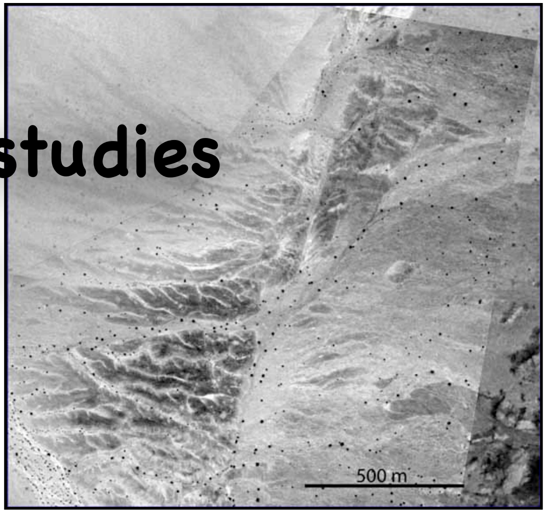
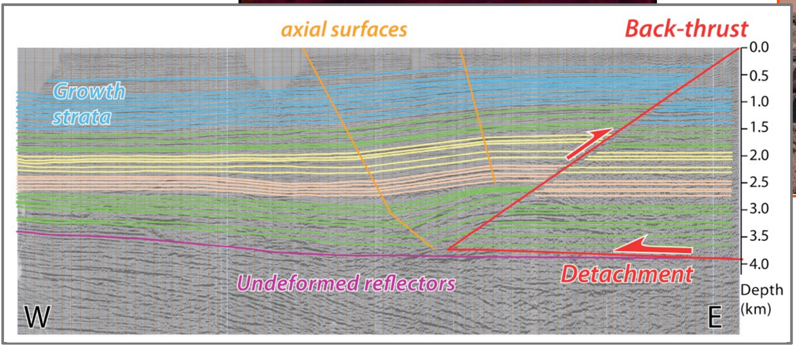
Results and perspectives from a decade of neotectonics studies in Taiwan and the Levant



Maryline Le Béon

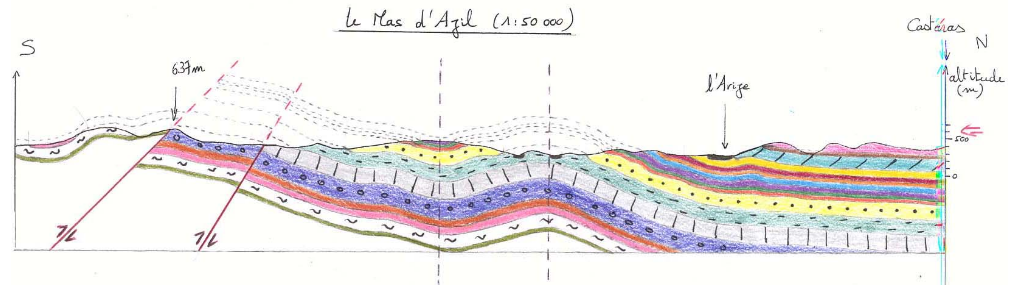
NCU, March 15th 2016



Curriculum

	MOST Assistant Researcher	*Nat. Central Univ.*
2015	**Post-doctoral Research Fellow**	*Nat.* **Taiwan** *Univ.* Prof. John Suppe
2013	**Distinguished Post-doctoral Research Fellow**	*Academia Sinica - iES* Dr. Lee Jian-Cheng
2011	**Post-doctoral Research Fellow**	*Nat.* **Taiwan** *Univ.* Prof. John Suppe
2008	***Teaching and Research Assistant*** *(ATER)* **PhD** *Advisor: Y. Klinger* *6 months at L. Livermore Nat. Lab.* (***USA***)	*IPG Paris*
2005	**MASTER** Geophysics	*IPG Paris*
	BACHELOR Earth and Planetary Sciences *3-month internship - San Diego State Univ.* (***USA***)	*ENS Lyon, France*
2000		

Teaching Experience



Example of a simple geological cross-section in SW France

- Teaching Assistant 2007-2008:

- 42 hours **Practical Classes**

  Senior B.S. level

Introduction to geological maps and construction of geological cross-sections

- 24 days **Field Trips** - Master Level

Geological mapping, Structural geology and tectonics, active tectonics

- **Undergraduate students training**:

- Odin Marc (Spring 2010)
- Chen Ya-Lin (2010-2011)
- Tseng Ya-Chu (since February 2016)

- **Broadcasting science to public**:

- "Fête de la Science" open-house event (2001-2007)
- On-line scientific forum for high-school students (2001-2005)

Active Tectonics field trip: Uplifted marine terraces in SW Greece

Teaching Abilities and Classes Proposal

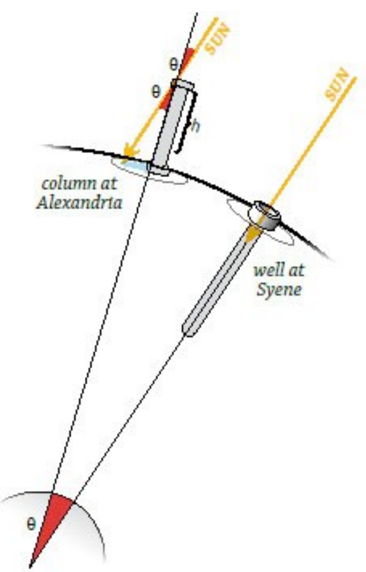
- Ability to teach **basic geology classes** at the **bachelor level**, in particular structural geology and tectonics, physical geology, natural hazards, field classes, geodesy...

  and **others according to current needs**.

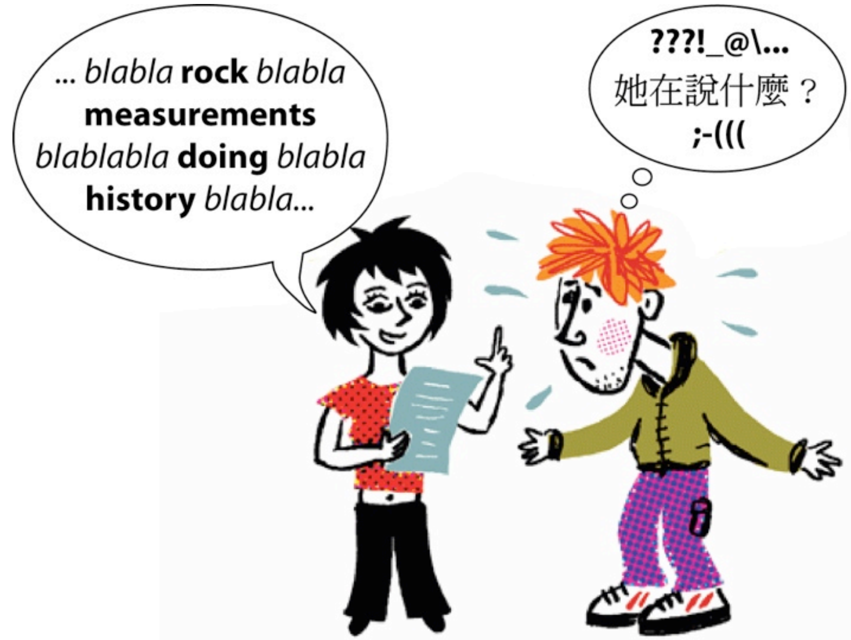
- Proposal for **in-depth master-level classes** :

- Geomorphology, Quaternary geology and natural hazards
- Active tectonics and seismic hazard
- Geochronology (Quaternary or all timescales)
- Geographic Information System
- History of Geosciences and Philosophy of Science
- ...

Determination of Earth's circumference (Erastothenes, 2nd century BC)



Teaching in English



- Make the students comfortable

- Provide clear visual documents

- English-Chinese glossary of scientific terms

- Repeat...

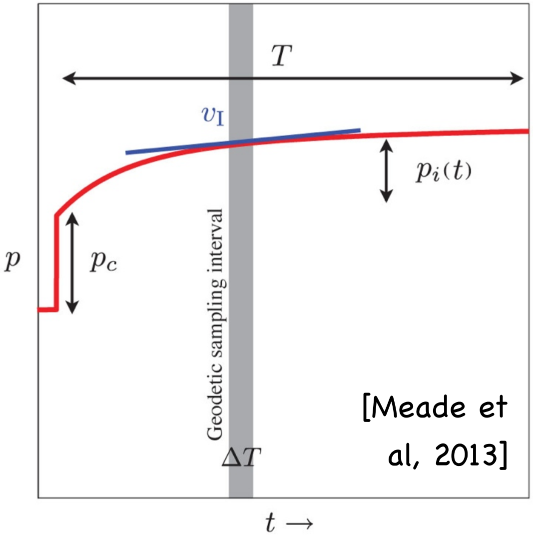
- Develop interactive classes

Pleistocene	更新世
Fault	斷層
Luminescence dating	螢光定年
Paleo-earthquake	古地震
Taiwan Straight	台灣海峽
...	

Research Focus:

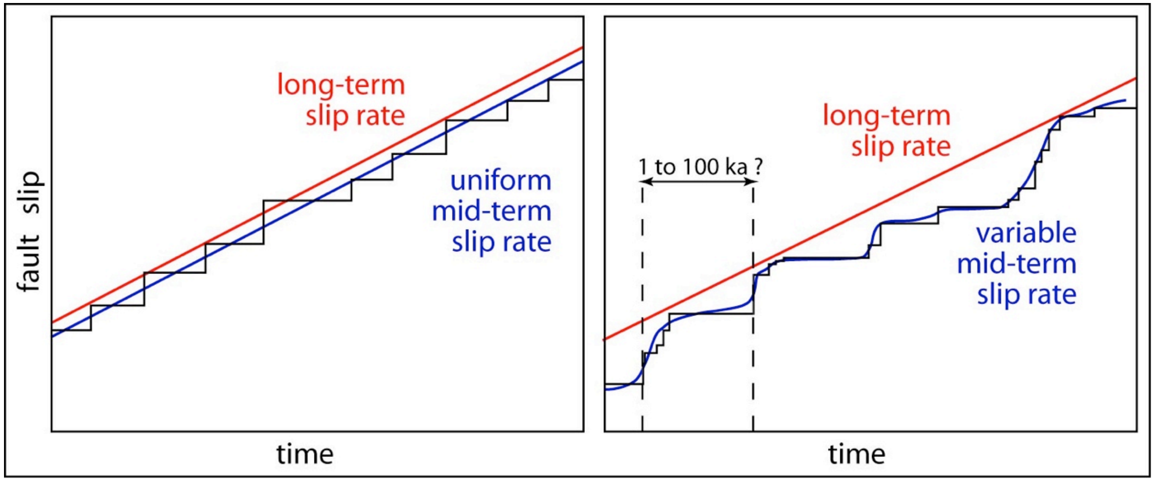
Long-term seismic behavior of active faults

Interseismic deformation :



Quasi-static ? or **Dynamic ?**

Temporal distribution of earthquakes :



Modified from Chéry & Vernant 2006

Quasi-periodic cycles ? OR **Clusters + periods of quiescence ?**

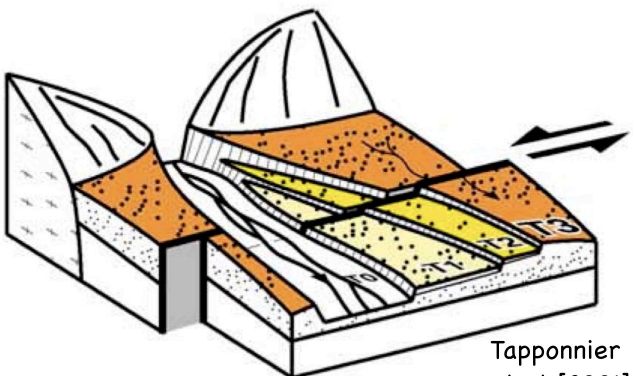
=> Approach : Compare fault slip rates determined at different time scales

First reviews: Meade et al, 2013; Vernant, 2015

Research Focus:

Moving towards folding and mountain building questions

Strike-slip setting :

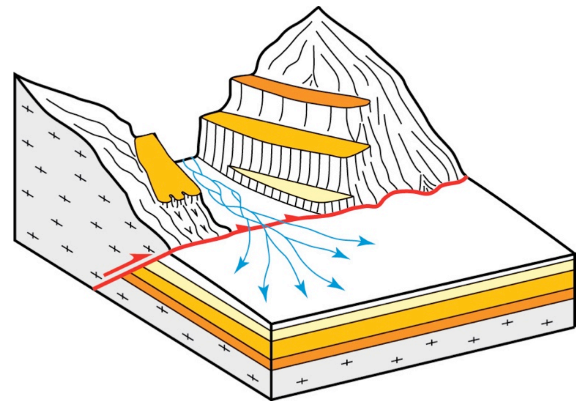


Tapponnier et al [2001]

Simple geometry:

fault slip = lateral offset

Collisional setting :



More complex geometric problem:

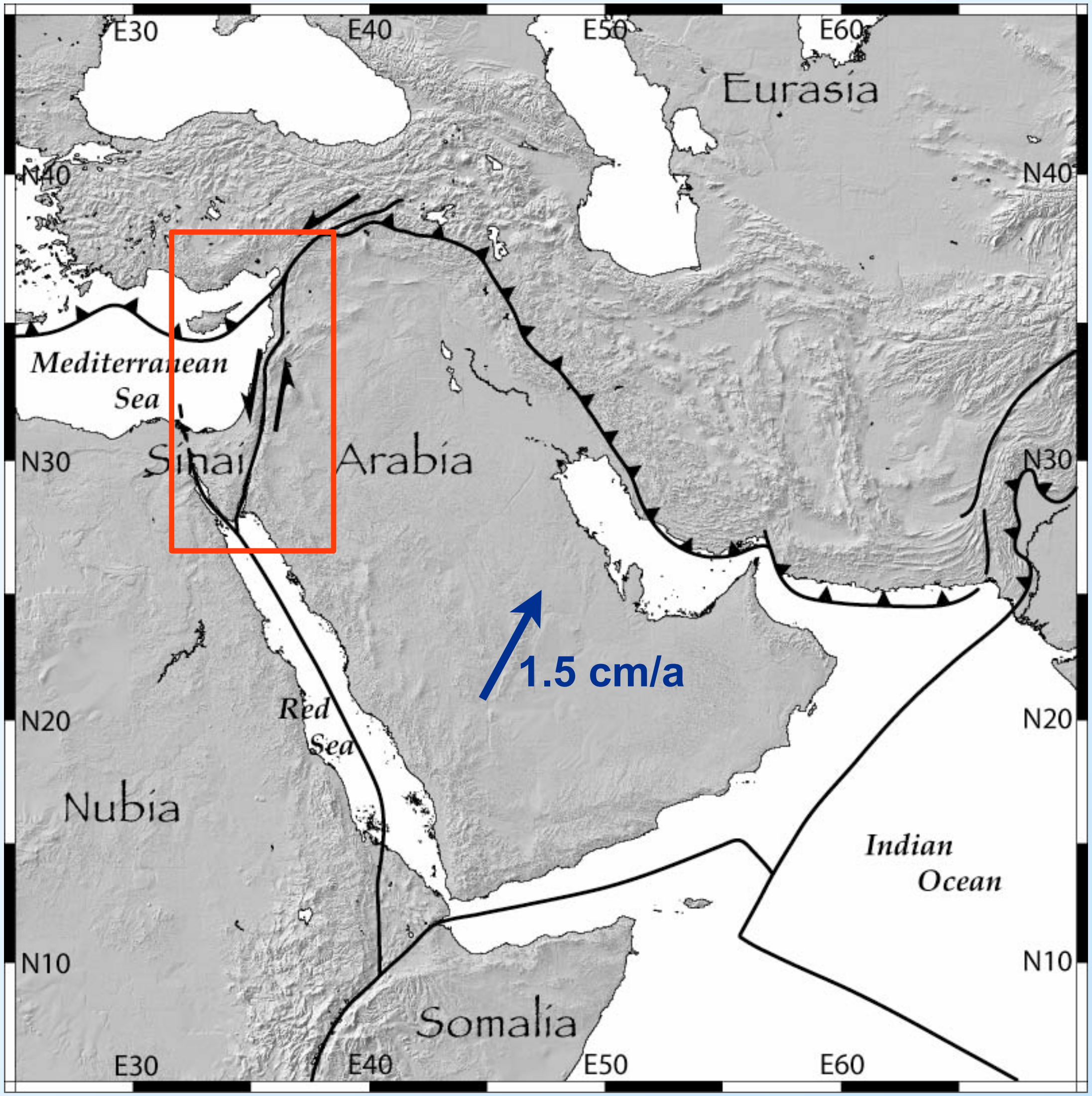
fault slip = f (terrace deformation, fault geometry, folding mechanism)

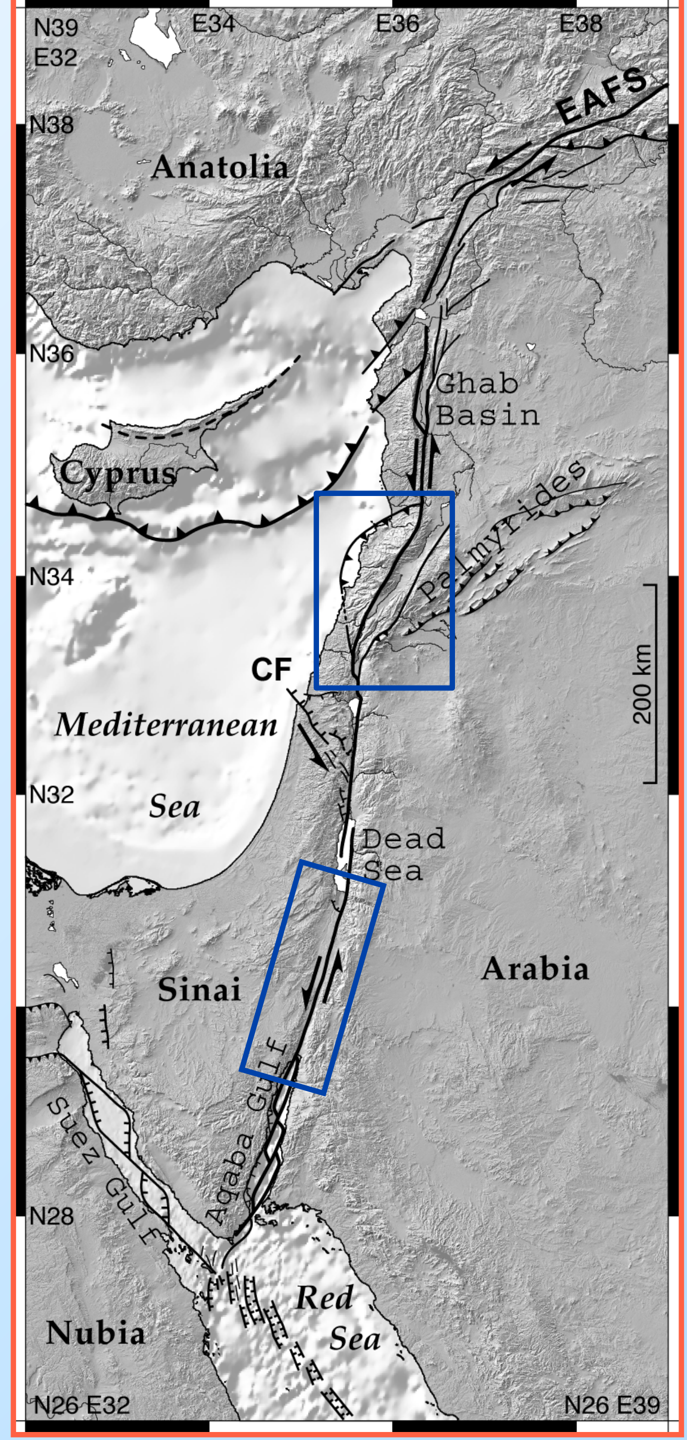
FIELD AREAS

Dead Sea Fault system

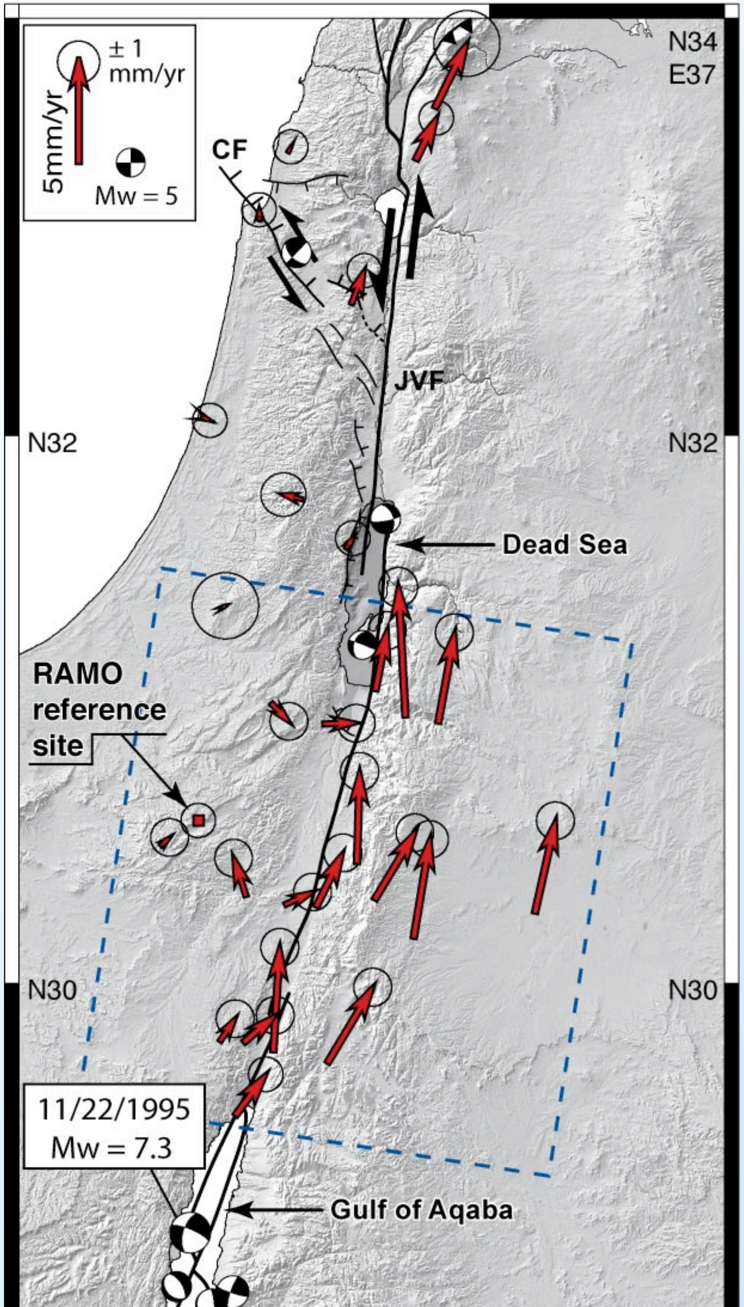
Western Foothills of Taiwan

Dead Sea fault regional setting



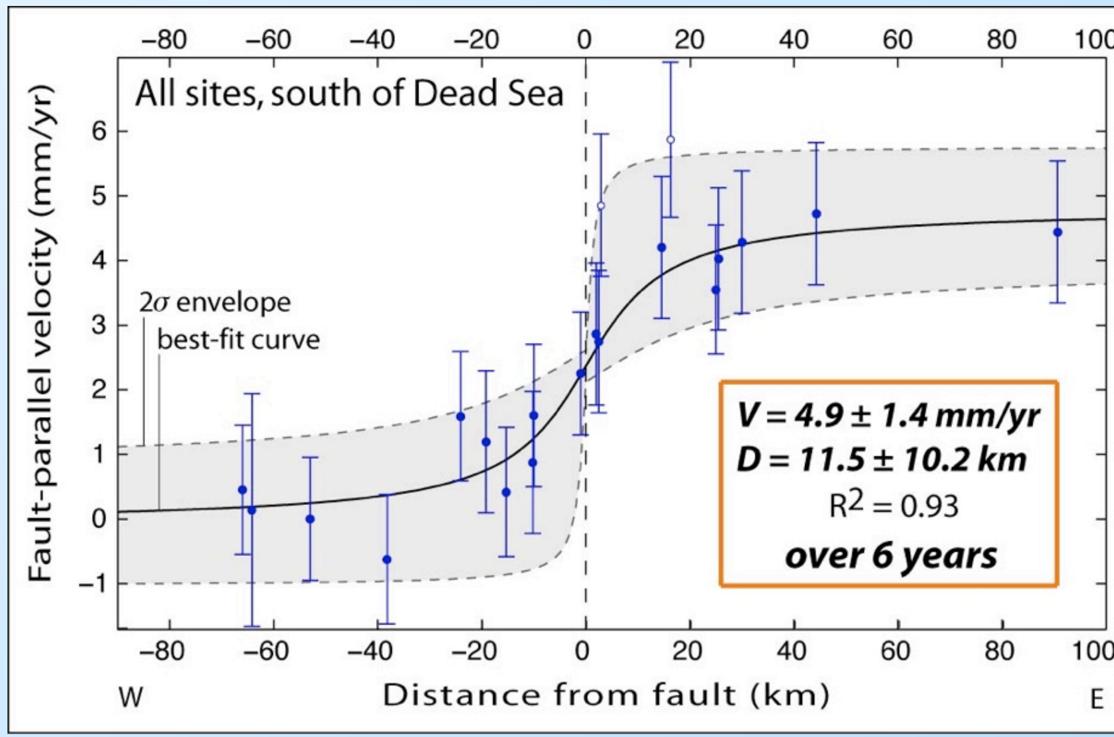


Present-day fault slip rate from GPS



- Campaign **measurements**
- **Data processing**
- Simple **elastic modeling** of interseismic velocity field

Le Béon et al, 2008, JGR



Result confirmed by a **3rd campaign in 2012:**

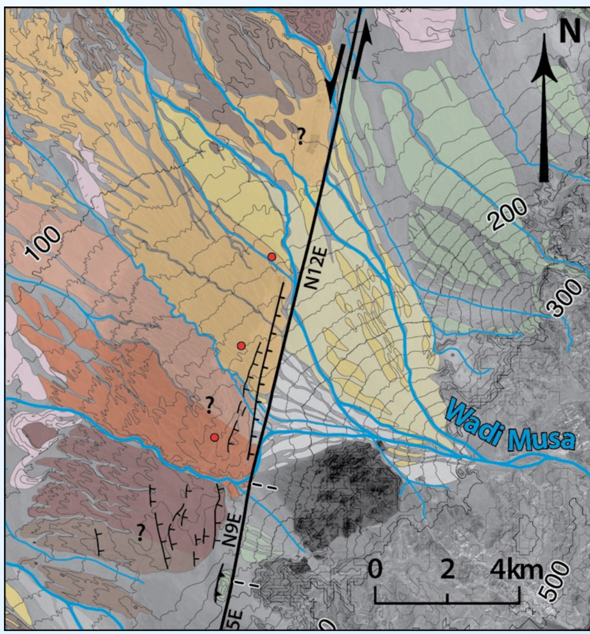
4.9 ± 0.5 mm/a [Masson et al, 2015]

Morpho-tectonic map of the Wadi Araba

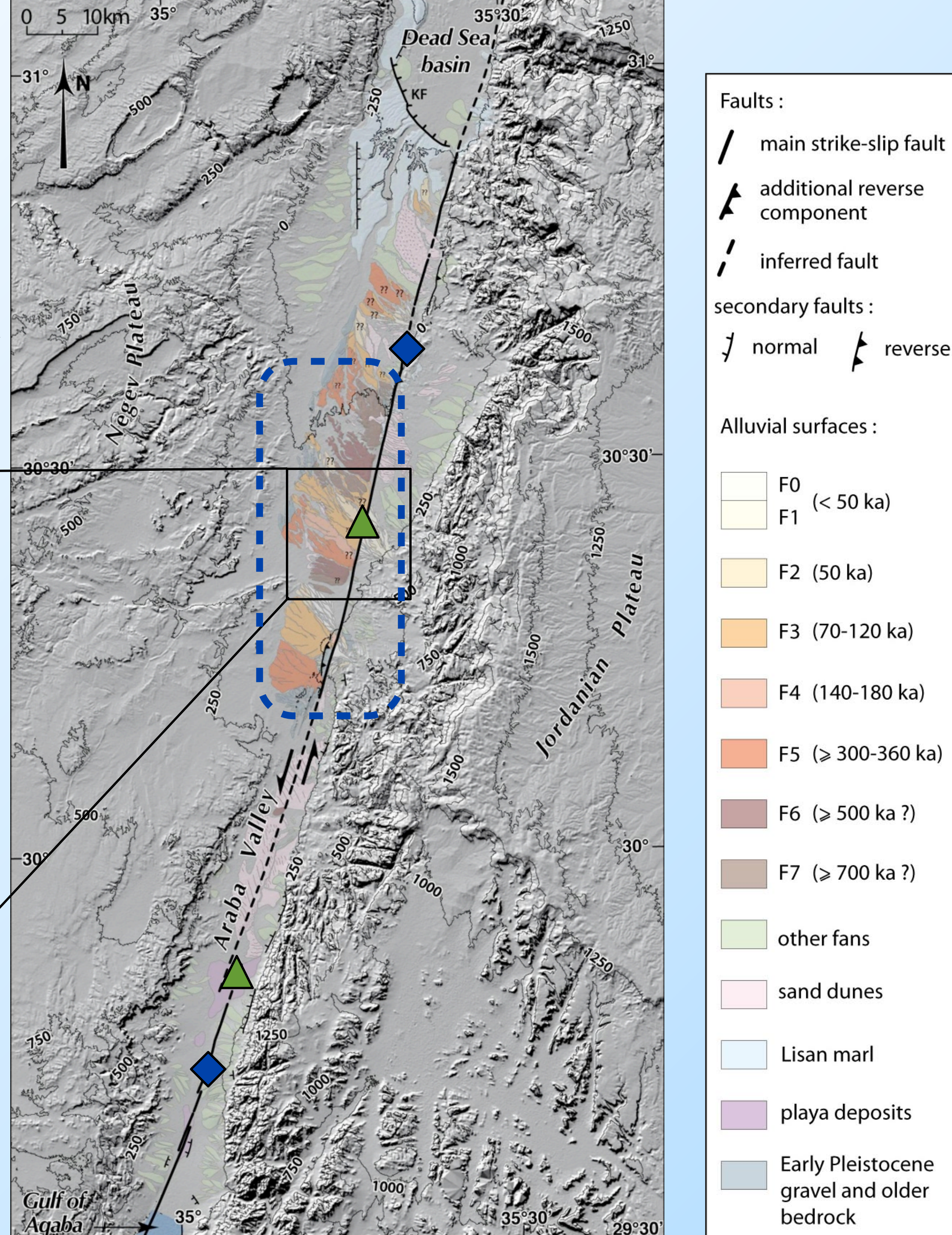
> Detailed fault trace

> Identification of offset markers ◆

> Potential paleoseismologic sites ▲

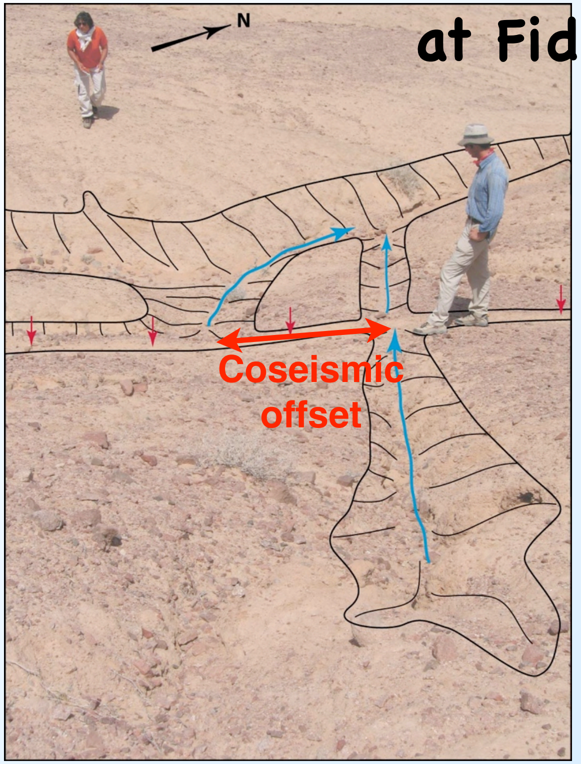


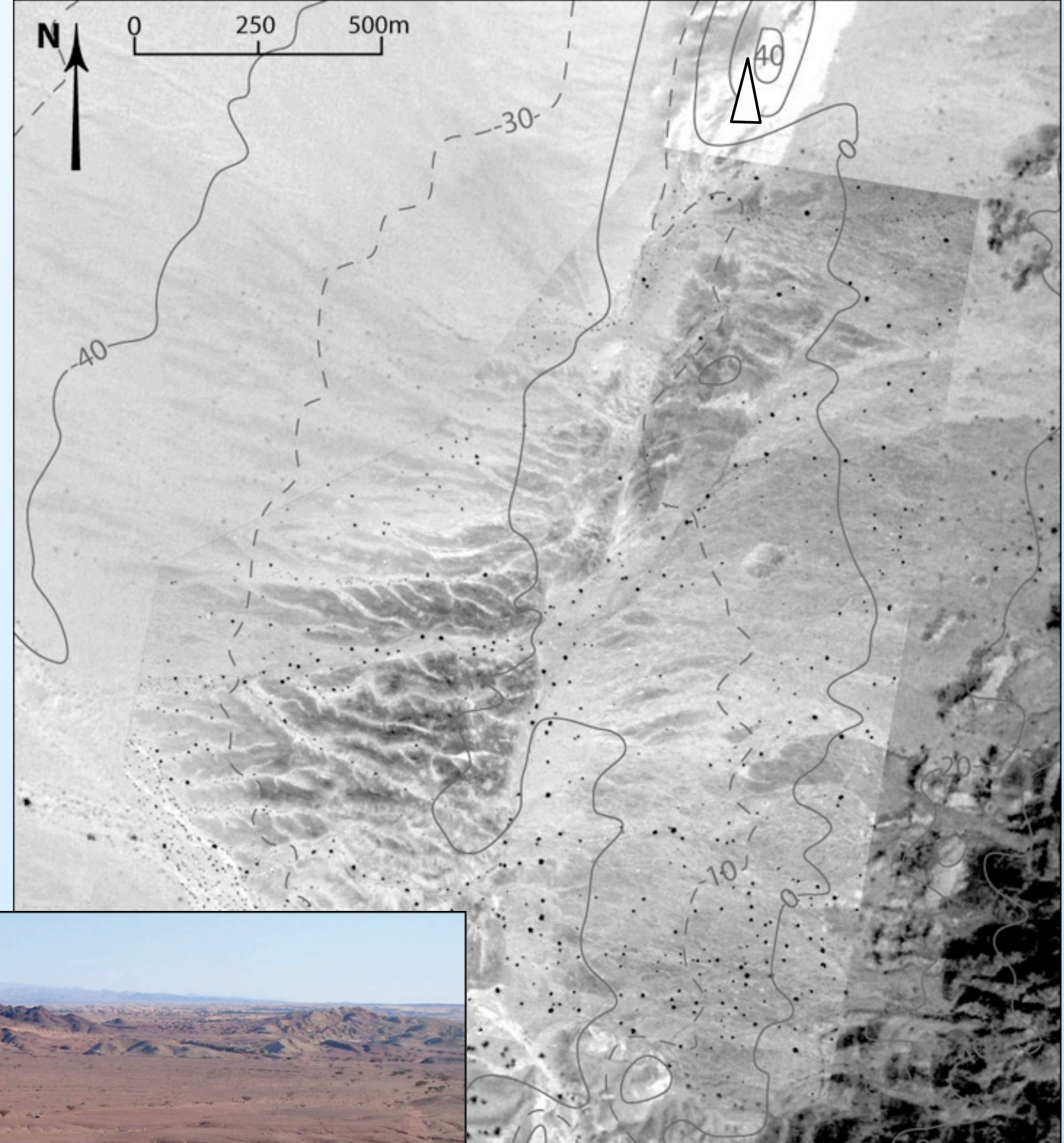
Topographic contour lines superimposed on SPOT5 image (pixel=2.5m)



Le Béon et al, 2012, Tectonics

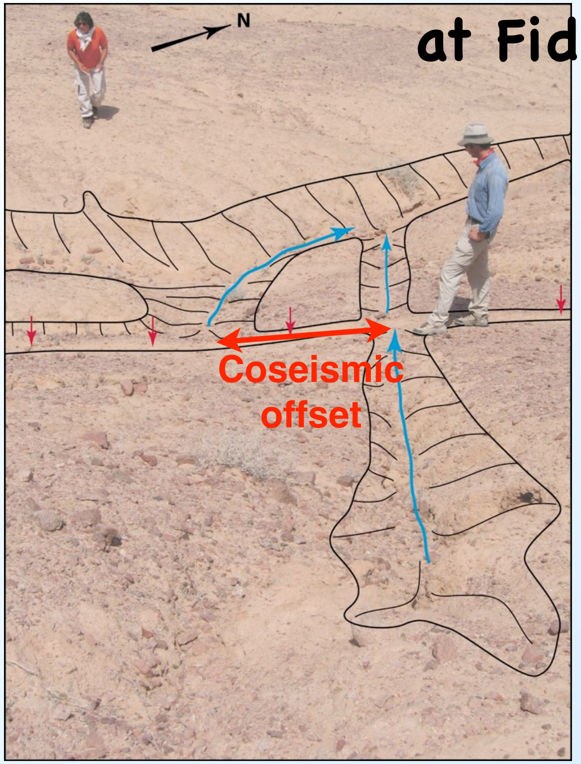
Offset alluvial deposits at Fidan

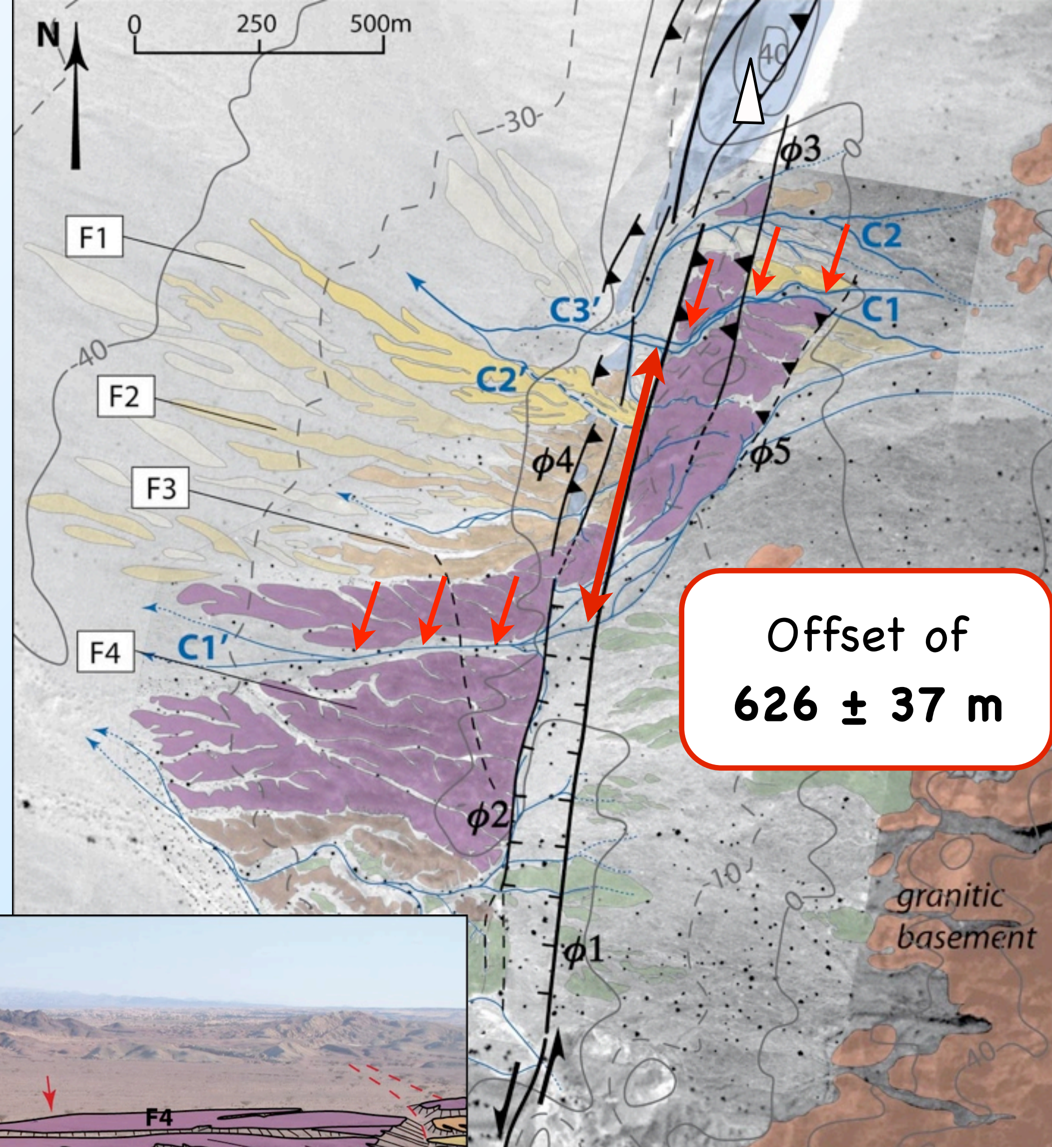




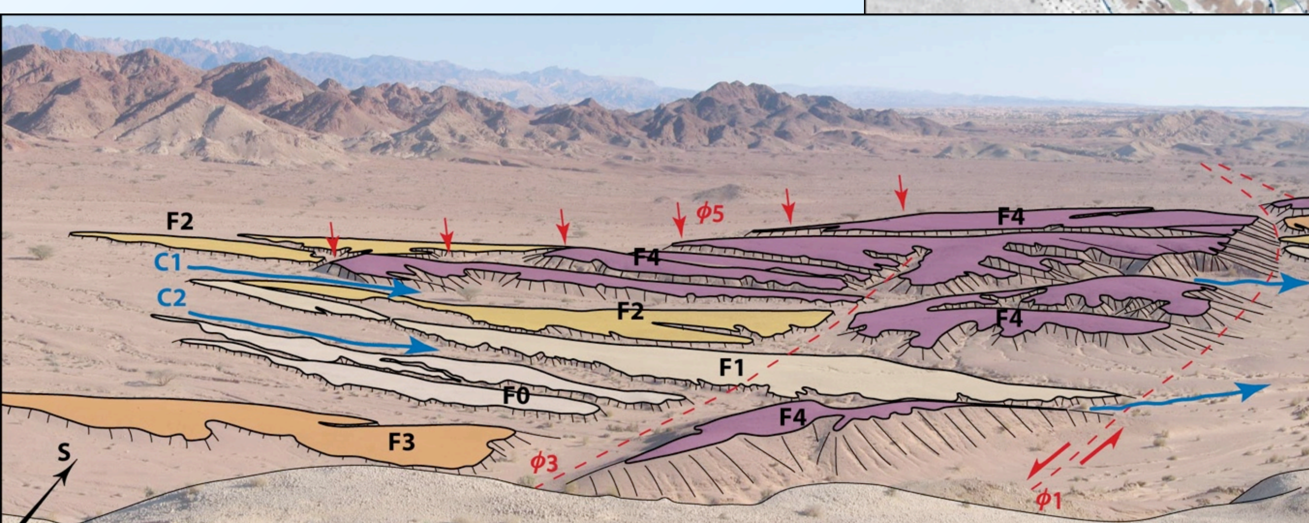
Aerial view superimposed on SPOT5 image

Offset alluvial deposits at Fidan





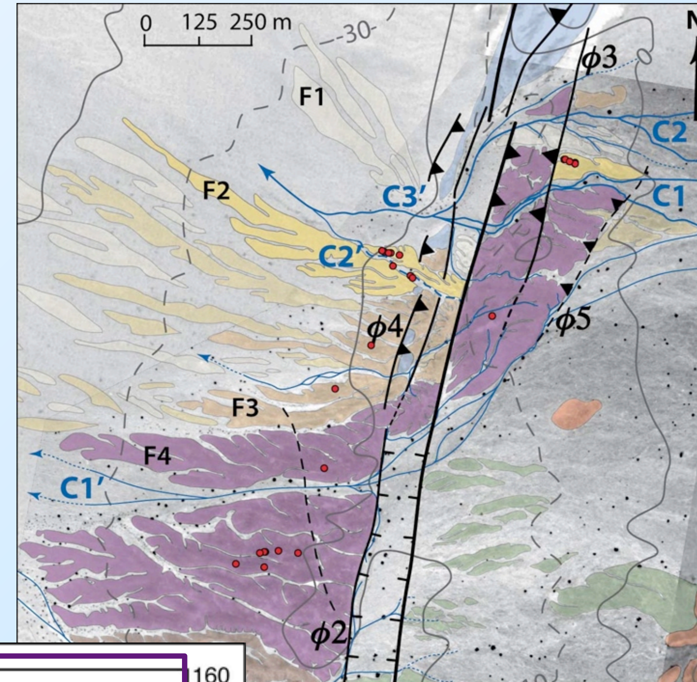
Aerial view superimposed on SPOT5 image

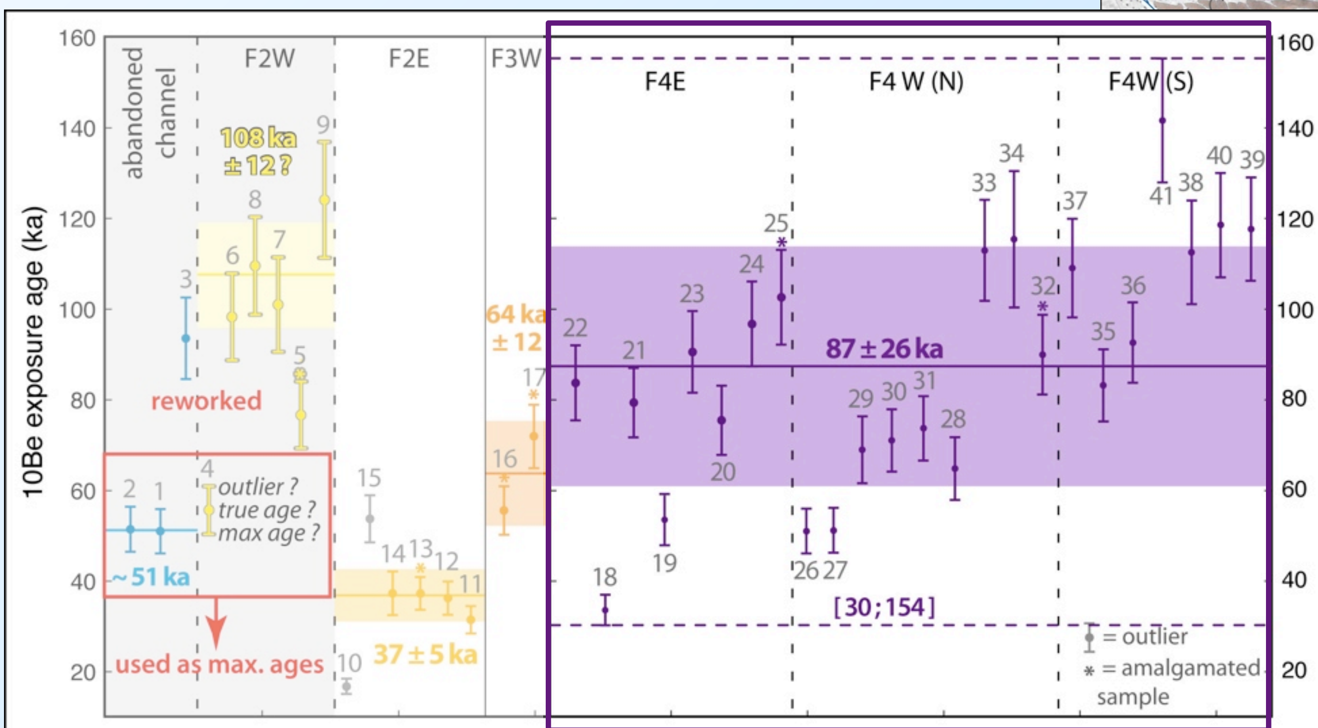


^{10}Be exposure ages

=> **Scattered**

age distribution !





Le Béon et al, 2010, JGR

Cross-dating ^{10}Be - Luminescence (OSL)

Exposure age — Burial age

Traditional techniques failed

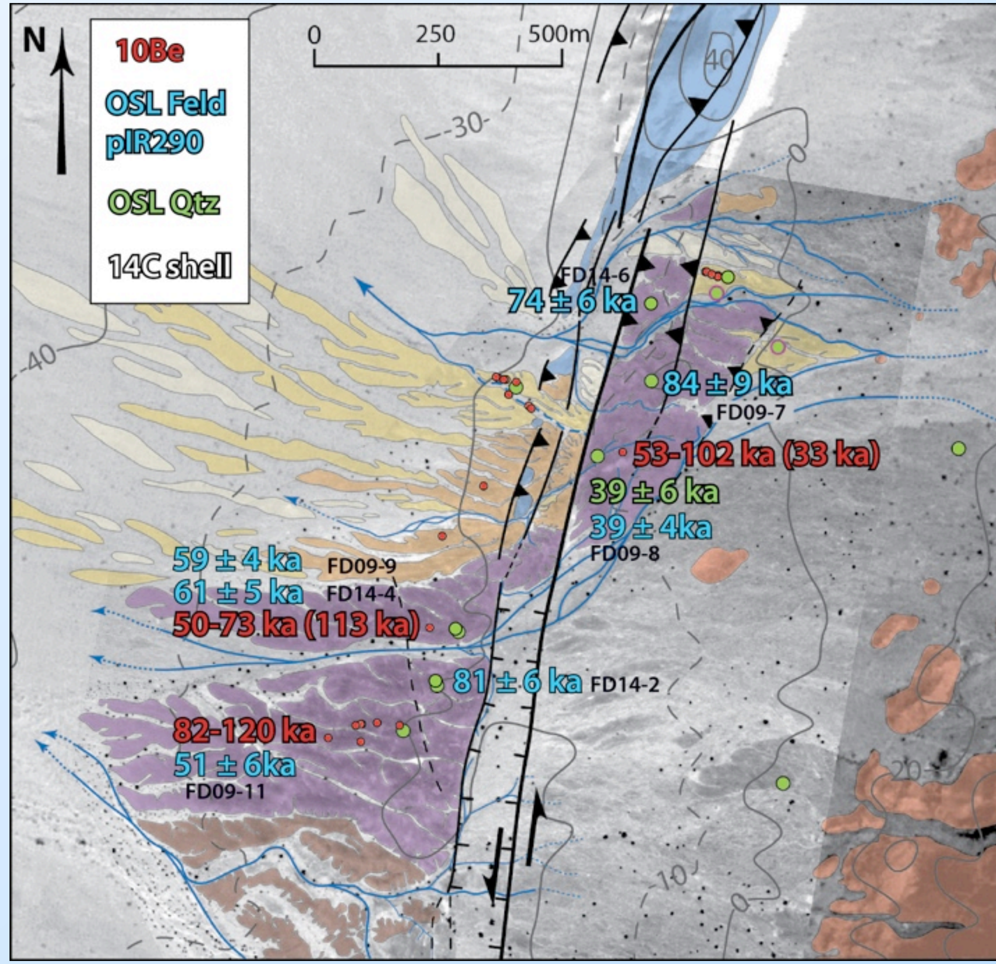
=> **New technique** MET-pIRIR on K-Feldspar

[Buylaert et al 2012]

Sampling
for OSL,

in PVC tube

or in
light-proof
bag under
black cover

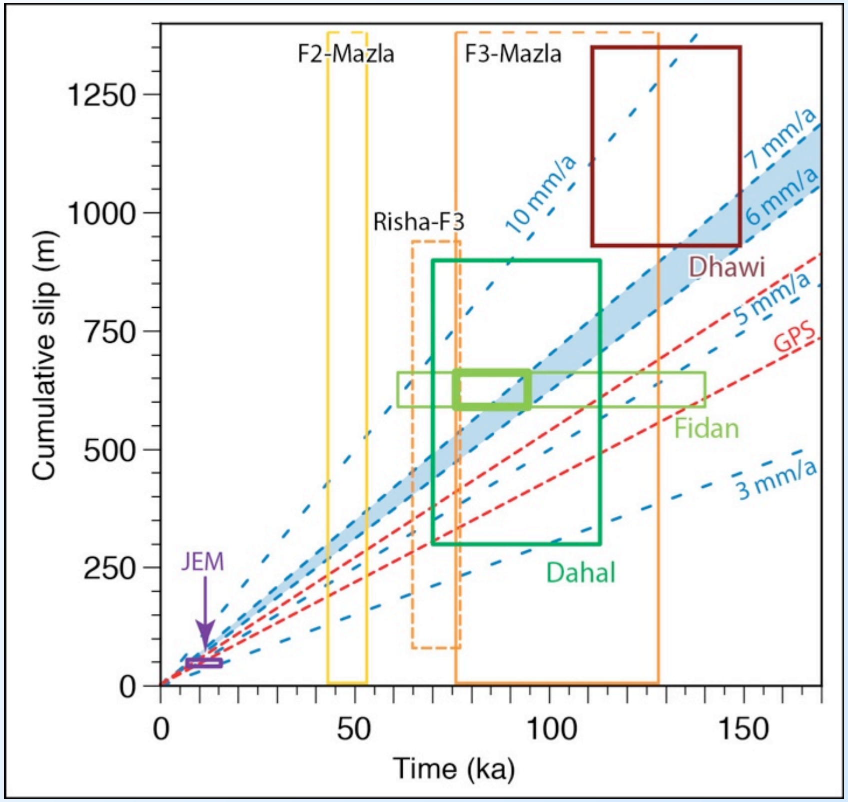


=> **Several phases of alluvial aggradation and incision** that started **84 ka** ago

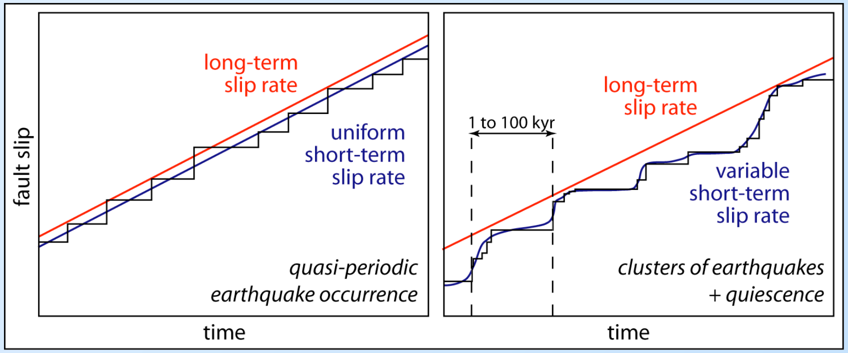
Slip rate results & Fault seismic behavior

CONSTANT long-term fault slip rate = 6-7 mm/a

Inconsistent with **Geodetic slip rate** = 4.4-5.4 mm/a



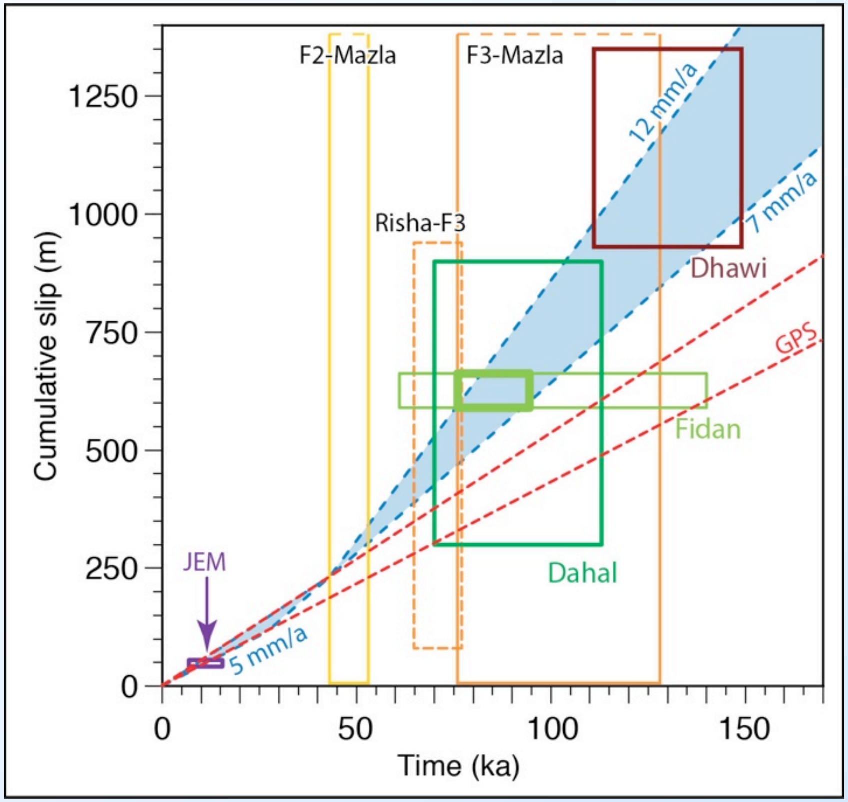
Data compiled from Klinger et al, 2000; Le Béon et al, 2010, 2012, in prep; Masson et al, 2015



Slip rate results & Fault seismic behavior

VARIABLE fault slip rate over time => **How?**

Holocene slip rate = **Geodetic** fault slip rate



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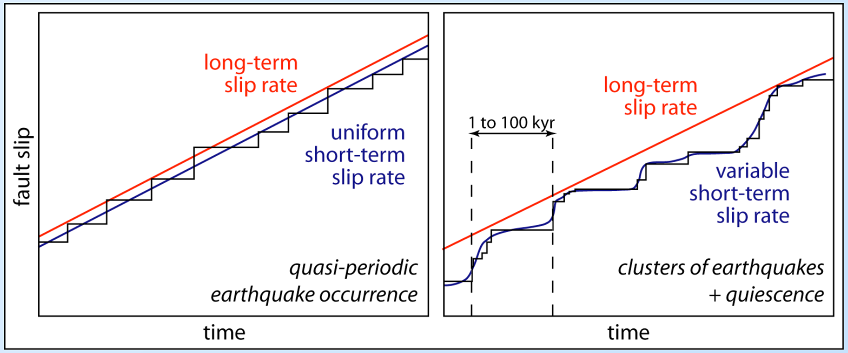

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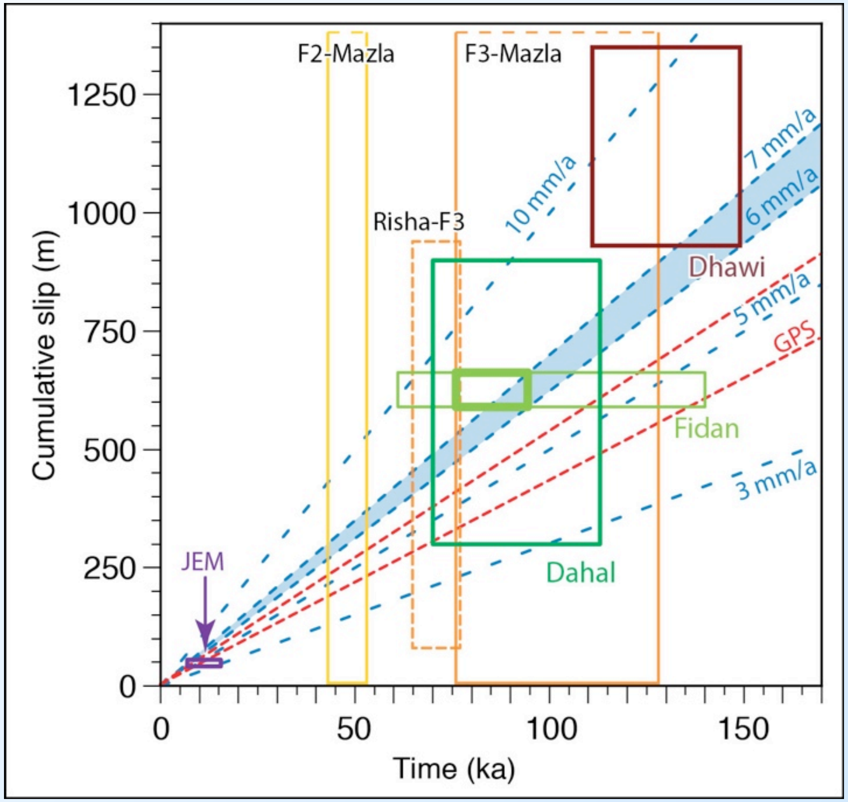

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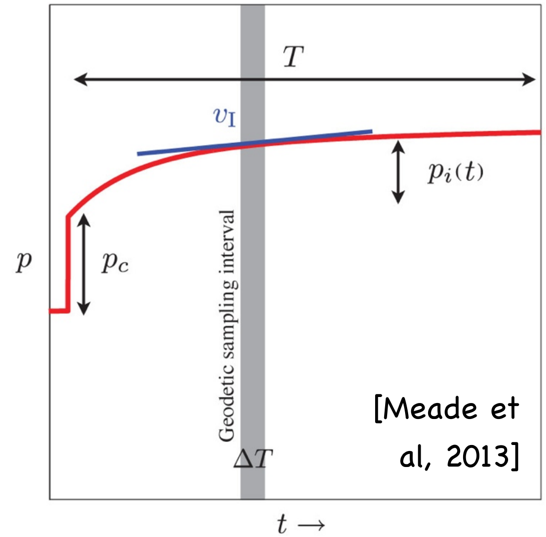
Interseismic deformation :



Quasi-static ? or **Dynamic ?**

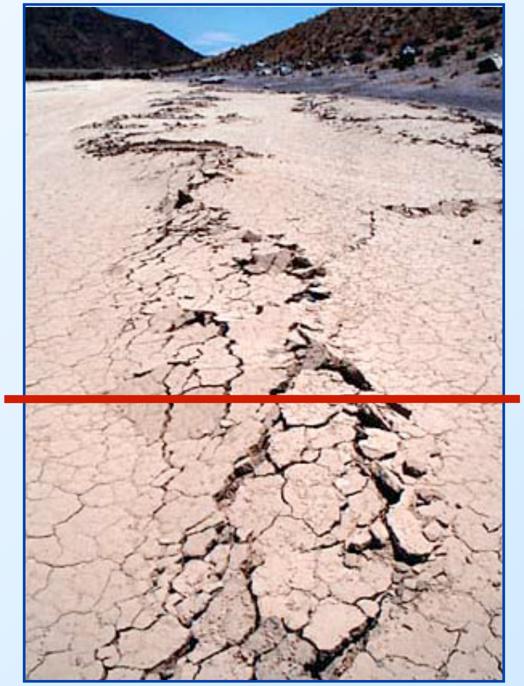
Late stage of the earthquake cycle ?

Last earthquake in 1293 or 1458 !

Occurrence of large earthquakes during the Holocene

Coseismic

ground surface rupture :



Excavation of a paleo-seismologic trench

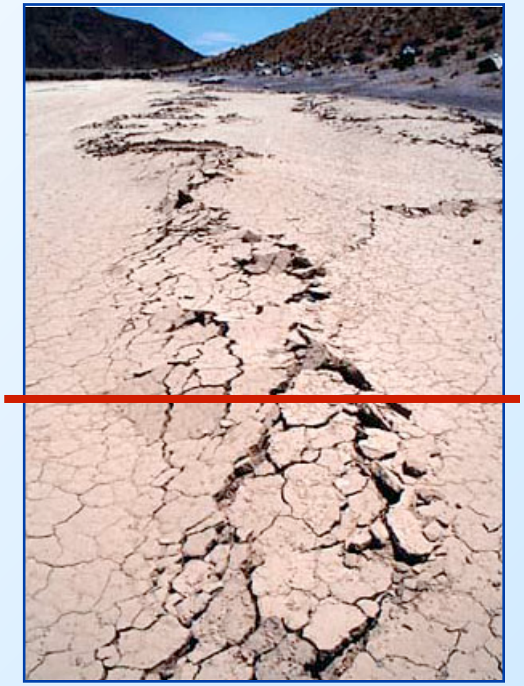
across the active fault trace

1 m

Occurrence of large earthquakes during the Holocene

Coseismic

ground surface rupture :



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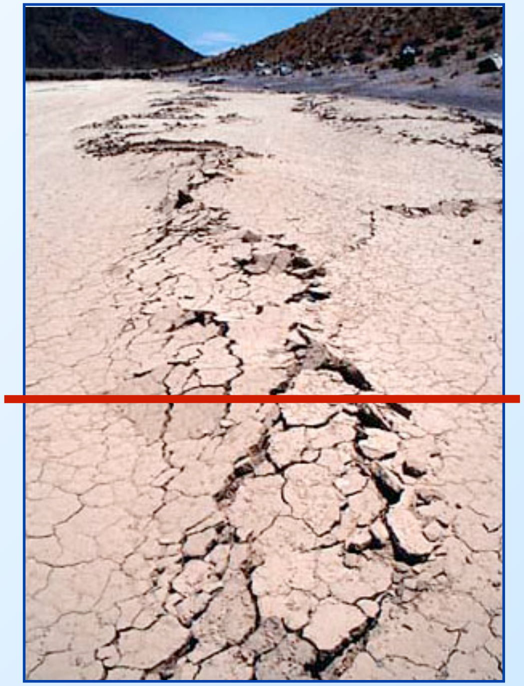

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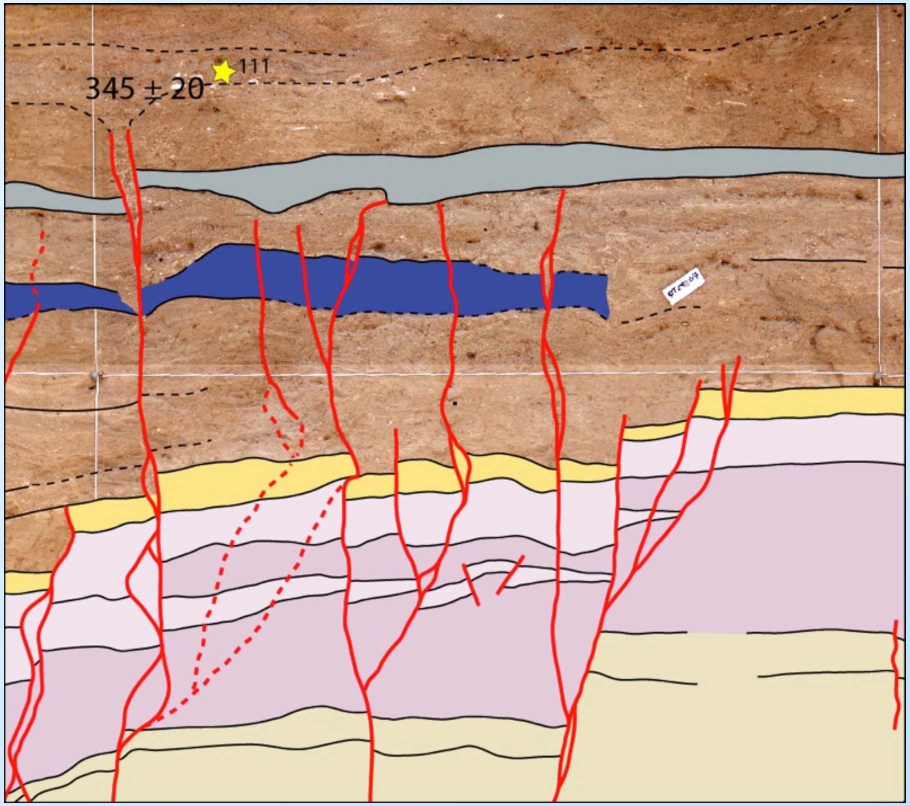

1 m

Occurrence of large earthquakes during the Holocene

Coseismic

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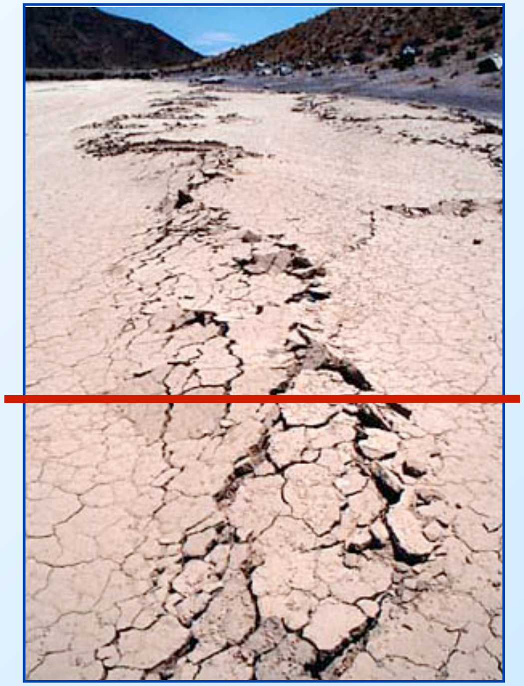

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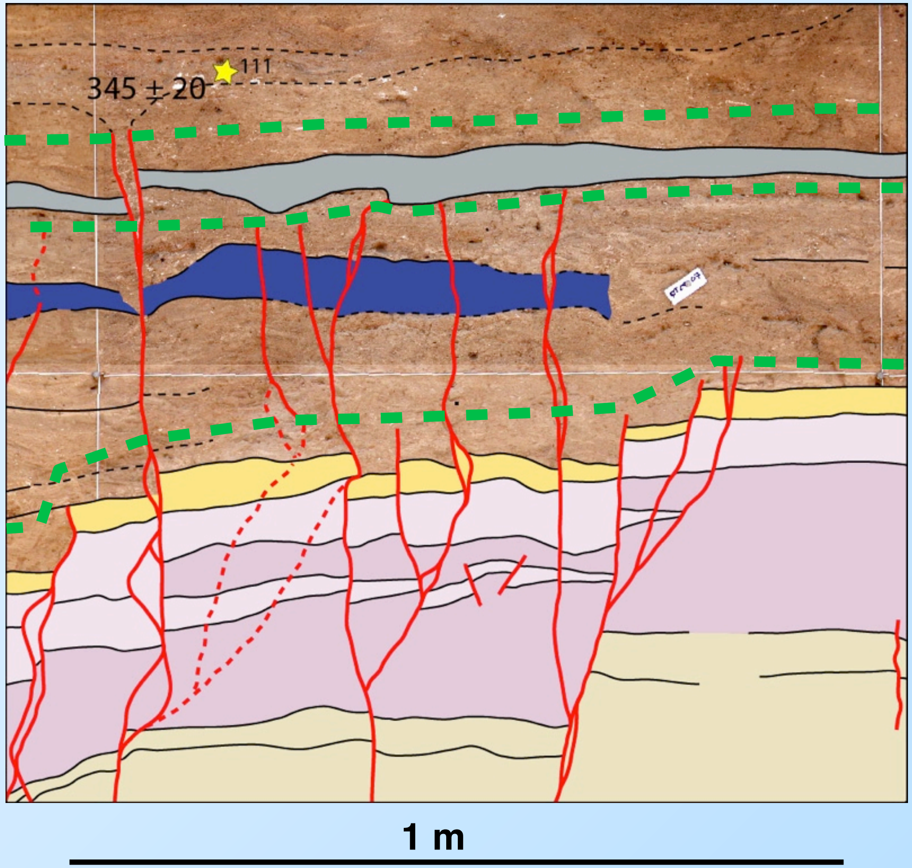
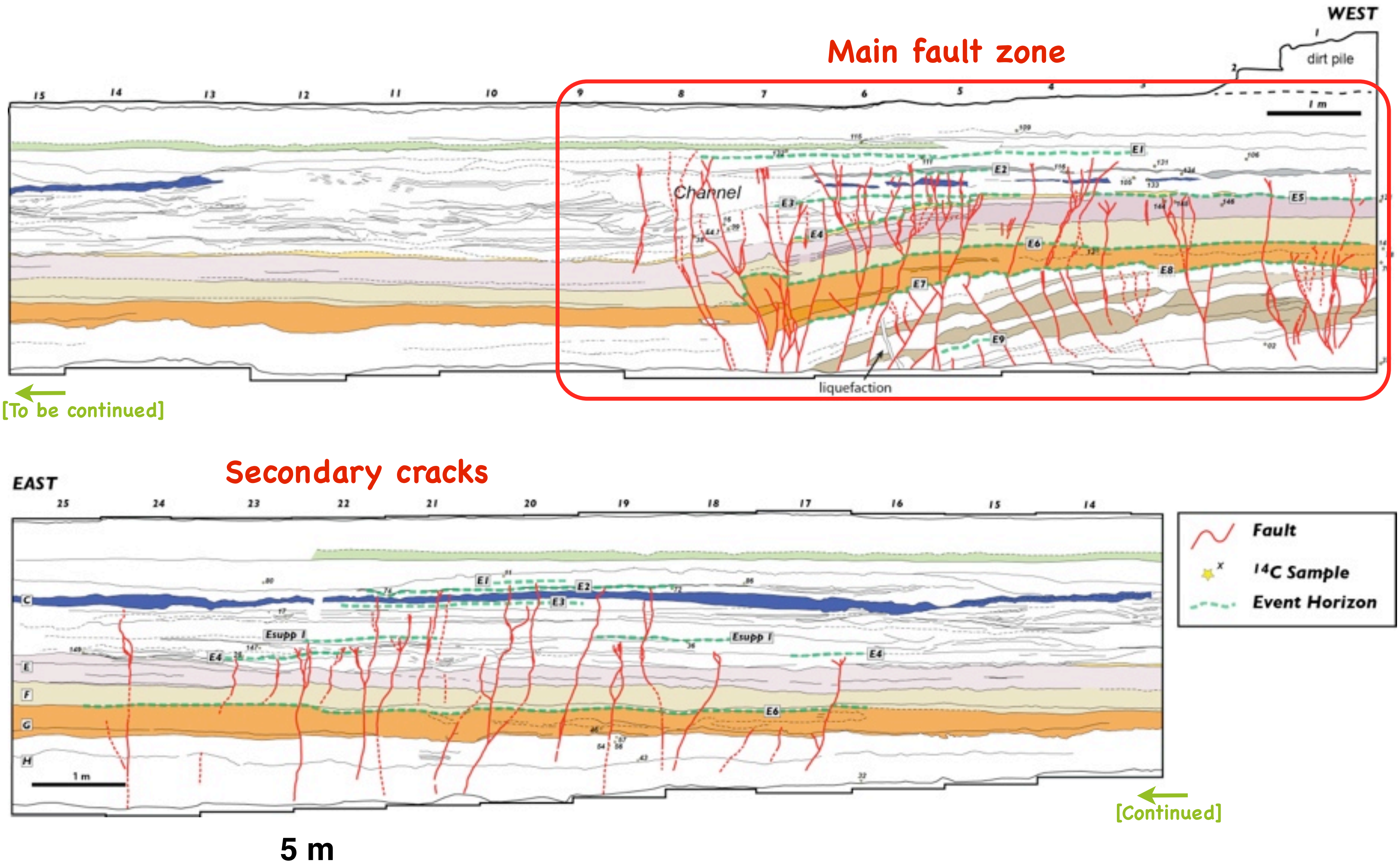
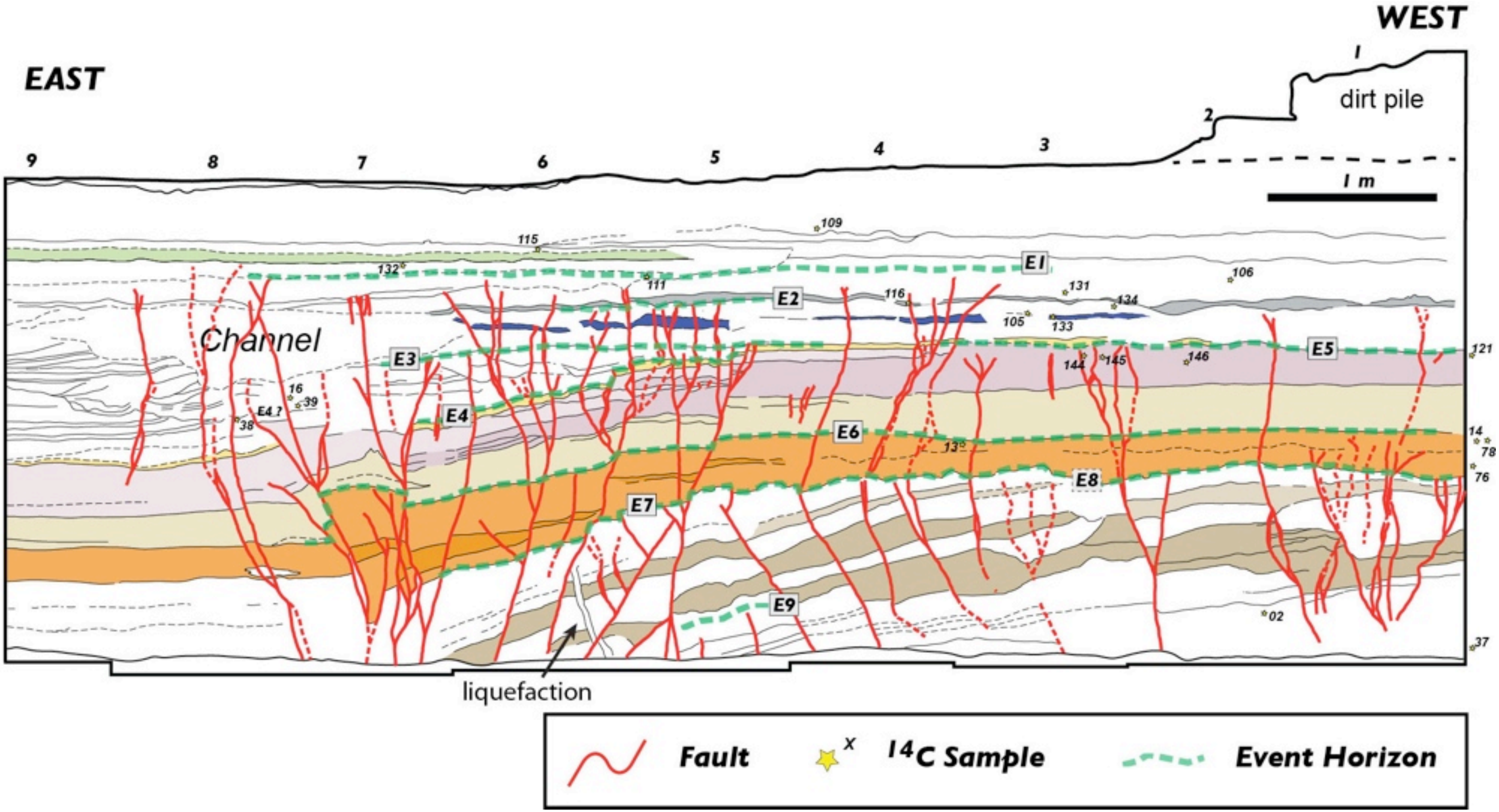


Overview of the trench



Klinger, Le Béon & Al-Qaryouti, 2015, GJI

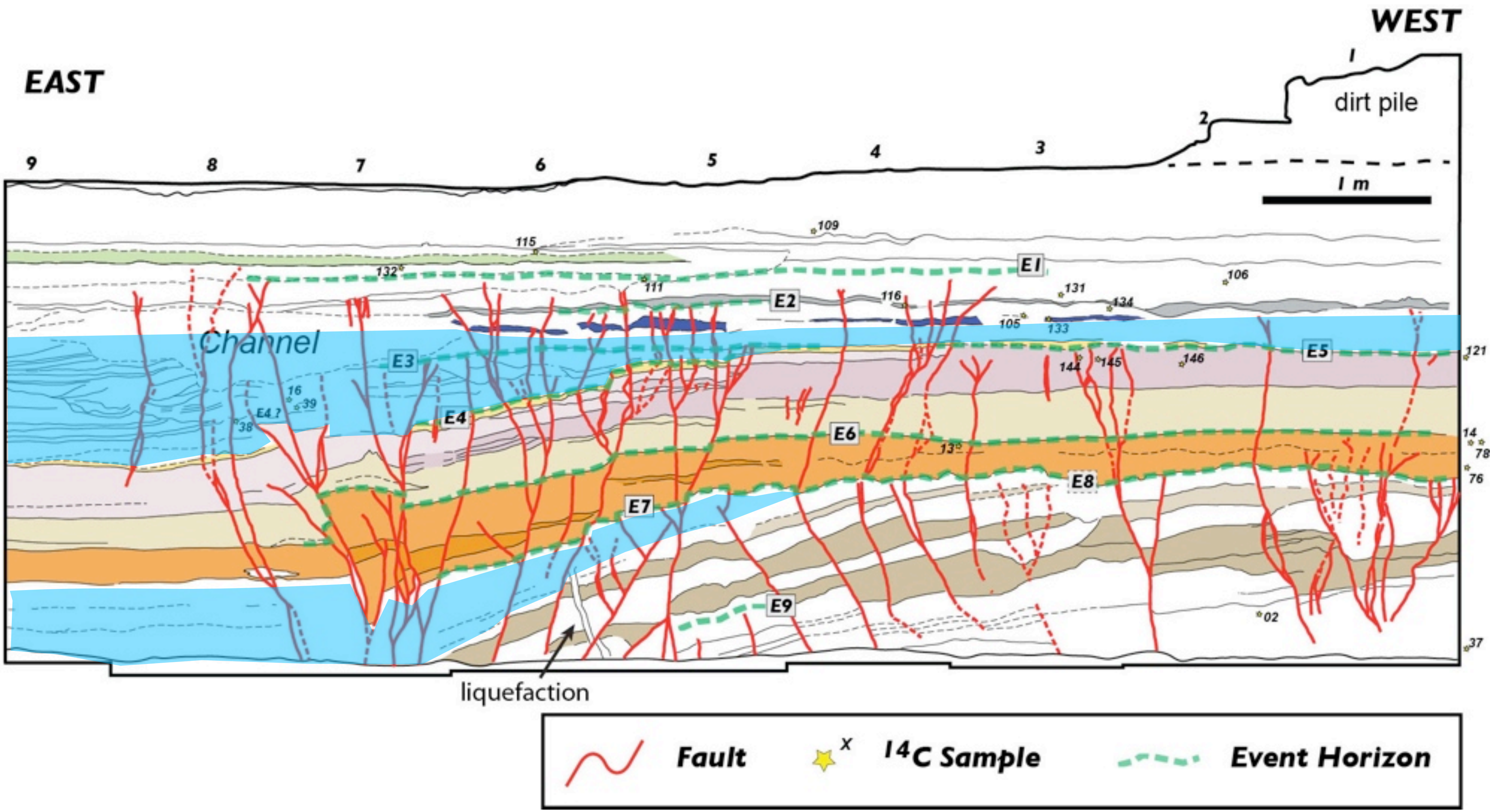
Identification of paleo-earthquakes



9 paleo-earthquakes identified,

2 of them associated with **significant vertical offset**

Identification of paleo-earthquakes



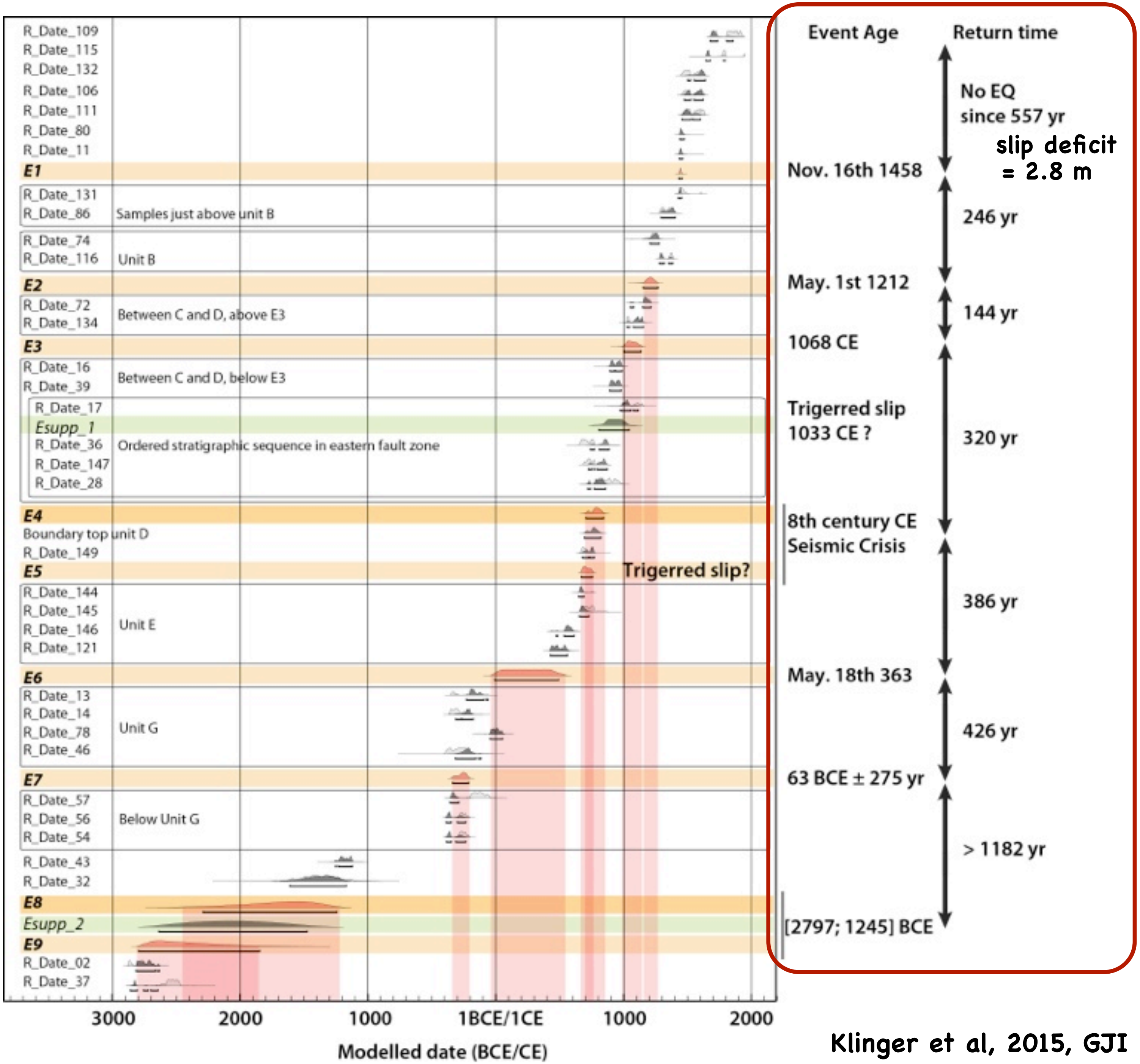
9 paleo-earthquakes identified,

2 of them associated with **significant vertical offset**

Timing of paleo-earthquakes

Age model based on **32 ^{14}C dates** using Oxcal

+ a **2000-year long historical catalog** [Ambraseys et al, 1994]



Klinger et al, 2015, GJI

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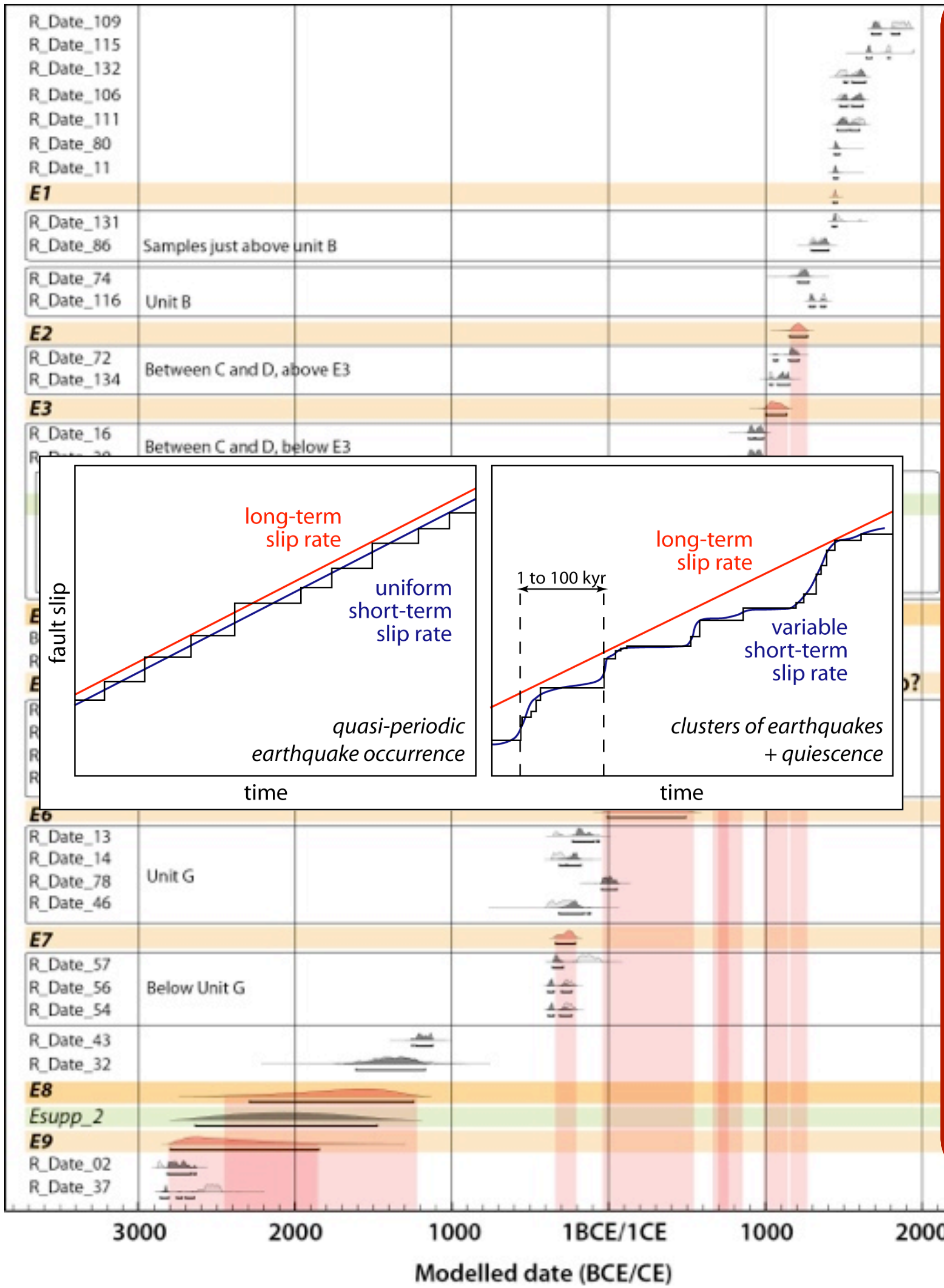


Event Age	Return time
	No EQ since 557 yr slip deficit = 2.8 m
Nov. 16th 1458	
	246 yr
May. 1st 1212	
	144 yr
1068 CE	
Trigerred slip 1033 CE ?	
	320 yr
8th century CE Seismic Crisis	
	386 yr
May. 18th 363	
	426 yr
63 BCE ± 275 yr	
	> 1182 yr
[2797; 1245] BCE	

Klinger et al, 2015, GJI

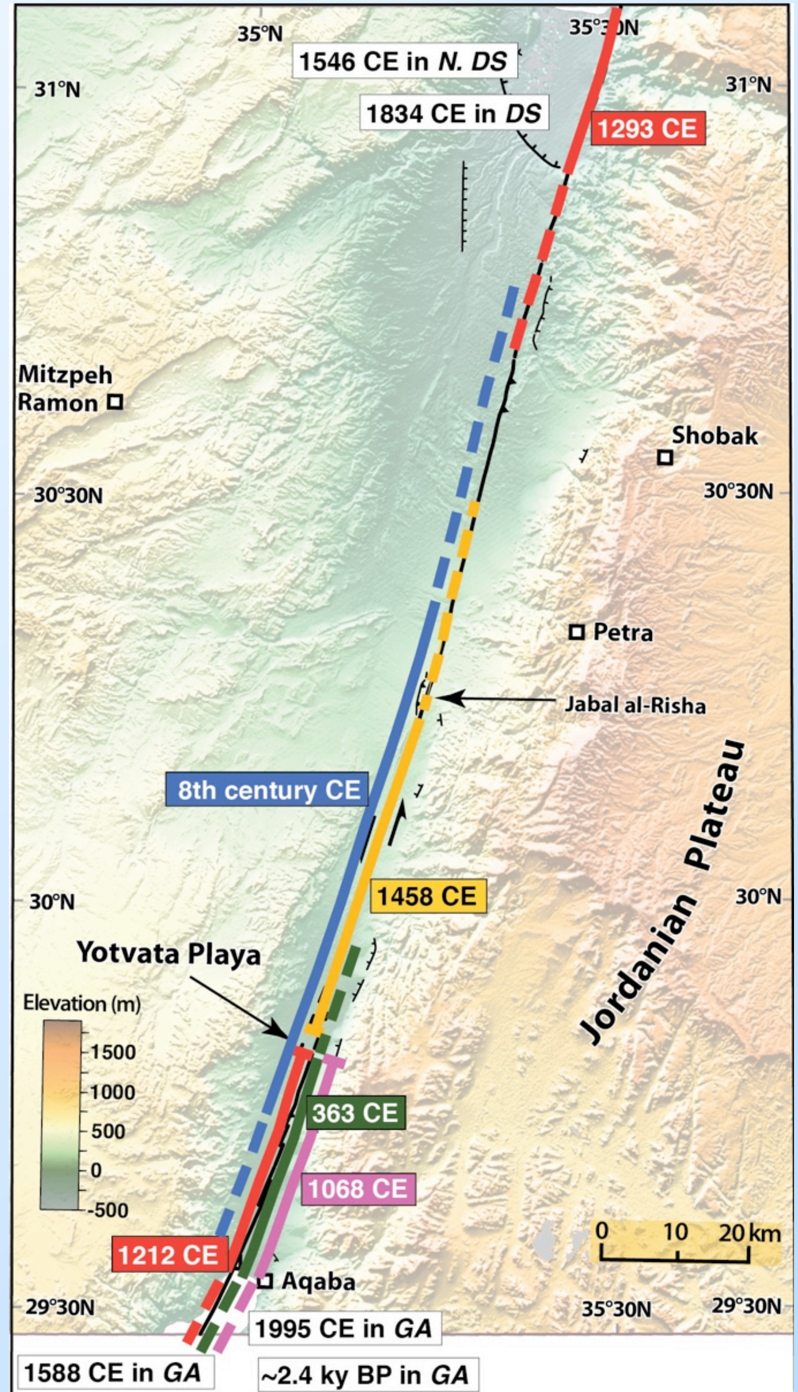
Rupture scenario

- 2 different types of events:

* Earthquake ruptures dying at the fault jog

* Larger earthquakes, less frequent, rupturing across the fault jog

- Proposed location of other reported historical earthquakes that we did not observe in the trench

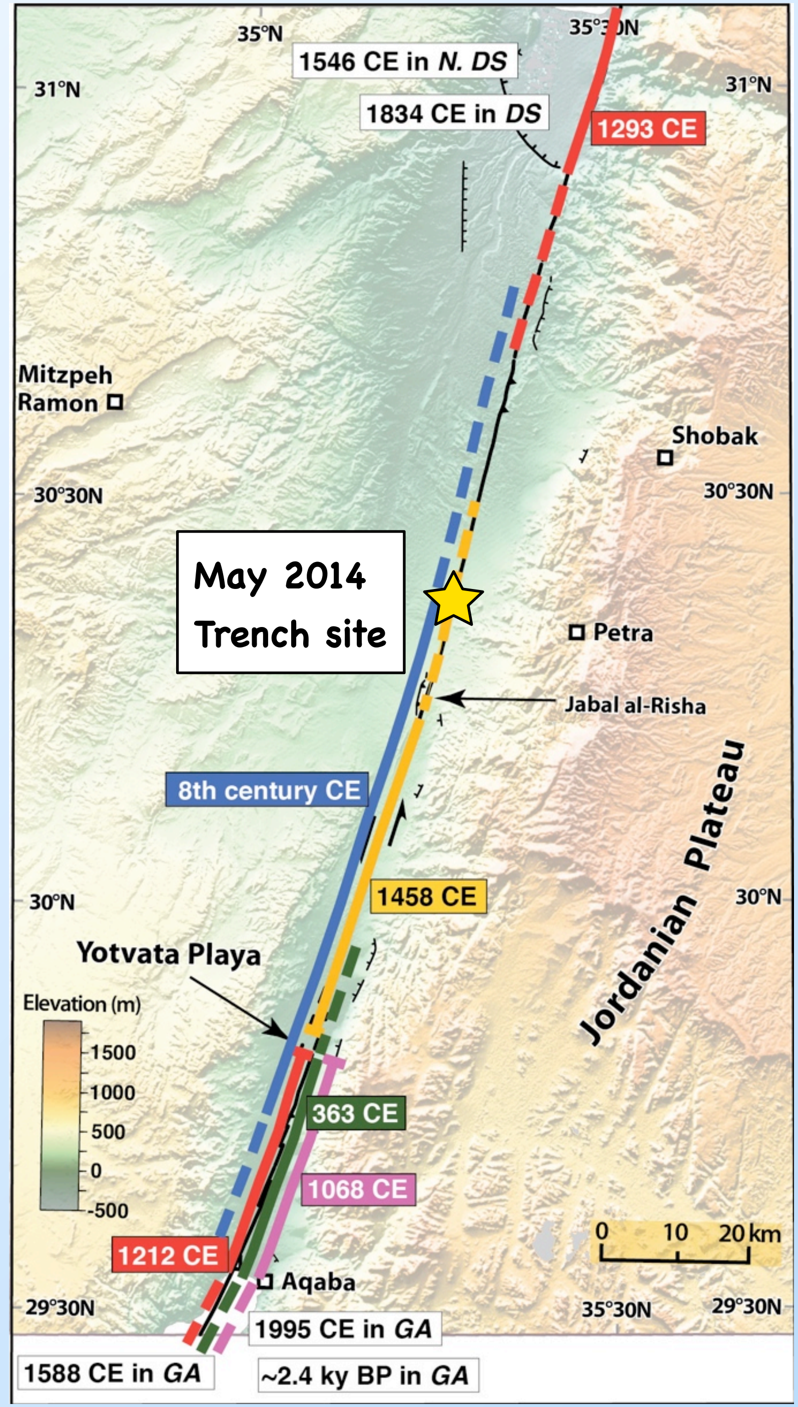


Klinger, Le Béon & Al-Qaryouti, 2015, GJI

Perspectives #1/3

1/ **Excavation at another trench site** in May 2014 to **compare earthquake sequences** in order to test and complement our scenario

On-going PhD thesis in IPG Paris
[Lefevre et al, 2016, EGU abstract]

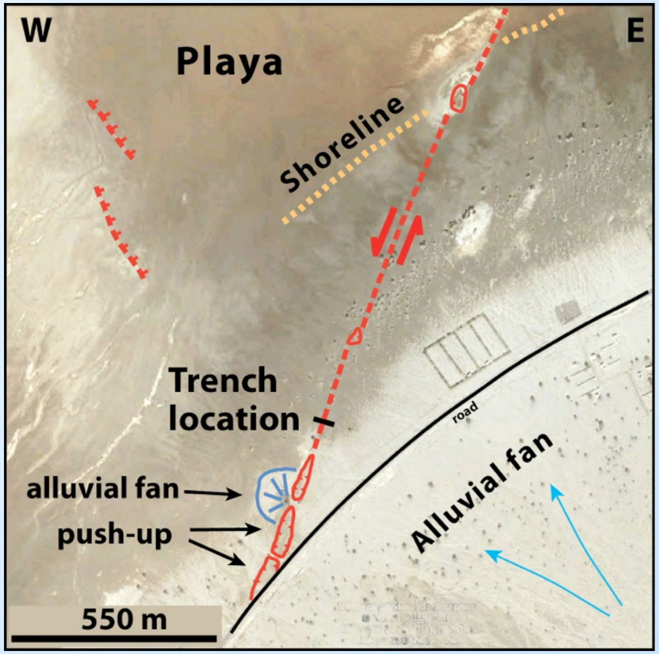


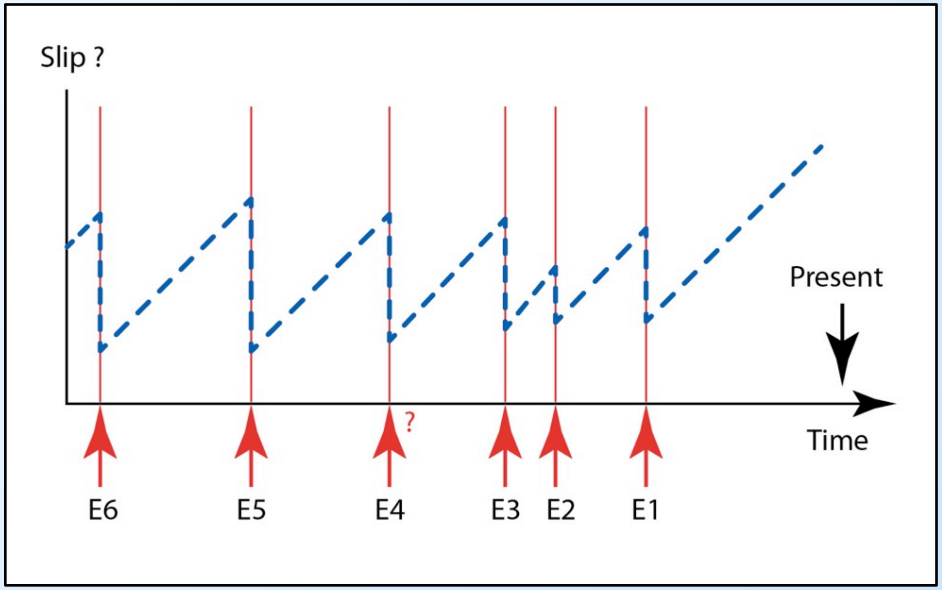
Perspectives #2/3

2/ **At the same site**:

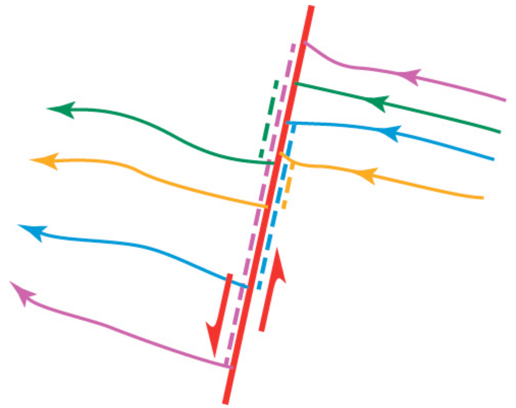
* A deeper trench for a **longer record**

* Fault-parallel trenching to access **slip per event** (channels identified)





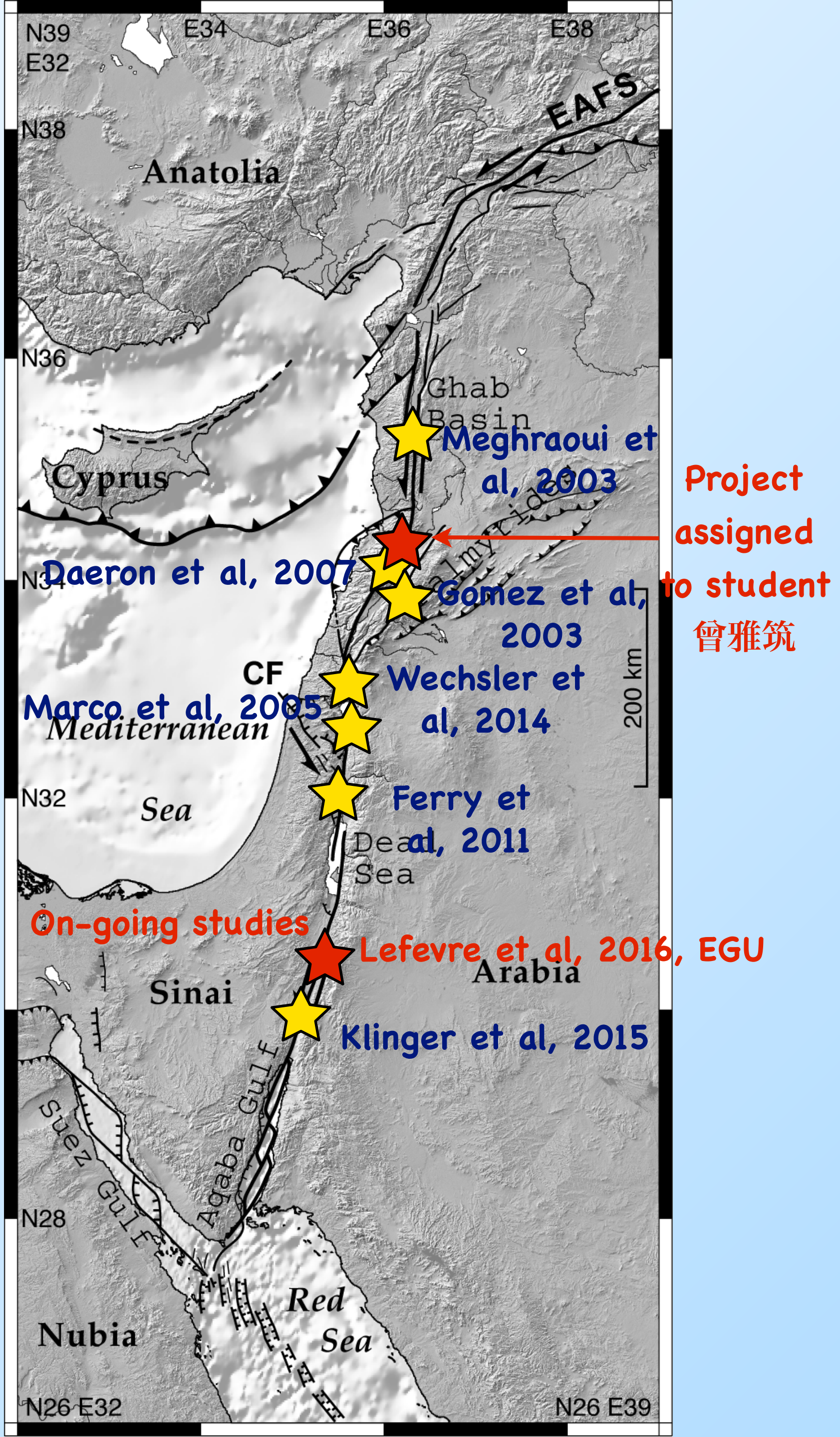
Channels of various ages offset by successive earthquakes



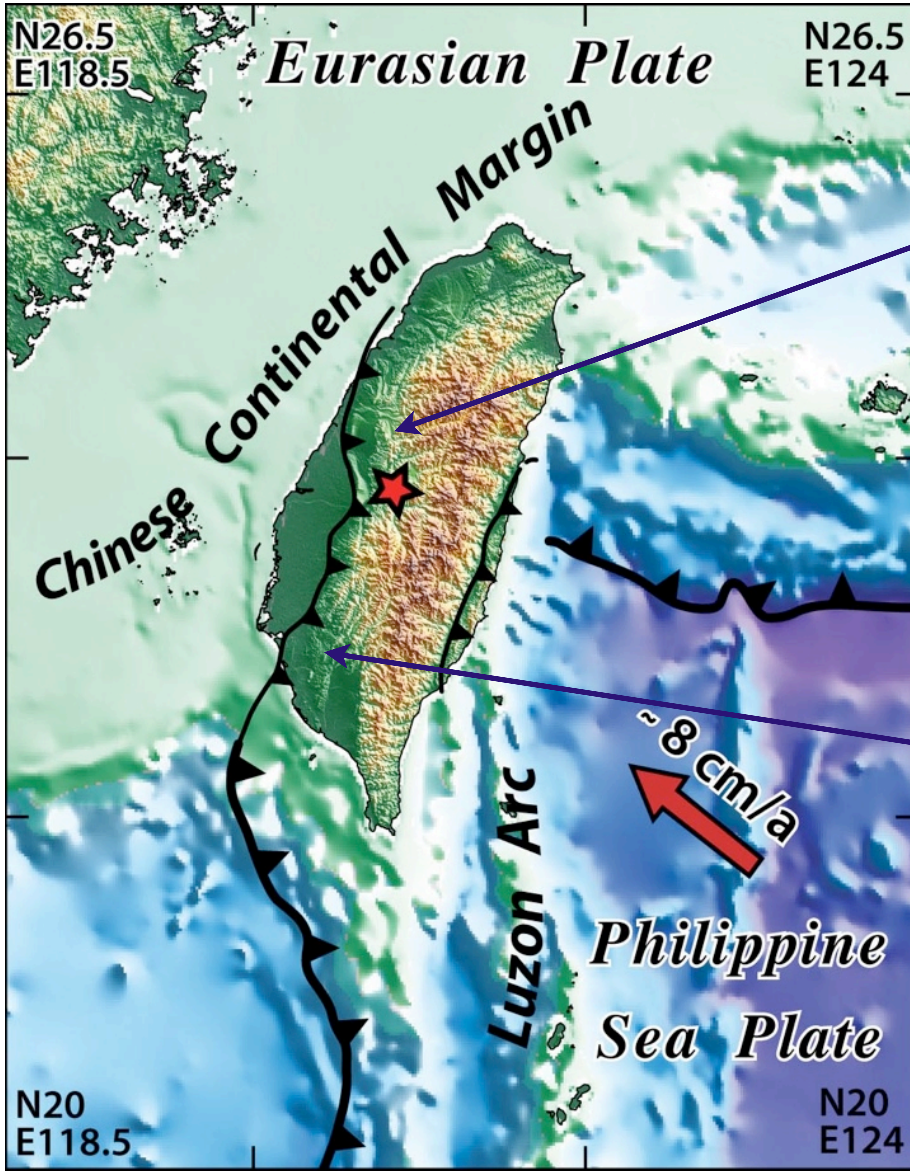
Perspectives #3/3

3/ **At the regional scale** :

Chief goal: point out the source of all historical earthquakes along the Dead Sea fault and observe **how fault segments interact with each other**.



Active faults at the front of Taiwan fold-and-thrust belt



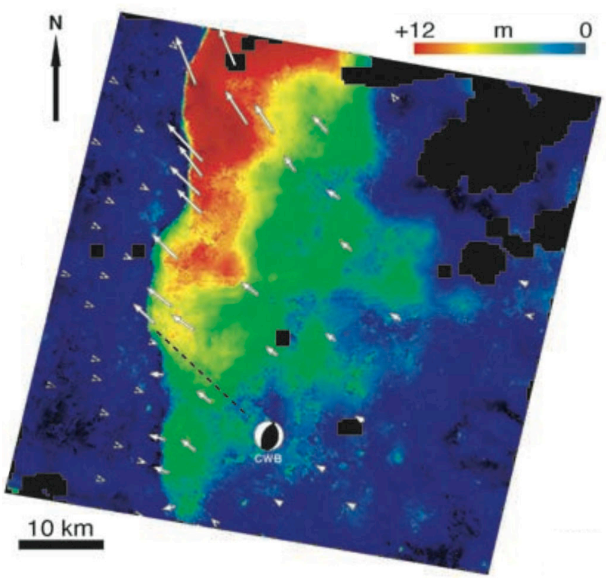
Chelungpu fault

Tainan anticline
& the Foothills
of SW Taiwan

Tectonic setting in central western Taiwan

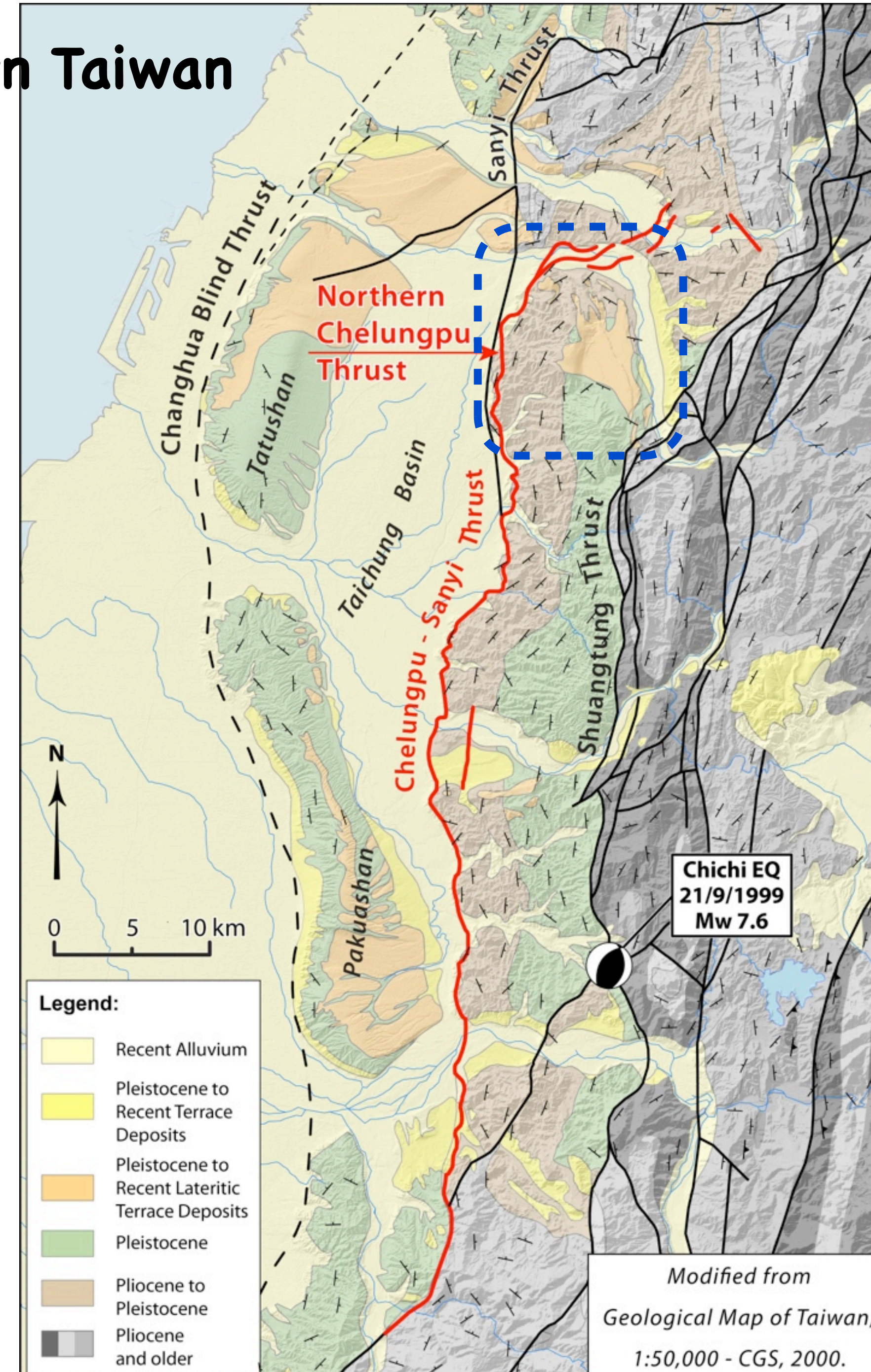
Mw 7.6 Chi-Chi earthquake rupture in 1999:

Highly heterogeneous displacement field:

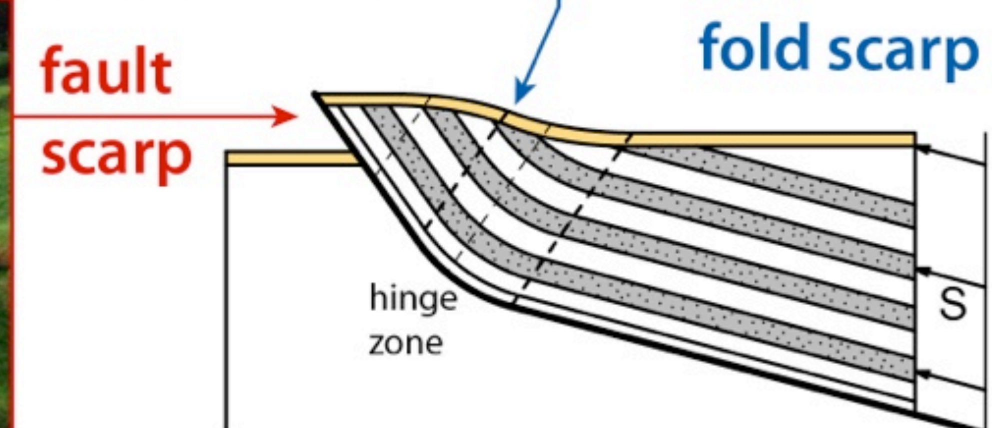


Horizontal coseismic displacements

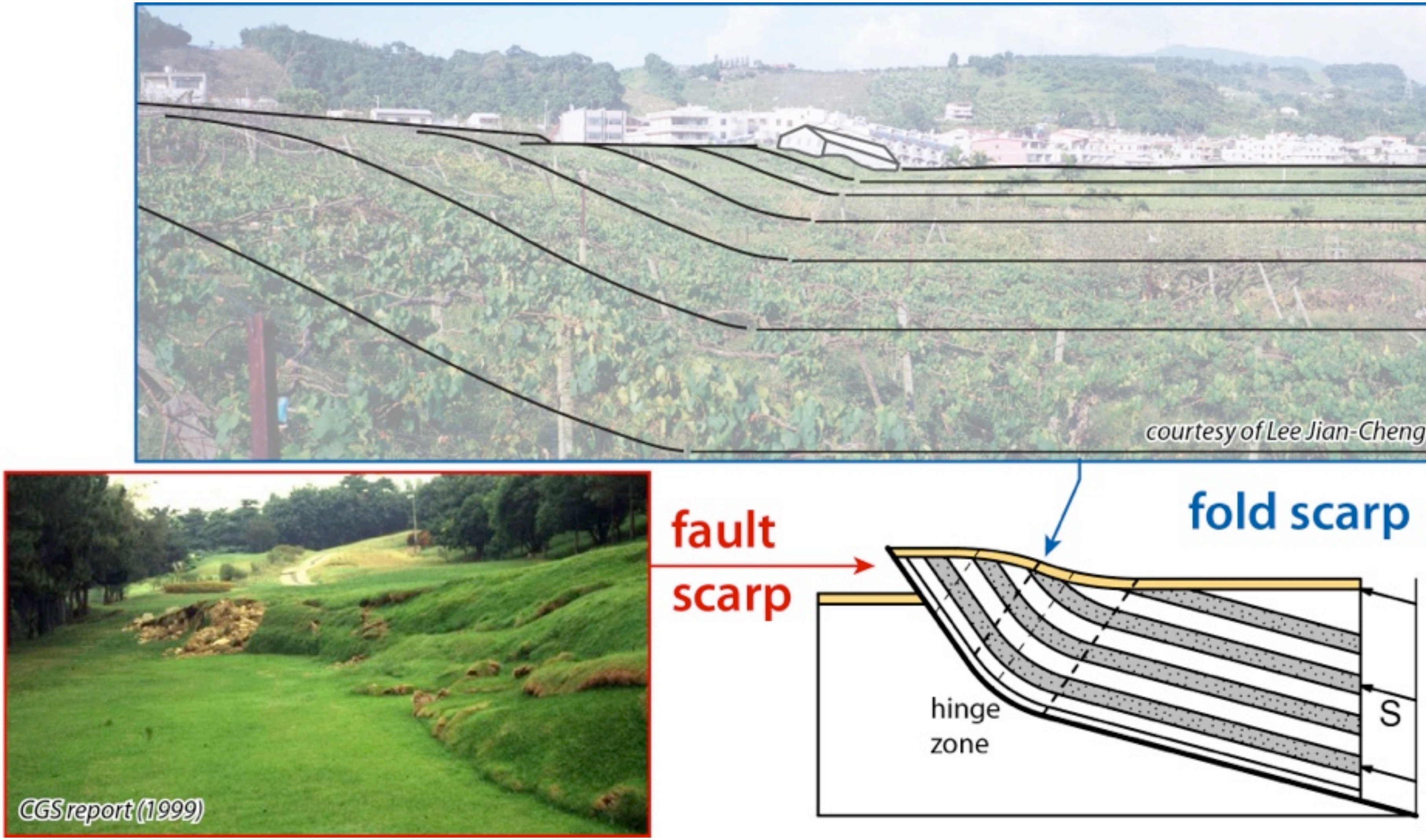
(Dominguez et al, 2003)



Coseismic fold growth during Chi-Chi earthquake



Coseismic fold growth during Chi-Chi earthquake

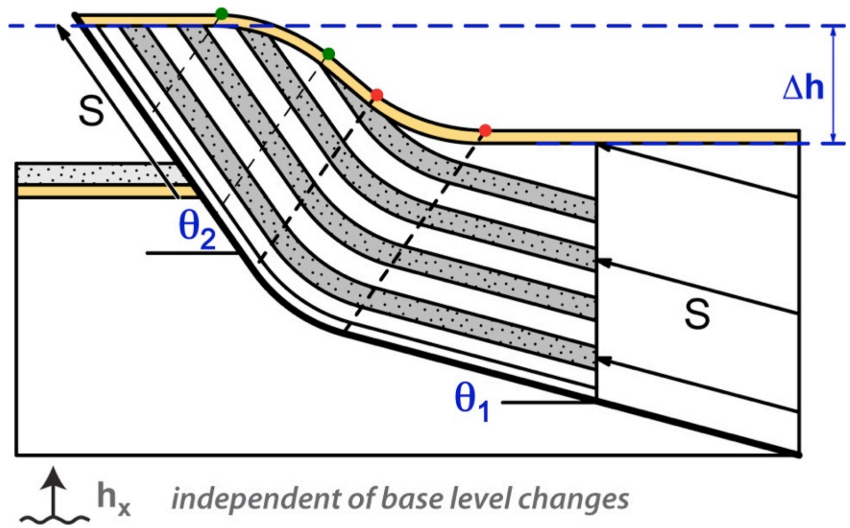


Fault-bend folding theory

Assumption :

Fault-parallel displacement

with conservation of bed length



Modified from Suppe et al (1997)

Relation between **relief across the fold scarp** Δh

and **cumulative fault slip** S:

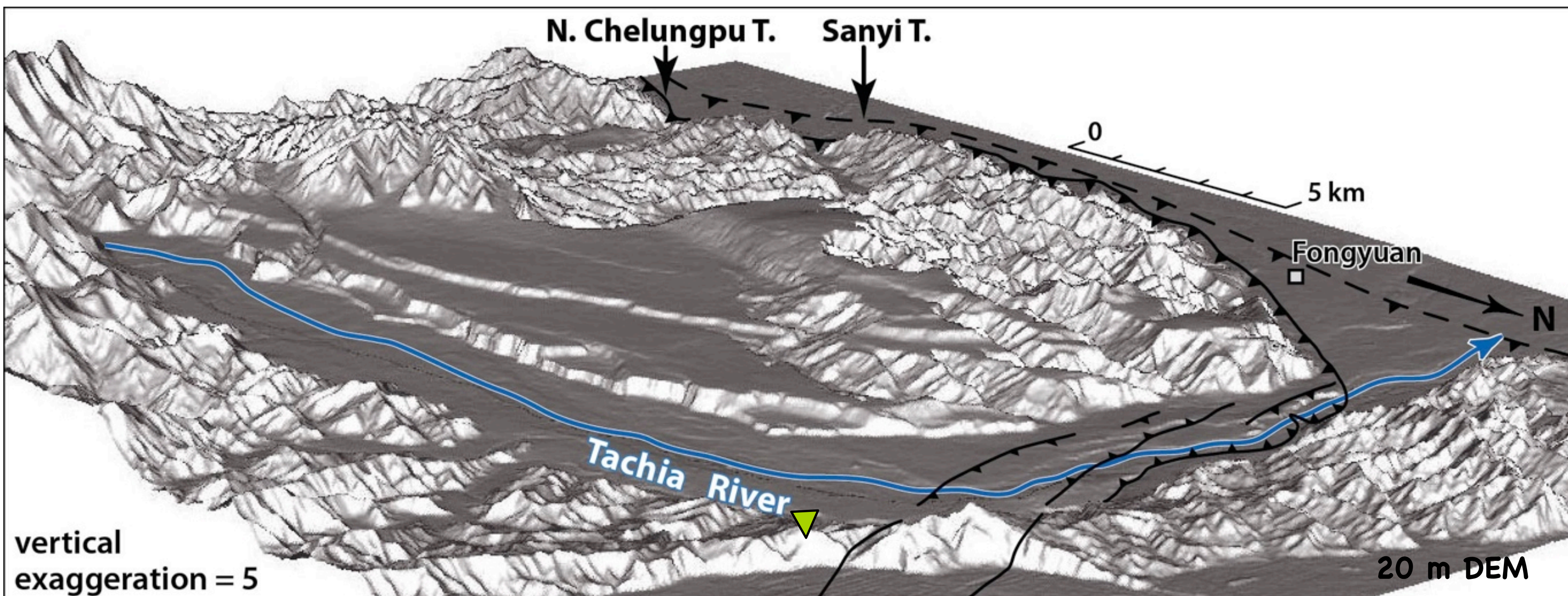
$$S = \Delta h \;/\; (\sin \theta_2 . \cos \alpha_2 - \sin \theta_1 . \cos \alpha_1)$$

Subsurface geometry

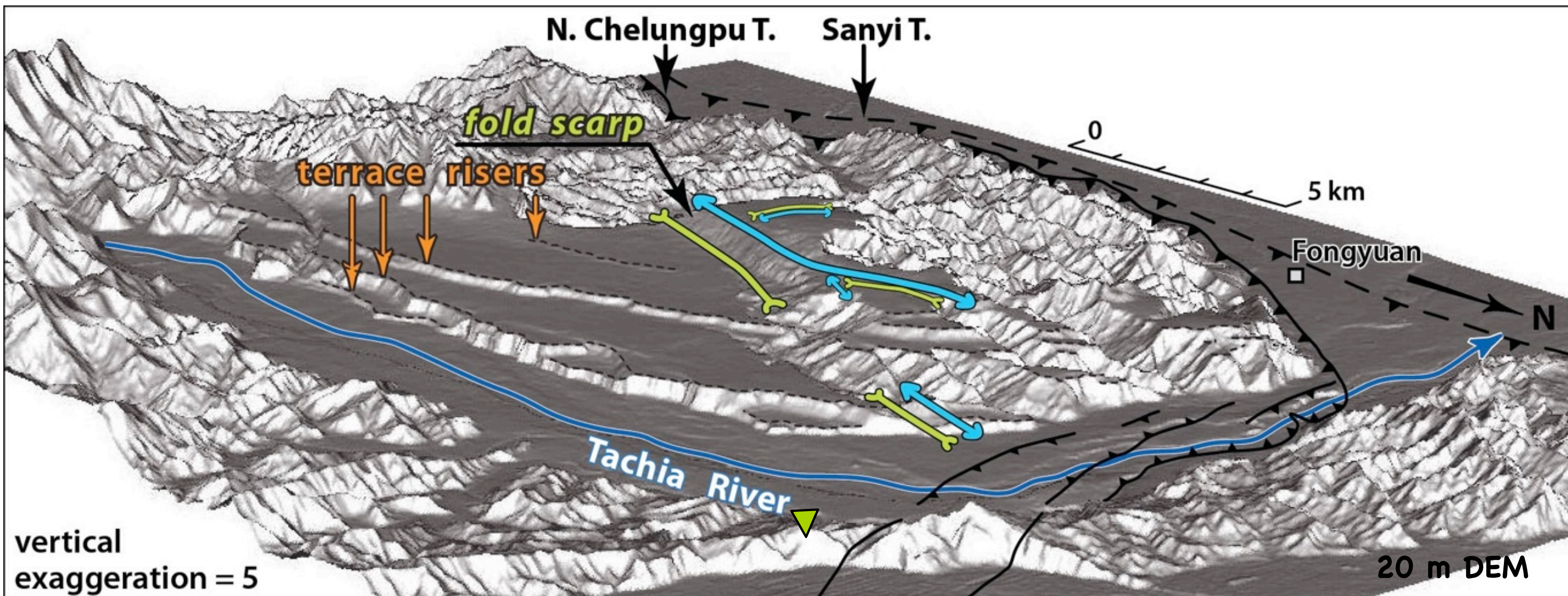
Oblique faulting :

Azimuth of slip vector

Morphology of the Hsinshe terraces



Morphology of the Hsinshe terraces



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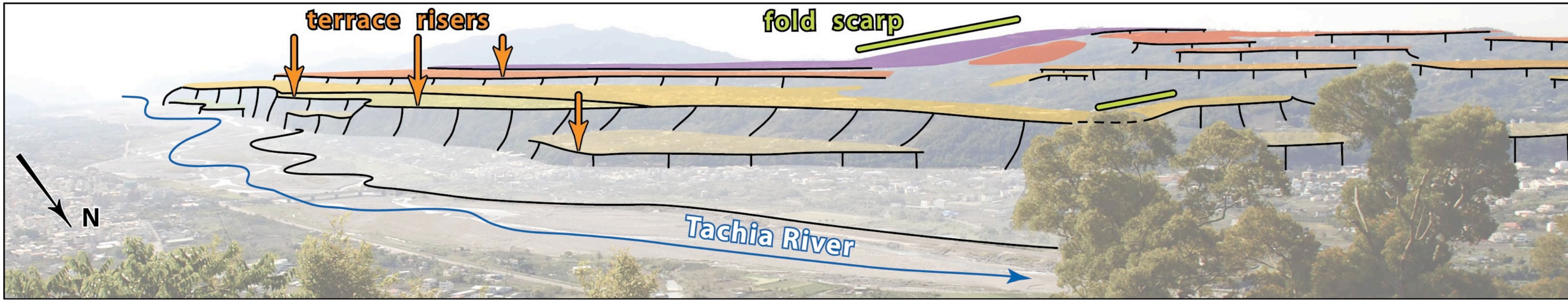
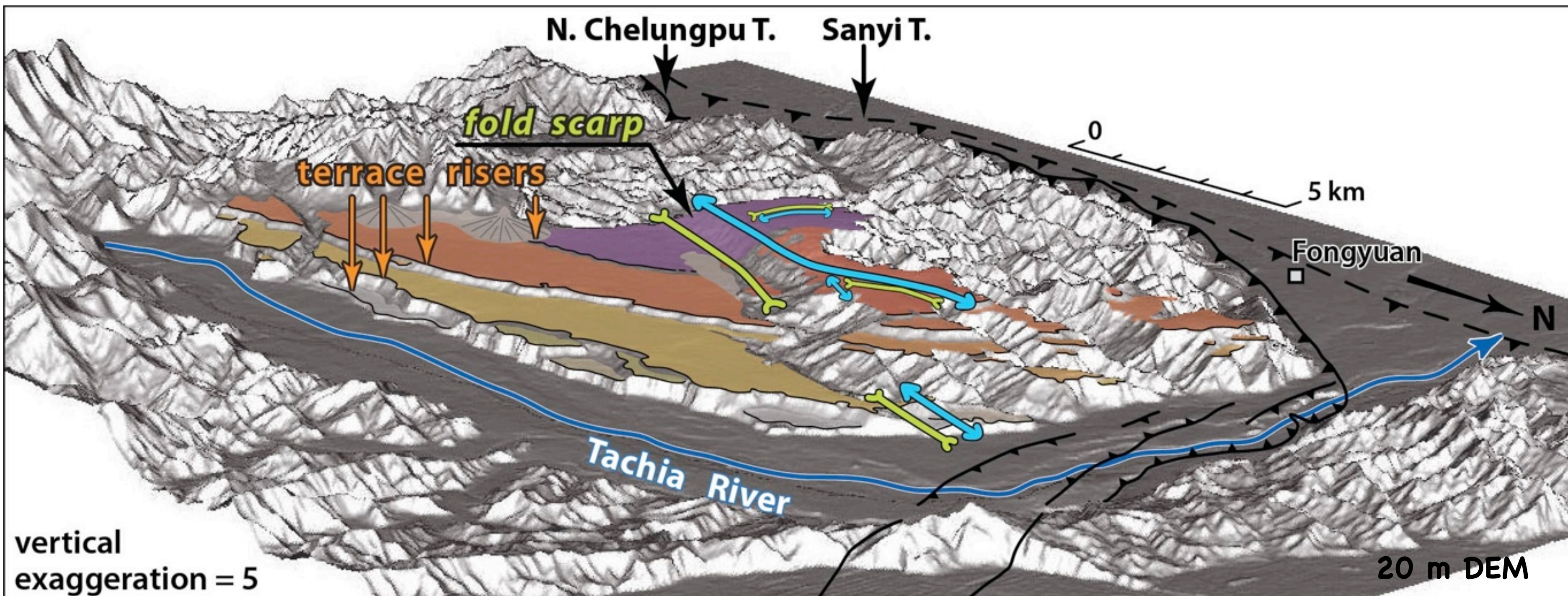
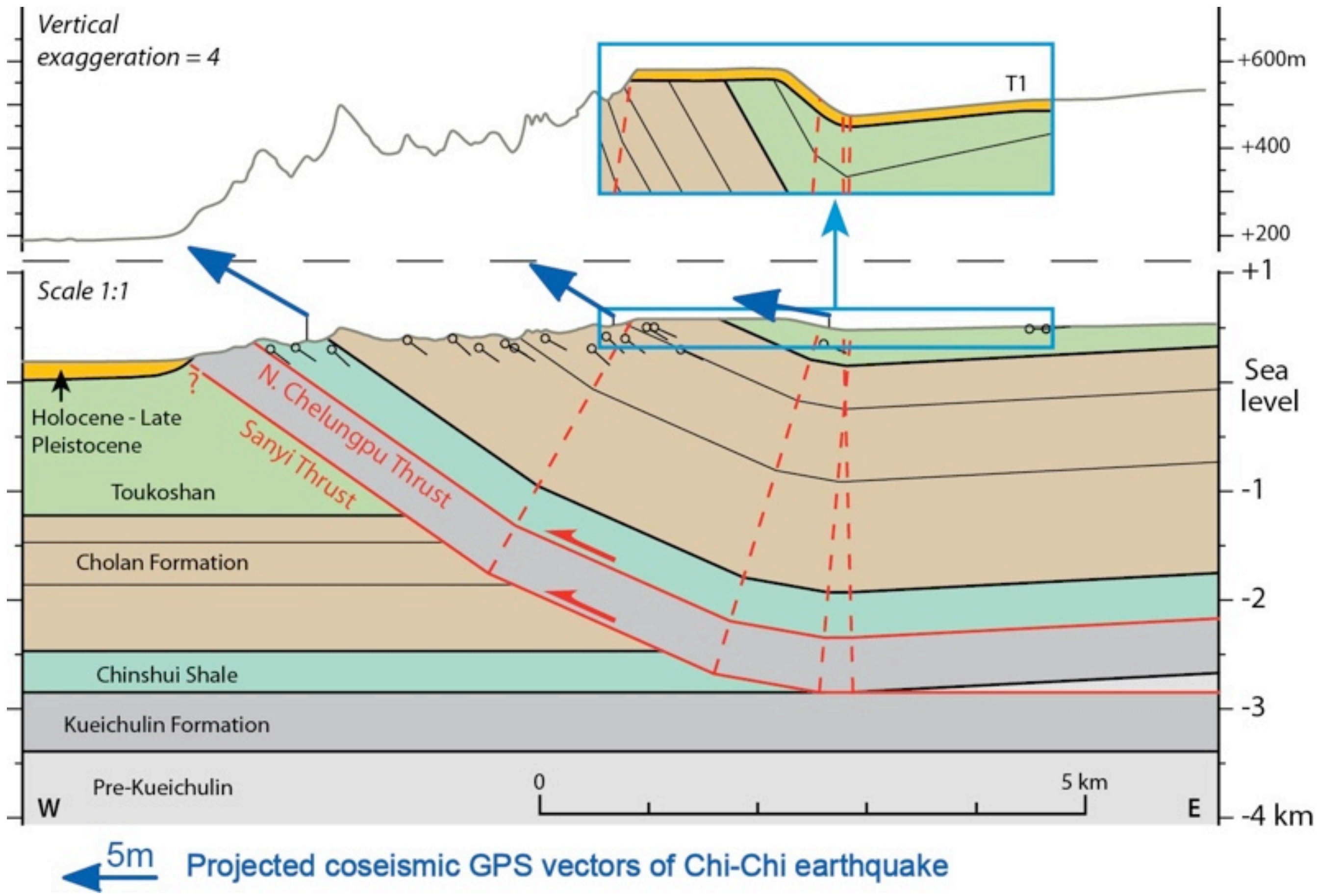


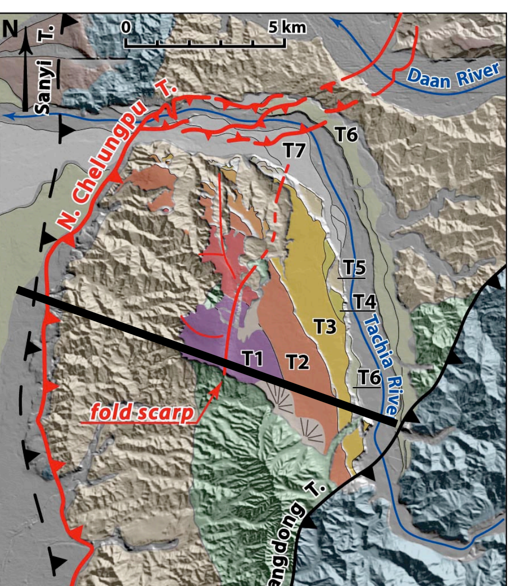


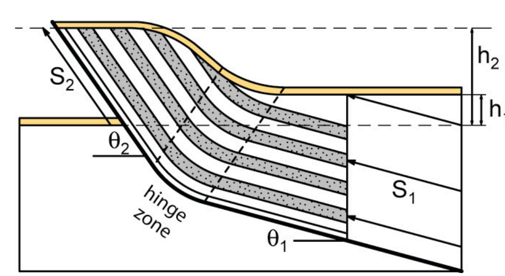
Subsurface structure of the Chelungpu Thrust

Bedding-parallel thrust ramp with **varying dip**

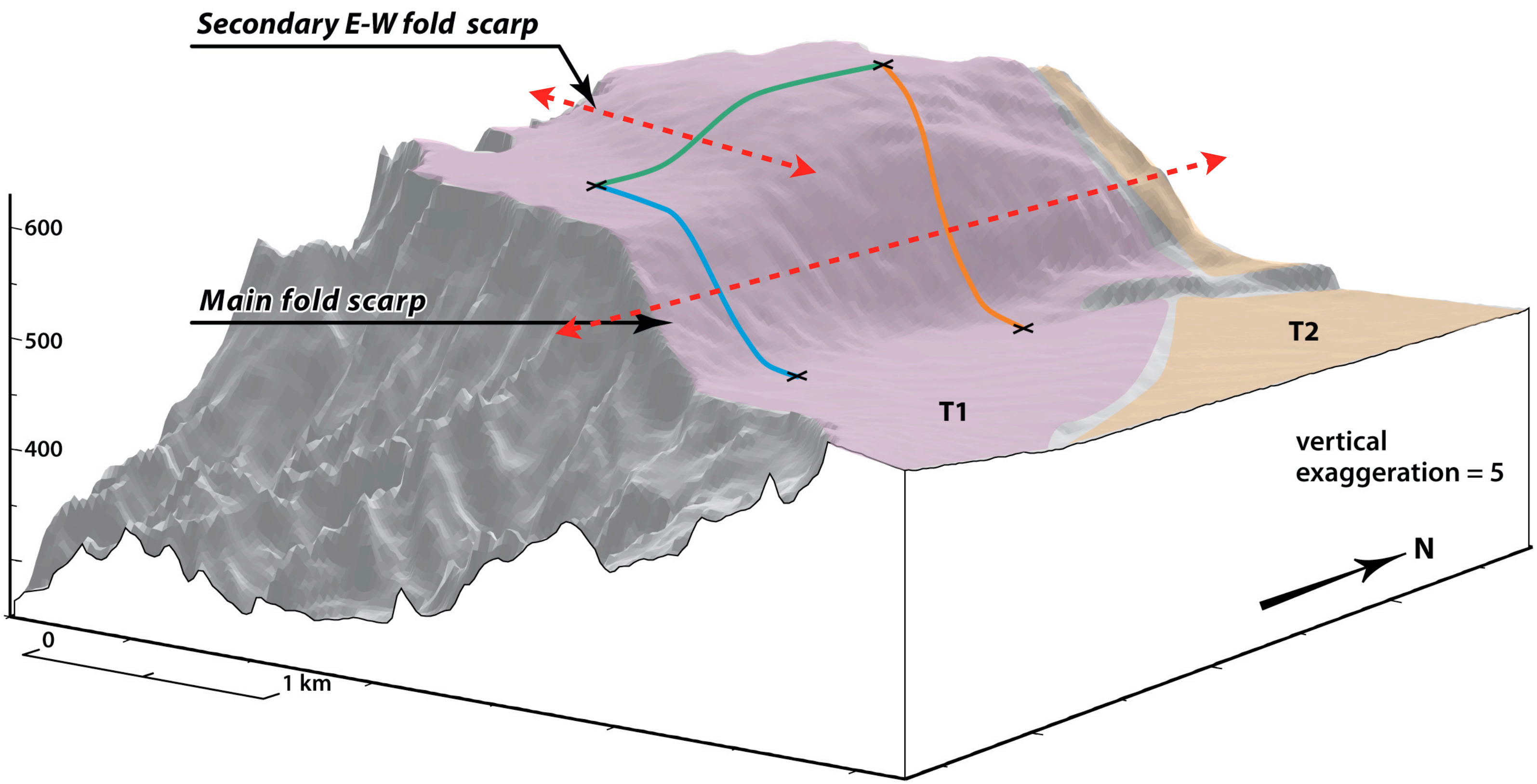
Chi-Chi GPS slip vectors parallel to the ramp dip





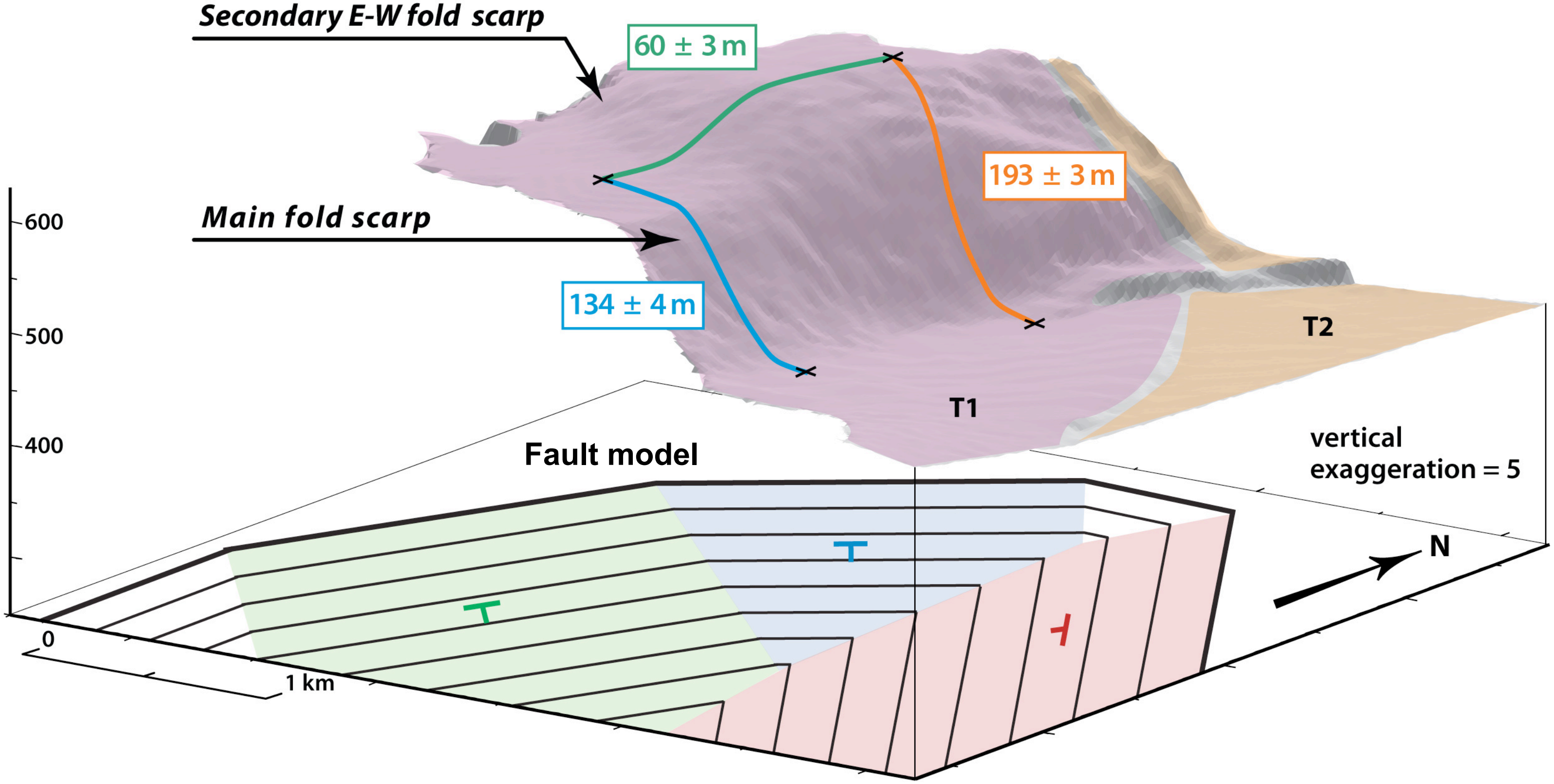


Deformation of terrace T1



Deformation of terrace T1

Measurements of **scarp relief Δh** for each of the 3 fold scarps.



For each scarp i:

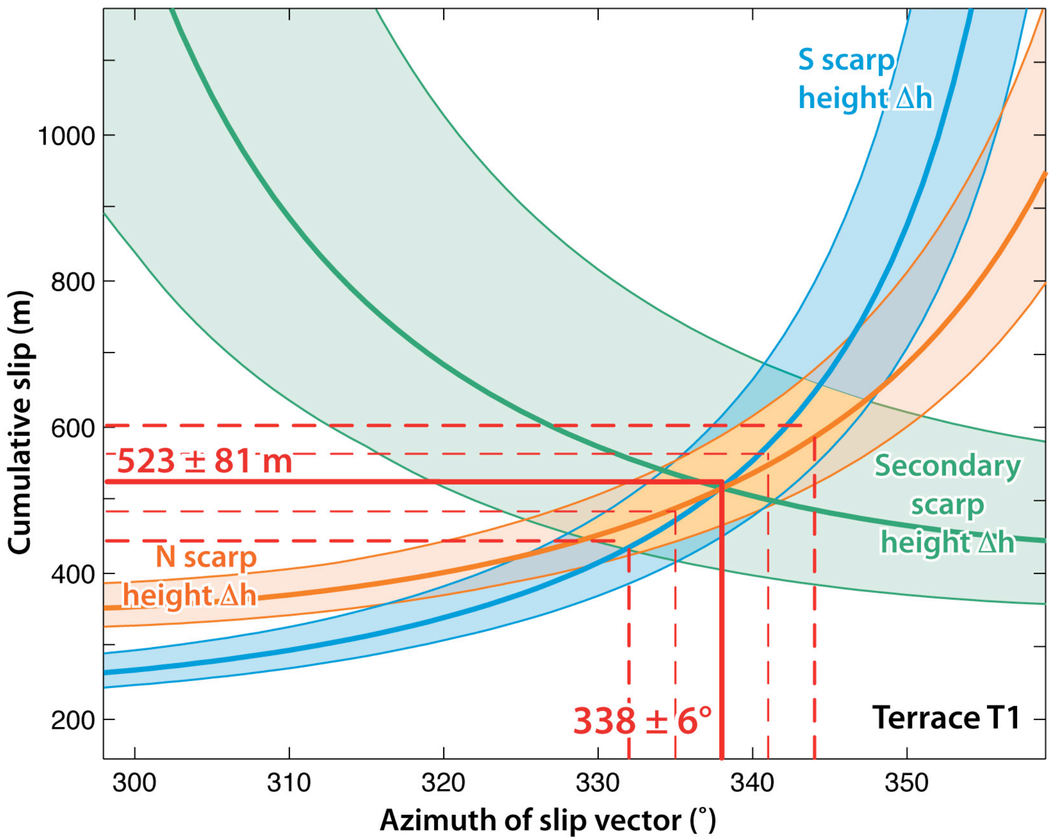
$S = \Delta h_i \;/\; (\sin \theta_{i2} . \cos \alpha_2 - \sin \theta_{i1} . \cos \alpha_1)$

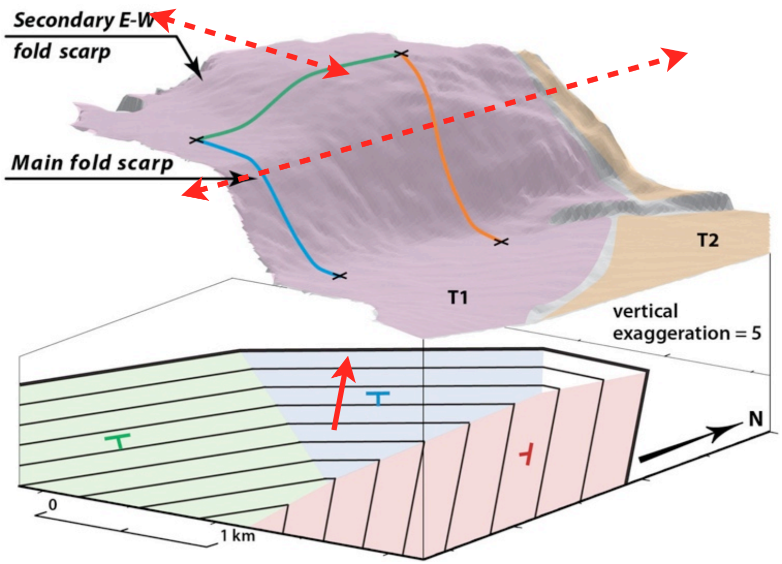
=> **3D** deformation: **simultaneous determination of amplitude and azimuth** of long-term slip vector

From terrace deformation to cumulative slip: T1

Results from scarp heights:

$$S = \Delta h \,/\, (\sin \theta_2 . \cos \alpha_2 - \sin \theta_1 . \cos \alpha_1)$$





Cumulative slip results and fault slip rate

Terrace T1 : 3D-deformation

=> 523 ± 81 m along N338° ± 6°

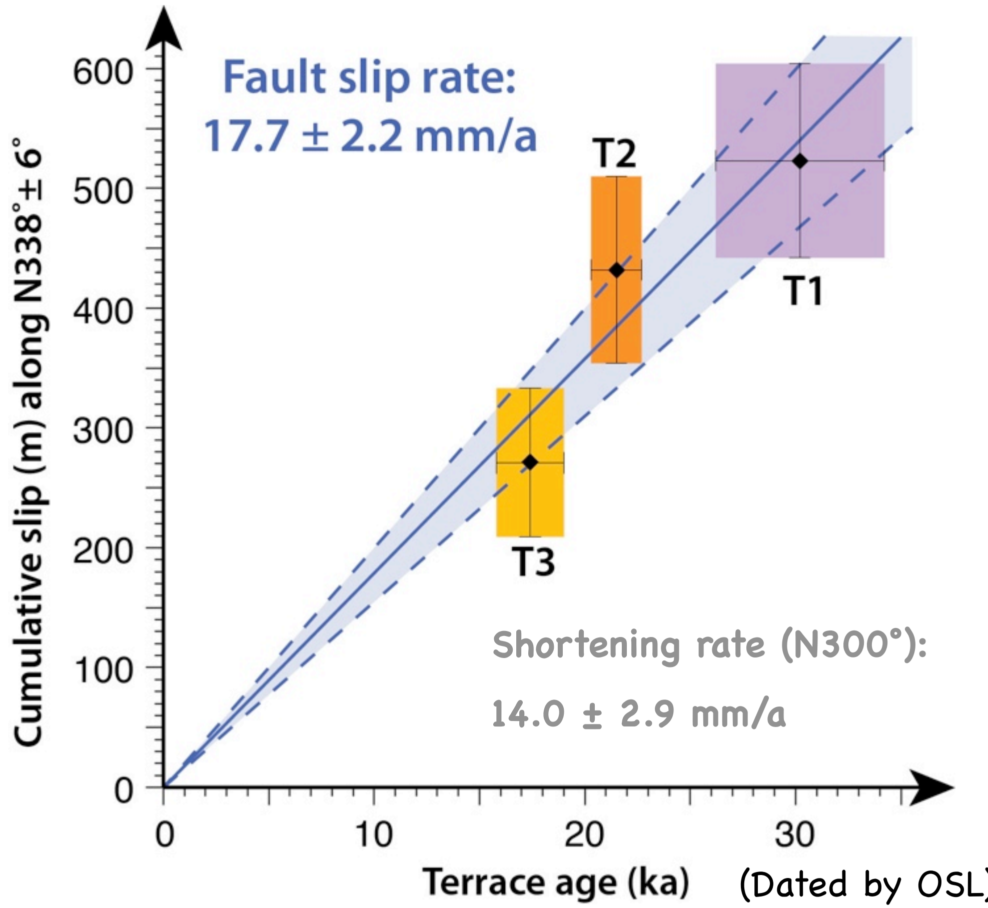
Terraces T2 and T3 :

Using N338° ± 6° & ΔH:

[Δh / (sin θ_2.cos α_2 - sin θ_1.cos α_1]

=> T2: 432 ± 78 m

=> T3: 274 ± 54 m



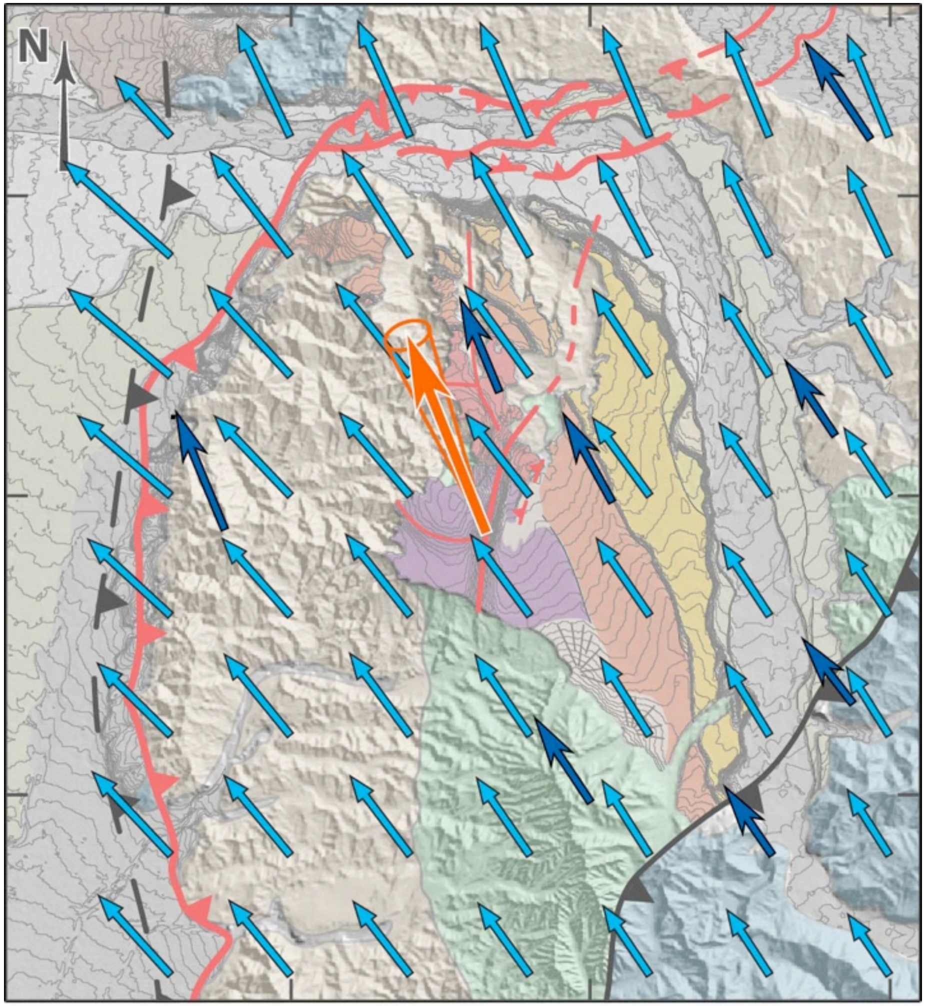
Long-term slip vector versus Chi-Chi coseismic displacements

30-ka average slip vector =

523 ± 81 m oriented N338° ± 6°

=> Long-term slip vector parallels

Chi-Chi coseismic displacements !



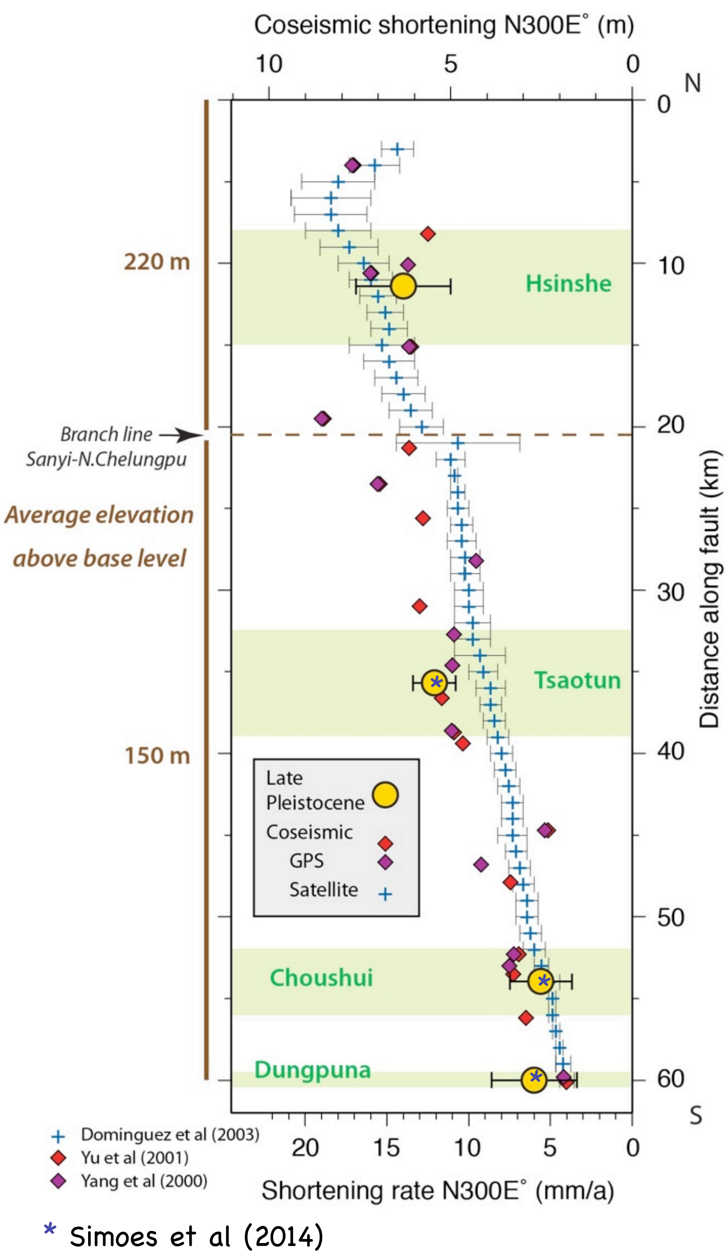
GPS Satellite Cumulative fold scarp

Coseismic displacements from Yang et al (2000), Yu et al (2001), Dominguez et al (2003)

Le Béon et al, 2014, JGR

Coseismic versus Long-term shortening along strike

Chi-Chi **coseismic displacements** and **long-term shortening rates** vary in **similar proportions !**



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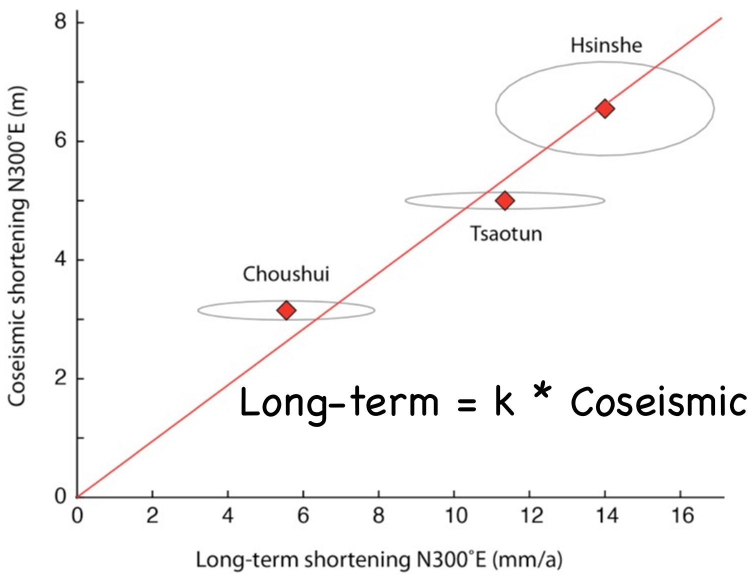


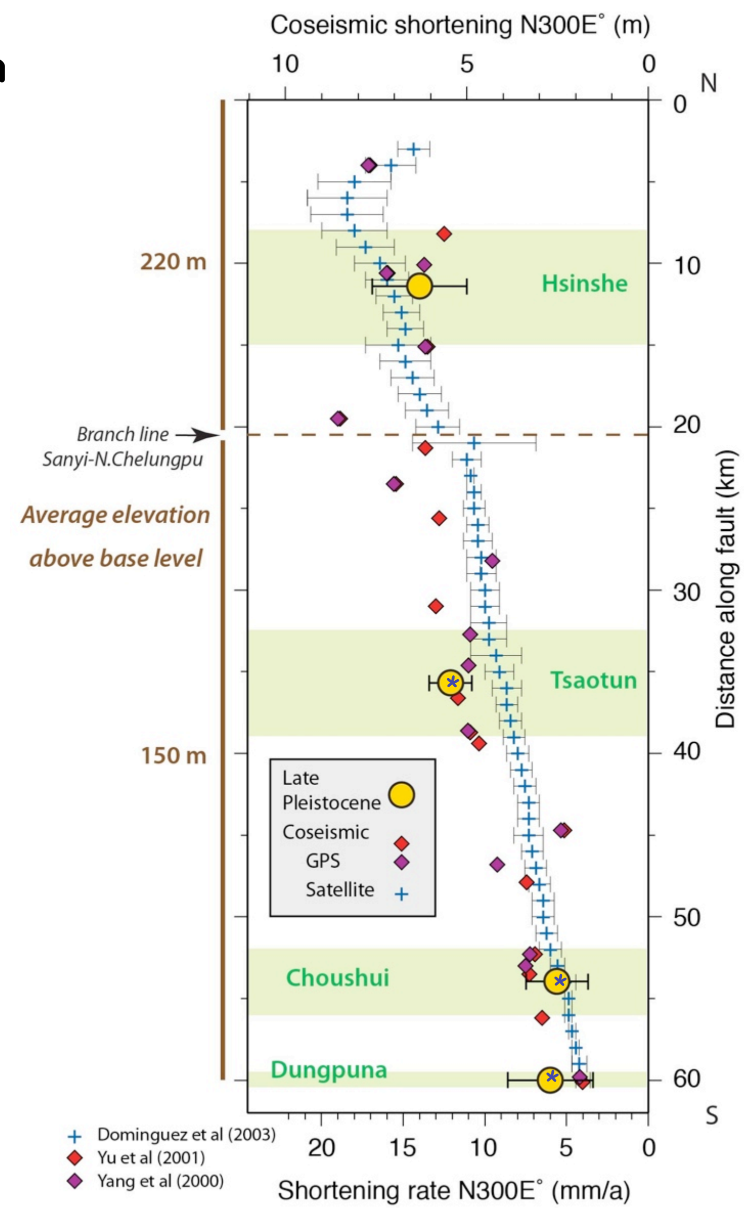
Long-term = k * Coseismic

with k = 1 / recurrence interval

470 ± 70 years

=> Chi-Chi could be

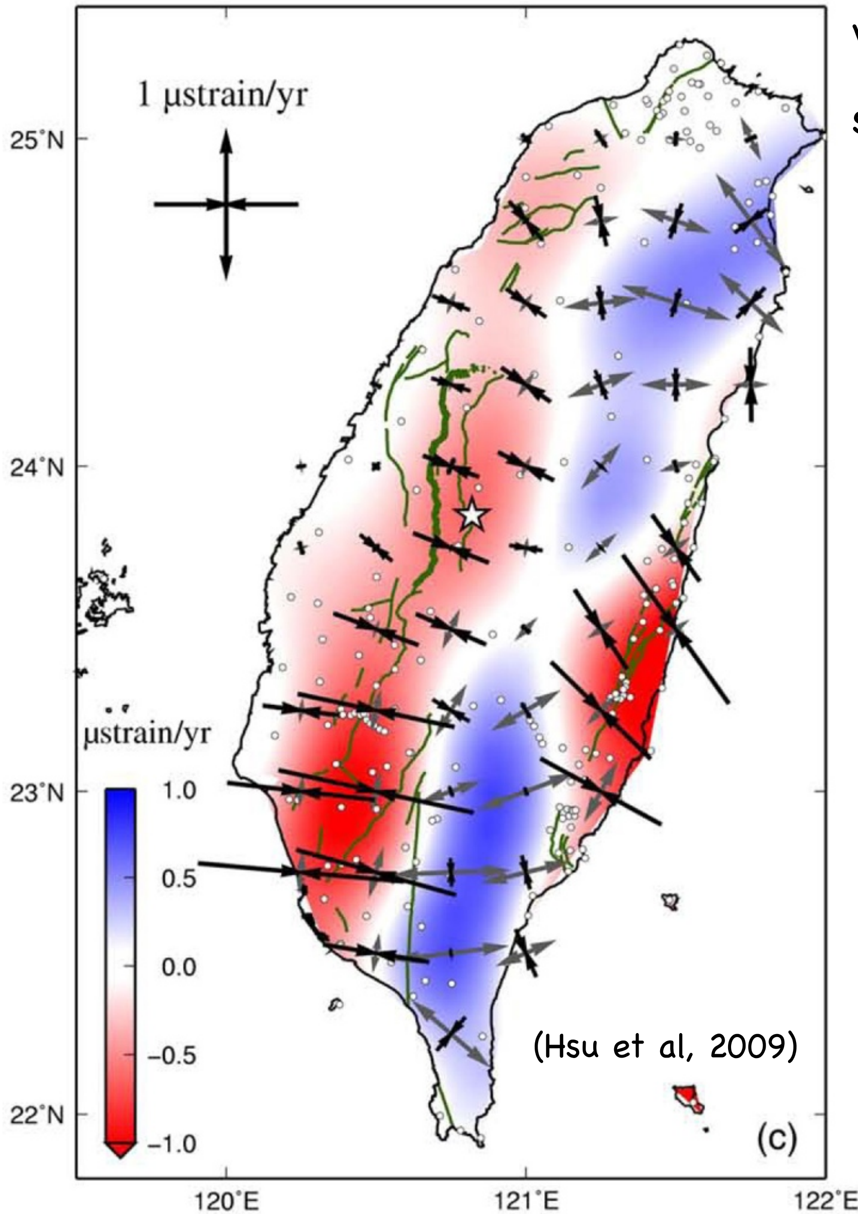
a characteristic earthquake !!



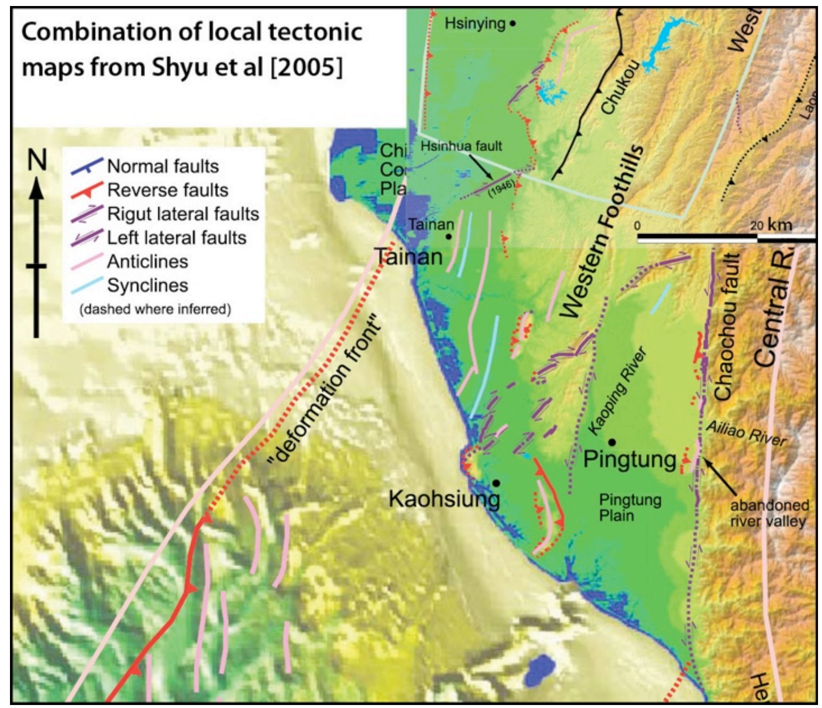
* Simoes et al (2014)

Tectonic setting in southwestern Taiwan

1993-1999 strain rate based on GPS



What are the **significant structures** accommodating shortening ? **Currently** and in **long term** ?



Multi-disciplinary approach :

Sub-surface data (seismic lines + boreholes),

Geodesy (InSAR + GPS), **Geomorphology**

Tainan Tableland

- **Present-day crustal deformation**:

GPS, leveling, InSAR

Fast uplift ~10-12 mm/a + Transient behavior

(Fruneau et al [2001], Rau et al [2003], Tung [2008], Huang et al [2009], Champenois [2011], Wu et al [2013])

- **Quaternary geology**: (Chen & Liu [2000])

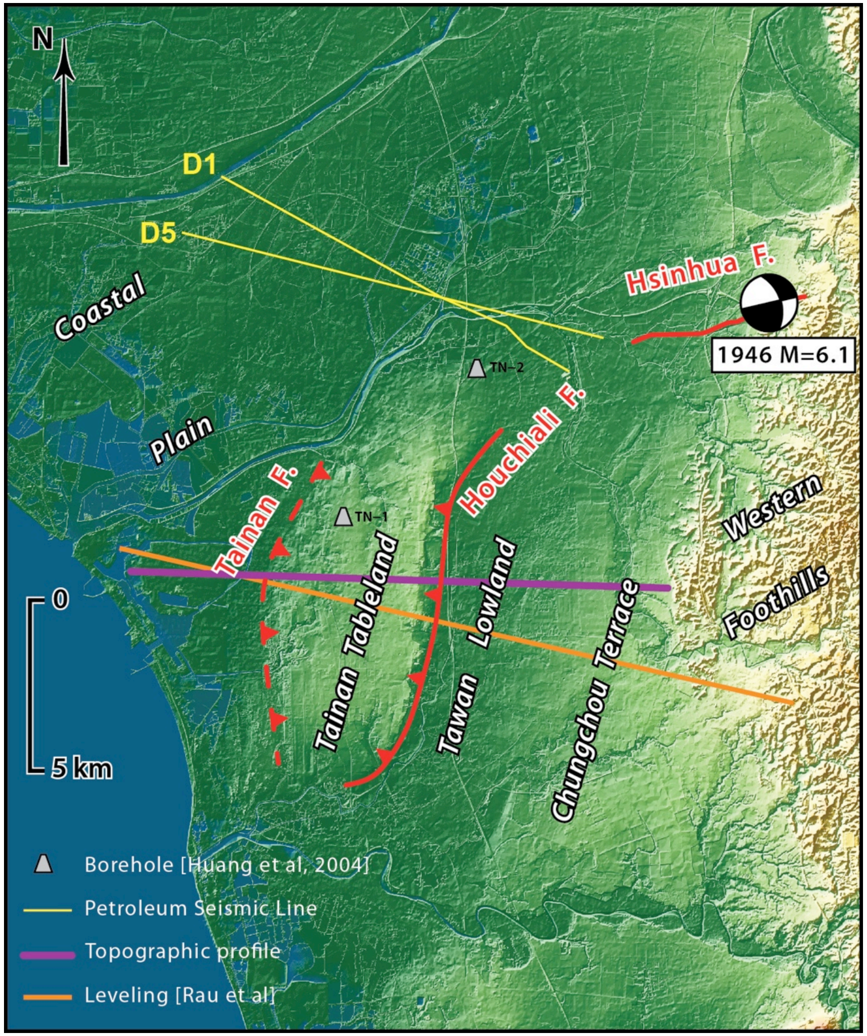
Holocene uplift rate = 5 mm/a

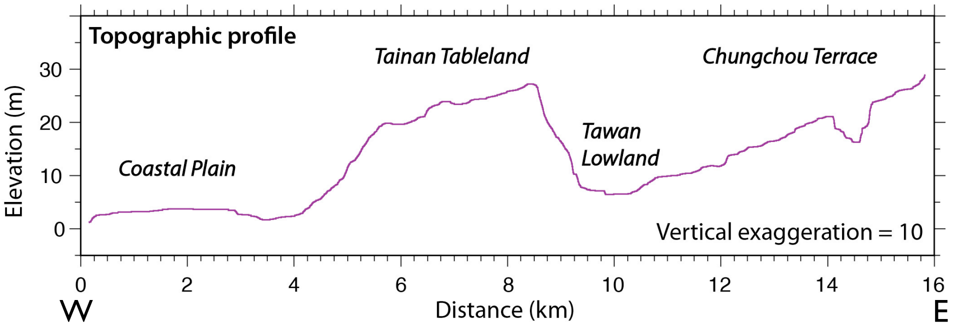
- **Subsurface structure...?**

Mud diapir (Liu et al [1997], Lin et al [2009])

Various fault-related fold geometries

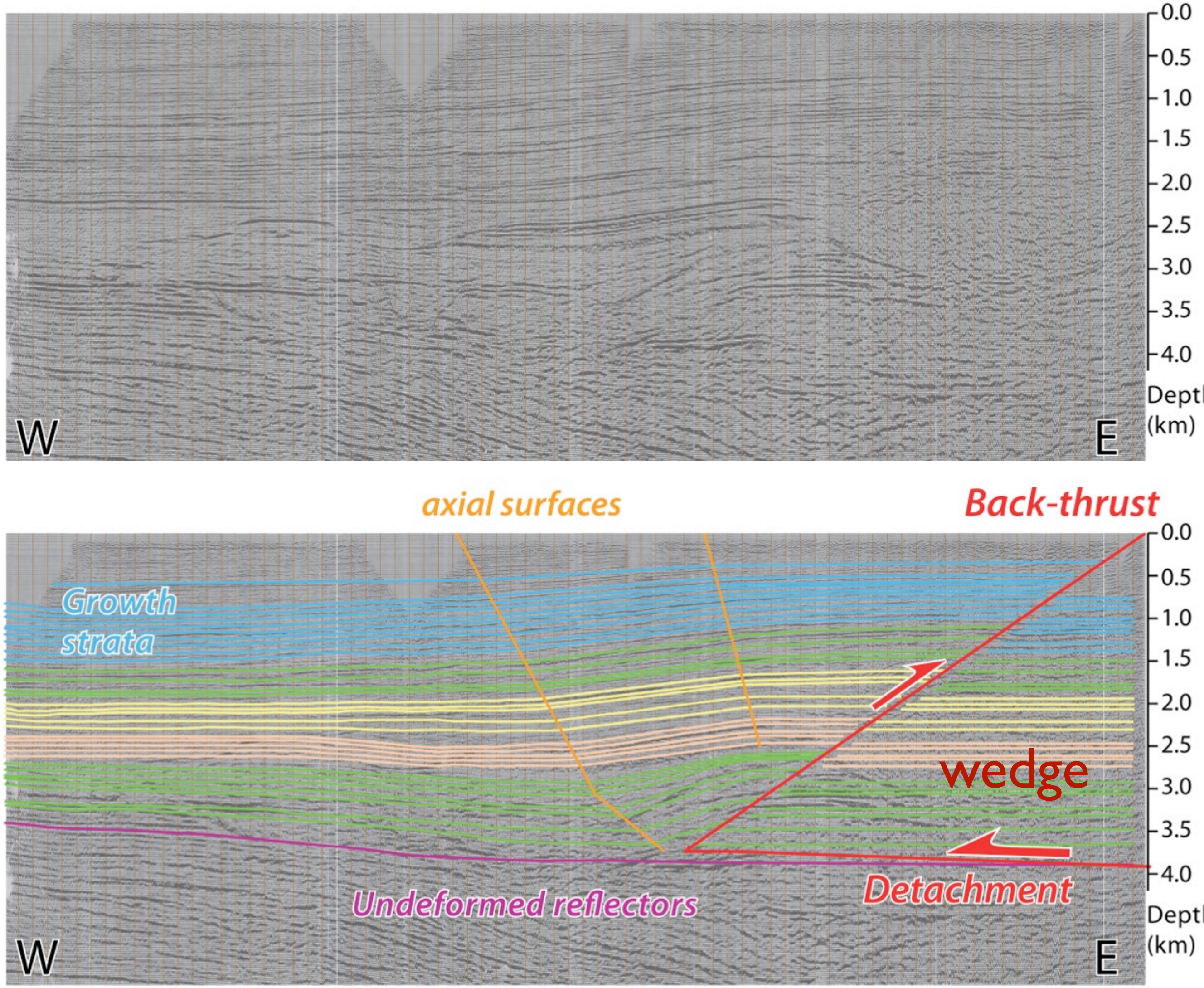
(Lacombe et al [1999], Fruneau et al [2001], Huang et al [2004], Lin et al [2007]...)





Subsurface structure North of Tainan tableland

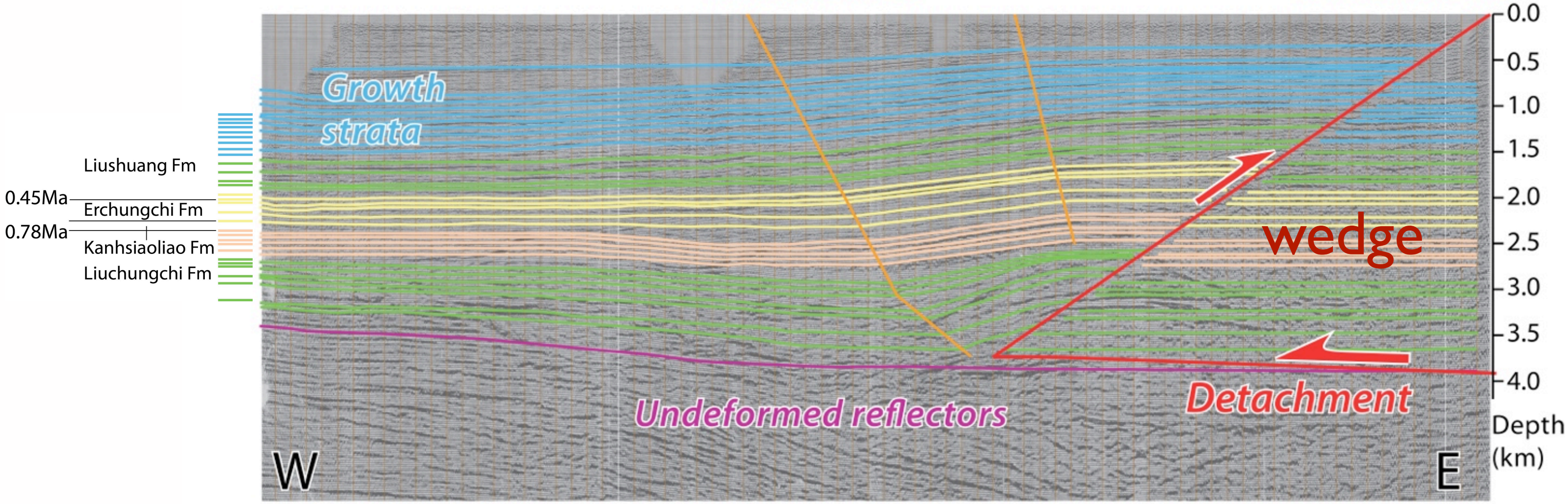
Petroleum seismic line D5 :



[Odin MARC summer project, 2010]

Subsurface structure North of Tainan tableland

Petroleum seismic line D5 :



- **East**: continuous reflectors, **no fault**

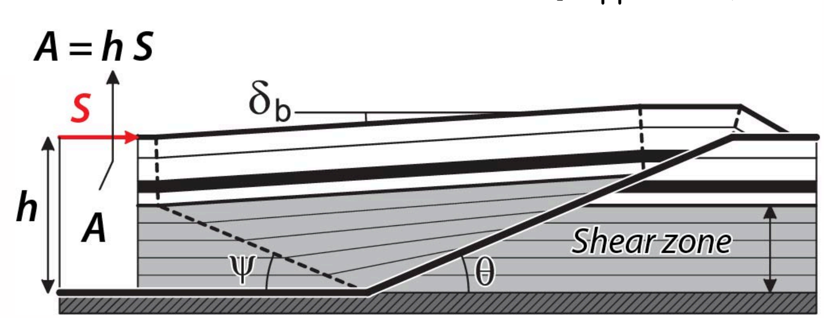
  West: 35° **W-dipping thrust**

- Detachment at **3.6** ± 0.1 **km depth**
- Basal shear zone
- Upper strata are syntectonic
- Beginning of growth much **younger than**

450 ka: **275 ± 25 ka** if constant sedimentation ?

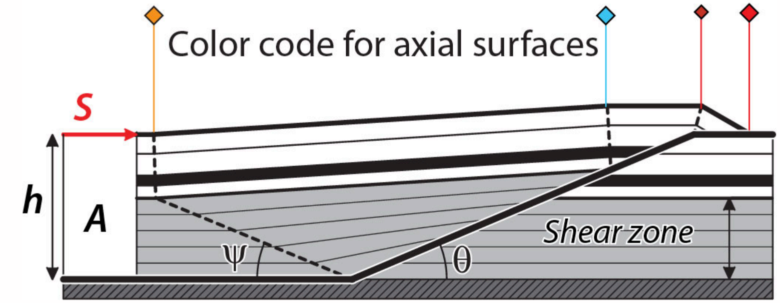
Pure-shear fault-bend fold model

[Suppe et al, 2004]

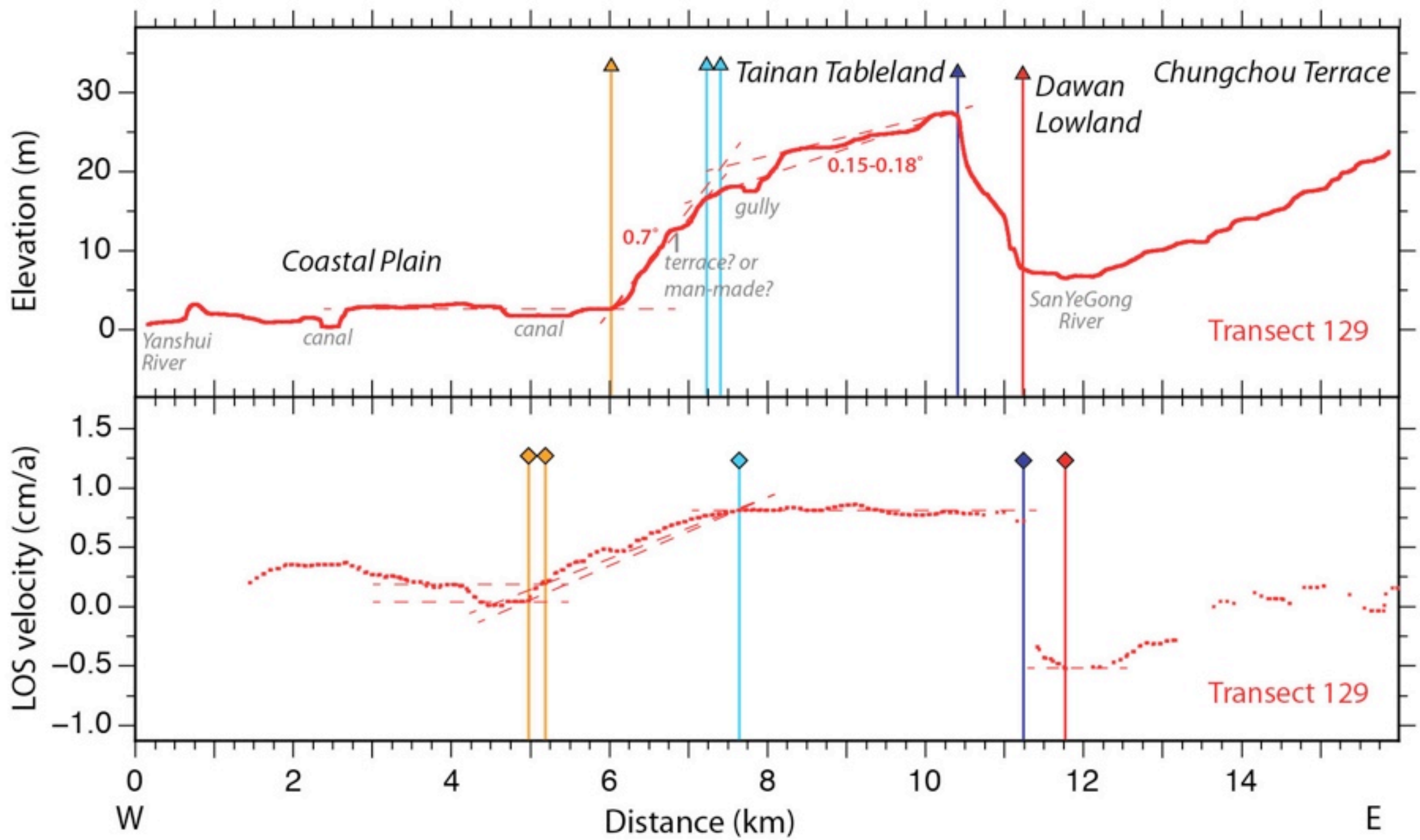


[Odin MARC summer project, 2010]

How does subsurface structure evolve southwards?



Structural axial surfaces mapping based on topography and InSAR LOS velocity :



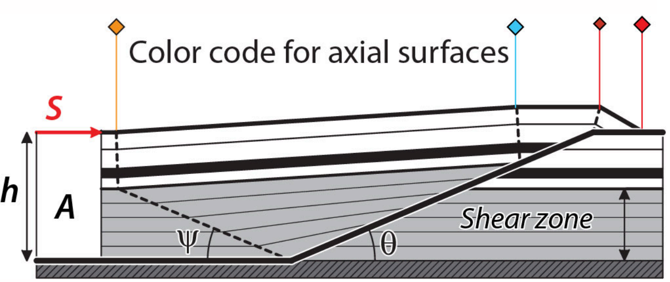
Axial surface mapping

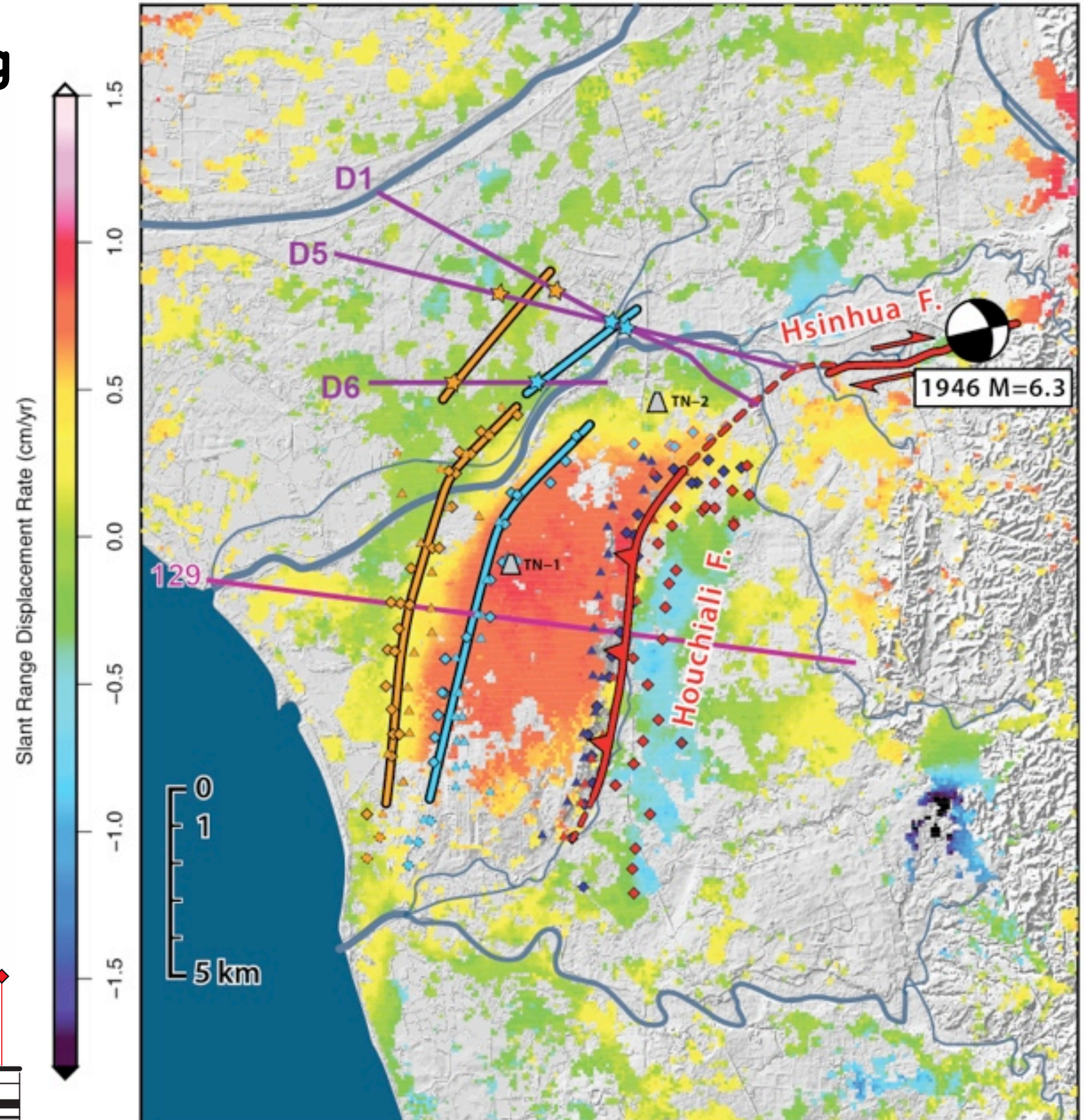
diamond = InSAR 1996-1999

triangle = topography

Fold of similar geometry

=> Extrapolation of the pure shear wedge fault-bend fold model to Tainan Tableland



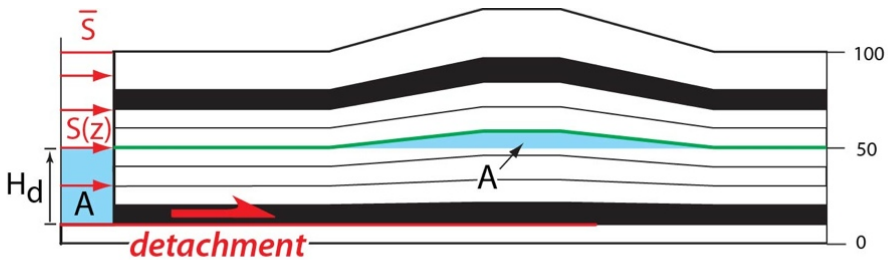


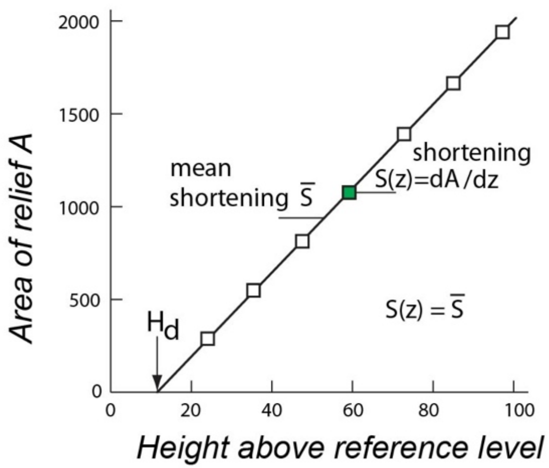
1996-1999 Envisat InSAR LOS velocity field from M-H Huang

Determination of total shortening in Tainan

Area of structural relief analysis

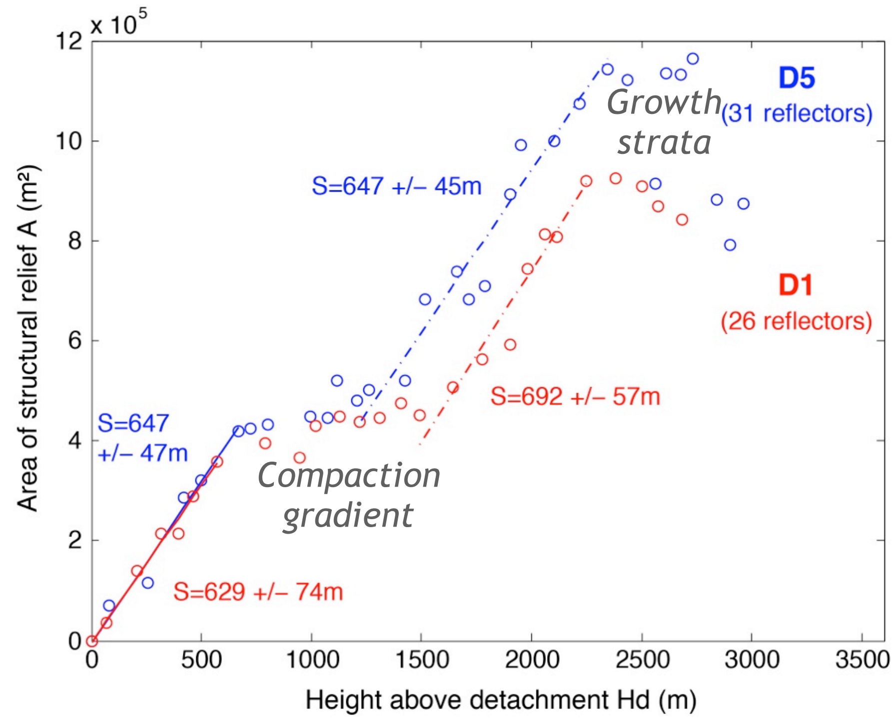
Assumption: conservation of area within the 2D section





- Linear regression

=> **Total shortening 654 ± 27 m** in the direction of seismic lines



Modified from Gonzalez-Mieres & Suppe [2011]

[Odin MARC summer project, 2010]

Tainan - Synthesis

- **Structure** :

Pure shear wedge fault-bend fold

above **3.6-km-deep** detachment

37-41° W-dipping back-thrust in North

- **Total shortening** along present-day

GPS vectors : **710 m** in North, only

Likely increasing southward

- If beginning of growth **275 ka ago**,

shortening rate = **2.6 mm/a** (North)

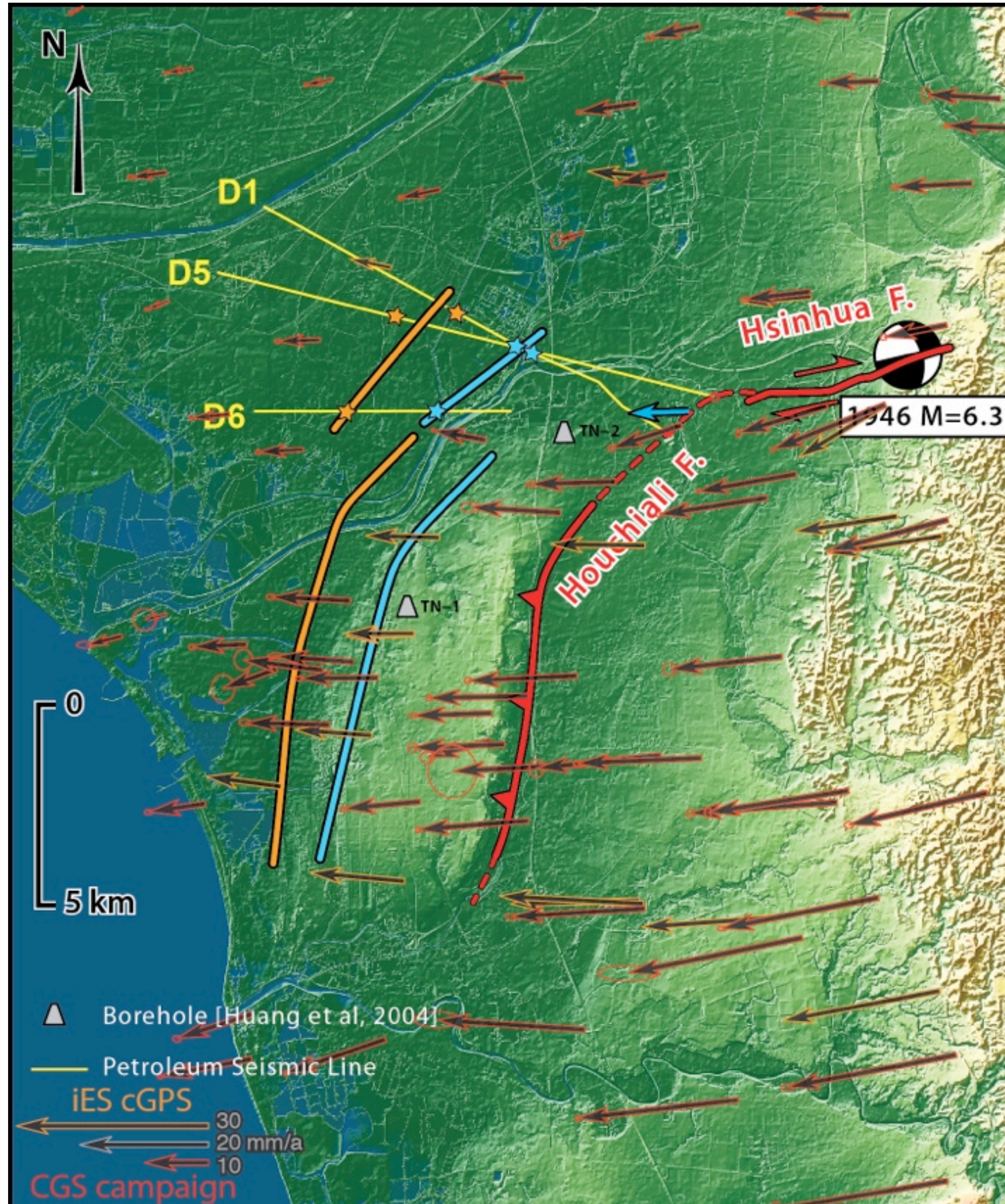
Much **slower** than present-day:

8-10 mm/a (North)

=> inception / mechanics of folding?

- Tainan anticline: **limited significance**

for collision history in SW Taiwan



Perspectives :

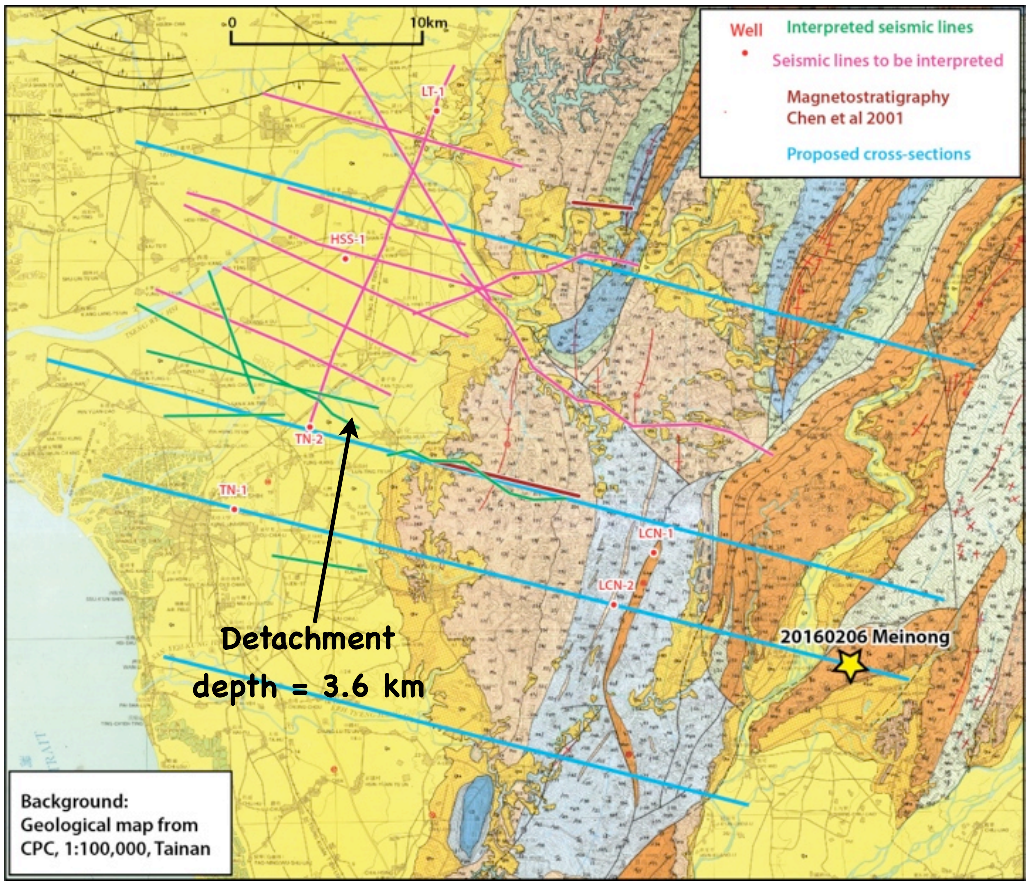
Active structures and evolution of the foothills of SW Taiwan

- Draw **regional cross-sections** based on **multi-disciplinary** datasets

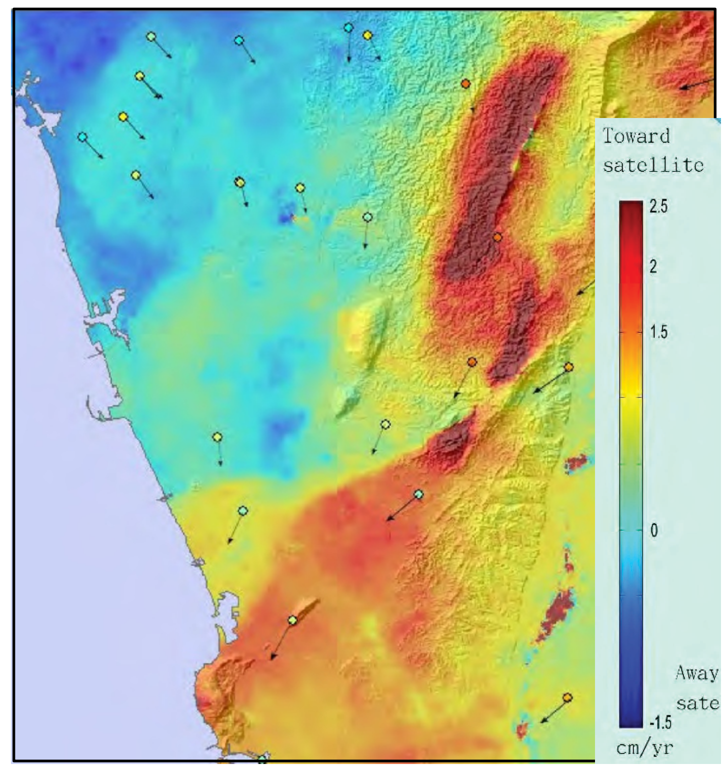
=> Locate and characterize active faults

=> Determine shortening at different timescales and fault/fold initiation

=> Chief goal: Restore the **evolution of the mountain belt** !



2007-2010 ALOS InSAR LOS velocity
from E. Pathier



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Active structures and evolution of the foothills of SW Taiwan

- Draw **regional cross-sections** based on **multi-disciplinary** datasets

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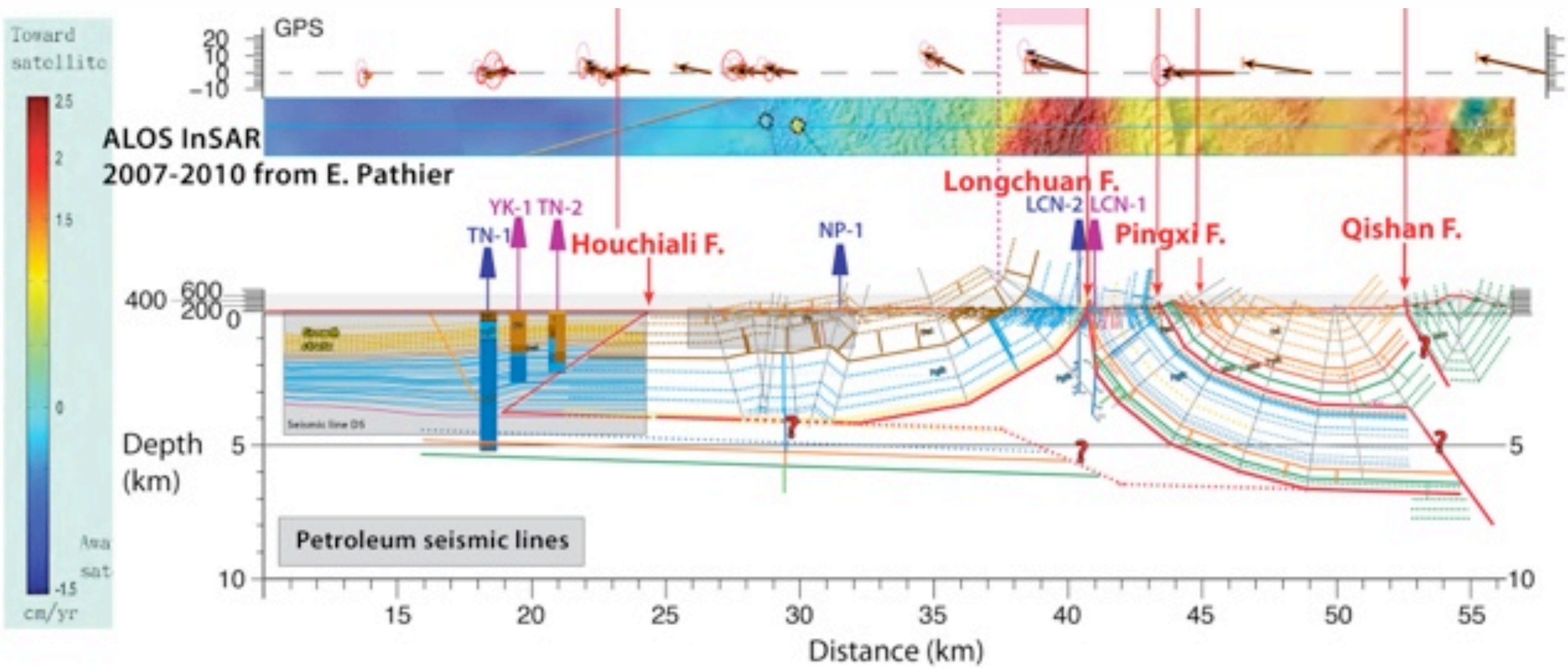
On-going work...



Integration within the Department

- New skills : **Neotectonics**
(Geomorphology, Quaternary geochronology, earthquake geology)

- Bridges
  * **Present-day** and **Long-term** processes
    (Geodesy, Seismicity) (mountain building, foreland basin)
  * **Surface** deformation and **sub-surface** structures
    (Geomorphology, geodesy) (exploration geophysics, tomography, gravity anomalies)
  * On-land and **offshore** tectonics (marine geophysics)
  * Fault seismic behavior and **Fault-zone** geology
  * Permanent deformation and **folding** mechanism (Geomechanics)

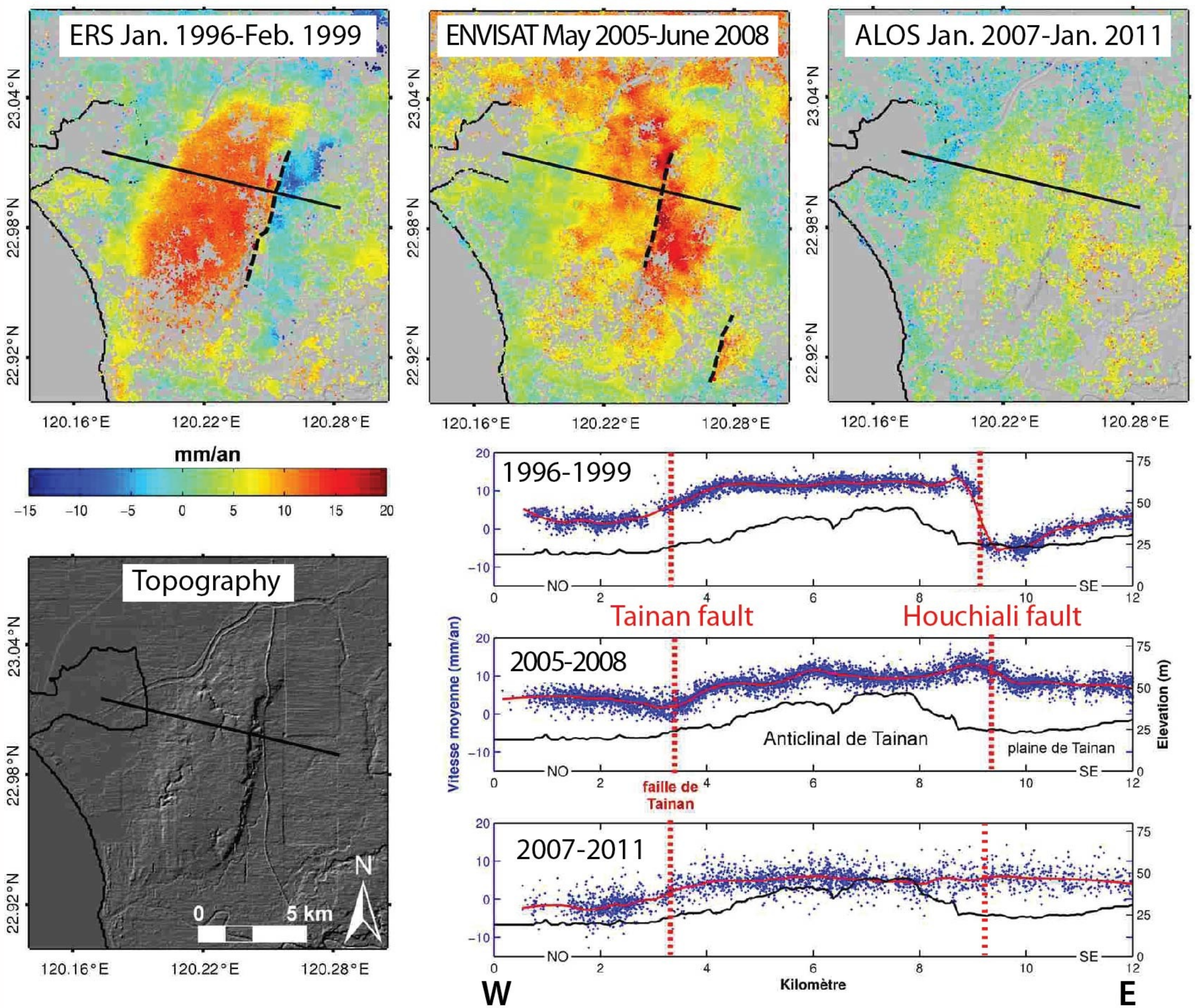
- **International collaborations :**

My Research Focus = Topic of France-Taiwan collaboration
+ of incipient Taiwan-USA collaboration


Thanks for your attention !

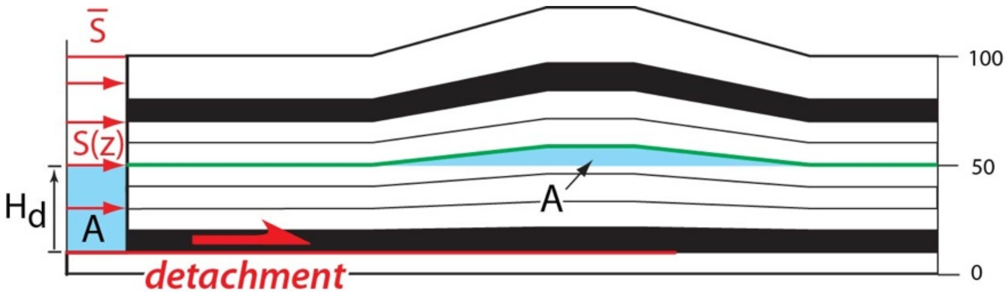
Transient deformation monitored by InSAR

Modified from Champenois [2011]



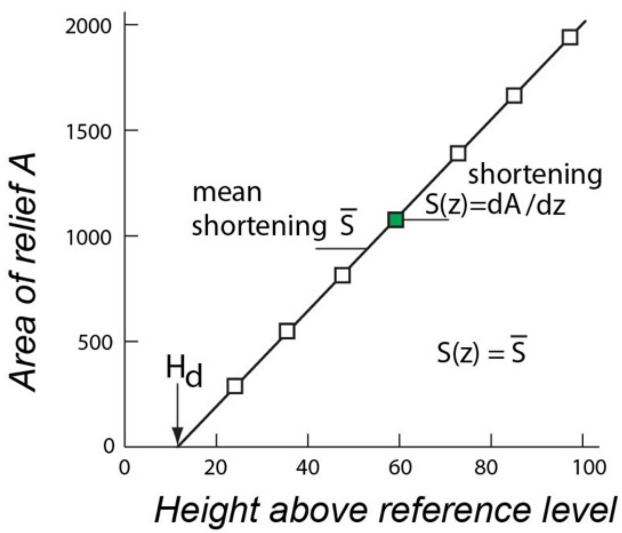
Area of structural relief and Shortening

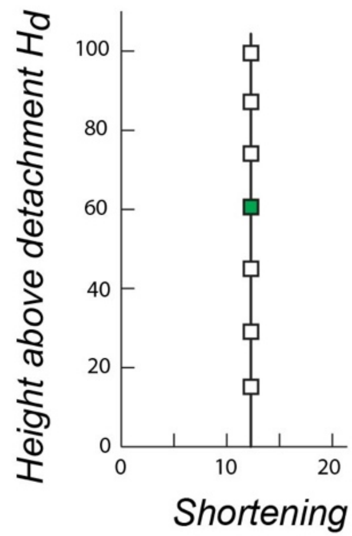
Modified from Gonzalez-Mieres & Suppe [2011]



$S(z)=A/H_d$

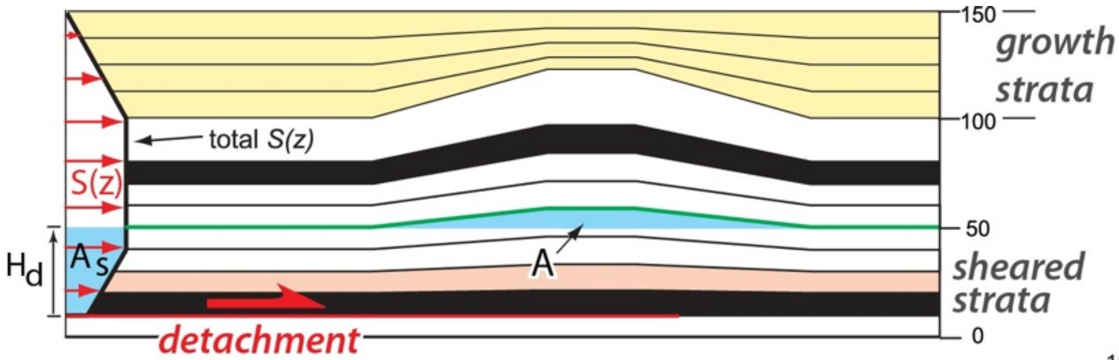
[Epard & Groshong, 1993]





Assumption:
conservation of area
within the 2D section

Area of structural relief and Shortening



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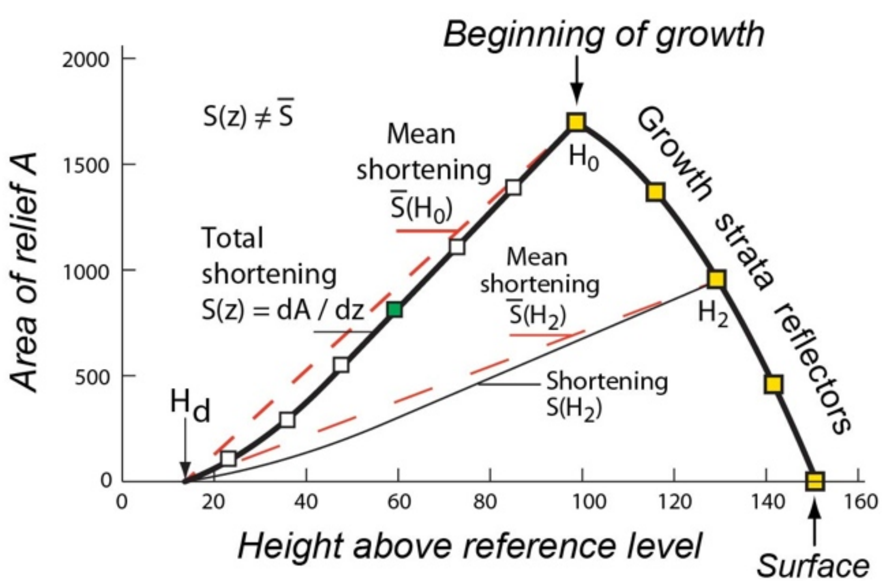
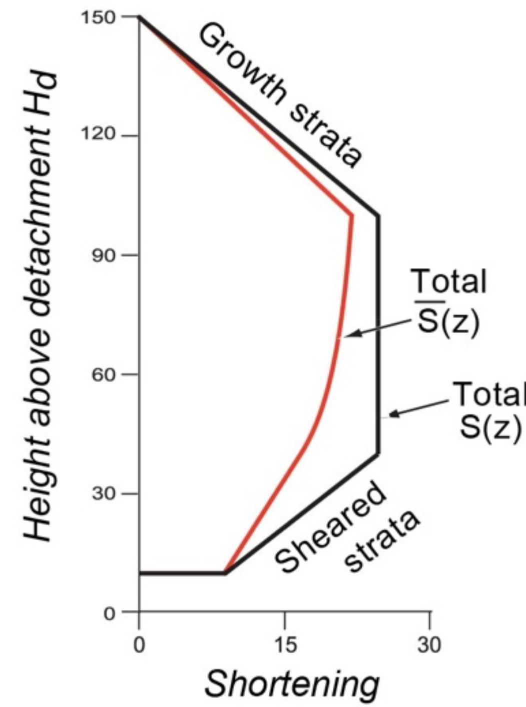
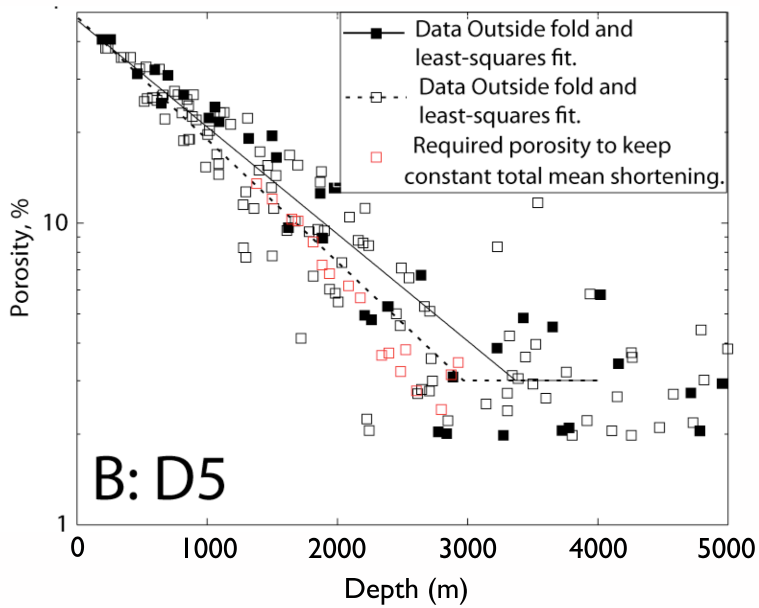




Impact of horizontal compaction on shortening



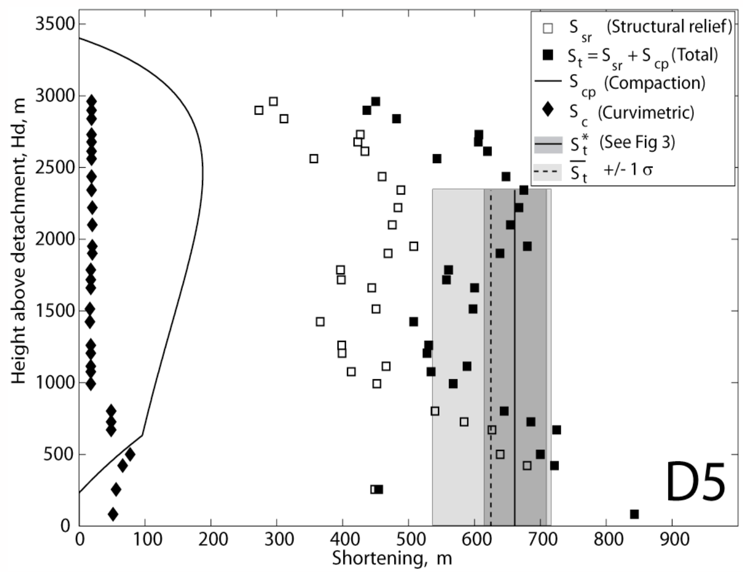
Porosity **within** the fold

lower than porosity **away** from the fold

=> **Shortening** partly absorbed by

horizontal compaction

Components of shortening :



For individual reflectors:

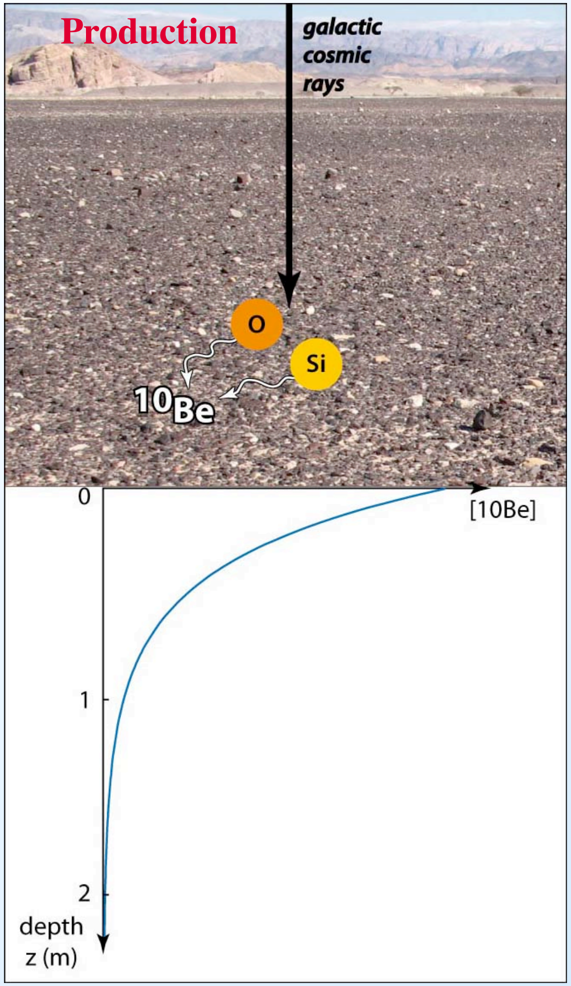
Structural relief shortening

corrected from **horizontal compaction**

=

Total structural relief shortening

About cosmogenic dating



Pre-exposure Production Decay

$$\mathcal{N}_{10Be}(z,t) = \boxed{\mathcal{N}_{10Be,t_0}} + \boxed{\frac{\mathcal{P}.\exp(-\mu z)}{\lambda+\mu\varepsilon}\Big(1} \boxed{- \exp(-(\lambda+\mu\varepsilon)t)}\Big)$$

$\mathcal{N}_{10Be}$: number of atoms $\mathcal{N}_{10Be,t_0}$: pre-exposure

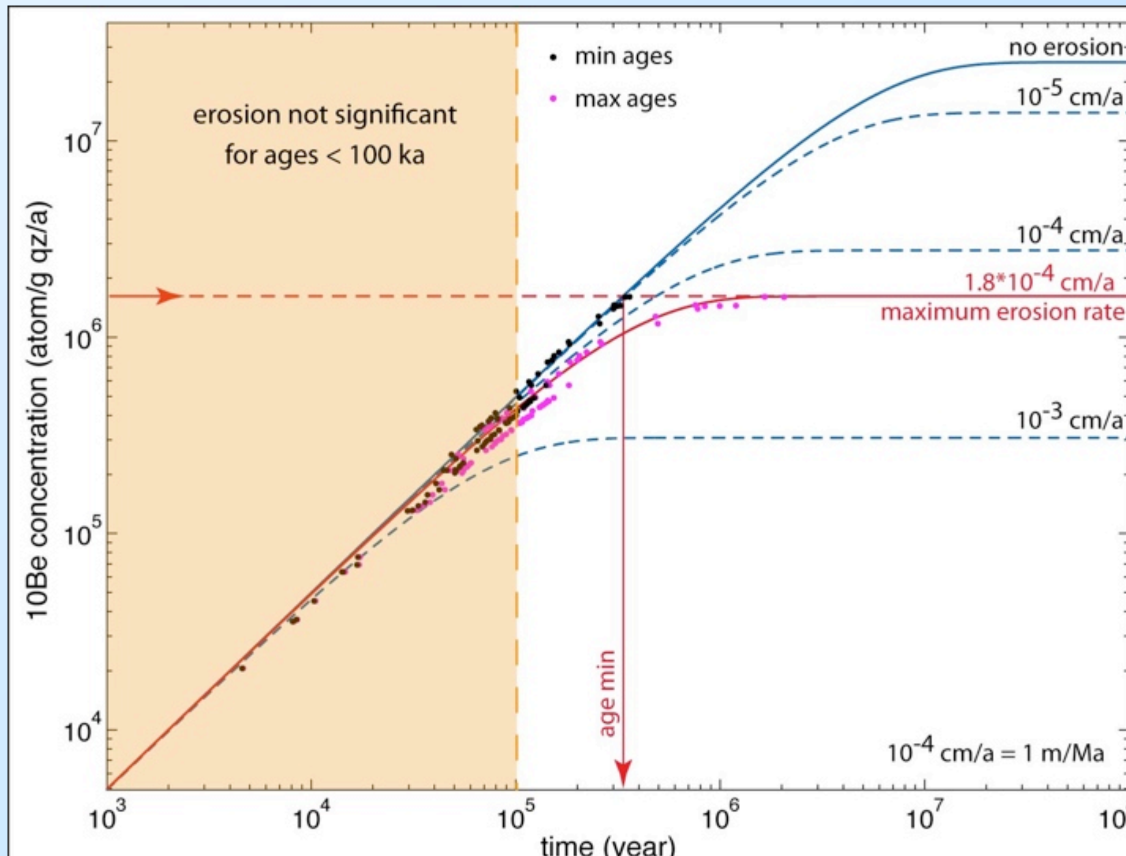
$\mathcal{P}$: production rate in at / g (qz) / yr

λ : half-life $\mu = \rho/\Lambda$

ε : erosion rate

Lal (1991)

Assuming no erosion and no pre-exposure : $\mathcal{N}_{10Be}(z,t) = \frac{\mathcal{P}.\exp(-\mu z)}{\lambda}\big(1 - \exp(-\lambda t)\big)$



Ages calculated with G. Balco's program

using Lal (1991) production rate

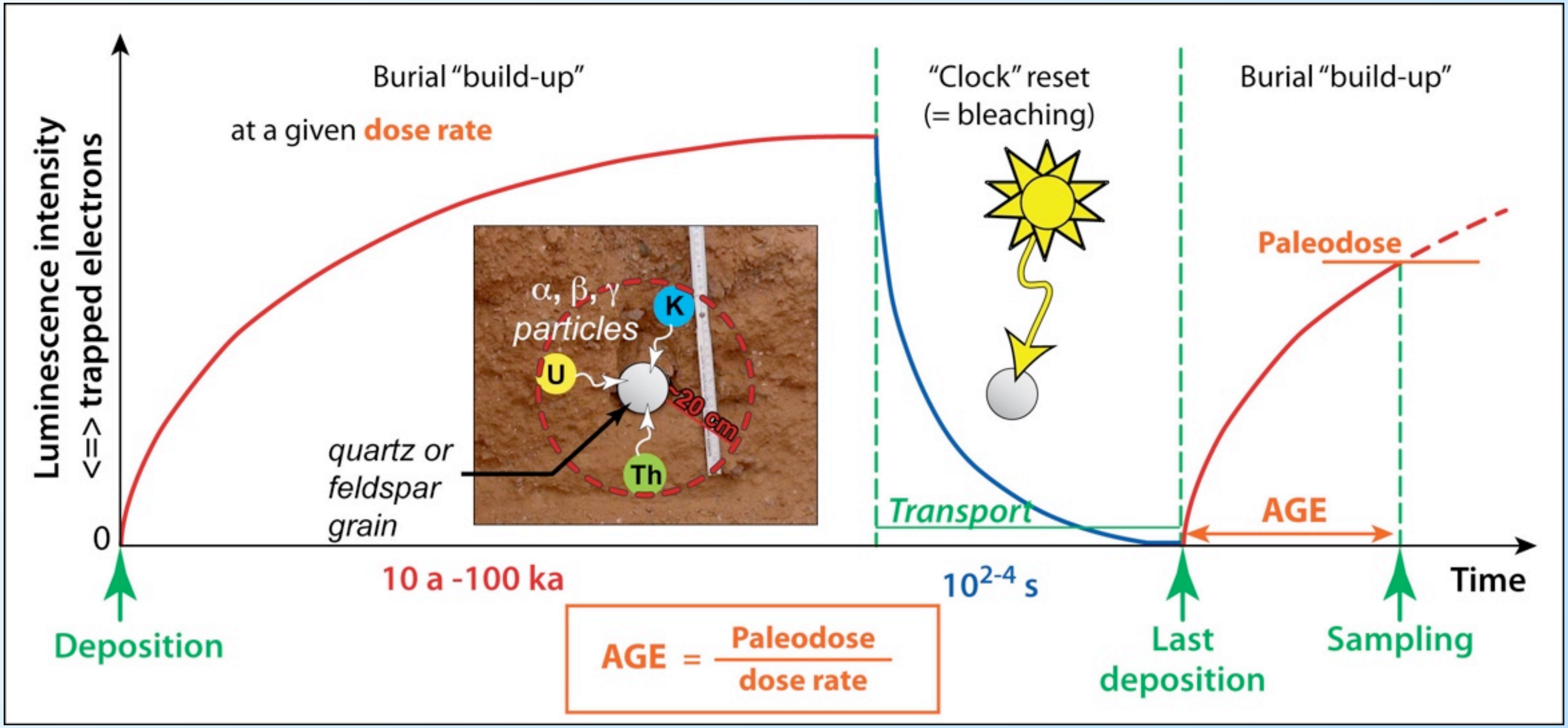
and Stone (2000) scaling factors.

(http://hess.ess.washington.edu/math/)

Cross-dating ^{10}Be - Luminescence (OSL)

Exposure age — Burial age

Principle of **luminescence dating** :



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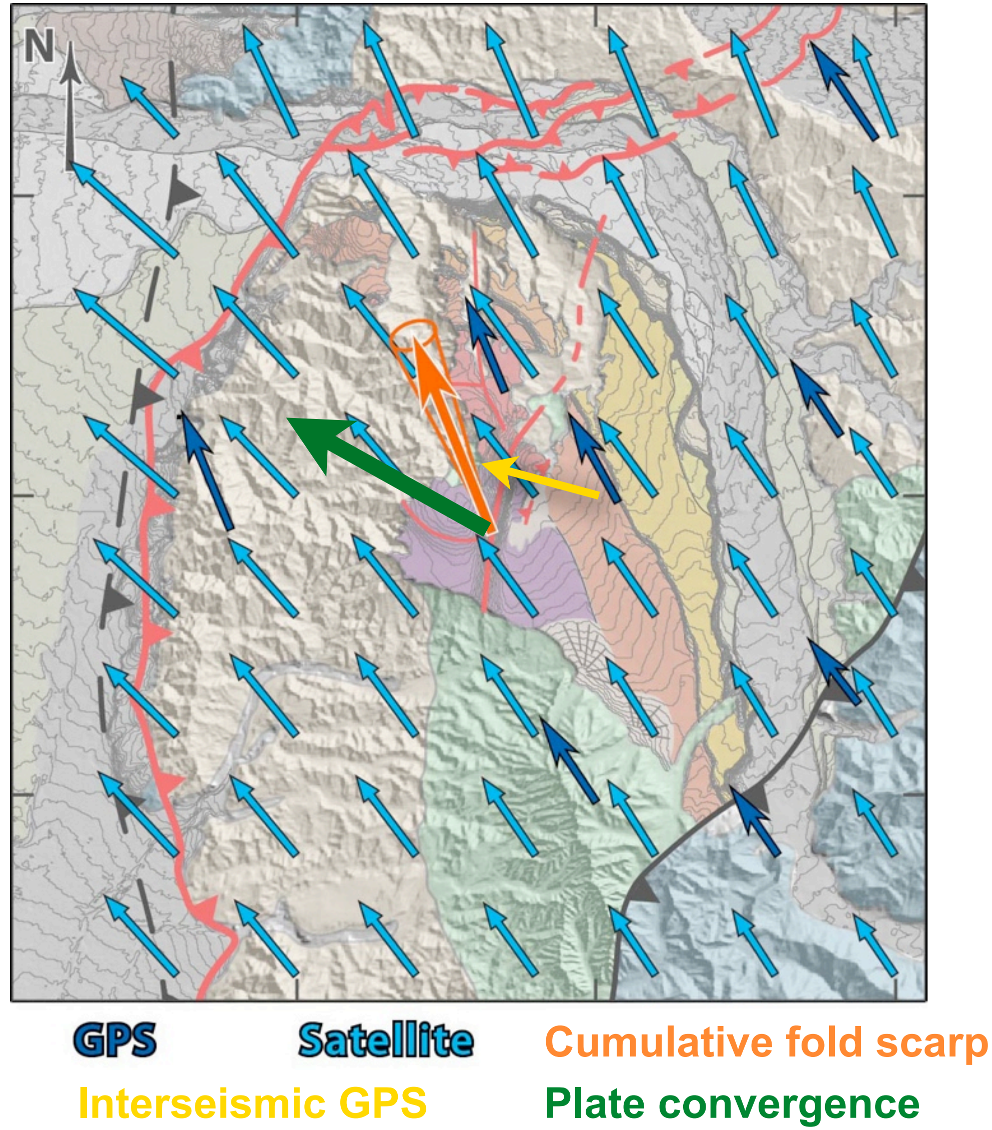


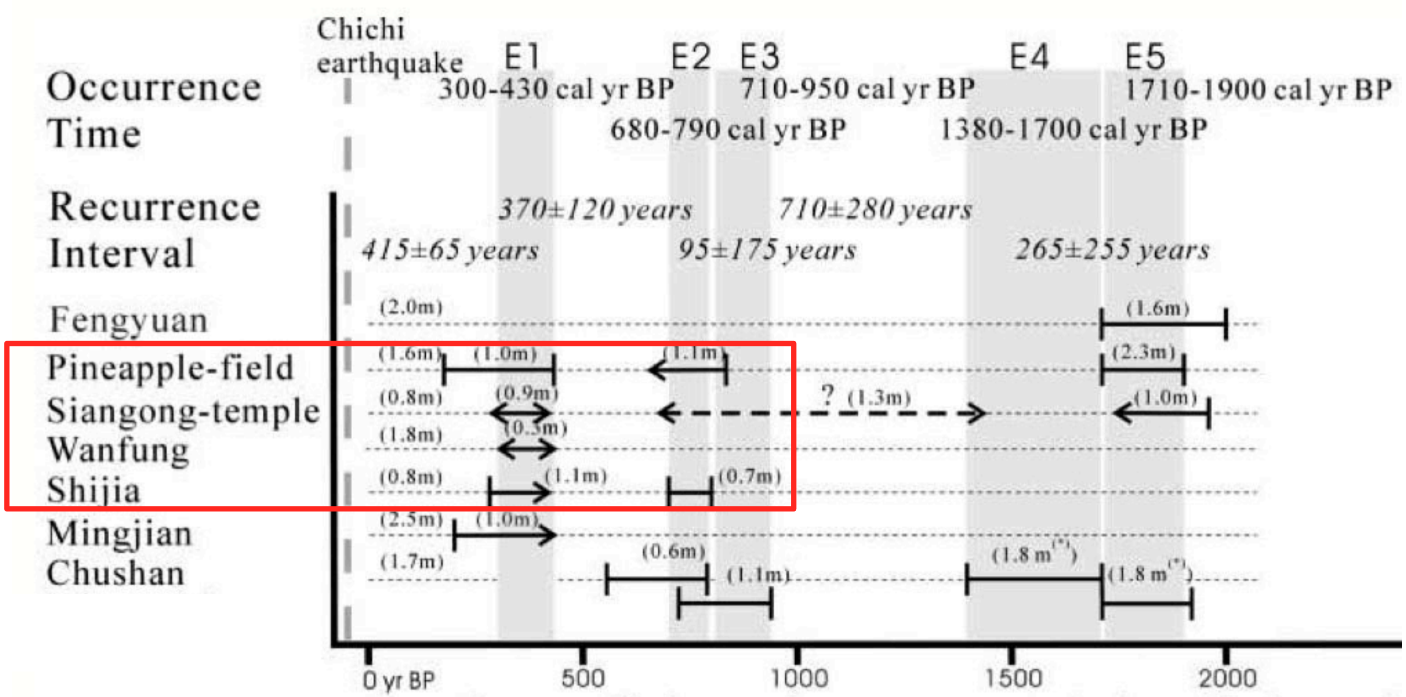
Interseismic displacement from Lin et al (2010)

Le Béon et al, 2014, JGR

Comparison with paleo-seismology studies

Late Pleistocene record: **Chi-Chi earthquakes recurrence interval : 470 ± 70 years.**

Paleo-earthquake record:



Chen et al [2007]