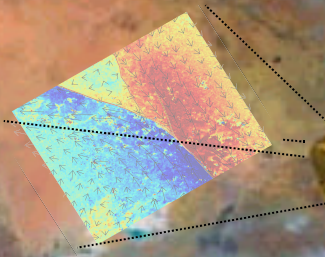




Mesure des Déformations Co-Sismiques par Imagerie Spatiale



- Introduction
- Méthodologie, performances et limitations
- Résultats

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Problèmes liés aux mesures de terrain



- Glissement distribué
 - Sous-estimation du glissement
- Absence de marqueur
 - Mauvaise géométrie de la faille
- Marqueur datant d'un séisme antérieur
 - Sur-estimation du glissement





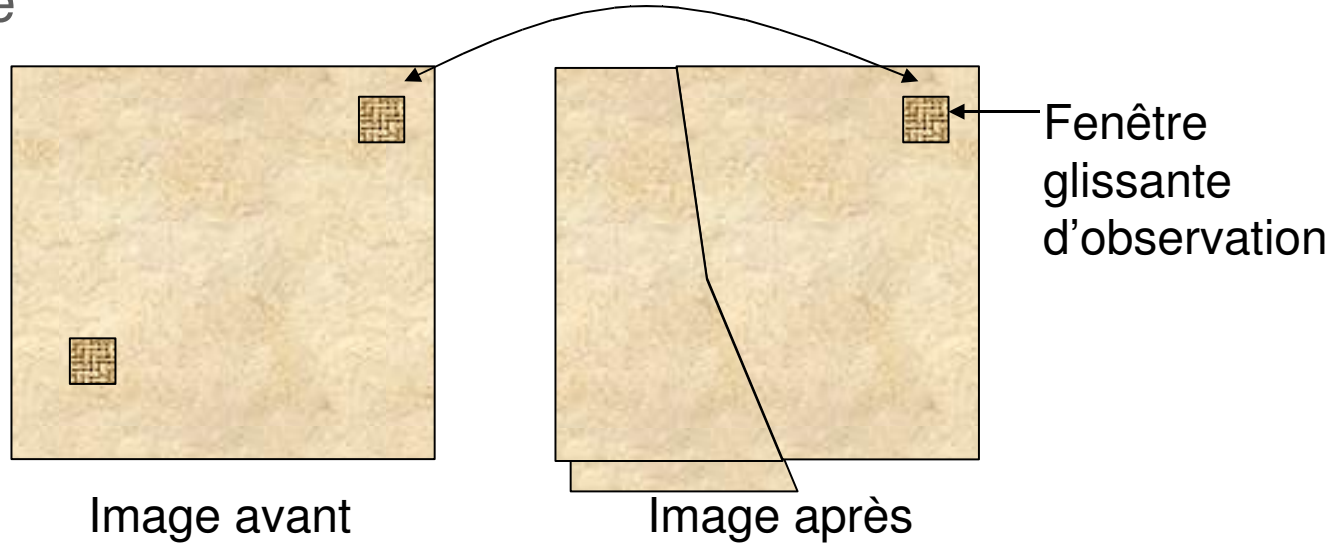
- Imagerie grand champ
- Comparaison de l'image de crise avec une image d'archive
 - Visible
 - Géomorphologie
 - Comparaison de la géométrie (déplacement horizontal)
 - Quantification des dégâts
 - Radar (InSAR)
 - Comparaison de la phase des images (déplacement plutôt vertical)
 - Comparaison de la géométrie (déplacement horizontal)
 - Mesure de la cohérence

Mesure d'un déplacement relatif intégré
sur plusieurs kilomètres

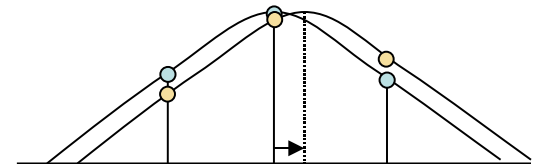
Principe de la mesure



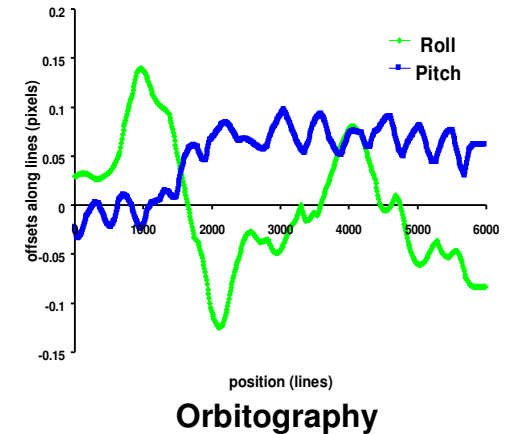
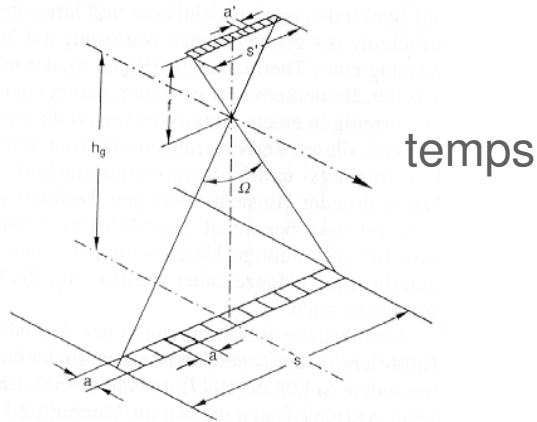
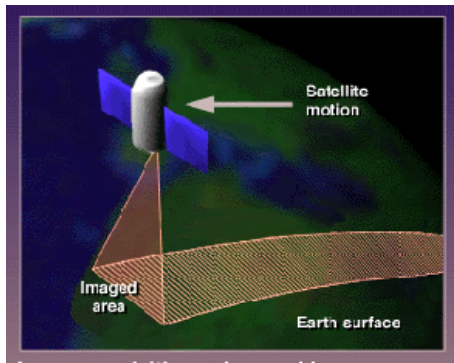
- Comparer la géométrie des images avant et après le séisme



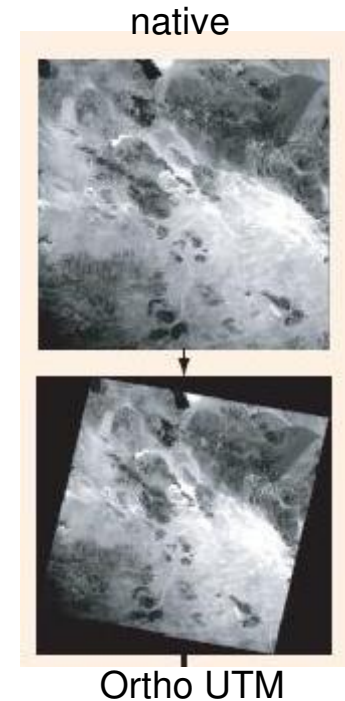
- Mise en géométrie commune
- Mesure de similarité des images basée sur la radiométrie
 - Mesure sub-pixel
 - Critères
 - Ressemblance des images
 - Qualité radiométrique
 - Richesse spectrale de l'image



Corrections géométriques des images pushbroom



- Géométrie native des images dépend de
 - Orbite et attitude (Roulis, Tangage, Lacet) du satellite
 - Géométrie du plan focal
 - Élévation terrain (MNT)
- Choix d'un référentiel géométrique commun
 - Orthorectification en UTM
 - Re-échantillonnage de l'image 2 dans la géométrie de l'image 1

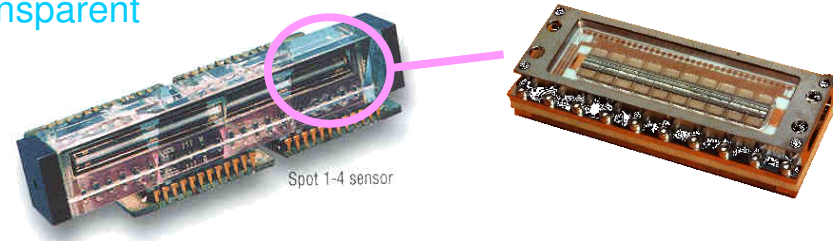
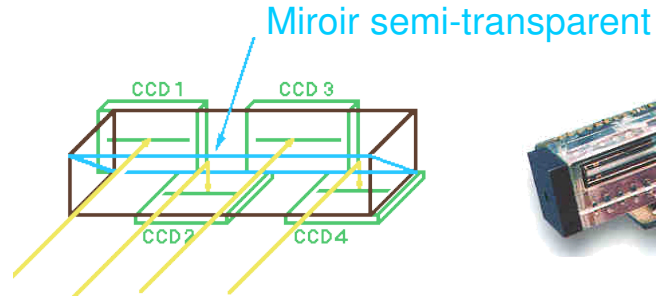


Plan focaux des systèmes SPOT

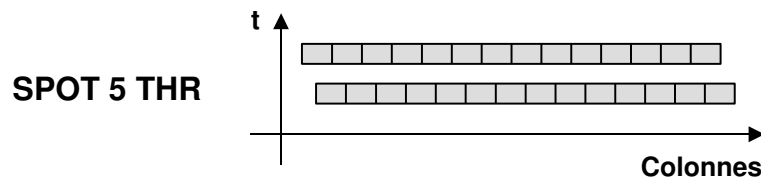
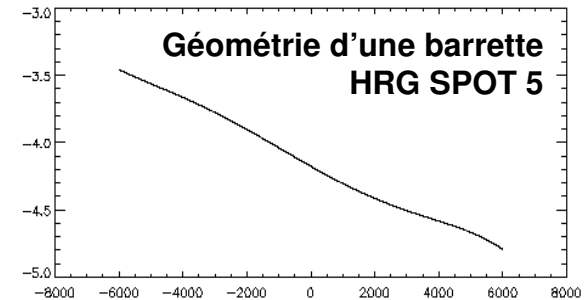
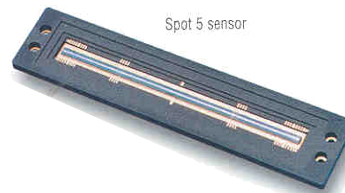


SPOT 1234 DIVOLI

Précision de calage des barrettes : 0.1 pixel



SPOT 5 HRG



$$5m + 5m = \sim 2.5m$$

2 barrettes HRG avec décalage de 0.5 pixel.

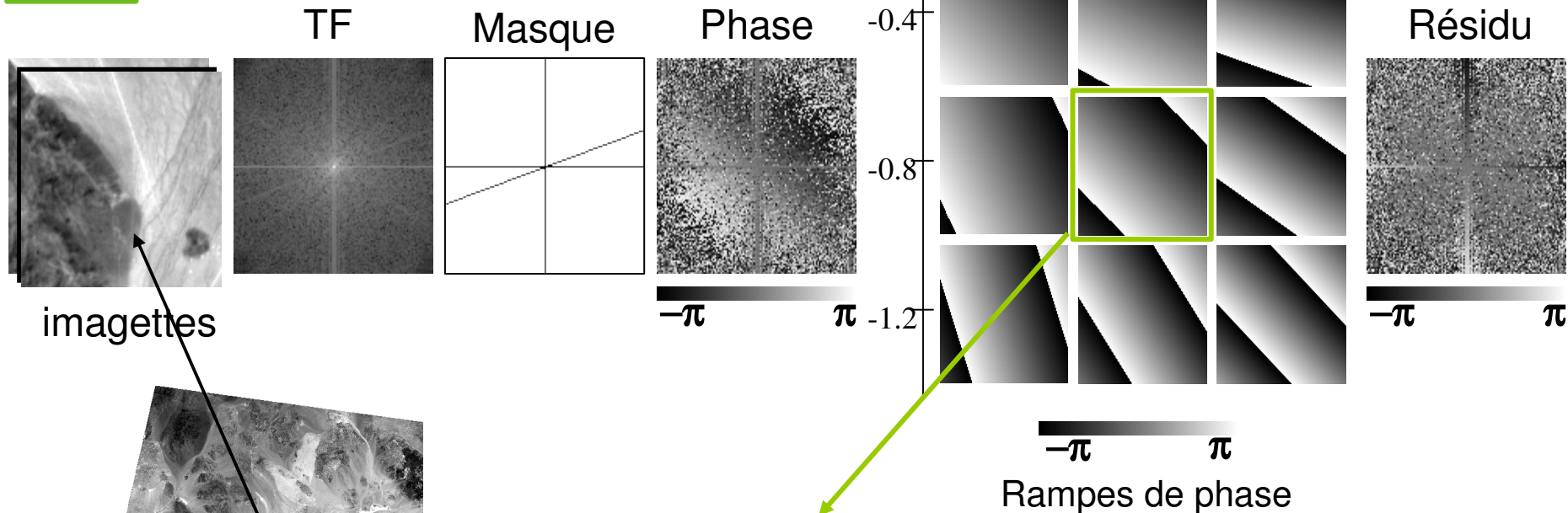
Échantillonnage idéal au sens de Shannon

Mesures de similarité par corrélation sub-pixel : principe



$$I_2(c, l) = I_1(c + u_0, l + v_0)$$

$$TF(I_2) = TF(I_1) \cdot e^{2i\pi(w_c u_0 + w_l v_0)}$$



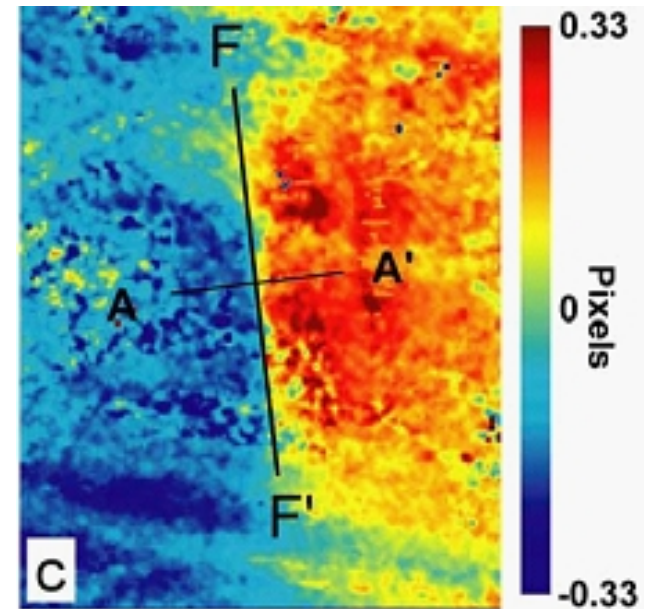
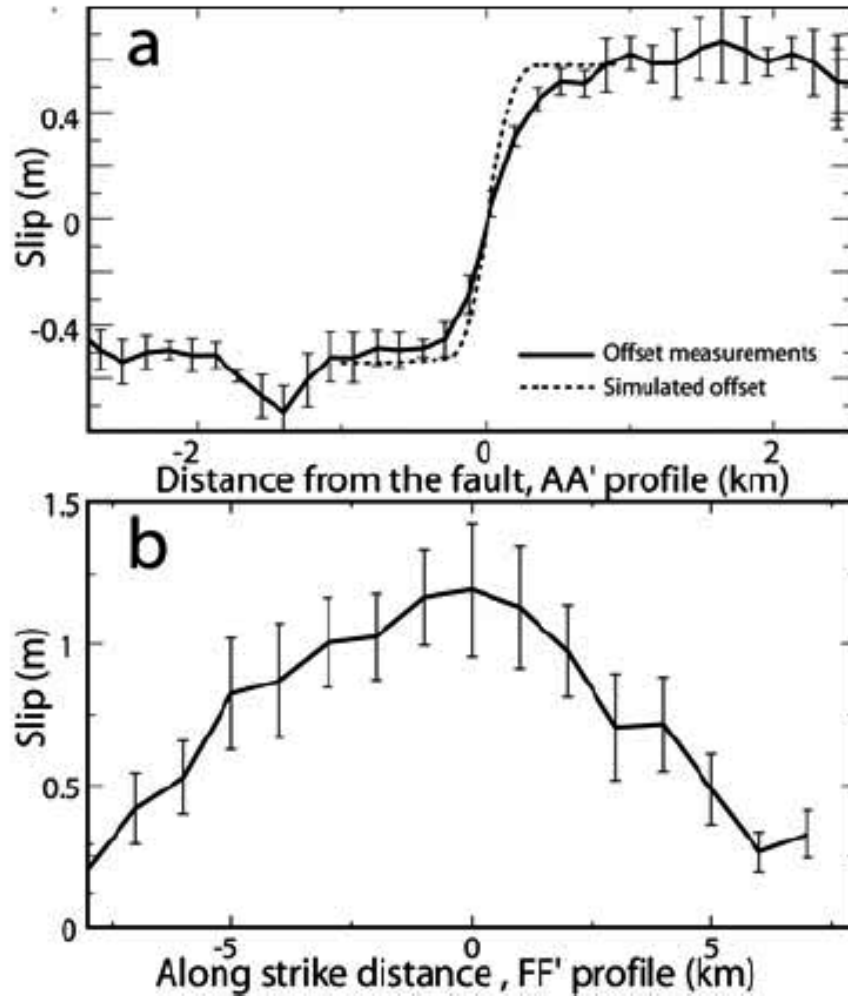
Meilleur modèle

$$(u, v) = \underset{(u_o, v_o)}{Arg} \left(\max \left| \sum_{mask} \exp[i\Phi] \cdot \exp[-2\pi i \cdot (w_c \cdot u_o + w_l \cdot v_o)] \right| \right)$$

$$snr = \left| \sum_{mask} \exp[i\Phi] \cdot \exp[-2\pi i \cdot (w_c \cdot u + w_l \cdot v)] \right|$$

Un exemple

- Séisme de BAM, Iran : $M_w=6.5$



Composante Nord-Sud

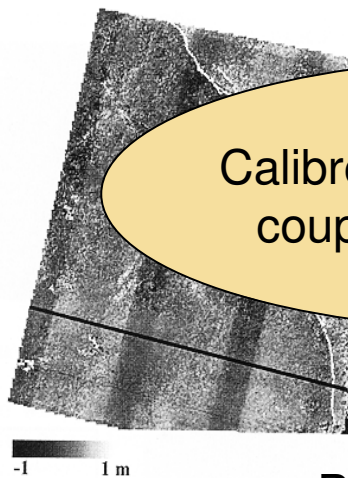
2 images SPOT5 THR

2.5 m de résolution

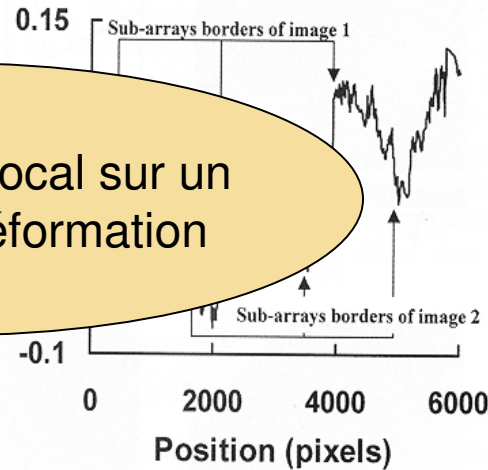
Faille invisible sur le terrain

Binet&Bollinger (2005), Horizontal coseismic deformation of the 2003 Bam (Iran) earthquake measured from SPOT-5 THR satellite imagery, Geophys. Res. Lett., 32, L02307.

Effets indésirables

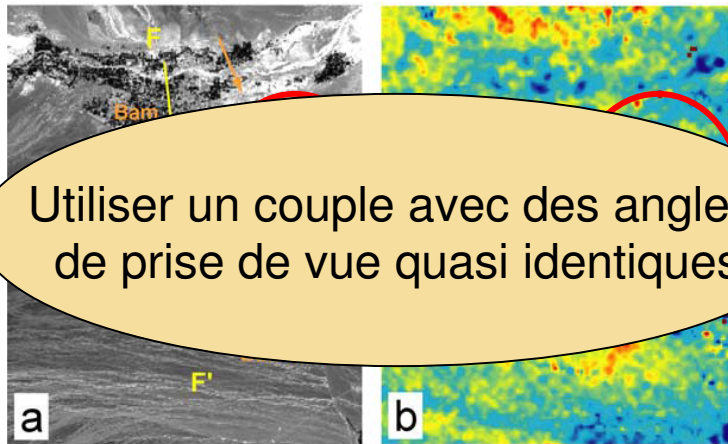


Calibrer le plan focal sur un couple sans déformation



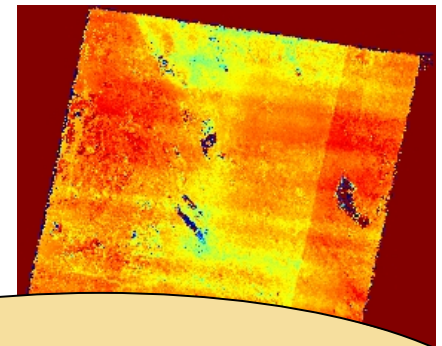
Décalage des barrettes mesuré sur l'image de disparité : ~ 0.1 pixel

Plan focal non corrigé

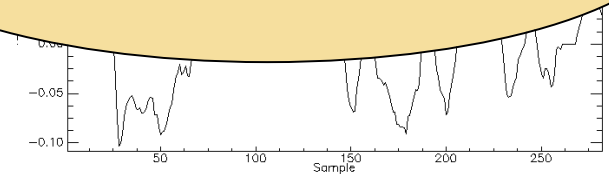


Utiliser un couple avec des angles de prise de vue quasi identiques

MNT non représentatif



Utiliser un modèle physique d'orthorectification

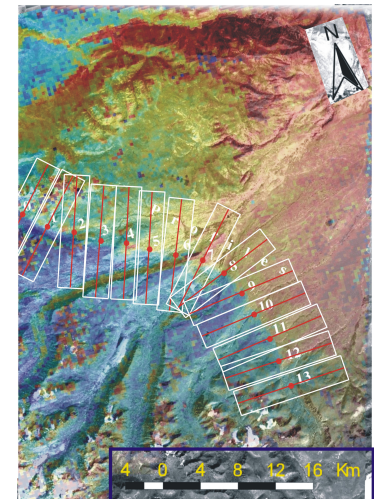
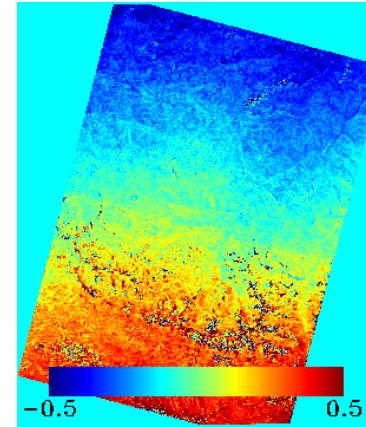


Microvibrations du satellite mal compensées

Limitations

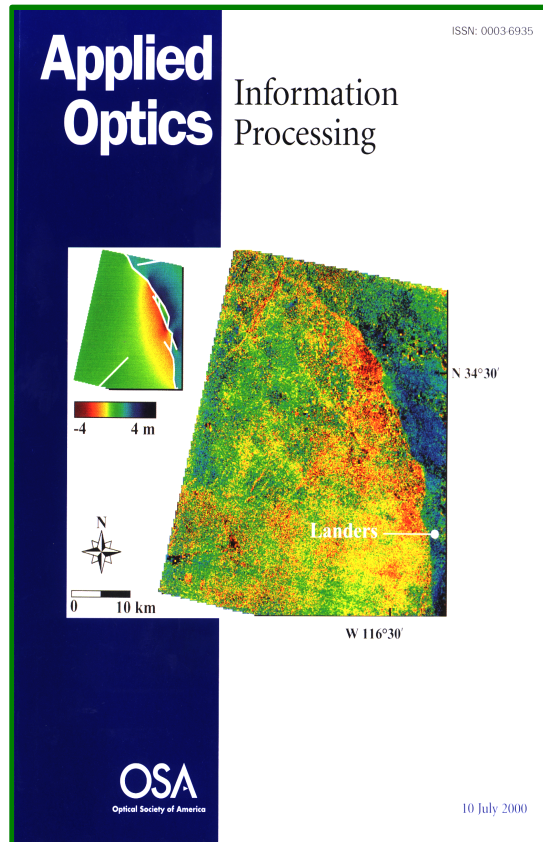


- Attitude du satellite mal contrainte :nécessite d'optimiser la prise de vue (Roulis, Tangage, Lacet, + dérives temporelles) à l'aide de points d'amers
 - Biais basses fréquences (plan)
 - Mesure du glissement non affecté mais inversion du mécanisme au foyer délicate
 - Complémentaire avec les mesures InSAR
- MNT imprécis
- Changements
 - Fenêtre de corrélation de taille adaptative
 - Corrélation = mesure de confiance
 - Stack des mesures
- Aliasing souvent présent dans les images
 - Biais sur mesure de corrélation (0.05 pixel max)



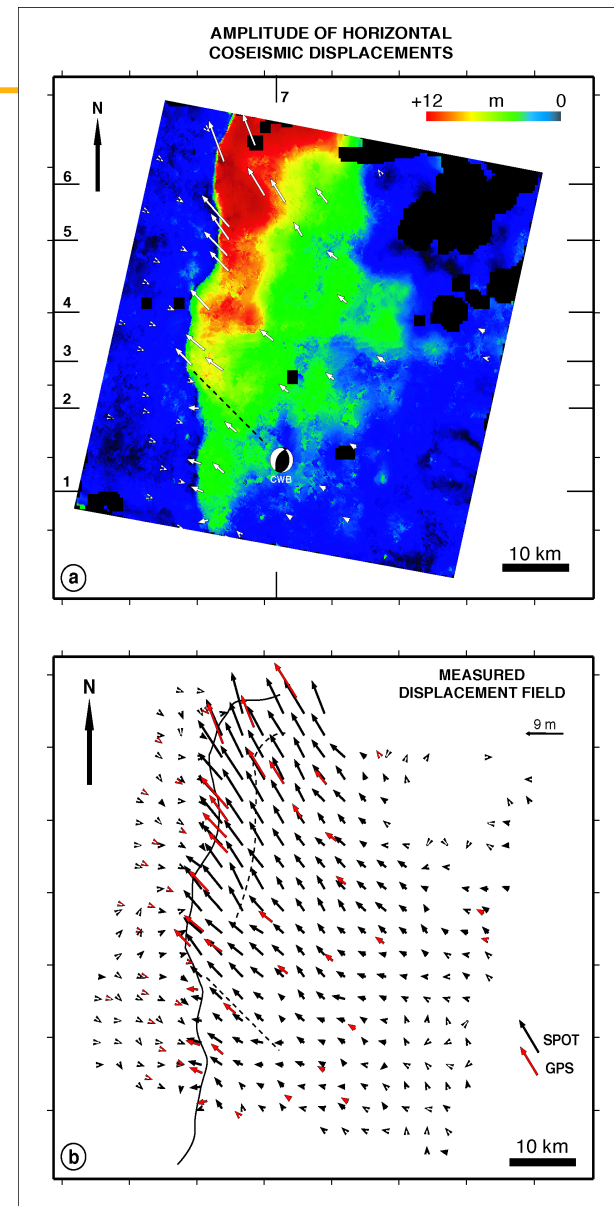


Quelques résultats ...



Landers

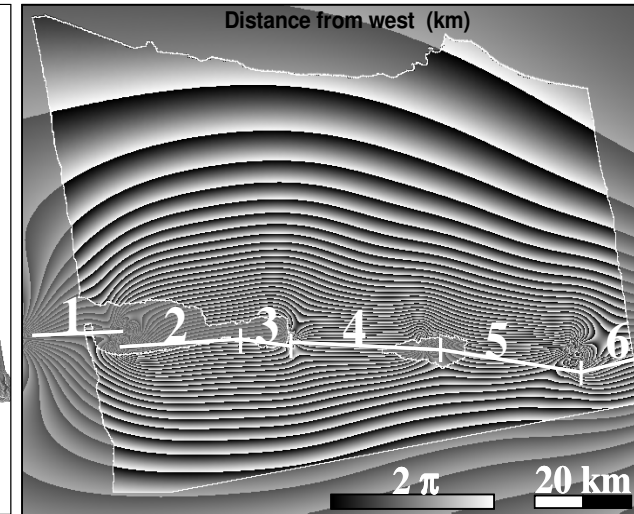
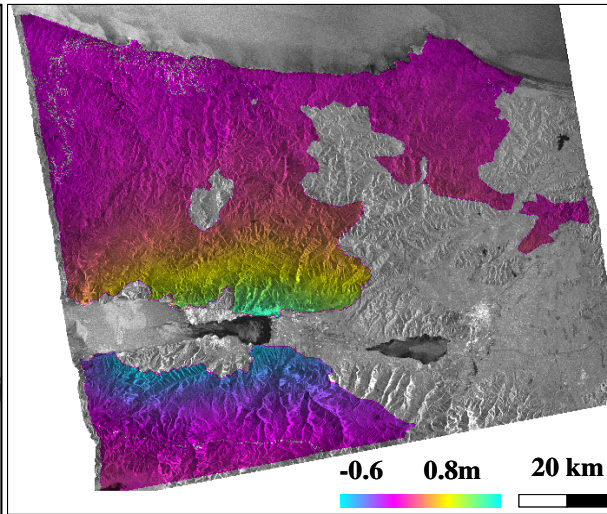
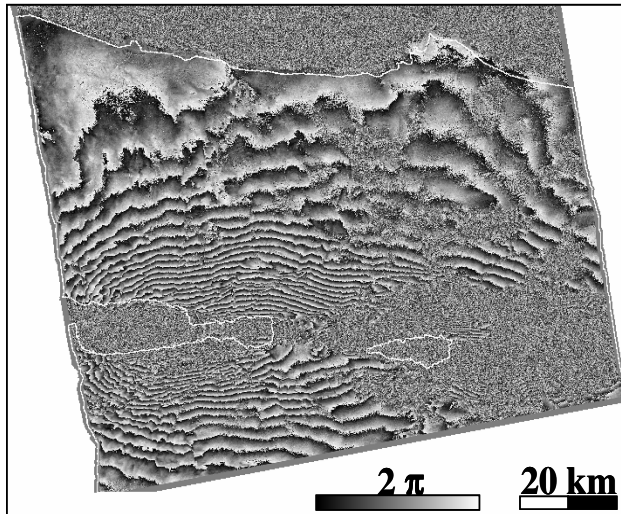
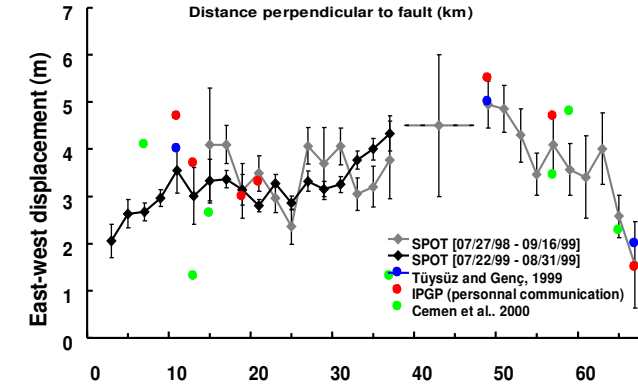
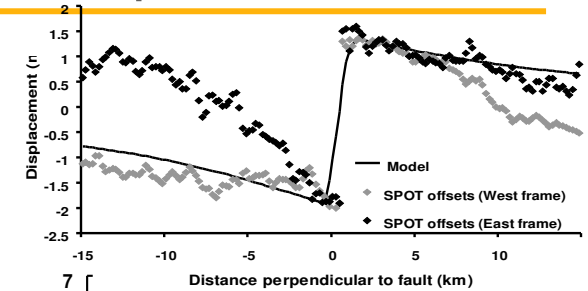
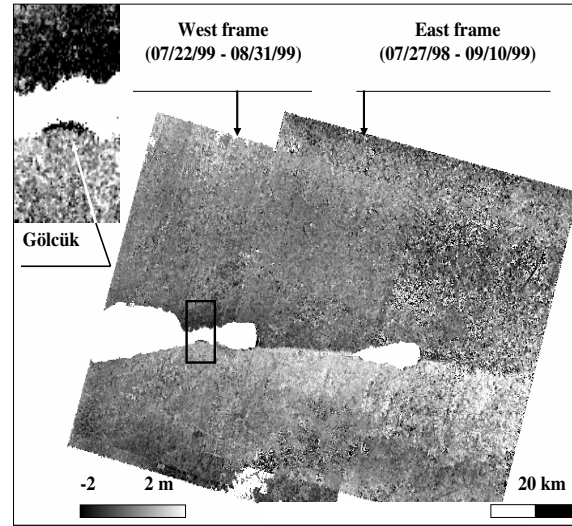
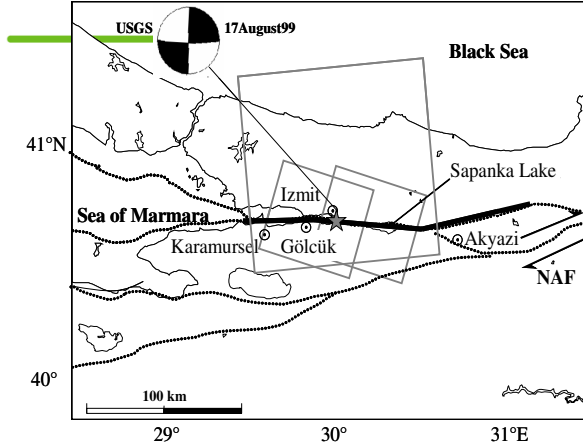
Michel, Van Puymbroeck, Binet



Chi-Chi, (Taiwan), 1999

Michel, Dominguez, Avouac

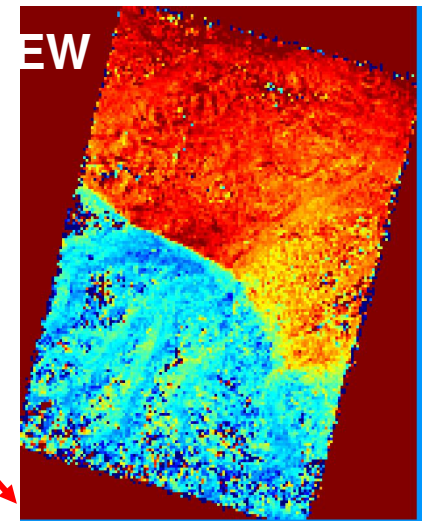
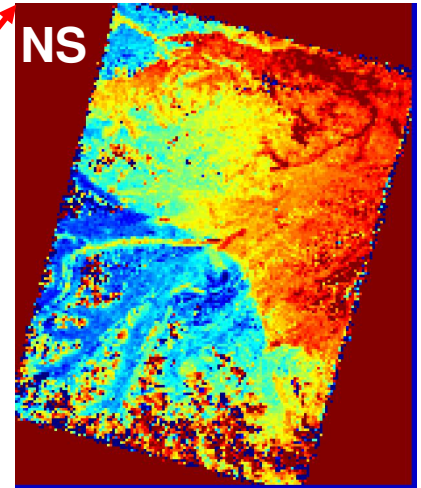
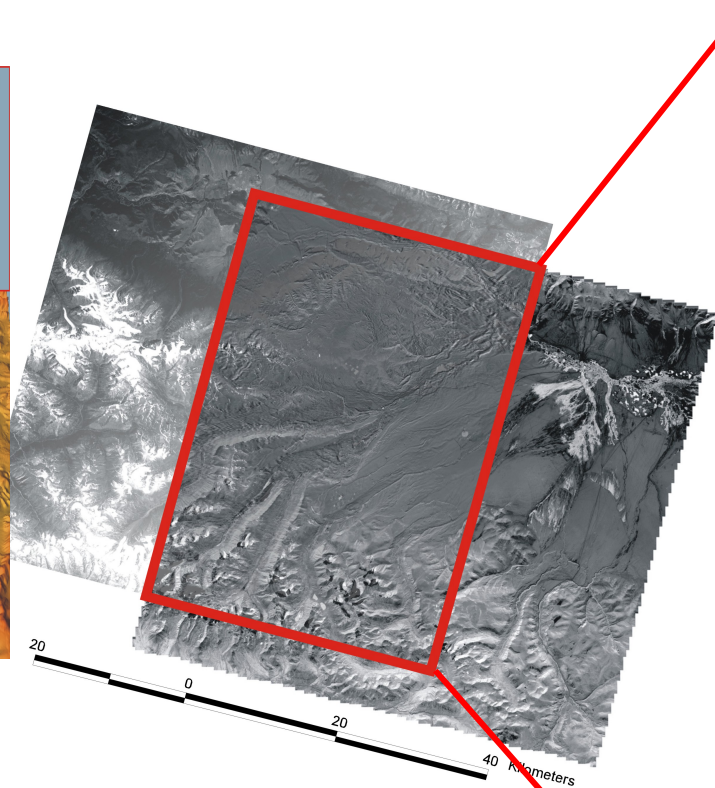
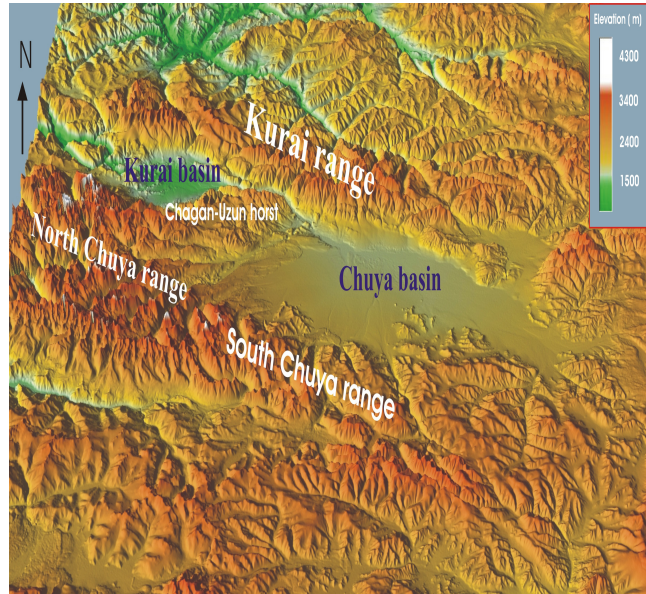
Etude de cas : Izmit, 1999, M_w 7.6, Turquie



Le signal interférométrique est généralement saturé et très bruité à moins d'un kilomètre des ruptures cosismiques de surface. Les artefacts aux grandes longueurs d'ondes spatiales limitent l'exploitation de l'interférométrie aux échelles inférieures au km. La complémentarité naturelle des mesures conduit à une description détaillée de la déformation cosismique [65].

Results from Binet, Munkhuu and Schlupp on Chuya EQ

Spot 5 Panchromatic image (ground resolution – 5 m)

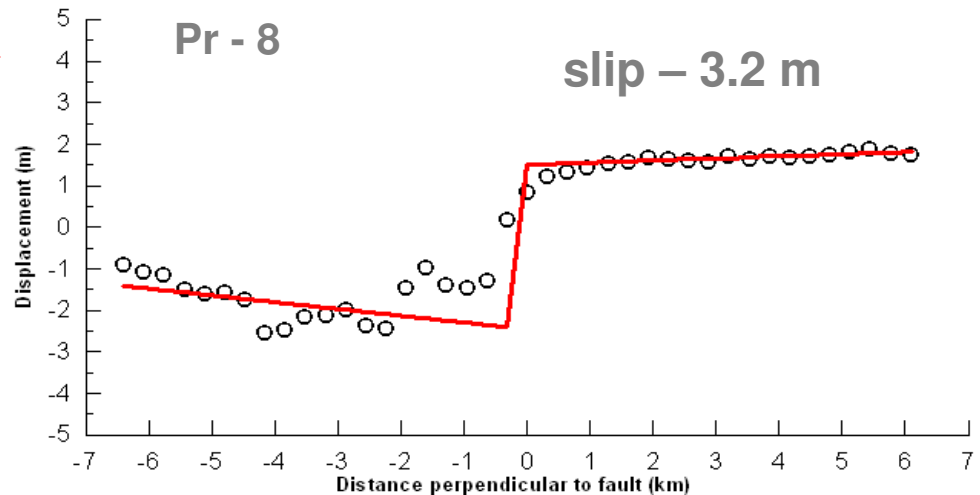
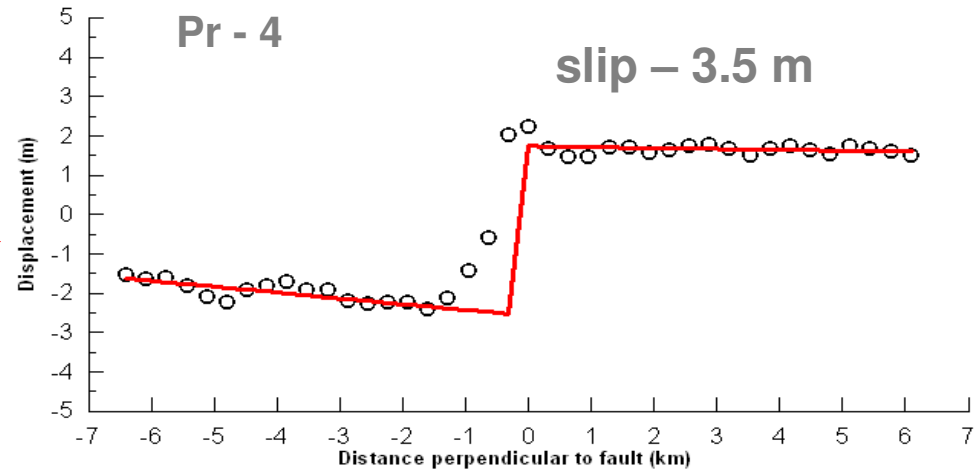
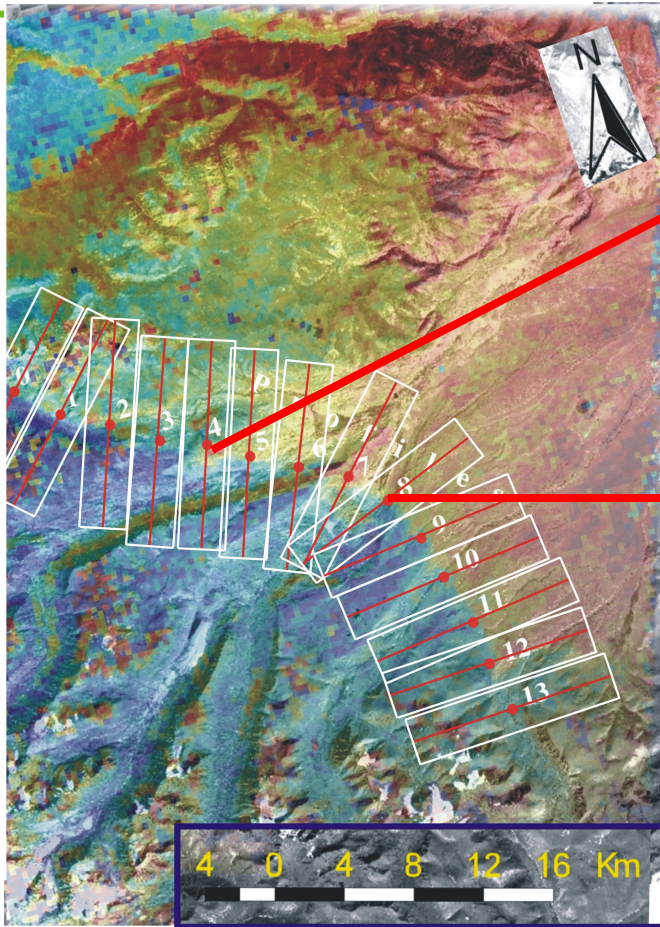


- Fault non visible on the SPOT image
- No data at the west part before the EQ (partial observation)
- Clear horizontal slip by spot correlation and clear position of the deformation
- Possible deformation at N ?

Result of SPOT 5 subpixel correlation

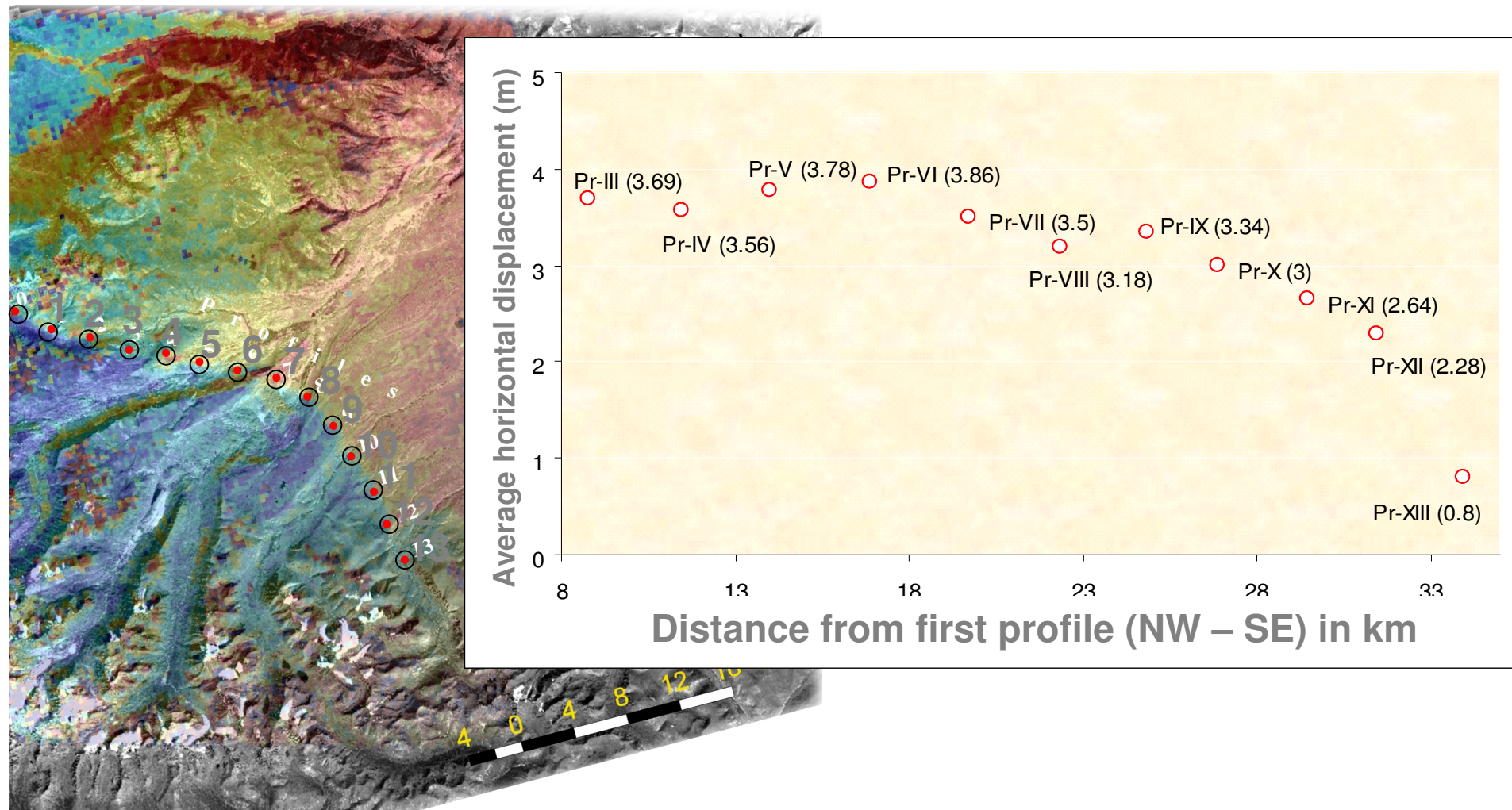
Profiles are perpendicular to the fault strike, by stacking all data along 3 km wide swaths. Displacements are horizontal

cea



SPOT Panchromatic (5 m resolution) after the EQ + NS correlation results

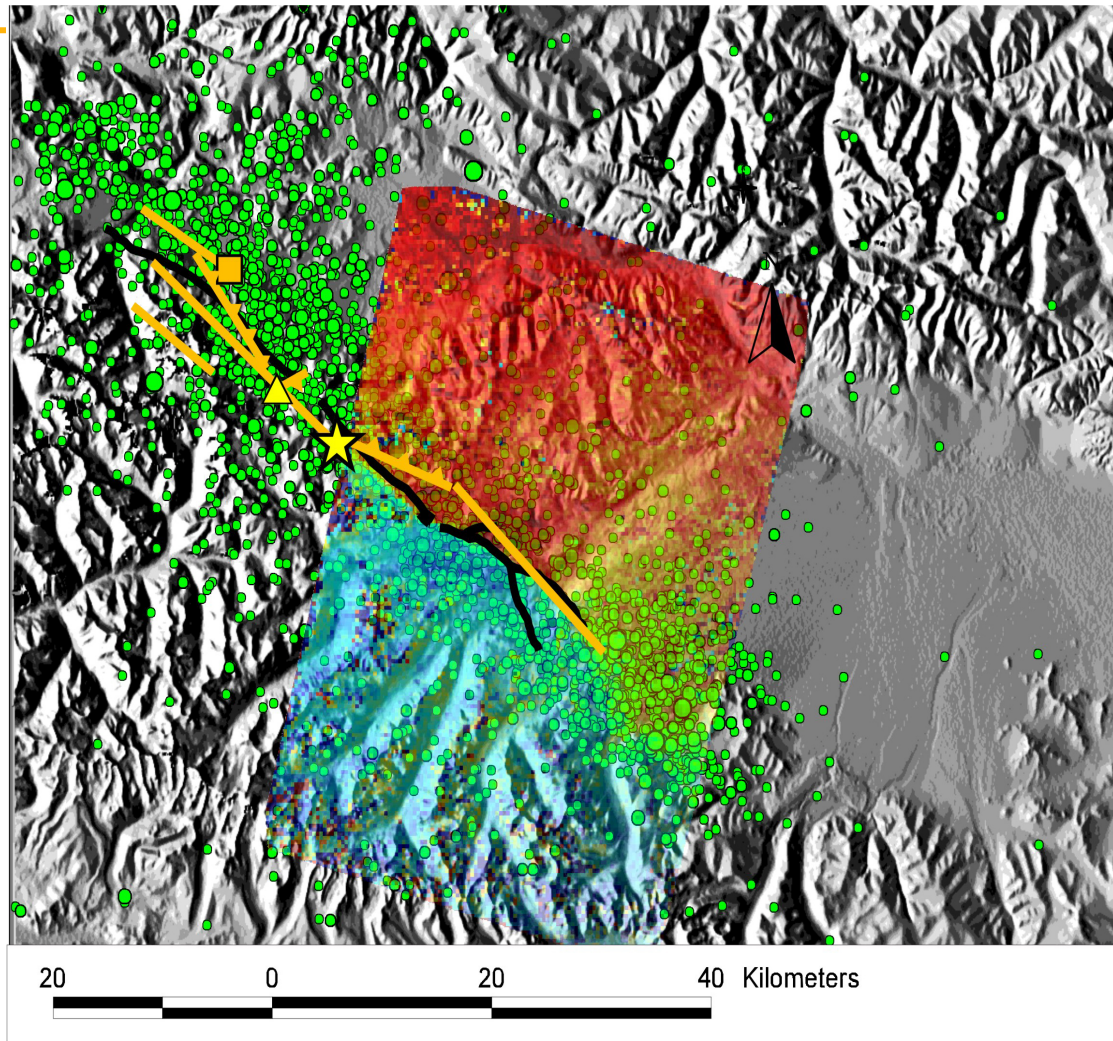
Horizontal displacements by subpixel correlation of Spot image along the south eastern surface rupture of Chuya earthquake



The horizontal slip is at least **two time larger** than the one observed along surface ruptures on the field (1.5 m)
Profile 13 - almost no motion (0.8 m) which can consider end of rupture
The deformation is also spread over a large distance from the fault.

Final results of study Chuya earthquake sequence

cea



- ★ Mainshock
Mw=7.2
- ▲ Aftershock with
Mw = 6.4
- Aftershock with
Mw = 6.9

Aftershock sequence

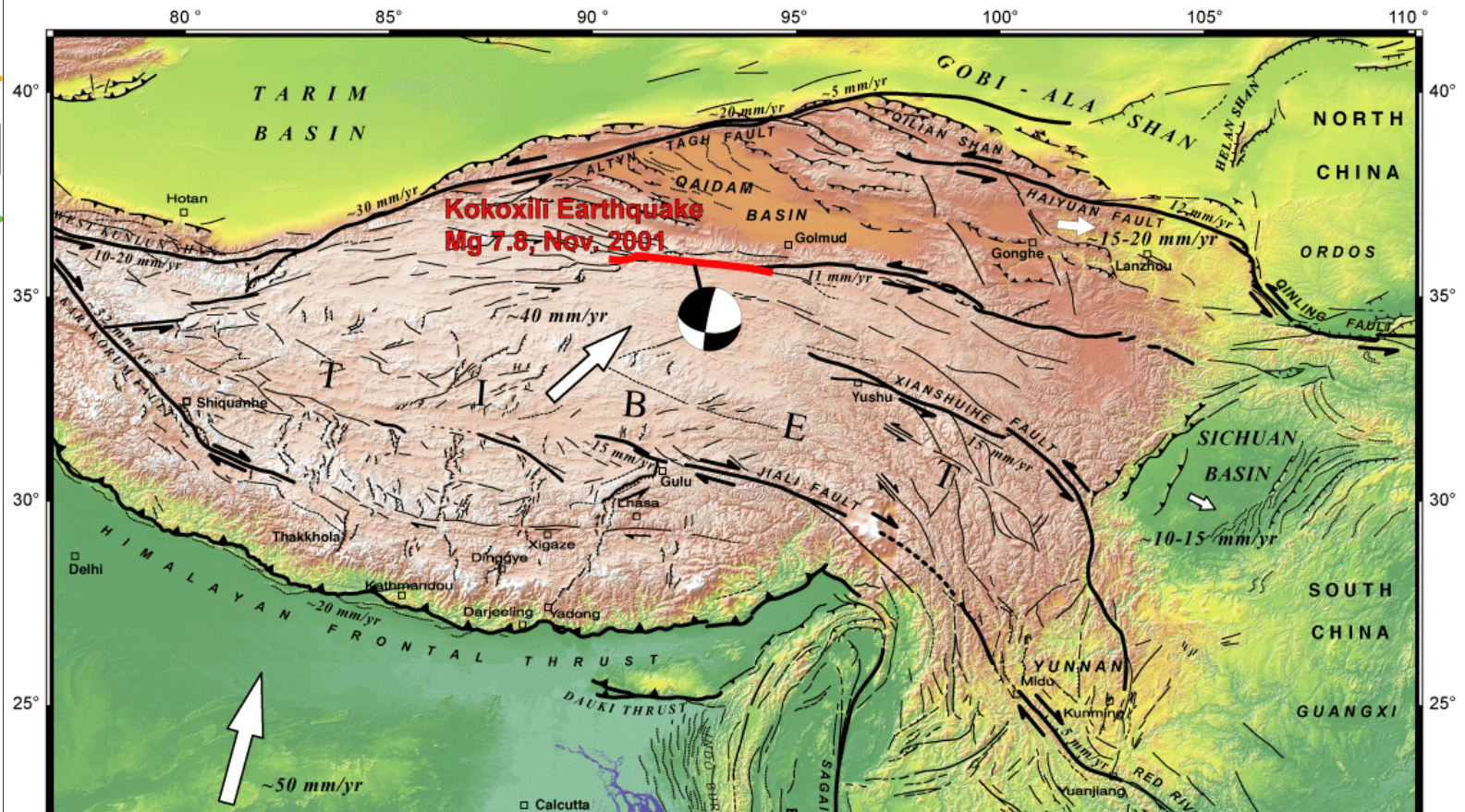
- M < 2.0
- M - 3.0
- M - 4.0
- M - 5.0

- ⚡ Observed surface rupture
- ⚡ Modelled surface rupture

Spot correlation

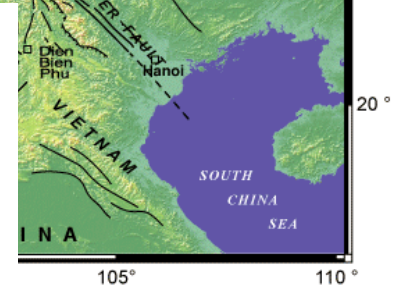
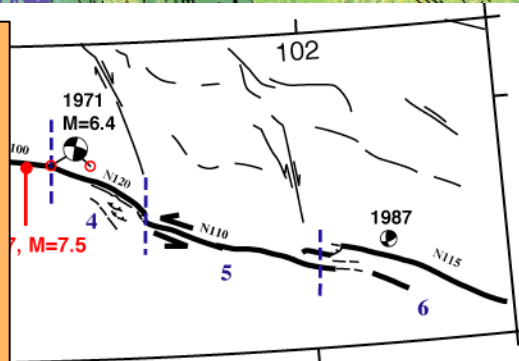
Field observation	Spot correlation	Aftershock	Body wave inversion
Length ~ 60 km	Trend – well corr. (SE part)	Trend – well corr	Length ~70 km
Displacement – 1.5 m	Displacement 2.2-3.8 m	Length – 90 km	Displacement – 2.8 m

Results from Klinger (IPGP) & Michel (CEA)

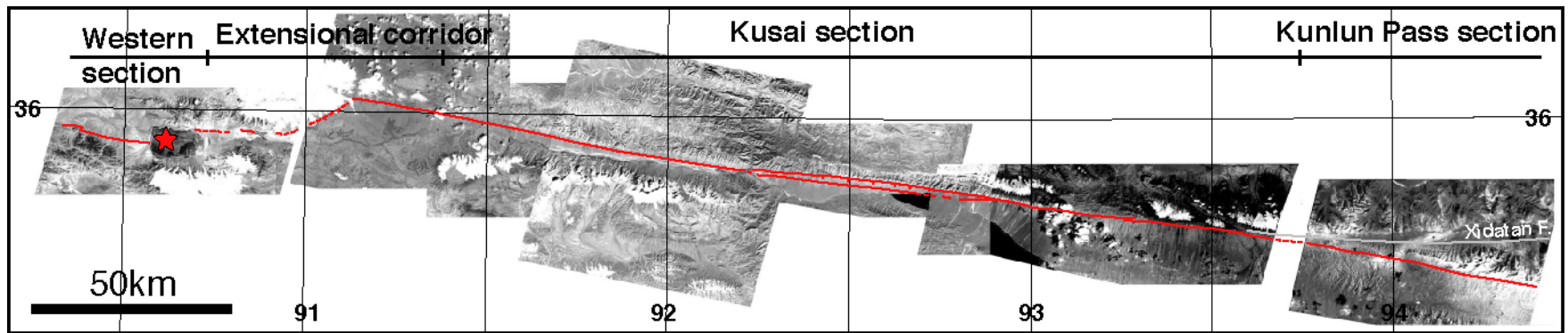


The Kokoxili Eq. rupture

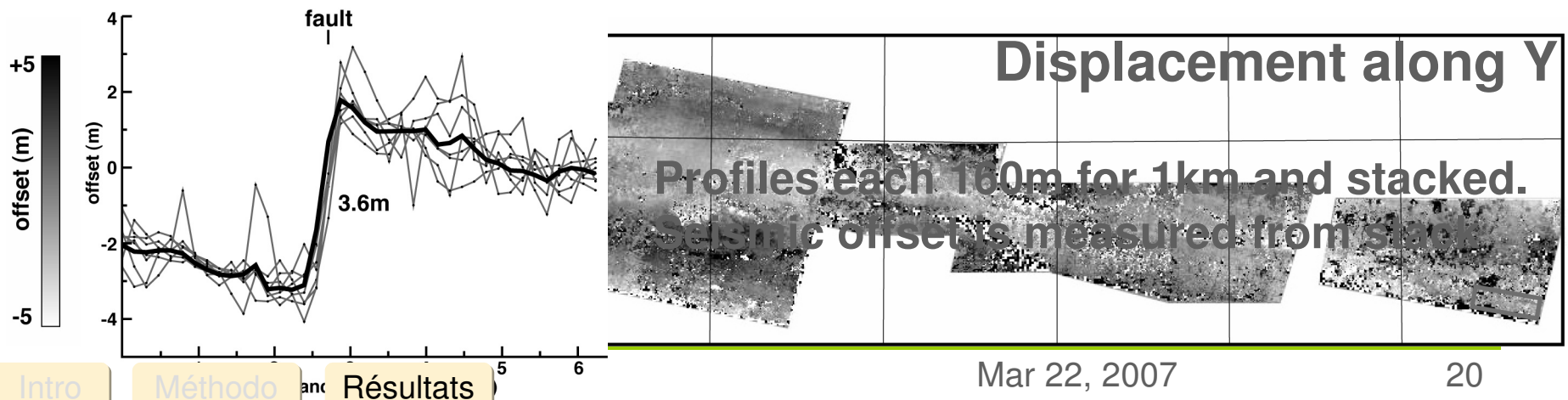
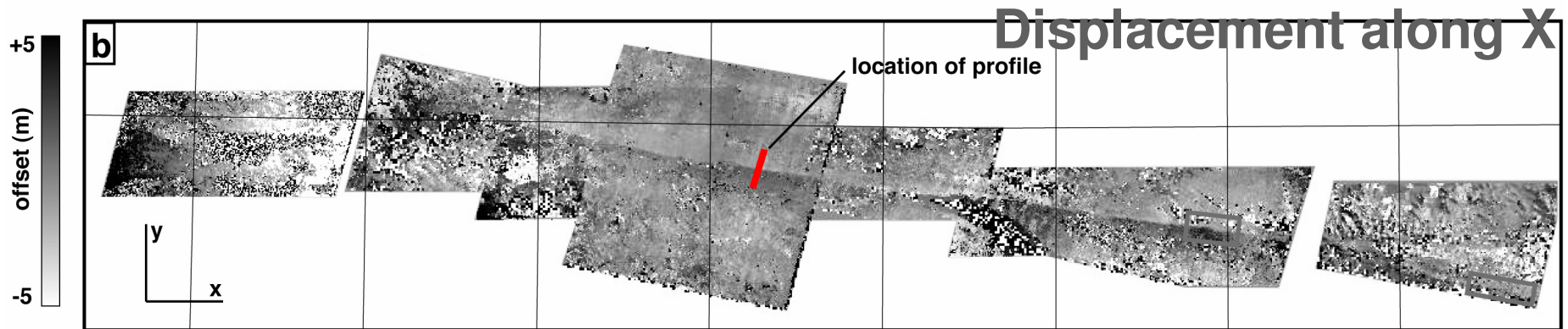
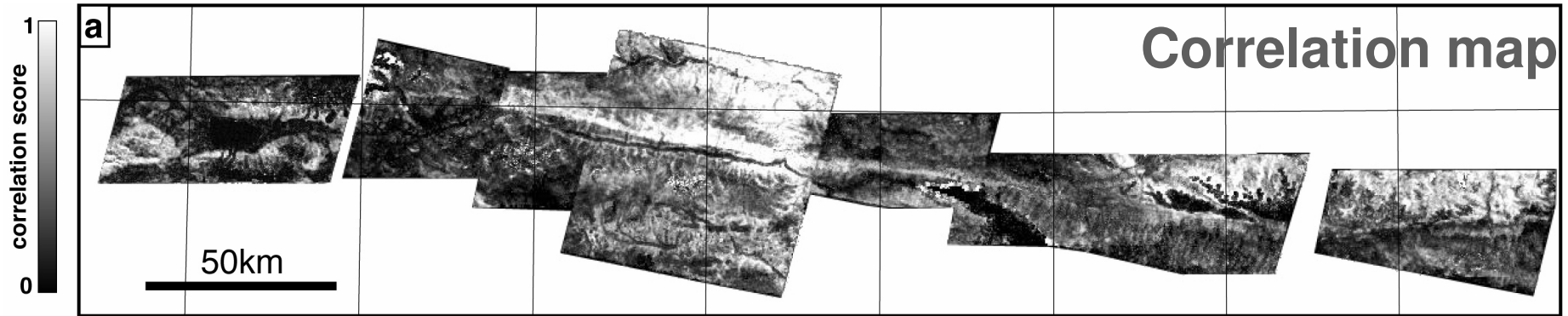
- a rupture of ~450km in total
- at mean elevation of 4500m



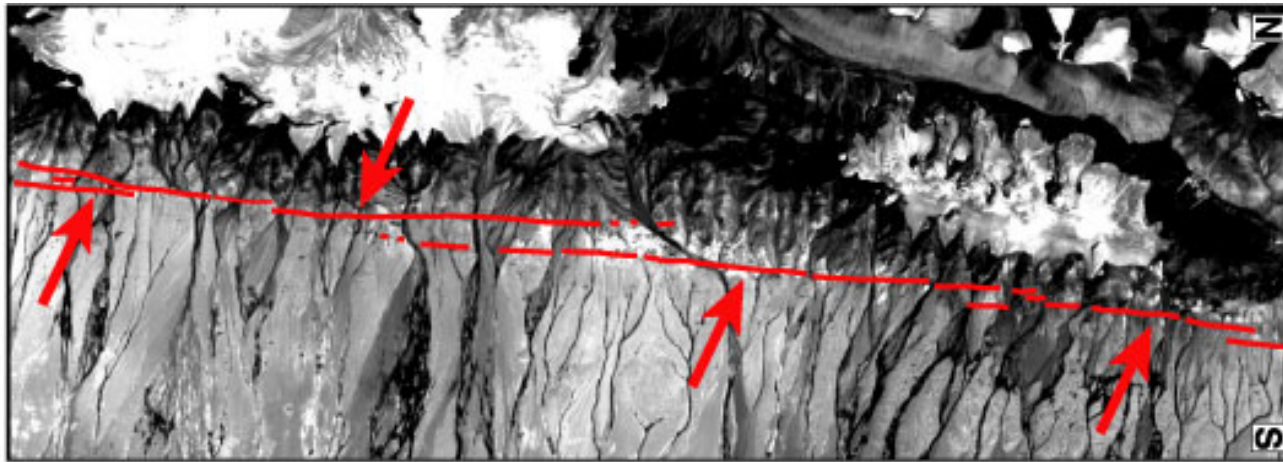
Detailed slip-curve from offset of optical images



The Kokoxili earthquake rupture is covered by 8 pairs of images

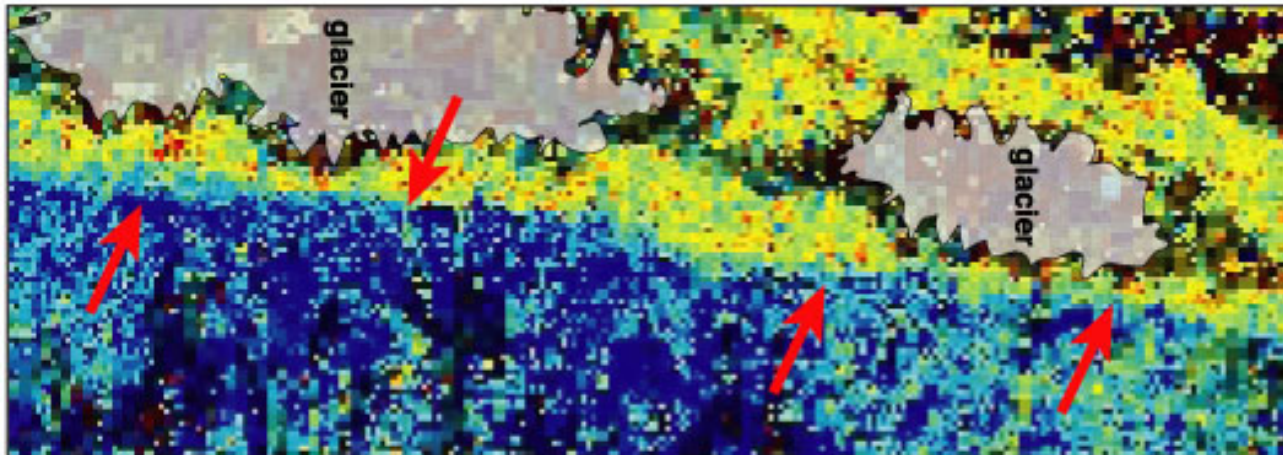


5km



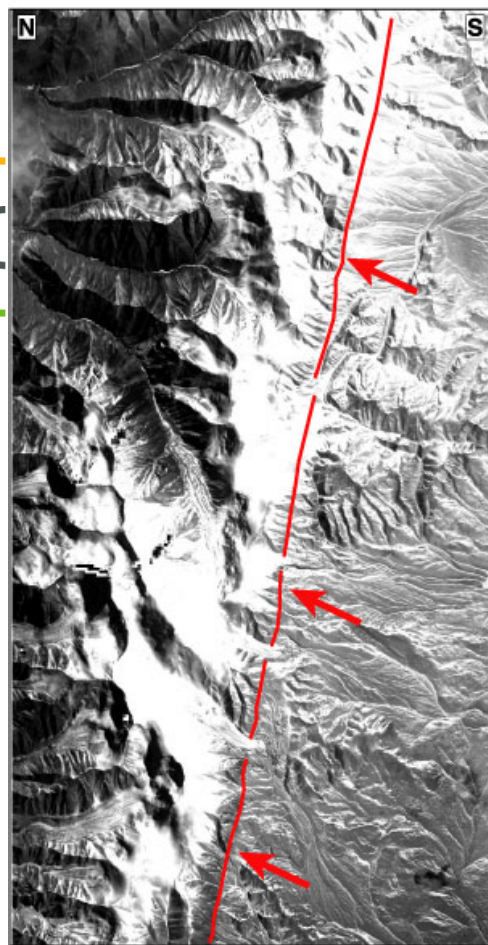
A)

-6m pixel offset +6m

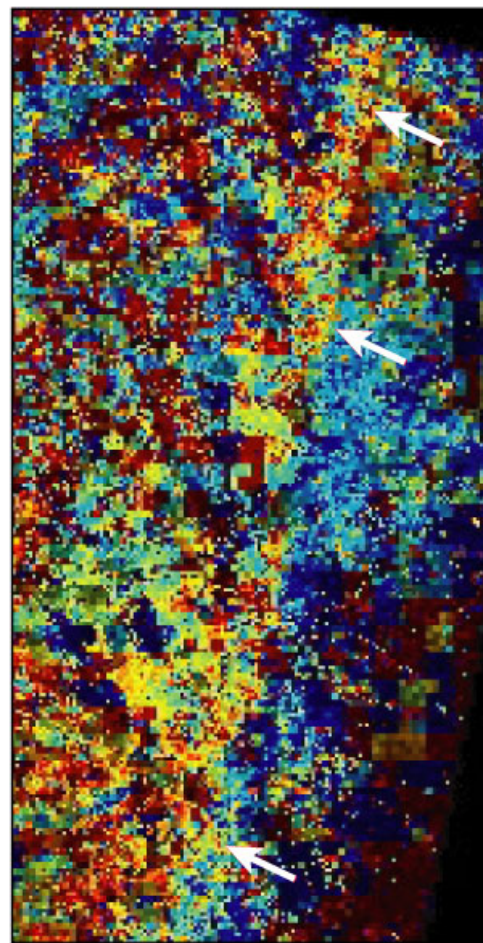


B)

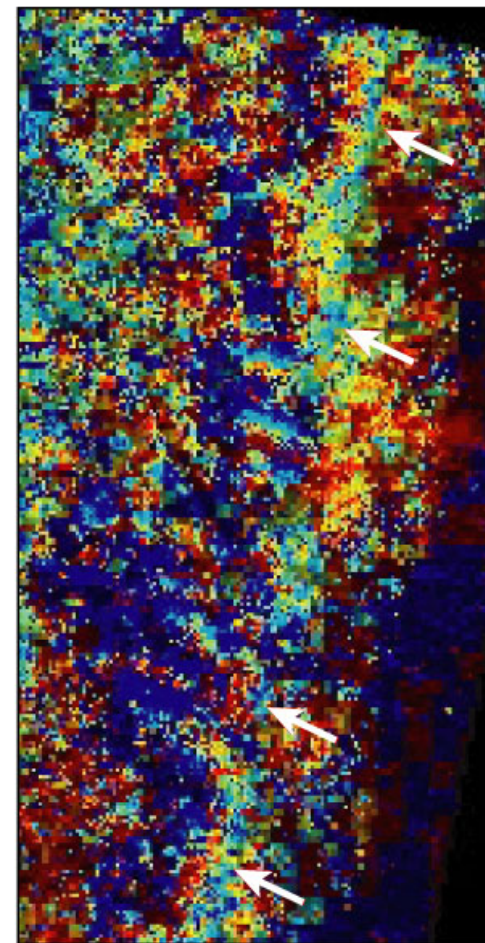
Detail of the offset map.
The compressive jog is clearly visible.



5km

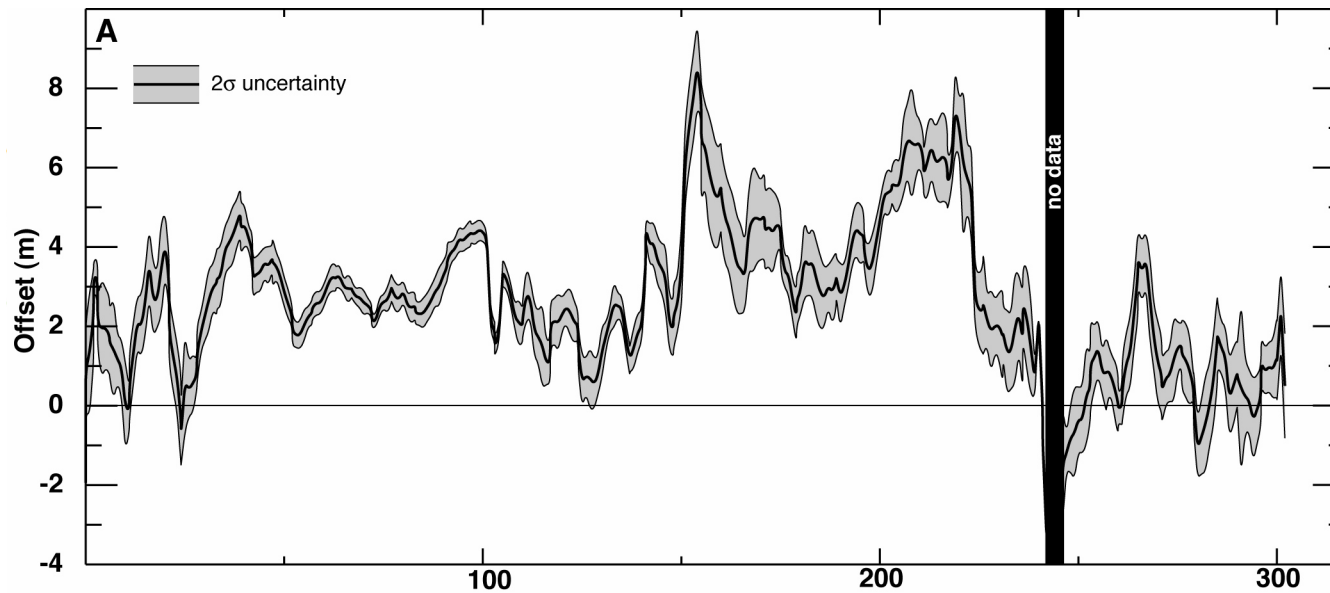


-4m pixel offset +4m

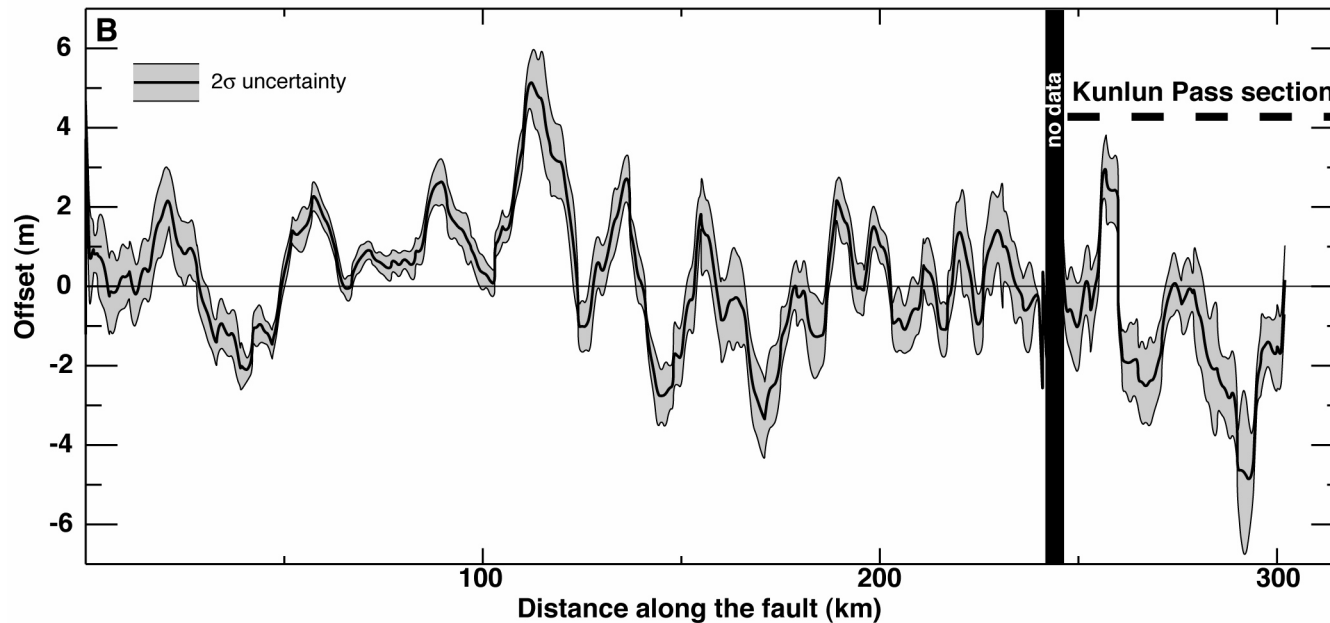


-3.5m pixel offset +7m

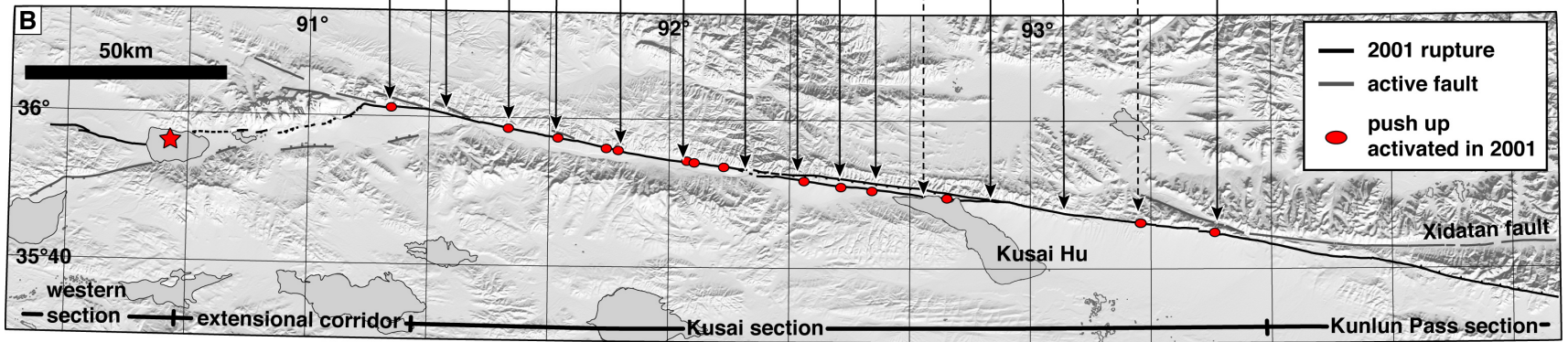
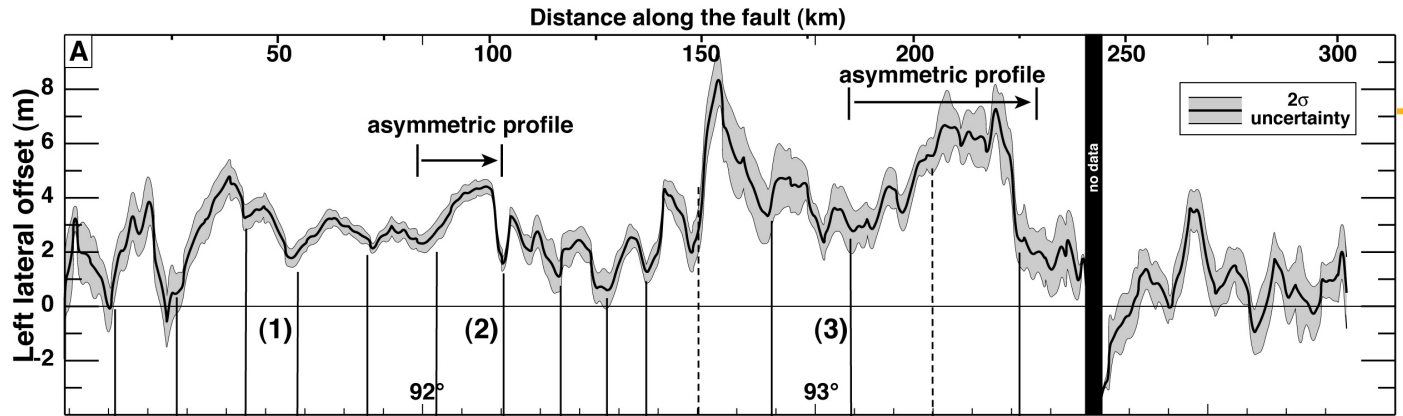
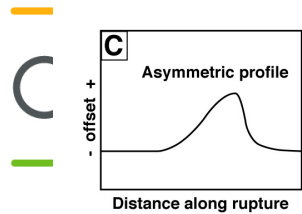
Large vertical motion is visible on the horizontal component of motion perpendicular to the fault



**Component
parallel to the
fault**



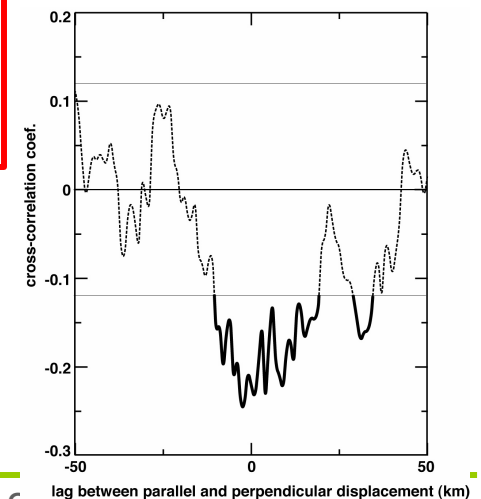
**Component
perpendicular
to the fault**



(Klinger et al., EPSL 2006)

Fluctuations of the slip curve correlate with geometrical barriers along the rupture

Anti-correlation of the two horizontal components advocates for distribution of the motion on multi-scale and multi orientation faults forming the barrier



Perspectives



- Augmenter la résolution des MNT
 - Génération à partir d'un couple stéréo THR
- Limiter l'influence de l'aliasing ou utiliser un instrument adapté à double barrettes type SPOT 5 THR
- Compenser les biais basses fréquences (mesures GPS) pour contraindre la source sismique en profondeur
- Étudier un grand nombre de cas