

# Fault kinematics in northern Central America and coupling along the subduction interface of the Cocos plate from GPS data in Chiapas (Mexico), Guatemala and El Salvador

A multidisciplinary project from 1998/1999

Guatemala: INSIVUMEH, CONRED, CUNOR, USAC-CESEM,  
IGN, Geologia Ambiental y Economica, MEM

Mexico: UNAM

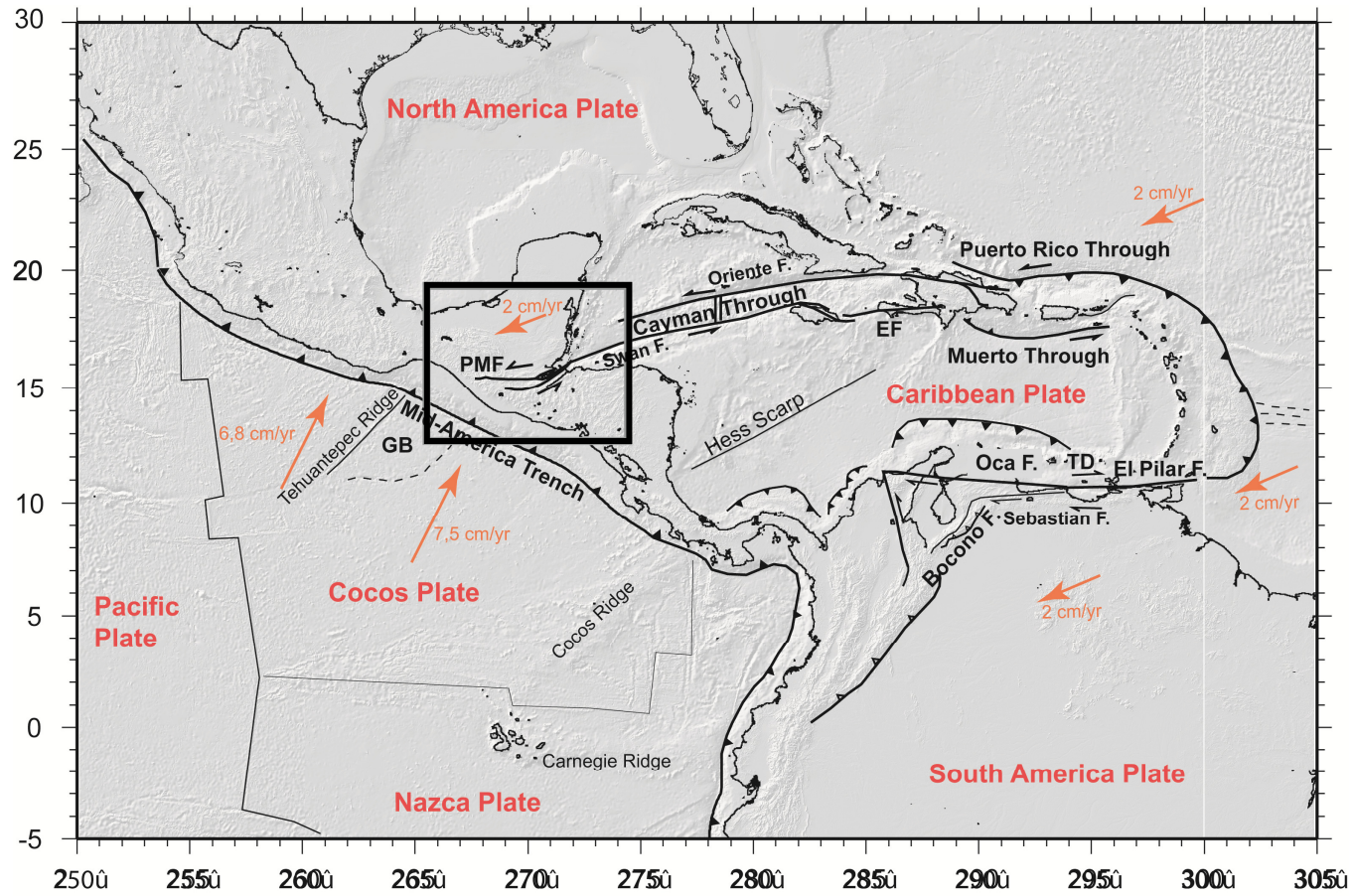
El Salvador: IGCN

France: Ecole Normale Supérieure, University Paris VI,  
ISTERRE (Grenoble University)

*Main collaborators: E. Molina, D. Monterosso, V. Robles, V. Kostoglodov, M. Guzman-Speziale, O. Flores, J. Romero, L. Chiquin, W. Amaya*

*Thesis work of Aurore Franco (ENS, Paris) with E. Barrier, C. Lasserre, H. Lyon-Caen*

# 1 - Geodynamic setting



- Interaction between 3 major tectonic plates (North America, Caribbean, Cocos)

# 1 - Geodynamic setting

- 3 major strike-slip faults

(Polochic, Motagua and Swan, Jocotan)

associated with large recent or historical earthquakes :

- Polochic : 1795 ?

1816,  $M_s \sim 7.6$

- Motagua : 1976,  $M_s = 7.5$

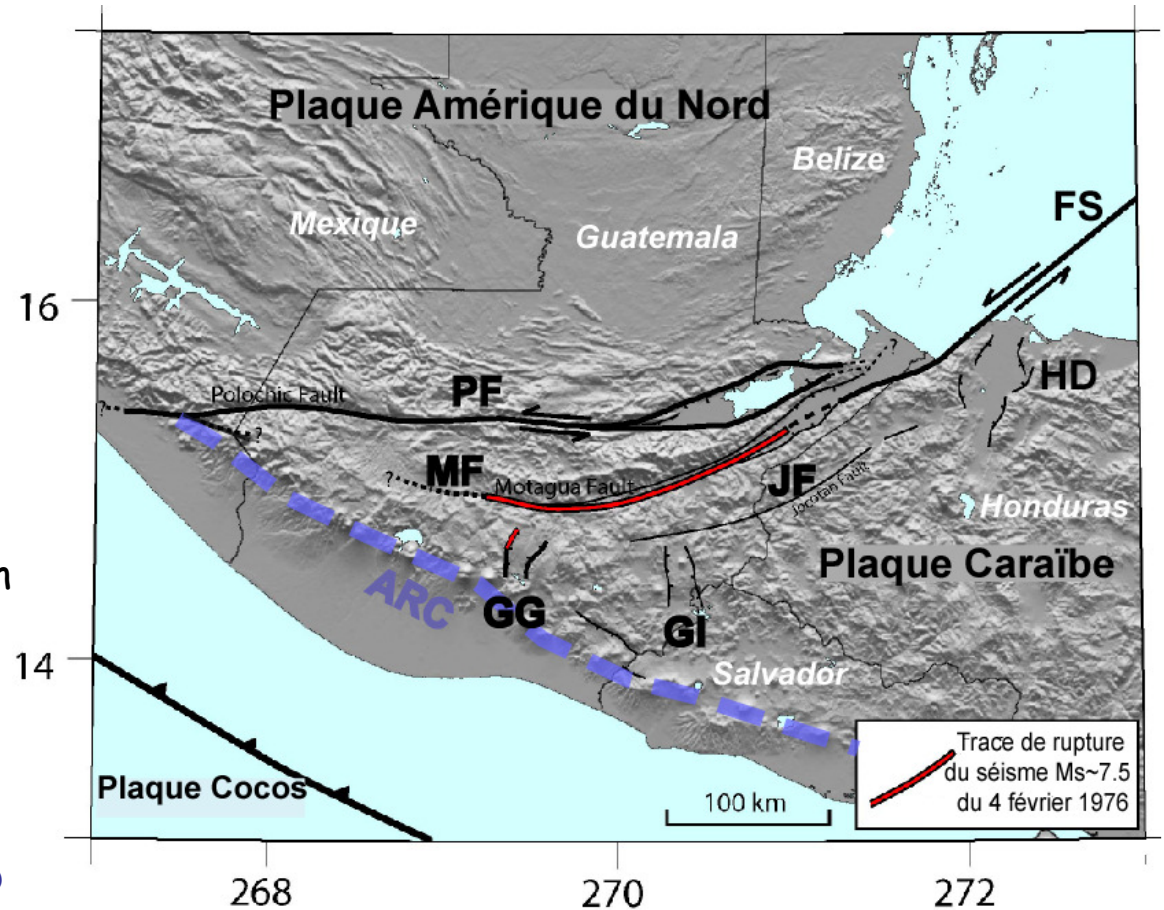
- Swan Fault: 2009,  $M_w = 7.3$ , Roatan

- Jocotan ?

- North-South grabens:

activated in 1976, 2011  $M_w \sim 5.5-6$  ?

- Volcanic arc fault: strike slip events  $M_w \sim 6$  in El Salvador (e.g 2001)

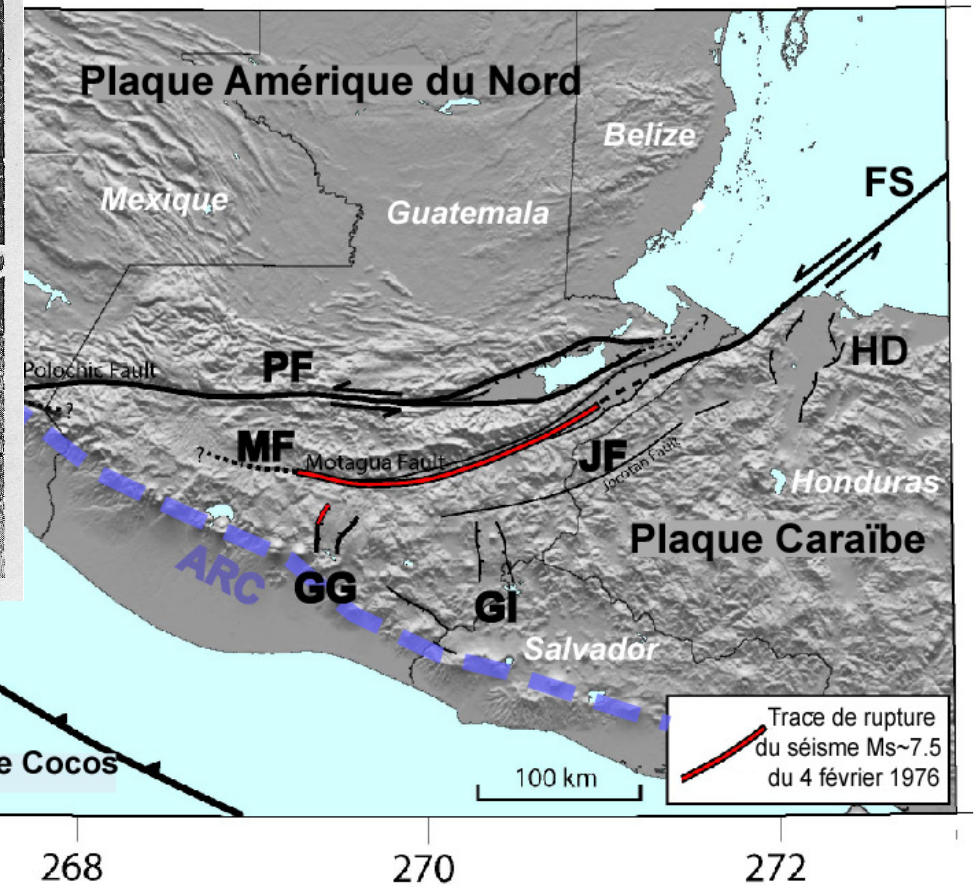


# February 4 1976, Motagua fault earthquake Mw=7.5



Rupture length ~200 km

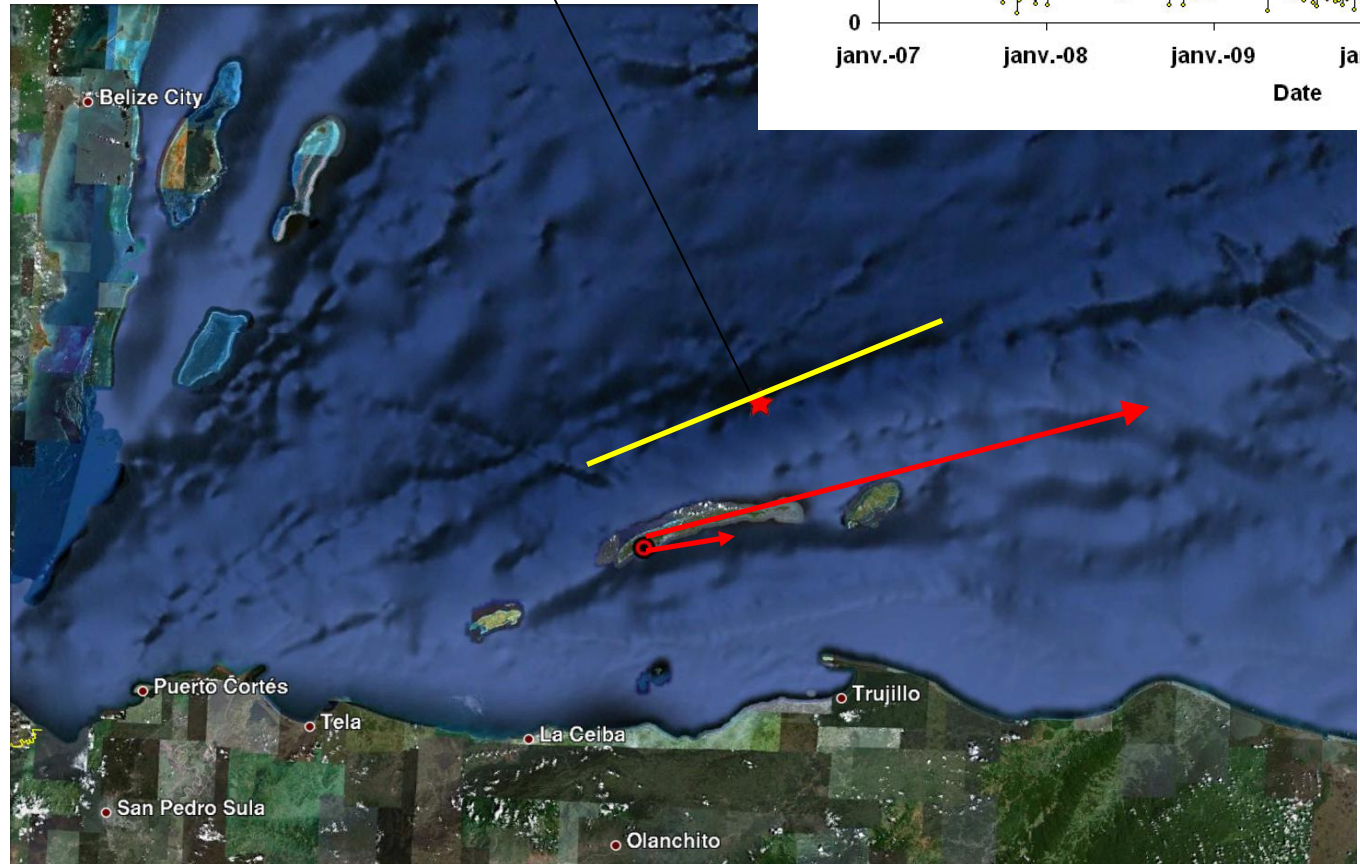
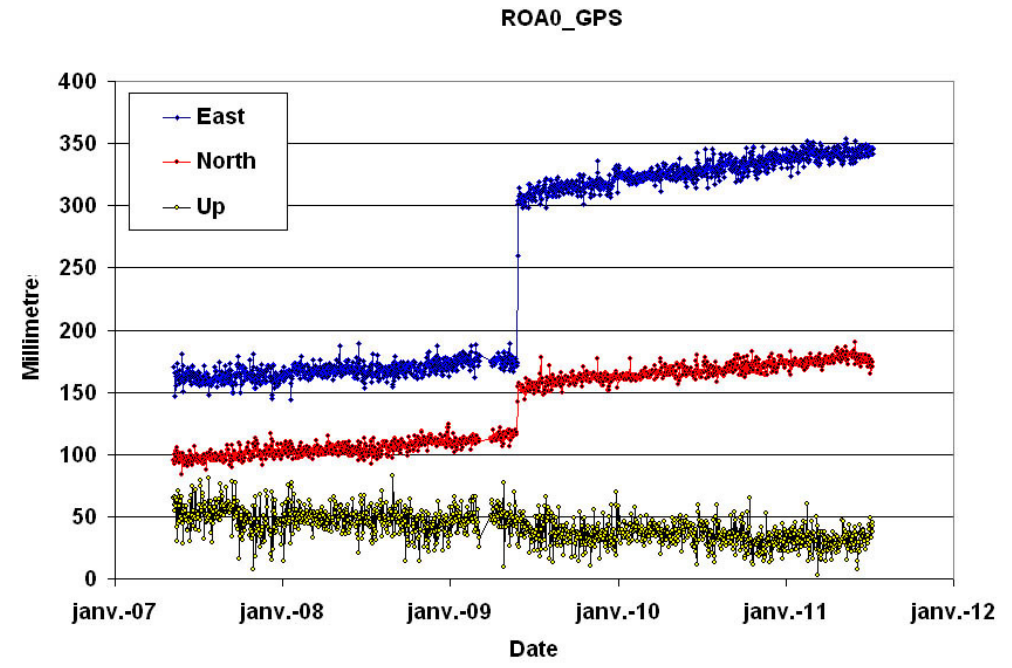
Mean displacement ~ 2 m



(Plafker, 1976)

# M<sub>w</sub>=7.3 Roatan earthquake, Swan Fault 28 May 2009

HARV-M<sub>w</sub>=7.3



### Co-seismic

140mm, az=17°  
dU= -8mm

### Post-seismic

10.7mm/yr, az=11°

### Fault model

Length = 90km  
Width = 15km  
Slip = 2.7m

*(P. Briole)*

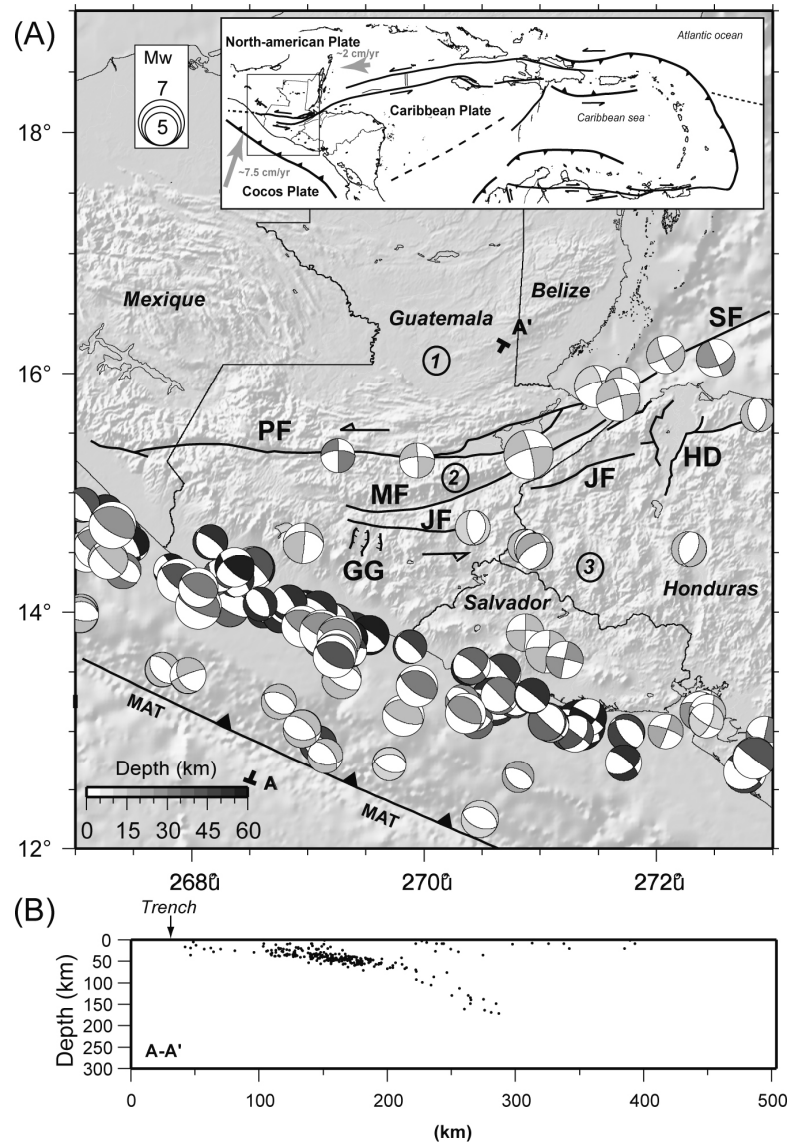
## 2 - Main scientific questions and goals of the study

- **Regional kinematics in a complex triple junction area :**  
Variations of the NA/CA relative velocity near the triple junction area?
- **Role of the different structures in the accomodation of the deformation?**
- **Plate coupling at the subduction interface?**
- **Short-term behavior of the faults?**  
Slip-rates?  
Locking depth?  
Potential creep?  
Faults interaction and mechanical behavior?

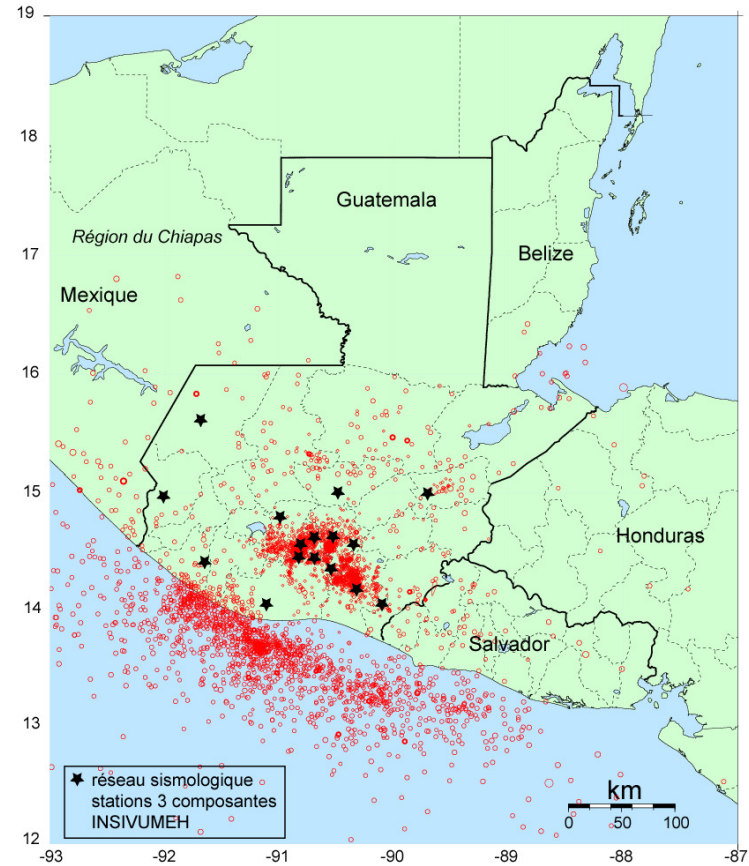
⇒ Geodetic (GPS) and seismological studies

1 PhD (Aurore Franco, ENS Paris)

### 3 - Seismological study



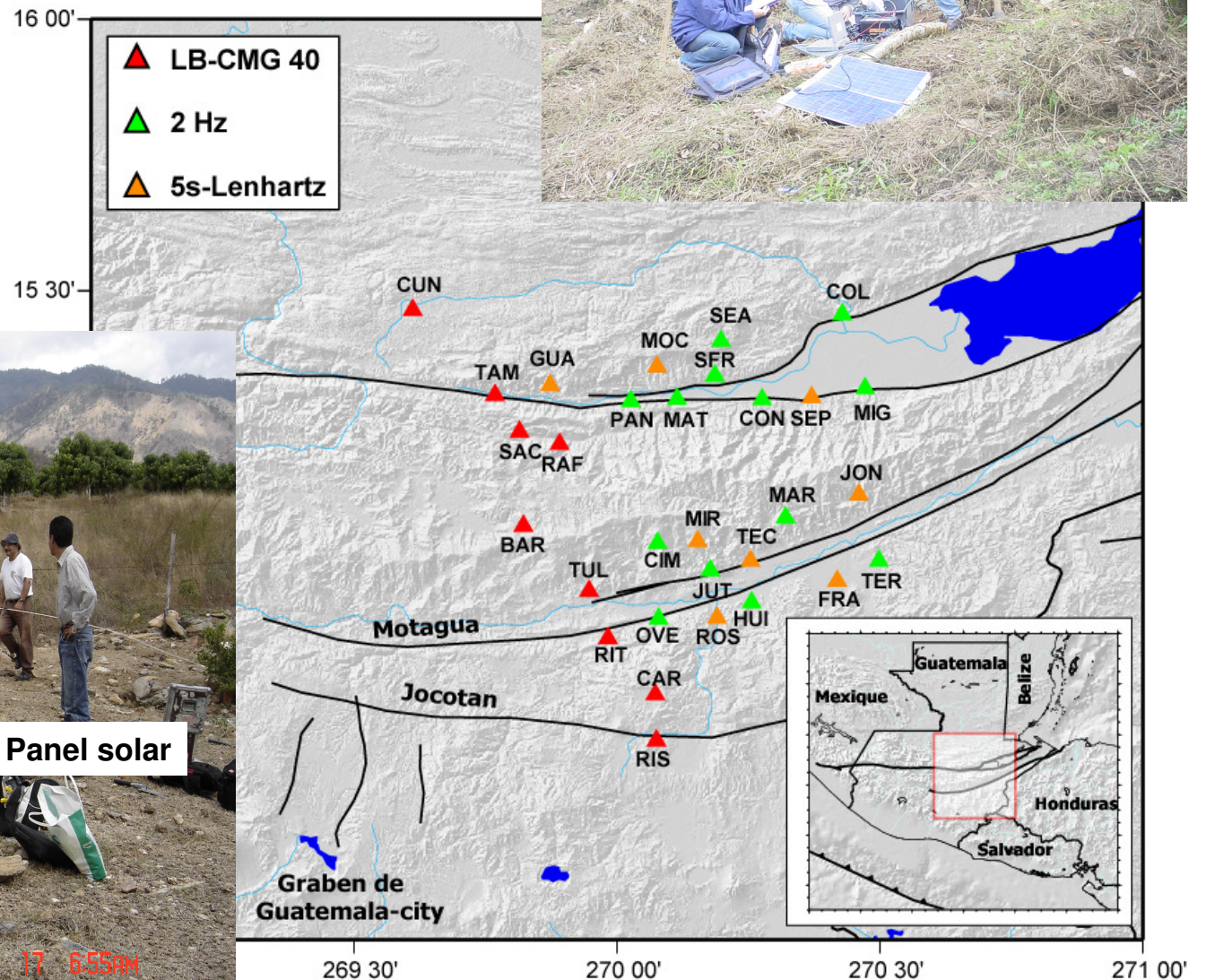
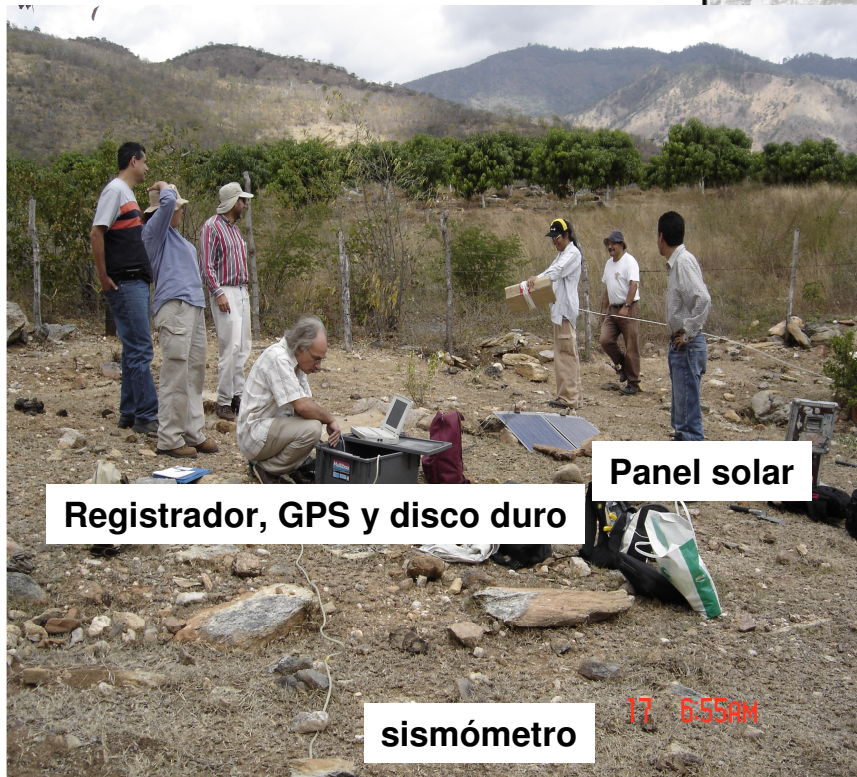
ISC Catalog and Havard CMT



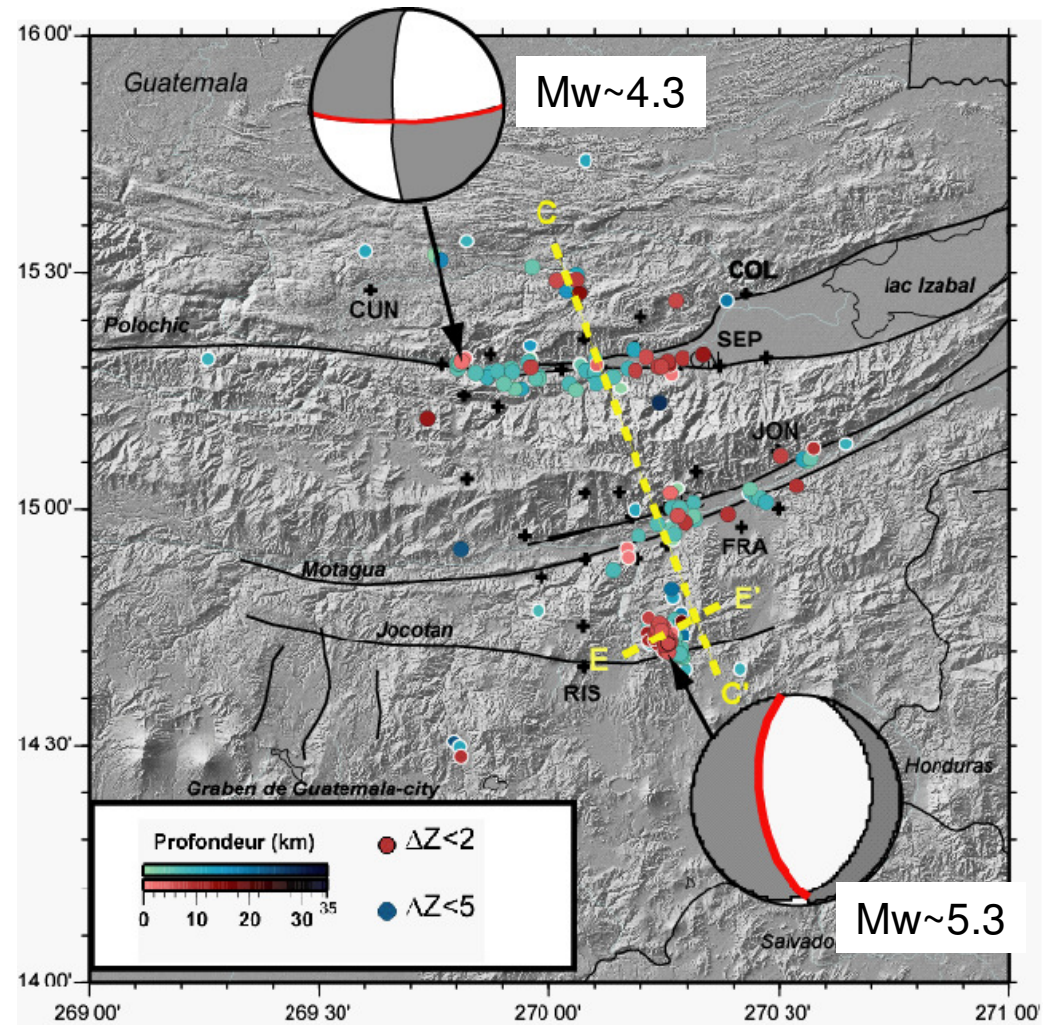
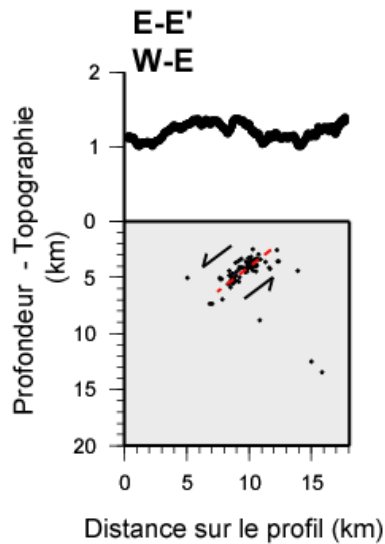
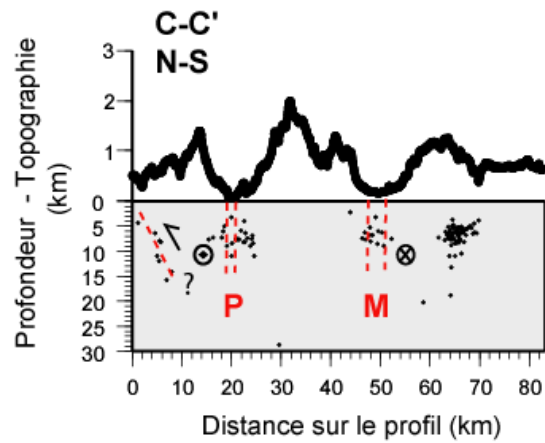
1992-2003 seismicity of Guatemala (from Insivumeh)

# 3 - Seismological study

- 6 months experiment
- 30 recording stations
- Seismicity and structure

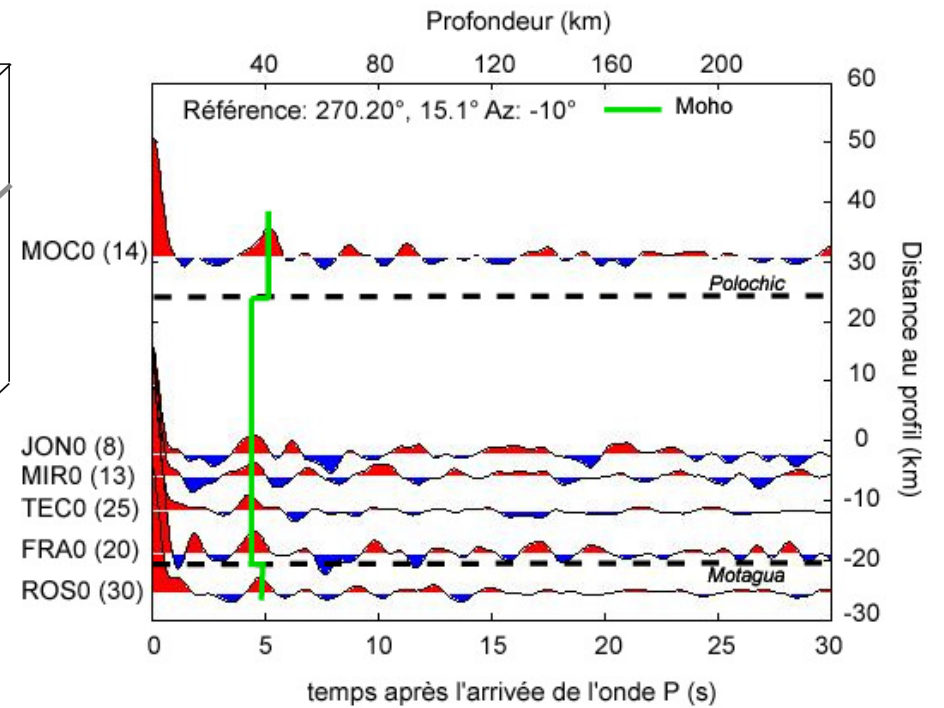
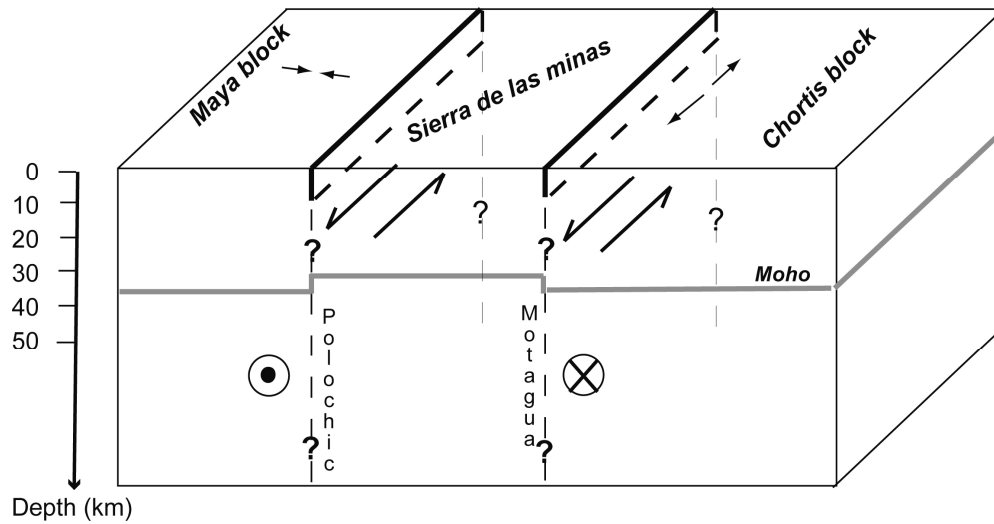
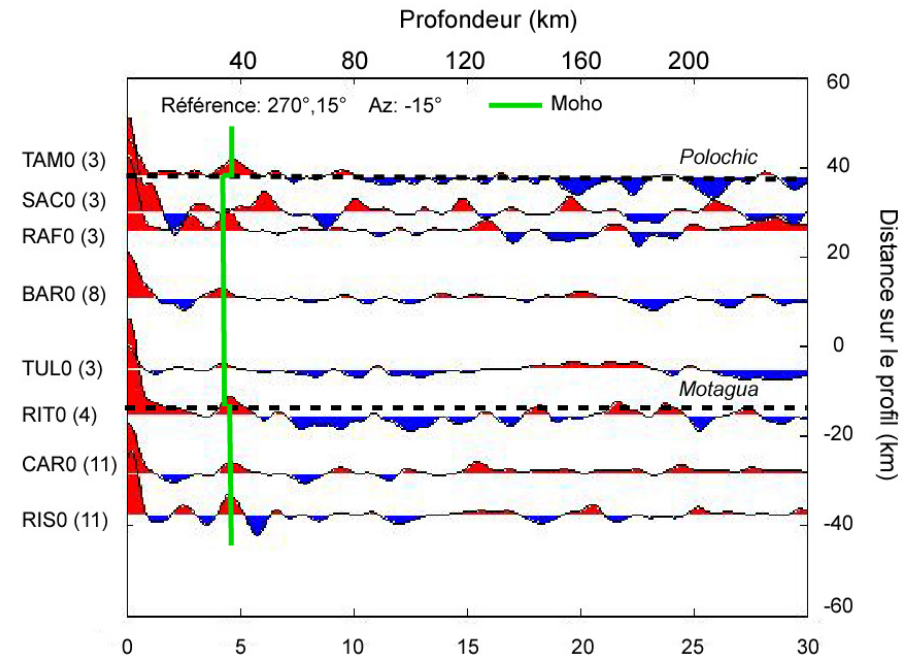
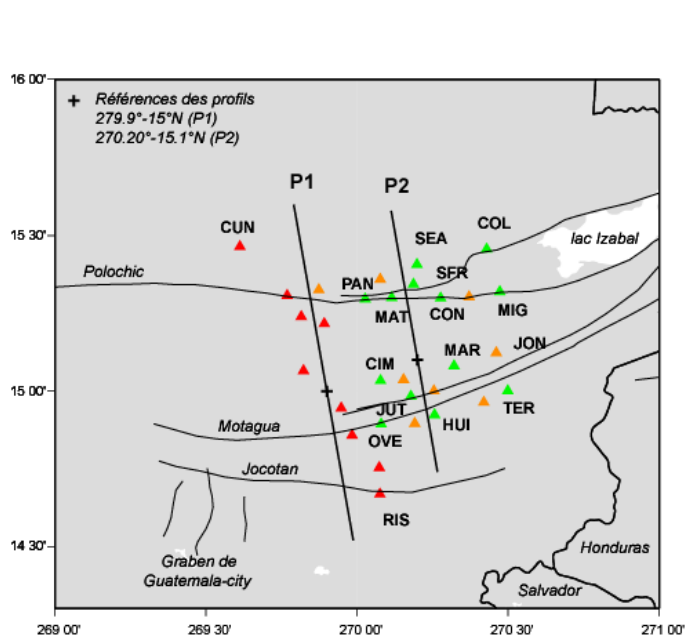






- Event depths < 15 km
- Localized mainly on Polochic and Motagua faults
- activity north of Polochic (thrusts in folds?) and south of Motagua (normal faulting)

(Franco et al., 2009)

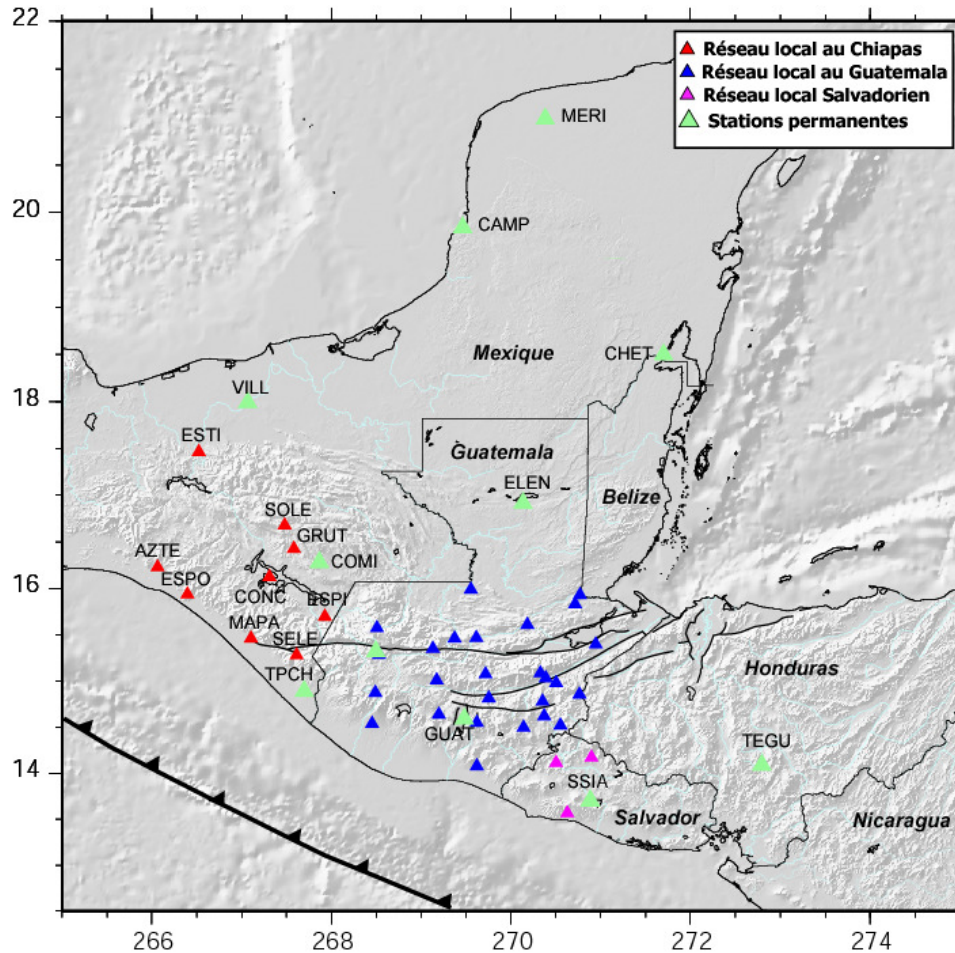


(Franco et al., 2009)

### 3 - Seismological study main results

- Seismogenic depth ~15 km
- Level of seismicity relatively low
- Strike slip activity on both Polochic and Motagua
- Some thrusting north of Polochic?
- Normal faulting just south of Motagua fault, Jocotan fault likely not active anymore
  
- Moho depth contrast across both Polochic and Motagua fault ~5 km

## 4 - Geodetic study of the Polochic-Motagua fault system



### GPS Observations :

**Guatemala** : 1999-2003-2006 (*ENS, P6, Guatemala*)

**Salvador** 2003-2006 (*IGN*)

**Chiapas** 2002, 2003, 2004, 2005 (*UNAM*)

*Total: 34 sites (23 Guatemala, 3 Salvador, 8 Chiapas) measured at least twice in 3 years.*

**Permanent stations**

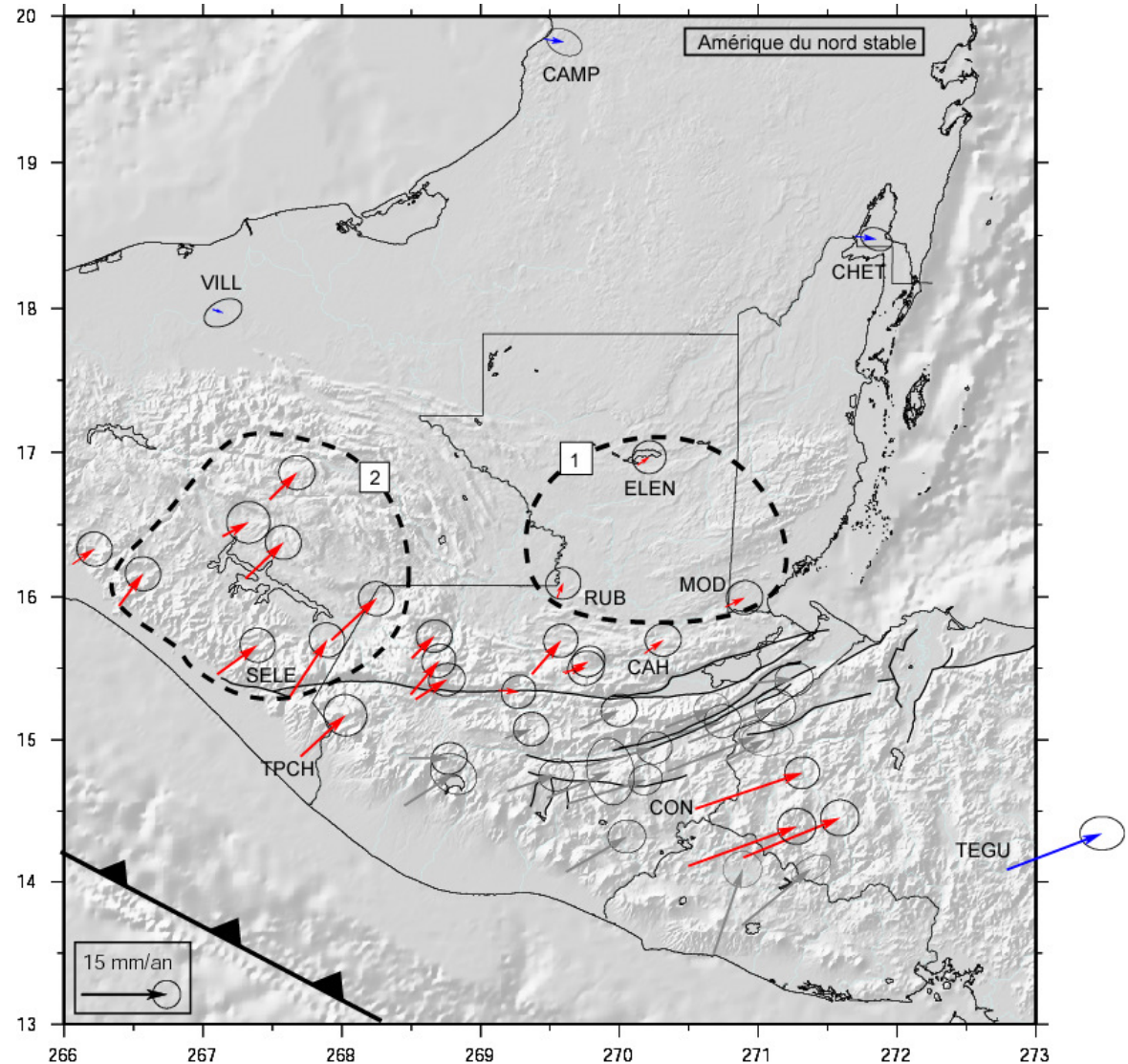
Separate processing of the 3 GPS sub-networks (GAMIT/GLOBK)  
then a combine solution

## 4 - GPS results

### Velocity field in the North American reference frame

NA/ITRF00 Pole : *DeMets et al., 2007*

- 1) Sites with low velocities belong to the stable North American plate
- 2) Motion perpendicular to the central american trench in Chiapas  
=> coupling of the subducting Cocos plate with NA plate
- 3) Left-lateral motion across the Polochic-Motagua fault system



# Velocity field in the Caribbean reference frame

CA/ITRF00 Pole :

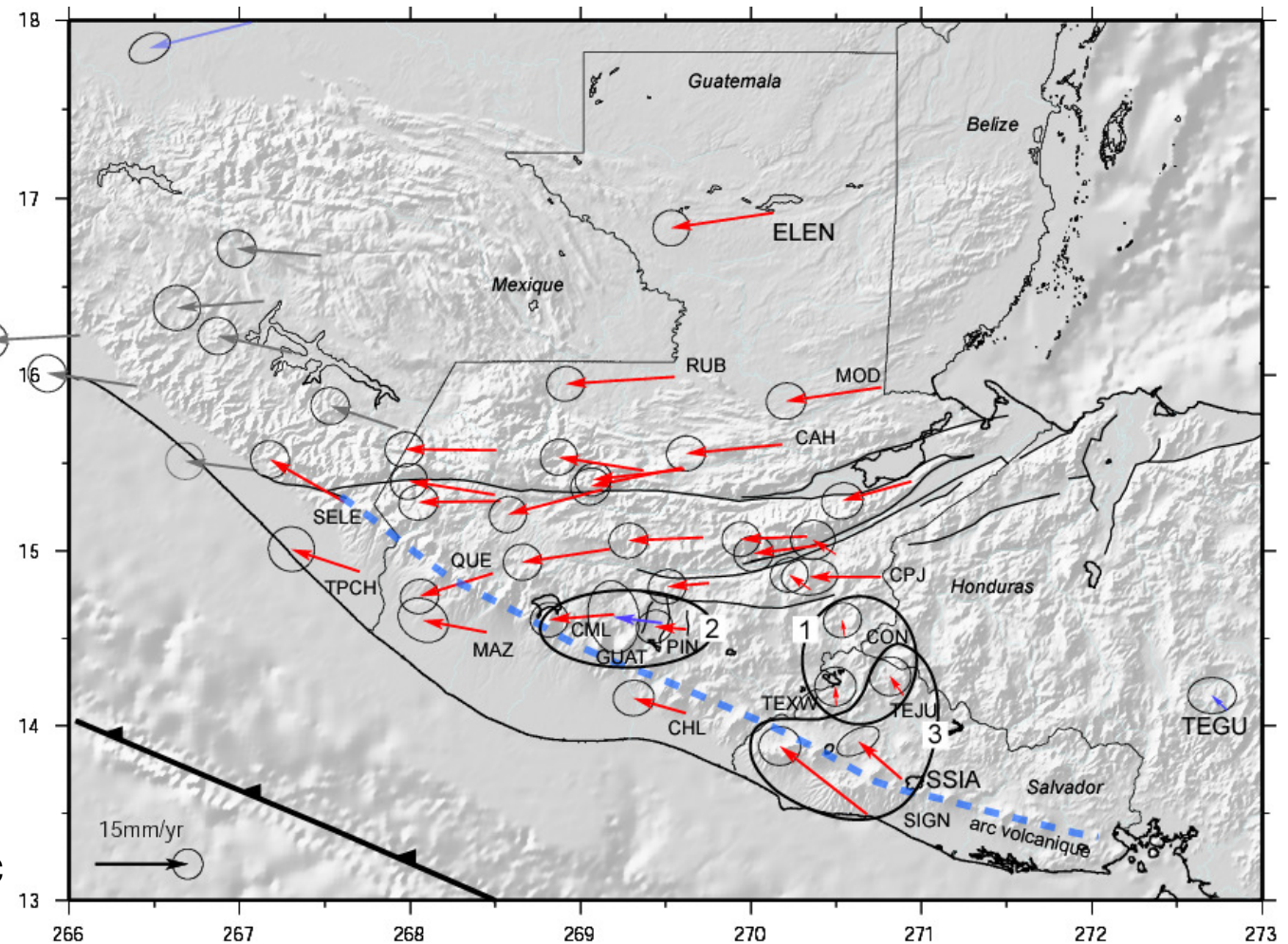
*DeMets et al., 2006*

1) Sites with low velocity belong to the stable Caribbean plate

=> Velocity CA/NA (ELEN-CON) ~ **20 mm.yr<sup>-1</sup>**

2) Internal deformation across the grabens

3) Right-lateral motion across the volcanic arc



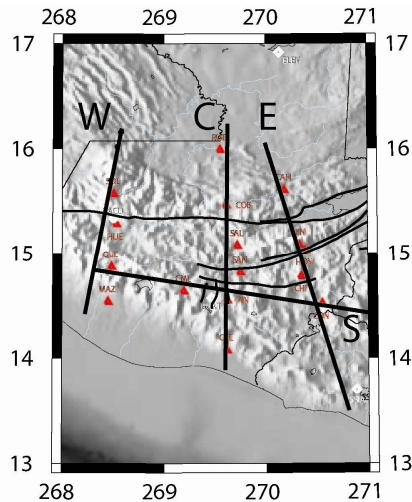
=> Kinematic analysis with fault-parallel and fault-perpendicular velocity profiles

=> Regional block model

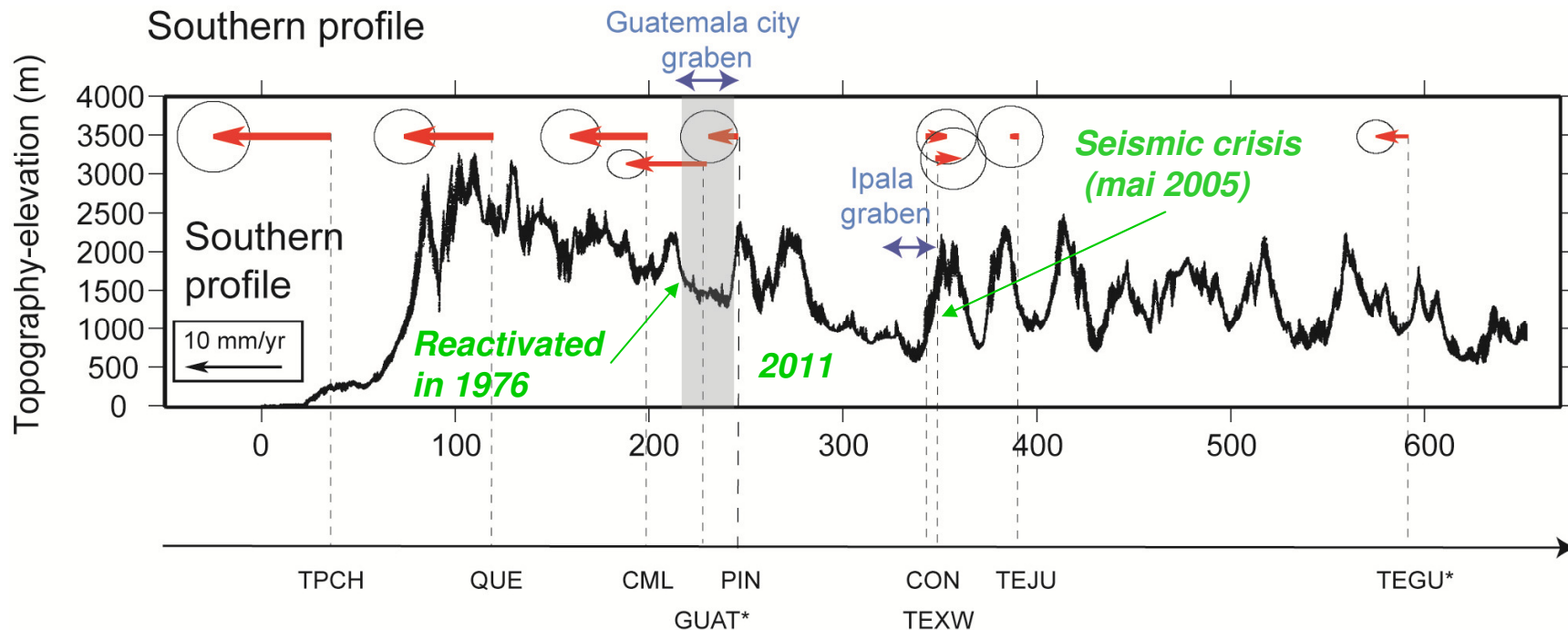
*Franco et al., in prep)*

## 5 - Velocity profiles analysis

### E-W extension across the grabens

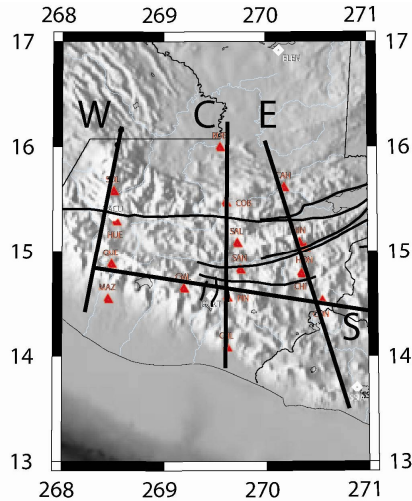


- $\sim 9 \text{ mm.yr}^{-1}$  (estimate of the extension rate)
- Extension mostly accommodated within the grabens of Guatemala-City ( $5 \pm 2 \text{ mm/yr}$ )
- Rodriguez et al. (2009) show that more extension is accommodated eastward in Honduras



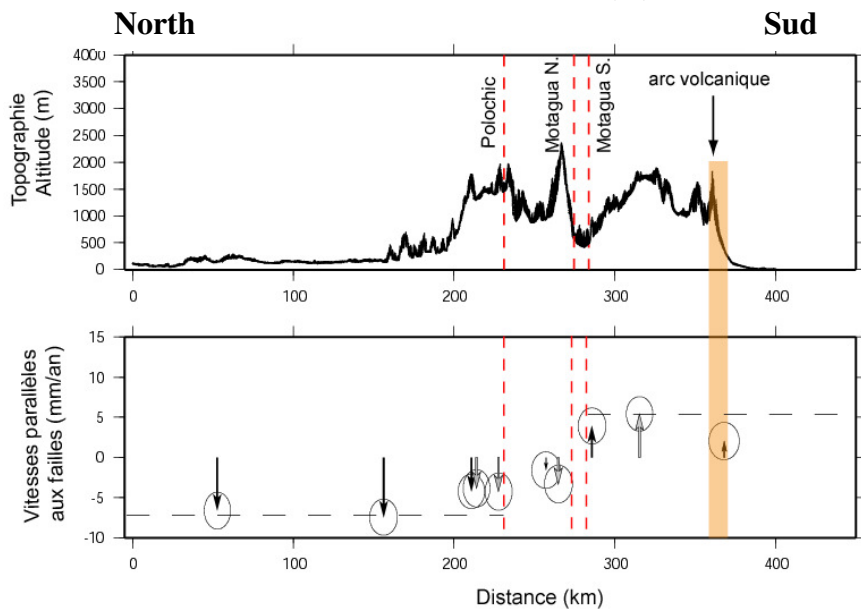
# 5 - Velocity profiles analysis

## Kinematics of the strike-slip faults

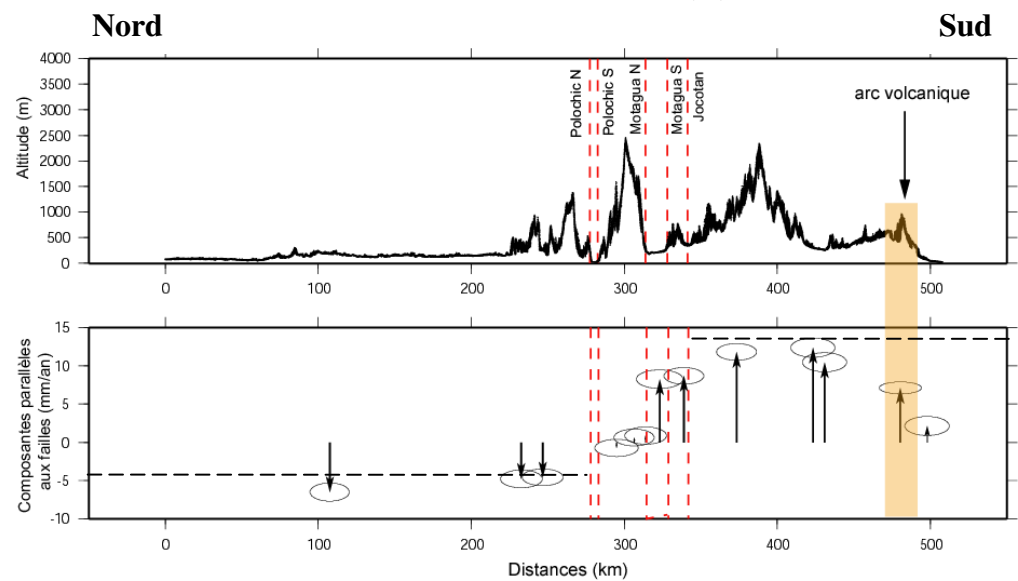


- East-West decrease of the velocity across the fault system
  - Right-lateral motion across the volcanic arc
- => Elastic modelling of a vertical fault in a semi-infinite half space

### Profil Central (C)



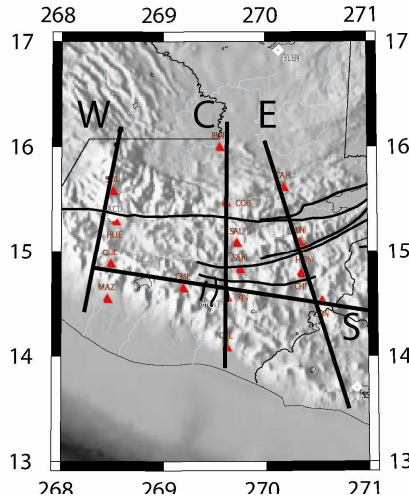
### Profile East (E)





# 5 - Velocity profiles analysis

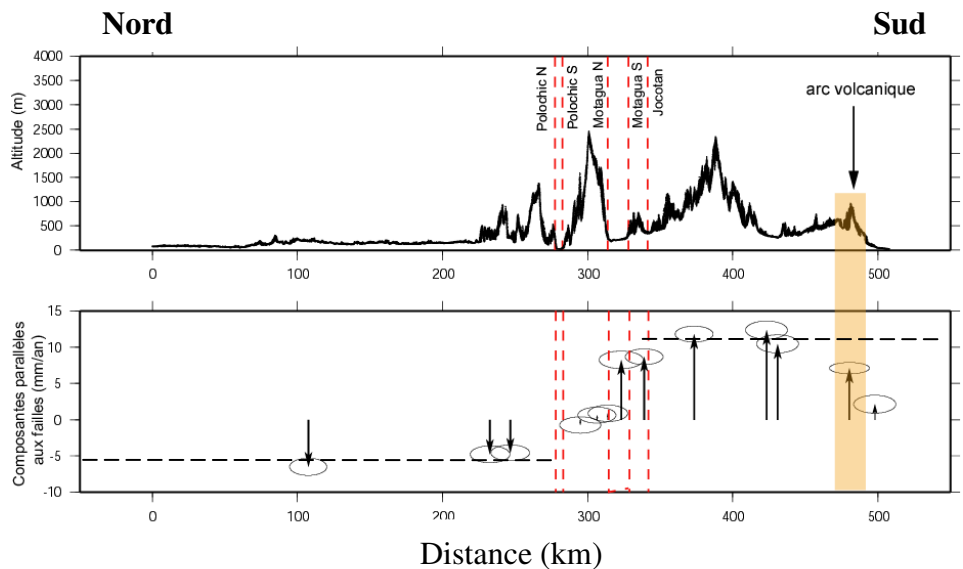
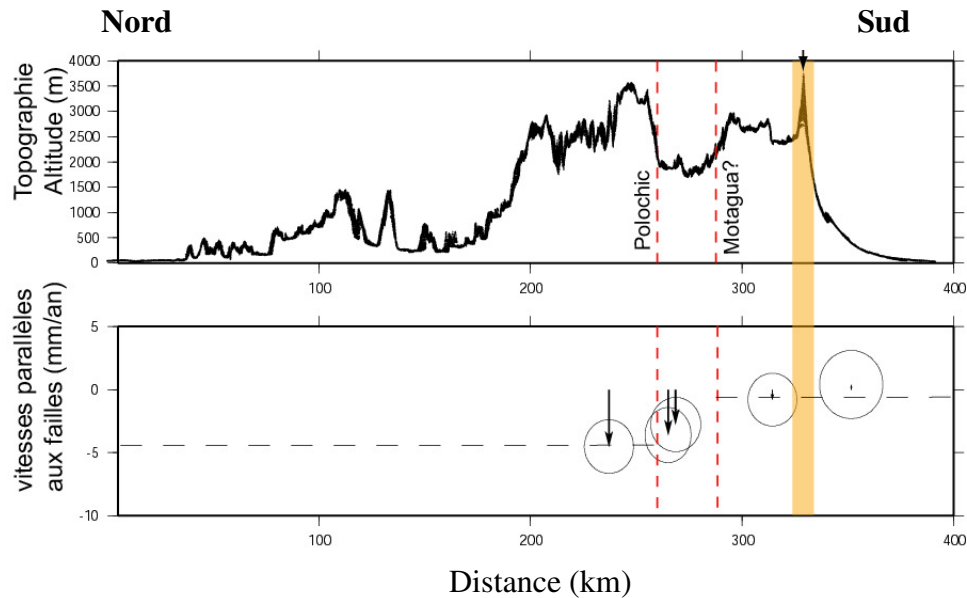
## Kinematics of the strike-slip faults



- East-West decrease of the velocity across the fault system
  - Right-lateral motion across the volcanic arc
- => Elastic modelling of a vertical fault in a semi-infinite half space

Profile West (W)

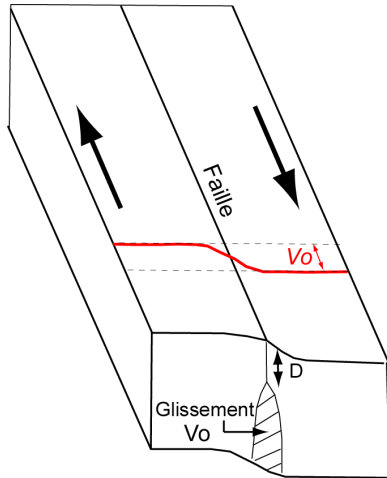
Profile East (E)



# 5 - Velocity profiles analysis

## Elastic model with 1 fault

Example for Profile East : Velocity profile and fit



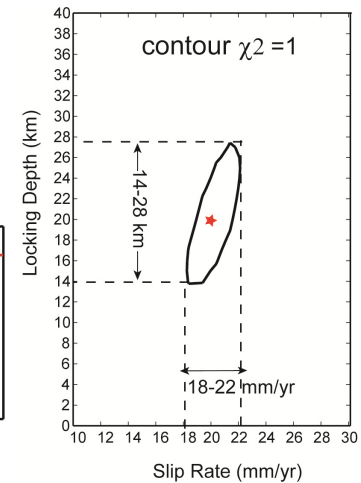
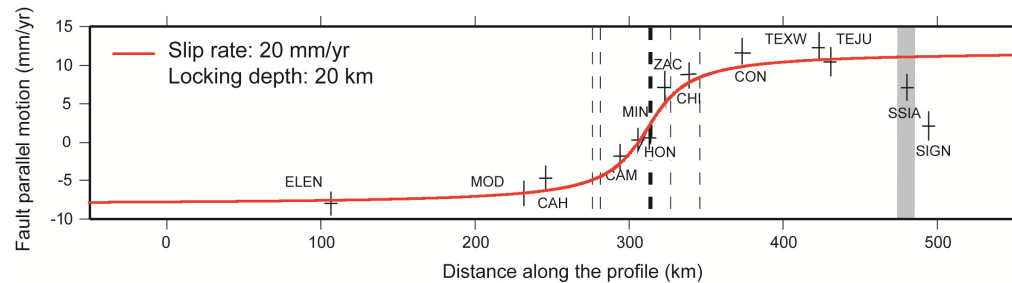
Parameters:  
D, locking depth  
V, far field velocity

$$V = \frac{V_{mot}}{\pi} \arctan\left(\frac{X-X_0}{D_{mot}}\right) + A$$

Profile East:  
**D<sub>mot</sub> = 20km**  
**V<sub>mot</sub> = 20mm.yr<sup>-1</sup>**

Profile Central:  
**D<sub>mot</sub> = 20km**  
**V<sub>mot</sub> = 16mm.yr<sup>-1</sup>**

Profil West:  
**V<sub>mot</sub> = 4mm.yr<sup>-1</sup> ?**



-The deformation is concentrated across the Motagua fault.

- What is the contribution of the Polochic fault?  
 < 15% from a 2 faults model.

## 6 - Towards a regional kinematic model of the deformation

### - Previous analysis:

- Simple characterizing of the different types of deformation
- Gives first order magnitude of these deformations

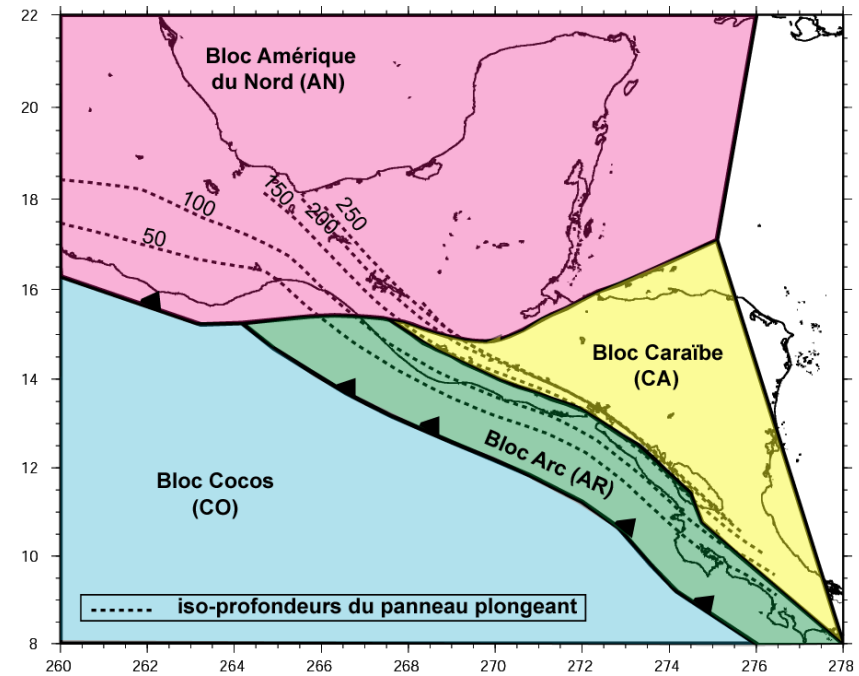
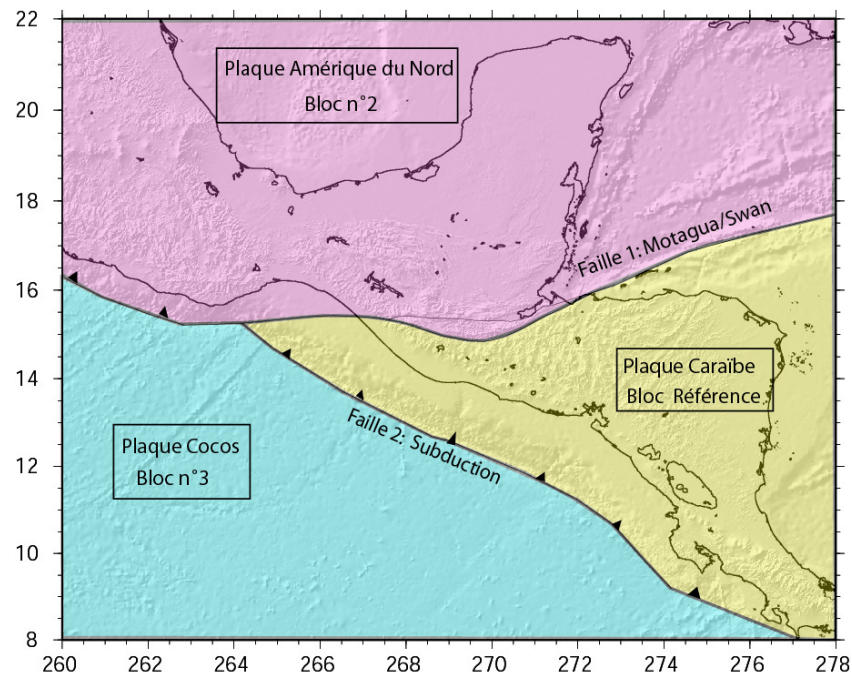
However : Block rotations and the complex geometry of the structures are not taken into account.

### - Regional block model:

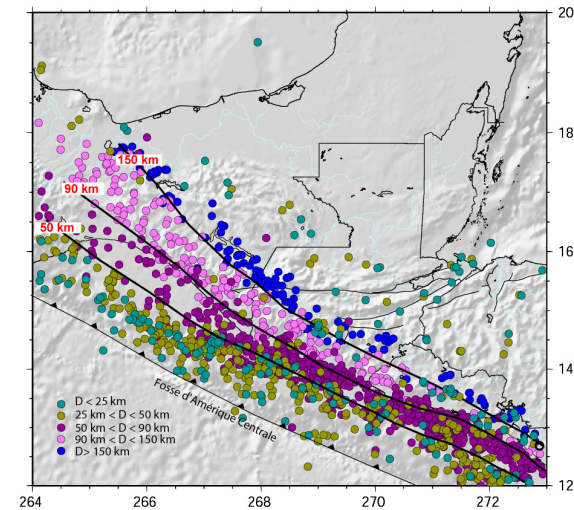
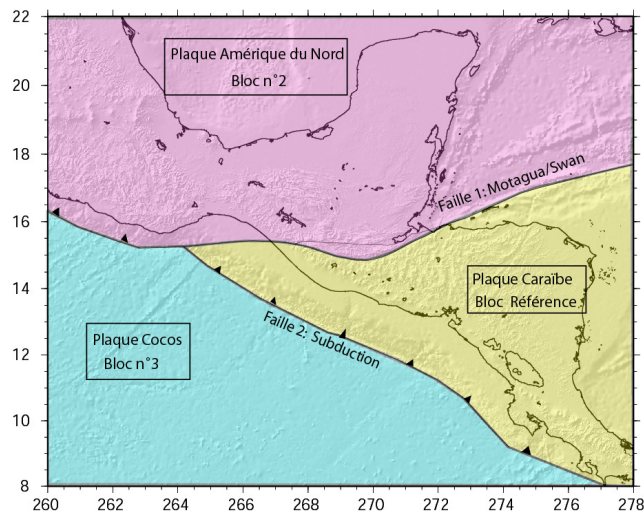
- Realistic geometry of the structures
- Interactions between rigid blocks motion + deformation localized on the different structures
- Volcanic arc, coupling along the subduction zone

# Regional model : DEFNODE (McCaffrey, 2002)

- Kinematics at a large scale : Rotation of rigid blocks
- Localized deformation at the blocks boundaries (faults with coupling parameters)



# Geometry and parameters of the model



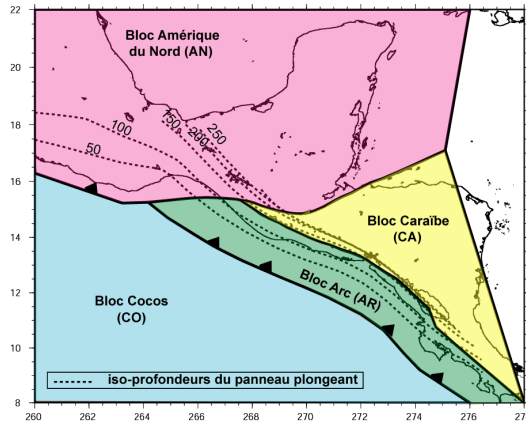
- **Geometry** : 3 blocks (NA, CO, CA) and 2 faults (Motagua, Subduction) minimum; geometry of the subduction zone defined from Engdhal seismicity (1998)

- **Parameters** :

- Poles and rotation velocities of blocks CO/CA and NA/CA are fixed (*DeMets et al., 2007*)
- Far field velocity  $V_0$  is fixed
- Coupling  $\Phi$  is inverted for each node defining the geometry of the faults at depth.
- For each node :  $V = V_0(1 - \Phi)$

=> **Coupling on the Motagua fault should decrease from east to west**

# Best 4 blocks model

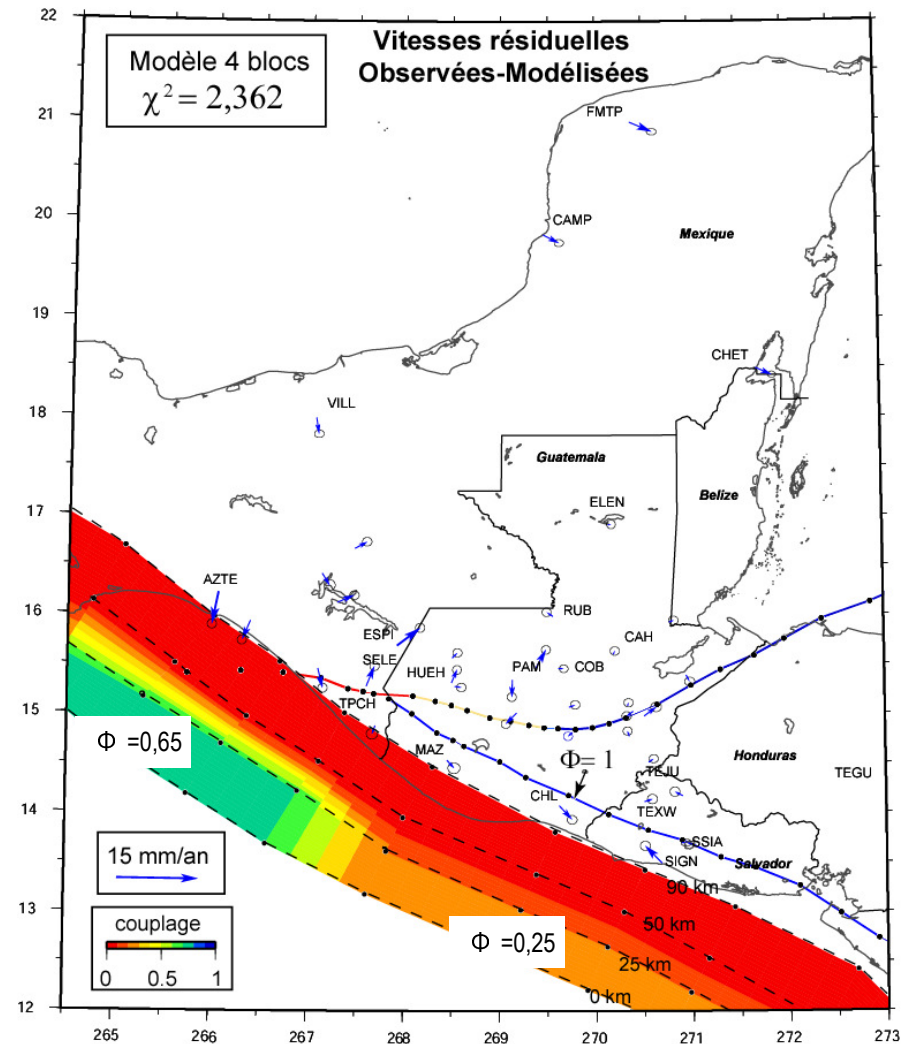


Fixed parameters : decreasing  $\Phi$  along the Motagua fault defined from a 3 blocks model, poles and rotation velocities NA/CA CO/CA

Inverted parameters:  $\Phi$  subduction,  $\Phi$  Central Am. fault, pole and velocity AR/CA (all correlated)

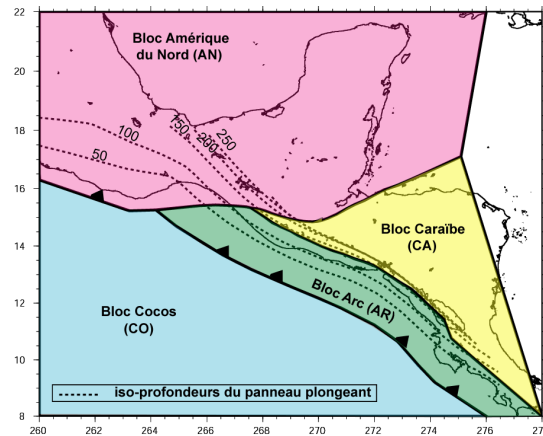
## Results:

- Most observations are explained (except for extension across the grabens) by a 4 blocks model
- Lateral variation of coupling along the Motagua fault and the subduction zone ( $CO/AR < CO/NA$ )



# Trade-offs in inverting parameters

- Pole and rotation velocity AR/CA
- Coupling at subduction subduction
- Coupling on the Volcanic America fault

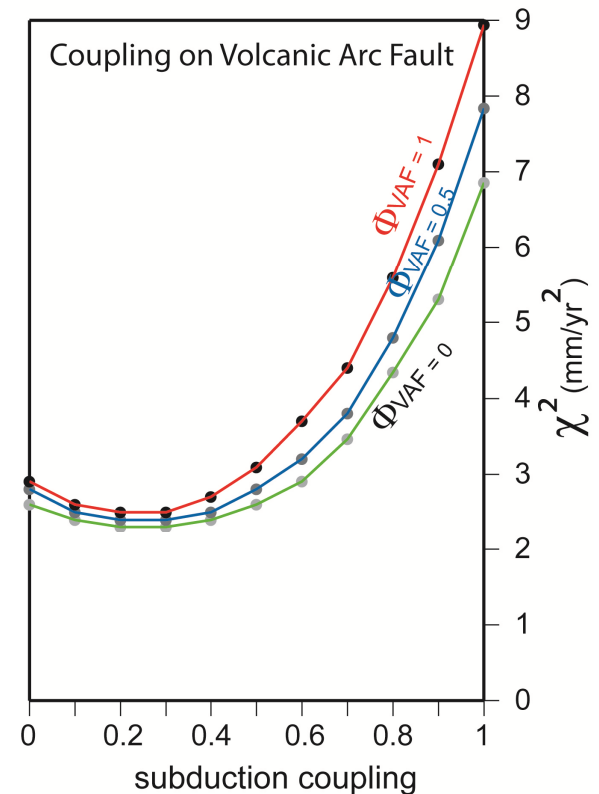


For all models: Coupling CO/AR between 0 and 40% with a minimum at 20%

(Correa-Mora et al., 2009 and Alvarado et al., 2011 : no coupling at all)

⇒ Lateral coupling variations CO/NA CO/AR

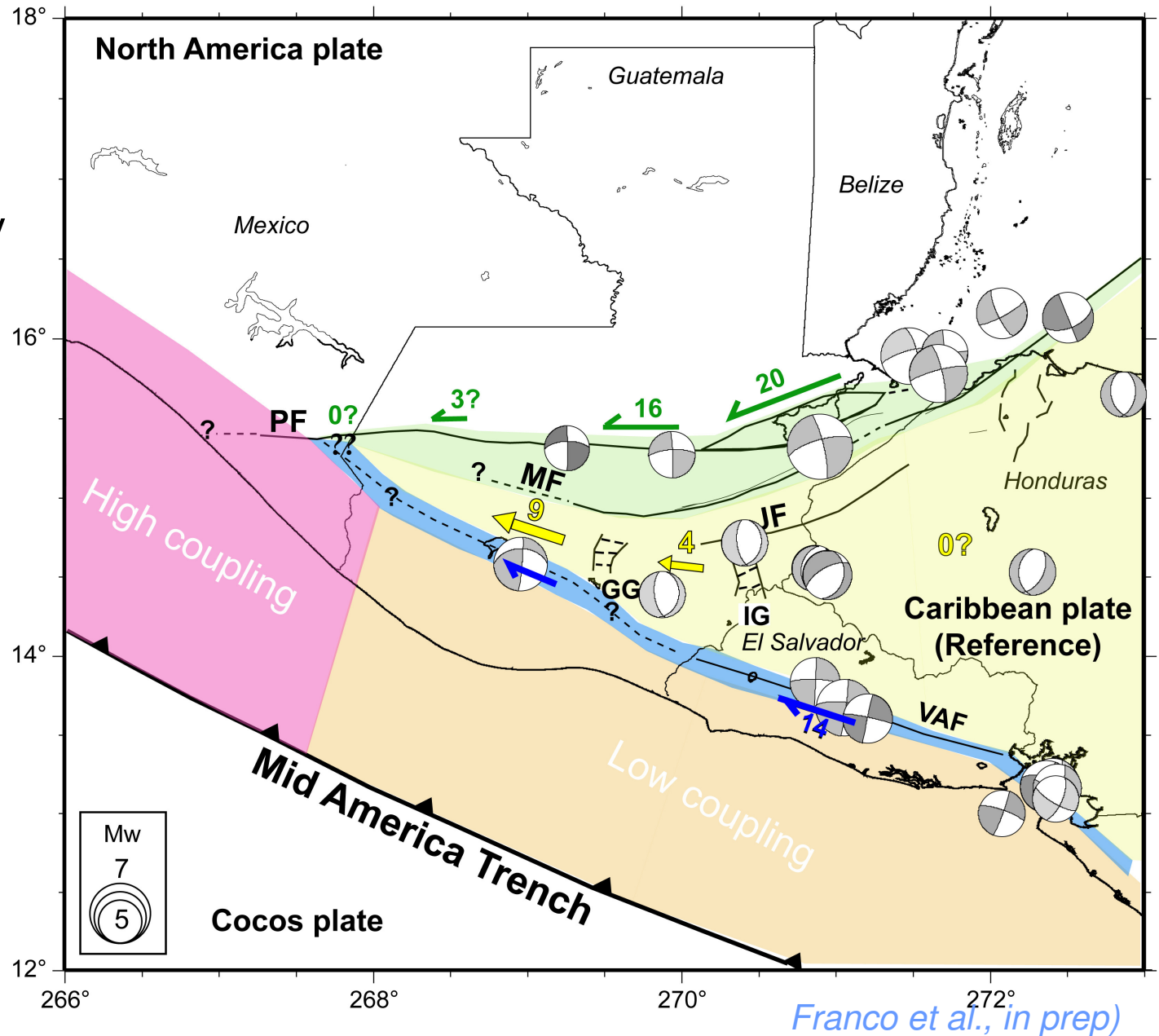
⇒ No possibility to constrain coupling on VAF



# 7 - Conclusions

## CA/NA velocity:

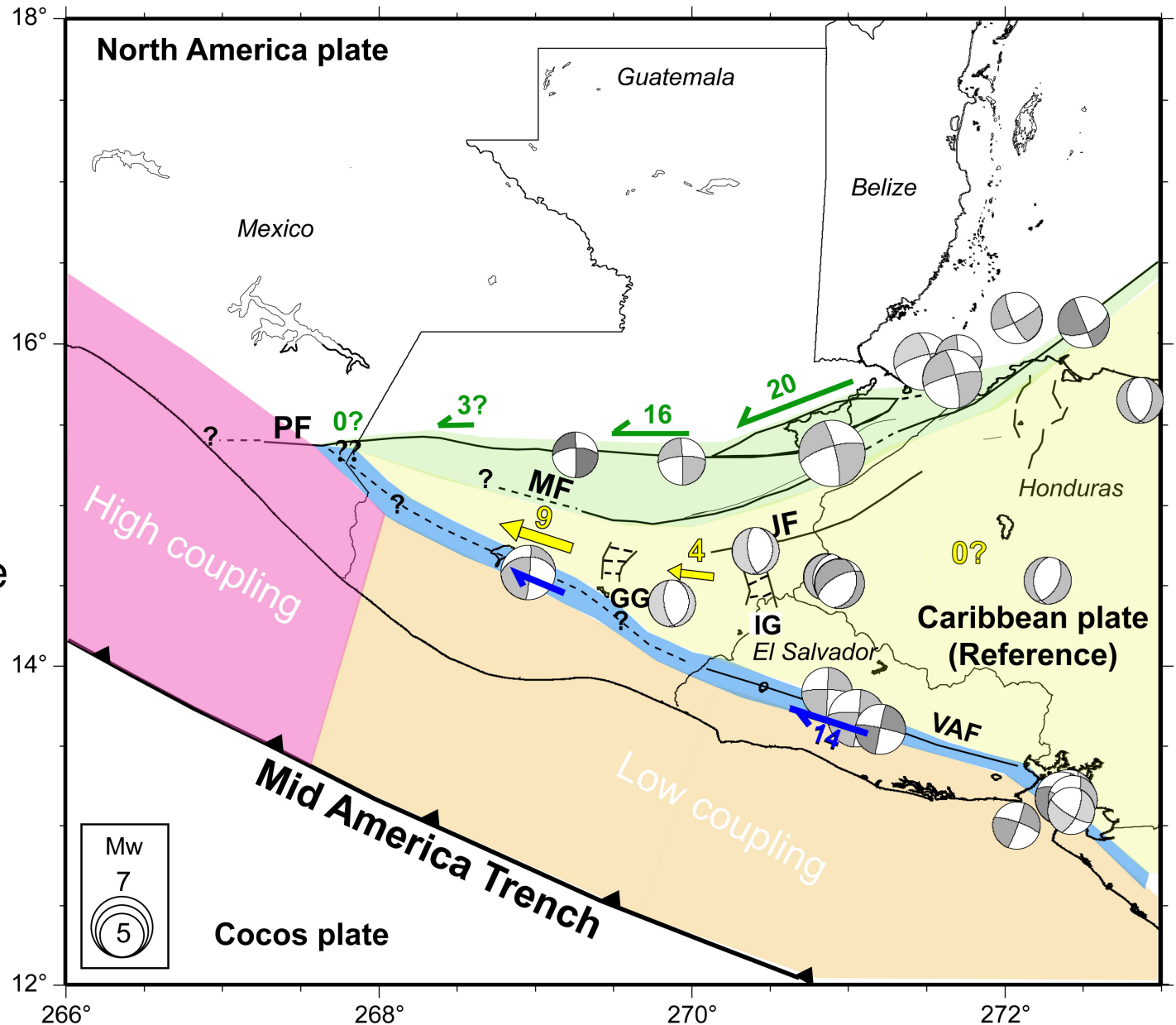
- The relative velocity CA/NA is estimated to be ~20mm/yr
- Consistent with previous estimates to the east (e.g. Dixon, 1998; DeMets, 2001; DeMets et al., 2007)





## 7 - Conclusions

- East-west decrease of the CA/NA velocity towards the triple junction
- Interseismic slip is localized below 20 km (~seismogenic thickness) and mainly under the Motagua fault (more than 85% of the deformation)
- The Polochic fault seems to accommodate a very small part of the deformation



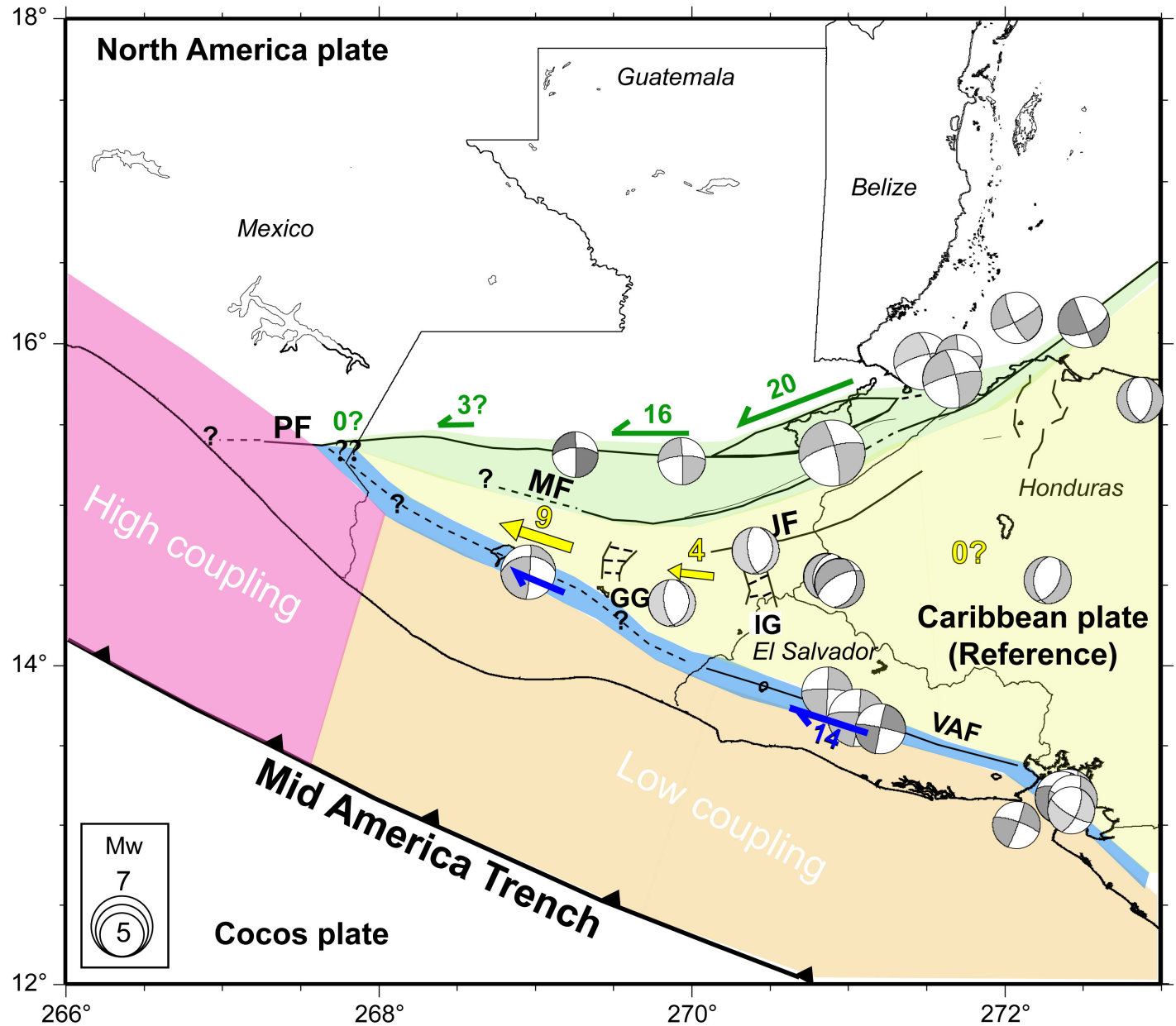
## 7 - Conclusions

- **East-west extension across the grabens**

- ~9mm/yr
- mostly partitioned across the Guatemala city and Ipala grabens

-The western tip of Caribbean plate is a zone of diffuse deformation

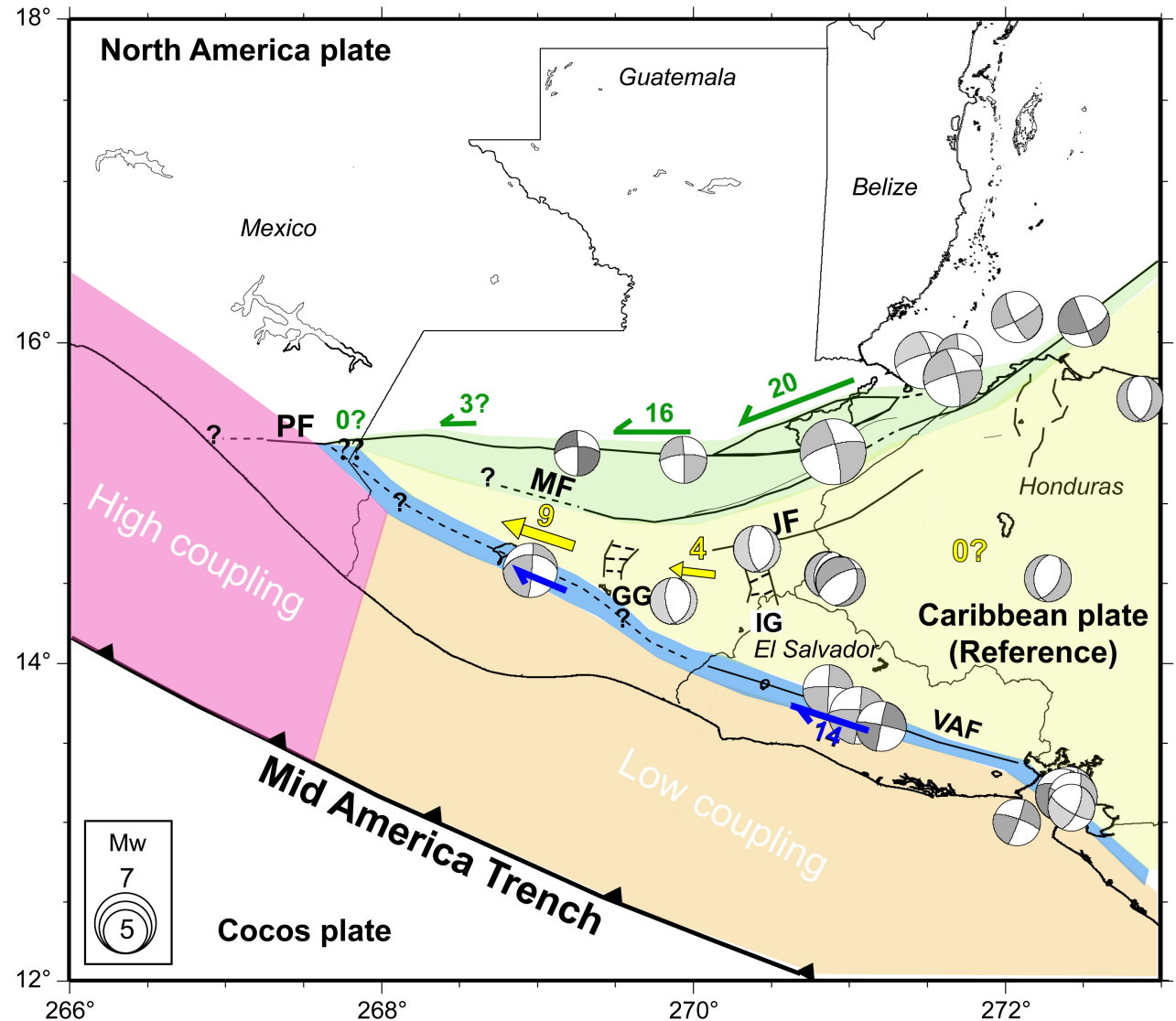
However somewhat different from *Rodriguez et al, 2009*



## 7 - Conclusions

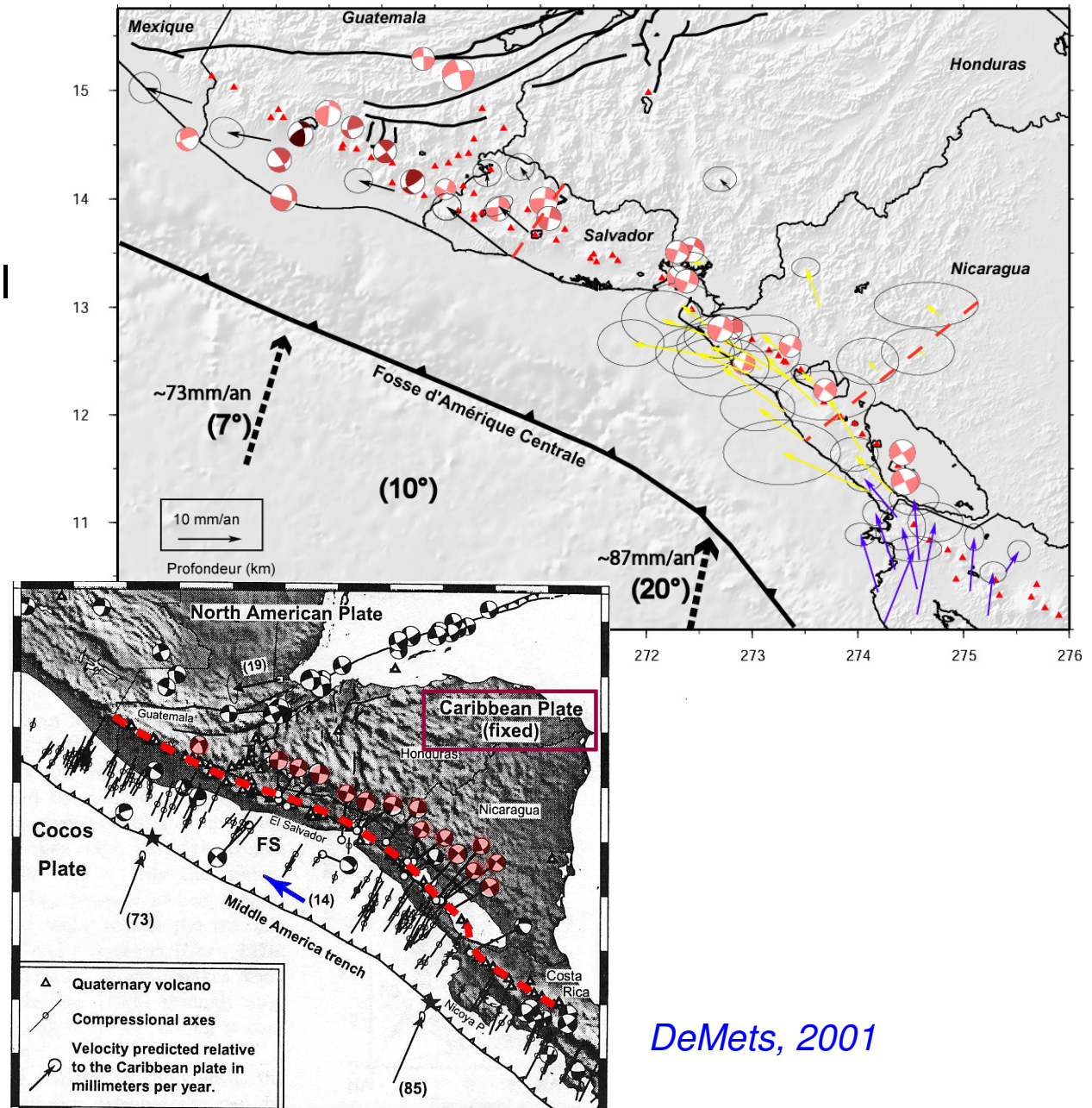
- **Right-lateral motion across the volcanic arc**
  - localized under a locked part of a fault?
  - Rotation of the arc micro-block?
  - slip rate has to decrease to the north

- **Lateral variations of coupling along the subduction (Chiapas/Guatemala/Salvador):**
  - Permanent?
  - Transients?
  - implications for seismic hazard, large subduction events? (*Correa-Mora, 2009, Pacheco et al, Alvarado et al., 2011*)



## Low coupling at subduction and active Volcanic Arc Fault:

- VAF has been related to subduction obliquity (e.g. DeMets, 2001)
- But obliquity is very small in Guatemala and El Salvador (e.g. Alvarado et al., 2011).
- In any case low coupling at subduction would not favor stress transmissions from the subducting plate to the upper plate
- LaFemina et al. (2011) suggest a mechanism: collision of Cocos Ridge



## 8. Open questions

### Onland faults:

- 20 mm/yr for NA/CA implies 1 Mw= 7.5 about every ~100 years in eastern Guatemala. Do we have enough events?  
Paleoseismological studies are incomplete (2 events seen on Motagua before 1976 but with old ages)
- Polochic fault: at present no apparent strain accumulation but the fault is clearly active with historical Mw~7.5 and clear morphology. Activity switch between Polochic and Motagua? , mechanism at depth ? The two faults are too far apart to join in the crust;
- VAF: is it fully locked or not? Known to generate Mw~6-6.5 events in El Salvador. Can larger events occur there? What about Guatemala?
- North-south grabens: active structures, with magnitudes 5.5 -6. larger events ?  
Guatemala City seats in a graben opening ~ 5 mm/yr !

## 8. Open questions

### **Subduction:**

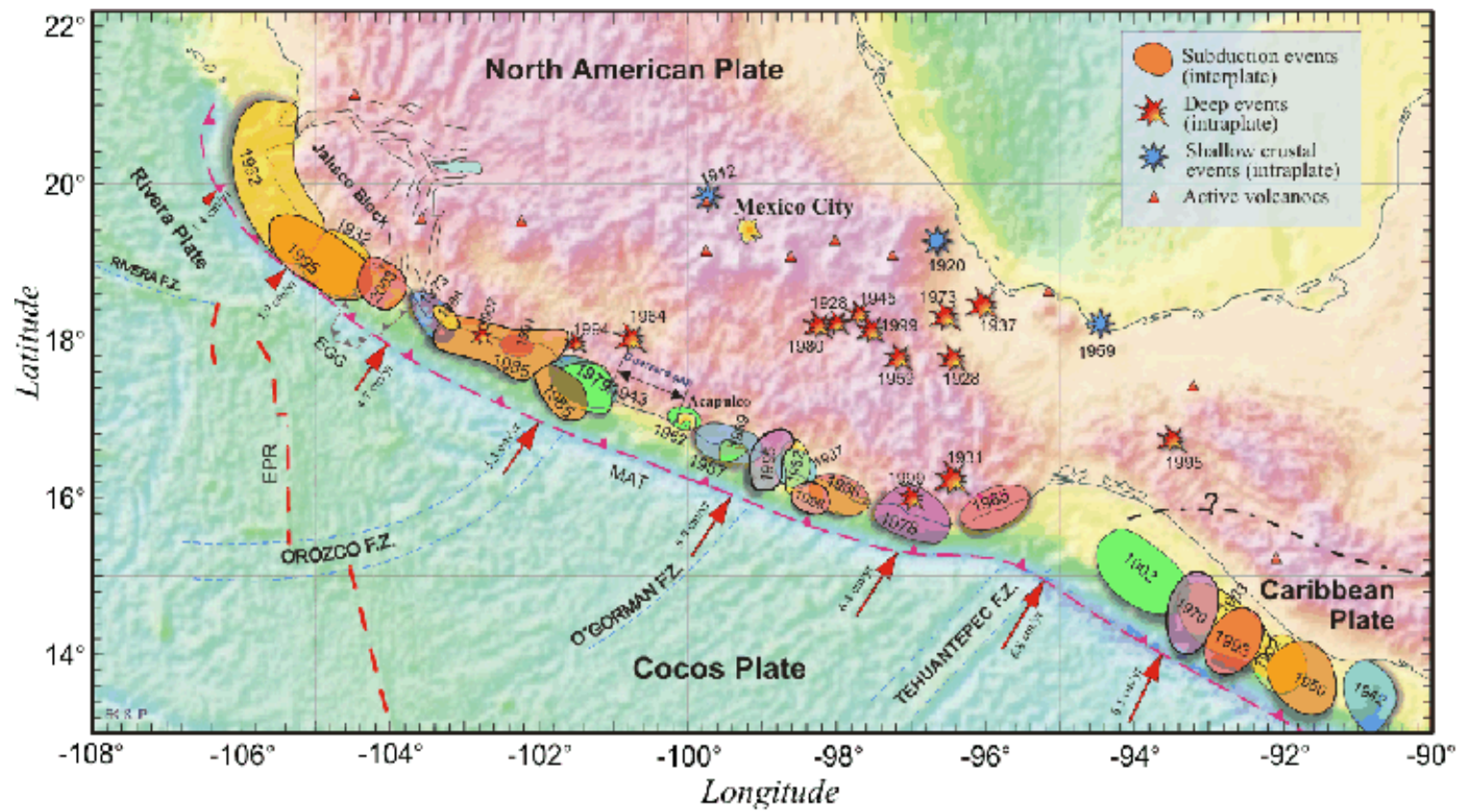
- Low coupling, what does it mean?

Large subduction events would not be expected however historical Mw 7.5 events are known (e.g. White et al., 2004). There does not seem to be any obvious difference between Chiapas, Guatemala and El Salvador in terms of historical seismic release at the subduction.

Can we well separate intermediate depths events and events on the subduction interface in the historical records?

GPS cannot well constrain coupling close to the trench.

Can the uppermost part of the subduction interface be coupled and generate large events?





**THANK YOU!**

