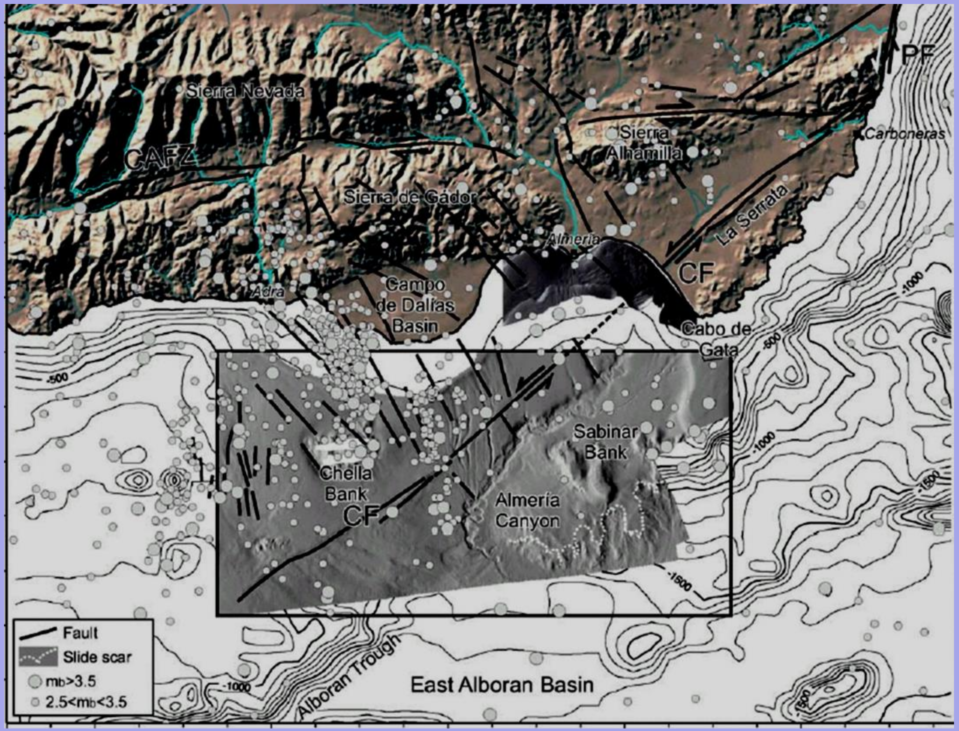
2) Measuring and dating of left-lateral movements based on offset channels

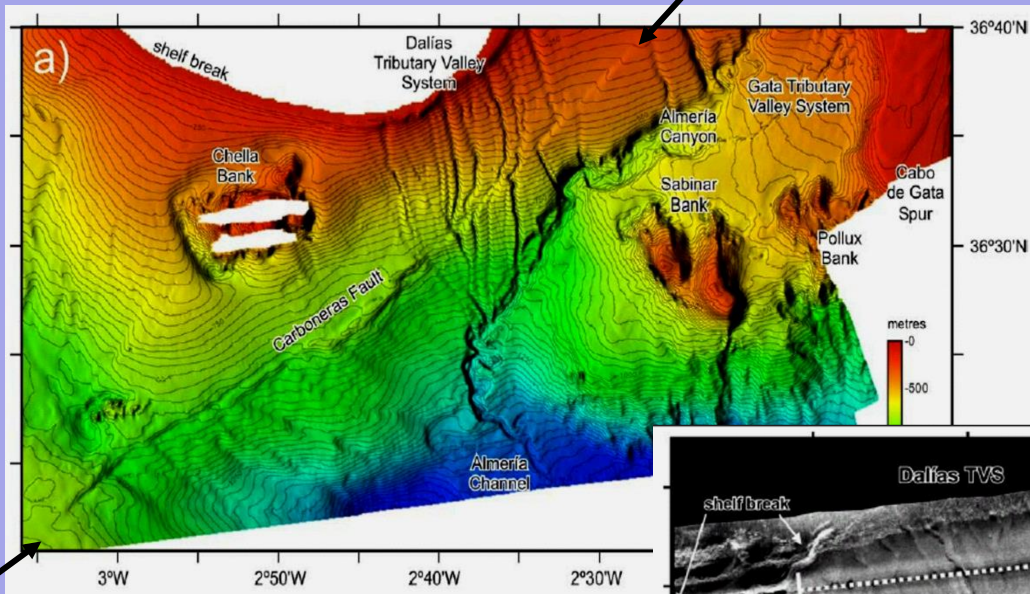


Movements in late Quaternary- relatively slow, **mainly vertical**, horizontal movements of 80-100m offset channels in La Serrata – older than 100.000 years

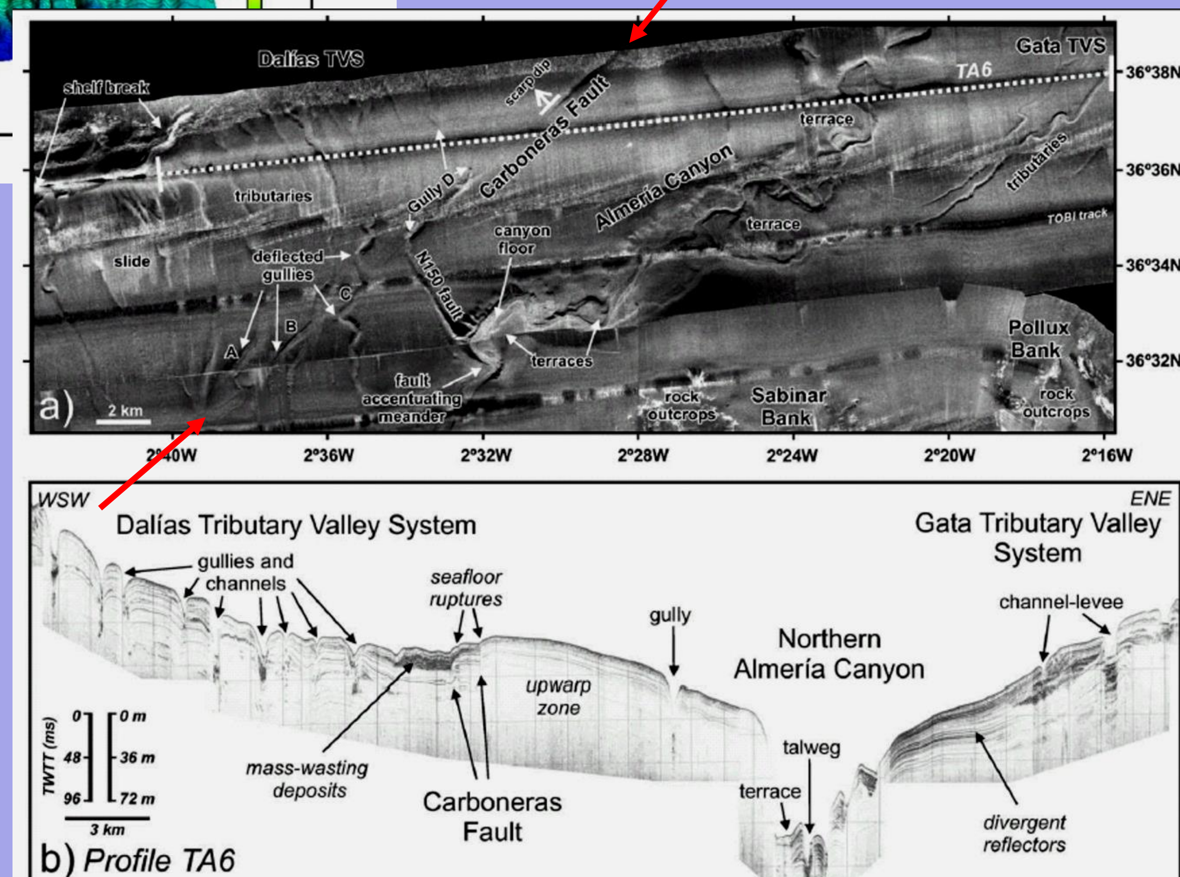
Methods of study of Carnoboneras fault on the sea

- Bathymetry
- Sidescan sonography
- High resolution seismic reflection
- Marinne sediments samples analysis
- Dating of the sediments



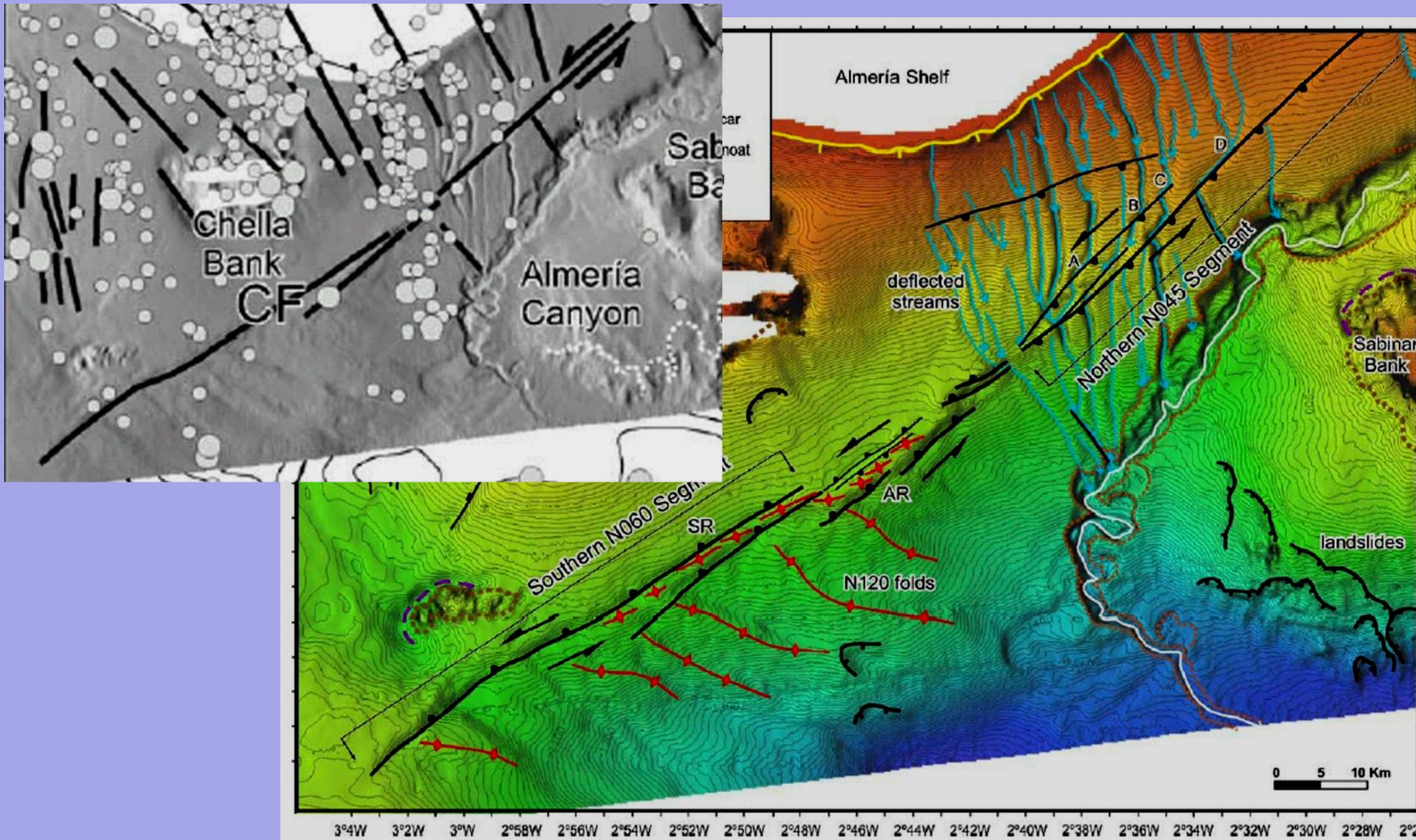


Bathymetry



Sonography – high resolution

Seismic profilling



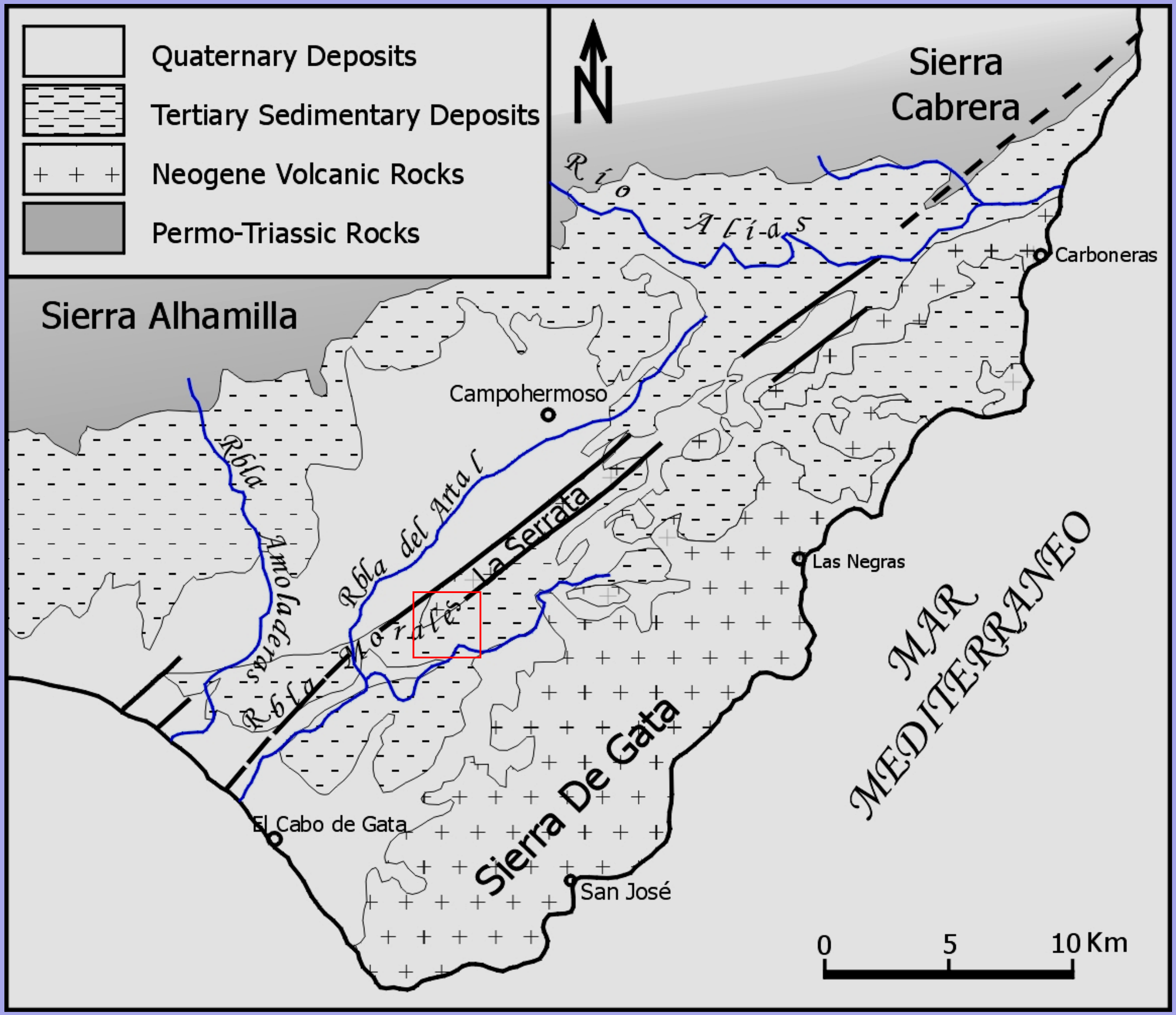
Results: Carboneras fault zone – 5-10 km wide, 100 km long, subvertical faults,

Drainage network on the inland margin – deflected,

Morphology formed by horizontal movements – **pressure ridges, water gaps, late Holocene sediments, landslides.**

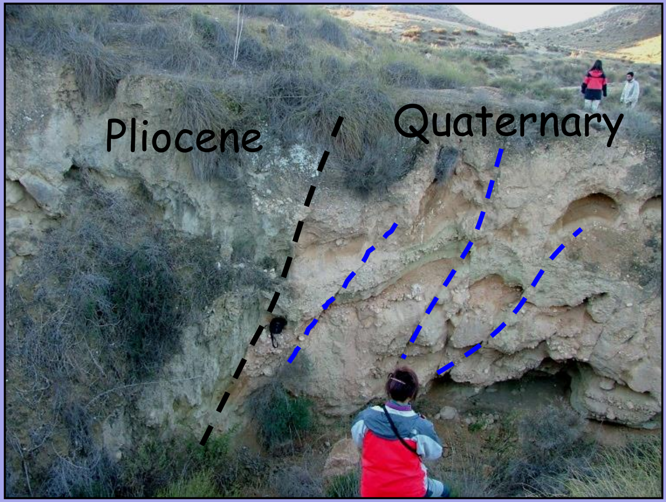
Methods of fault study on the land - offshore

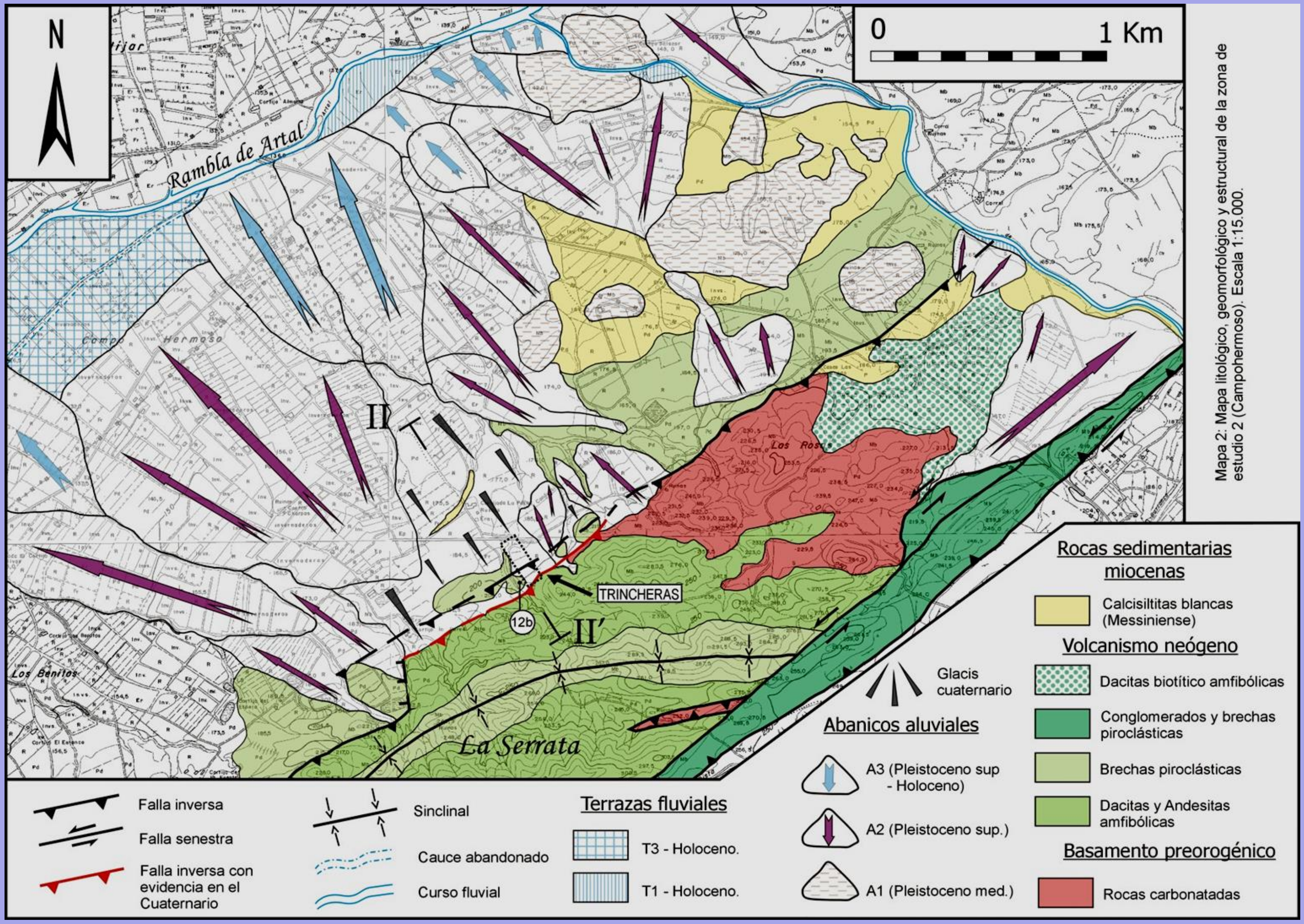
- Photointerpretation – air photos
- Geomorphological mapping of dislocated landforms
- Structural mapping (faults)
- Sedimentology (identification of generations of alluvial fans)
- Microtopography (total station)
- Geophysics (georadar, electrotomography – fault tracing and goundwater level)
- Paleoseismic trenching
- Dating of materials cut by the fault



El Hacho
2005

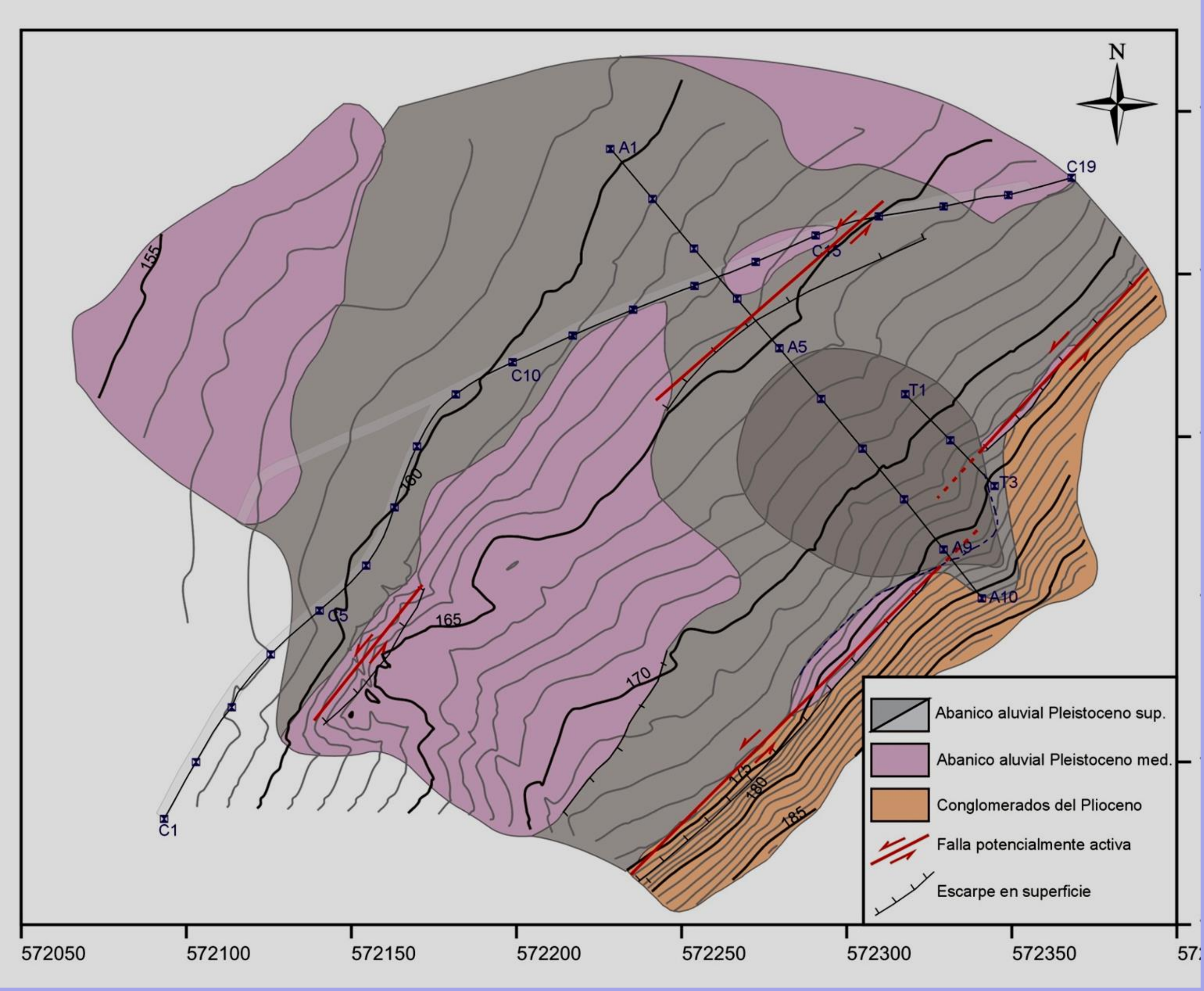

La Serrata


Pliocene
Quaternary



3 generations of alluvial fans – Mid and Late Pleistocene/Holocene - 3 various generations of fault movements (erosion - accumulation)

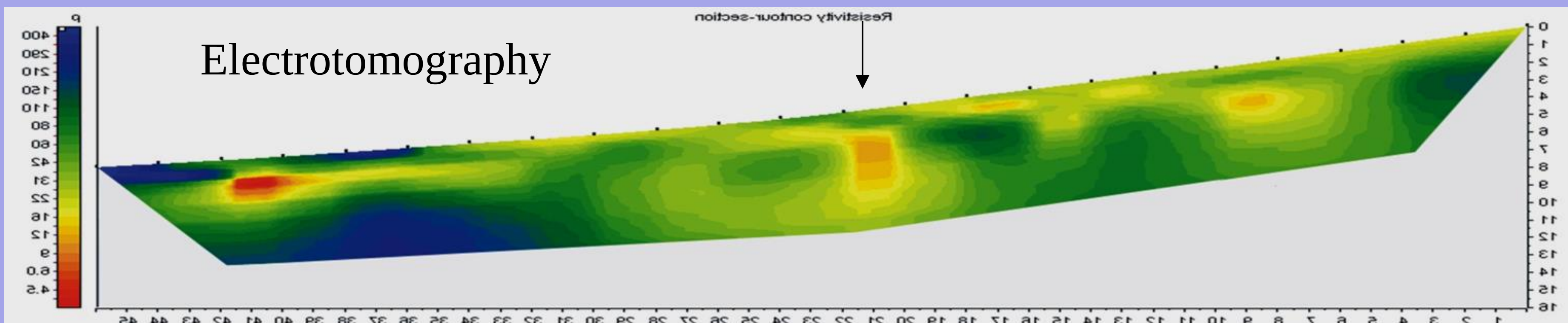
Paleoseismic trenches

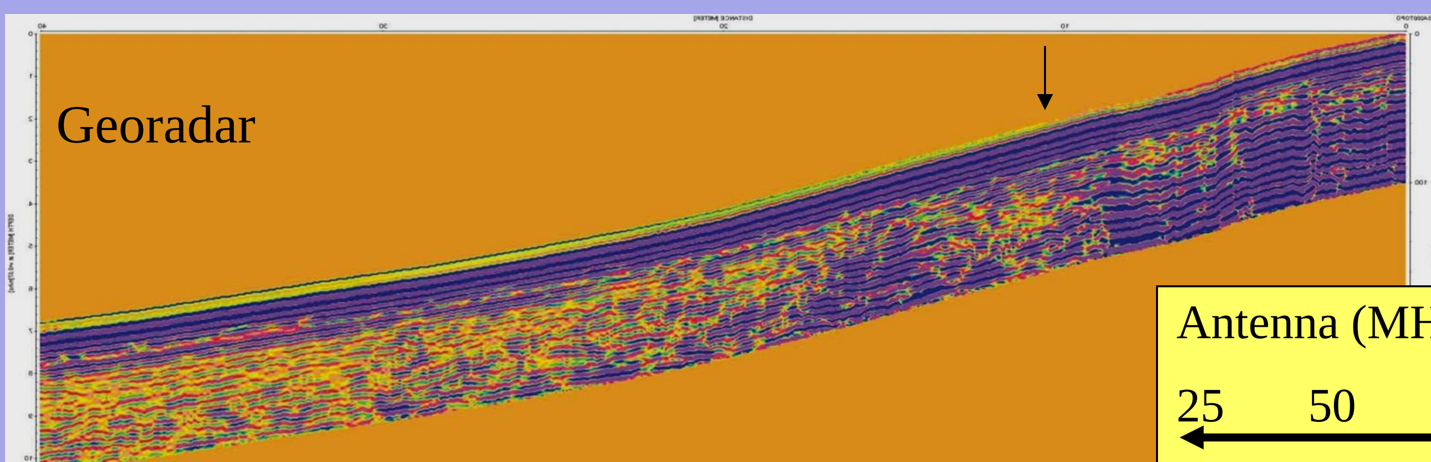


- all 3 alluvial fan generations (chronology)
- visible morphological scarps (0.7m)

Geophysics

- fault position and characterictsics of the material at the depth





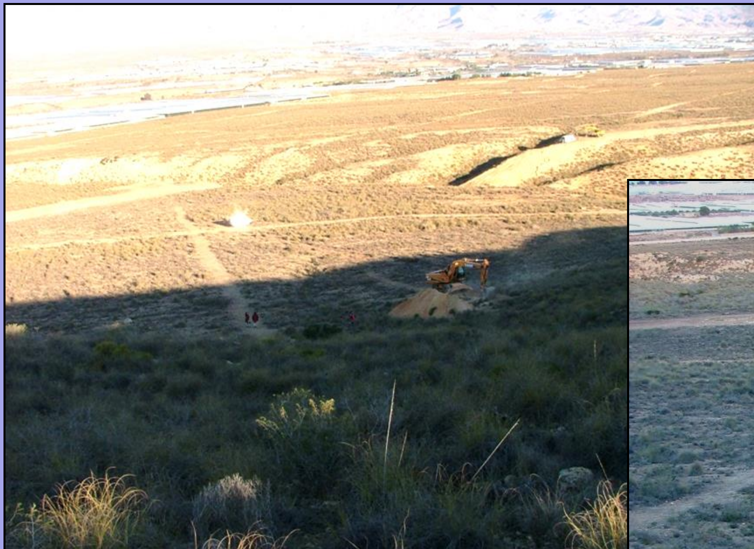
Antenna (MHz):

25 50 100 200

\- resolution +

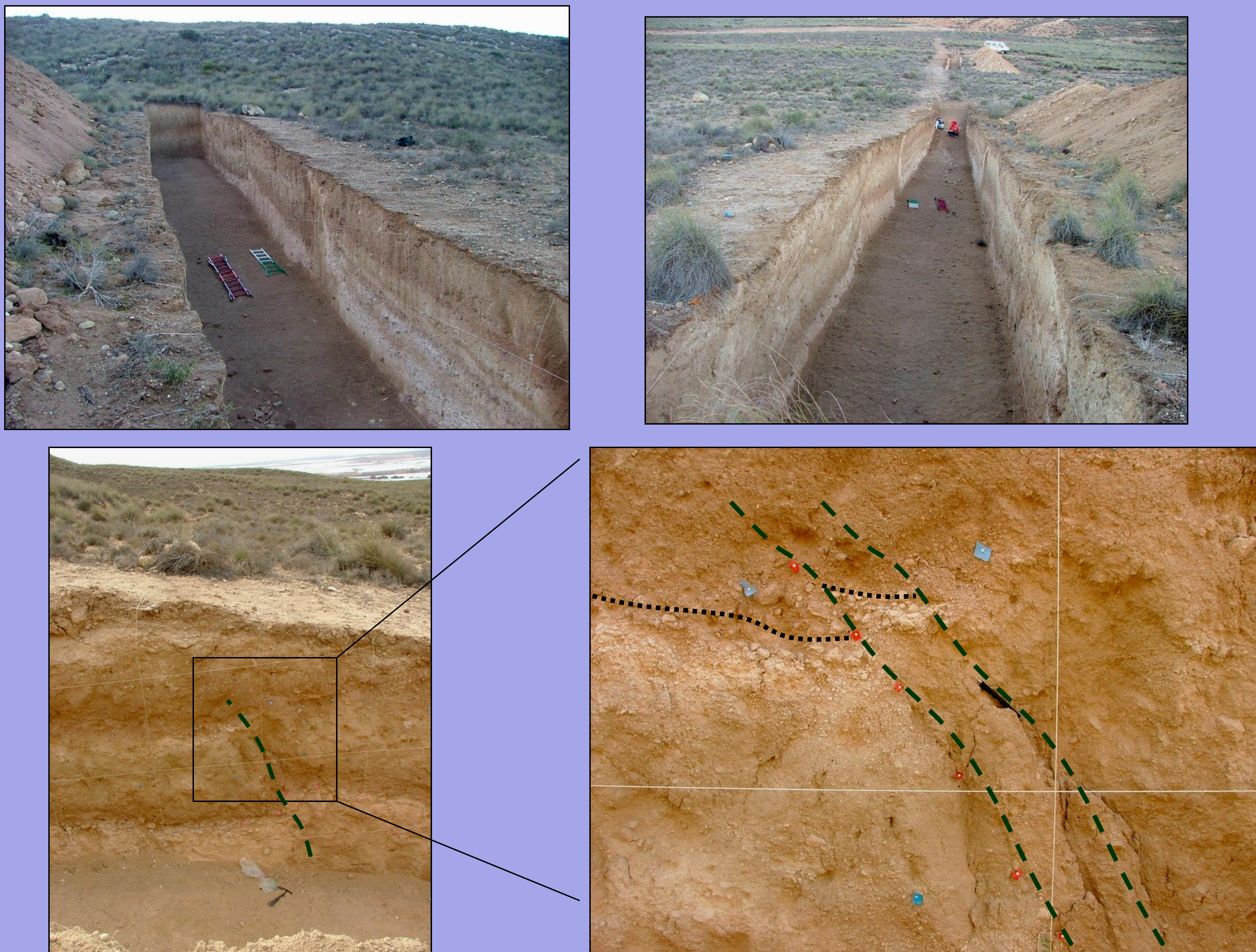
\+ reach -

November 2005

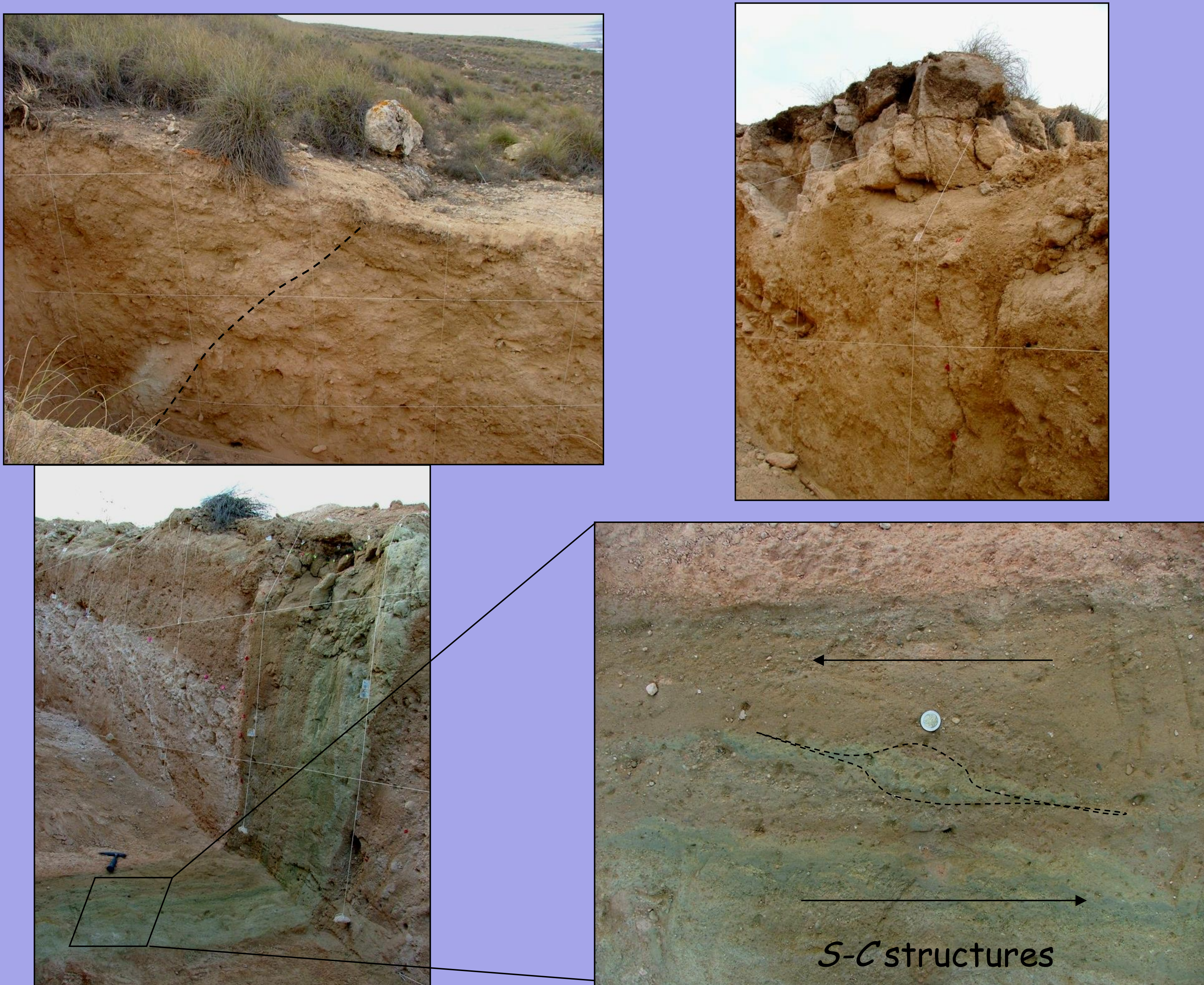


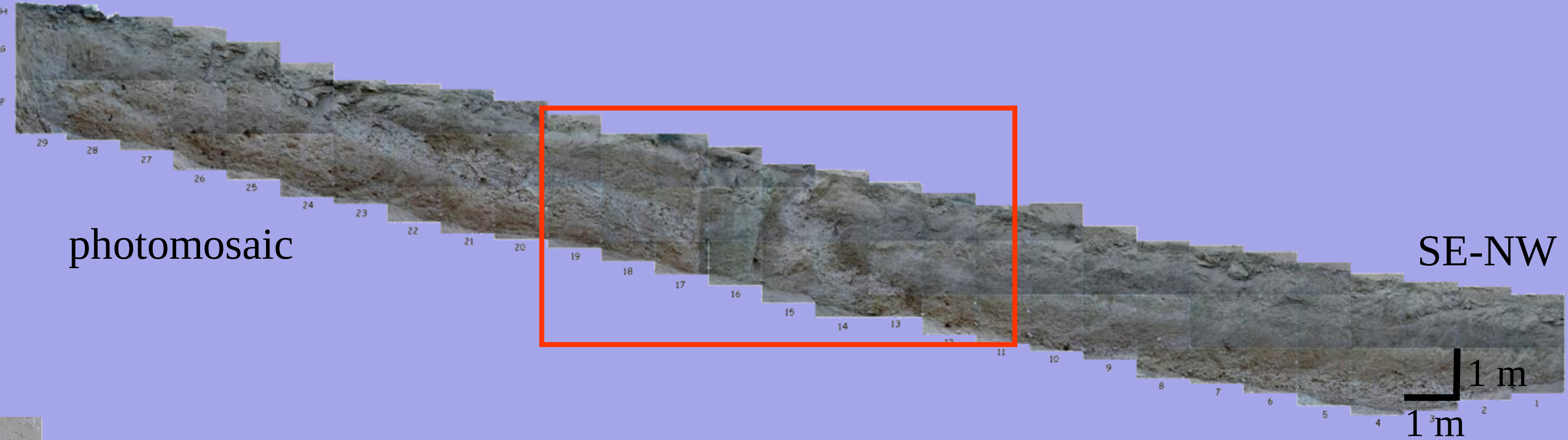
Cleaning the wall, grid

Identification of sedimentary layers and dislocations/faults



- Complex structure
    - flower structure
    - transpressive regime
- Horizontal movements
- strike-slips with vertical component-
- Repeated movements


S-C structures


photomosaic
SE-NW
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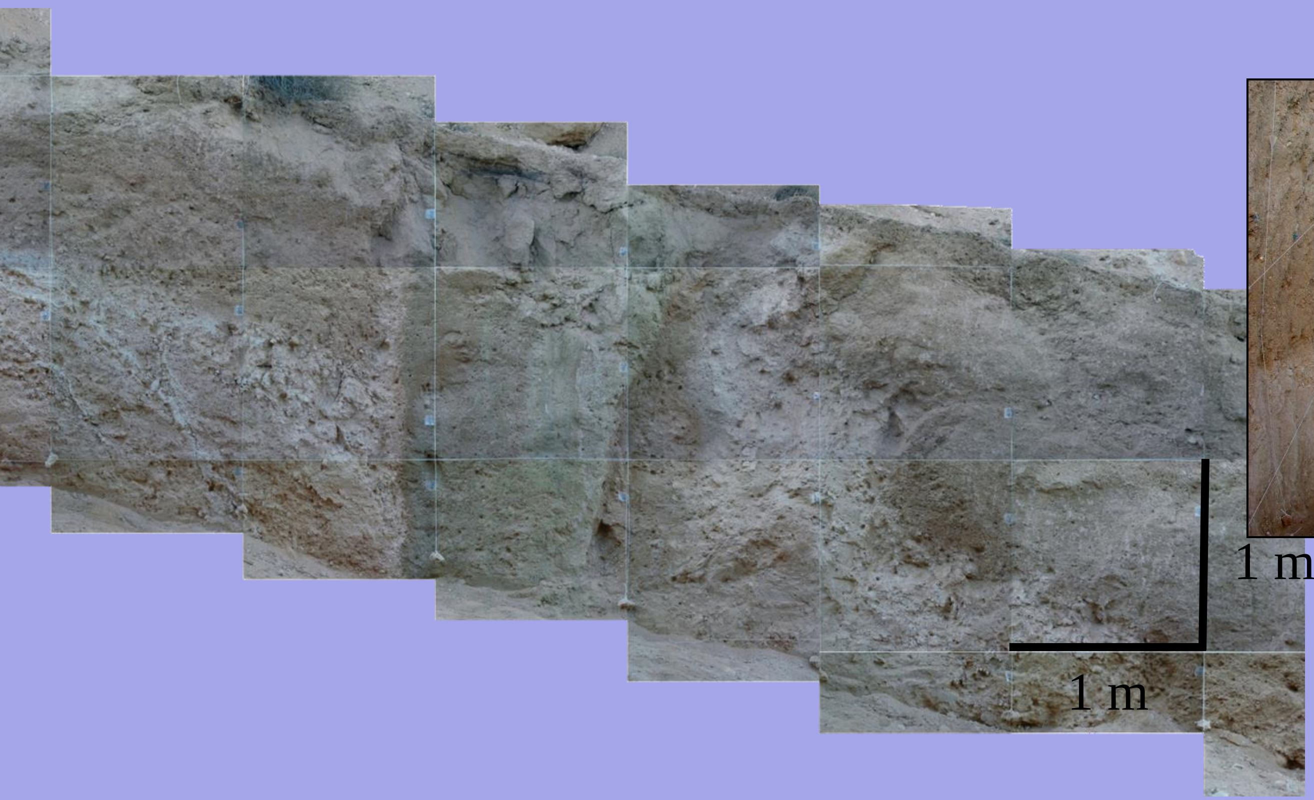
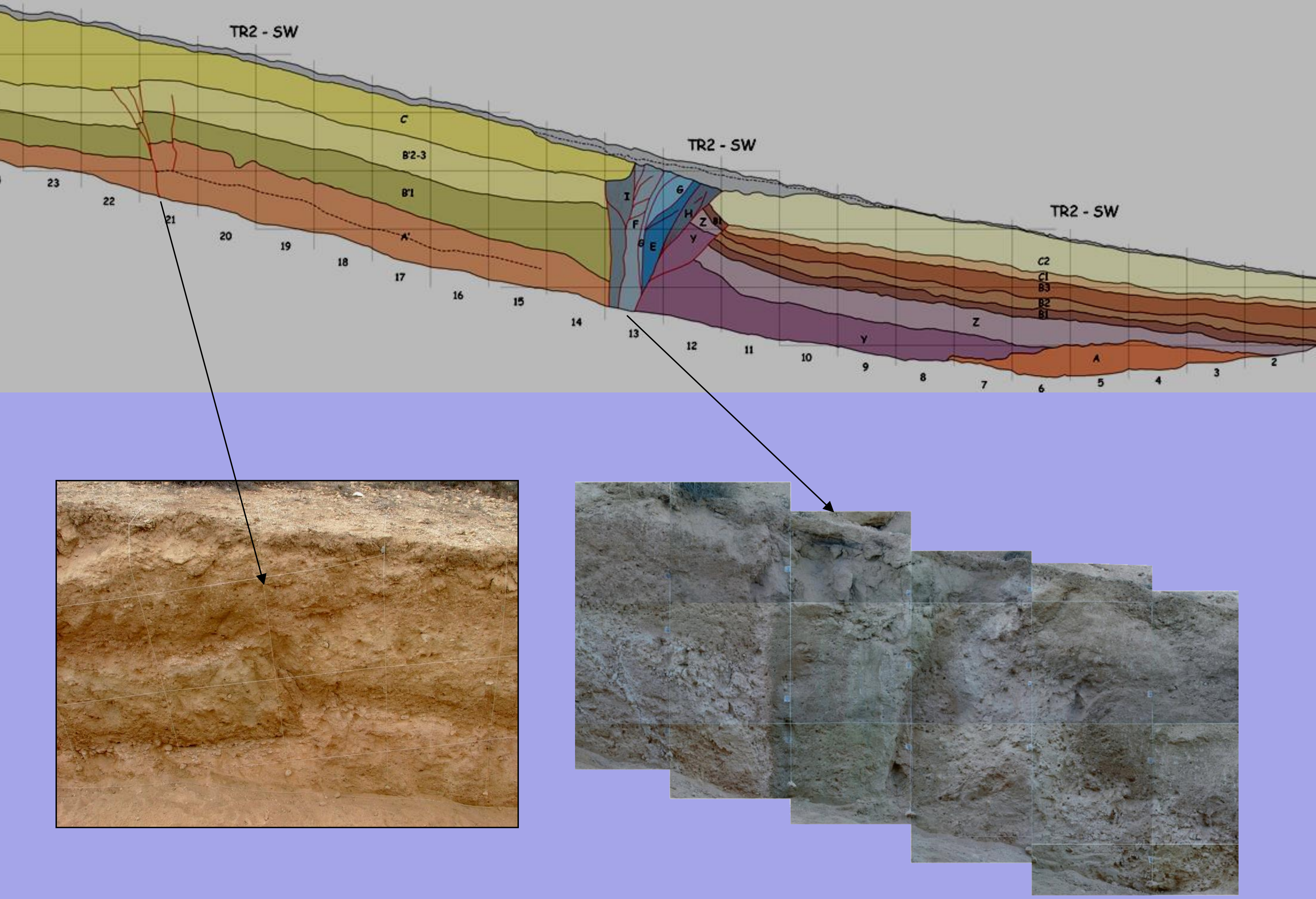
1 m


1 m
1 m


TR2 - SW
TR2 - SW
TR2 - SW
C
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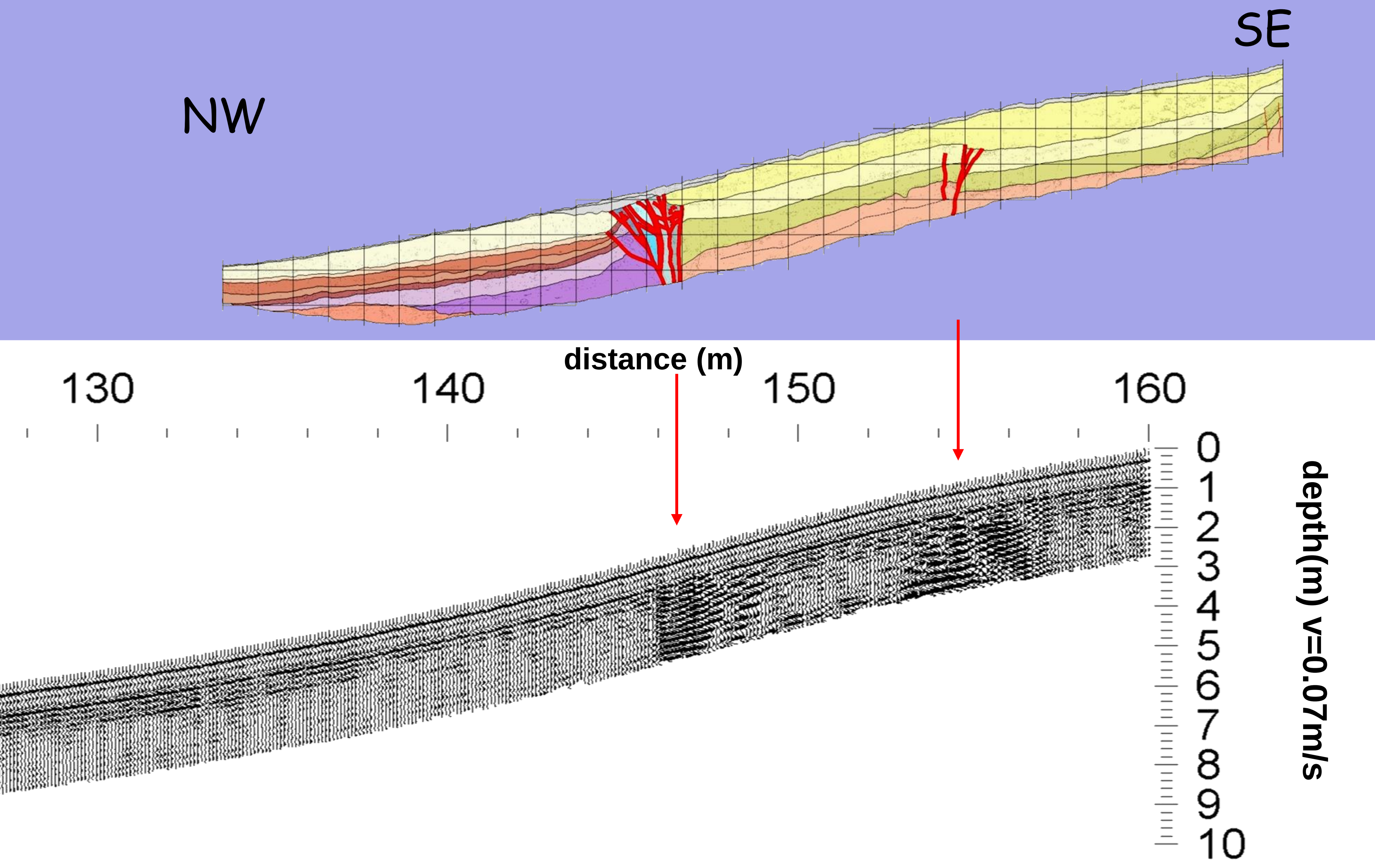
situation in situ versus geophysics



Dating – material cut by the seismic event

- **^{14}C radiocarbon dating method** → organic material and carbonatic shells (reach 40 thousands years) – charcoal, gastropodus, organic material, wood, etc.

  14C – in living organism, added from the environment, it decays, after death of organism, ratio of 14C/stabile 12C changes

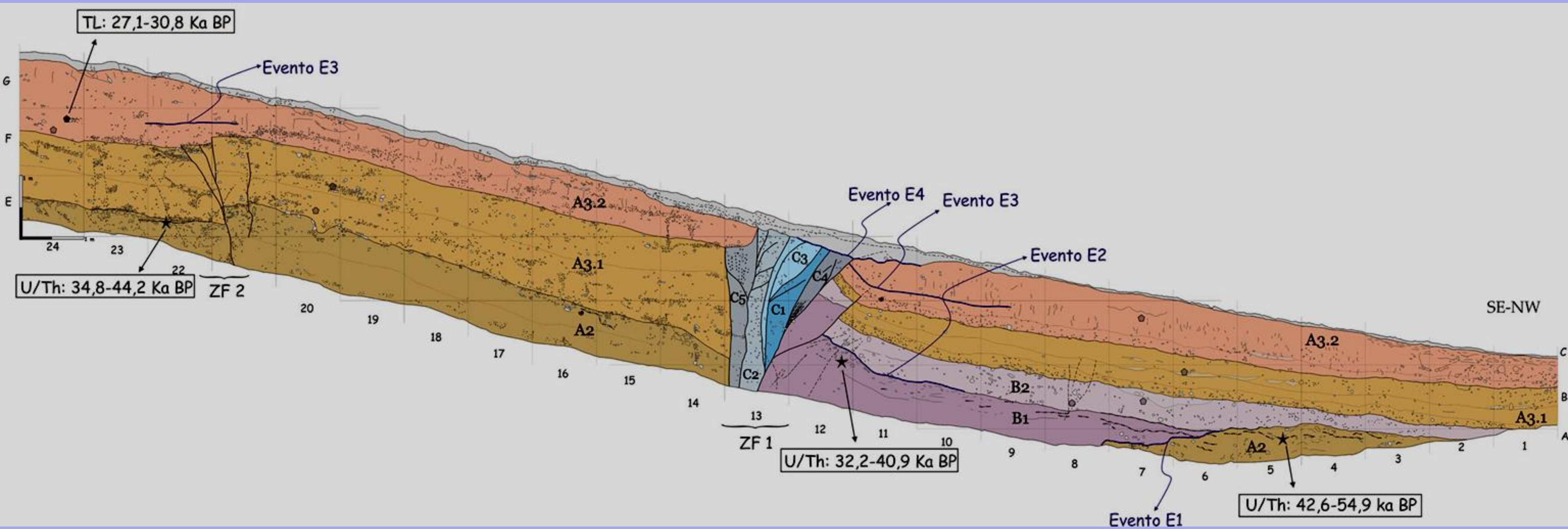
- **Optically stimulated luminiscence OSL –** electrones trapped in crystal lattice of sand grains - released by light activation or stimulation (reset – zero signal). After finishing of sedimentation – signal increases due to radioactive decay. Luminiscence relased by light activation in the lab is proportional to sediments age (the time until which the electrones were accummulated – until next reset (reach 250-300 thousands yrs)

- **Thermoluminiscence TL** → fine-grained sediments (100 thousands yrs)

- **U/Th** → carbonatic material (reach 300 thousands years) – **laminar caliche**

❖ interpretation of trench logs, assessment of type and amount of movements

reconstruction of deformation (retrodeformation)



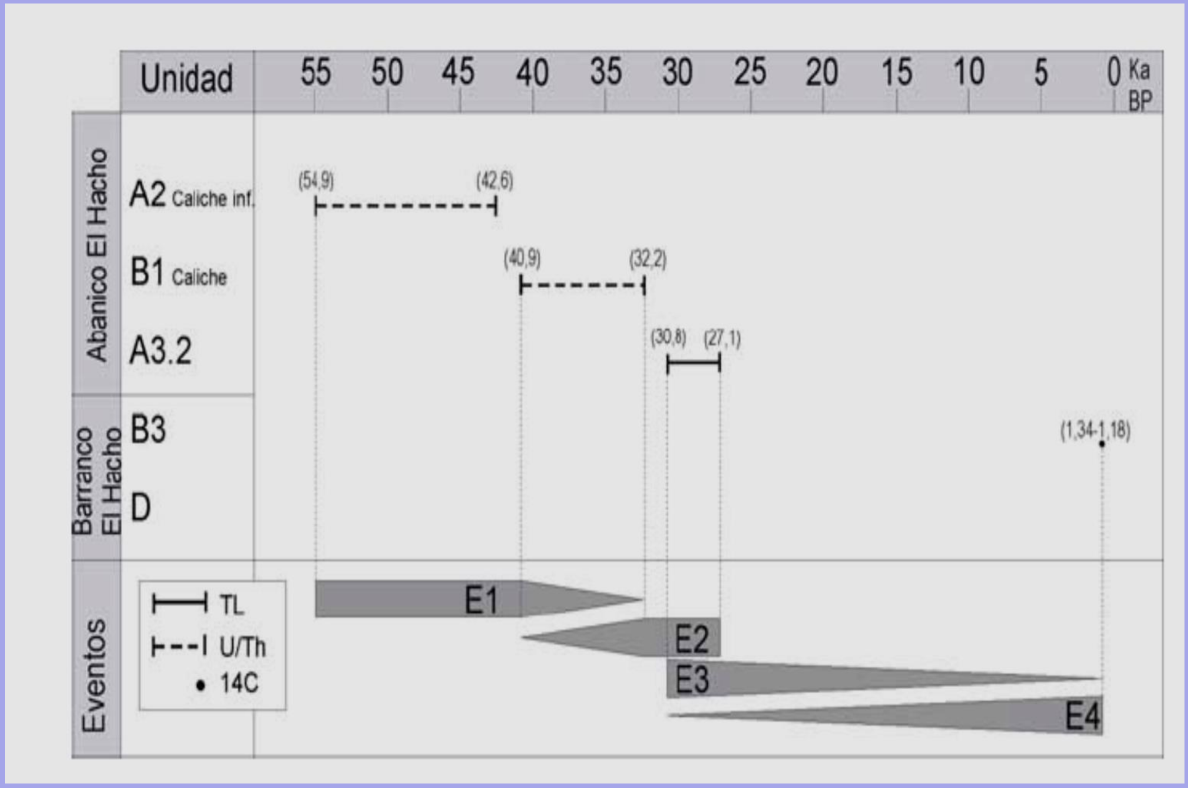
❖ laboratory results of dating

chronology of tectonic activity on the Carboneras fault

Results: Trench analysis and dating on Carboneras fault:

- B_1, B_2 – colluvial wedge were recognized (surface degradation after suddent event) – earthquake
- Minimum 4 earthquakes during last 50 thousands years
- Recurrence period – min. 14 thousands yrs
- Last event – minim 1310 years ago
- Empiric relationship Magnitude X Displacement for 2 events – minim.

M= 6.59 and 6.97



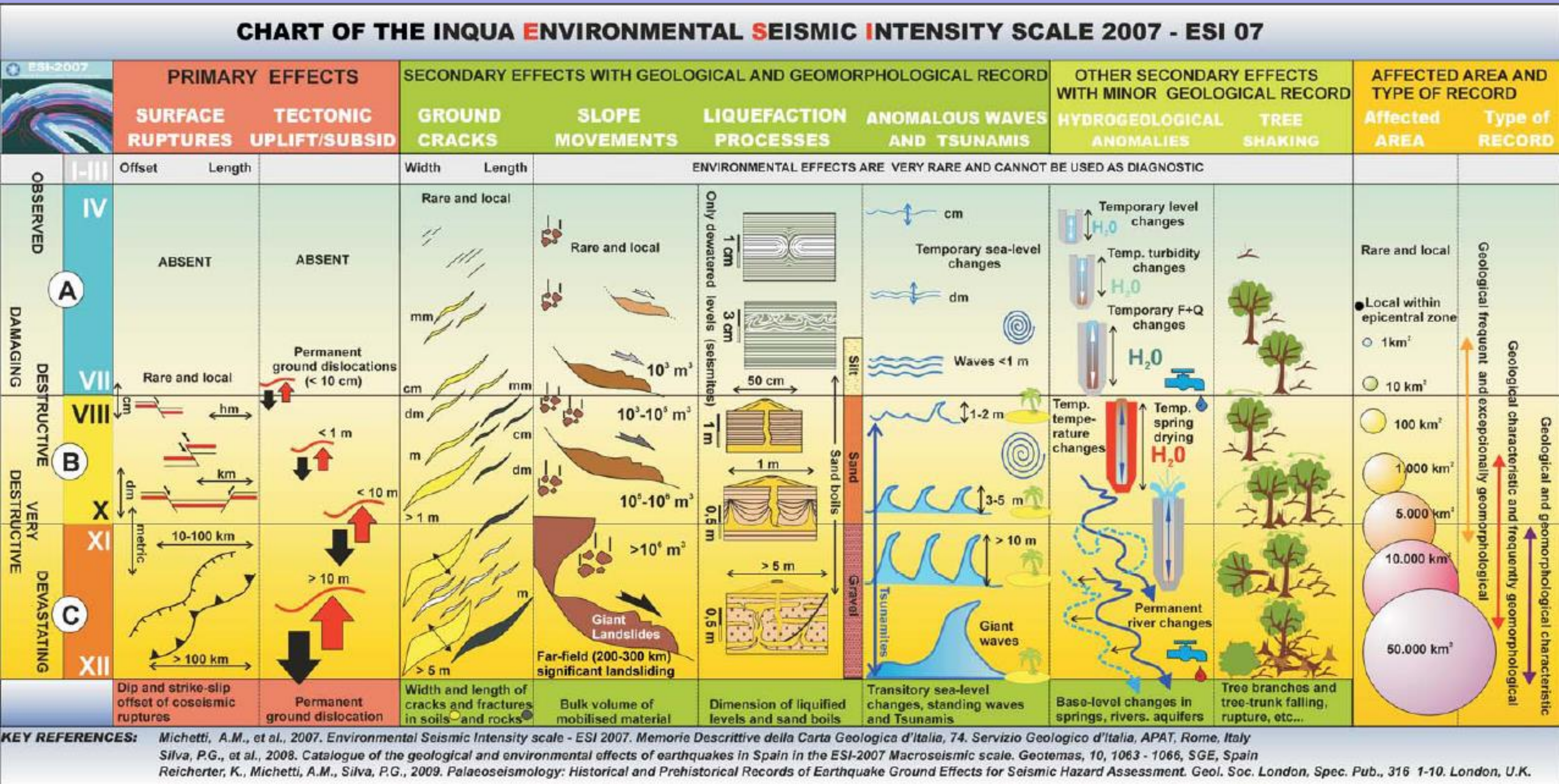


CHART OF THE INQUA ENVIRONMENTAL SEISMIC INTENSITY SCALE 2007 - ESI 07
ESI-2007
PRIMARY EFFECTS
SURFACE RUPTURES
TECTONIC UPLIFT/SUBSID
SECONDARY EFFECTS WITH GEOLOGICAL AND GEOMORPHOLOGICAL RECORD
GROUND CRACKS
SLOPE MOVEMENTS
LIQUEFACTION PROCESSES
ANOMALOUS WAVES AND TSUNAMIS
OTHER SECONDARY EFFECTS WITH MINOR GEOLOGICAL RECORD
HYDROGEOLOGICAL ANOMALIES
TREE SHAKING
AFFECTED AREA AND TYPE OF RECORD
Affected AREA
Type of RECORD
I-III
Offset
Length
Width
Length
ENVIRONMENTAL EFFECTS ARE VERY RARE AND CANNOT BE USED AS DIAGNOSTIC
OBSERVED
DAMAGING
DESTRUCTIVE
VERY DESTRUCTIVE
DEVASTATING
A
B
C
IV
VII
VIII
X
XI
XII
ABSENT
ABSENT
Rare and local
Permanent ground dislocations (< 10 cm)
cm
hm
km
dm
metric
10-100 km
> 100 km
< 1 m
< 10 m
> 10 m
Rare and local
mm
cm
mm
dm
cm
m
dm
> 1 m
m
> 5 m
Rare and local
10^3 m^3
10^3-10^5 m^3
10^5-10^6 m^3
>10^6 m^3
Giant Landslides
Far-field (200-300 km) significant landsliding
Only dewatered levels (seismites)
1 cm
3 cm
50 cm
1 m
1 m
0,5 m
> 5 m
0,5 m
Silt
Sand
Gravel
Sand boils
cm
Temporary sea-level changes
dm
Waves <1 m
1-2 m
3-5 m
> 10 m
Tsunamites
Giant waves
Temporary level changes
H_2O
Temp. turbidity changes
H_2O
Temporary F+Q changes
H_2O
Temp. temperature changes
Temp. spring drying
H_2O
Permanent river changes
Rare and local
Local within epicentral zone
1km²
10 km²
100 km²
1.000 km²
5.000 km²
10.000 km²
50.000 km²
Geological frequent and excepcionally geomorphological
Geological characteristic and frequently geomorphological
Geological and geomorphological characteristic
Dip and strike-slip offset of coseismic ruptures
Permanent ground dislocation
Width and length of cracks and fractures in soils and rocks
Bulk volume of mobilised material
Dimension of liquified levels and sand boils
Transitory sea-level changes, standing waves and Tsunamis
Base-level changes in springs, rivers. aquifers
Tree branches and tree-trunk falling, rupture, etc...
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