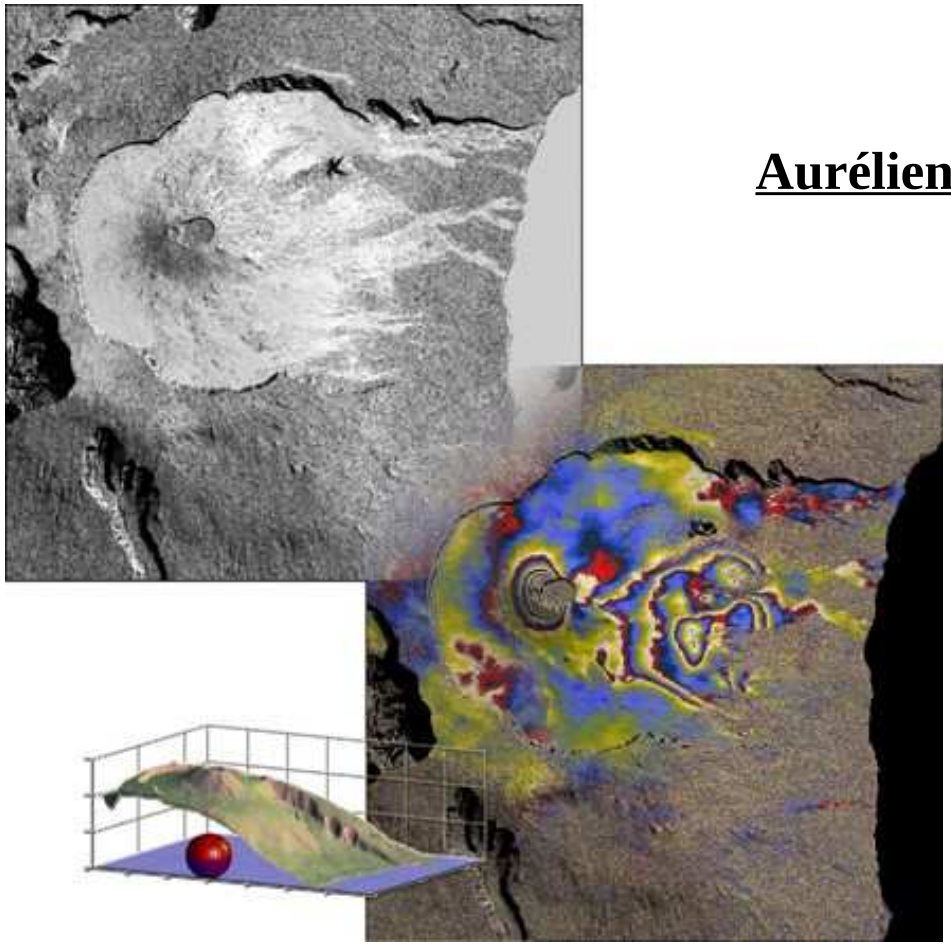
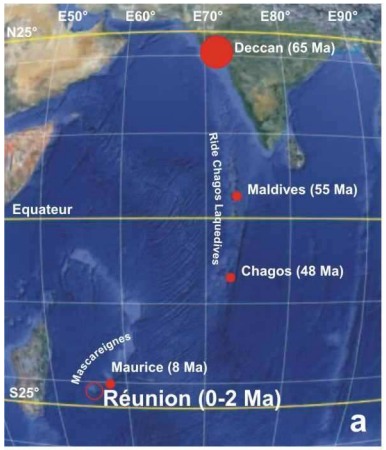
Étude de l'éruption d'avril 2007 du Piton de La Fournaise à partir de données d'interférométrie radar et GPS, développement et application de procédures de modélisation.

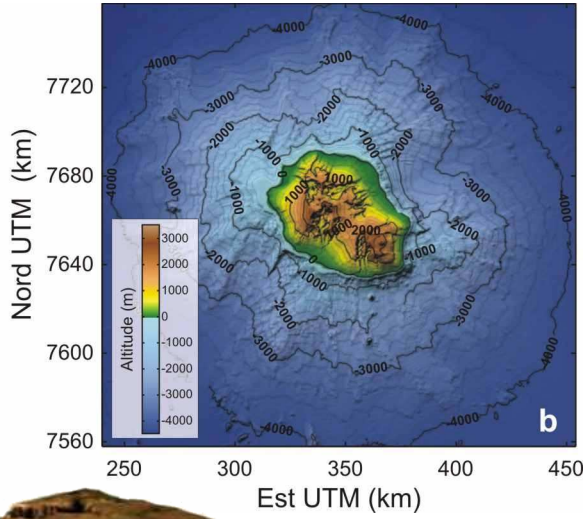


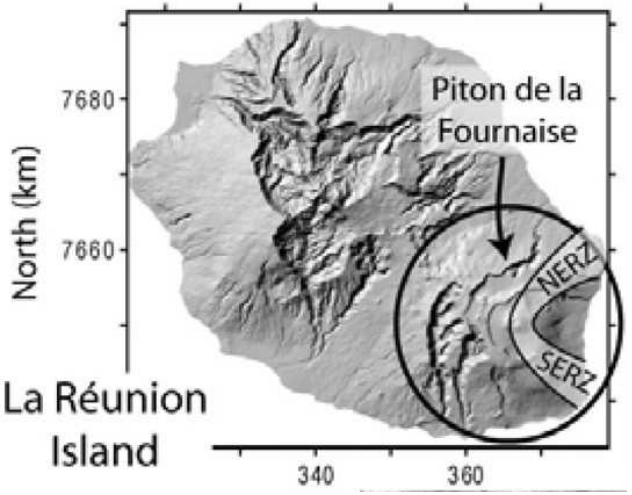
Aurélien Augier

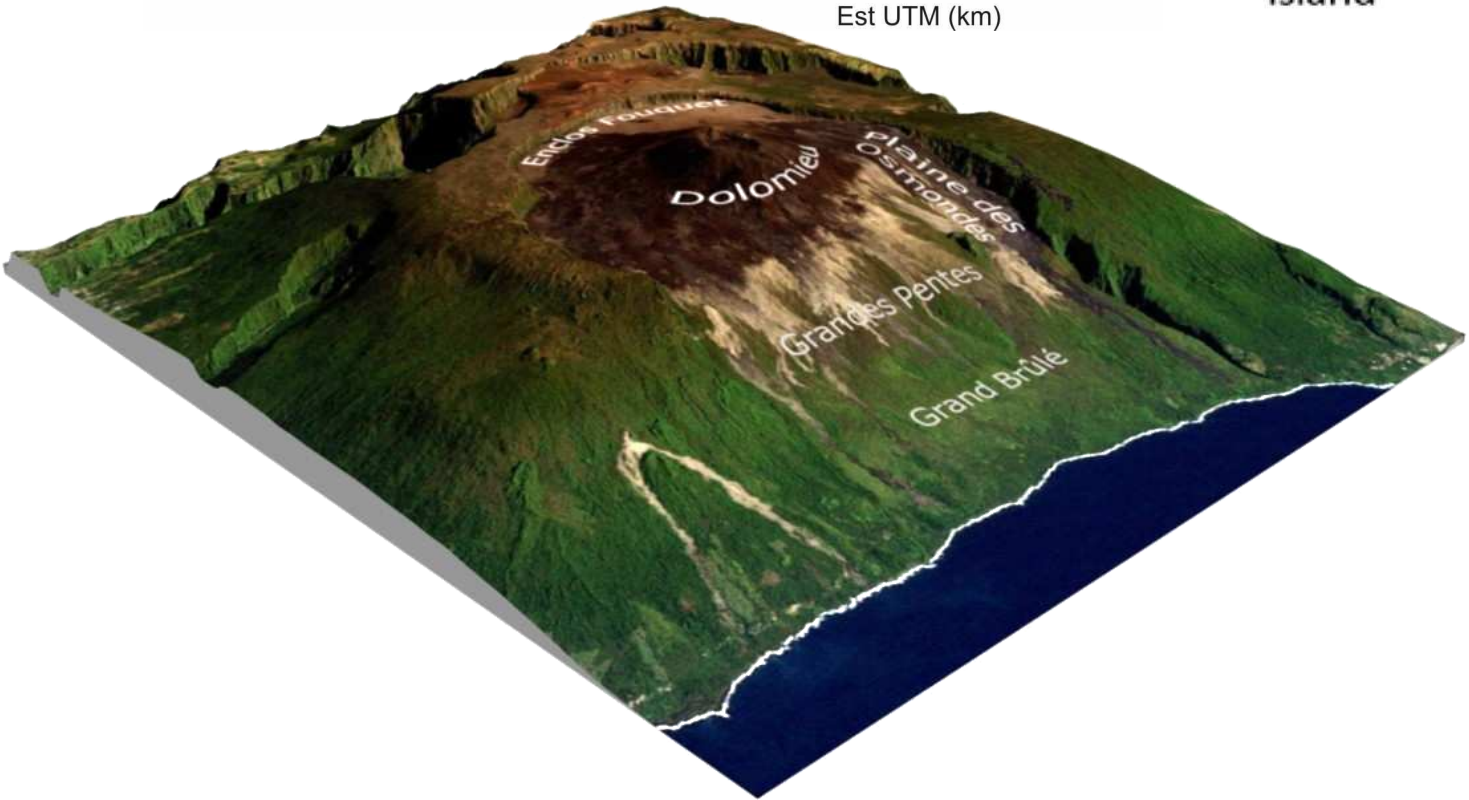
Séminaire au GeHCO,
20 novembre 2014

Le Piton de la Fournaise

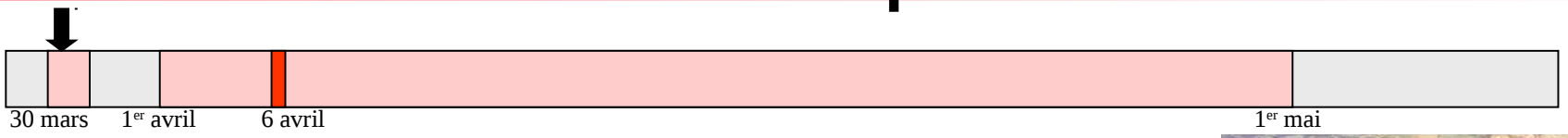


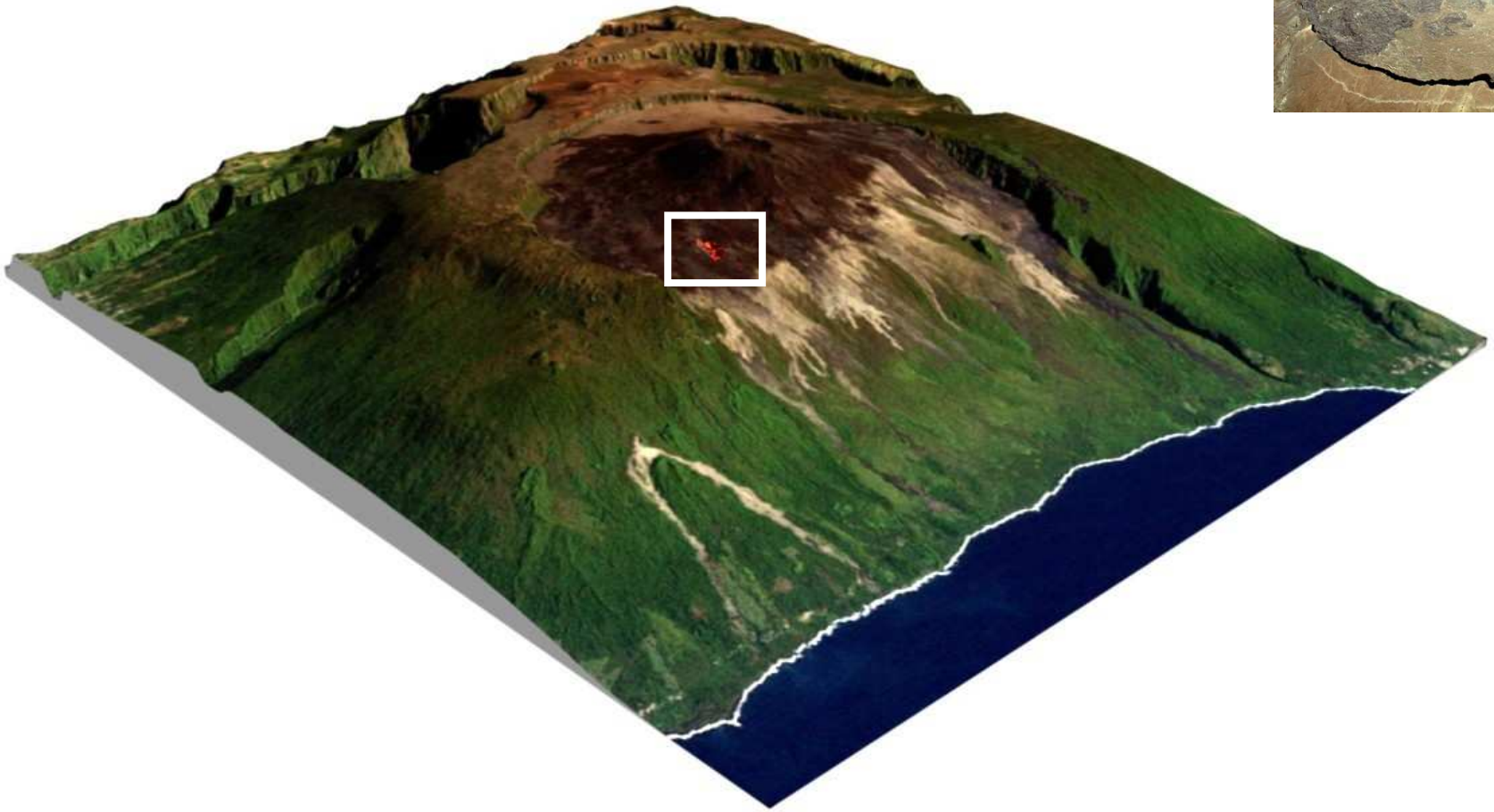




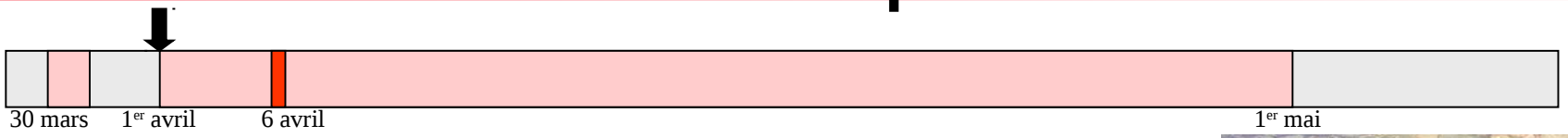


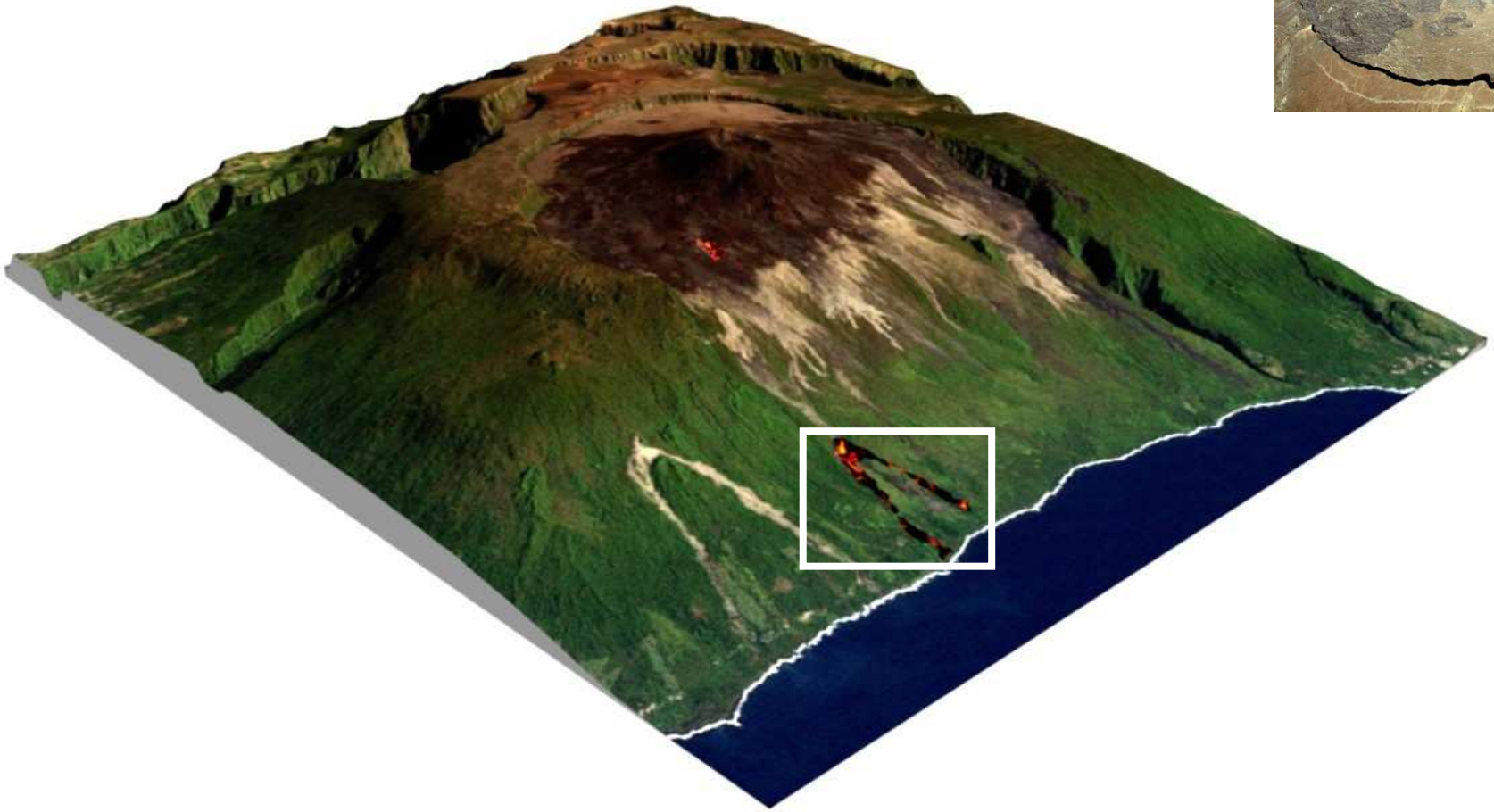
Le Piton de la Fournaise : éruption d'avril 2007



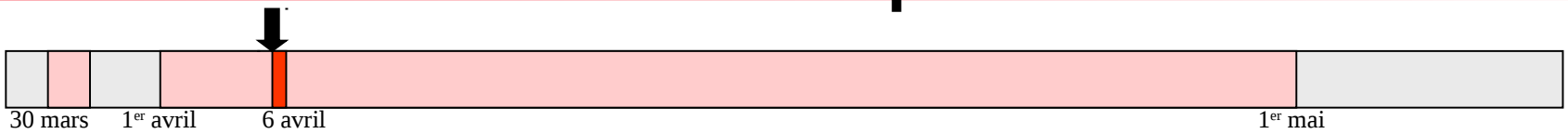


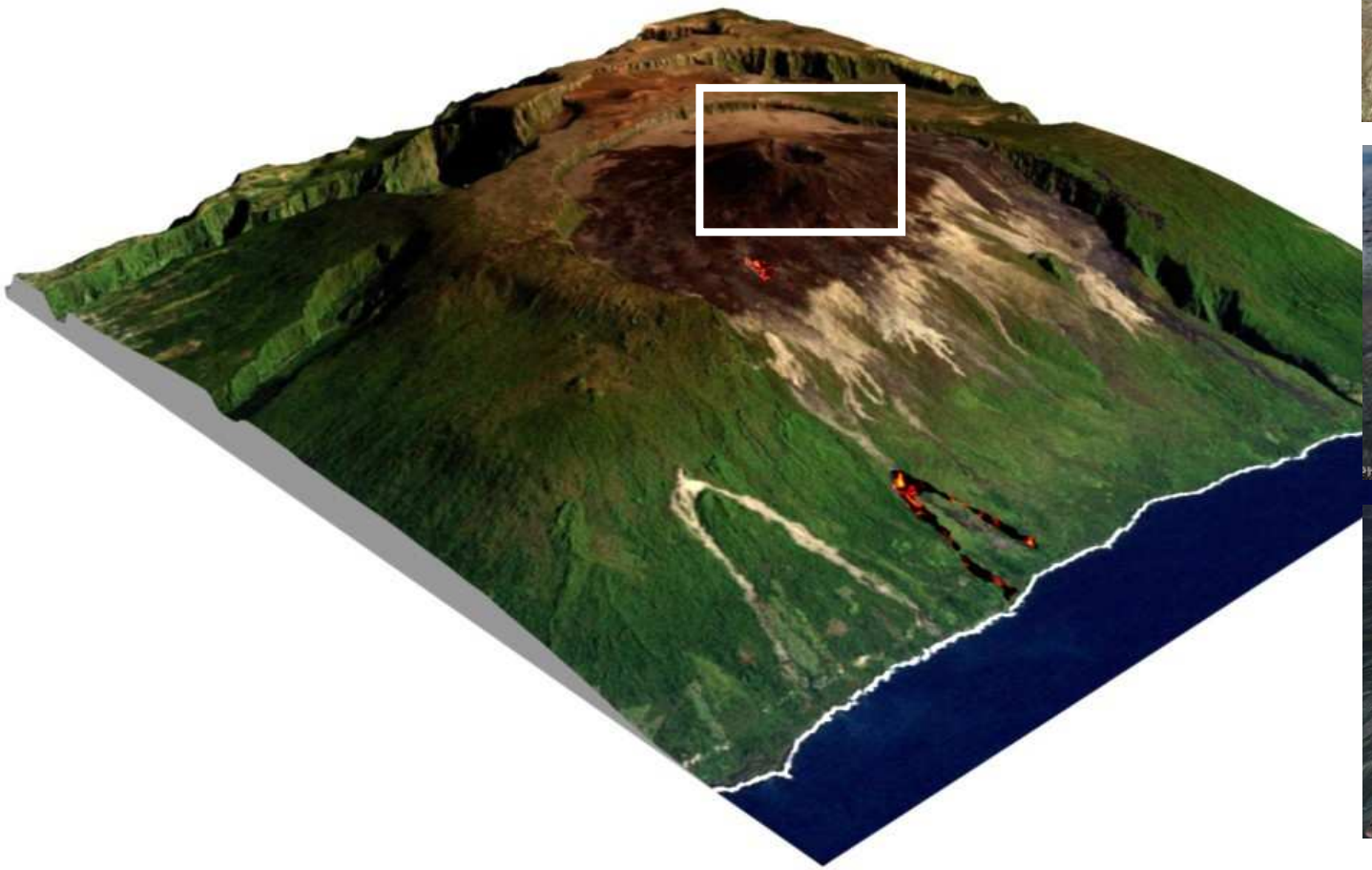
Le Piton de la Fournaise : éruption d'avril 2007



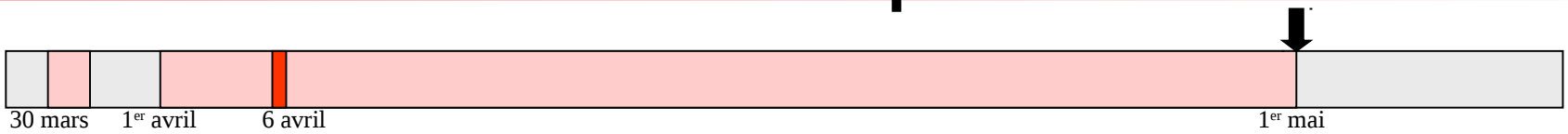


Le Piton de la Fournaise : éruption d'avril 2007





Le Piton de la Fournaise : éruption d'avril 2007



Que s’est-il passé durant cette éruption extraordinaire ?

Un exemple de démarche

I Étude qualitative de l’éruption à partir de données de déplacements

L’acquisition des données de déformation permet de comprendre qualitativement la dynamique du volcan

II Procédures de modélisation

La modélisation permet de contraindre de manière quantitative les sources à l’origine de la déformation

III Étude quantitative de l’éruption, interprétation des résultats de modélisation

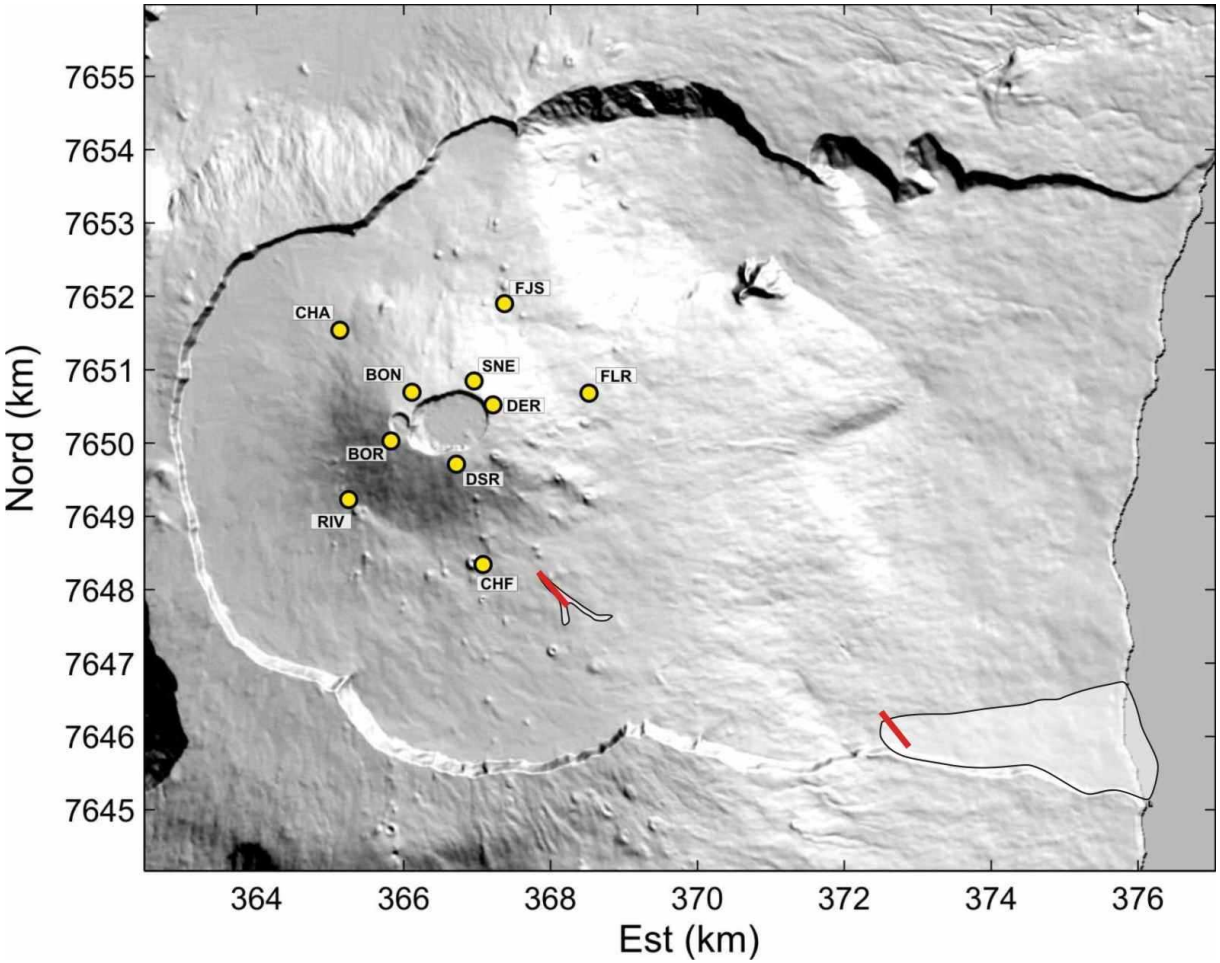
La confrontation des résultats de modélisation avec d’autres observations permet l’interprétation des modèles

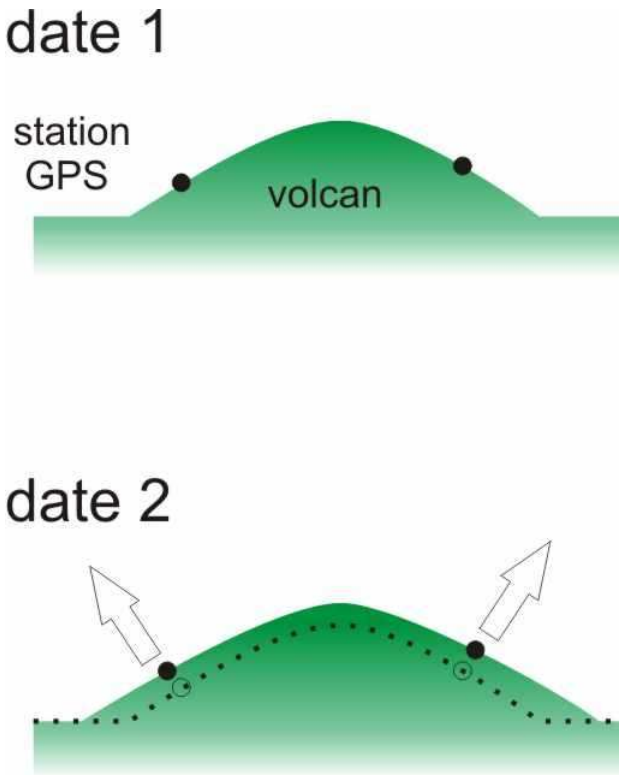
Partie I

Étude de l’éruption à partir de données de déplacements : InSAR et GPS

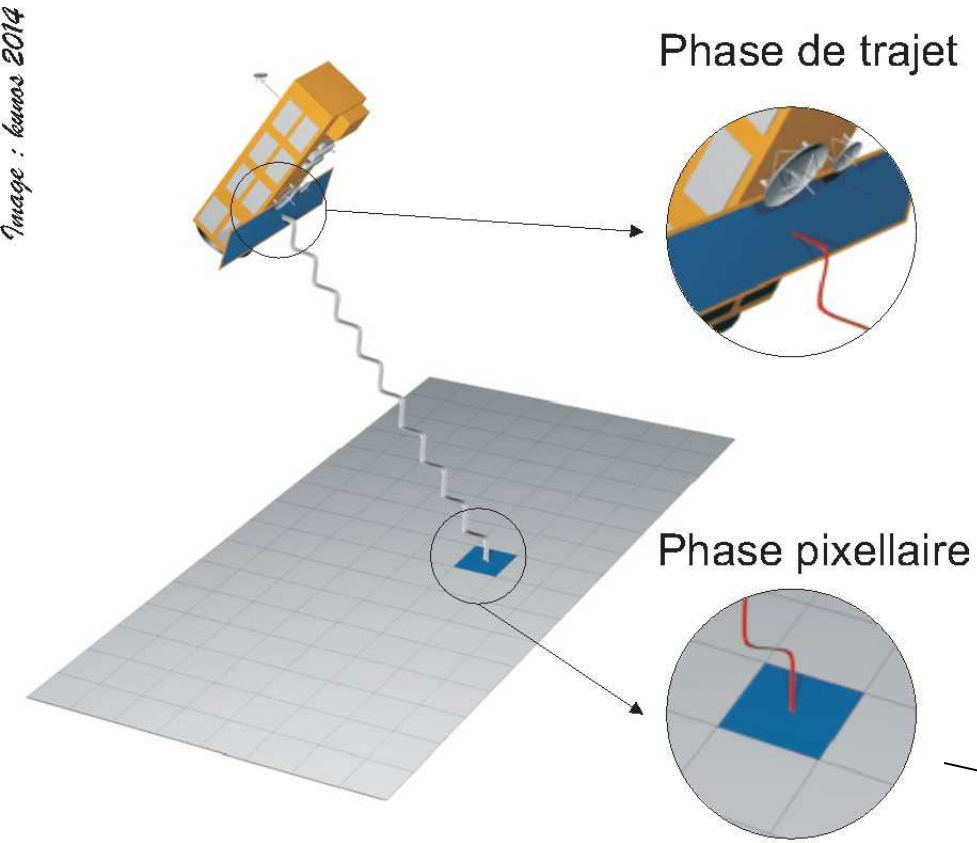
Surveillance de la déformation du volcan par GPS

Carte du réseau GPS au Piton de la Fournaise

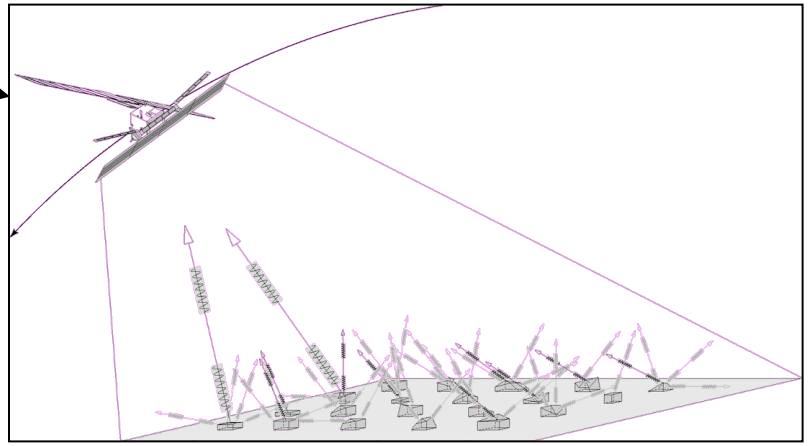




Surveillance de la déformation du volcan par GPS



Mesure de la **phase** et de **l'amplitude** du signal rétrodiffusé



Surveillance de la déformation du volcan par GPS

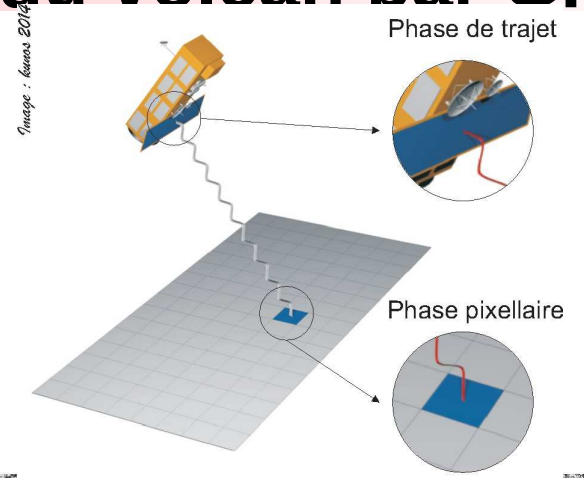


Image : kunos 2014

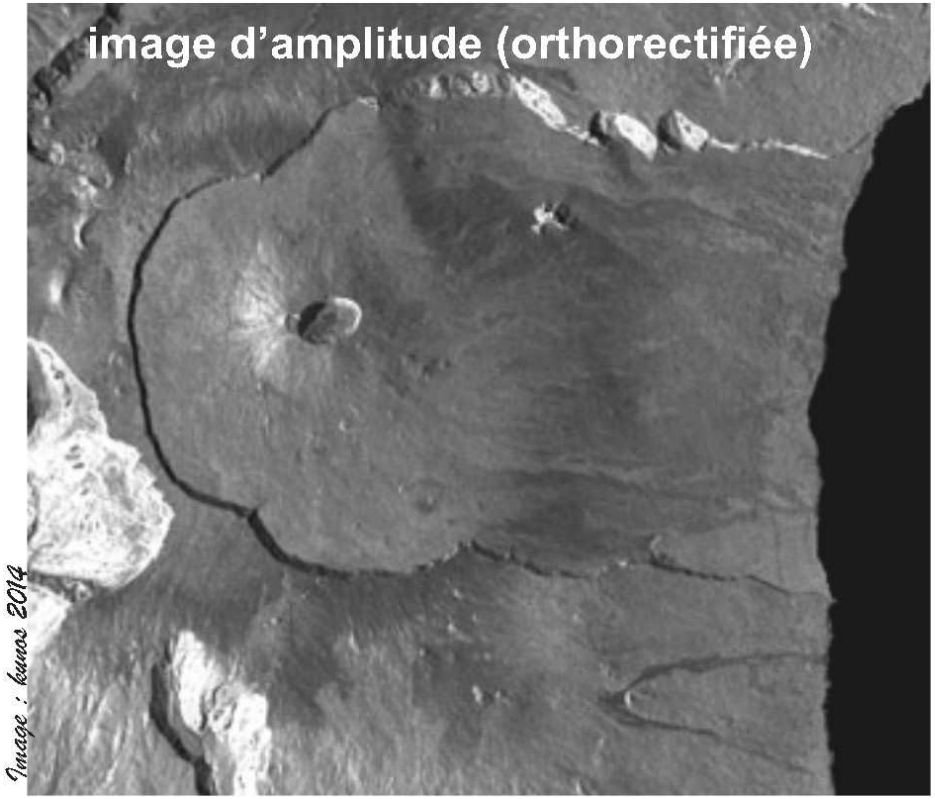
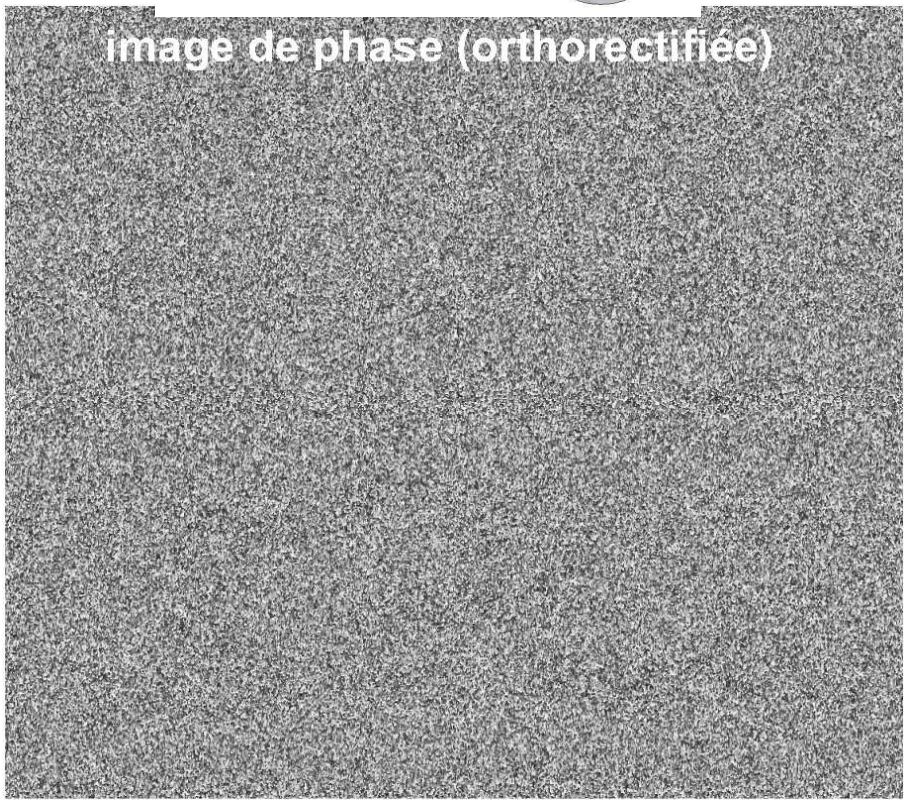
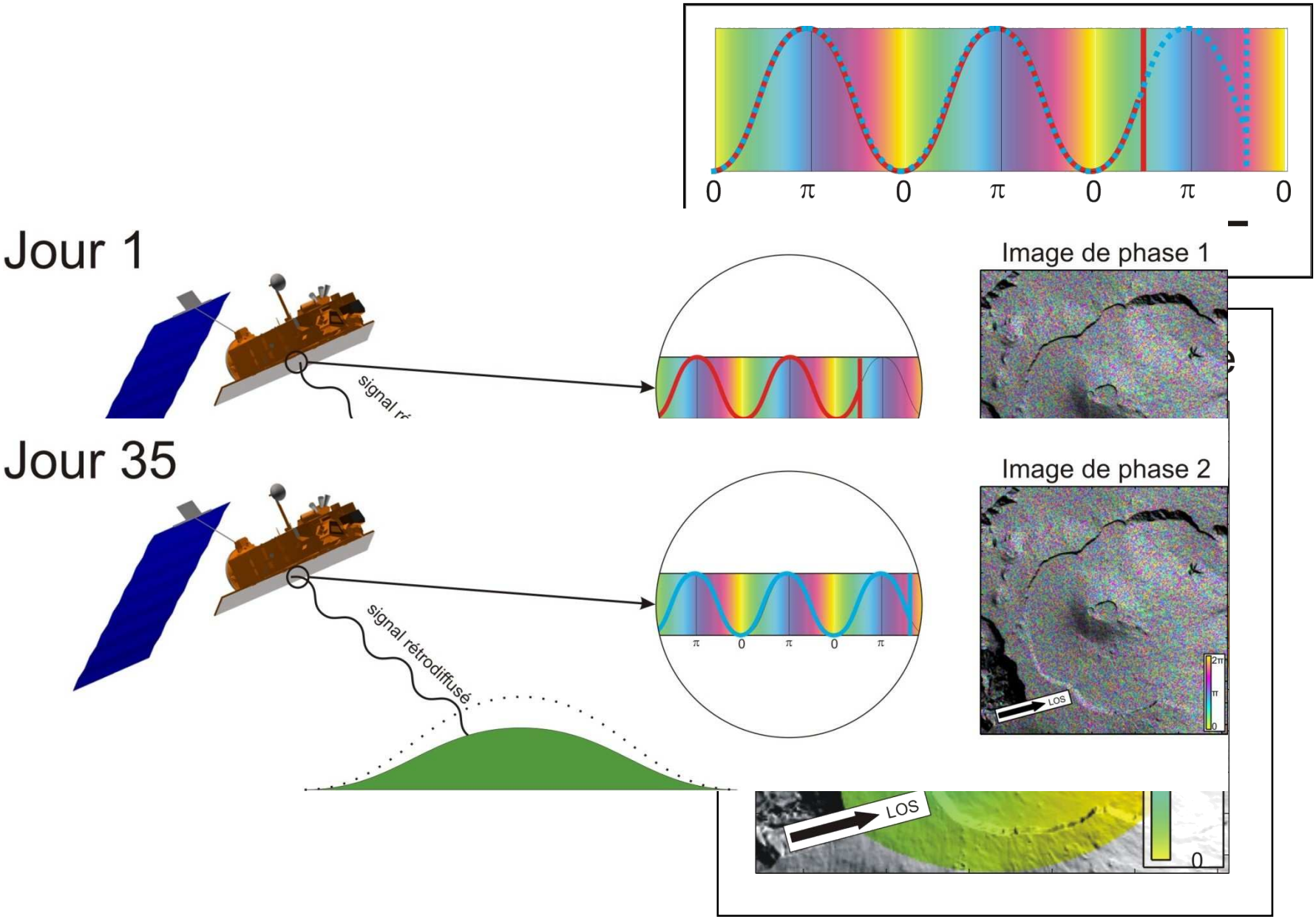


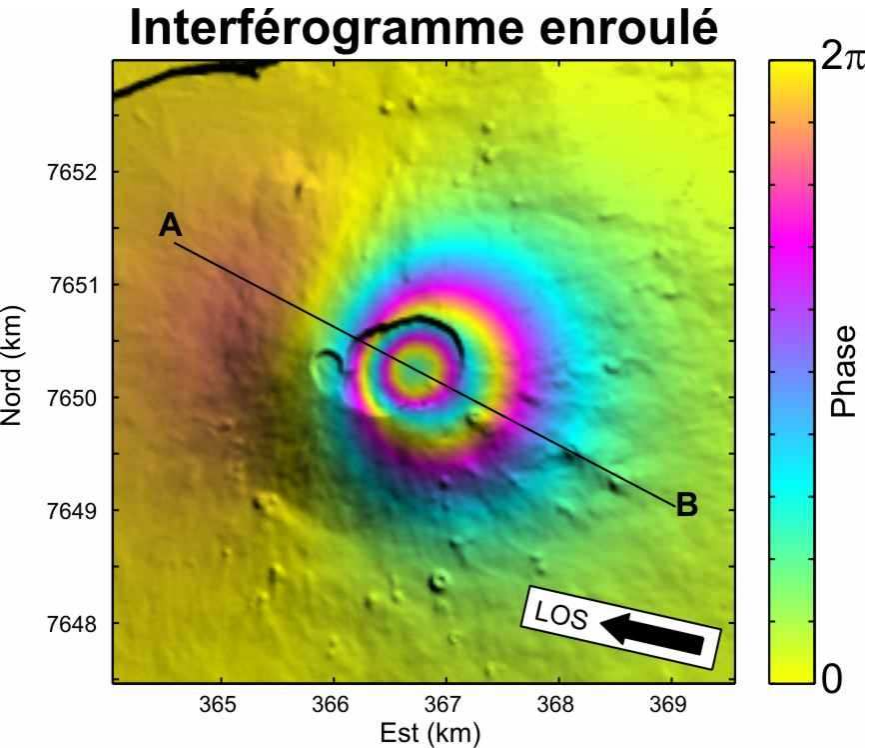
Image : kunos 2014

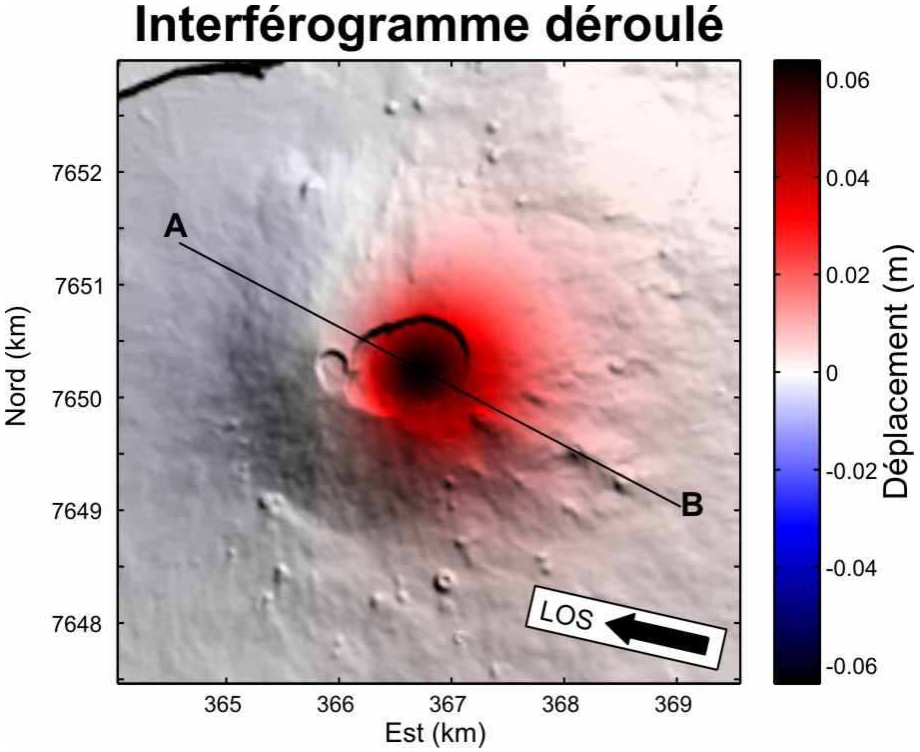


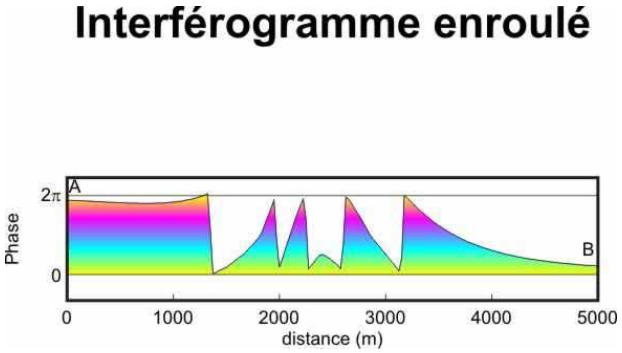
L'InSAR : Calcul des interférogrammes

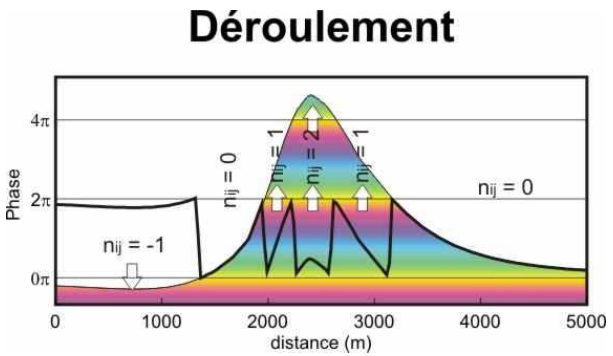


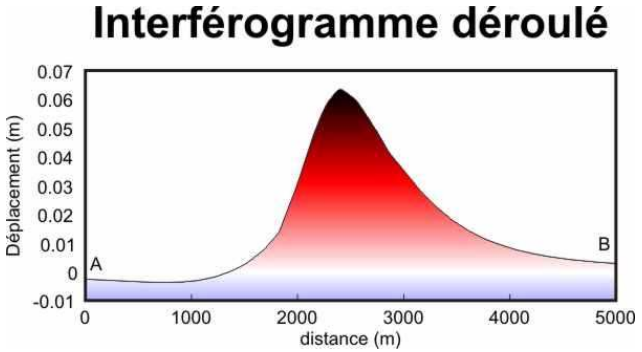
L'InSAR : Déroulement des interférogrammes





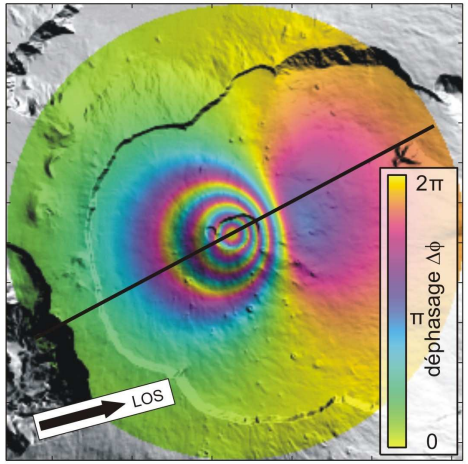




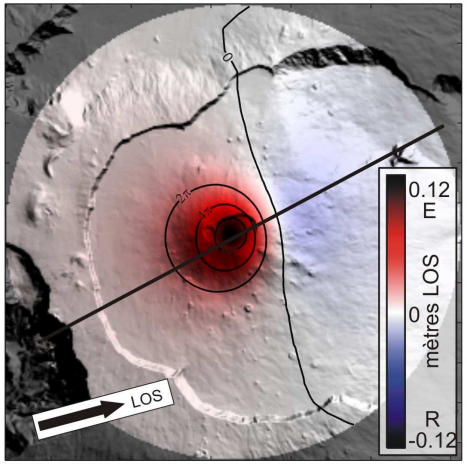


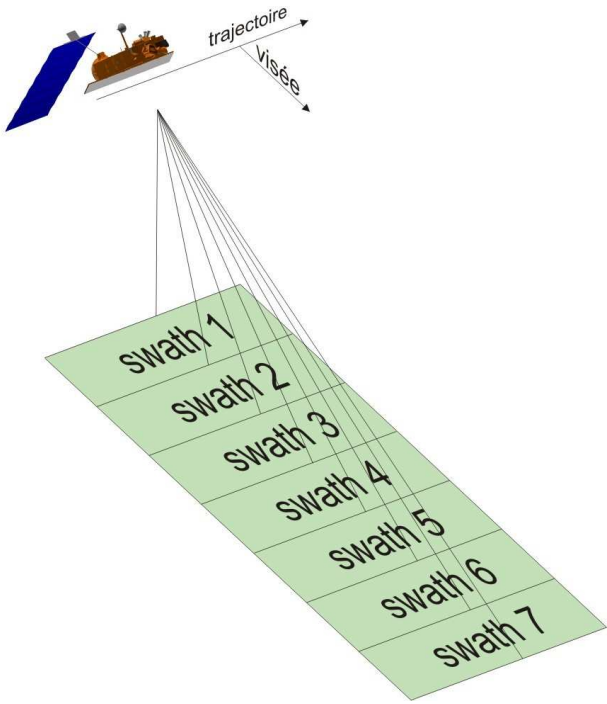
Ligne de visée et mètres LOS

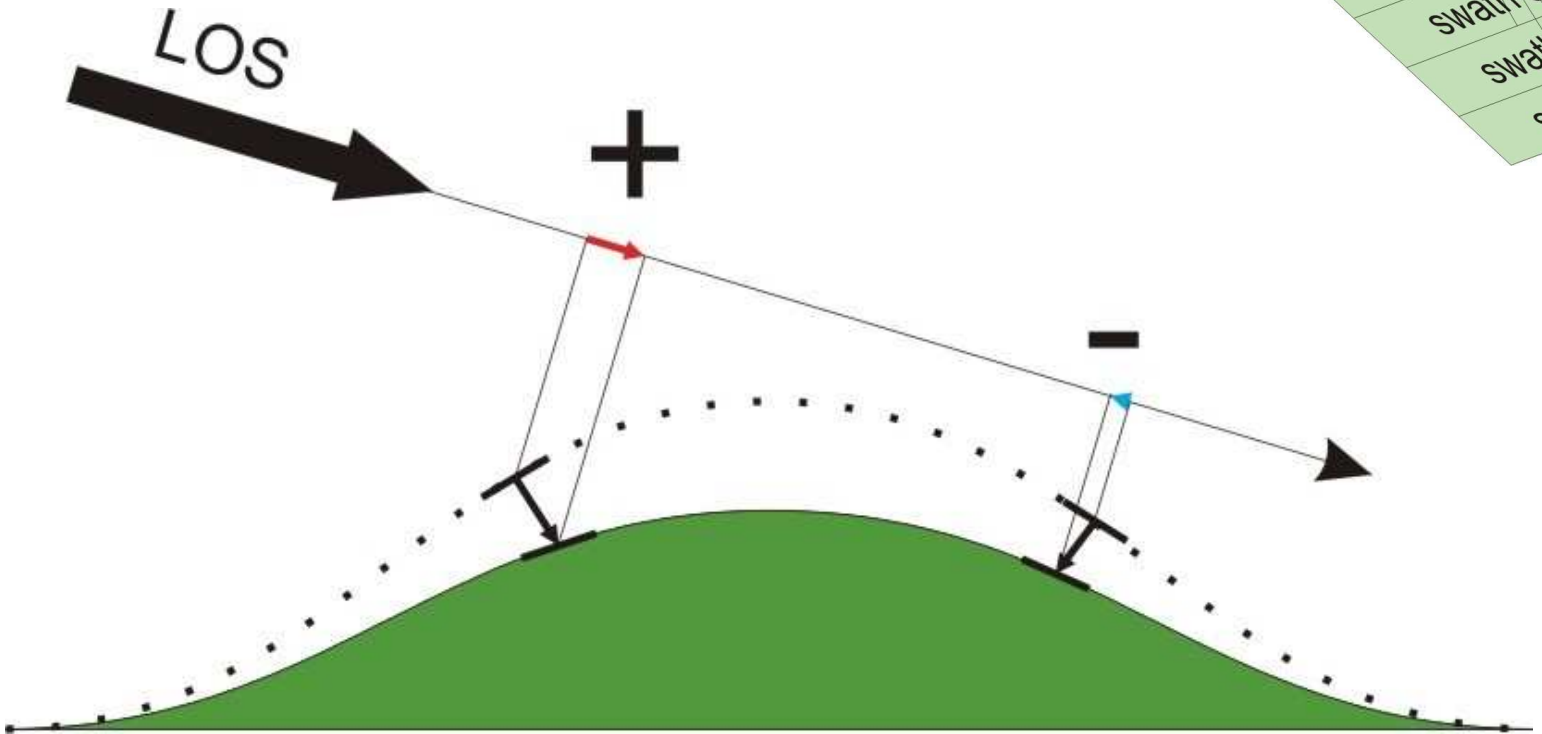
Interférogramme enroulé



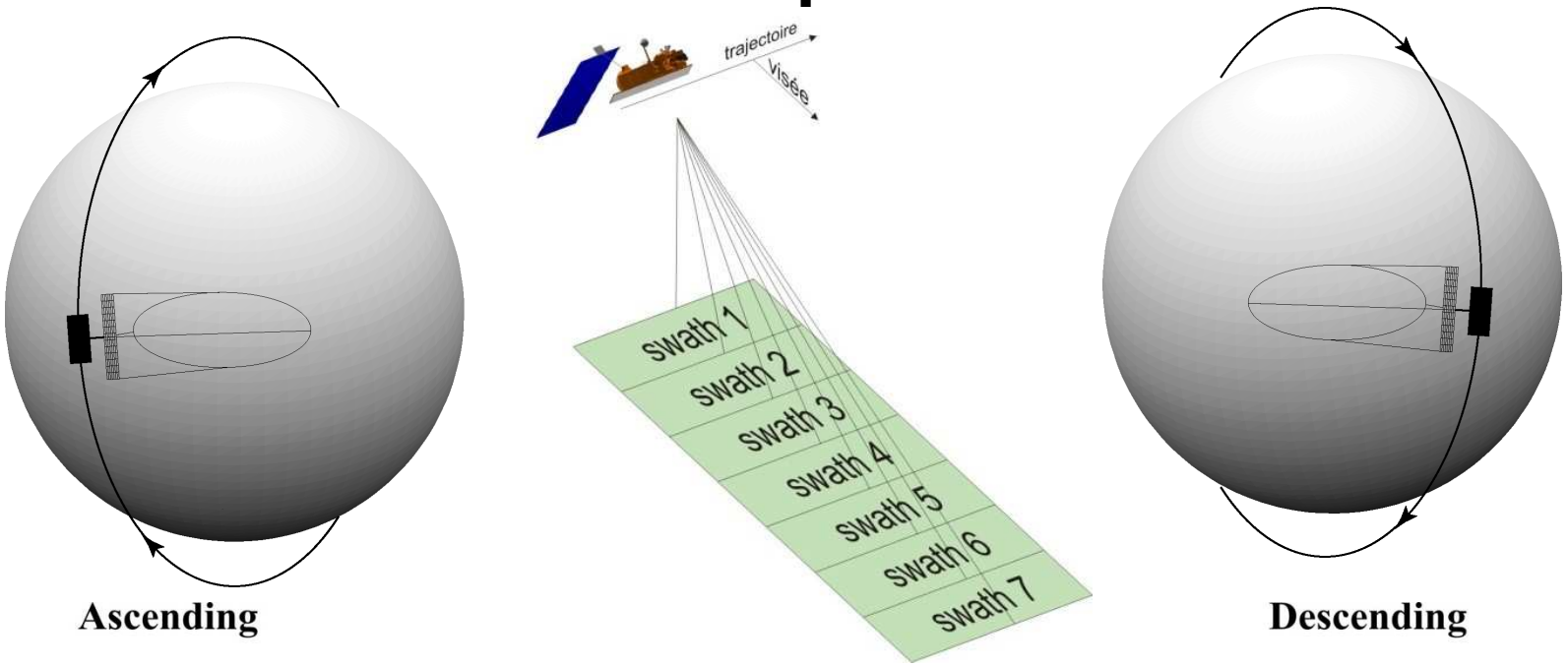
Interférogramme déroulé

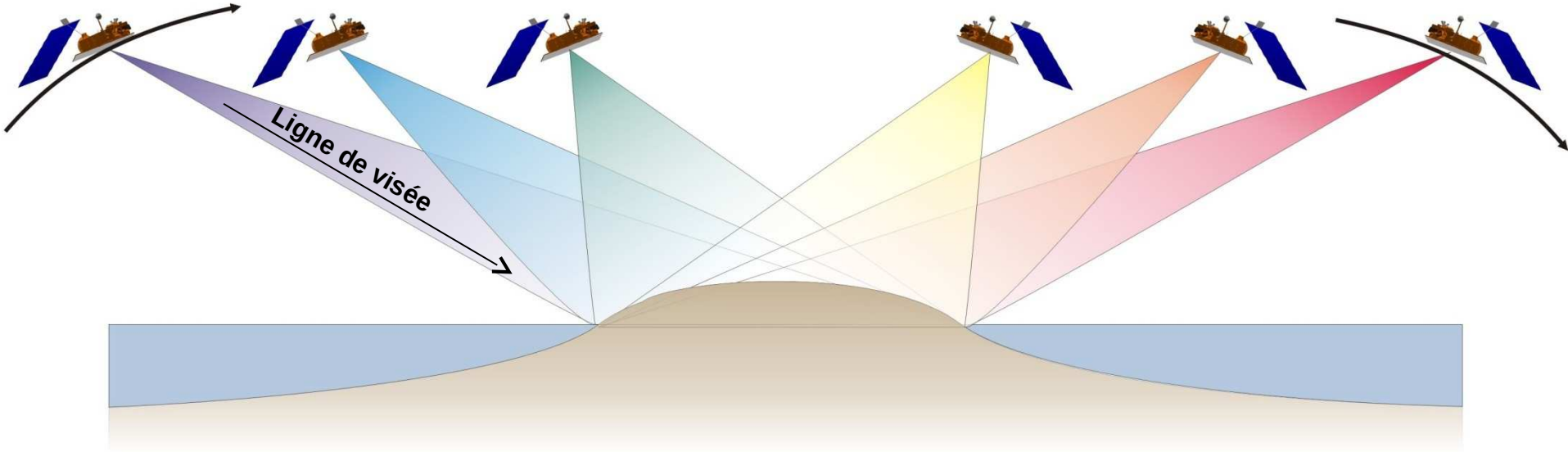






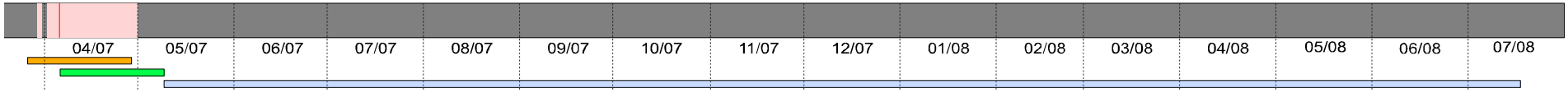
L'InSAR : Géométries d'acquisistion



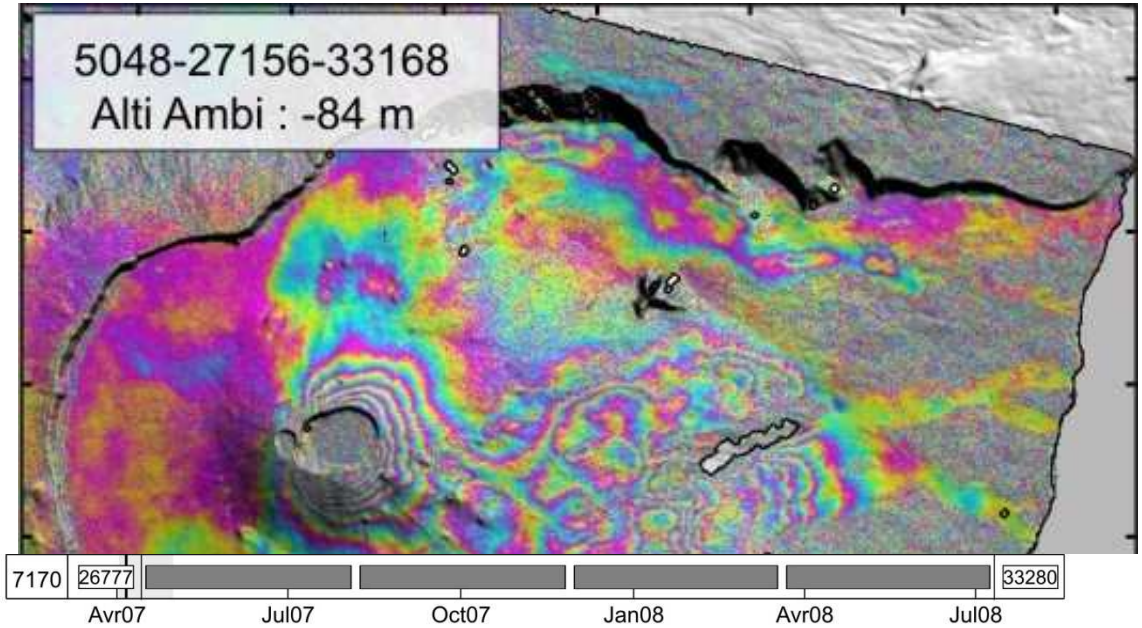


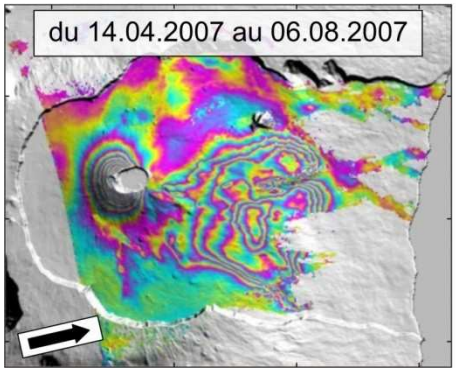
Satellites radars (travail multi-capteur)

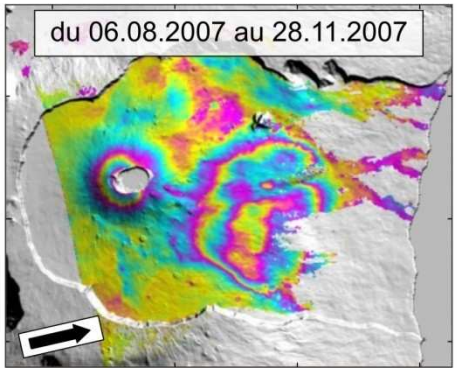
L'éruption vue par InSAR

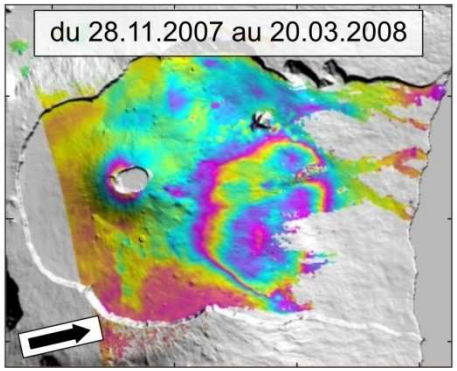


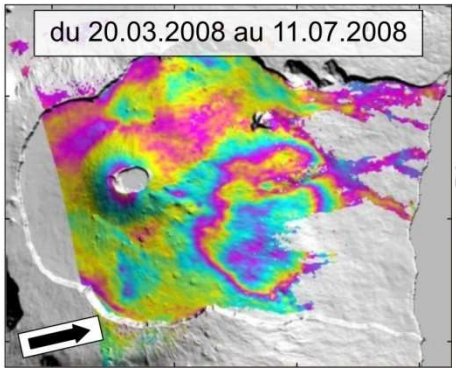
Période syn-éruptive **Période post-effondrement** **Période post-éruptive**



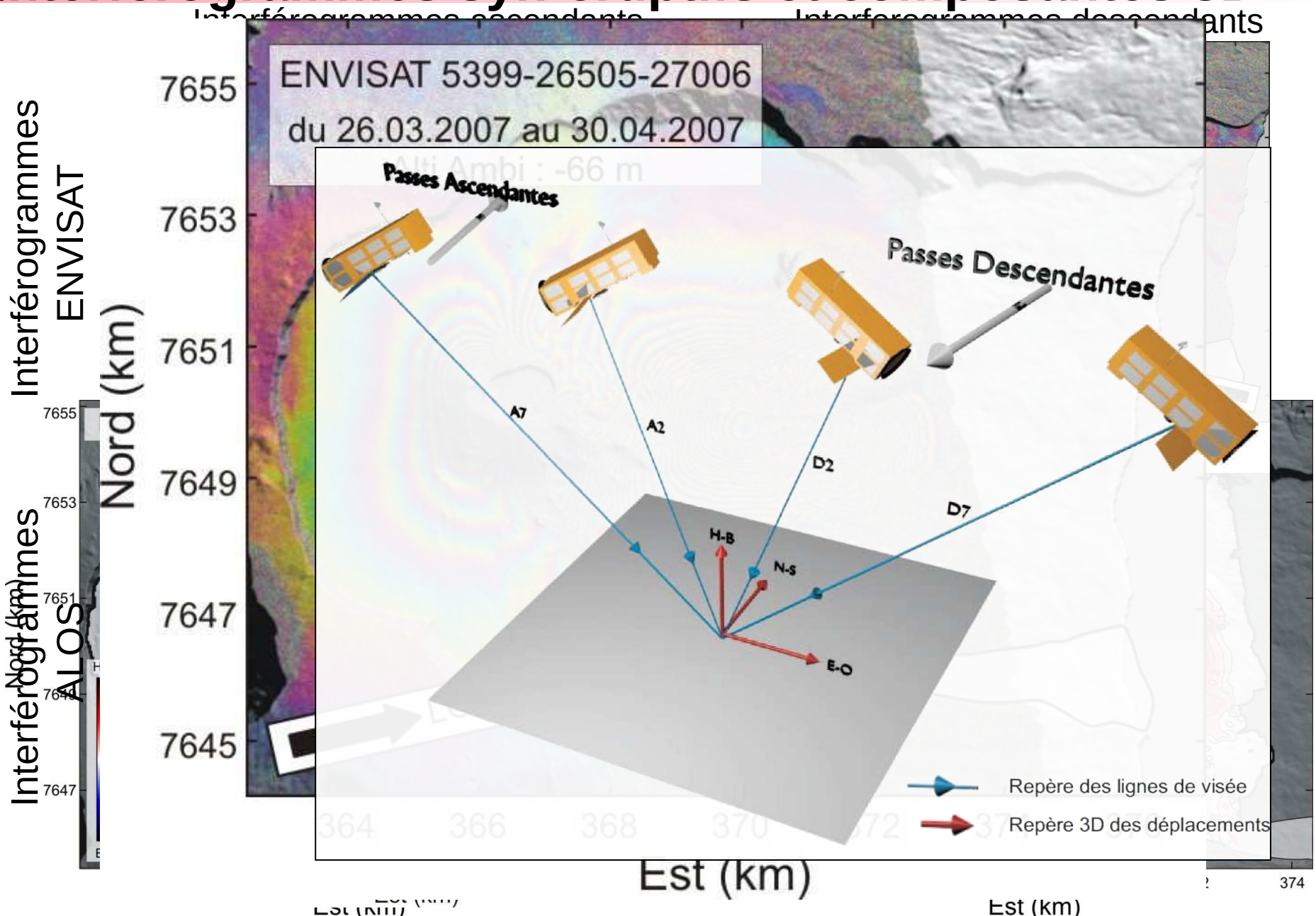




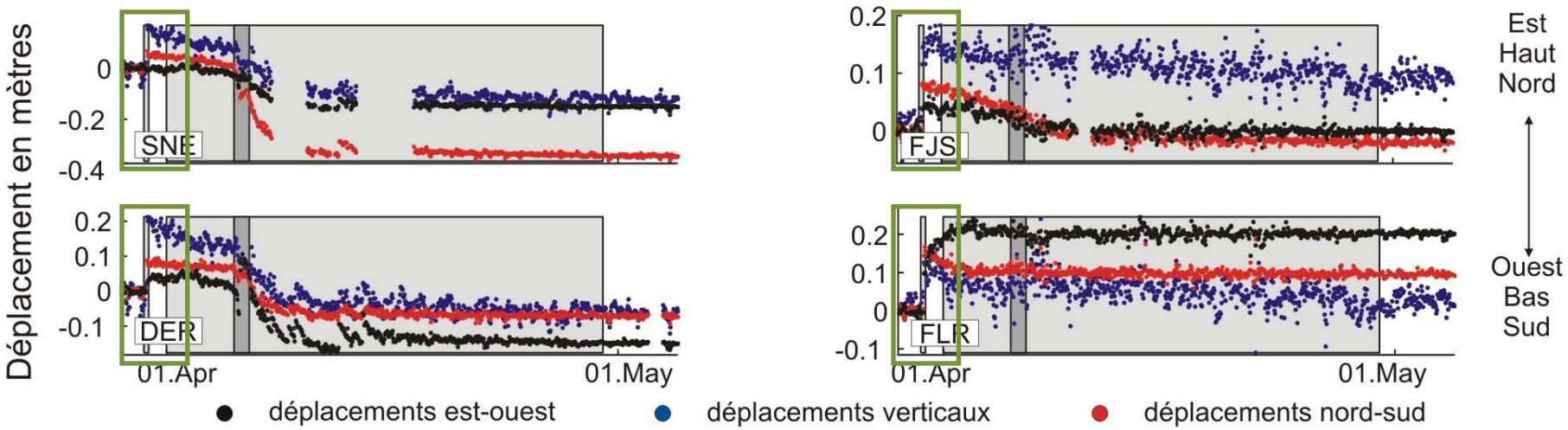


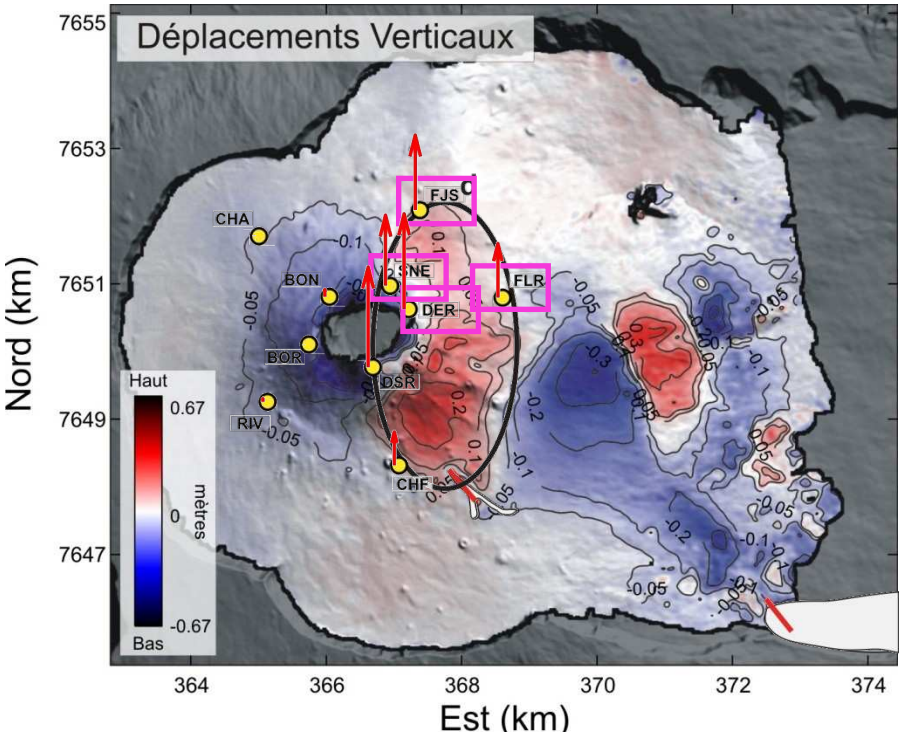


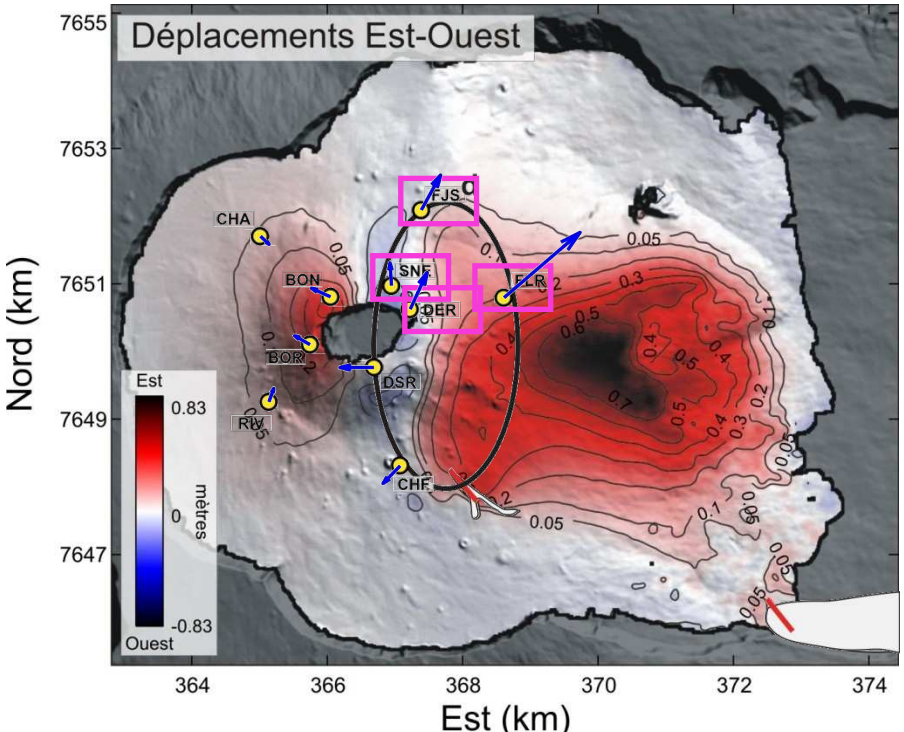
Interférogrammes syn-éruptifs et composantes 3D



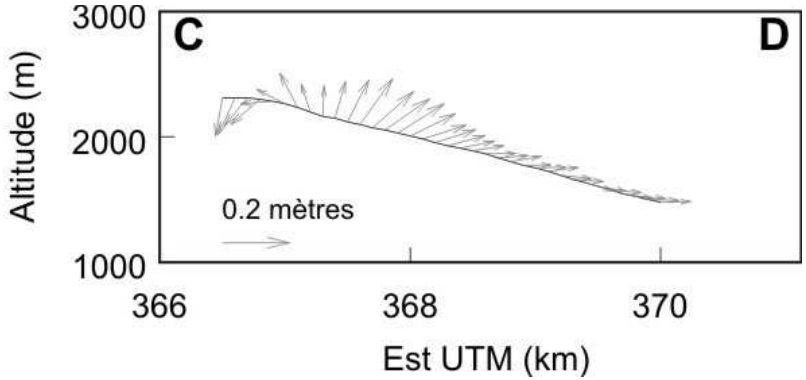
Déplacements associés à l'injection du 30 mars

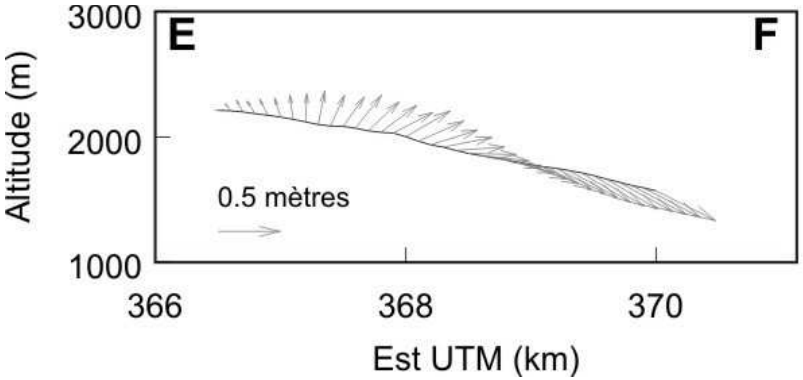


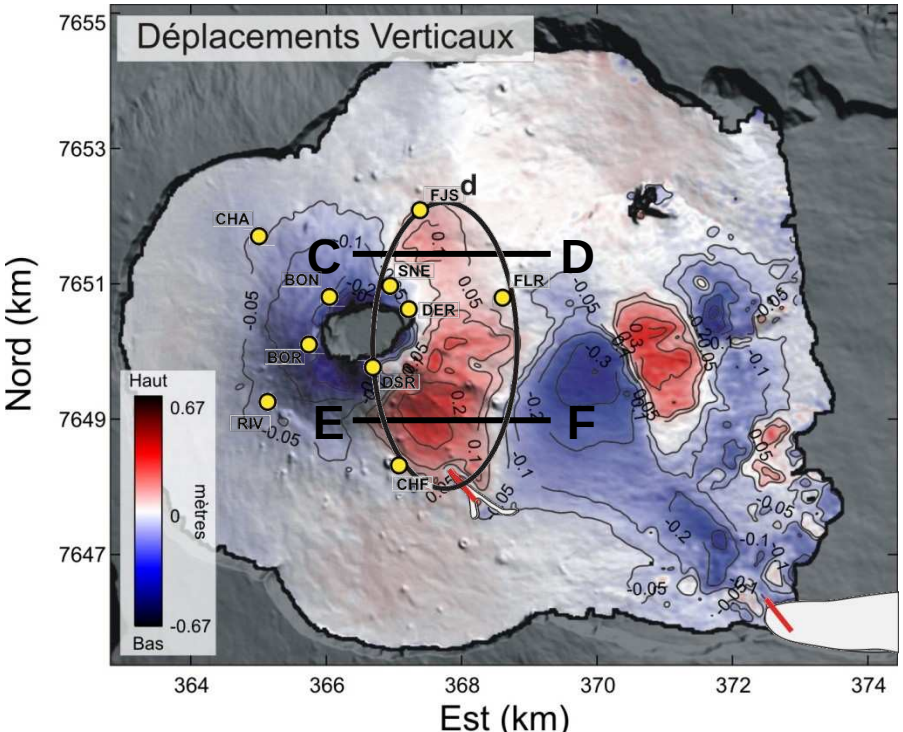


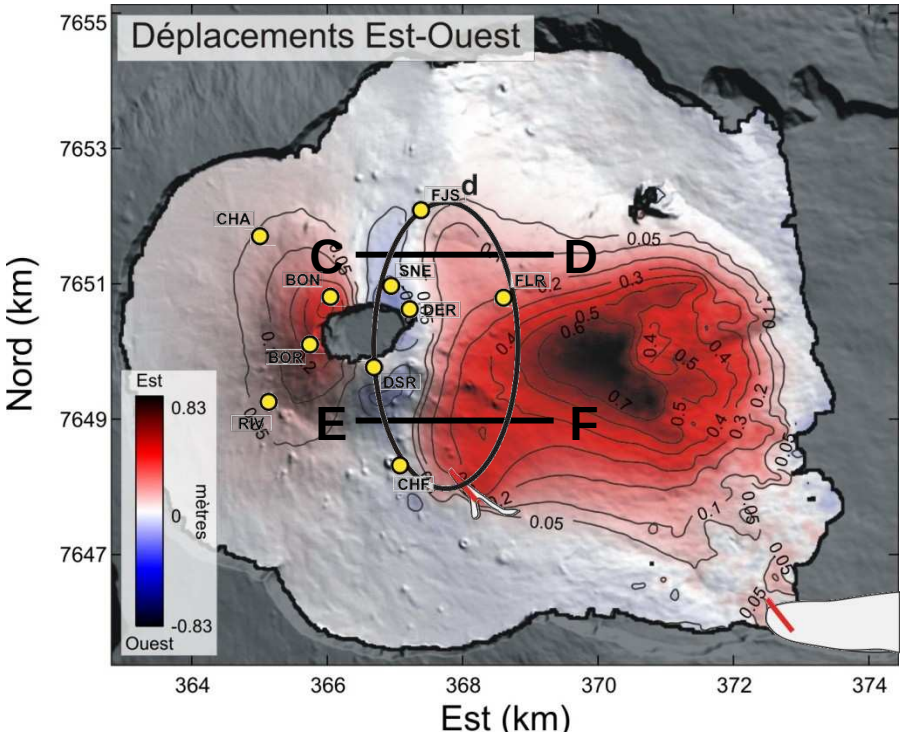


Déplacements associés à l'injection du 30 mars

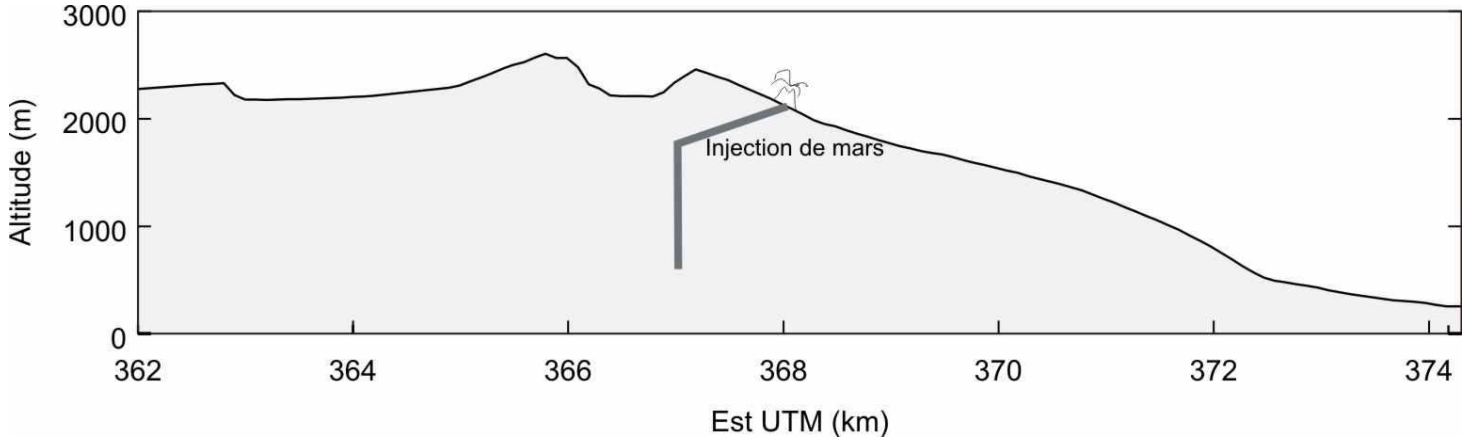


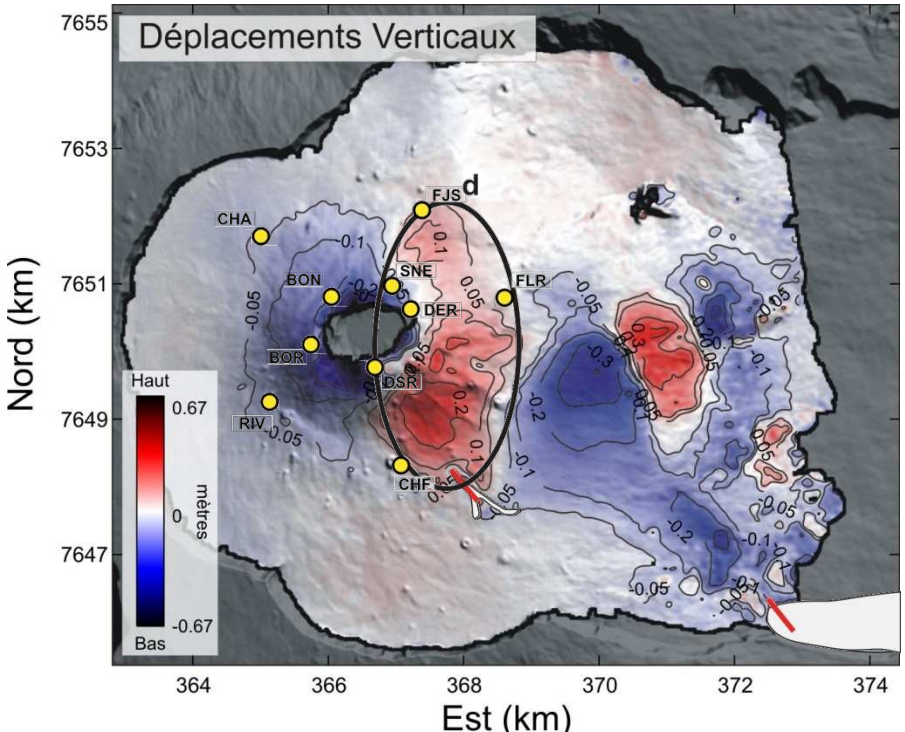


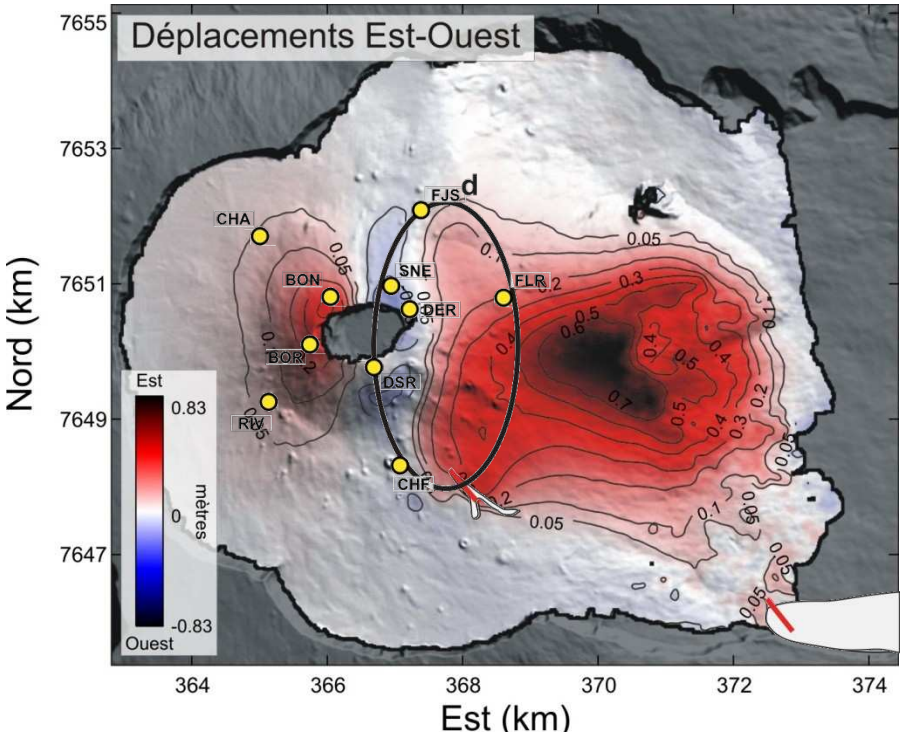




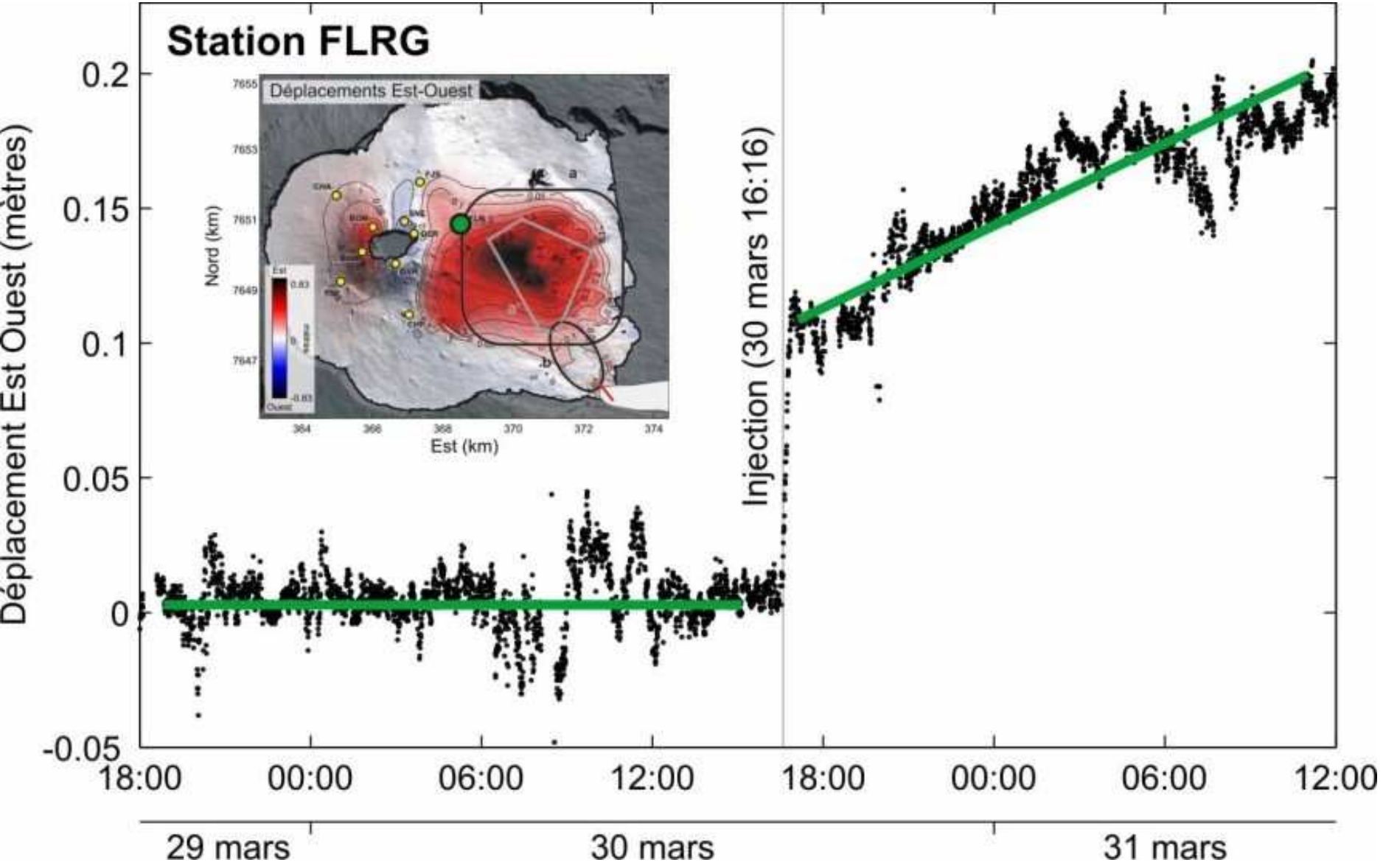
Déplacements associés à l'injection du 30 mars







Déplacements associés à l'injection du 30 mars

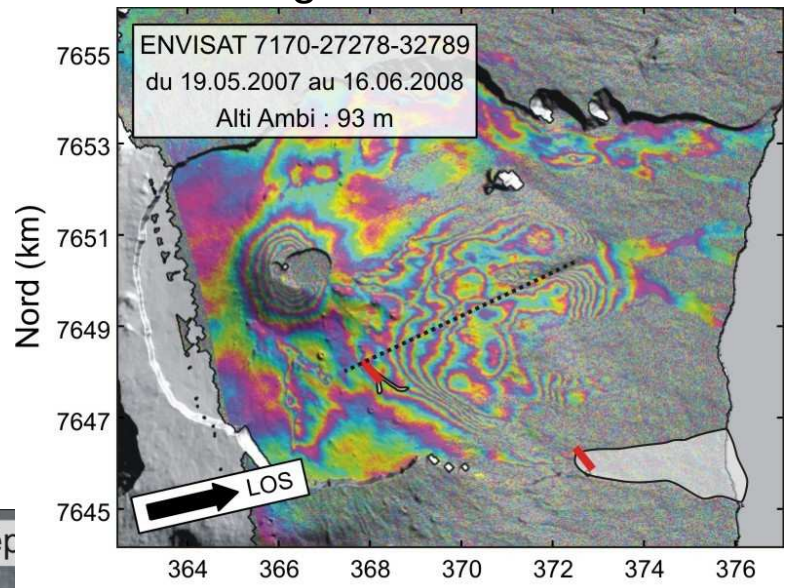


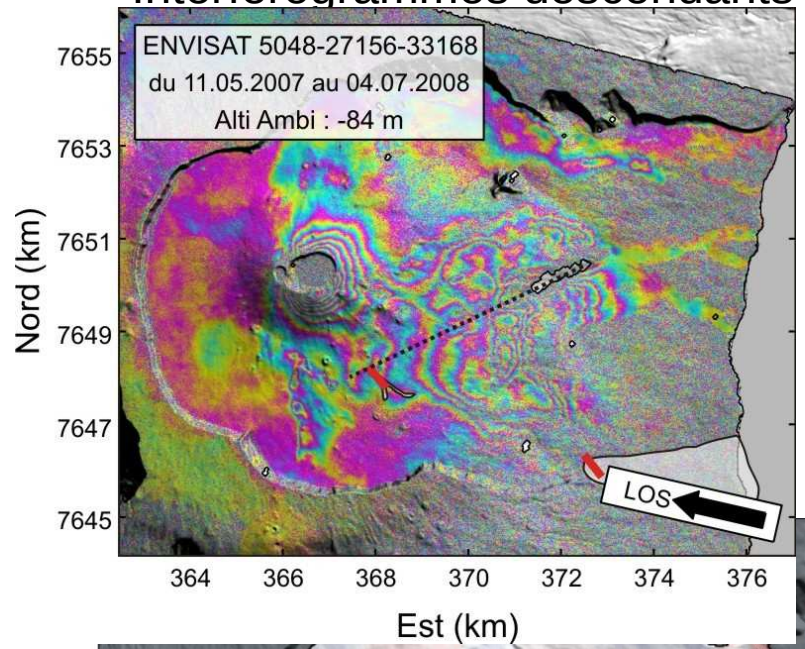
Caractérisation des déplacements post-éruptifs

Interférogrammes ascendants

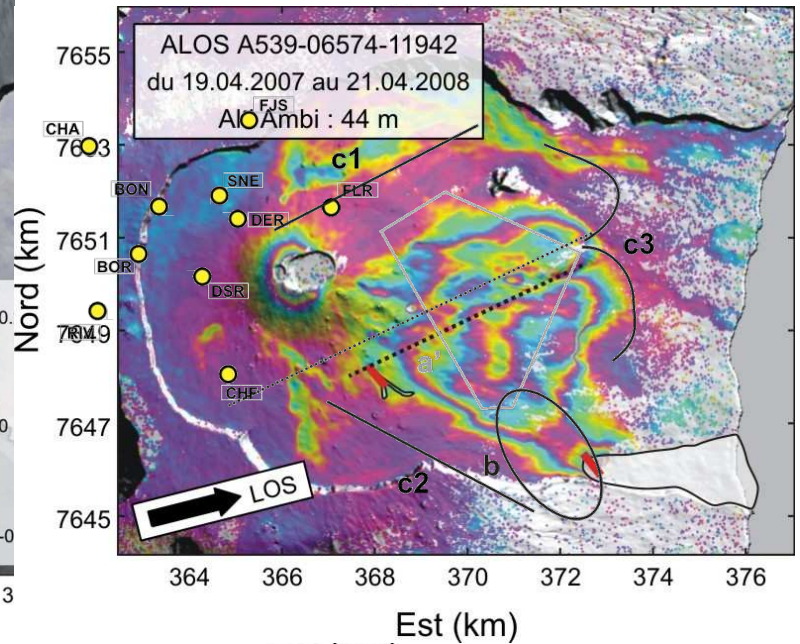
Interférogrammes descendants

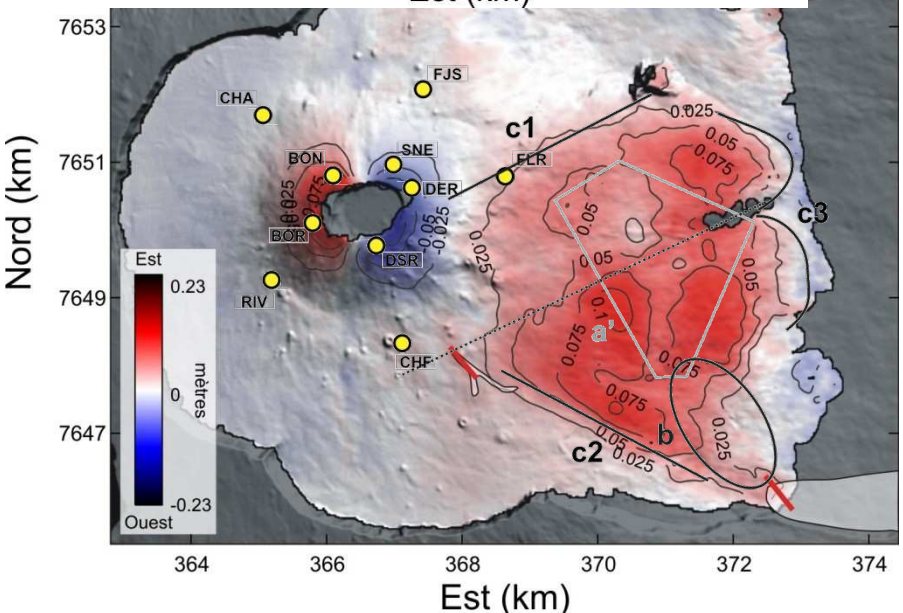
Interférogrammes ENVISAT



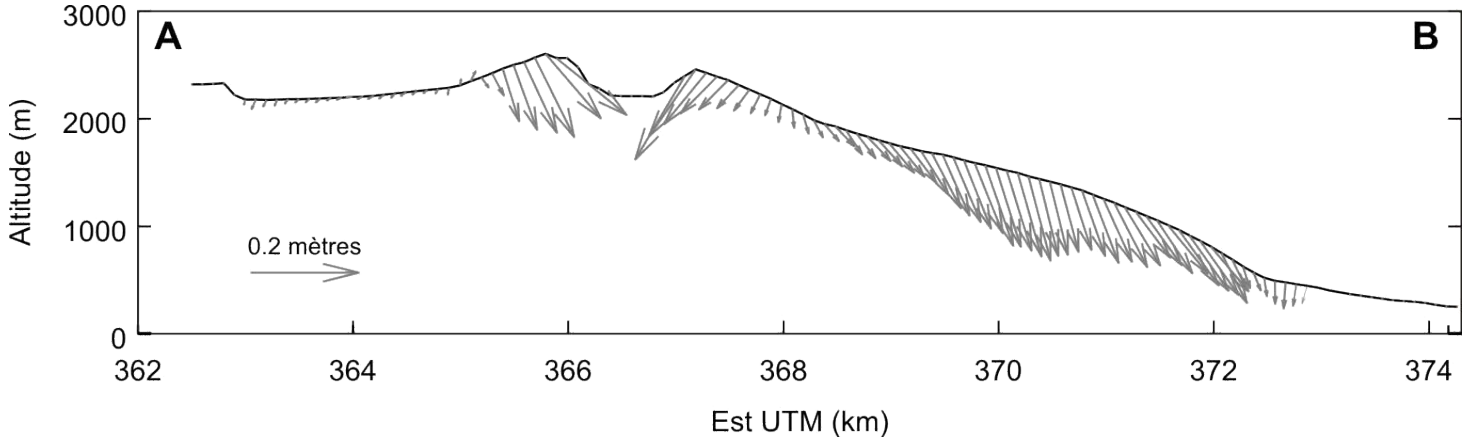


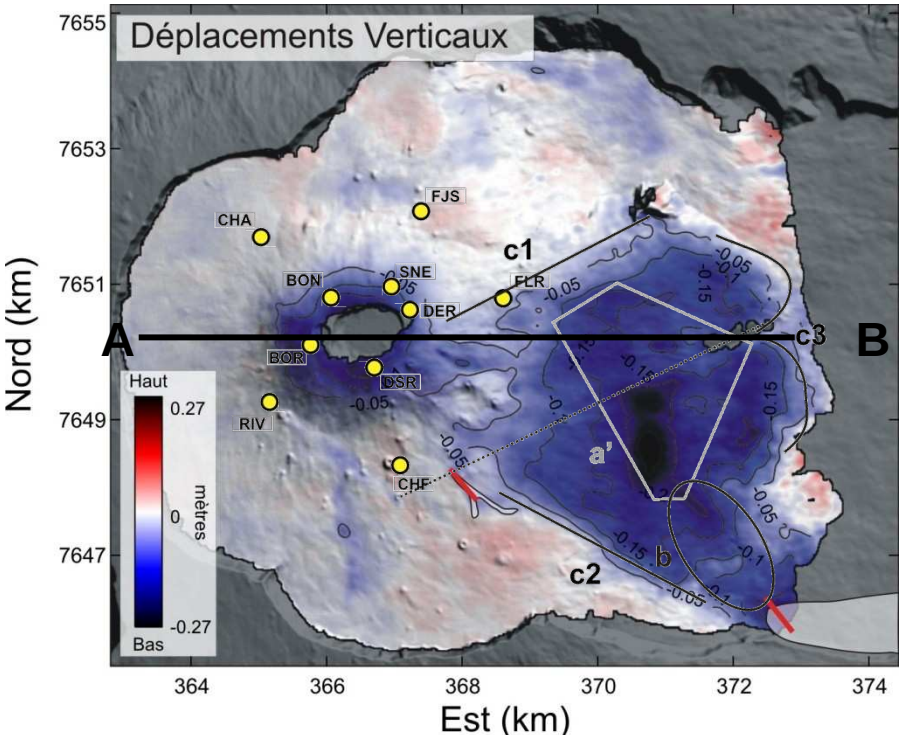
Interférogrammes ALOS

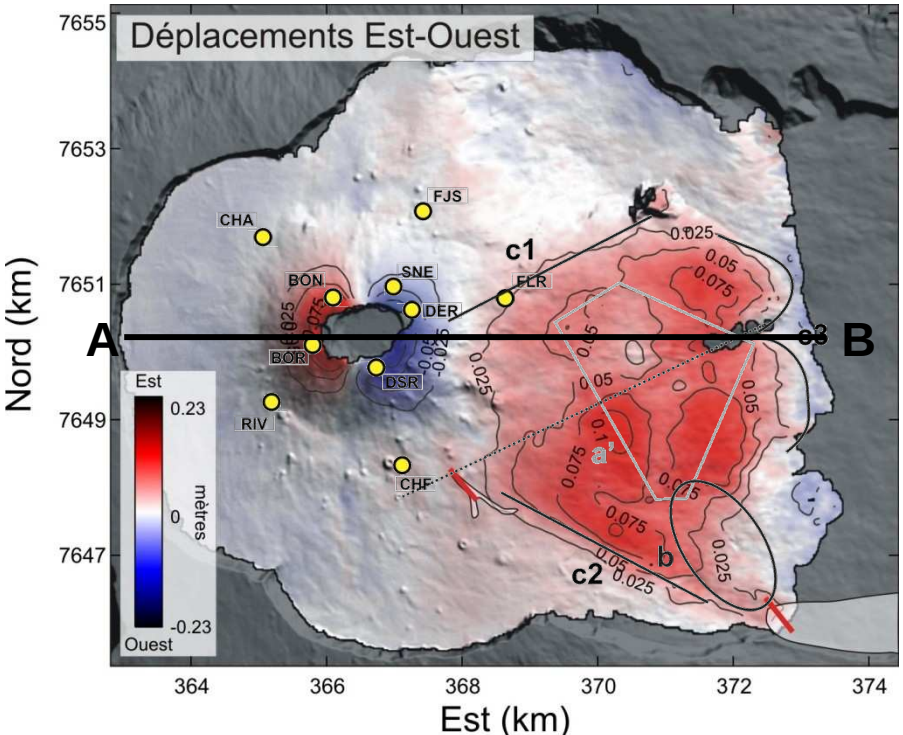




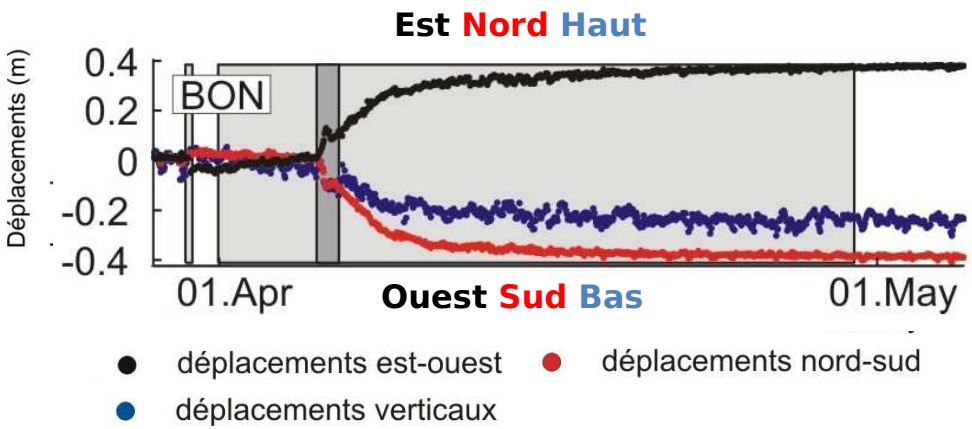
Caractérisation des déplacements sommitaux

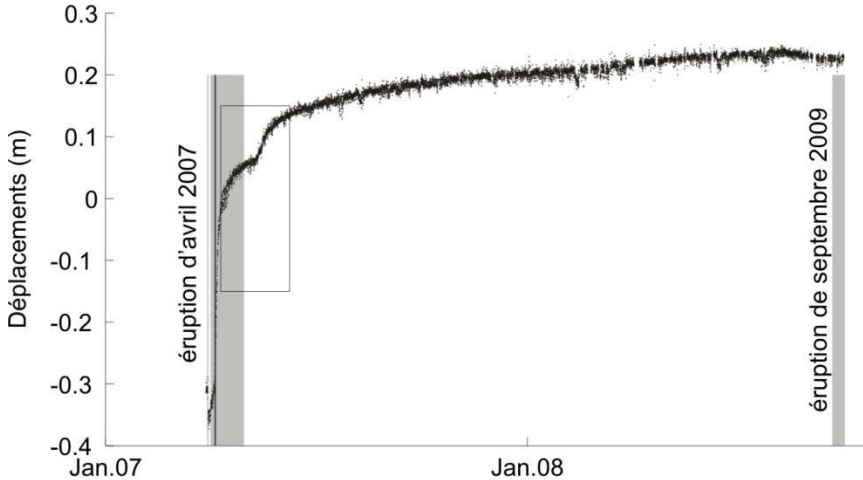


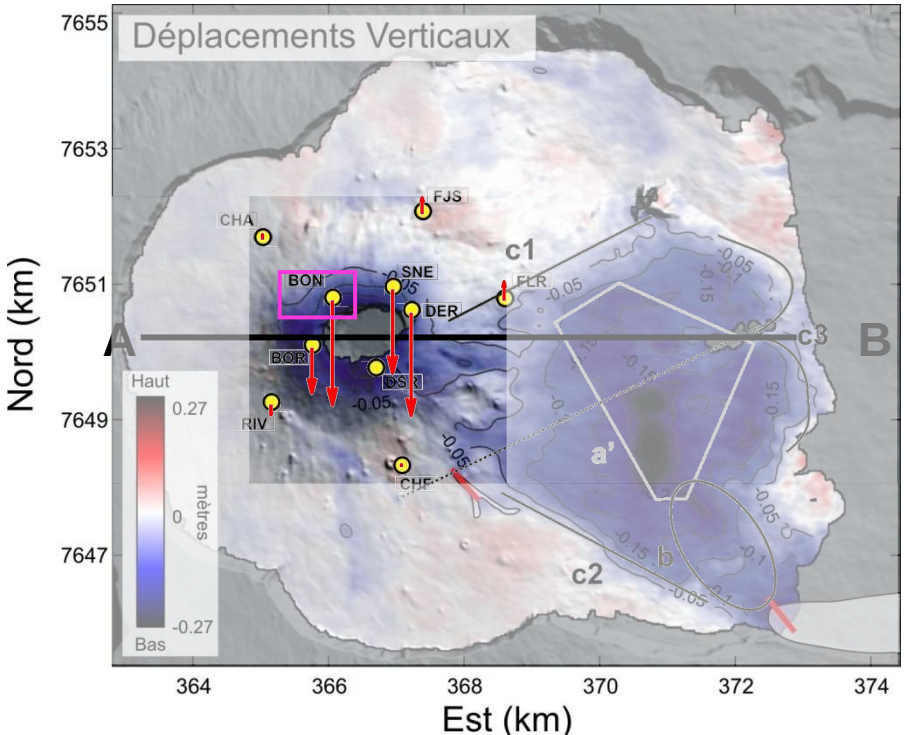


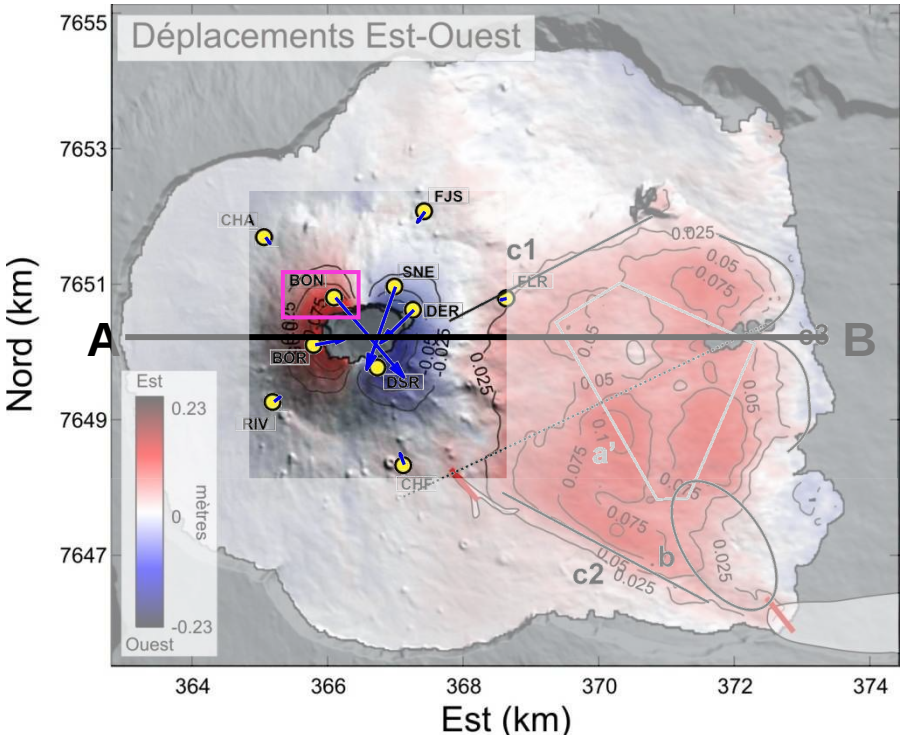


Différents motifs de déformation

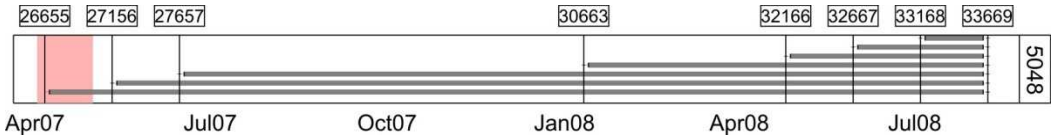


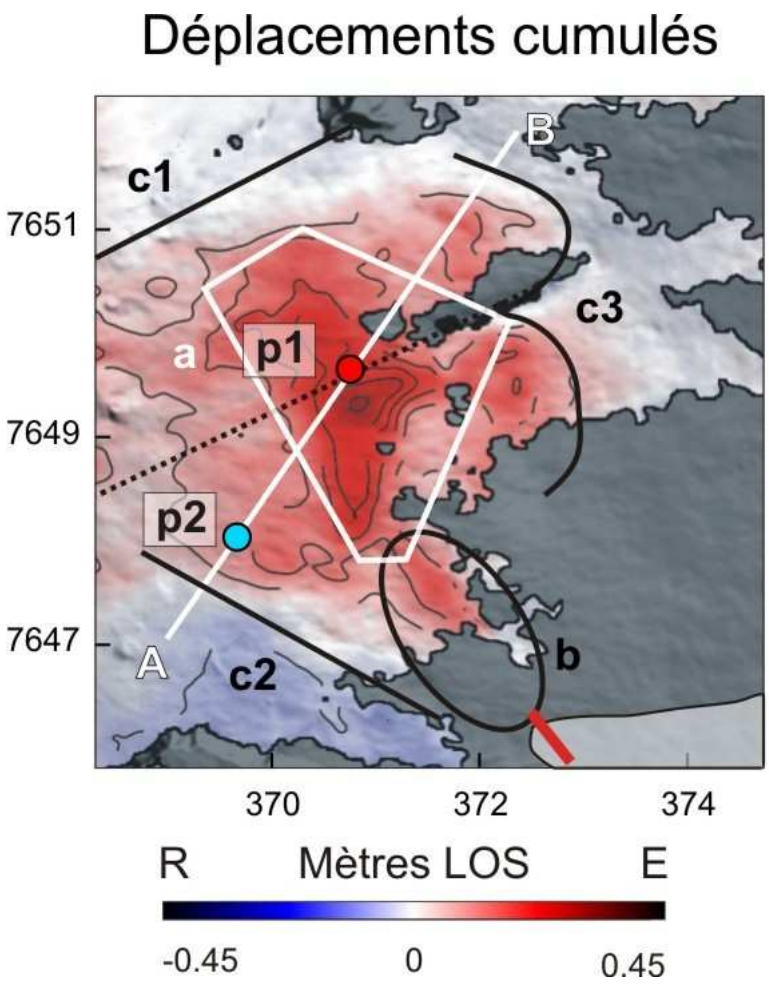


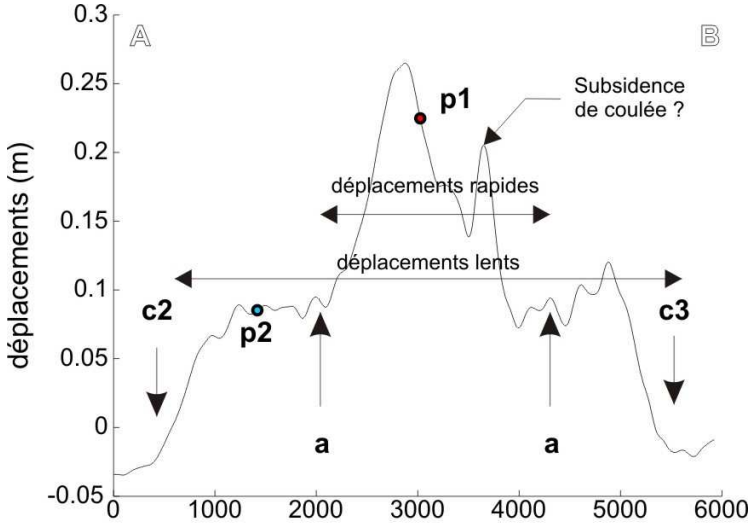


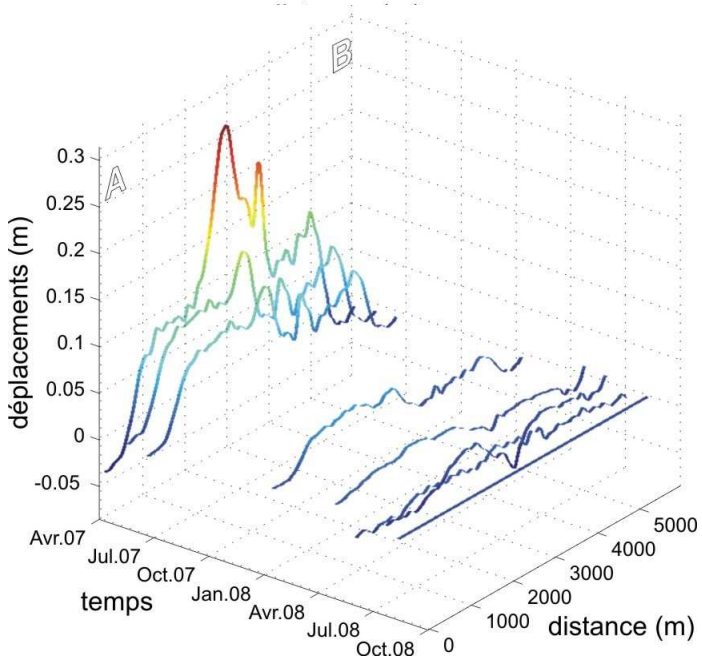


Dynamique des déplacements du flanc est

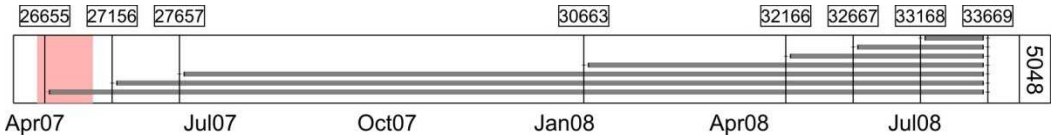


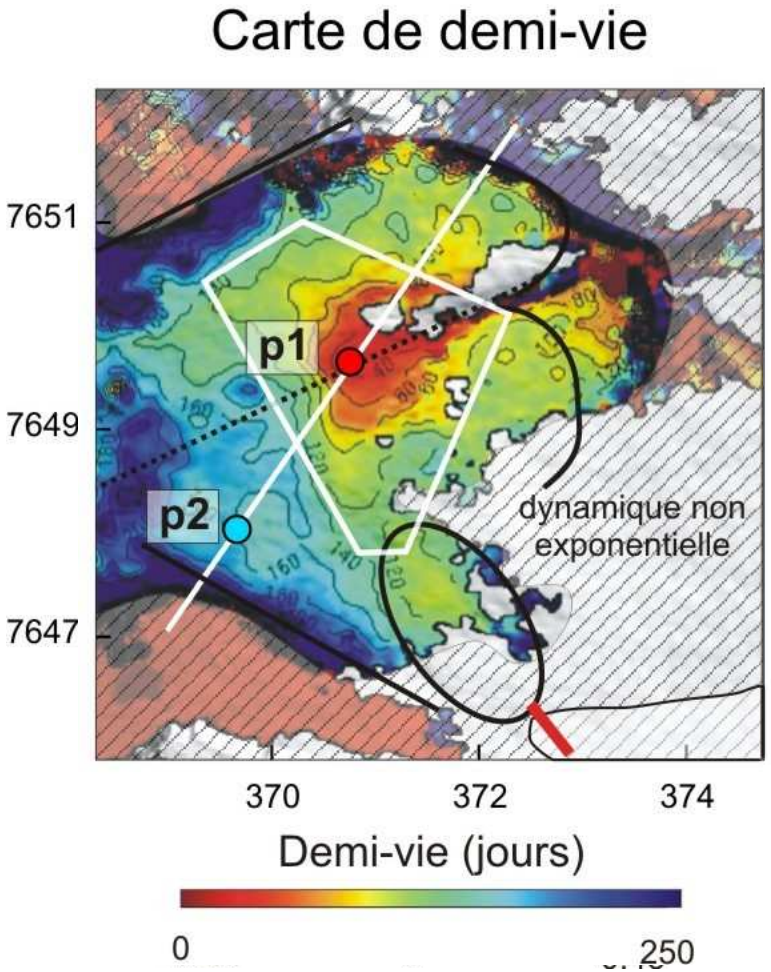


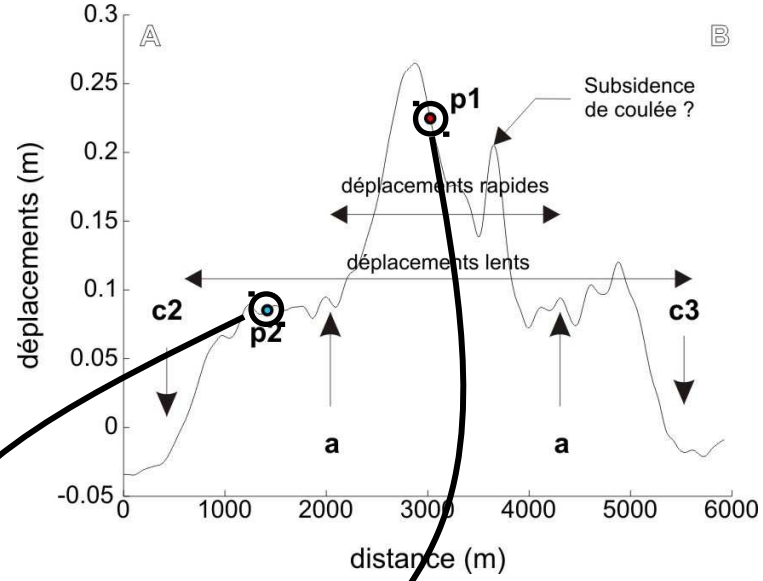


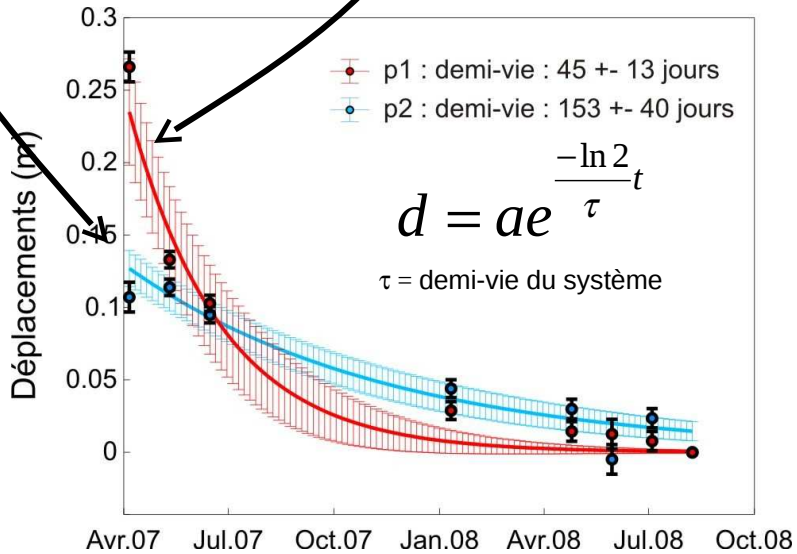


Dynamique des déplacements du flanc est

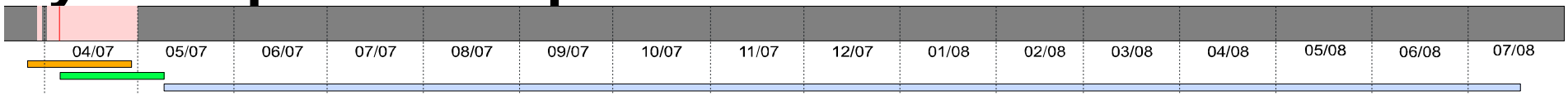


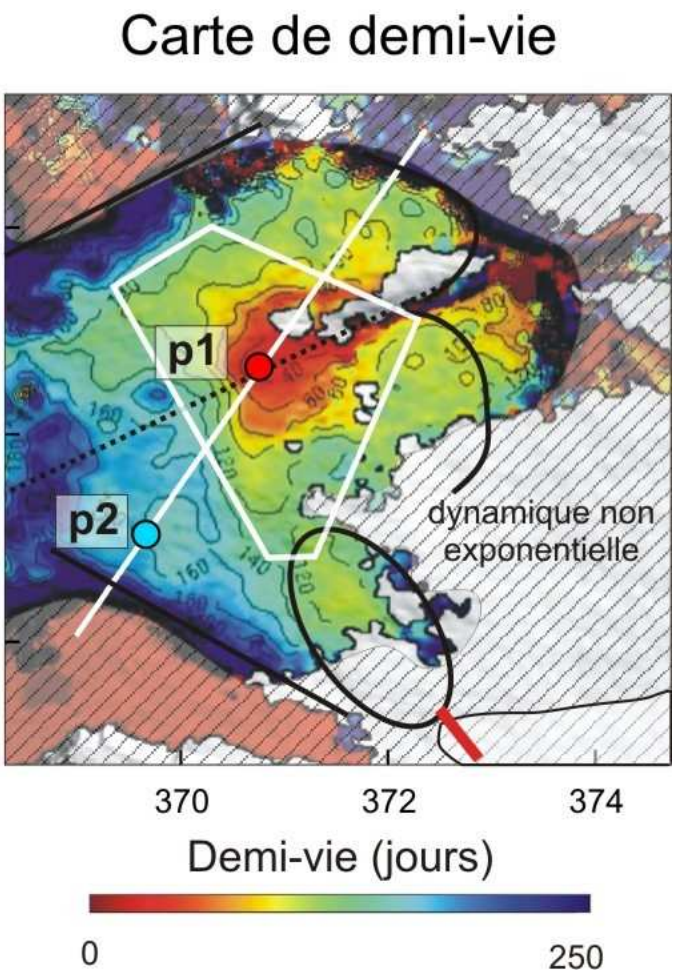


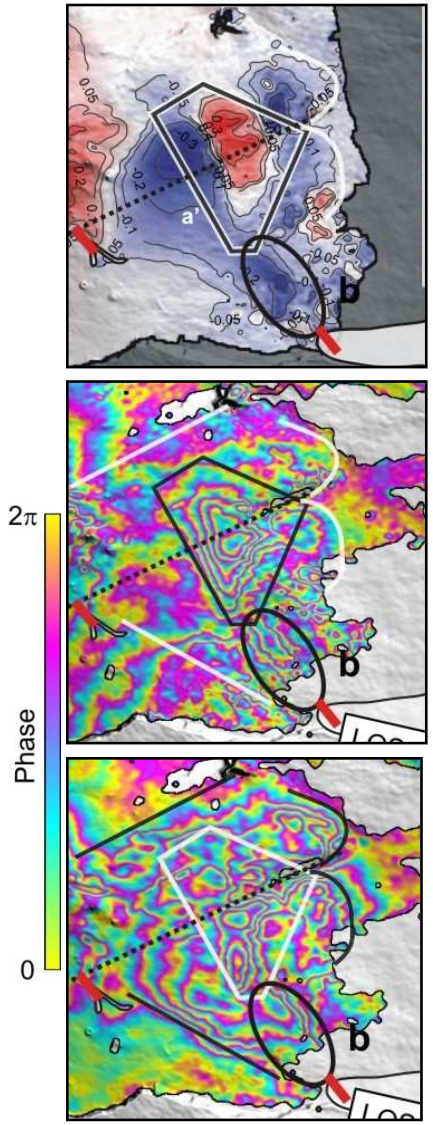




Dynamique des déplacements du flanc est





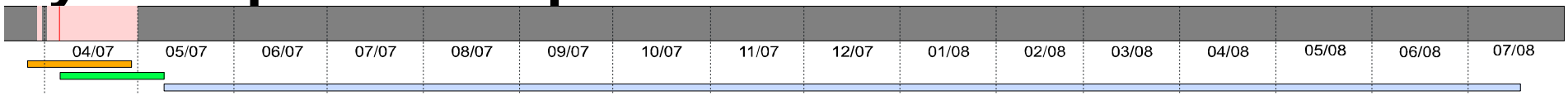


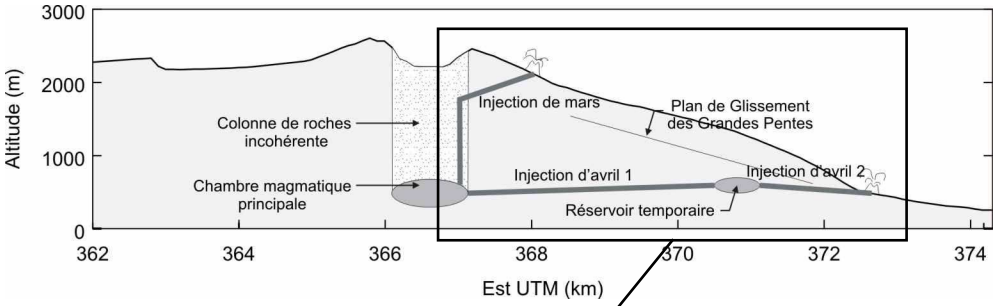
Début de l'éruption :
Gonflement rapide

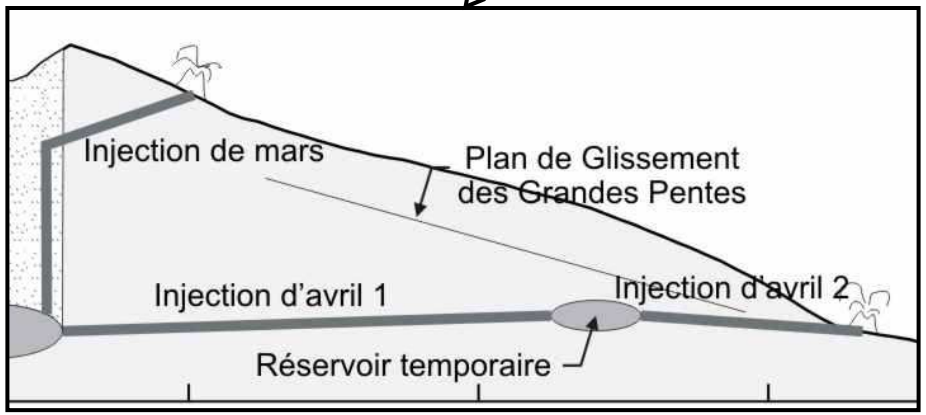
Fin de l'éruption :
dégonflement rapide
Corrélation avec la fissure éruptive

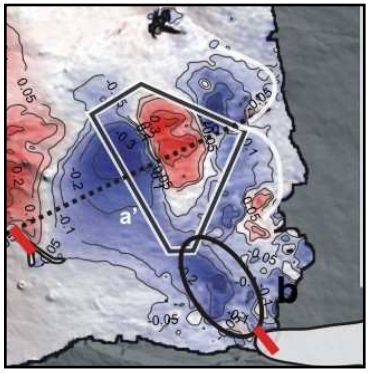
Après l'éruption :
Déplacements lents

Dynamique des déplacements du flanc est

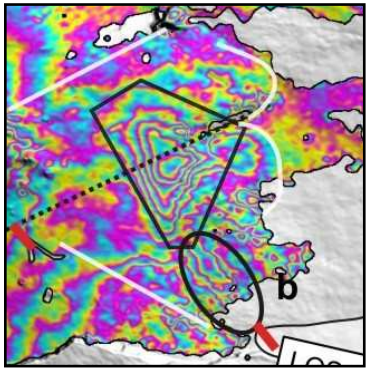




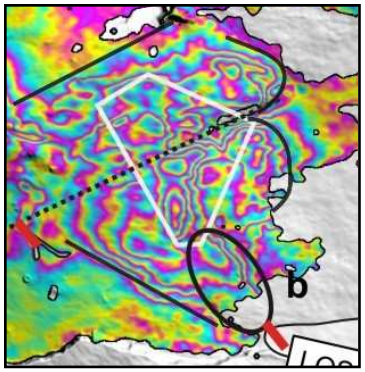




Début de l'éruption :
Gonflement rapide

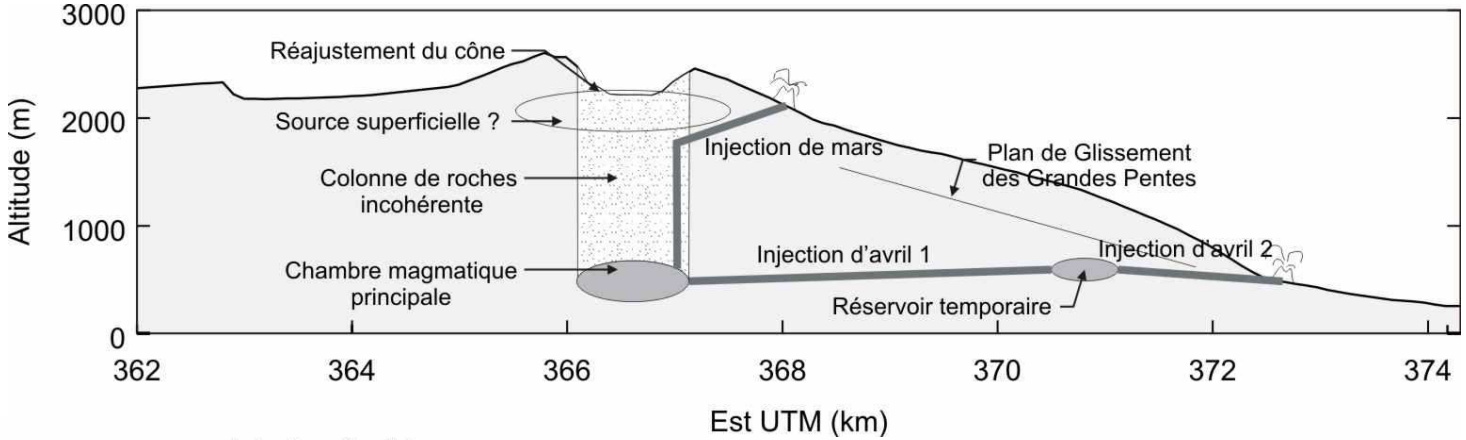


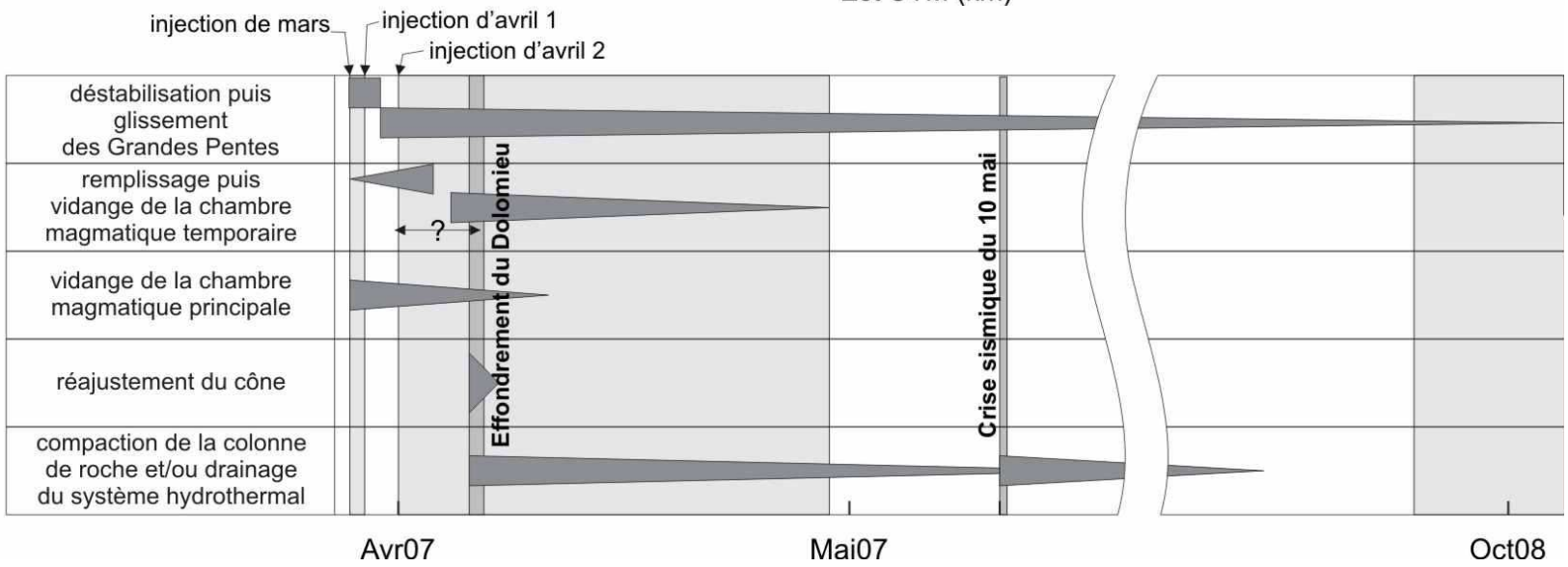
Fin de l'éruption :
dégonflement rapide
Corrélation avec la fissure éruptive



Après l'éruption :
Déplacements lents

Bilan de l'analyse qualitative de la déformation





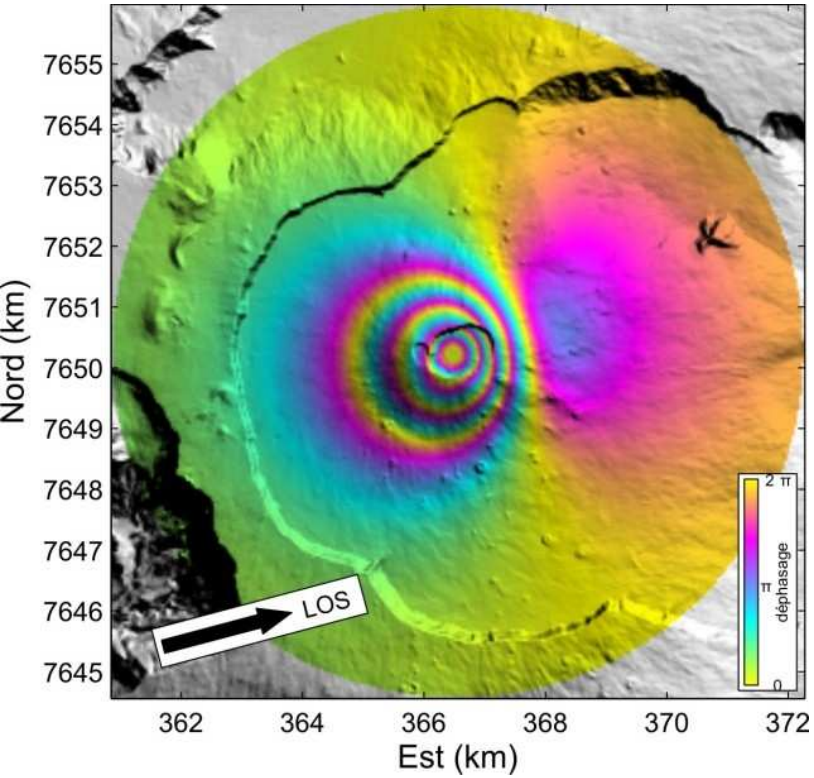
Nécessité de contraindre les sources par des méthodes de modélisation

Partie II

Méthodes de modélisation

Problèmes liés à la détermination des sources

Difficile de revenir directement à la source si l'on connaît les déplacements

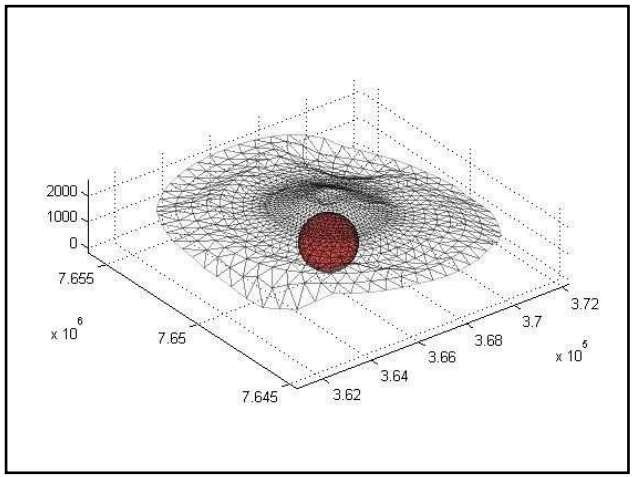


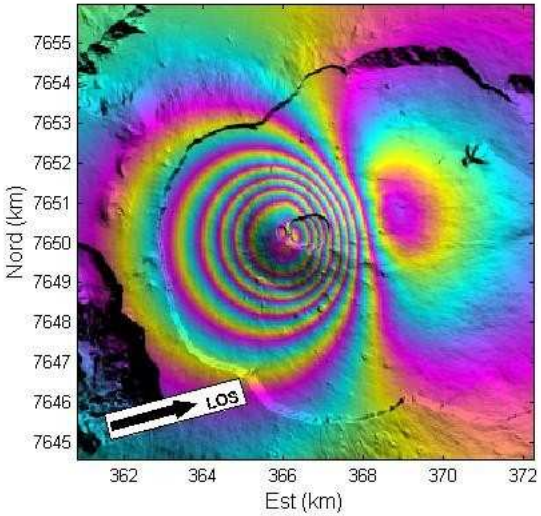
Forme ???

Centre ???
Rayon ??
Variation de volume ???

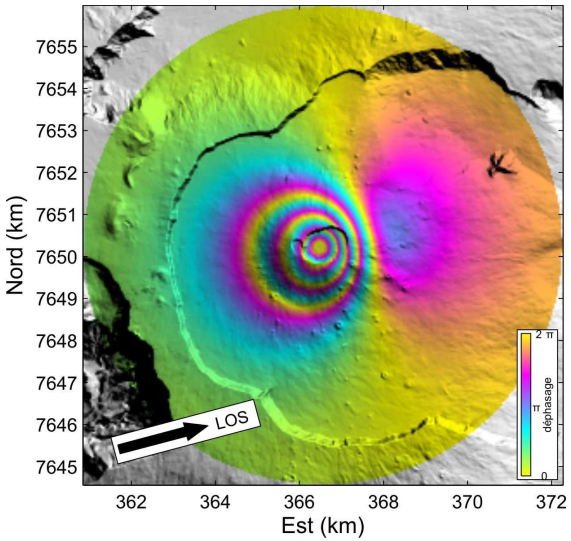
Problèmes liés à la recherche des sources

Possibilité de calculer les déplacements dus à une source, en connaissant les paramètres





Impossible de revenir directement à la source si on connaît les déplacements



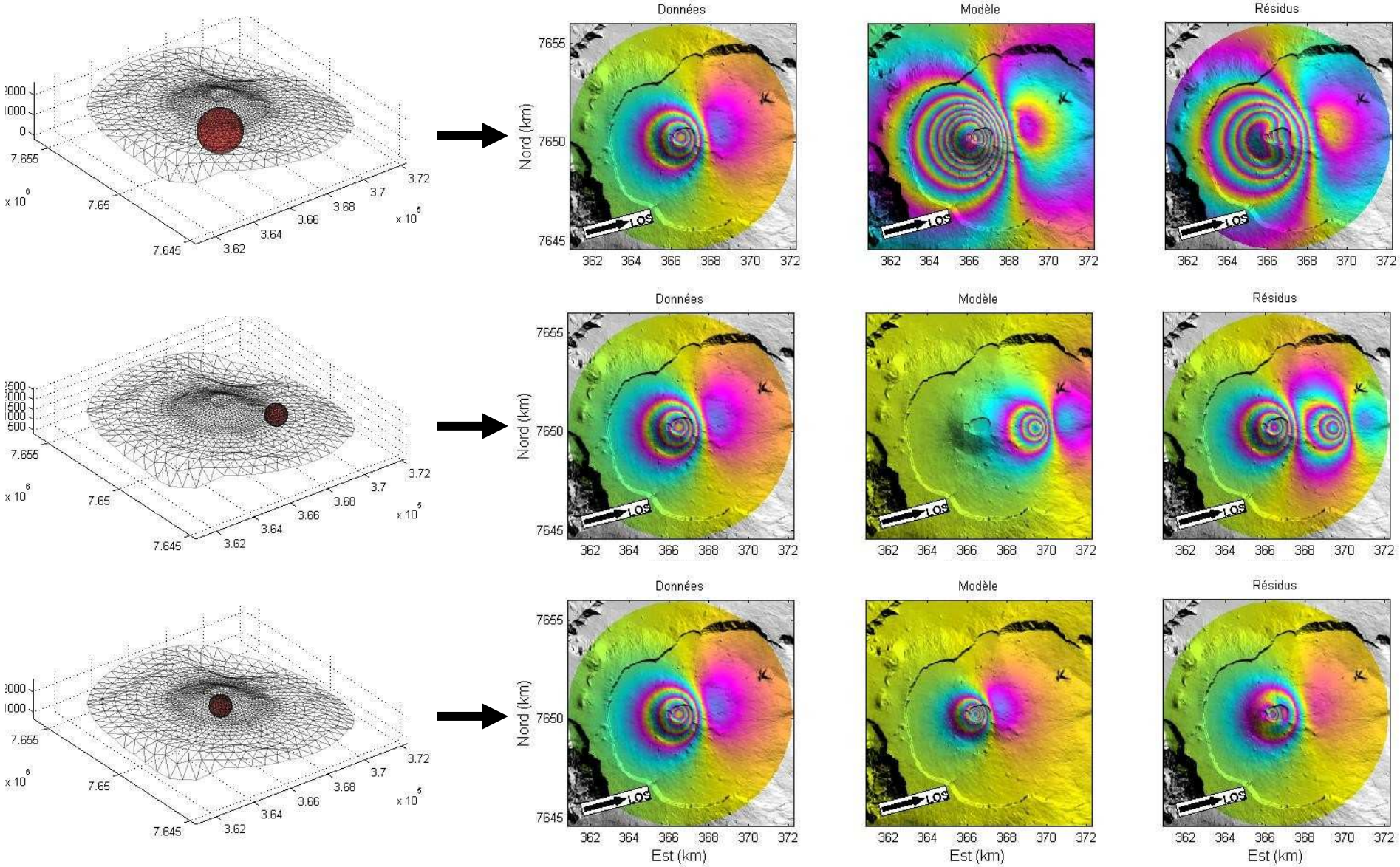
Centre ???

Rayon ??

Pression ???

Procédure d'inversion NA-MBEM

Choix des paramètres au hasard (en fait, hasard orienté), sélection du modèle le plus proche des donnés



MBEM : Calcul de la fonction coût (misfit)

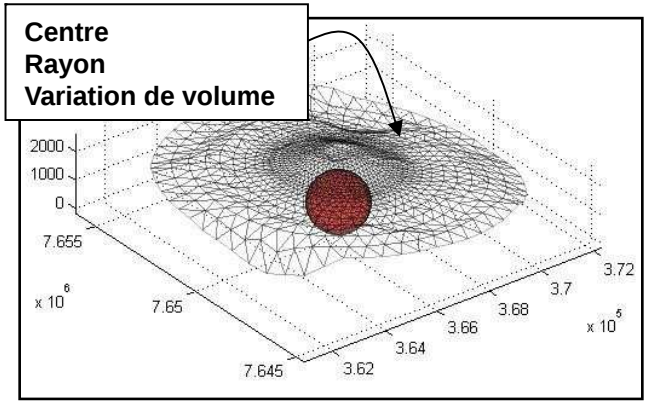
A priori : géométrie, nombre de sources

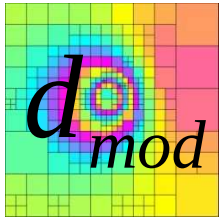
↓

Choix des paramètres de la source

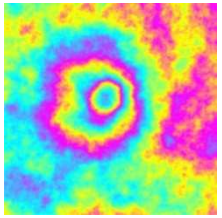
Modèle direct MBEM (Cayol et al. 1998)

Centre
Rayon
Variation de volume

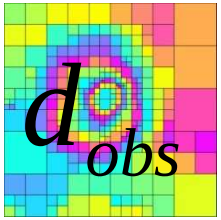




Préparation des données



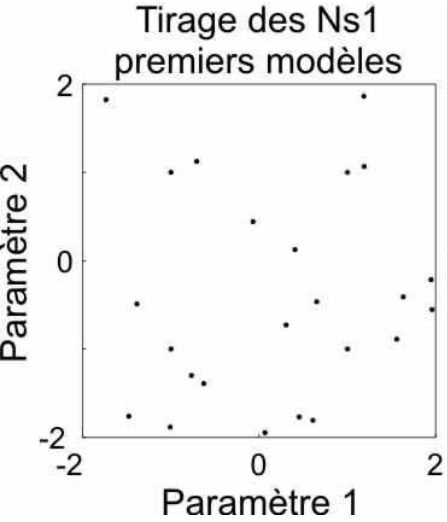
Sous-échantillonnage des données



Fonction coût (misfit)

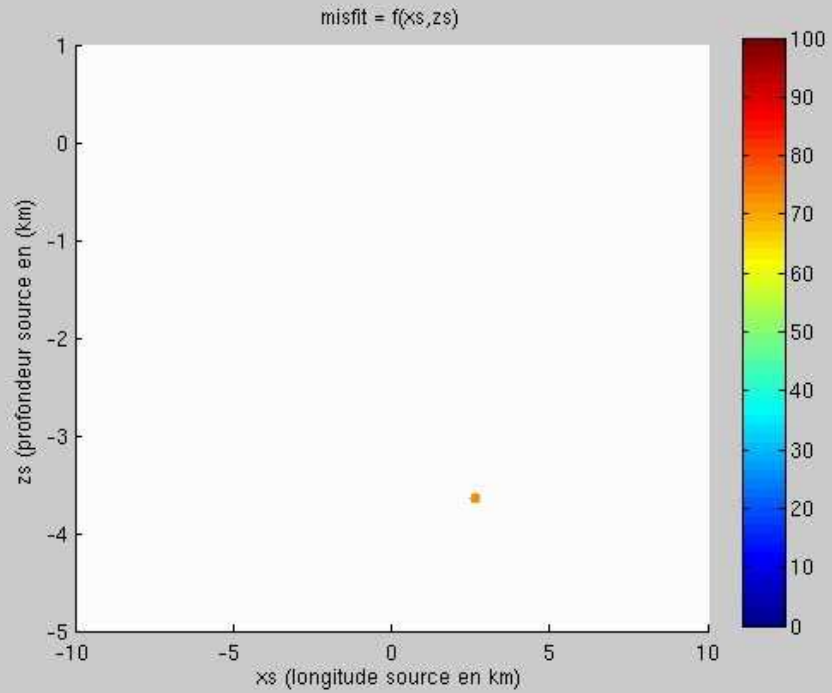
$$\chi^2 = \sum_{i=1}^{n} \frac{1}{\sigma^2} \left(d_i^{mod} - d_i^{obs} \right)^2$$

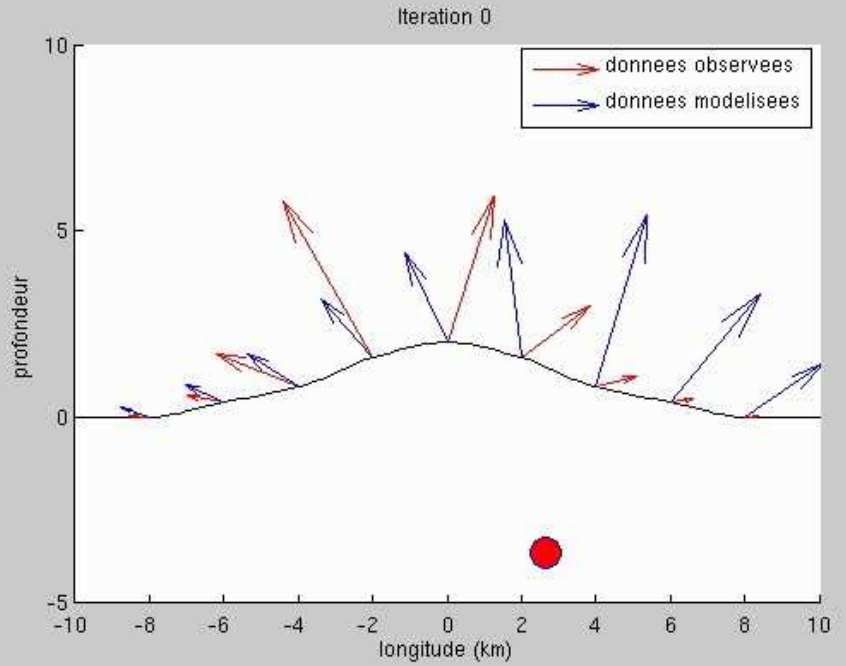
Recherche du meilleur modèle (NA)



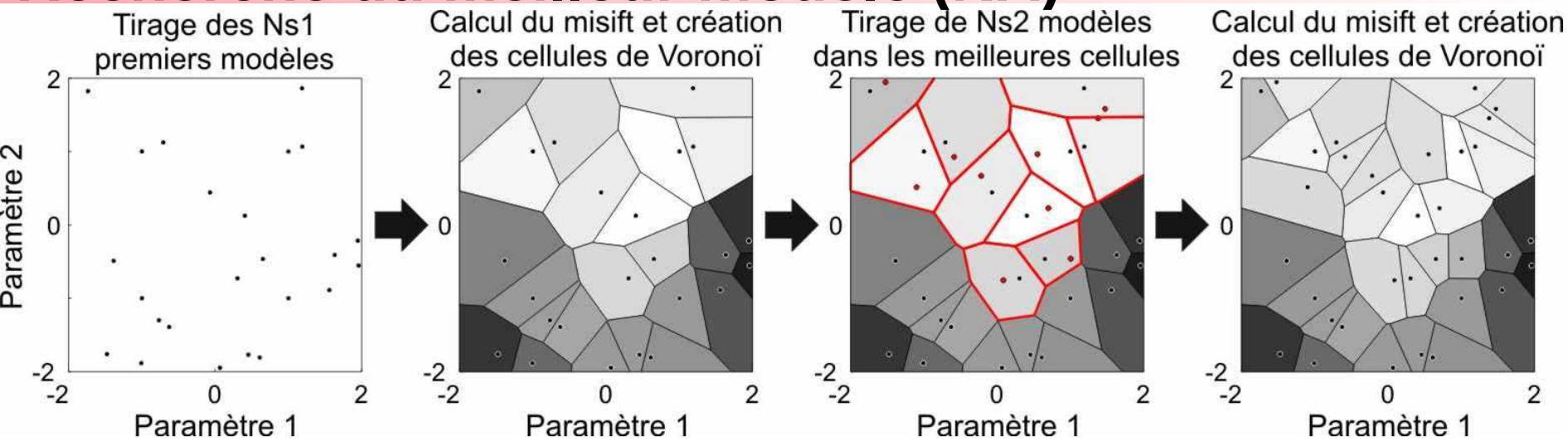
Minimisation de la fonction coût (misfit)

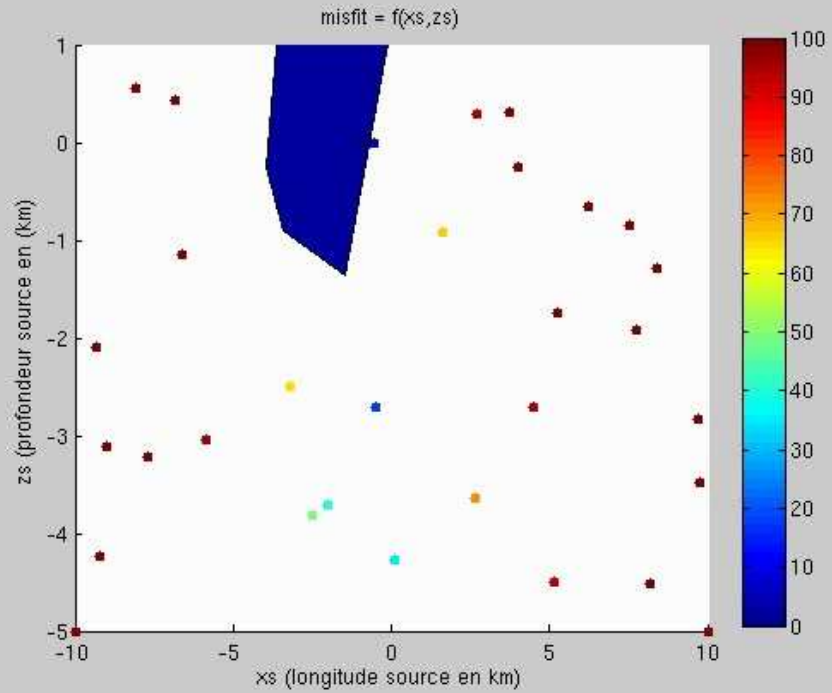
$$\chi^2 = \sum_{i=1}^{n} \frac{1}{\sigma^2} \left(d_i^{mod} - d_i^{obs} \right)^2$$

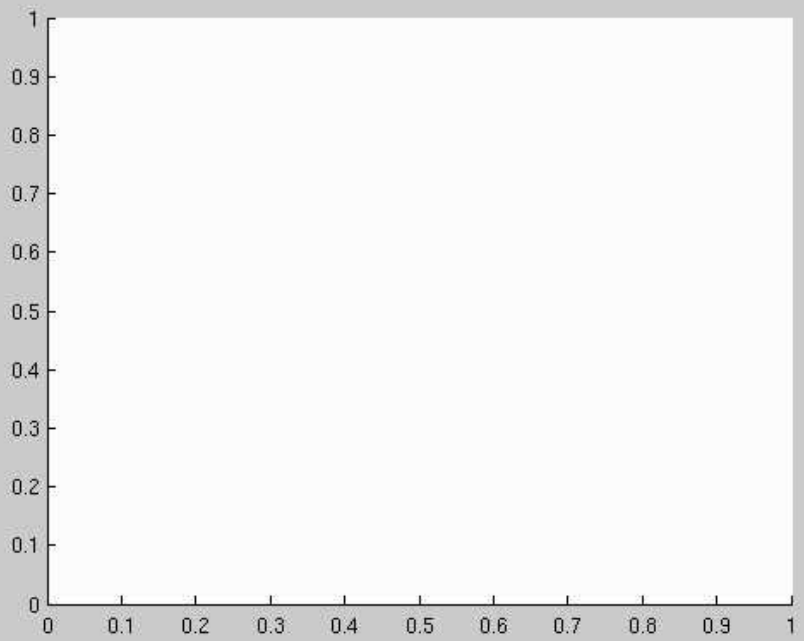




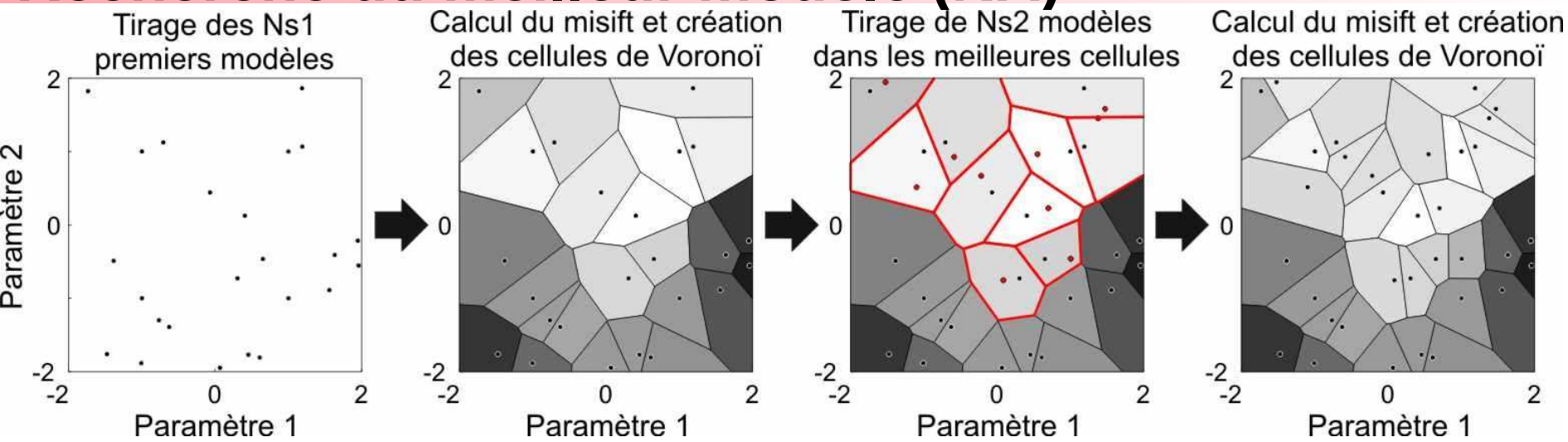
Recherche du meilleur modèle (NA)

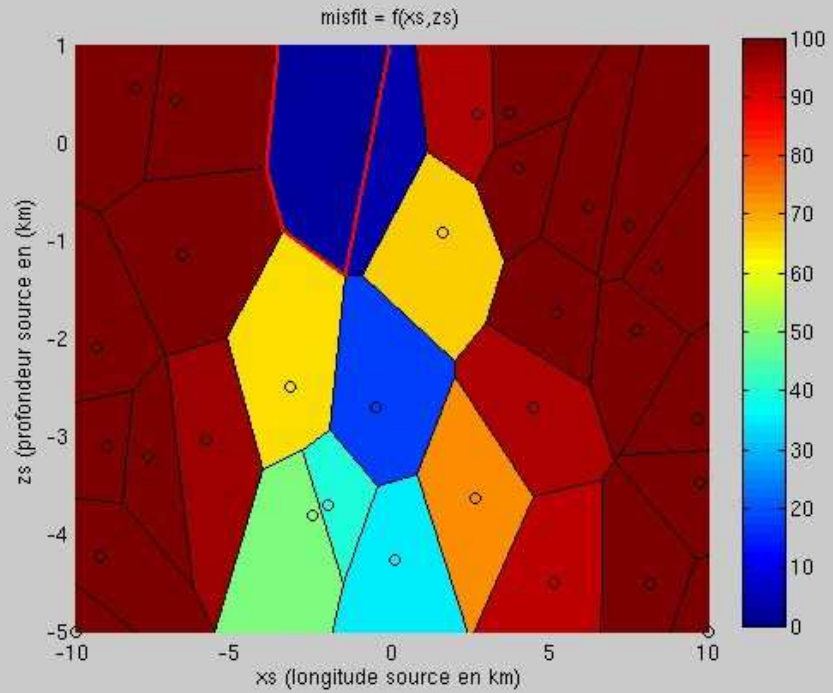




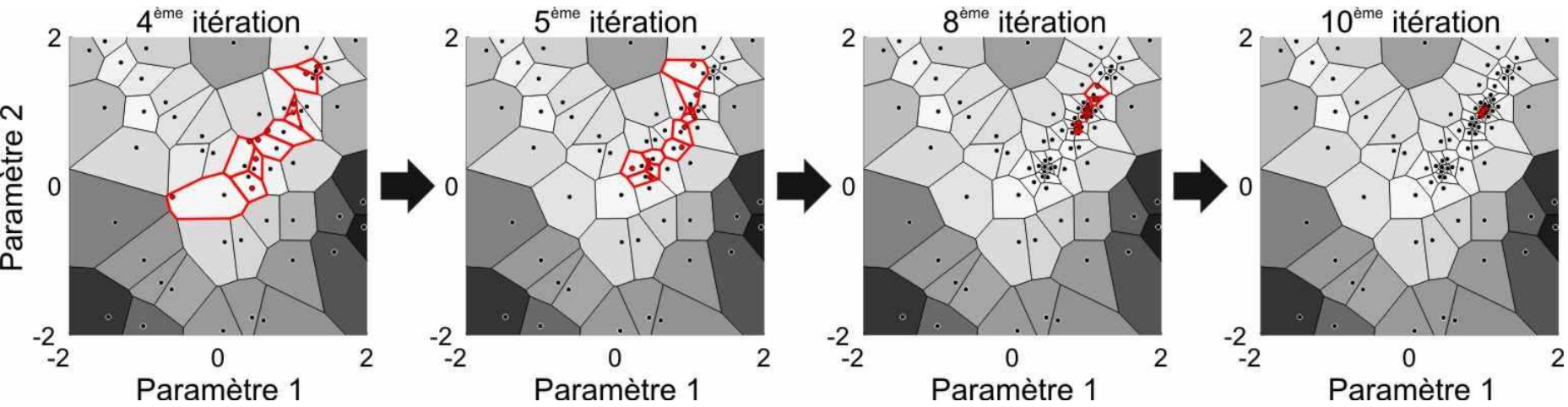


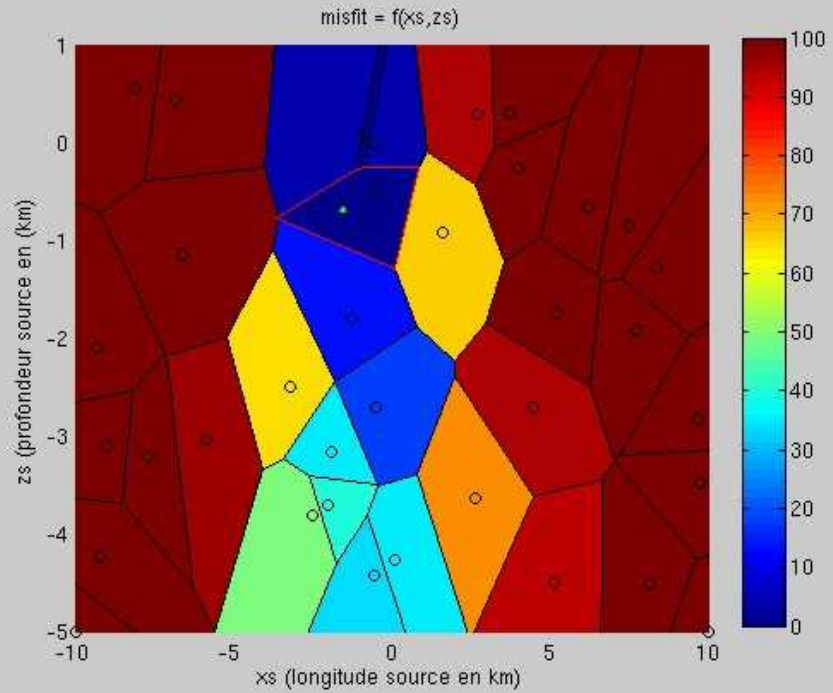
Recherche du meilleur modèle (NA)

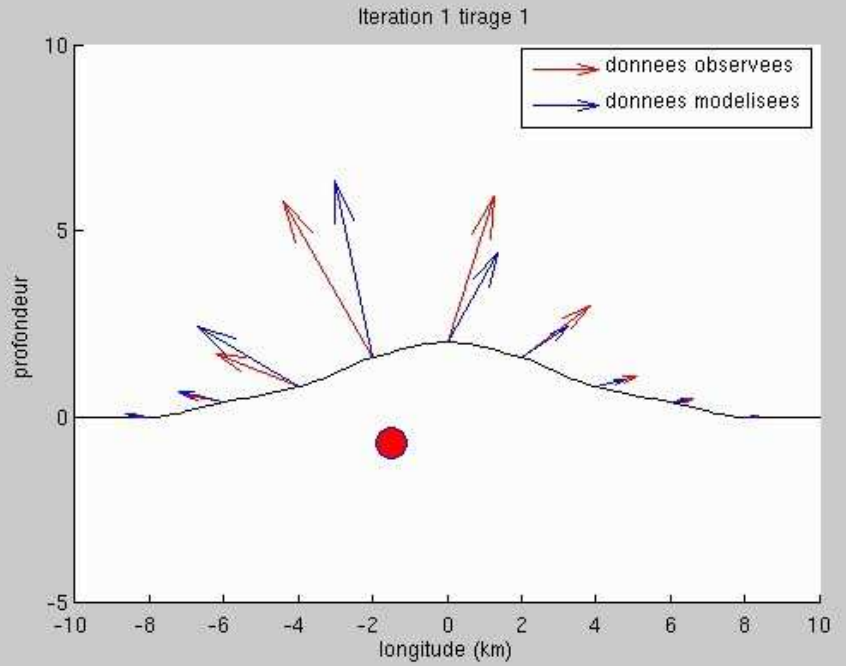




Recherche du meilleur modèle (NA)

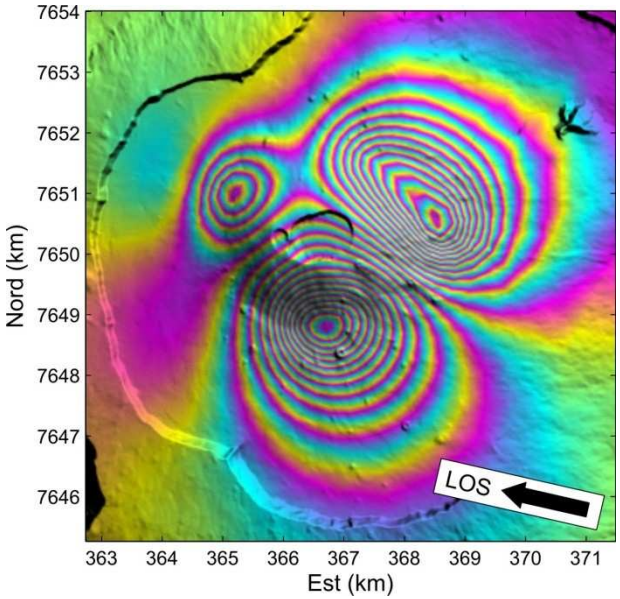


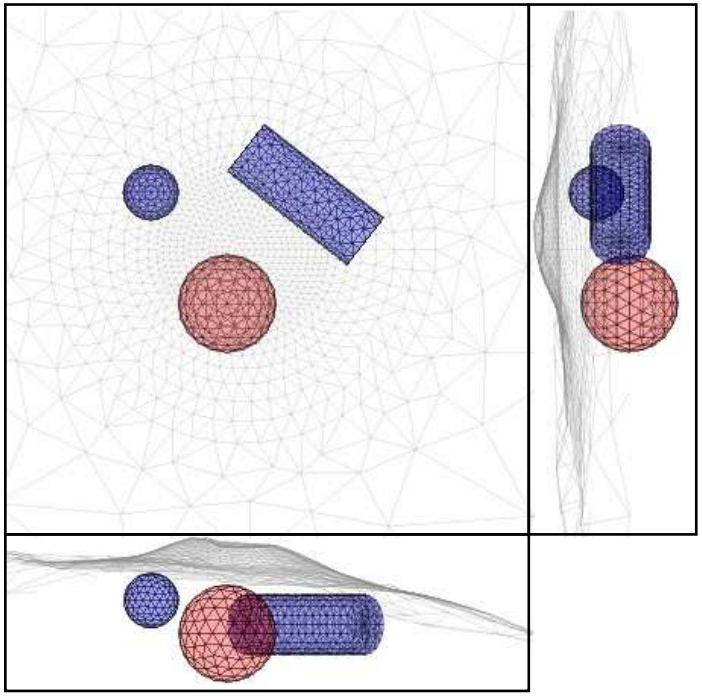




Limites à l'inversion par procédure NA-MBEM

Soient les déplacements synthétiques suivants :





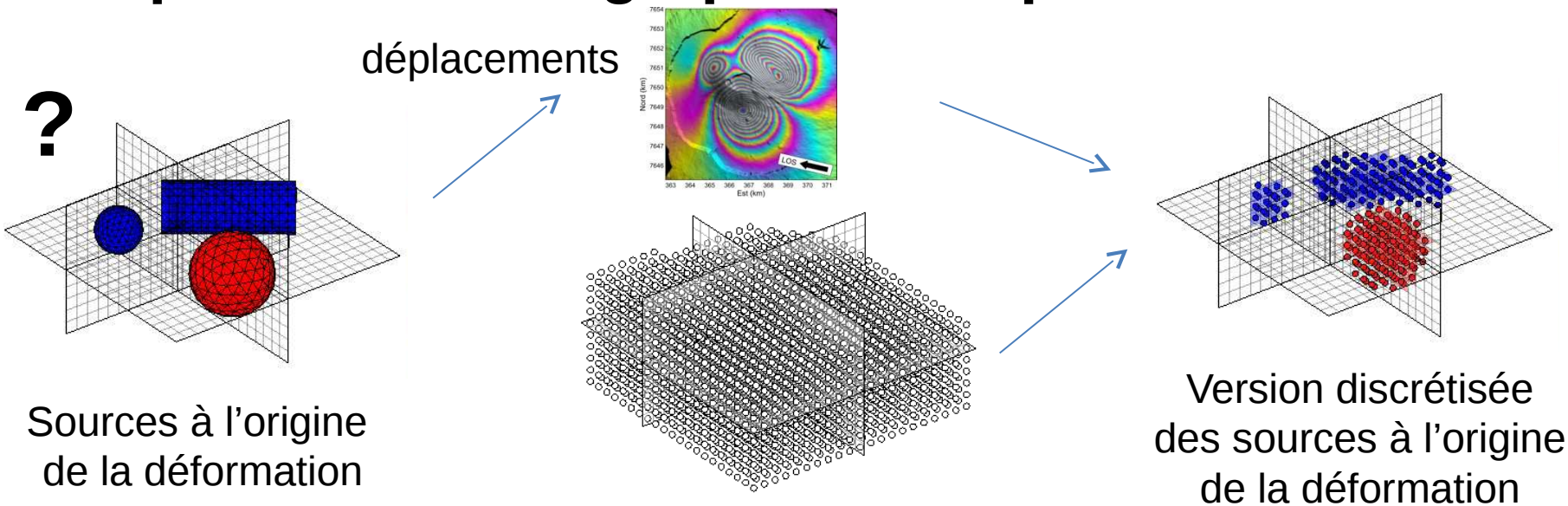
Pour l'inverser avec une procédure NA-MBEM il est nécessaire d'avoir :

- Un a priori sur le nombre de sources
- Un a priori sur la géométrie des sources

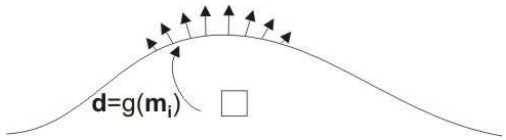
Ici : **2 sphères** (2x5 paramètres) et **un cylindre** (8 paramètres) = 18 paramètres

Beaucoup de paramètres pour une inversion avec NA-MBEM

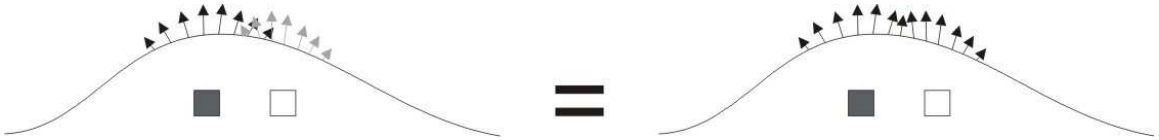
Principes de la tomographie de déplacements



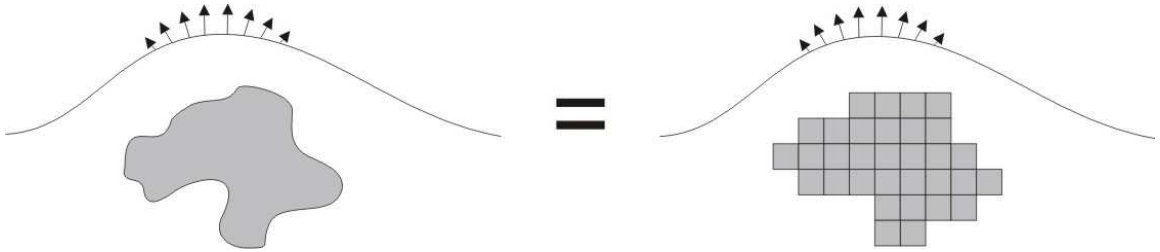
Hypothèse 1 : calculabilité



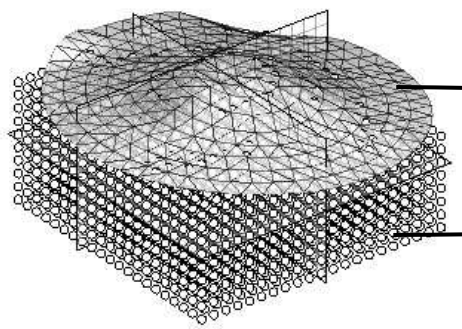
Hypothèse 2 : sommabilité



Hypothèse 3 : discrétisabilité



Résolution simple



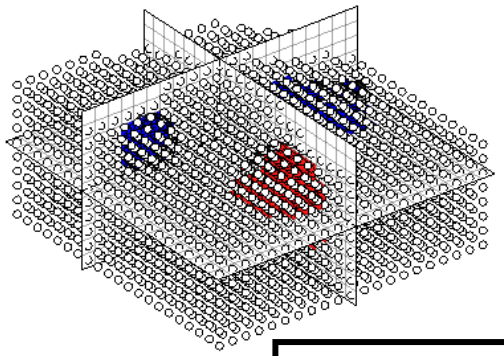
Discrétisation du sous-sol sous la topographie

$$d_{s_i p_j} =$$

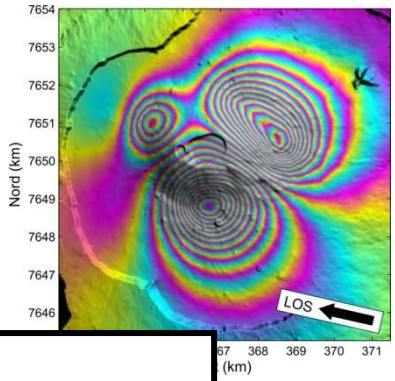
Déplacements du $j^{ème}$ point sous l'effet de la $i^{ème}$ source *(Cube d'Okada, $\Delta V = 1$)*

$$G = \begin{pmatrix} d_{s_1 p_1} & \cdots & d_{s_n p_1} \\ \vdots & & \vdots \\ d_{s_1 p_m} & \cdots & d_{s_n p_m} \end{pmatrix}$$

Matrice des fonctions de Green



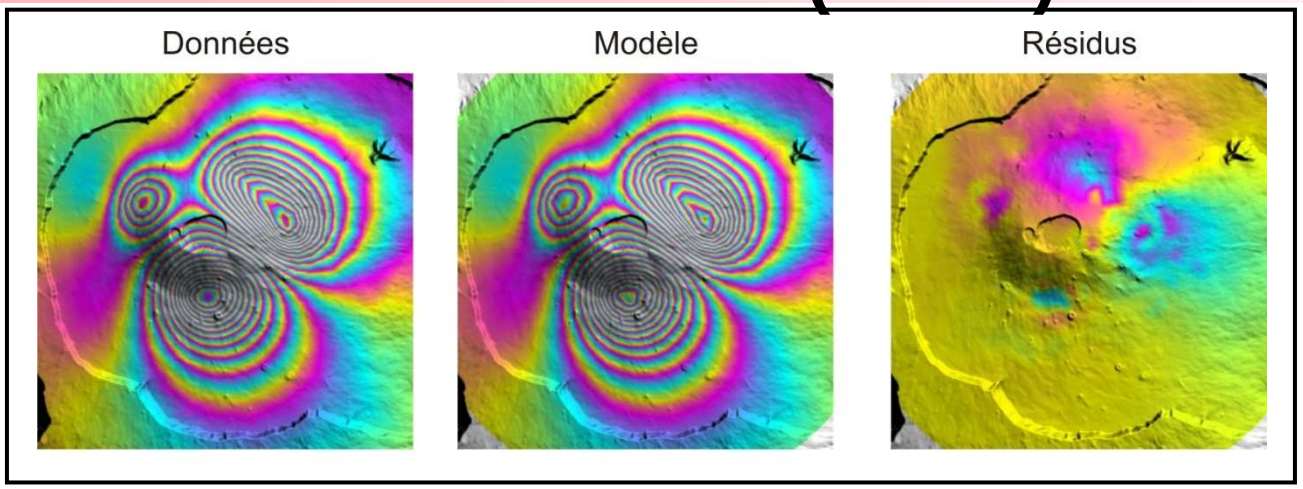
$$\begin{pmatrix} G \\ \beta L \end{pmatrix} \mathbf{m} = \begin{pmatrix} \mathbf{d}_{obs} \\ 0 \end{pmatrix}$$

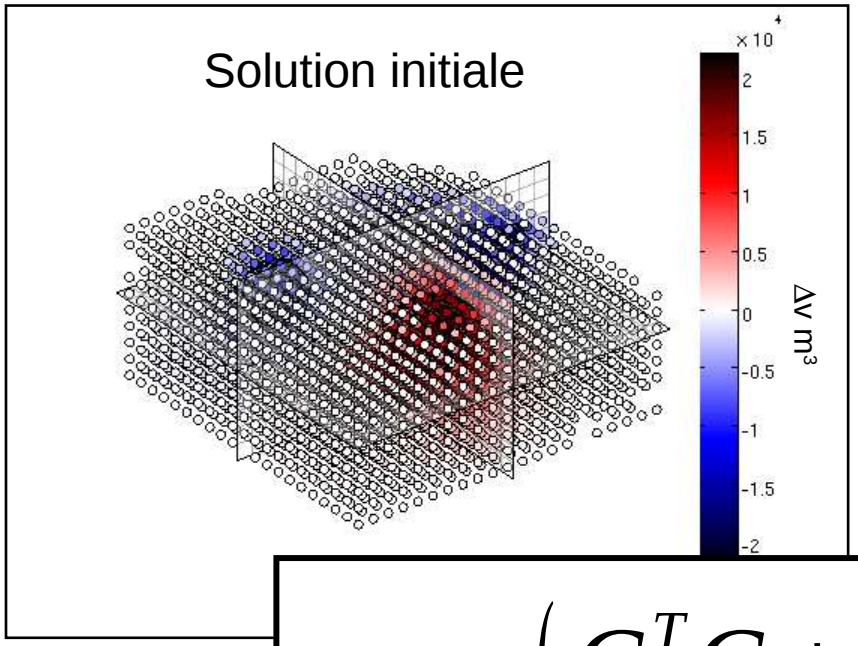


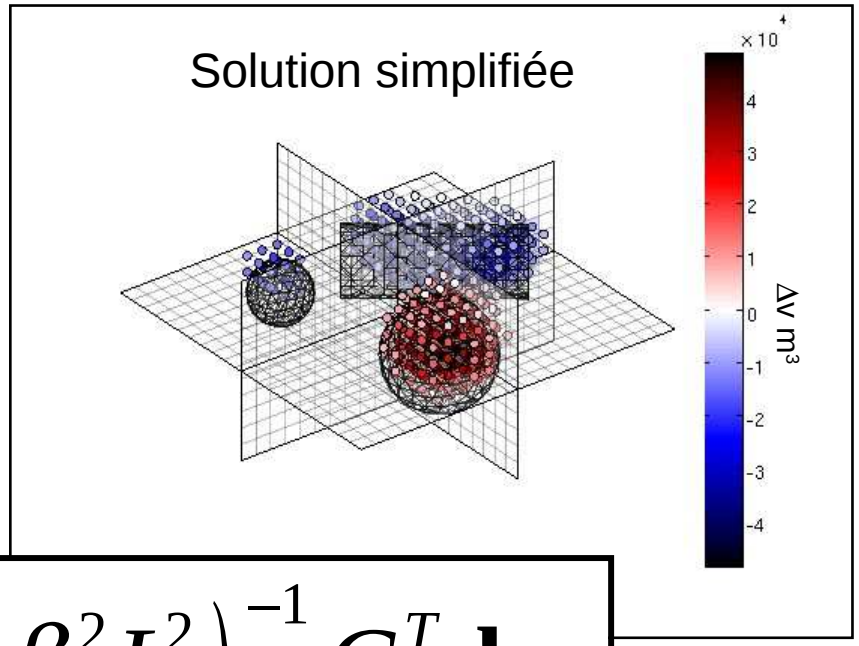
$\mathbf{m}$ = ΔV variatio … chaque sour … expliquant les … $\mathbf{d}_{obs}$ … nts observés

$$\mathbf{m}_\beta = \left(G^T G + \beta^2 L^2 \right)^{-1} G^T \mathbf{d}_{obs}$$

Recherche du meilleur modèle (CVSS)

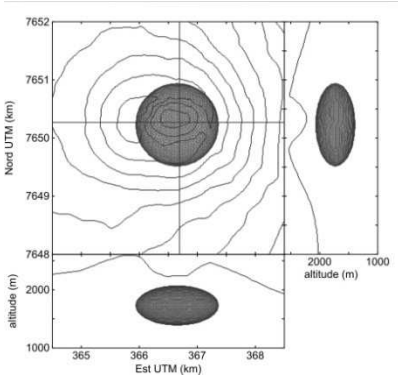


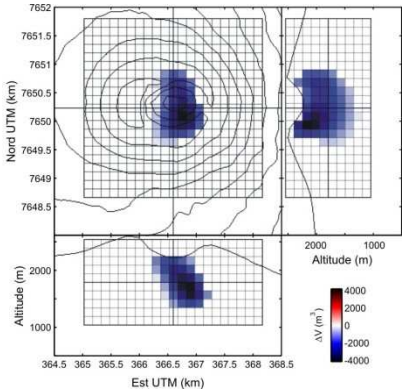




$$\mathbf{m}_\beta = \left(G^T G + \beta^2 L^2 \right)^{-1} G^T \mathbf{d}_{obs}$$

Comparaison des caractéristiques des méthodes



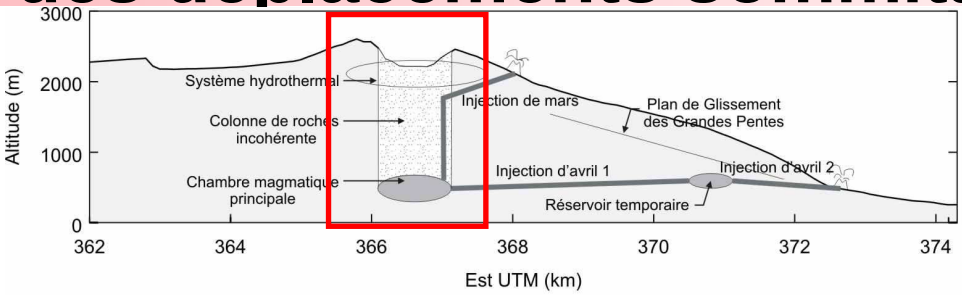


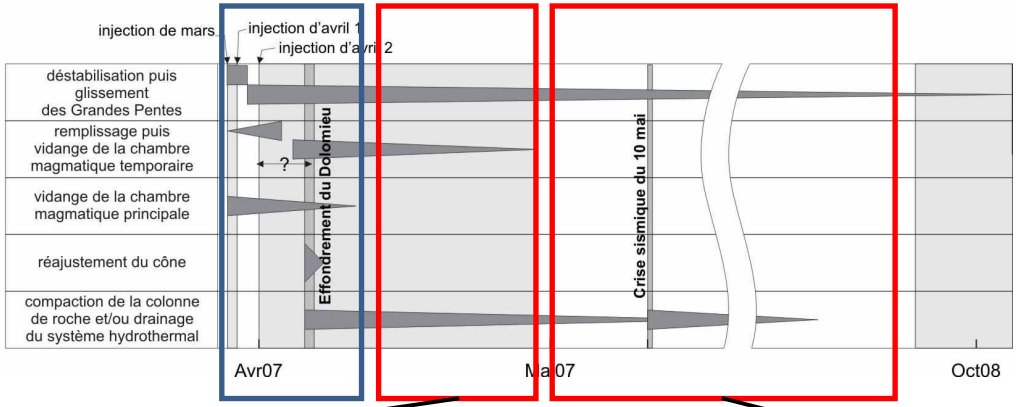
	NA-MBEM	Tomographie
A priori sur le nombre de sources	OUI	NON
A priori sur la géométrie des sources	OUI	NON
Temps de calcul	dépend du nombre de paramètres (semaines)	dépend de la discrétisation (heures/jour)
Sources modélisables	fractures (failles dykes), sources massives	Uniquement les sources massives

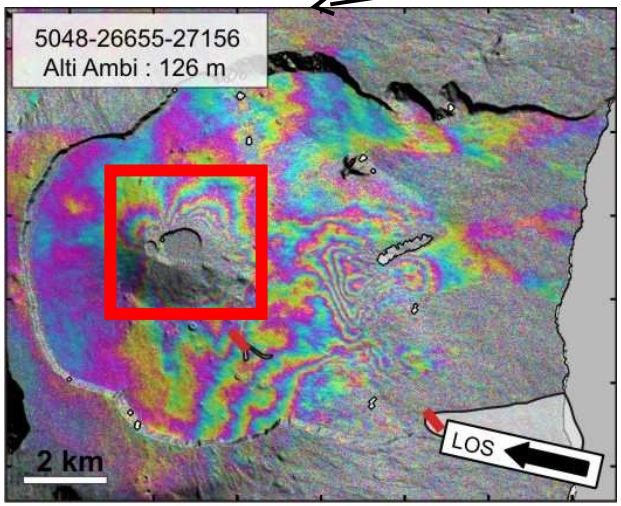
Partie III

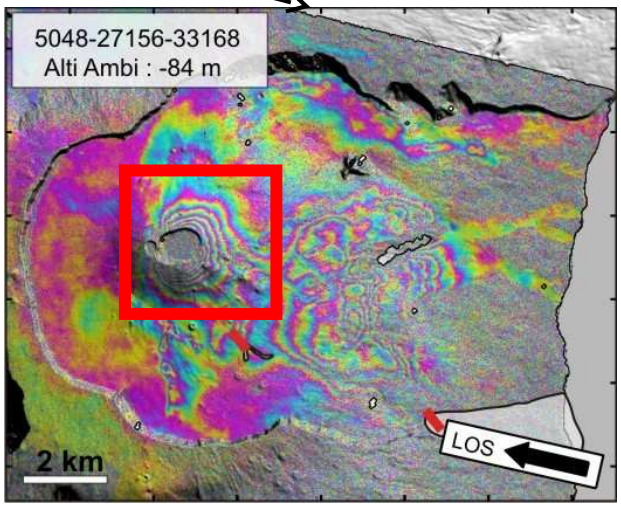
Modélisation des déplacements liés à l’éruption d’avril 2007

Modélisation des déplacements sommitaux

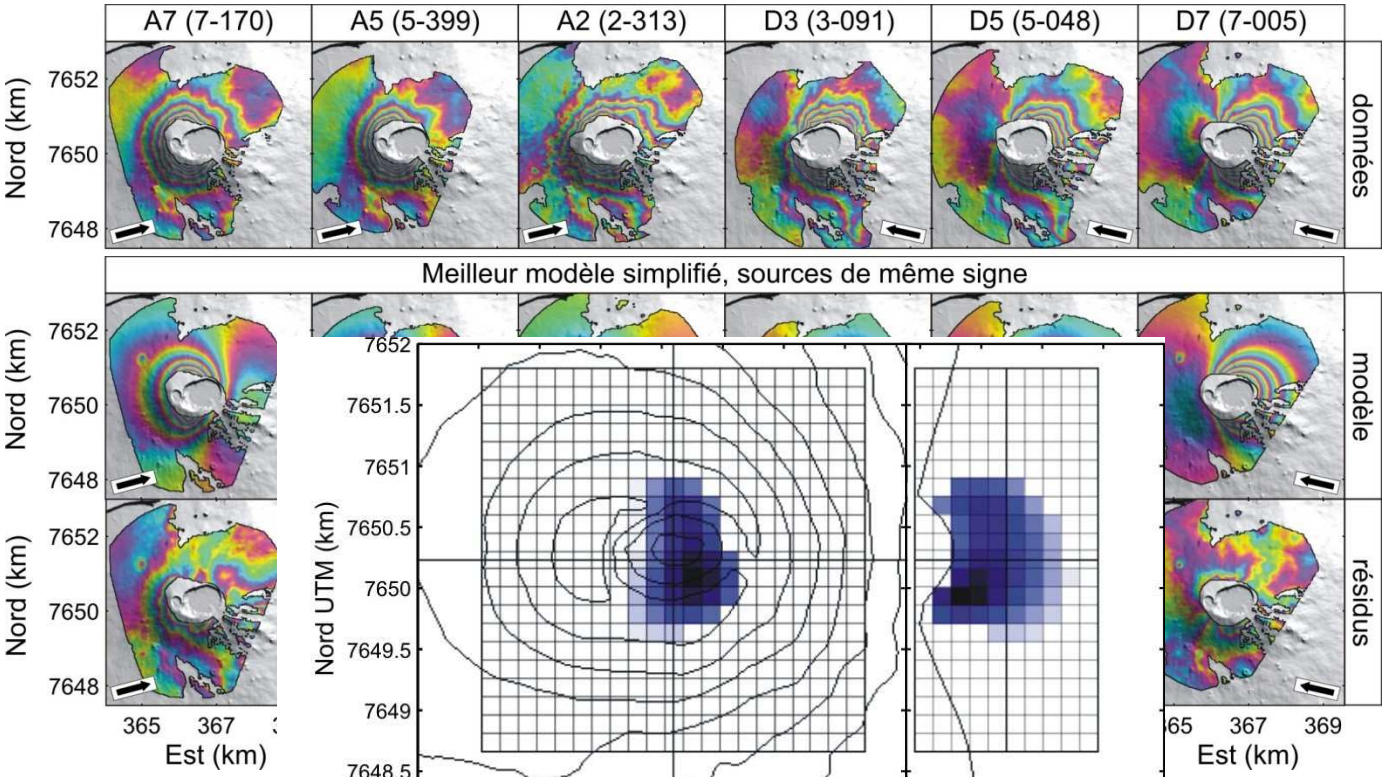


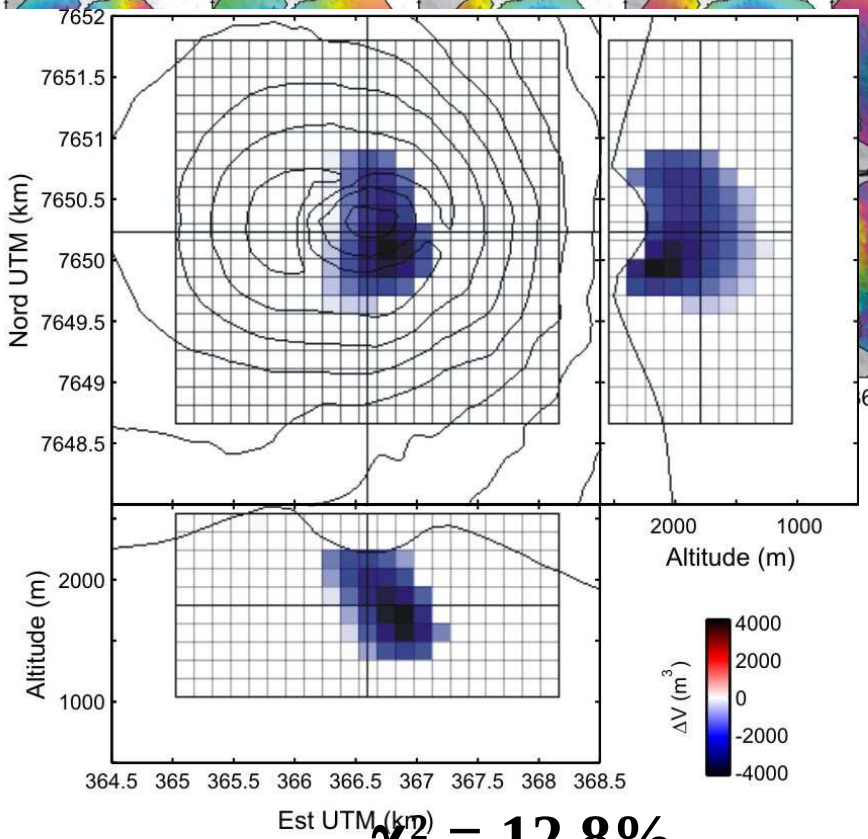




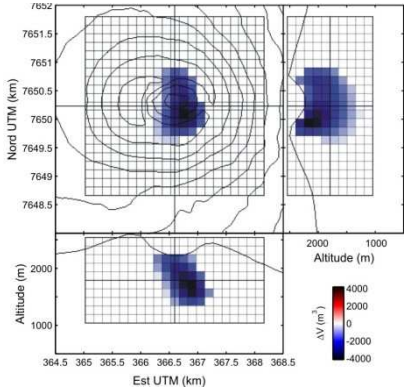


Modélisation des déplacements sommitaux



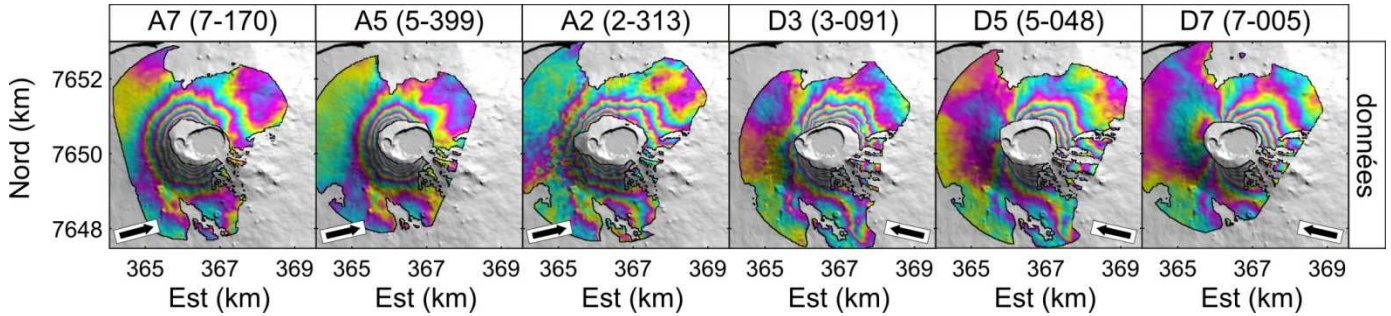


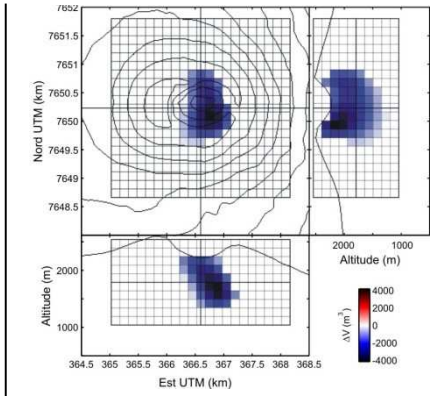
$\chi^2 = 12{,}8\%$



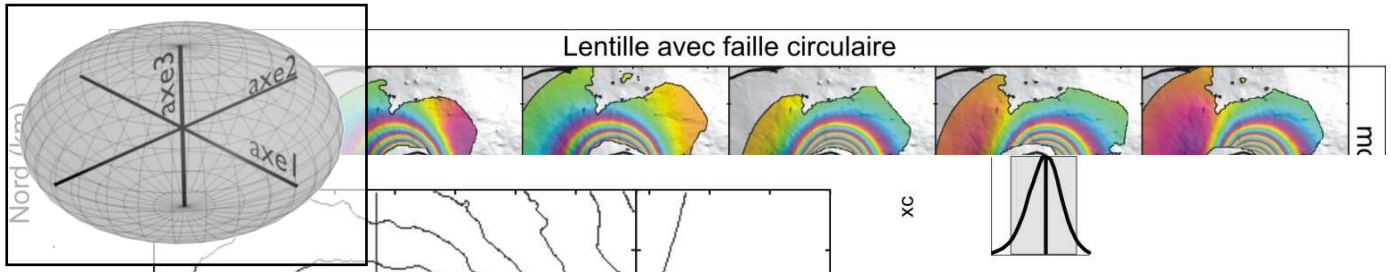
$\chi^2 = 12{,}8\%$

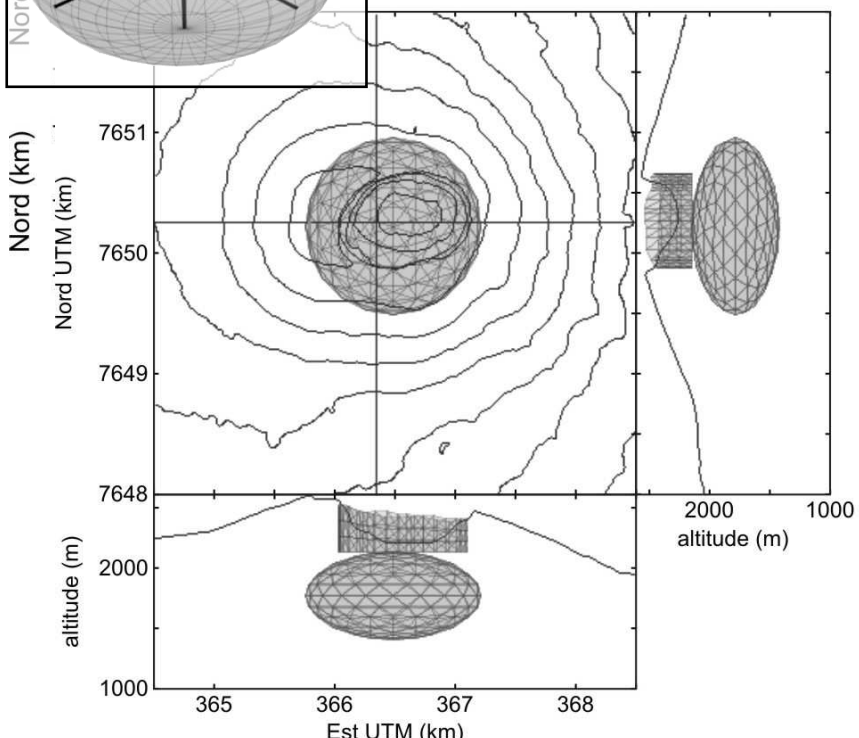
Modélisation des déplacements sommitaux

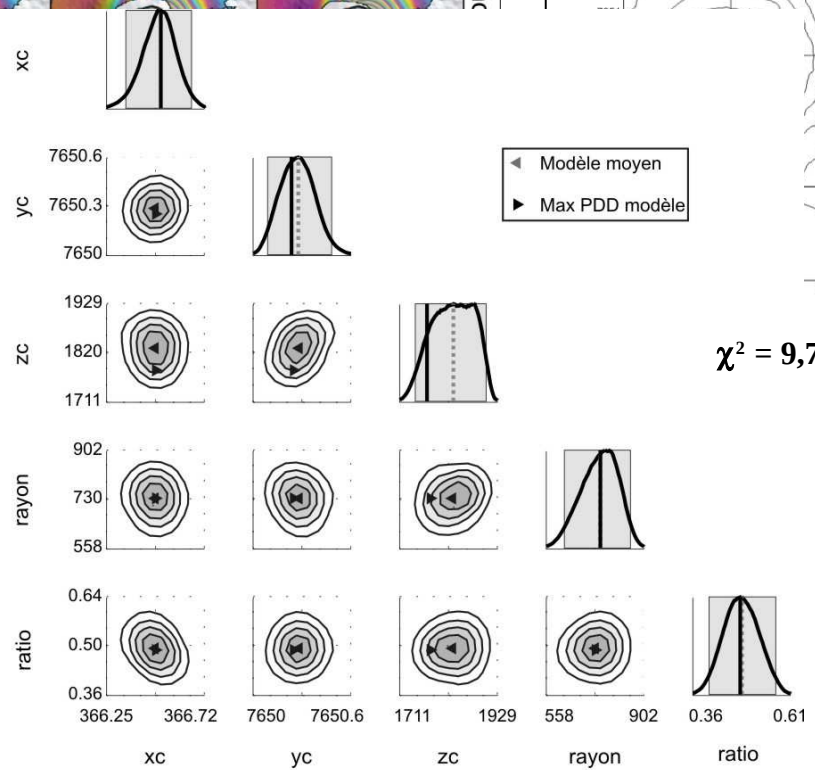


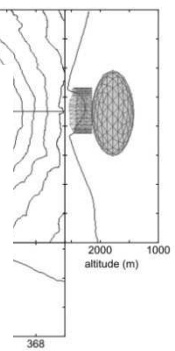


$\chi^2 = 12{,}8\%$









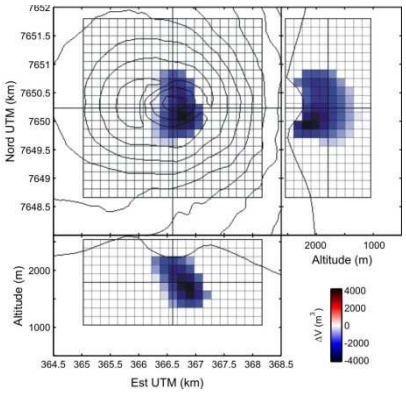
$\chi^2 = 9{,}7\%$

Origine des déplacements sommitaux

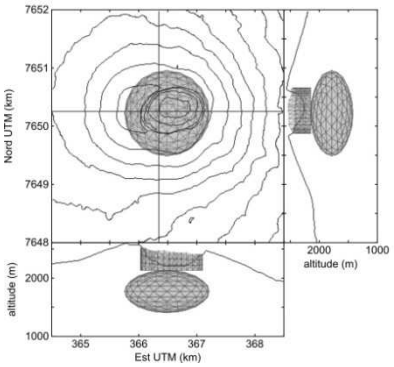
Trop superficiel pour Chambre Magmatique

Décompression du système hydrothermal ????

Réajustement mécanique de l'édifice ????

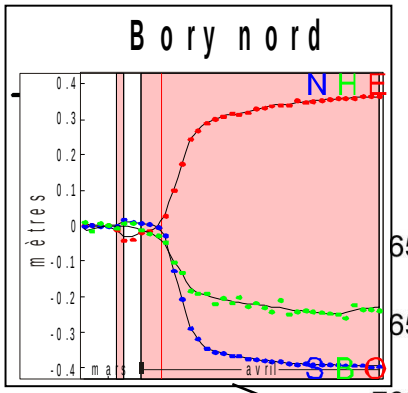


χ^2 = 12,8%

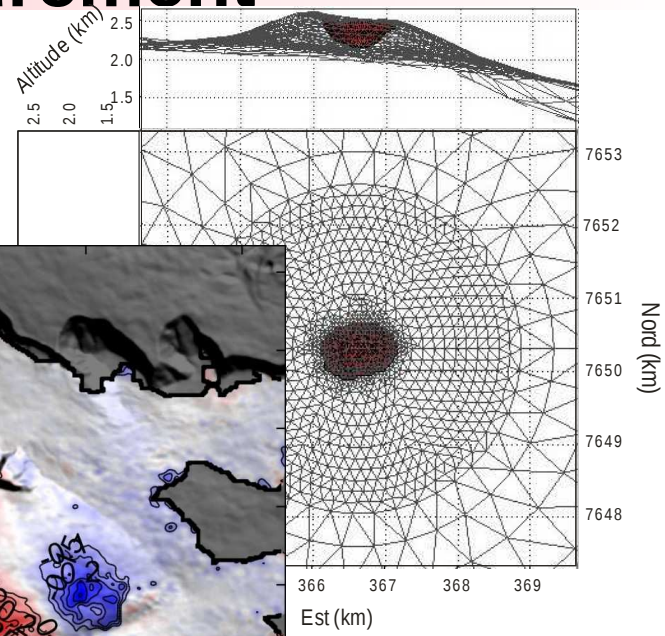


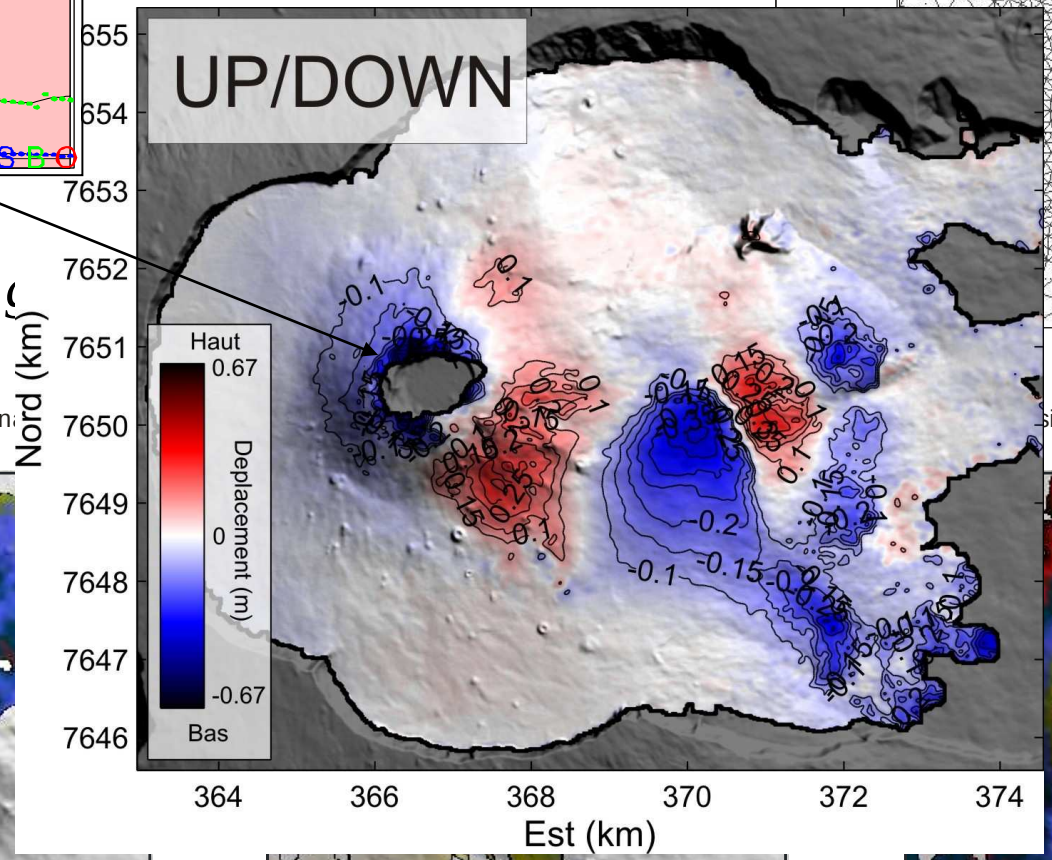
χ^2 = 9,7%

Ajustement du cône après l'effondrement



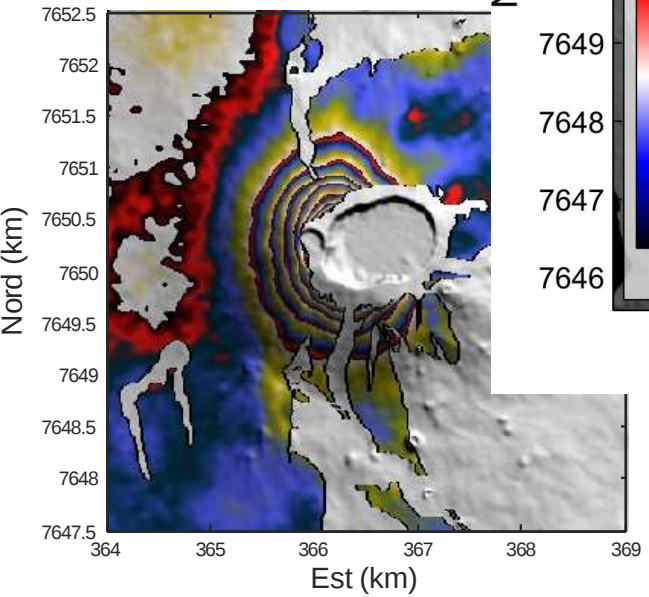
$$P(h) = -\rho g$$

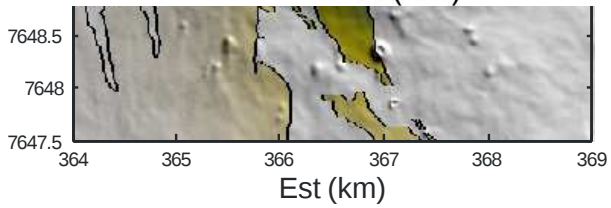


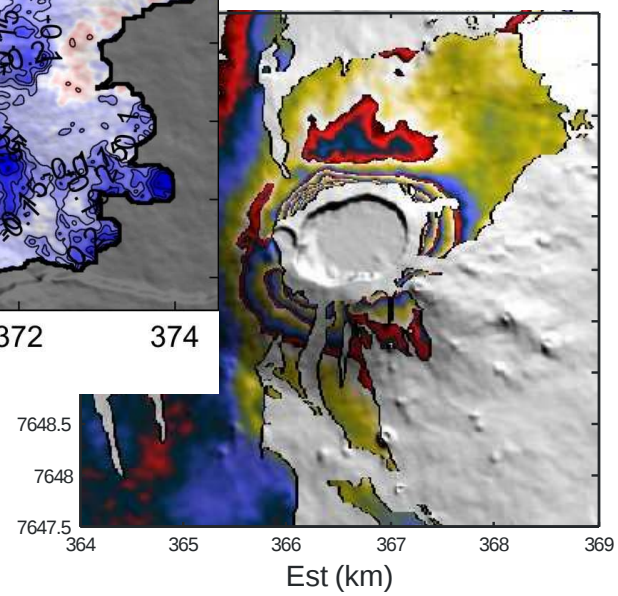


interférogramme origin

sidus (modélisé - original)

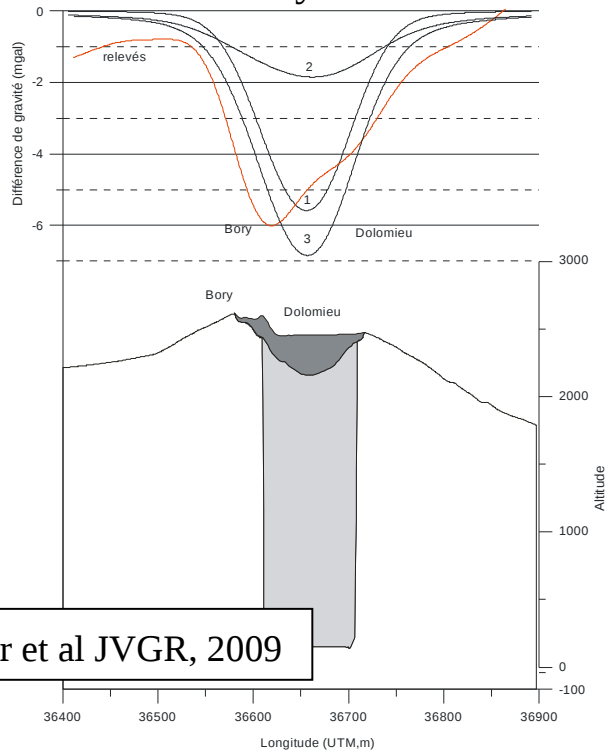






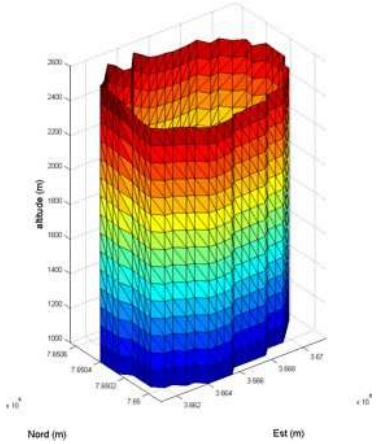
Compaction de la colonne de roche

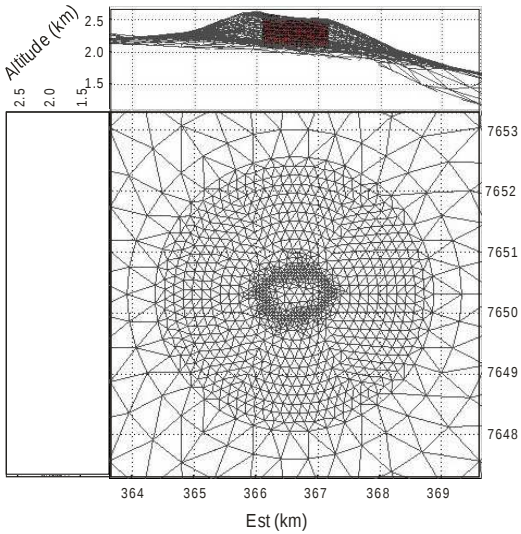
Gravimetry results



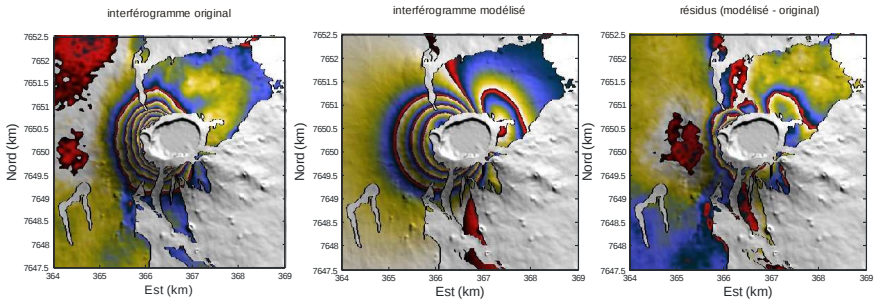
Gailler et al JVGR, 2009

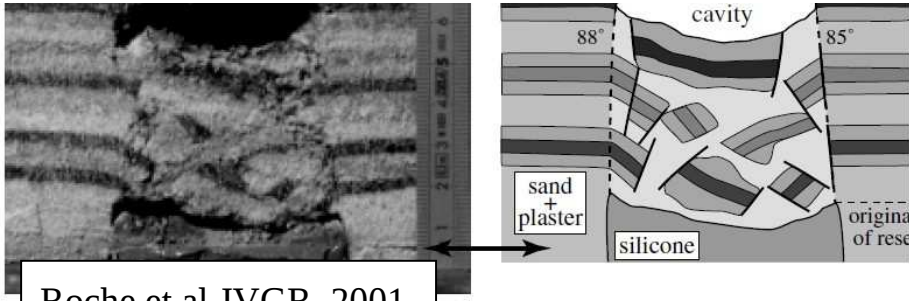
Model results





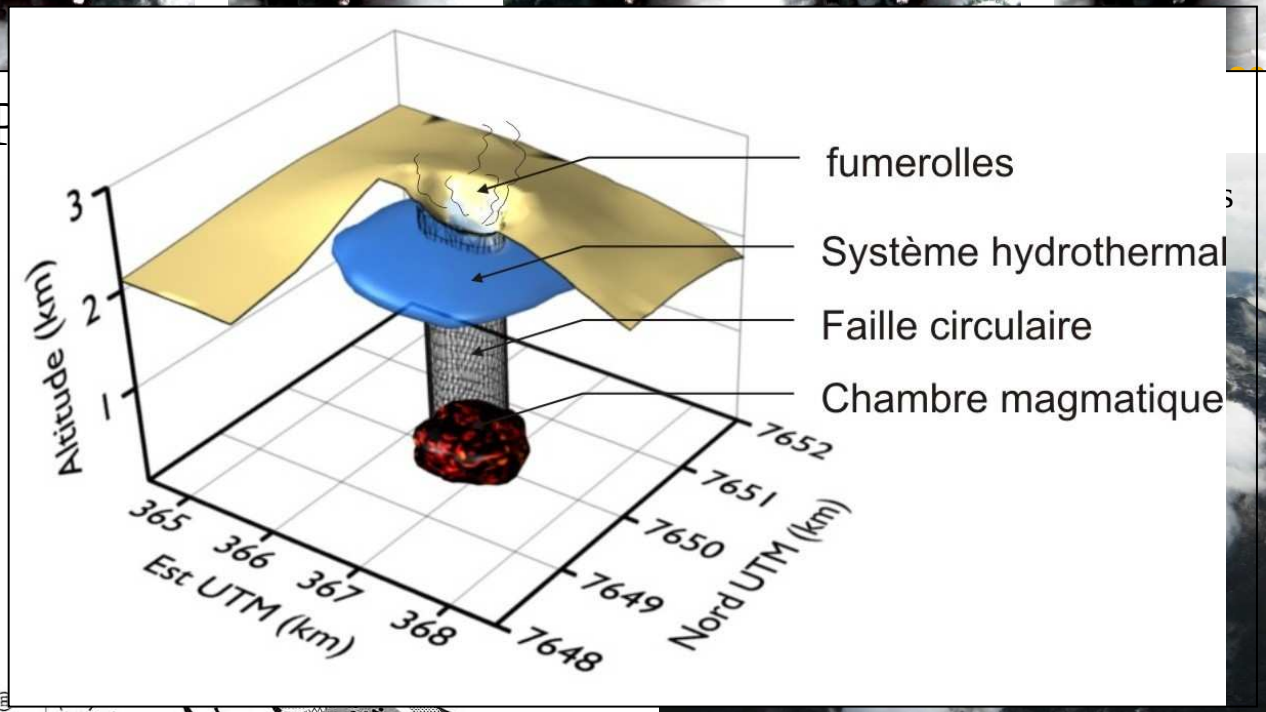
$$P(h) = -(\rho_e - \rho_c) g (\text{altitude}_{\max} - h)$$

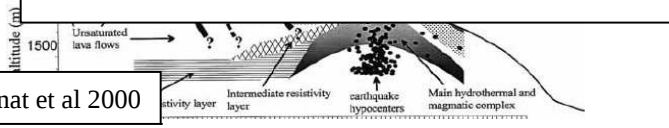




Roche et al JVGR, 2001

Origine des déplacements sommitaux





Lenat et al 2000

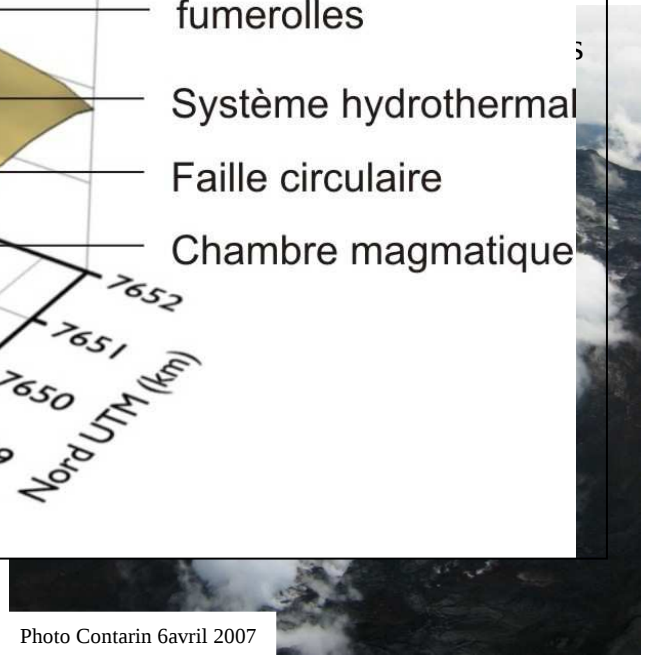
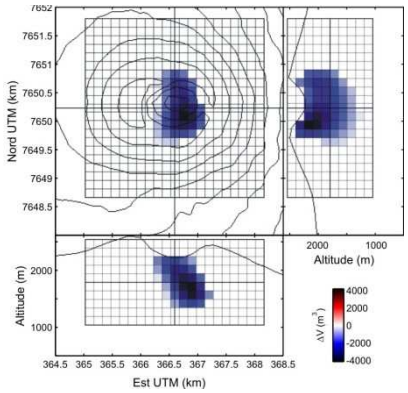
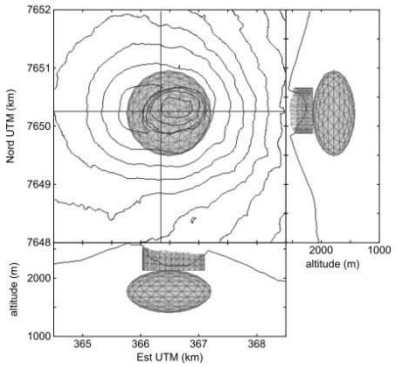


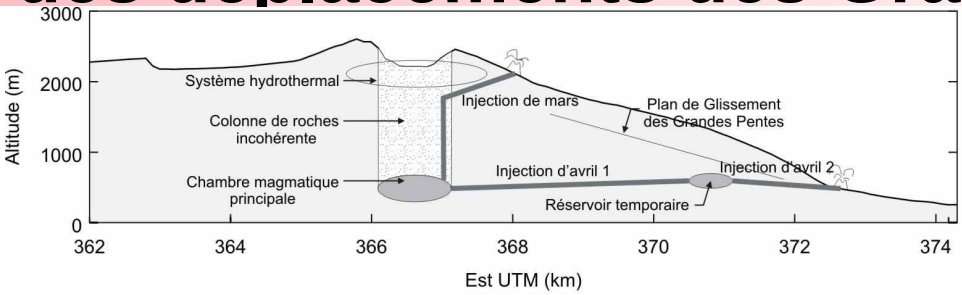
Photo Contarin 6avril 2007

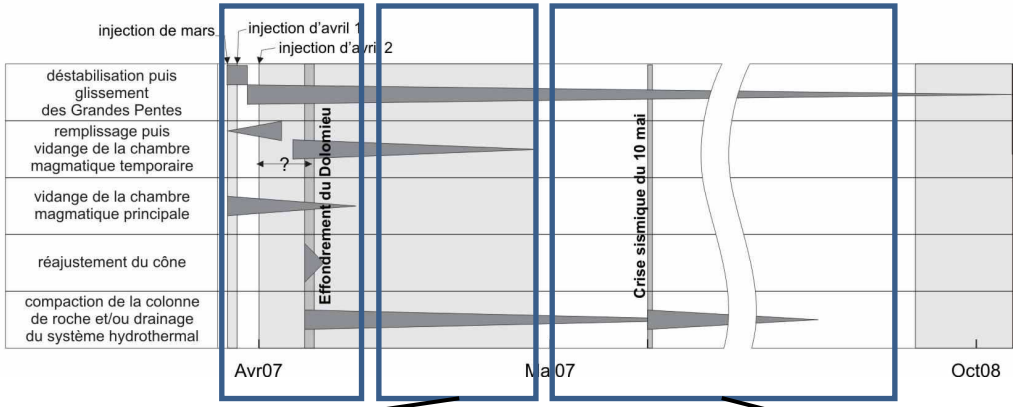
Staudacher 2009

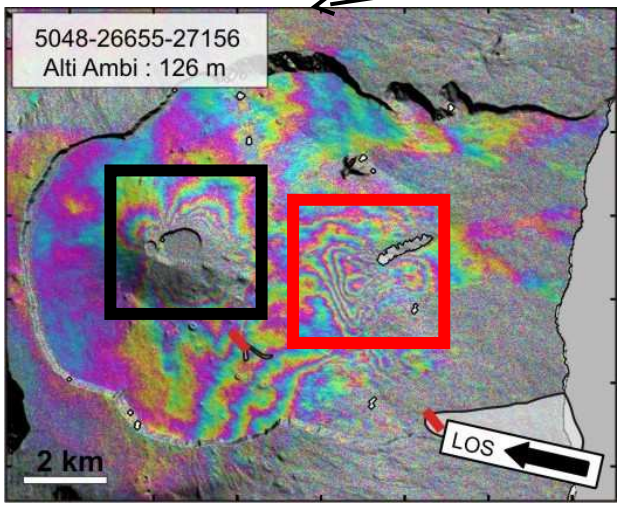


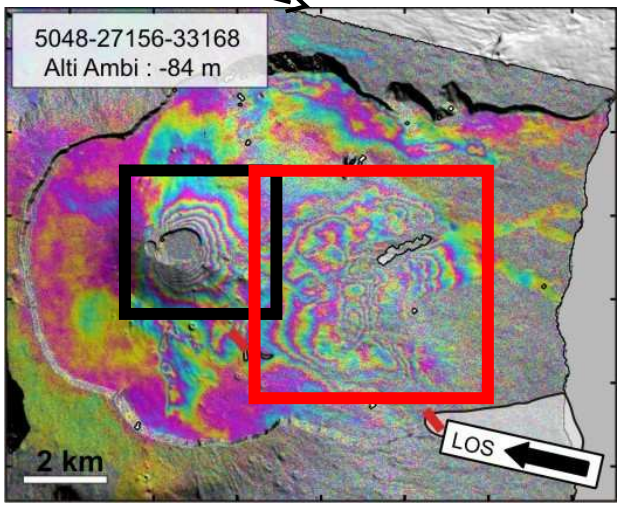


Modélisation des déplacements des Grandes Pentes

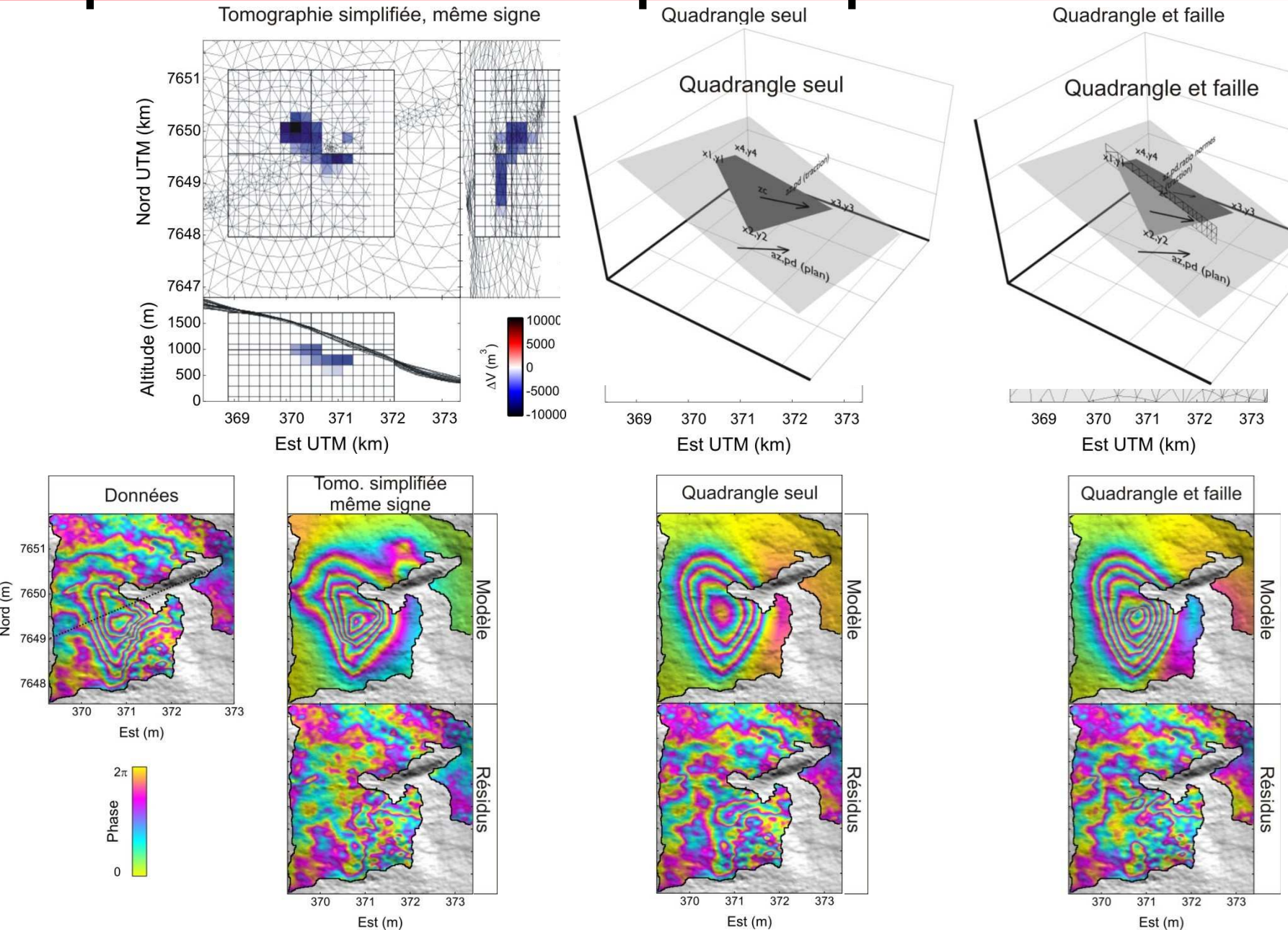




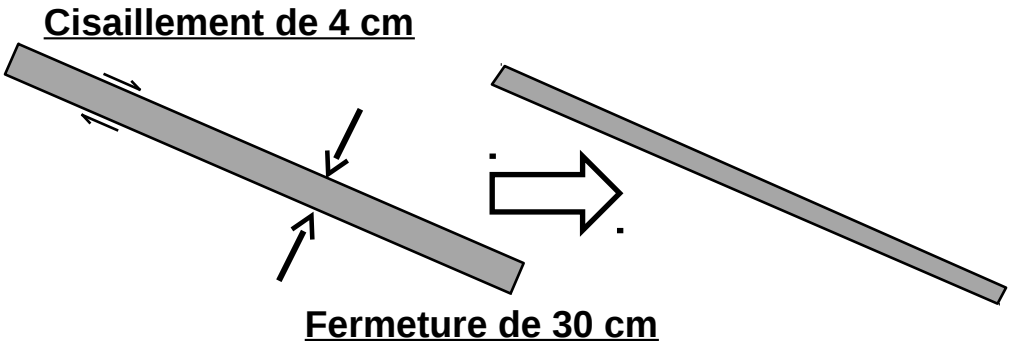


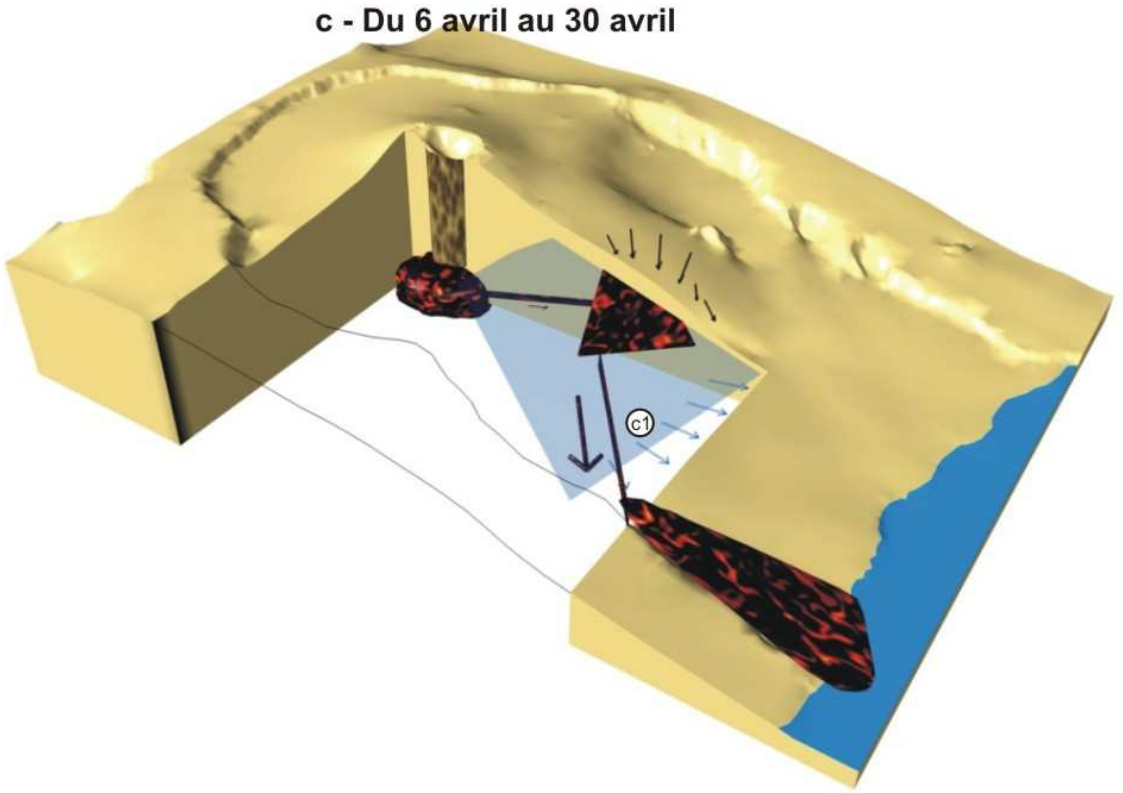


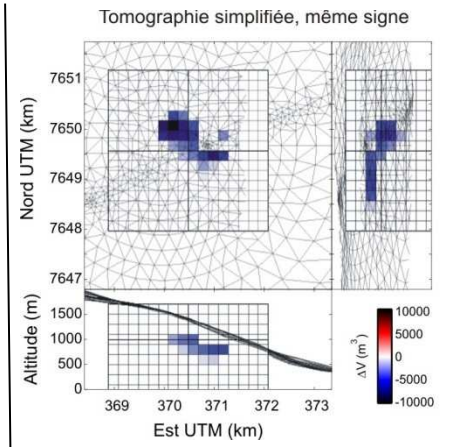
Déplacements durant la période post-effondrement

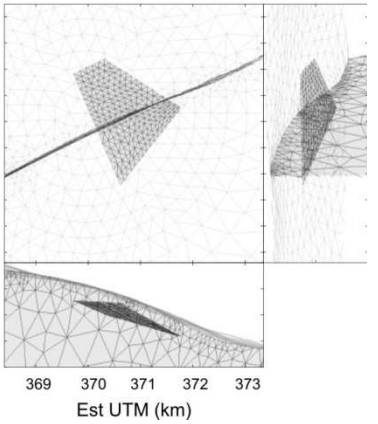


Déplacements durant la période post-effondrement



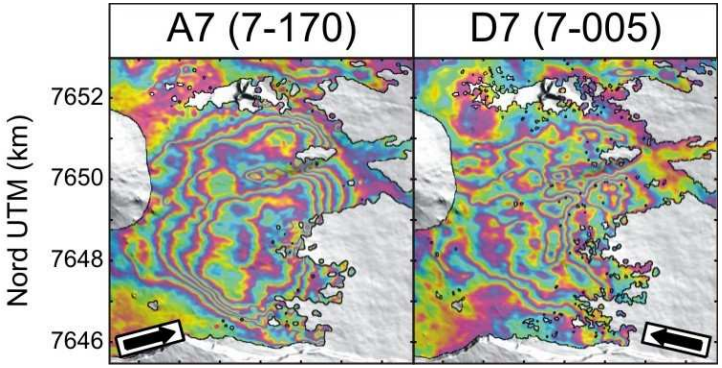


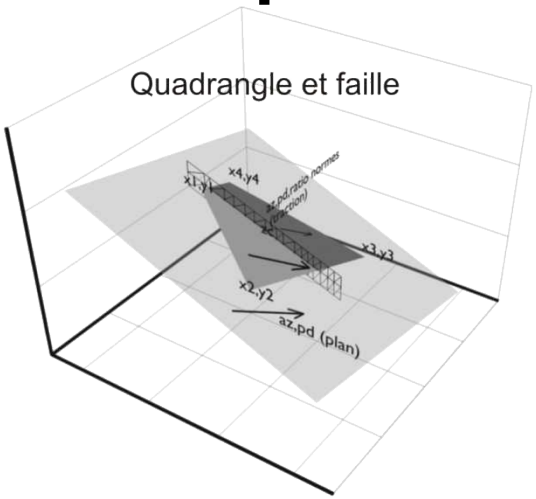




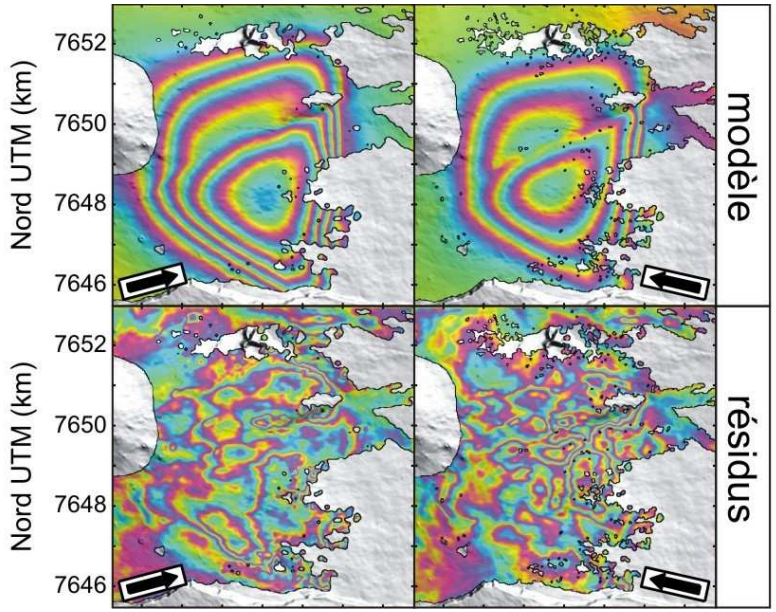
Déplacements durant la période post-éruptive

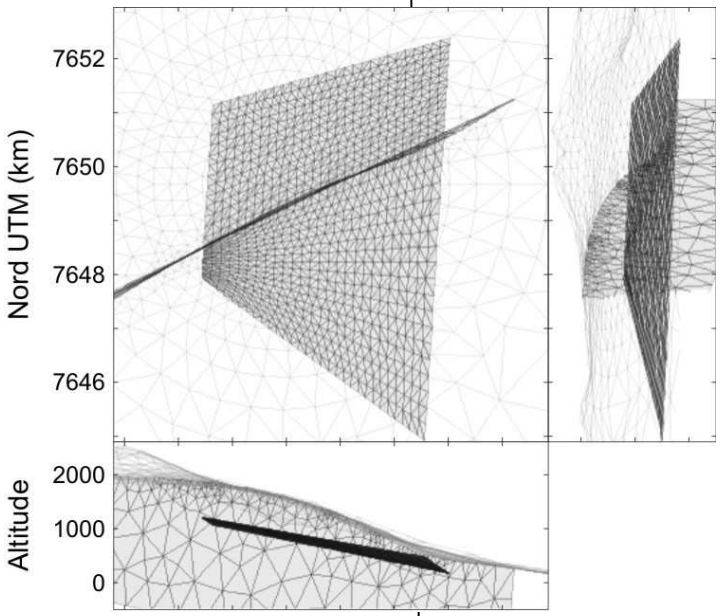
Données





1 Quadrangle, 1 faille

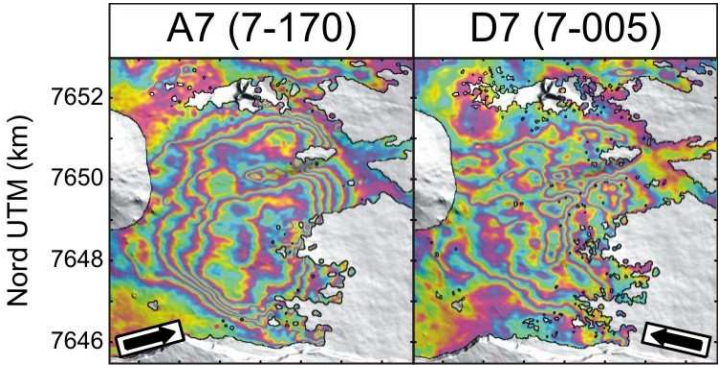


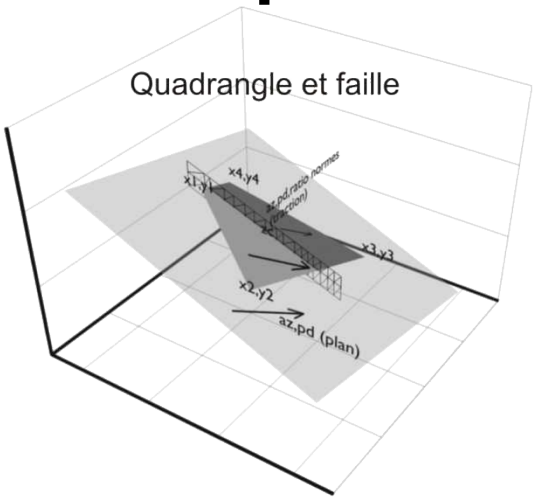


$$\chi^2 = 11.02\%$$

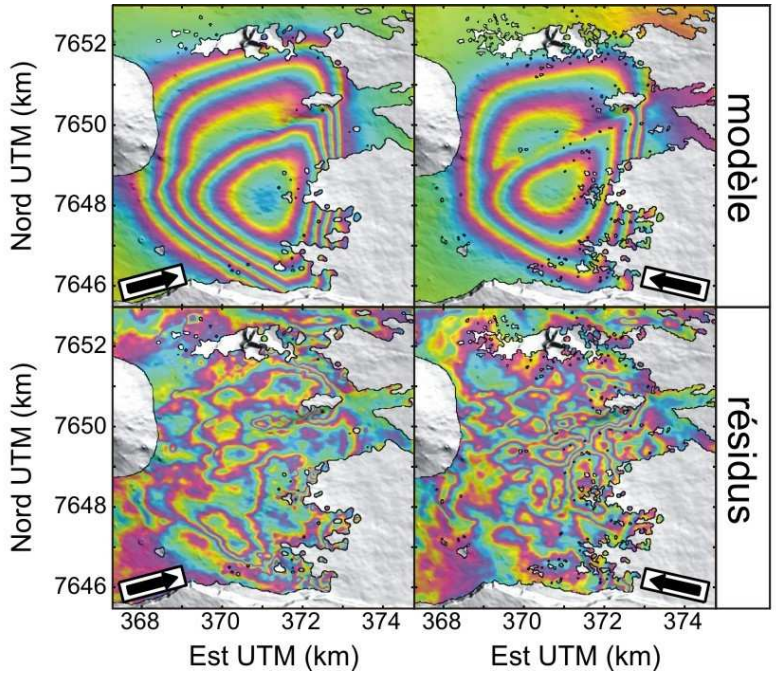
Déplacements durant la période post-éruptive

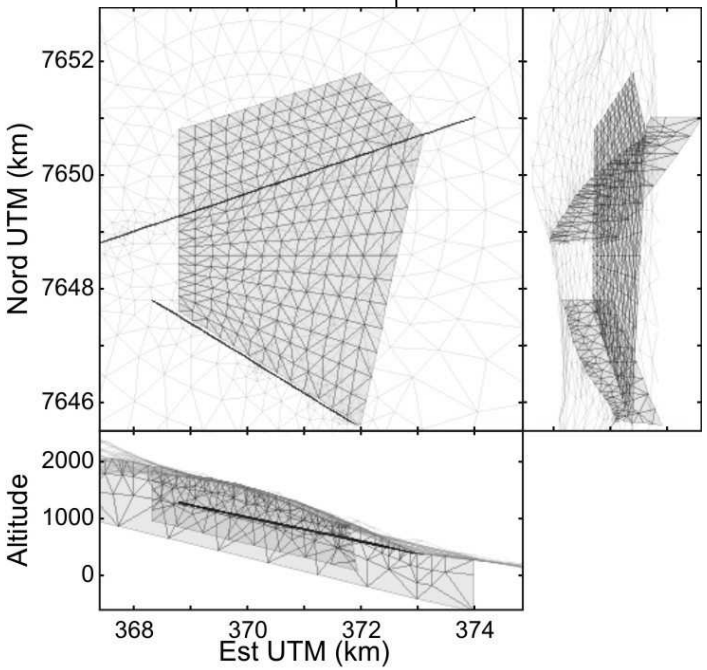
Données





1 Quadrangle, 1 faille

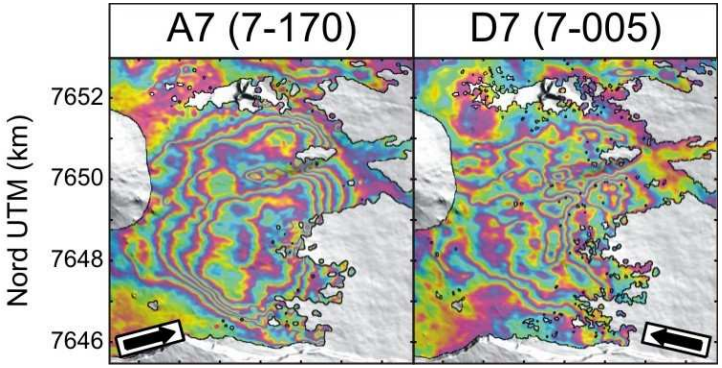


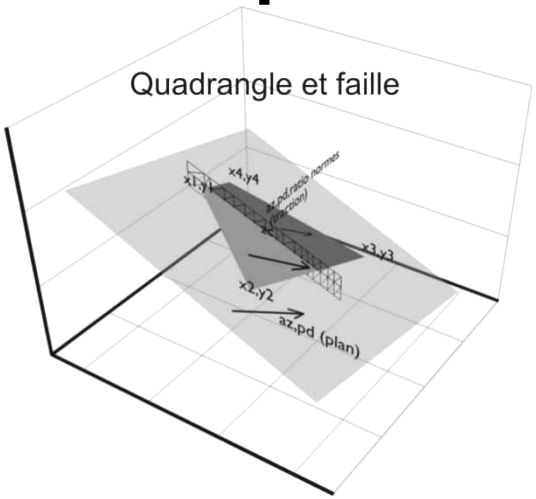


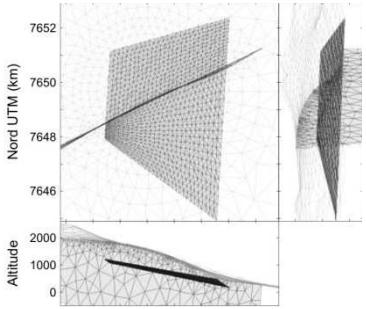
$$\chi^2 = 11.02\%$$

Déplacements durant la période post-éruptive

Données

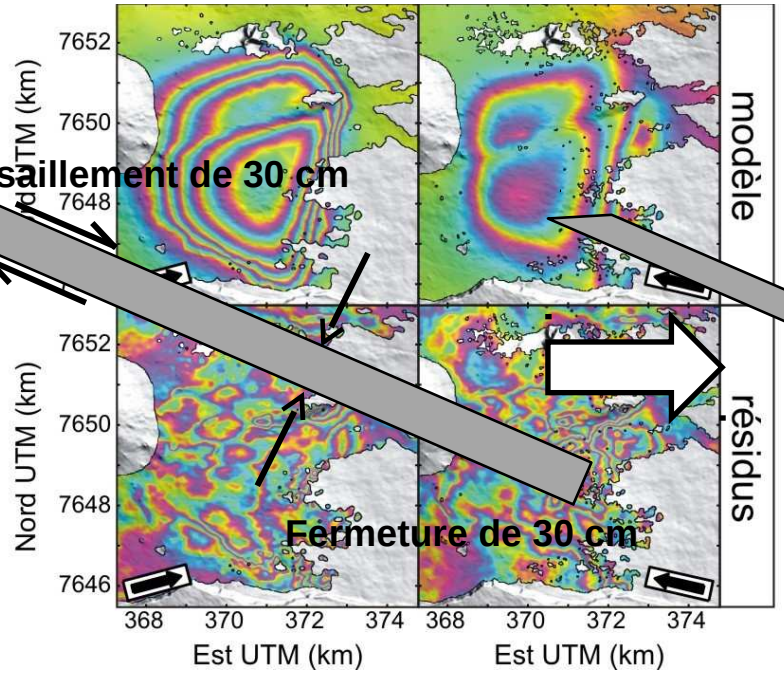


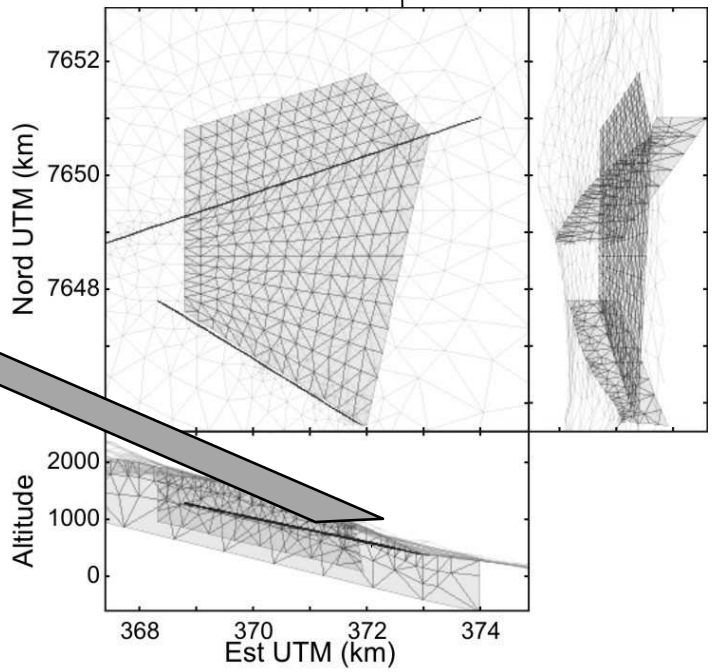




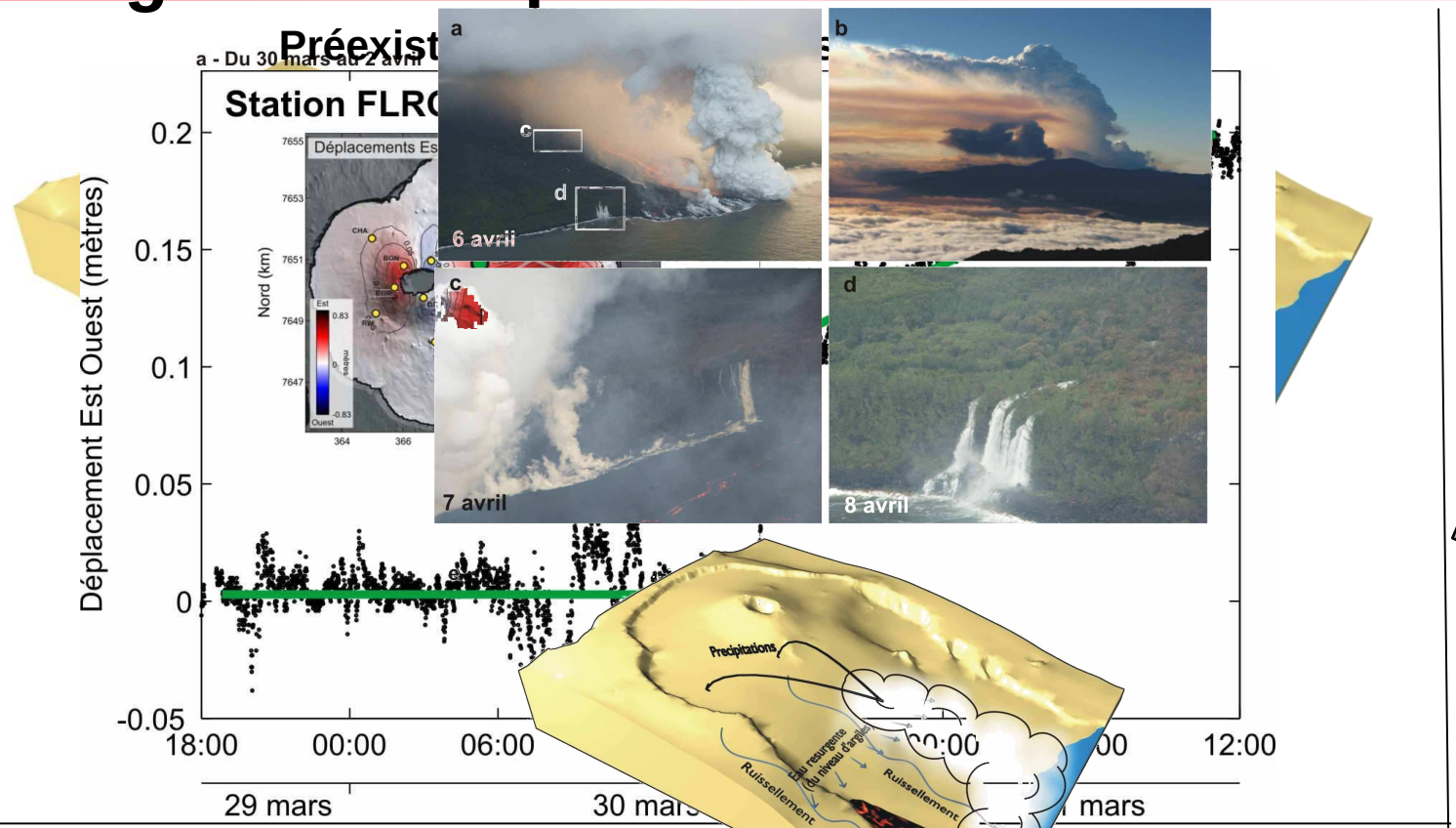
$\chi^2 = 11.02\%$

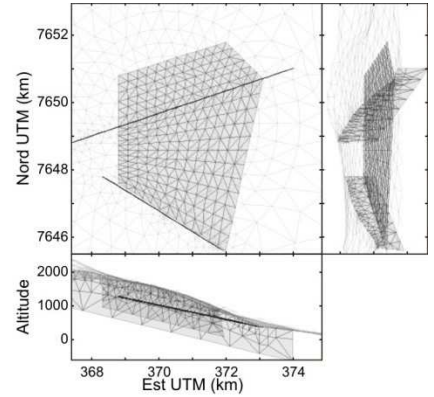
2 Quadrangles, 2 failles
(modèle direc



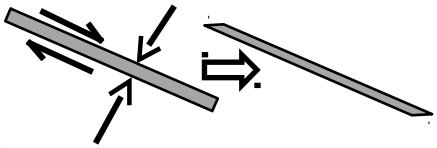


Origine des déplacements des Grandes Pentes

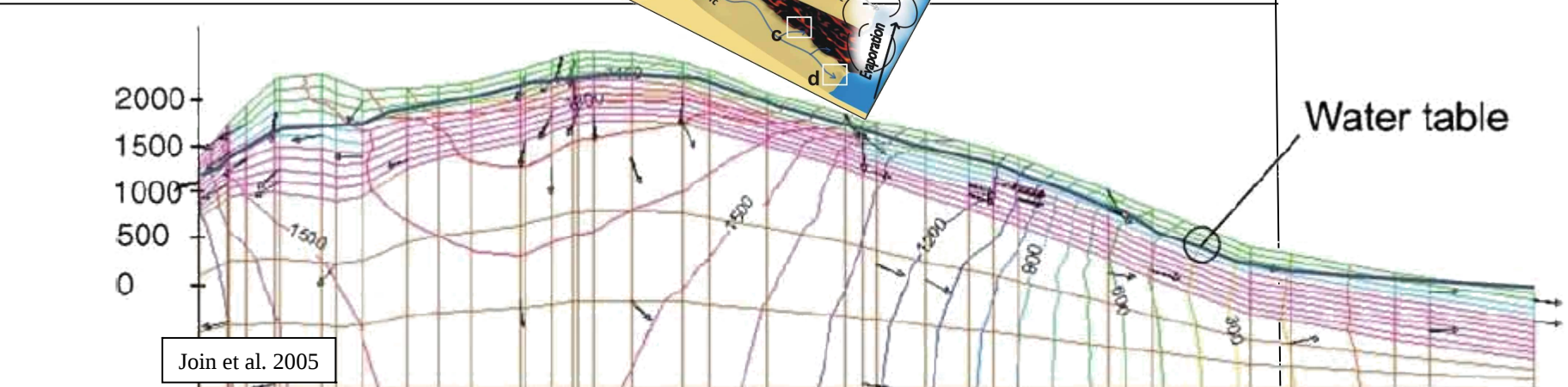




Cisaillement de 30 cm



Fermeture de 30 cm

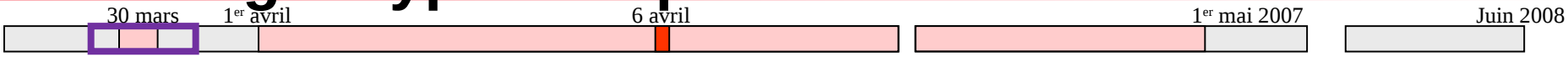


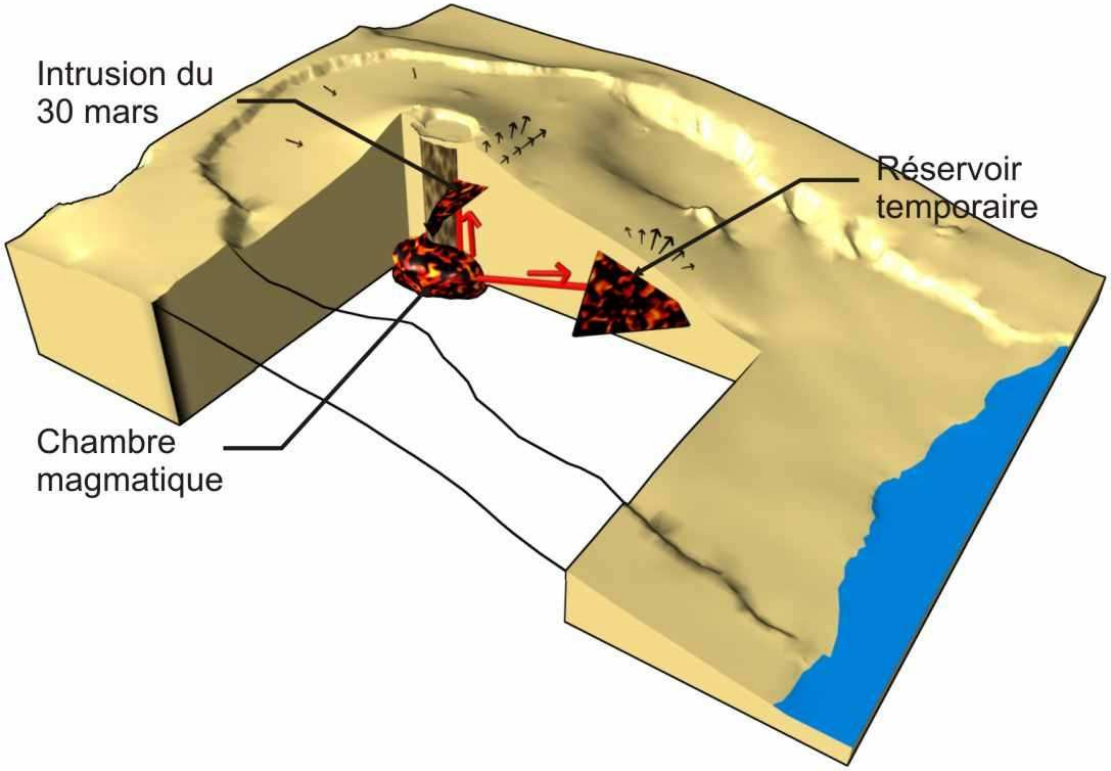
Join et al. 2005

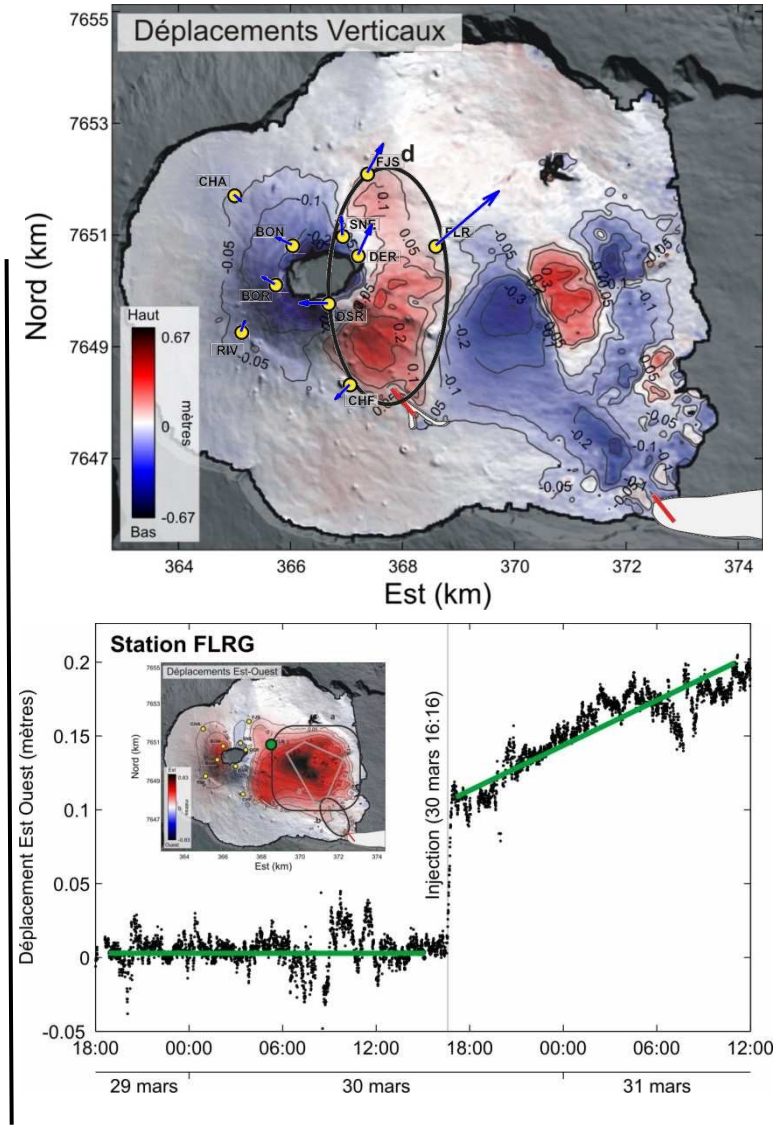
Partie IV

Modèle conceptuel de l’éruption

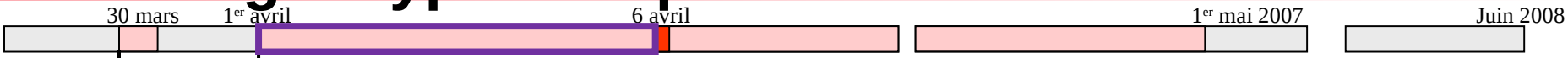
Chronologie hypothétique des événements

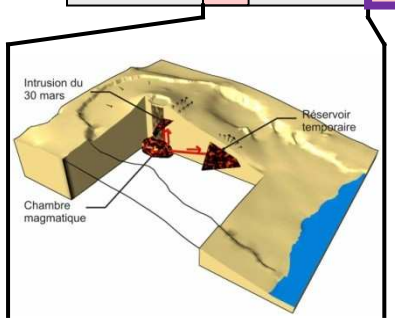


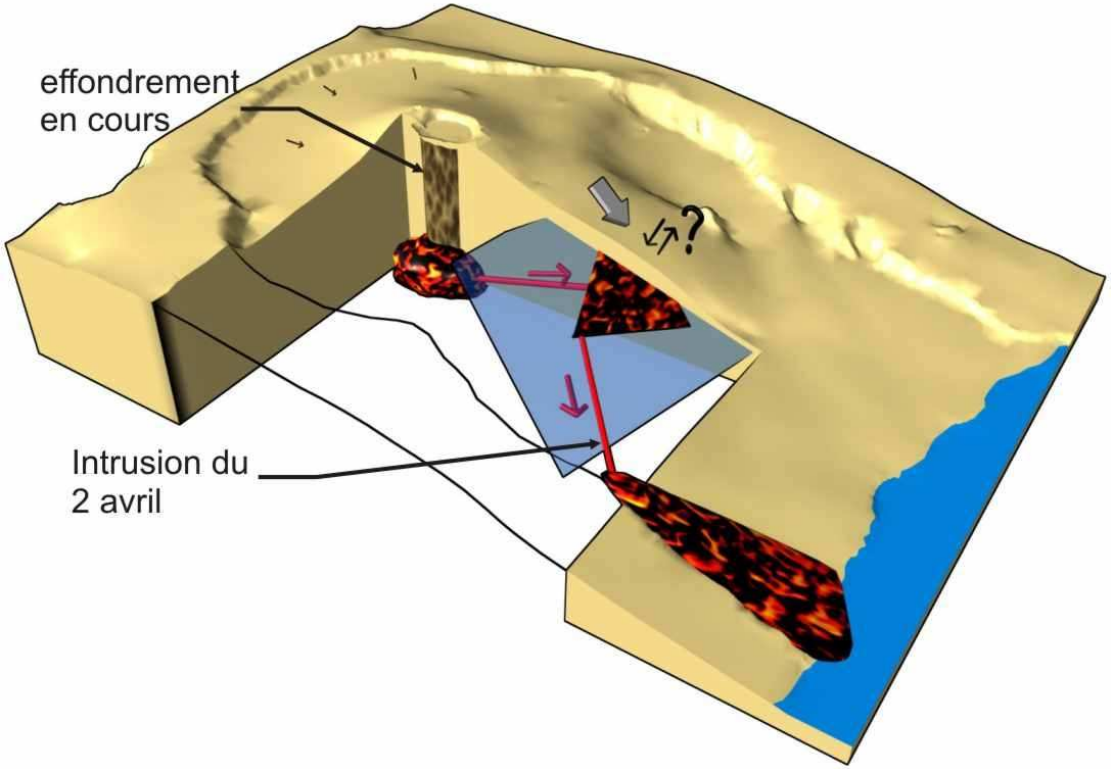


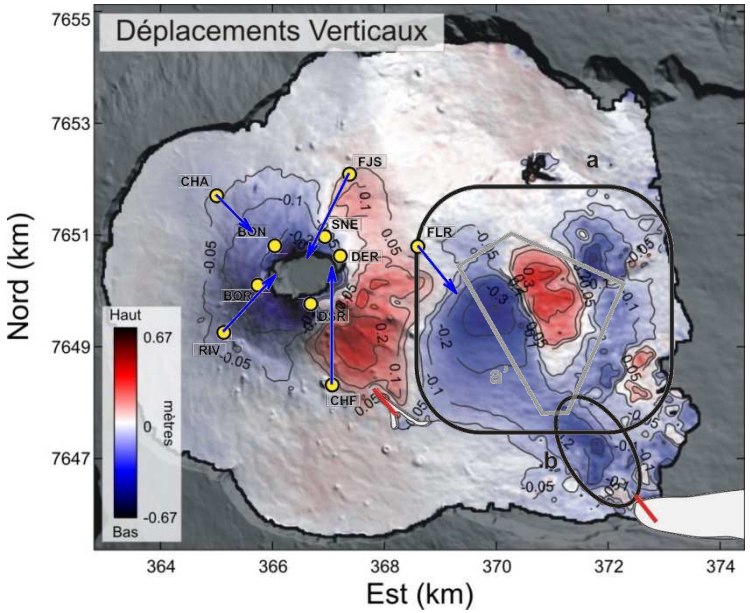


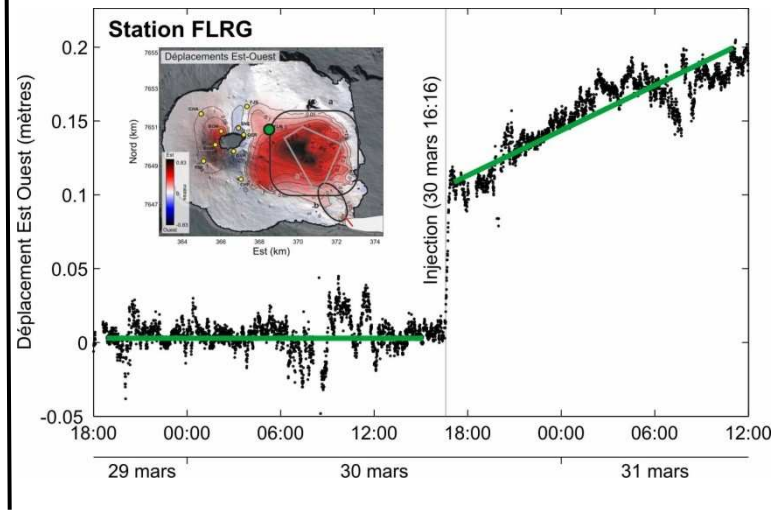
Chronologie hypothétique des événements



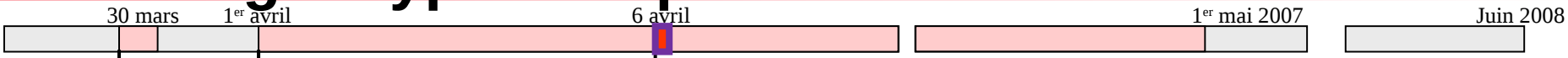


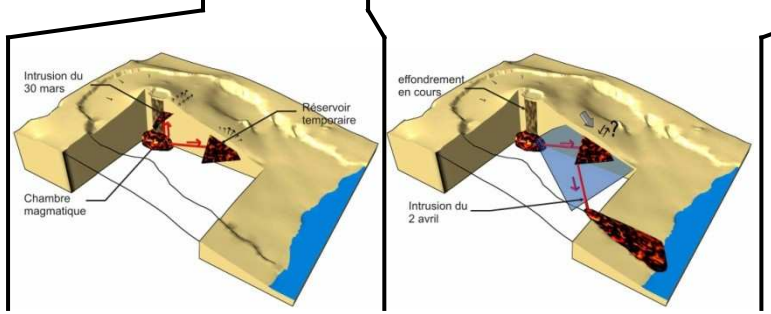


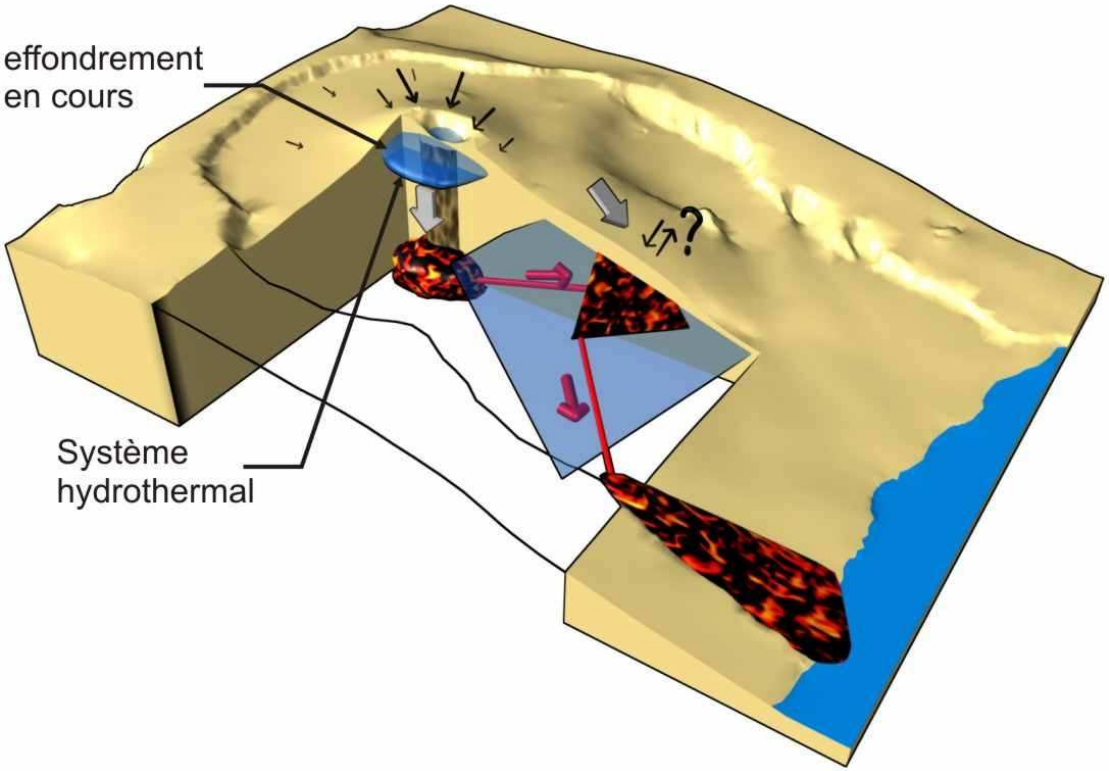


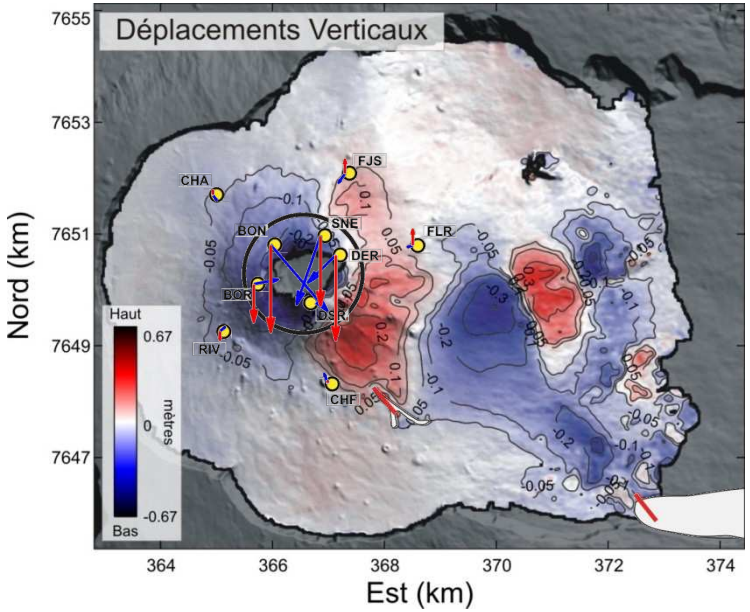


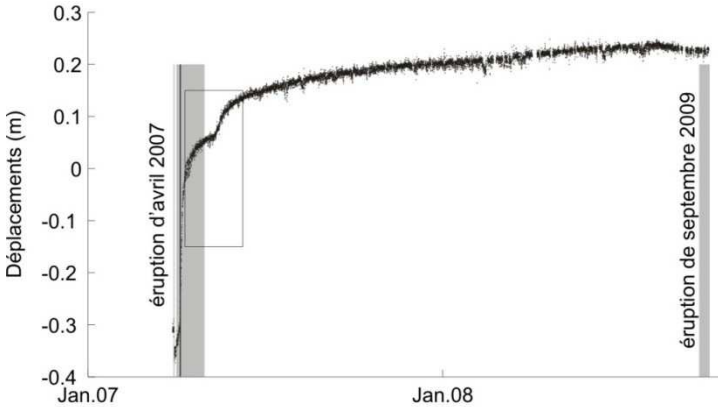
Chronologie hypothétique des événements



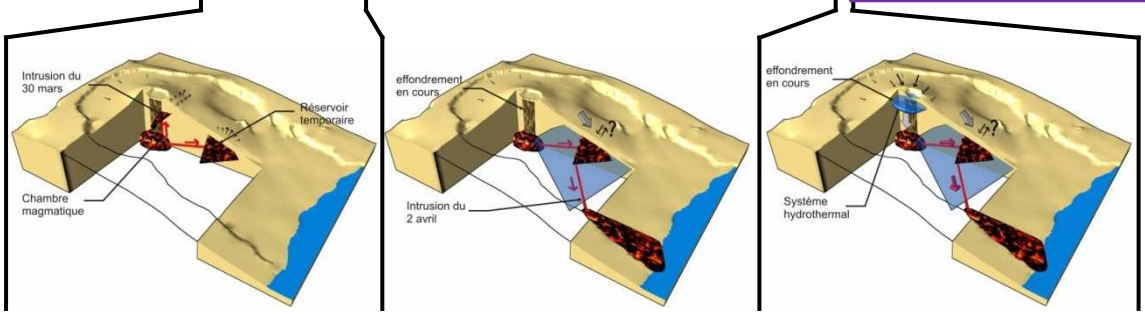


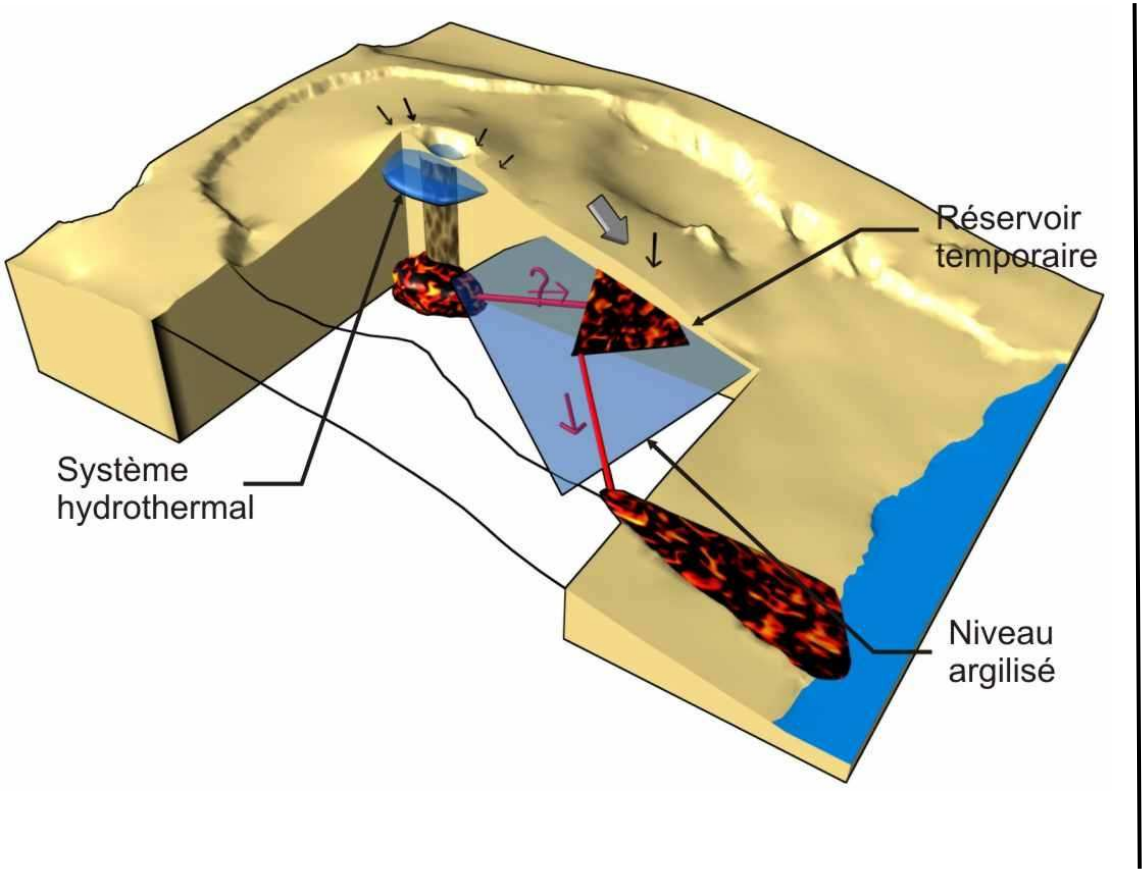


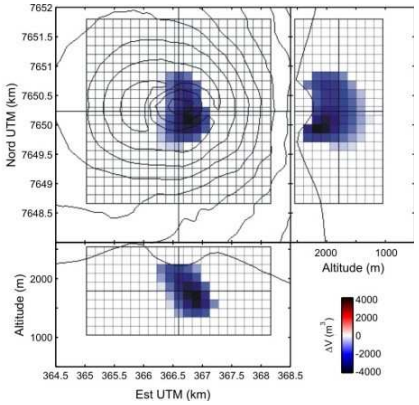




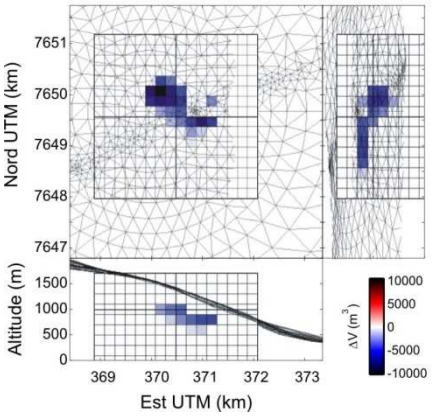
Chronologie hypothétique des événements



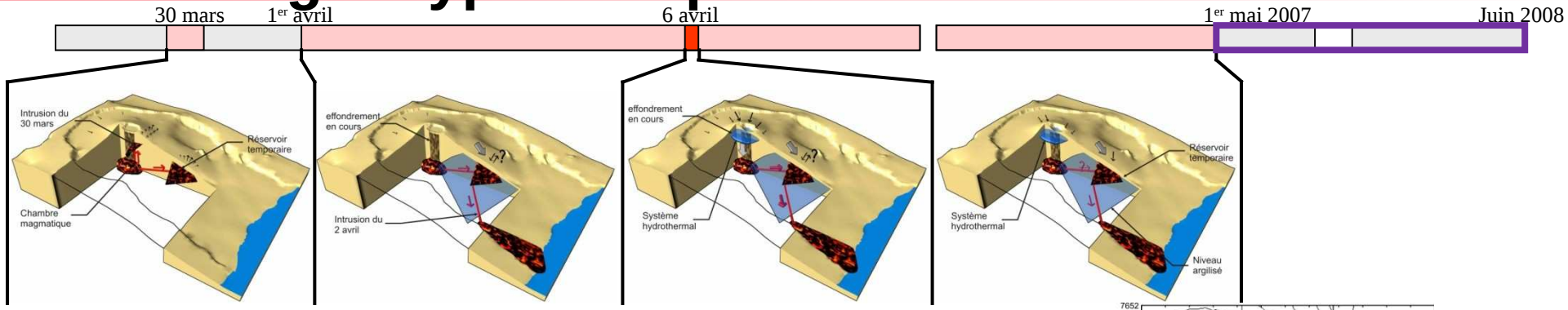


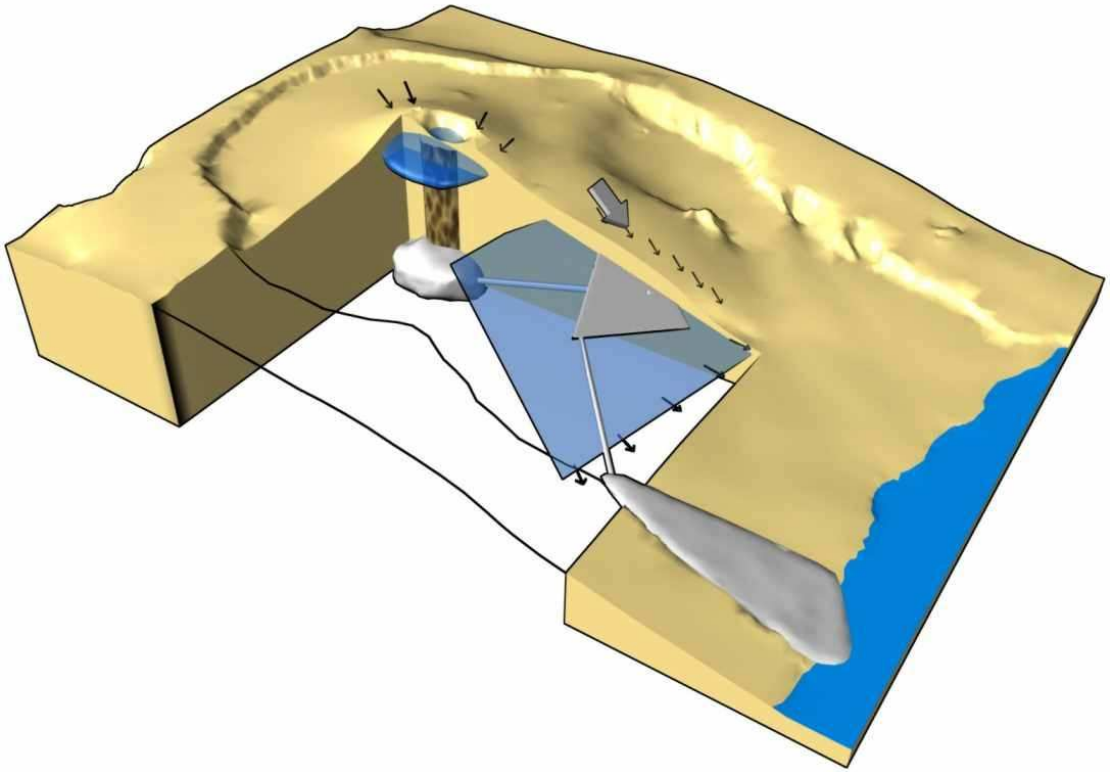


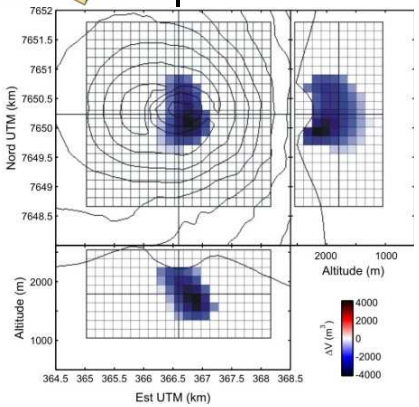
Tomographie simplifiée, même signe

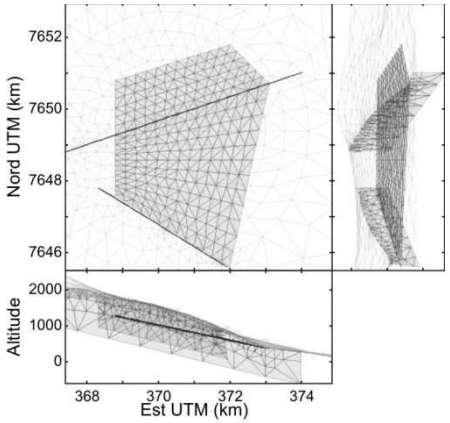


Chronologie hypothétique des événements

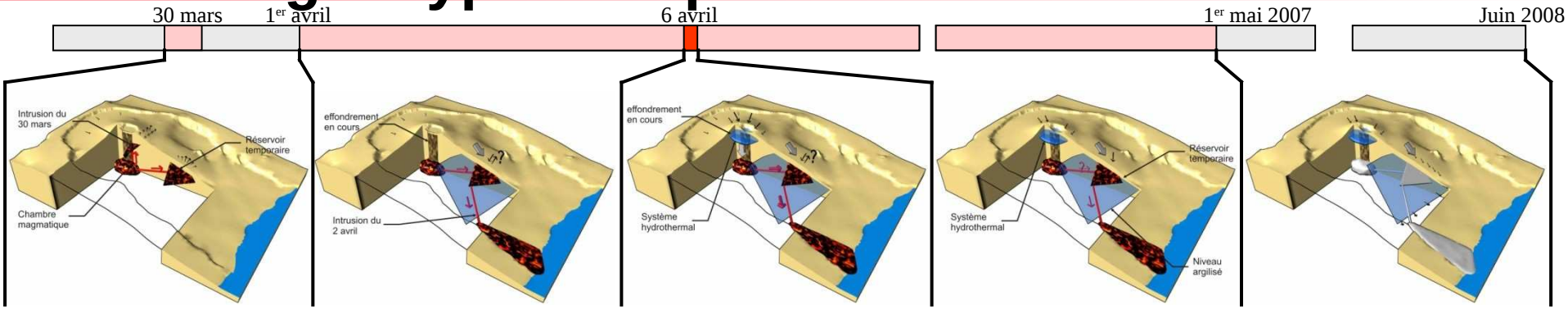








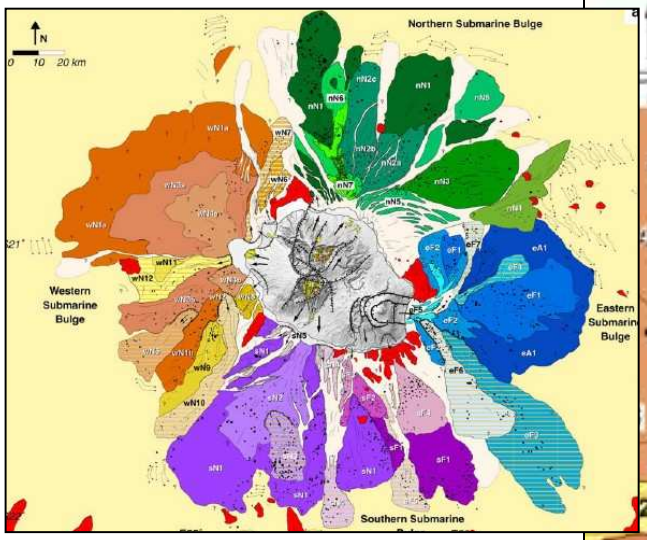
Chronologie hypothétique des événements



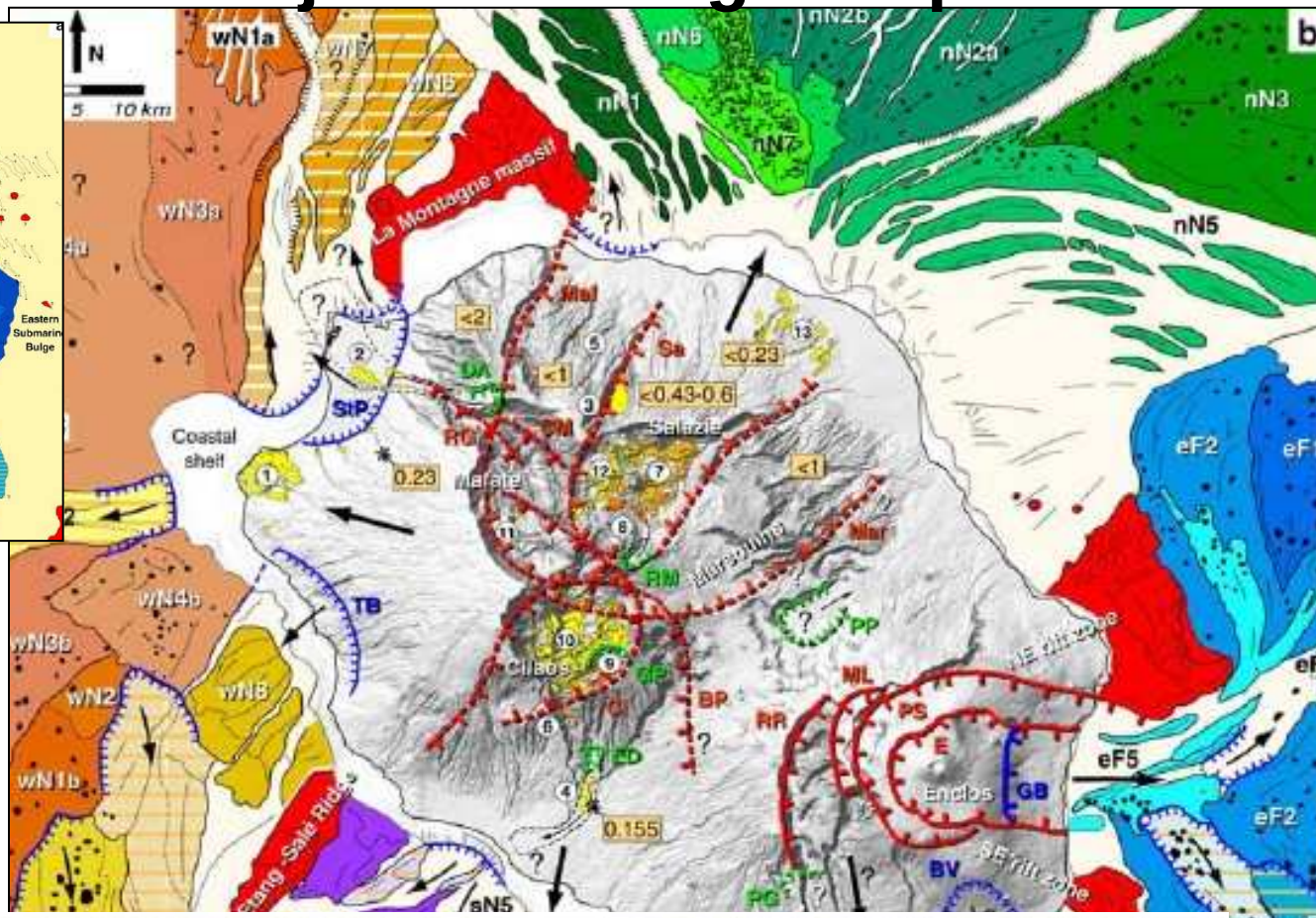
Partie V

Perspectives

Morphologie de l'île et injections magmatiques



Oehler et al 2007



Famin et Michon 2009

Morphologie du Piton de la Fournaise

Michon Saint-Ange 2008

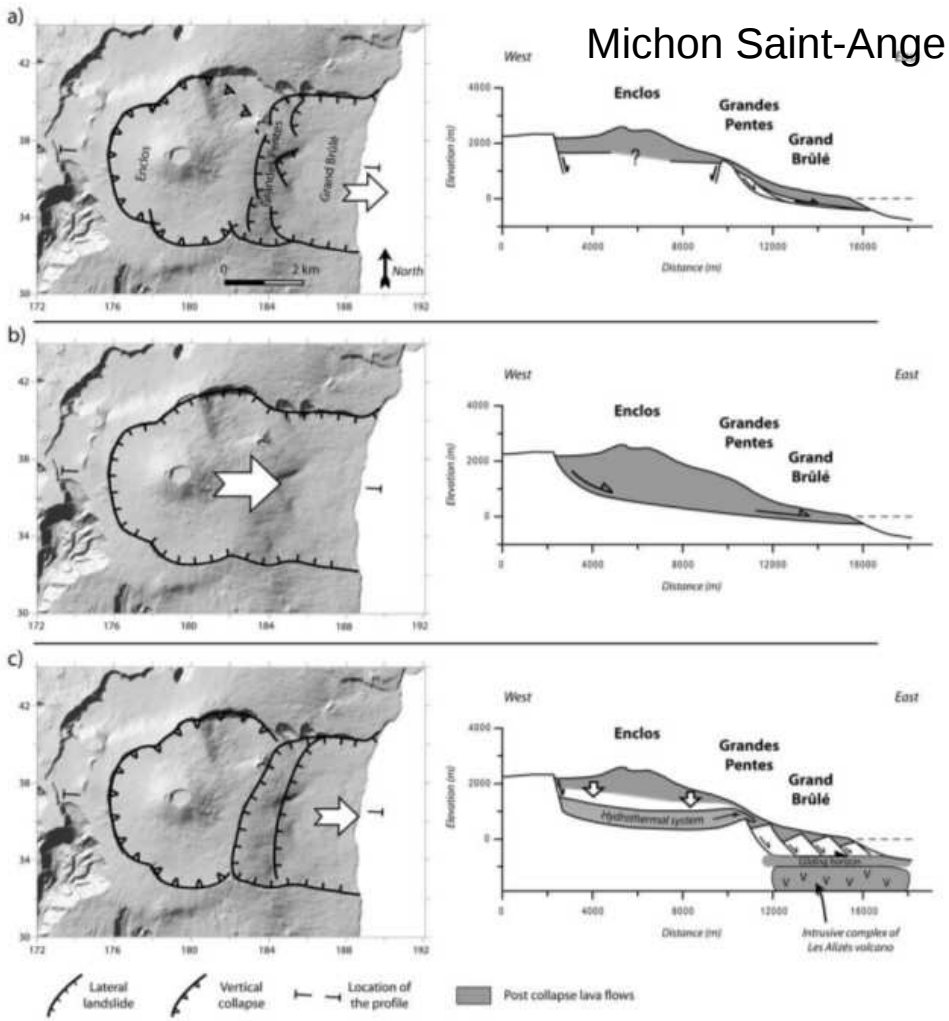
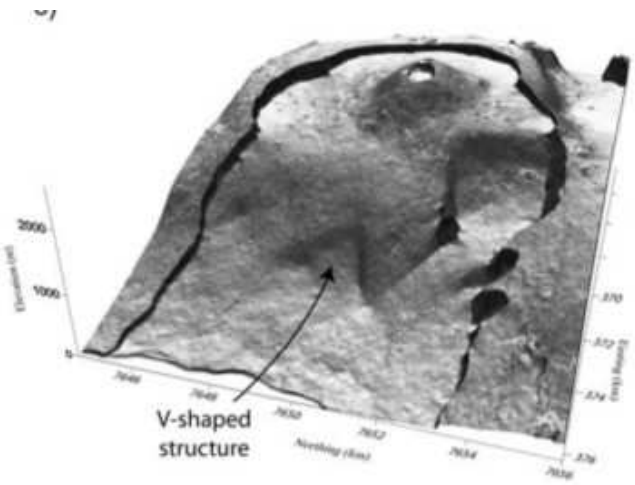
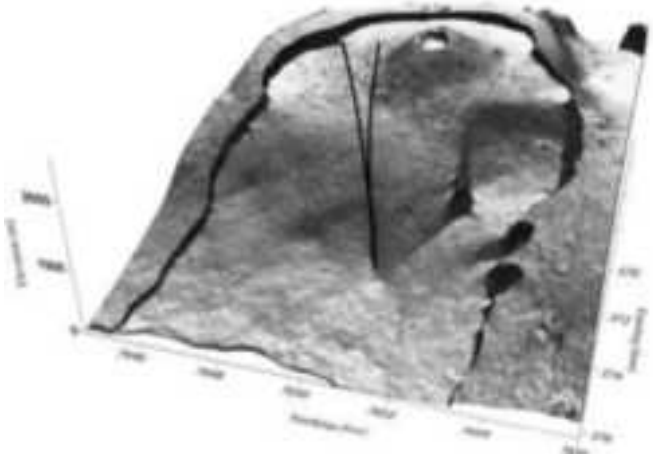
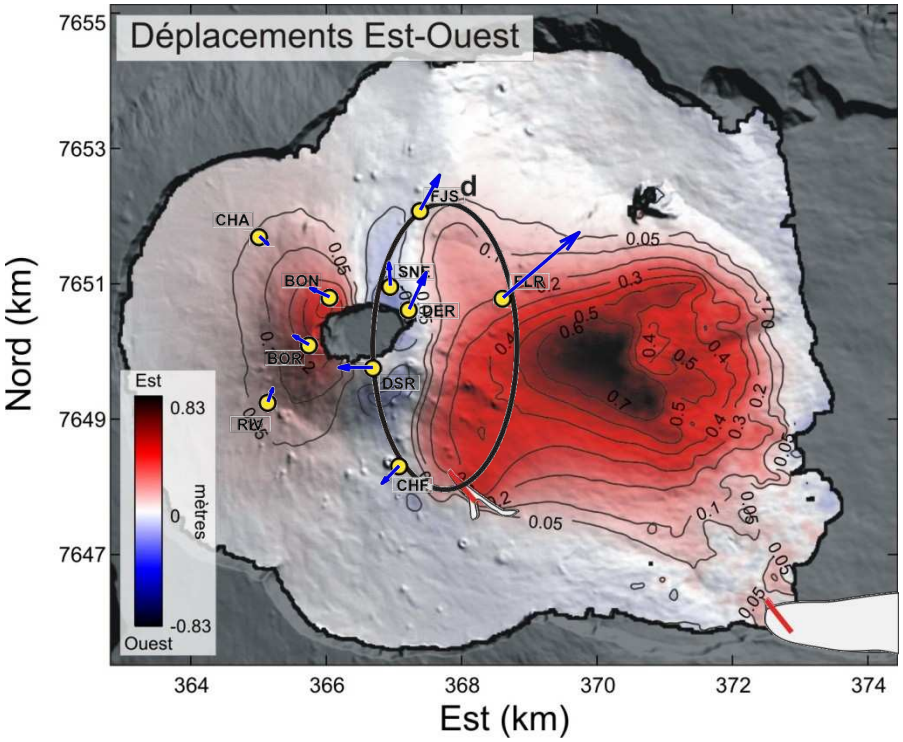


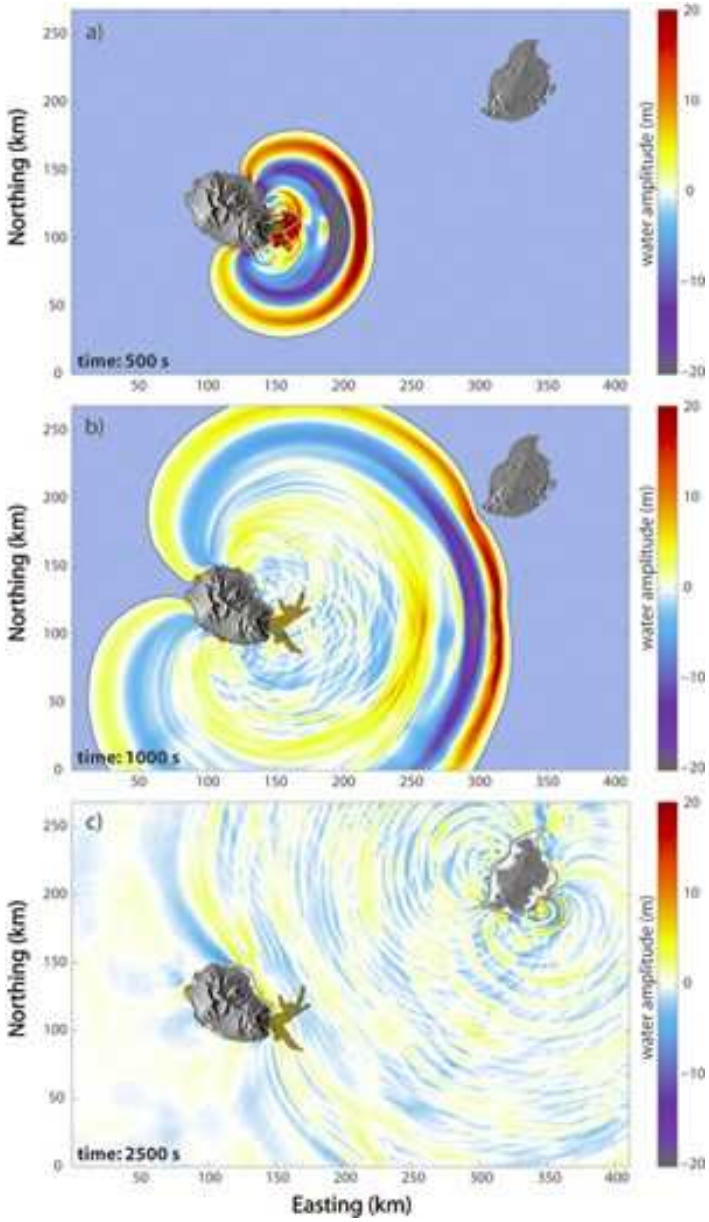
Figure 2. Schematic views and cross sections of the three different models previously proposed to explain the formation of the large Enclos-Grand Brûlé structure (EGBS). (a) A polyphase caldera collapse and the Grand Brûlé is the scar of one or several lateral landslides, the Grandes Pentes being the headwall of these slides [after *Bachèlery*, 1981]. (b) The entire structure is the scar of a single, landslide [after *Labazuy*, 1996; *Oehler et al.*, 2004]. (c) A slide of the Grand Brûlé due to a deep décollement induced a collapse of the Enclos caldera [after *Merle and Lénat*, 2003]. Coordinates are in Gauss Laborde Réunion (km).





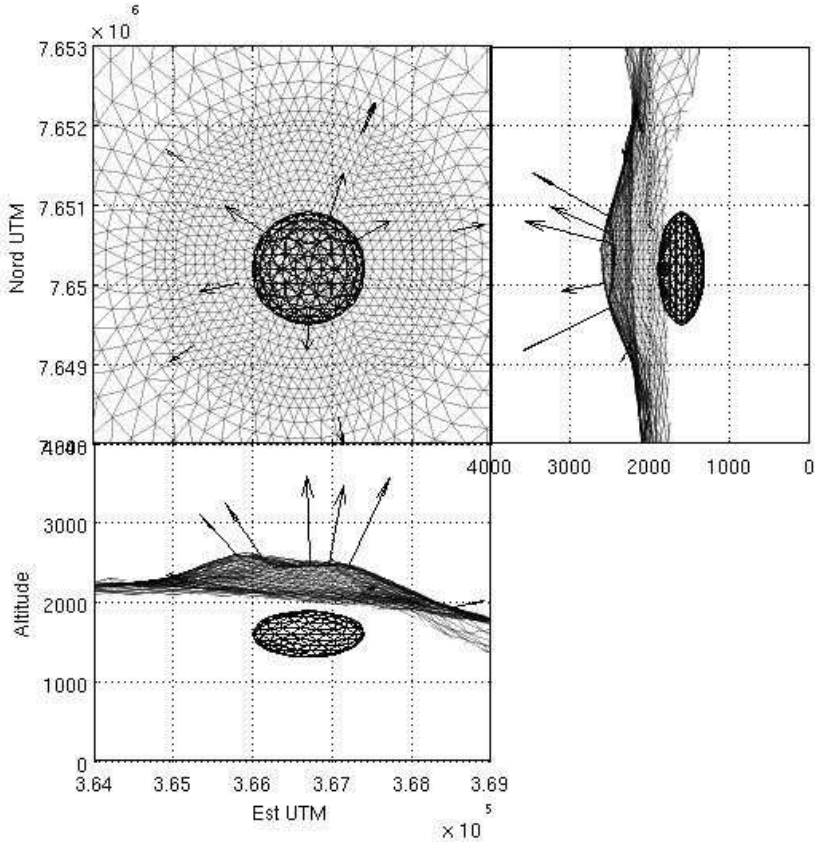
Gestion du risque Tsunami

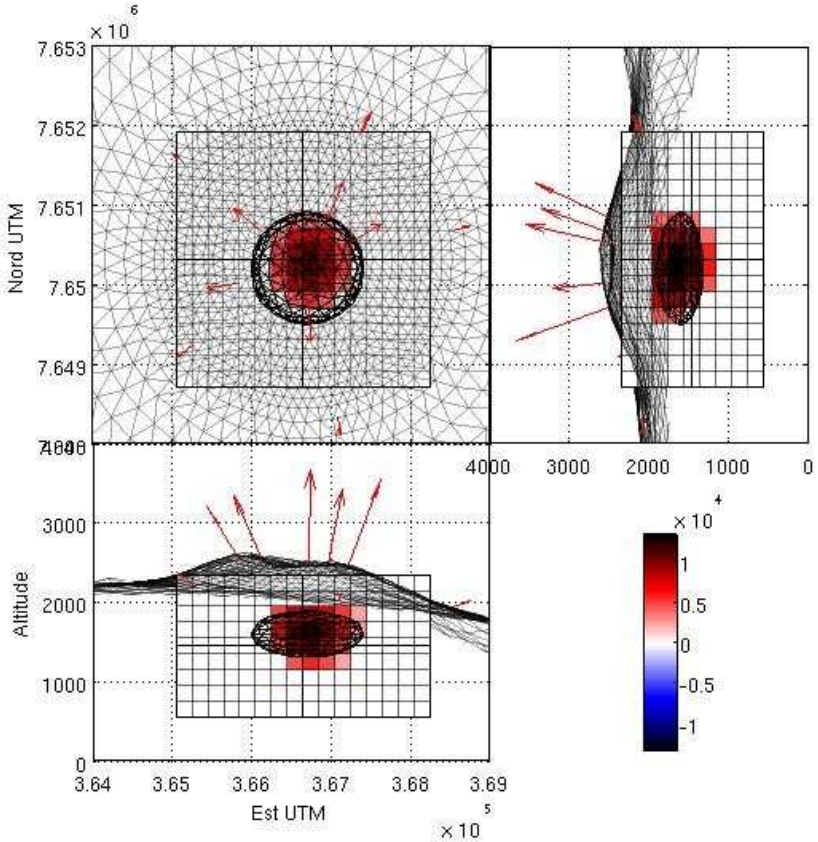




Kelfoun et al 2010

Tomographie sur données GPS en temps (quasi) réel





	Tomographie
Misfit	3,2%
Temps de calcul	22 minutes

Amélioration et mise à disposition de la toolbox_MOI (Modélisation et Optimisation pour l'InSAR)

ENVISAT DATA : ESA AO-ENVISAT 746

ALOS DATA : ESA JAXA ALOS-ADEN 3622

Données GPS : OVPF / IPGP

Merci à tous !!