

Surveillance volcanologique : de la mesure instrumentale au modèle prédictif

Exemple des études de déformations du sol

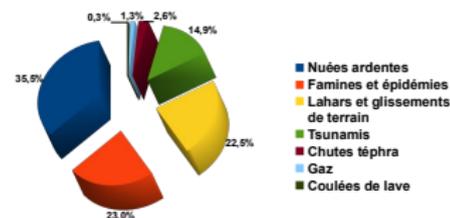
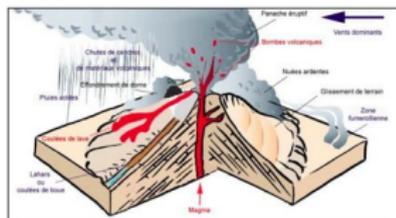
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Les risques volcaniques



Les grandes catastrophes historiques

Tambora, Indonésie	1815	60 000	famine
Krakatau, Indonésie	1883	36 417	nuée ardente + tsunami
Montagne Pelée, Martinique	1902	29 000	nuée ardente
Nevado del Ruiz, Colombie	1985	25 000	lahar
Unzen, Japon	1792	15 118	tsunami
Laki, Islande	1783	9 336	famine
Santa Maria, Guatemala	1902	6 000	nuée ardente
Kelud, Indonésie	1919	5 110	coulée de boue
Galunggung, Indonésie	1822	4 000	coulée de boue
...

Total depuis 1600 A.D.

≈ 300 000 morts



St-Pierre (Martinique), 1902

- ▶ 0 évacués
- ▶ 29 000 morts

Kinahrejo (Indonésie), 2010

- ▶ $\approx 1\,000\,000$ évacués
- ▶ 249 morts

Soufrière : crise sismo-volcanique 1975-1977

La crise en chiffres

- ▶ 7 mois d'activité de surface
- ▶ 16 000 séismes
- ▶ 26 explosions
- ▶ 800 000 m³ de matériaux éjectés + coulées de boue
- ▶ 73 422 personnes évacuées pendant 3 mois $\frac{1}{2}$

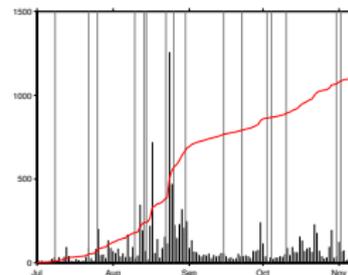
2 hypothèses contradictoires...

- A purement phréatique sans risque
- B intrusion magmatique avec risque



Soufrière : quel retour d'expérience ?

Arguments supporting purely phreatic eruption	Arguments supporting still-born magmatic eruption	
Nothing happened...	✓	-
Surface observations (gas content, temperatures, ash) only phreatic	✓	-
Lack of any violent historical eruption at La Soufrière, small proportion of pyroclastic flows deposits... [Tazieff, 1976]	✗	Recent geological evidences [Boudon et al., 1987; 2008, Komorowski et al., 2005; 2008]
Frequent seismic crisis in the Caribbean without any eventual eruption (e.g. Montserrat)... [Tazieff, 1976]	✗	Posterior facts: St-Vincent 1979; Soufrière Hills 1995-present
No migration of seismic events during crisis [Tazieff, 1976]	✗	Evidence for migration of seismic events [Hirn and Michel, 1979]
-		Seismicity energy and magnetic anomaly [Feuillard et al., 1983]
-		Hot springs chemical modeling (degassing pulses of Cl) [Villemant et al., 2005]
Phreatic surface phenomena usually not followed by magmatic stage	✗	Posterior facts: St-Helens, Pinatubo, Unzen, Soufrière Hills

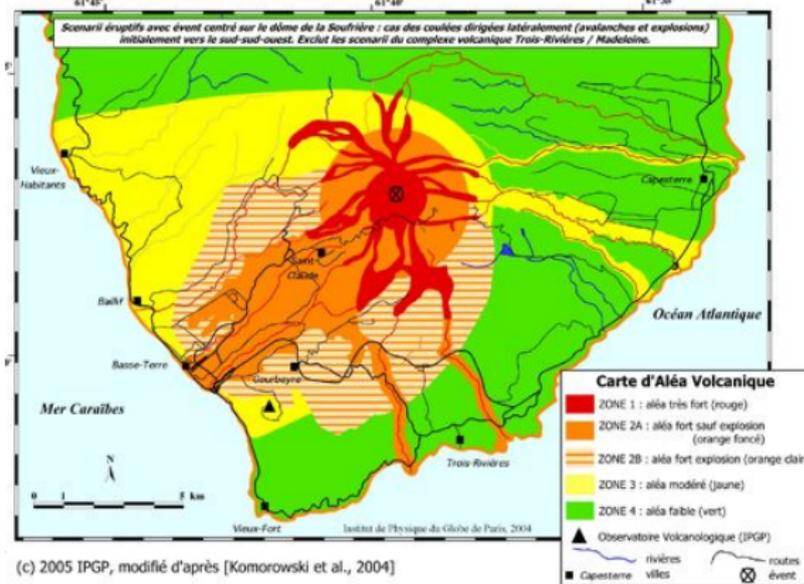
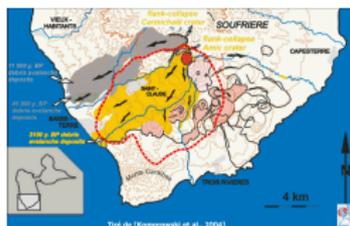
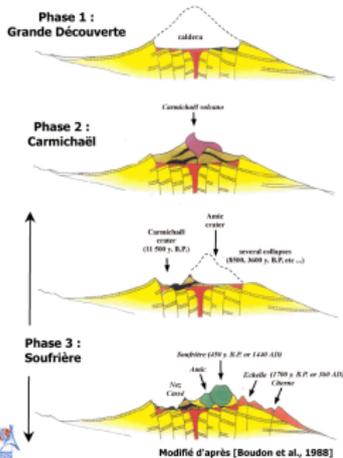


Déficits de connaissance...

- ▶ rien sur le passé géologique
- ▶ méconnaissance des scénarios éruptifs
- ▶ peu d'expérience de suivi instrumental
- ▶ pas de modèle physique quantitatif

Soufrière : la réponse du passé éruptif

Carte d'aléa volcanique de la Soufrière de Guadeloupe

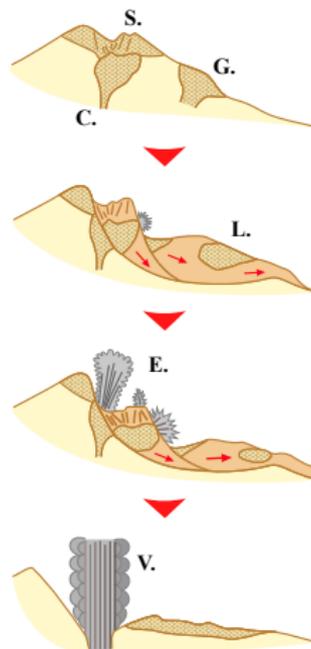


(c) 2005 IPGP, modifié d'après [Komorowski et al., 2004]

[Boudon et al., 1986 ; Komorowski et al., 2005, 2008]

- ▶ éruption type St-Helens 1530 AD
- ▶ nombreuses déstabilisations de flanc

St-Helens 1980 : naissance de la volcanologie instrumentale

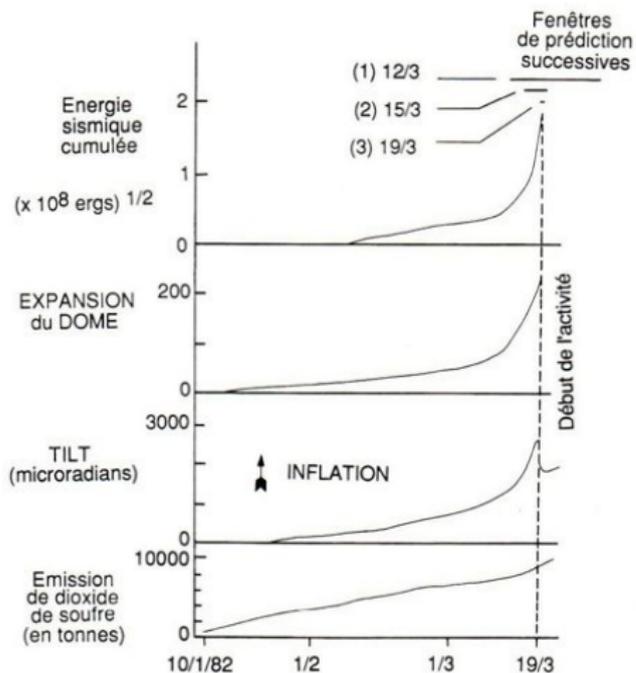


Éruption du 18 mai 1980

- ▶ précurseurs = larges déformations
- ▶ évacuation préventive
- ▶ 3 km³ de roches éjectées
- ▶ 600 km² dévastés (jusqu'à 24 km)
- ▶ observations sismiques, déformations et gaz

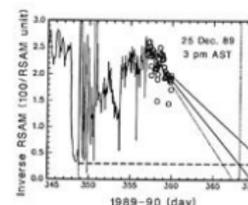
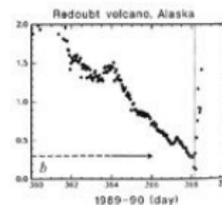
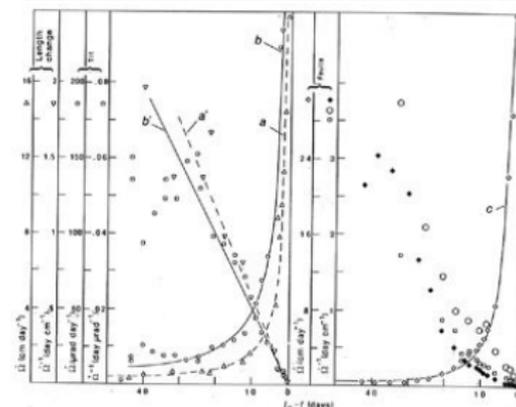


Prédiction : méthode empirique



[Voight, 1988]

$$\dot{\Omega}^{-\alpha} \ddot{\Omega} - A = 0$$



Prévision : approche déterministe



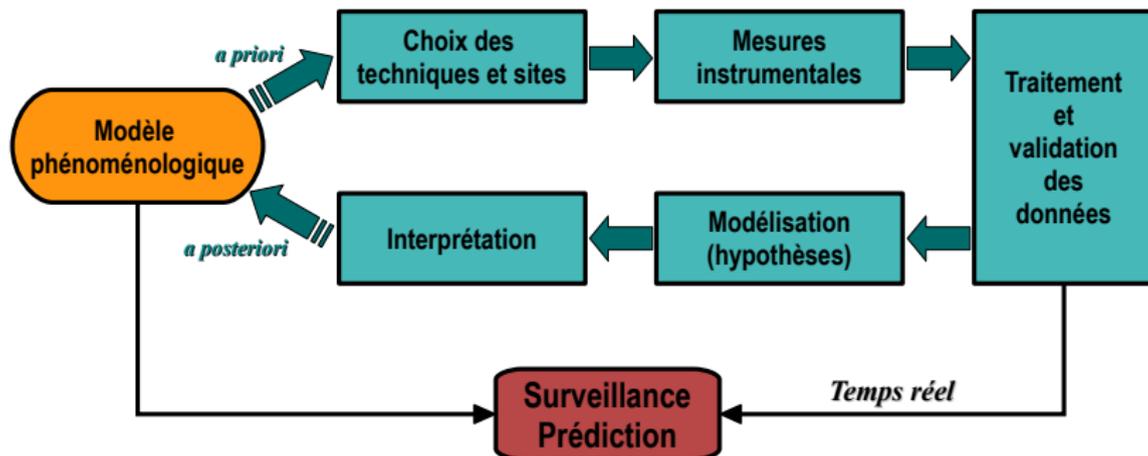
Questions posées

- ▶ Caractéristiques de l'aléa :
 - source magmatique / phréatique / instabilités
 - amplitude, volumes
 - localisation, directions
 - délais temporels
- ▶ Complexité des phénomènes

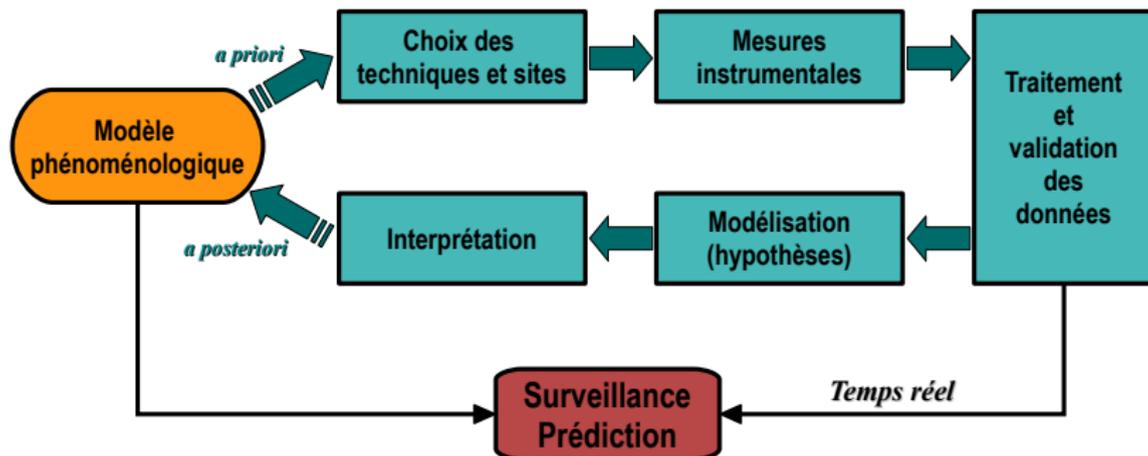
Les besoins

- ▶ Données physiques et géométriques
quantitatives

Ambivalence surveillance/recherche



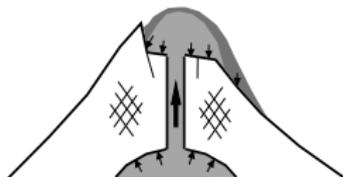
Ambivalence surveillance/recherche



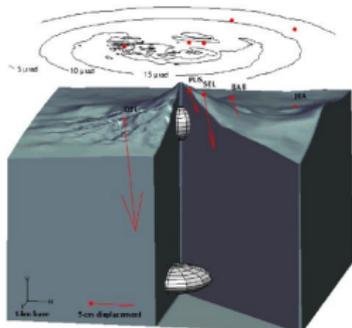
Axiome

Prédiction = données temps-réel + modèle d'interprétation

“Tomographie mécanique”



MERAPI ELASTIC MODEL: Tilt & Displacements



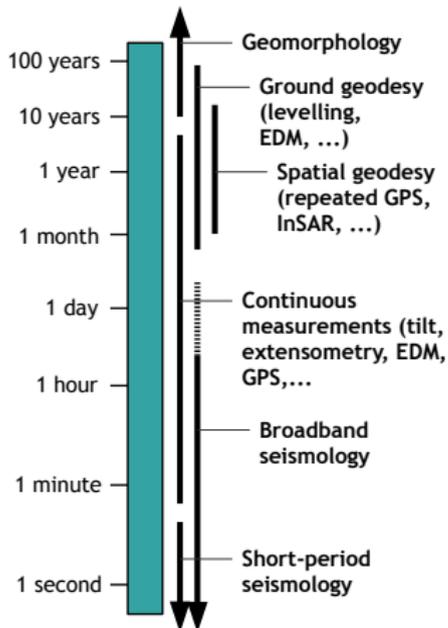
Pourquoi un volcan se déforme-t-il ?

- ▶ Mouvements de fluides (magma, gaz)
- ▶ Modèles = **conditions aux frontières**
dynamique des fluides magmatiques /
mécanique édifice :
 - géométrie des substructures internes
(chambre et conduit magmatique, fractures)
 - paramètres des sources (ΔV , ΔP , $\Delta\sigma$, $\Delta\rho$)

Modèles mécaniques

- ▶ Contraindre les sources et les structures à
partir des déformations de surface
- ▶ Non-unicité des solutions : intégration d'autres
observations (information a priori)
- ▶ Nécessité d'une méthodologie

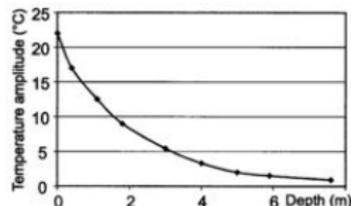
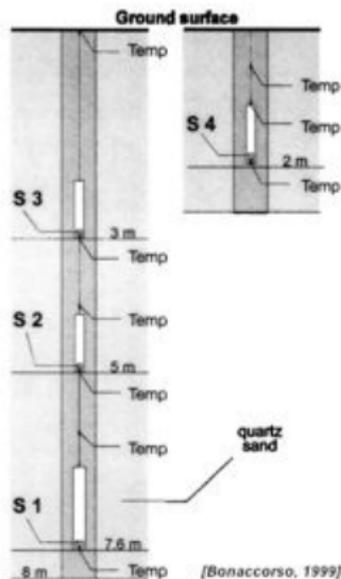
Mesures du champ de déformation



Techniques complémentaires

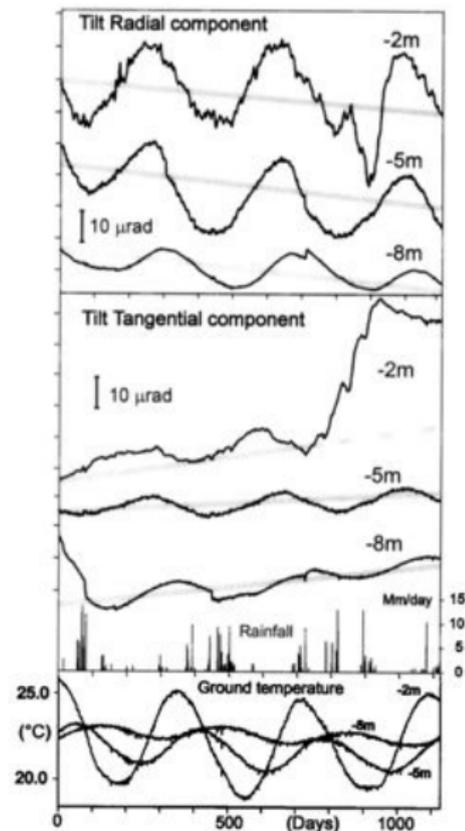
- ▶ Besoin d'observations **spatiales et temporelles** "continues"
- ▶ Classification des méthodes :
 - **Échantillonnage spatial** = ponctuel / réseau / imagerie
 - **Échantillonnage temporel** = périodique / continu / bande passante
 - **Couplage** = sol / télédétection
 - **Paramètre mesuré** = déplacement (1D/3D), angle, déformation
- ▶ Chaque méthode a ses avantages et artefacts propres...

Inclinométrie : couplage et effets thermiques



[Bonaccorso et al., 1999]

- ▶ expérimentation sur 3 ans
- ▶ gradient thermique vertical
- ▶ effets de la pluie

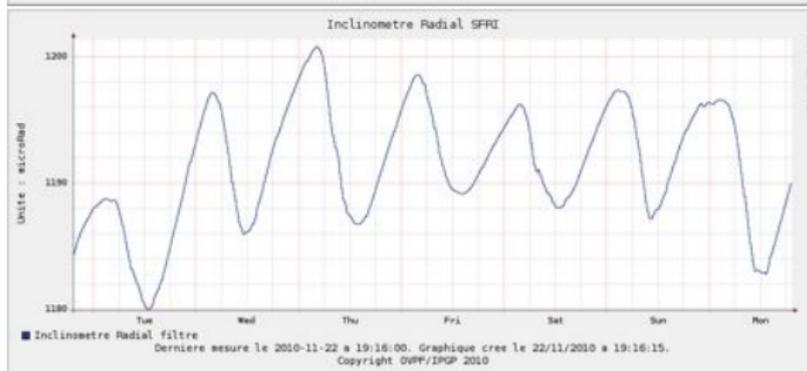
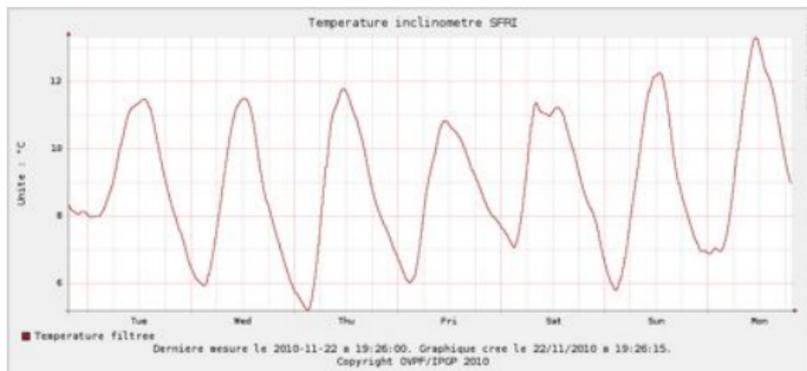


Couplage : installation de surface

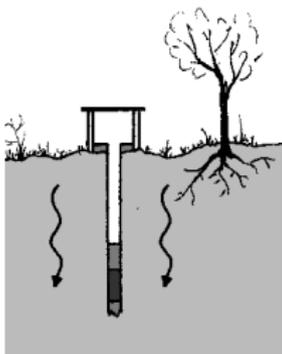


[OVSG-IPGP, 2010]

- ▶ ex : Fournaise
- ▶ effets thermo-mécaniques
- ▶ fractures = non linéaire

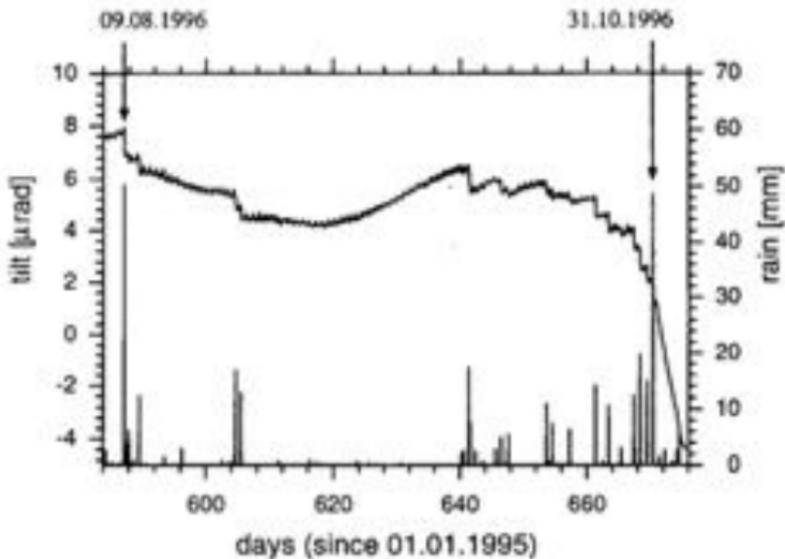


Couplage : puits dans sol poreux

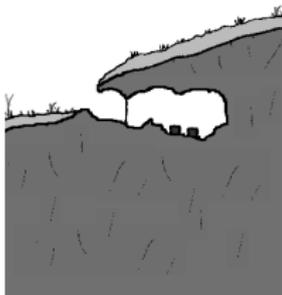


[Rebscher *et al.*, 2000]

- ▶ ex : Merapi
- ▶ circulation de fluides

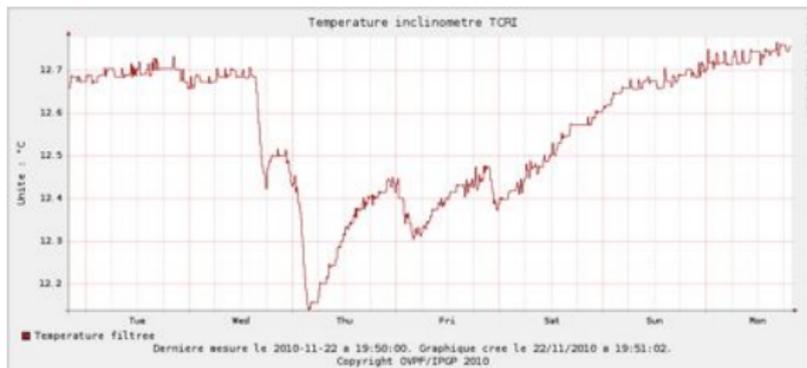


Couplage : cavité naturelle

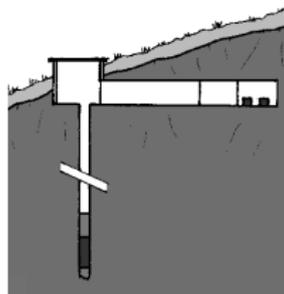


[OVSG-IPGP, 2010]

- ▶ ex : Fournaise
- ▶ effets de cavité
- ▶ non linéaire

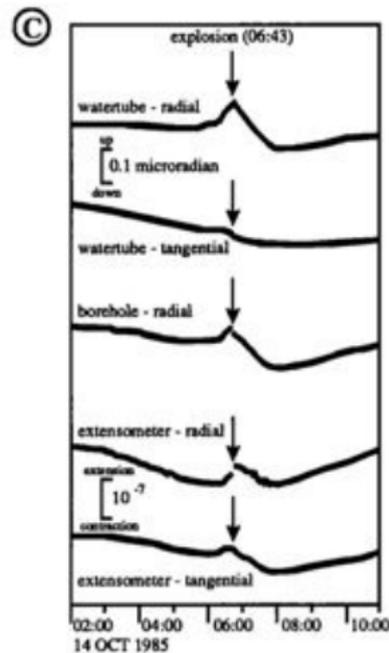
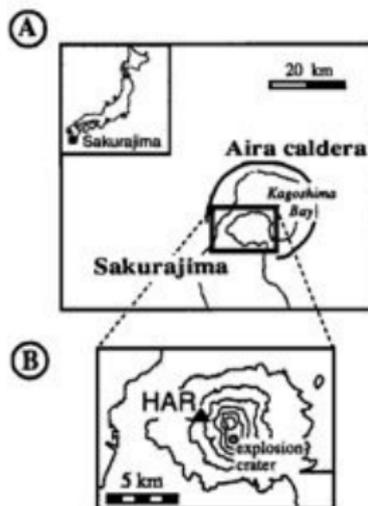


Couplage : forage/tunnel dans roche massive



[Ishihara, 1990]

- ▶ ex : Sakurajima
- ▶ parfait
- ▶ coûteux...



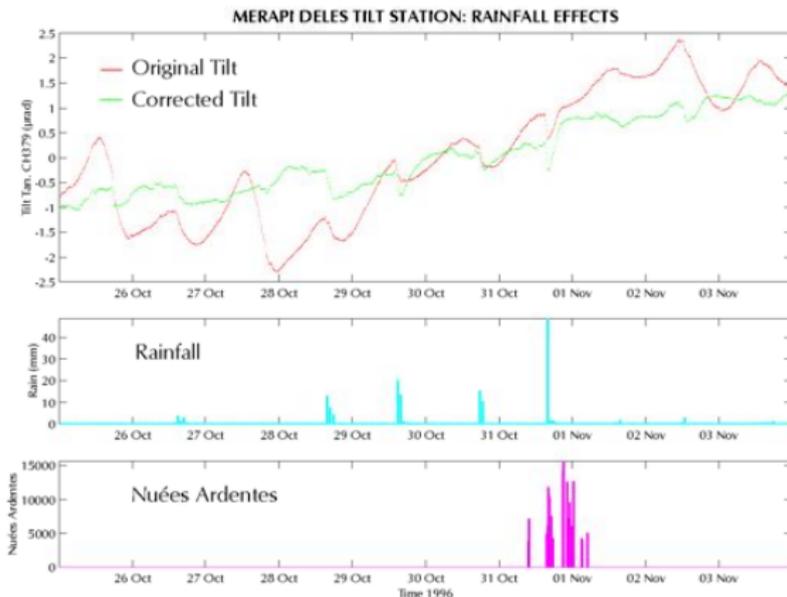
[Ishihara, 1990 ; Dvorak & Dzurisin, 1997]

Couplage : solution "Merapi"



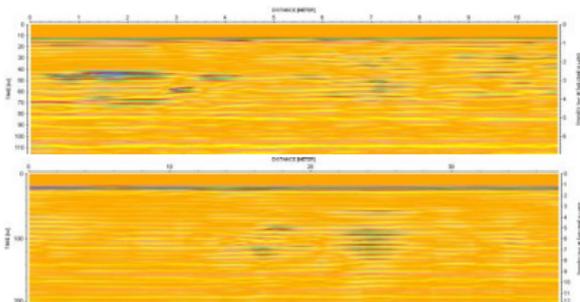
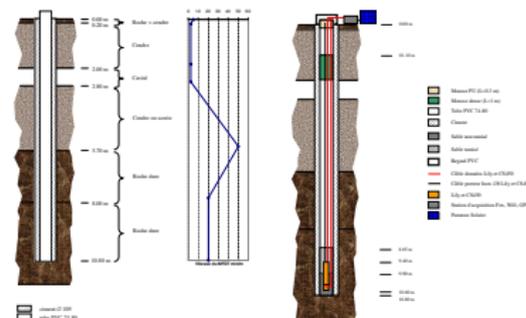
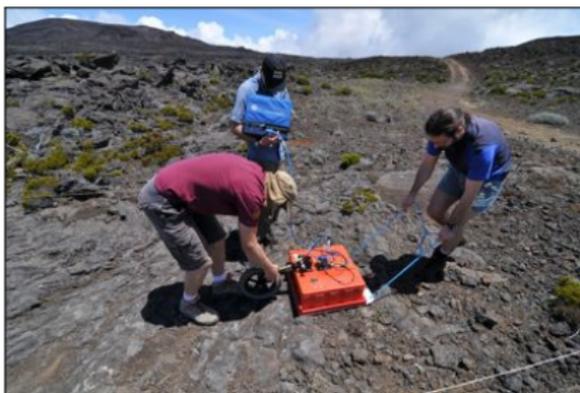
[Beauducel & Cornet, 1999]

- ▶ Ex : Merapi
- ▶ dépôts cendreux sur lave massive = isolant naturel



[Beauducel, 1998]

Piton de la Fournaise : forages peu profonds



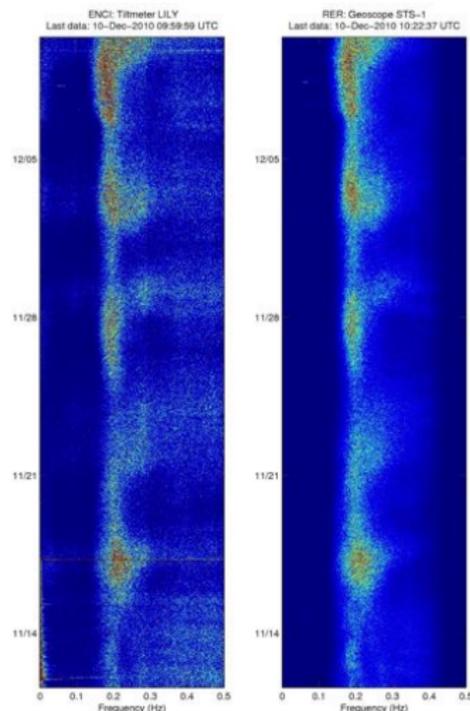
Piton de la Fournaise : forages peu profonds



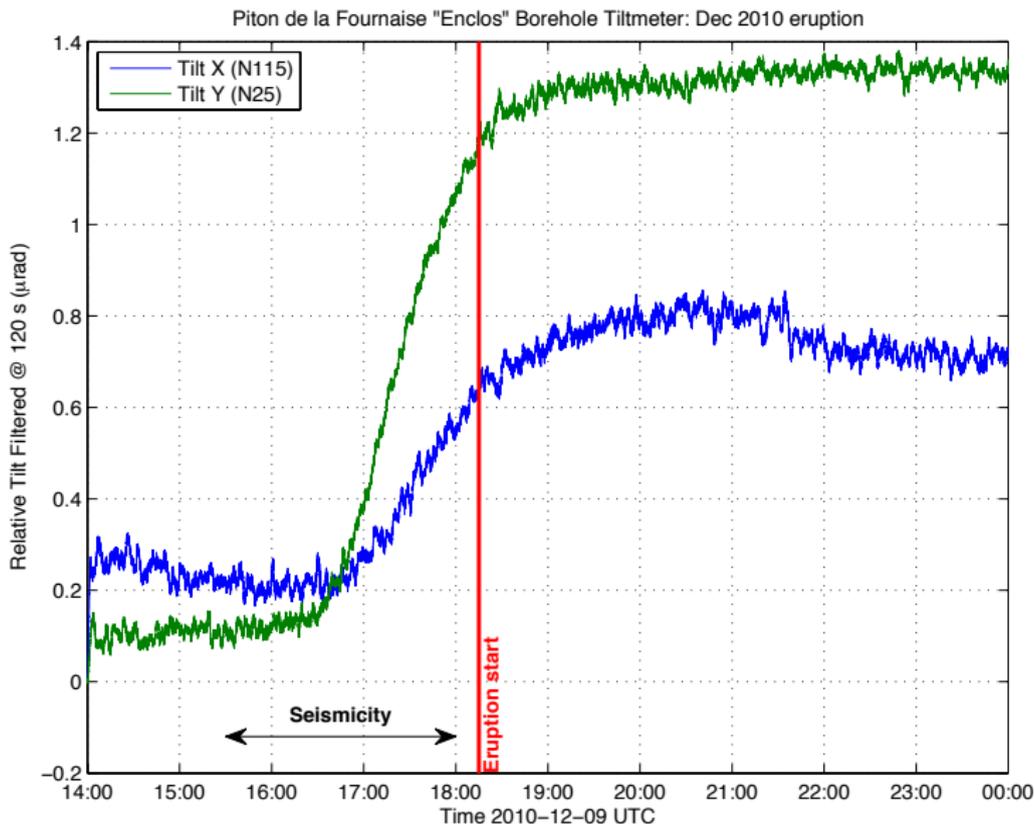
[Beauducel et al., 2010]

Piton de la Fournaise : forages 10 m

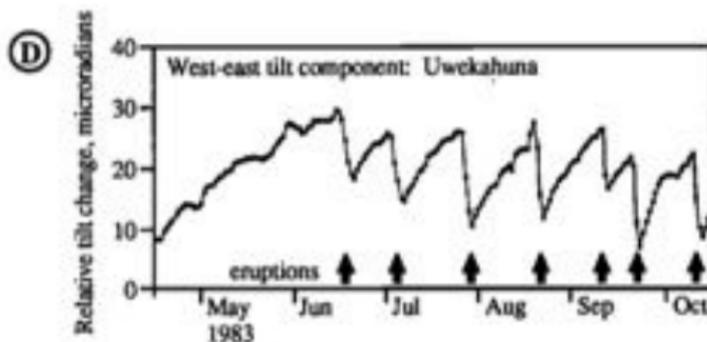
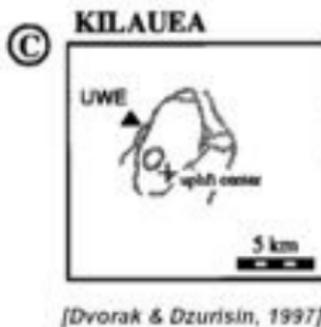
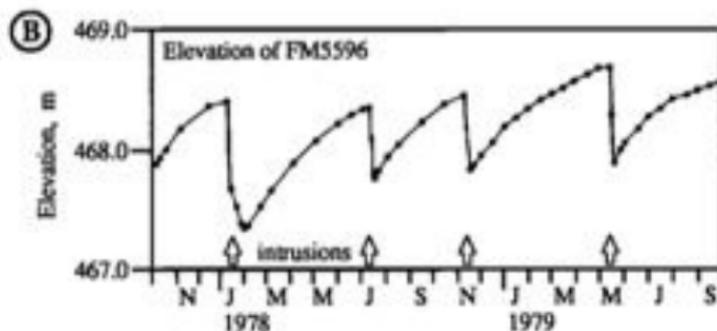
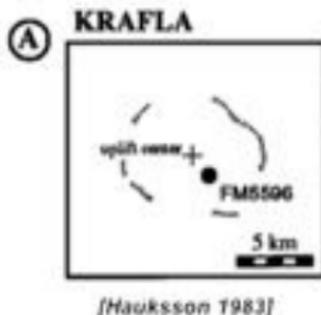
- ▶ variations diurnes = 0.002 °C
- ▶ marées terrestres
- ▶ éruptions et pluies > 200 mm/h



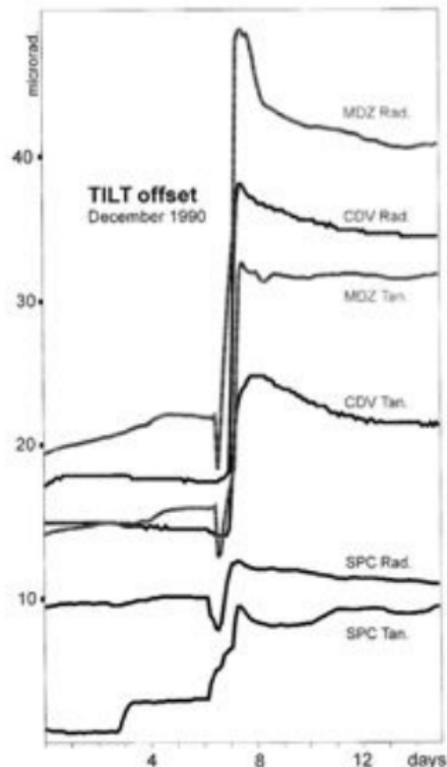
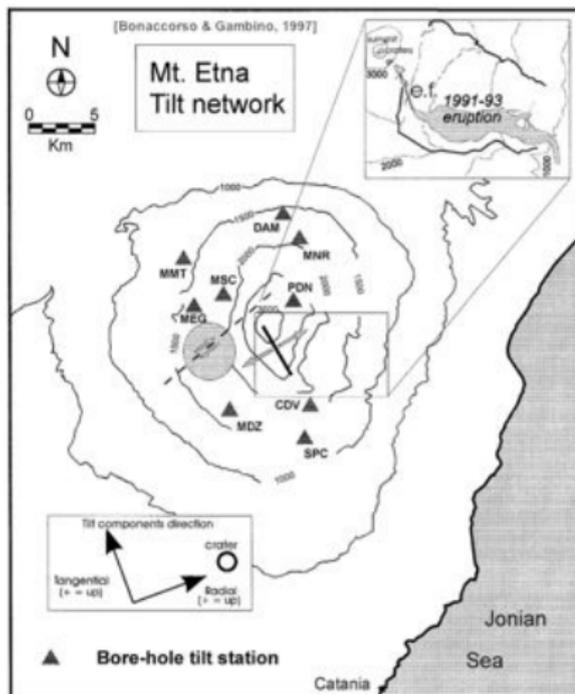
Piton de la Fournaise : forages peu profonds



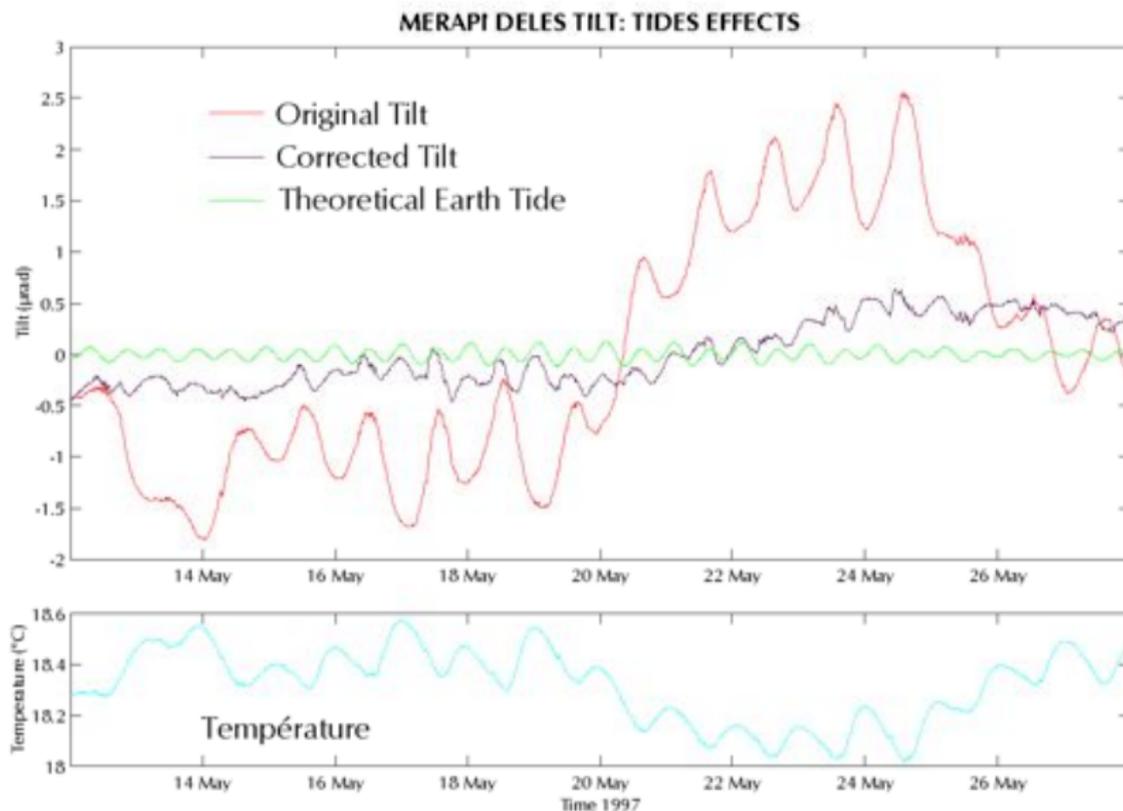
Inclinométrie : signaux associés aux éruptions



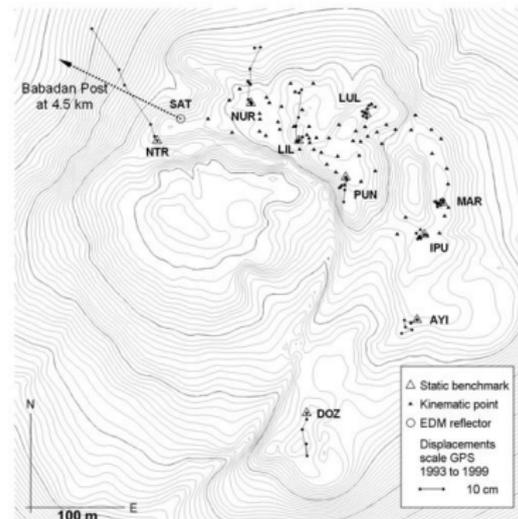
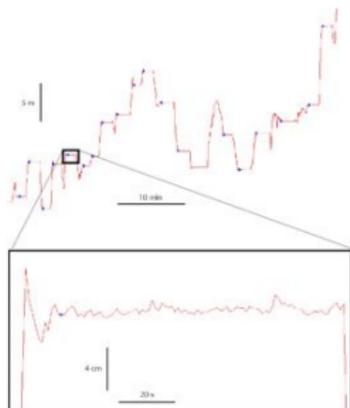
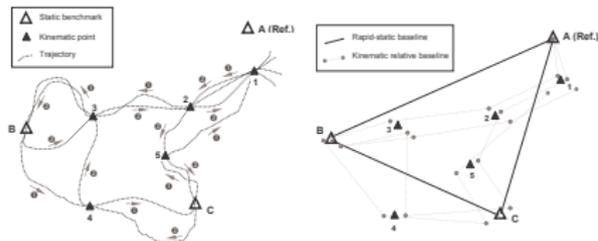
Inclinométrie : signaux associés aux éruptions



Traitements a posteriori



GPS : réseau mixte statique/cinématique



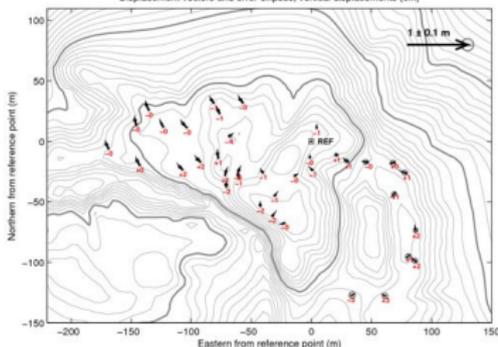
[Beauducel et al., 2006]

- ▶ Compensation jointe
- ▶ ≈ 1.5 cm d'erreur sur le réseau
- ▶ Identification fractures et blocs

GPS : réseau mixte statique/cinématique

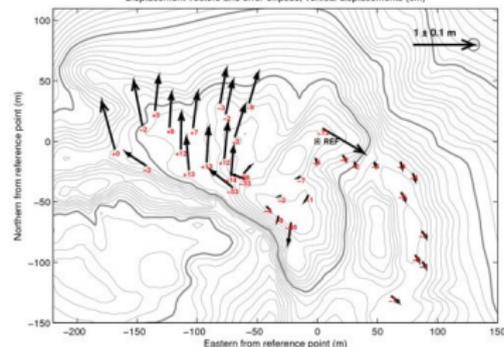
Merapi summit: GPS 1999-12 to 2000-07

Displacement vectors and error ellipses, vertical displacements (cm)



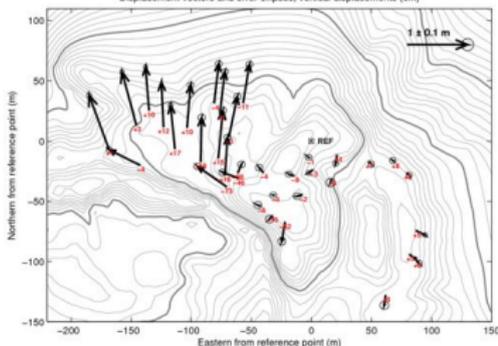
Merapi summit: GPS 1999-12 to 2002-10

Displacement vectors and error ellipses, vertical displacements (cm)



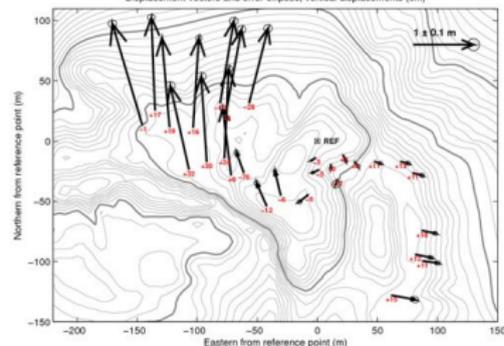
Merapi summit: GPS 1999-12 to 2005-07

Displacement vectors and error ellipses, vertical displacements (cm)

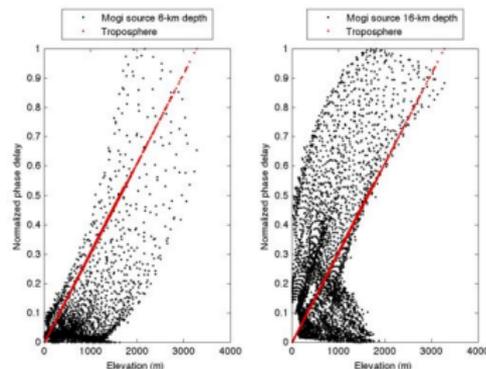
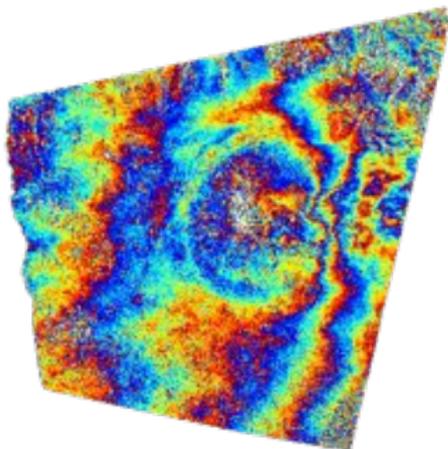
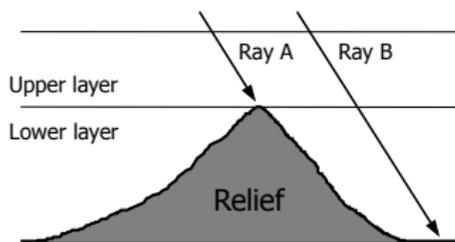


Merapi summit: GPS 1999-12 to 2007-01

Displacement vectors and error ellipses, vertical displacements (cm)



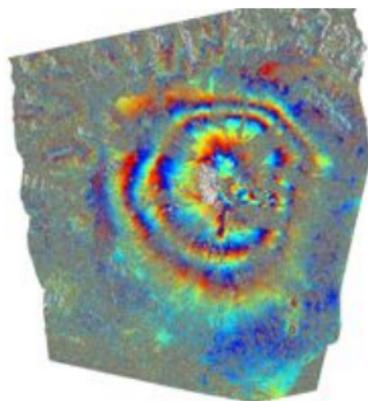
InSAR : artéfacts troposphériques



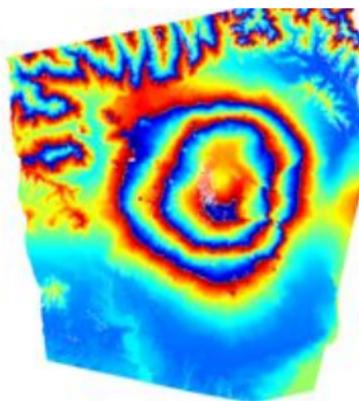
Corrélation avec la topographie ?

- ▶ angle du rayon d'incidence + assymétrie :
- ▶ phase troposphère \neq phase déformations
- ▶ modèle conjoint possible

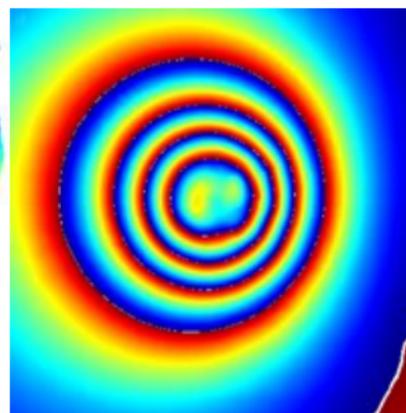
InSAR : modélisation conjointe



[*Massonnet et al., 1995*]

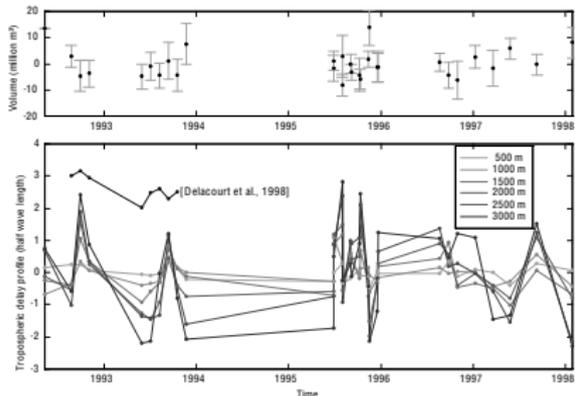


[*Beauducel et al., 2000*]



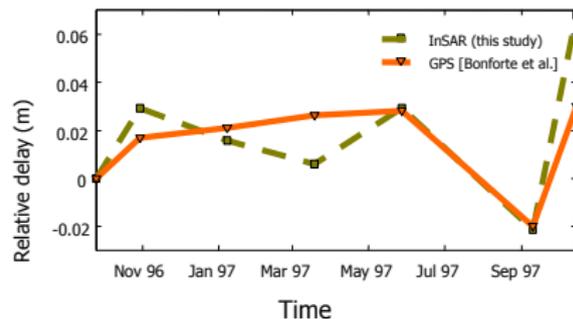
[*Cayol & Cornet, 1998*]

InSAR : modélisation conjointe



[Beauducel et al., 2000]

- ▶ inversion conjointe troposphère + déformations
- ▶ délais troposphériques compatibles avec autres méthodes indépendantes



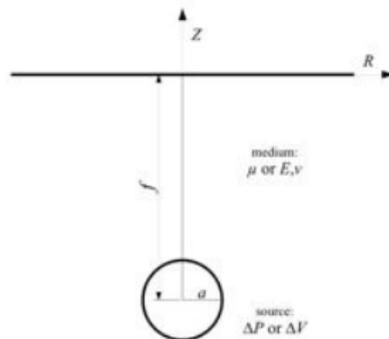
[Massonnet et al., Nature 1995]



Modèles : quelle complexité ?

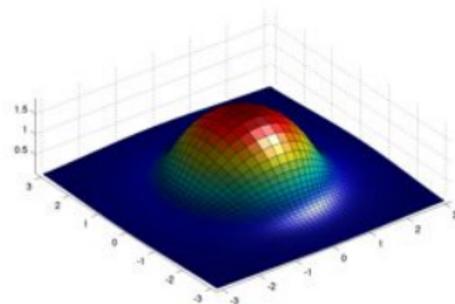
“Top 2” des modèles analogiques

- ▶ Point source (pression isotrope) en semi-espace élastique homogène [*Anderson, 1936 ; Mogi, 1958*]
- ▶ Discontinuité plane (faille) en semi-espace élastique homogène [*Okada, 1985*]



Complexités requises

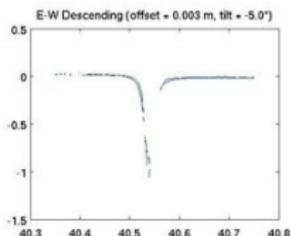
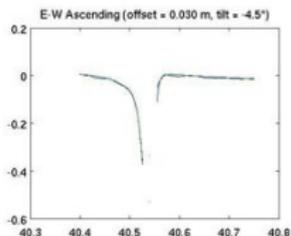
- ▶ sources et géométries multiples
- ▶ 3-D : topographie et structures
- ▶ Discontinuités du milieu (fractures)
- ▶ Rhéologies du milieu : anisotropie élastique, visco-élasticité, poro-élasto-plasticité...



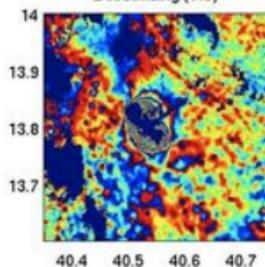
Alu-Dala Filla : modèle de sources ponctuelles (InSAR)

[Le Mevel, 2010]

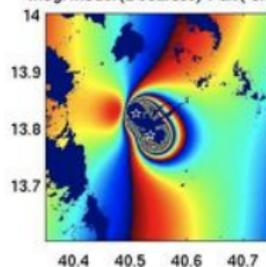
- ▶ orbites A/D
- ▶ ΔV et profondeur



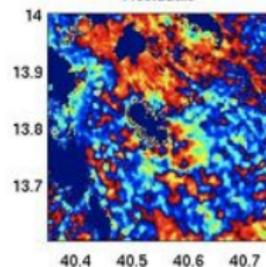
Descending (149)



Mogi model (2 sources) + tilt (-5.0°)

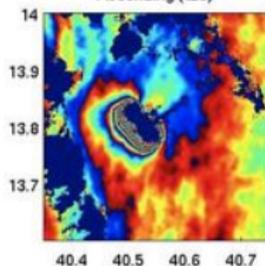


Residuals

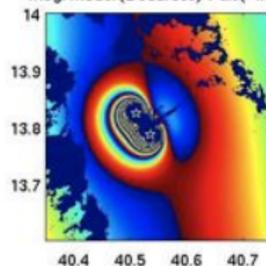


depth₁ = 1.0 km / $\Delta V_1 = -7.7 \cdot 10^6 \text{ m}^3$
depth₂ = 1.2 km / $\Delta V_2 = -6.5 \cdot 10^6 \text{ m}^3$

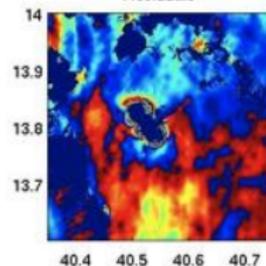
Ascending (128)



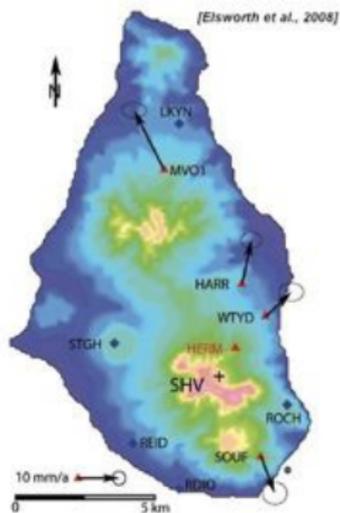
Mogi model (2 sources) + tilt (-4.5°)



Residuals

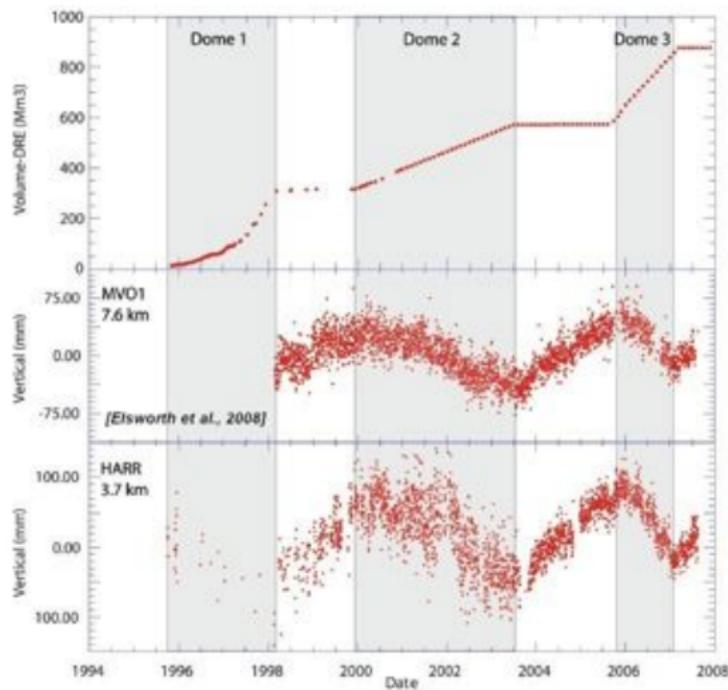


Soufriere Hills Montserrat : modèle de chambres (cGPS)

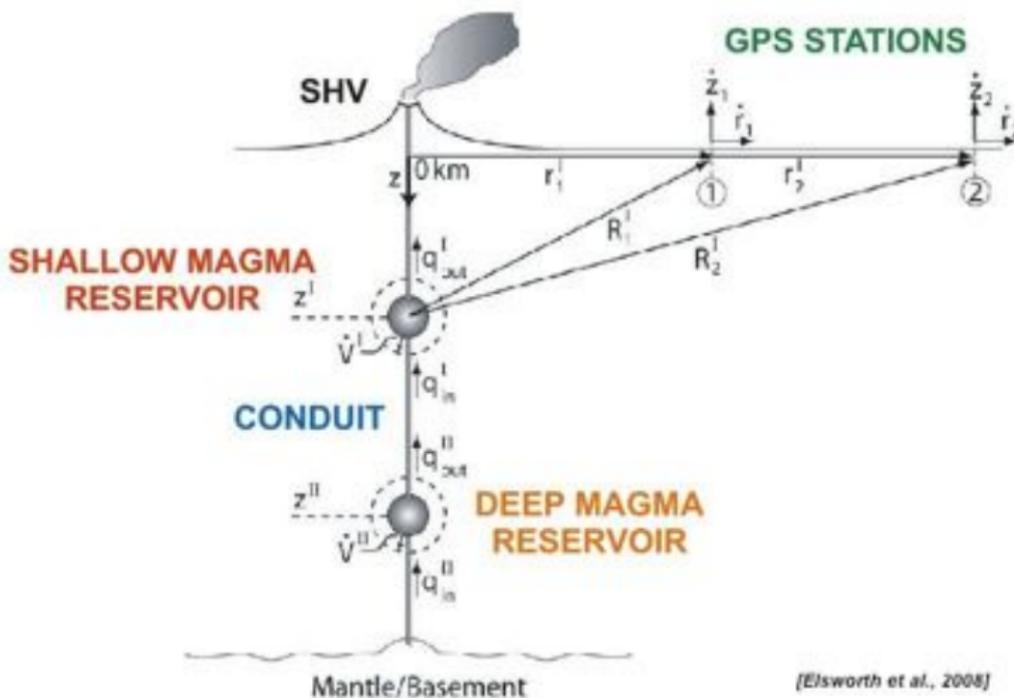


[Elsworth et al., 2008]

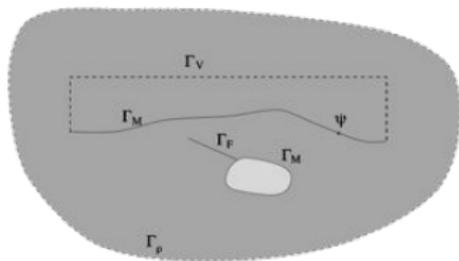
- cycles
inflations/déflations



Soufriere Hills Montserrat : modèle de chambres (cGPS)



Méthode mixte d'éléments frontières



[Cayol & Cornet, 1997]

$$LX = R$$

L = coefficients d'influence

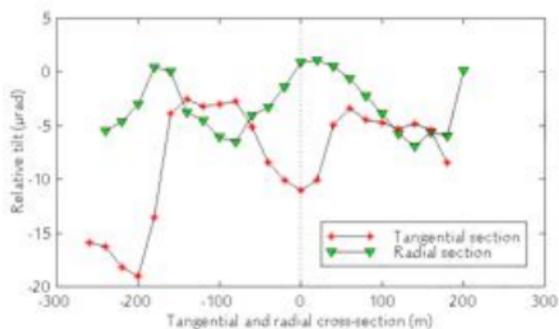
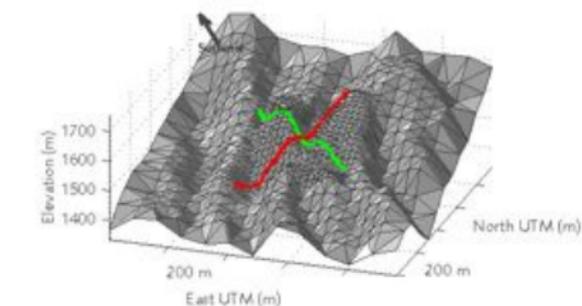
X = inconnues (déplacements + DD)

R = conditions frontières

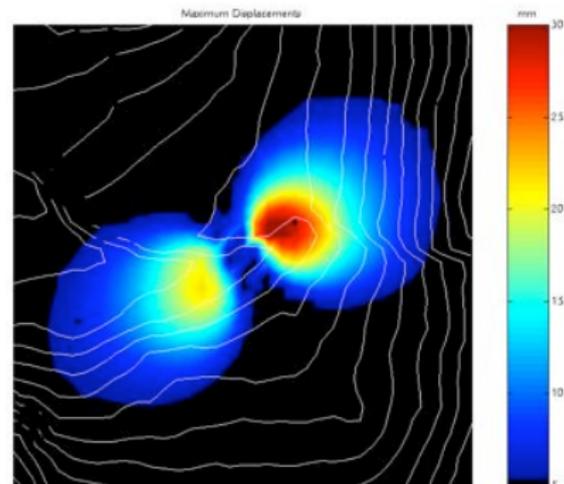
Principe de modélisation

- ▶ Combinaison de 2 méthodes en domaine élastique :
 - Méthode directe [Rizzo, 1967]
 - Discontinuités de déplacements [Crouch, 1976]
- ▶ 3-D avec maillage de surfaces :
 - Structures massives :
 - topographie (surface libre)
 - réservoirs et conduits (pressions)
 - Discontinuités : fractures
 - Maillage simple (Delaunay) + problème direct rapide = **inversion possible**
- ▶ Adapté aux systèmes volcaniques

Effets de la topographie

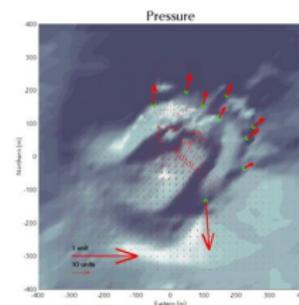
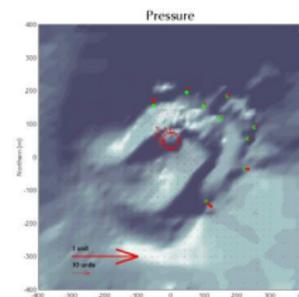
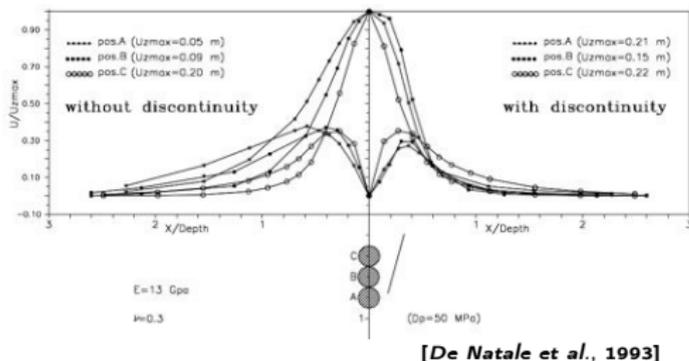


Dyke n°2 "Rempart" (181,32.5) km, N330, $\Delta P = 1$ MPa



*Beauducel & Cornet [JGR 1999]
Beauducel et al. [IPGP report 2000]*

Importance des fractures

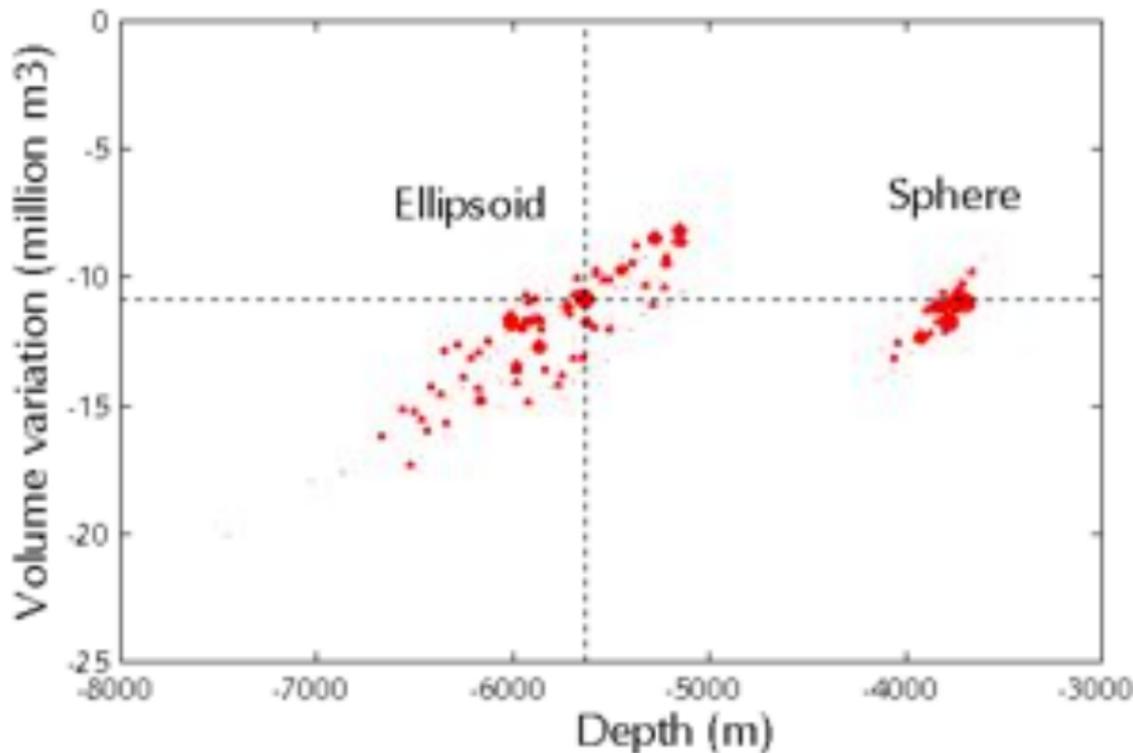


[Beauducel et al., 2000]

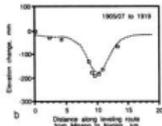
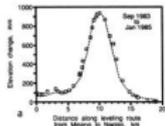
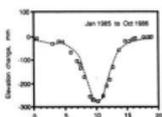
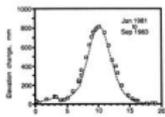
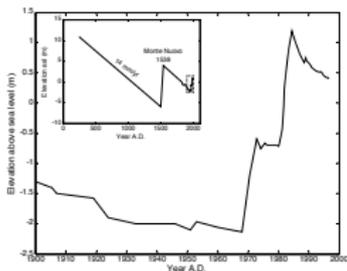
- ▶ Source de pression dans un conduit
- ▶ 1 ordre de grandeur dans les déplacements



Inversion à objectif représentationnel



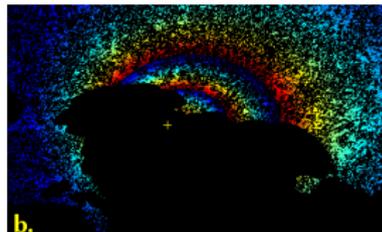
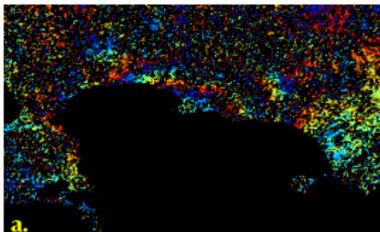
Campi Flegrei : un cas d'école



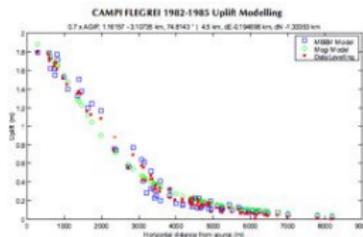
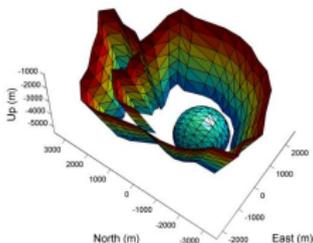
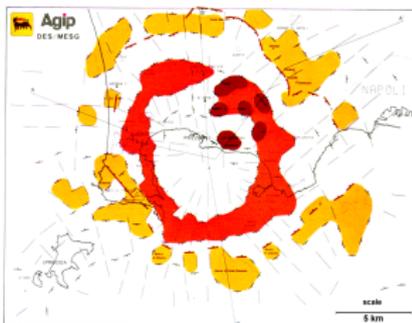
Modélisation du "bradisismo"

- ▶ Bradisisme : ≈ 2 m d'inflation (1982-1985)
- ▶ Modèle de *Mogi* [1958] : bon accord avec données mais profondeur source < 2.5 km
- ▶ Autres données géophysiques (sismique, gravimétrie, forages) indiquent une source magmatique > 4 km
- ▶ **Modéliser \neq "fitter les données" !**

[Dvorak & Berino, 1991]
[Avalonne et al., 1999]



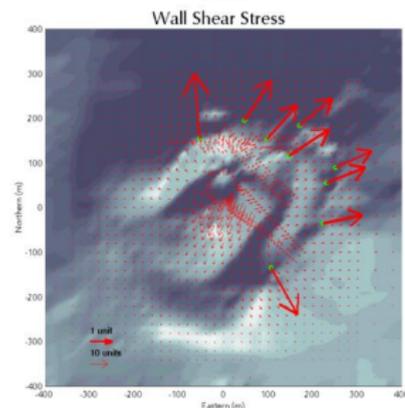
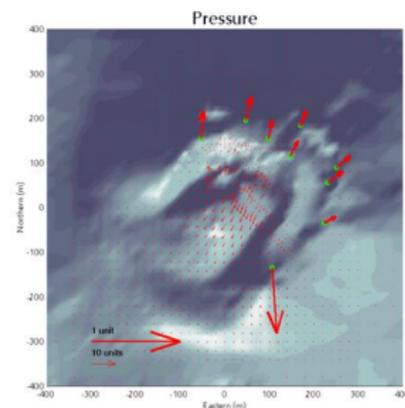
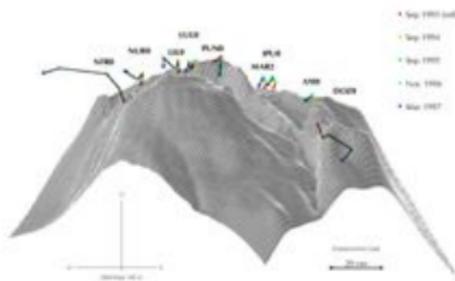
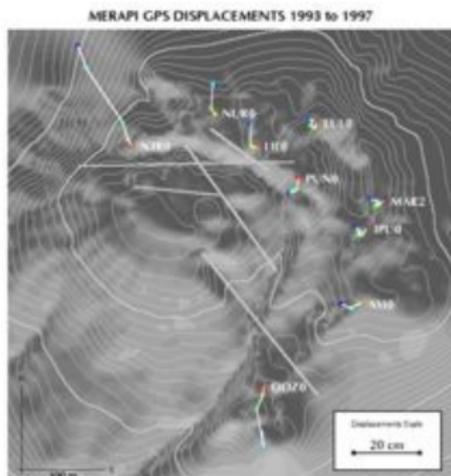
Campi Flegrei : effets de la caldeira



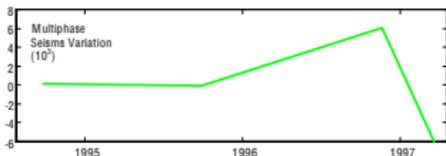
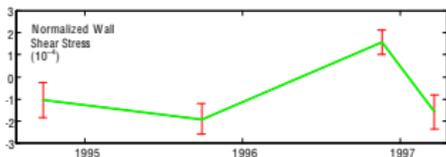
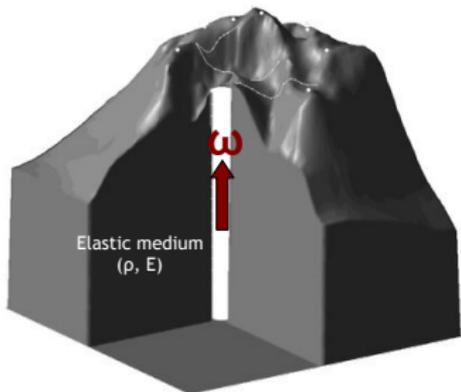
[Beauducel et al., 2004]

- ▶ **Information a priori :**
structure très hydrothermalisée localisée par gravimétrie + forages
- ▶ modélisation 3D de la caldeira
- ▶ Inversion inclinaison et profondeur discontinuité + source simple
- ▶ Meilleur ajustement des données + source à 4.5 km de profondeur

Merapi : flux de magma et module d'Young



Merapi : flux de magma et module d'Young



[Beauducel et al., 2000]

- ▶ Frottement visqueux du magma sur les parois du conduit :

$$\tau = -\mu \left. \frac{\partial \omega}{\partial r} \right|_{r=a}$$

- ▶ Inversion déplacements GPS : modèle 3D combinant contraintes cisailantes, pression et discontinuités
- ▶ Estimation indirecte variations de flux
- ▶ Bonne corrélation avec sismicité de cisaillement [Shimozuru et al., 1969]
- ▶ Estimation in situ du module d'Young $E \approx 1 \text{ GPa}$

InSAR : déformations co-éruptives

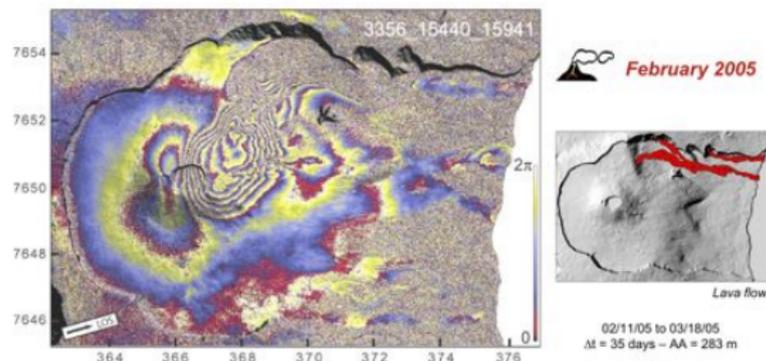


[Tinard et al., 2005]

- ▶ Images ENVISAT-ASAR co-éruptifs
- ▶ Inversion géométrie dyke (8 param.) + ΔP

ASAR-ENVISAT Dataset

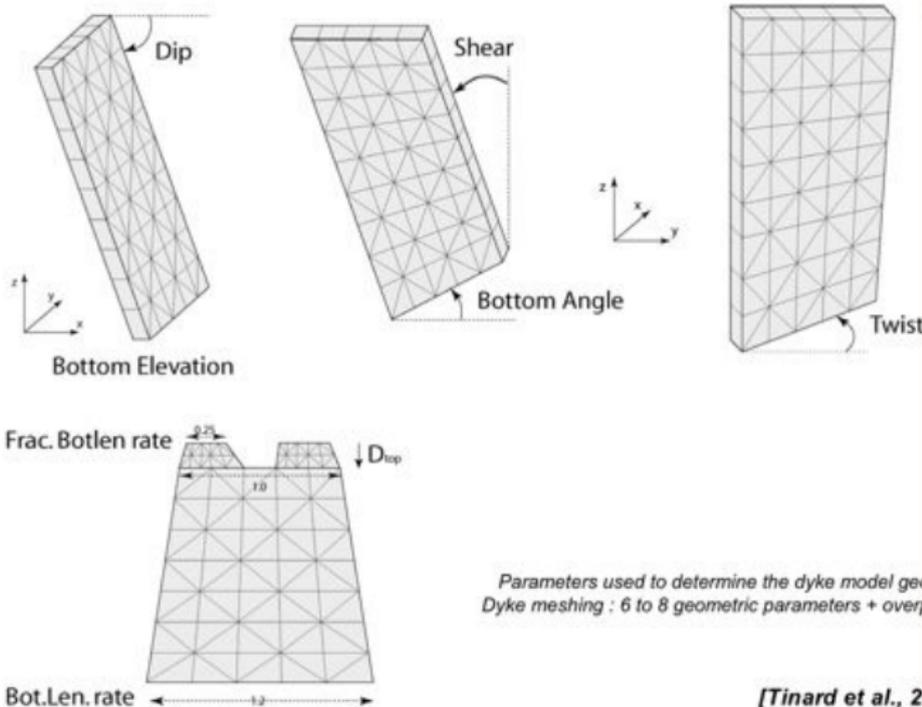
[Tinard et al., 2005]



Vent location	Deforming area (10 ⁶ m ²)	Lava area (10 ⁶ m ²)	Lava volume (10 ⁹ m ³)	Deformation gradient (rad.km ⁻¹)	Interferograms available
Plaine des Osmondes Trou de sable	16.4	4.0	15.0	34.1 – 55.6	3 asc. – 4 desc.

InSAR : déformations co-éruptives

Meshdyke and 3D-MBEM (Cayol and Cornet)

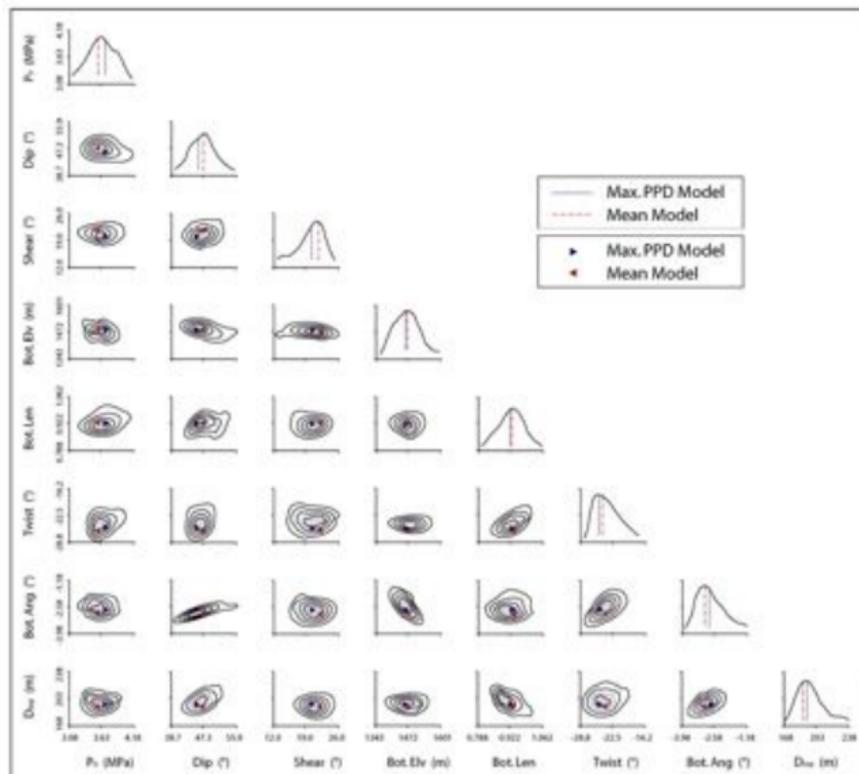


Parameters used to determine the dyke model geometry.
Dyke meshing : 6 to 8 geometric parameters + overpressure.

[Tinard et al., 2005]

InSAR : déformations co-éruptives

Neighbourhood Algorithm and Apraising (Sambrige, Fukushima)

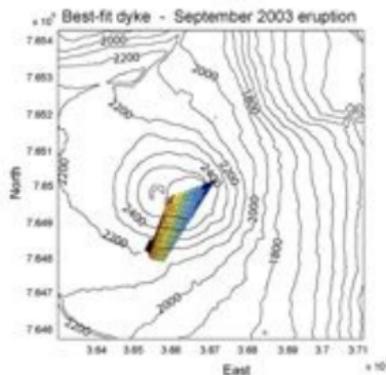
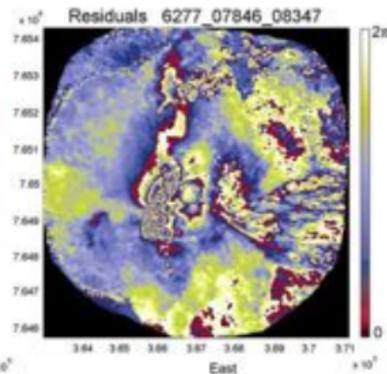
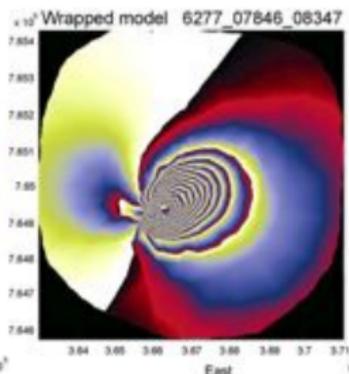
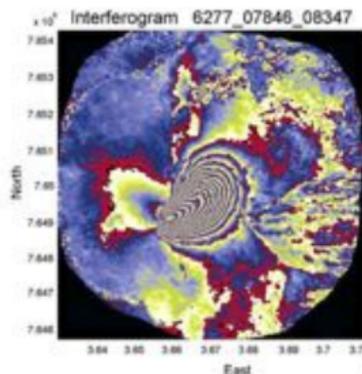


One- and two-dimensional marginal Probability Density Functions for the September 2003 eruption best-fit dyke model. The contour interval is 0.2x the max. value. Parameters are well constrained with small uncertainties.

[Tinard et al., 2005]

InSAR : déformations co-éruptives

September 2003



$P_0 = 3.60 \pm 0.18$ MPa
 Shear = 22.5 ± 2.0 °
 Bot. Length = 0.94 ± 0.08
 Theta = -3.1 ± 0.5
 Misfit = 4.97 %

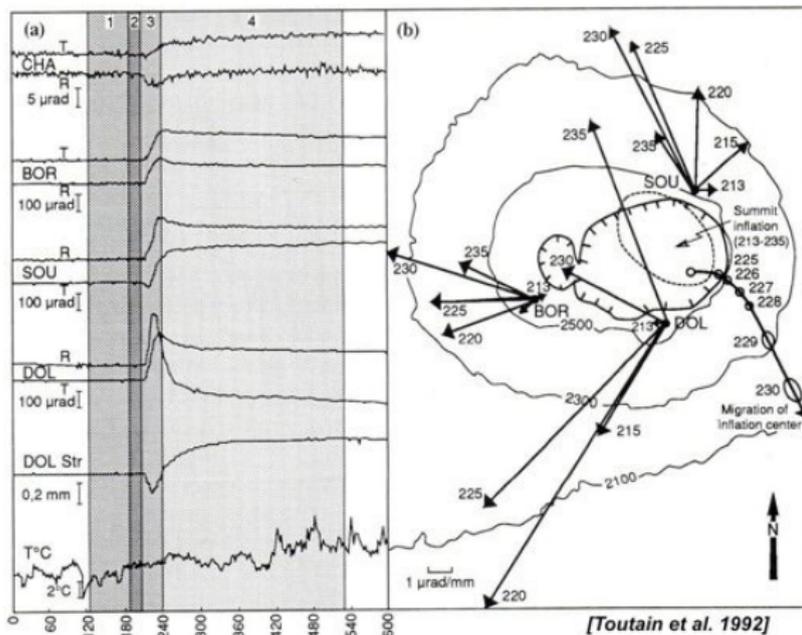
Av. opening = 0.71 m
 Volume dyke = $1.33 \cdot 10^6$ m³

Dip = 47.1 ± 3.8 °
 Bot. Elv = 1470 ± 85 m a.s.l.
 Twist = -25 ± 3.5 °
 D_{top} = 185 ± 20 m

Max. opening = 1.18 m

[Tinard et al., 2005]

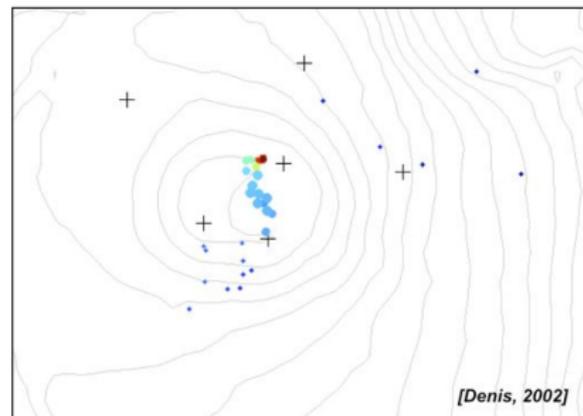
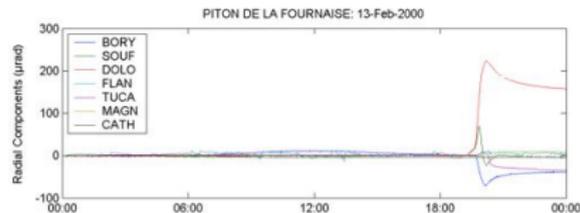
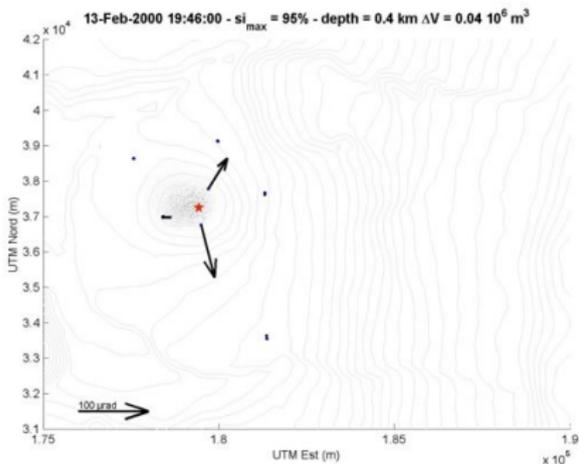
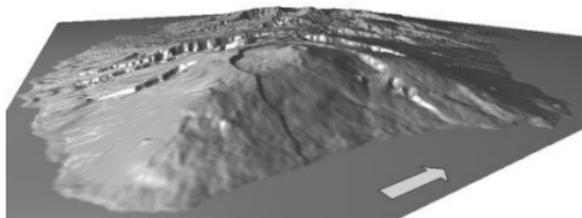
Piton de la Fournaise : suivi temporel des intrusions



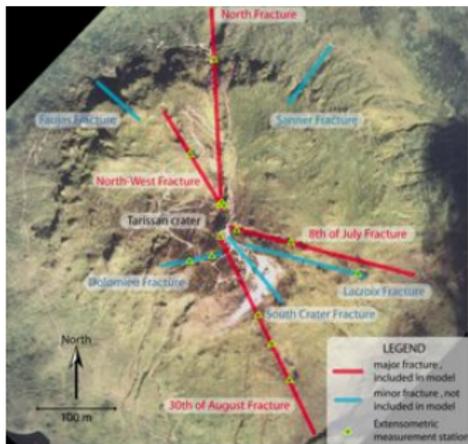
[Toutain et al., 1992]

- ▶ réseau inclinomètres
- ▶ localisation du centre d'inflation
- ▶ point de sortie de l'éruption
- ▶ pas d'estimation de volume

Piton de la Fournaise : suivi temporel des intrusions



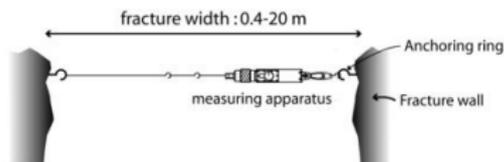
Soufrière : un vrai cas tridimensionnel



Dôme de lave fracturé

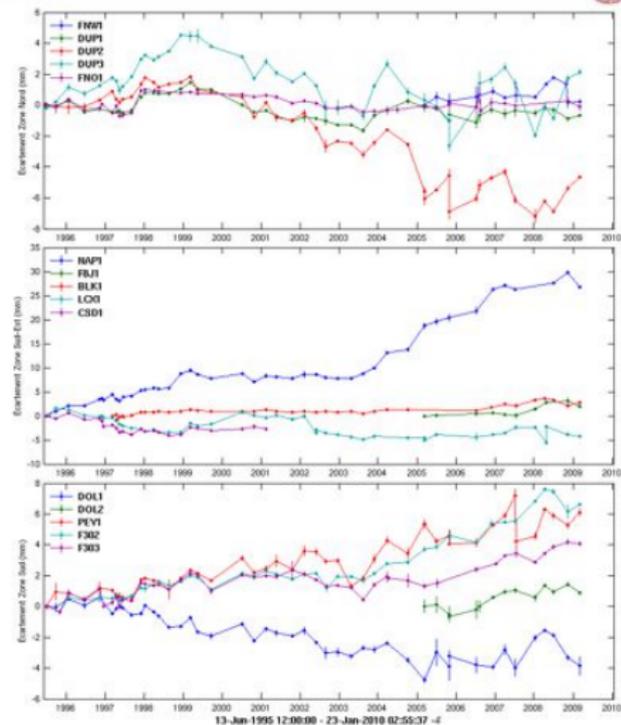
- ▶ Activité hydrothermale intense (sources, fumerolles, sismicité)
- ▶ Dôme 1530 AD : topographie marquée + fractures profondes (> 300 m)
- ▶ Mesures d'extensométrie depuis 1995 : variations complexes > 15 mm

Soufrière : un vrai cas tridimensionnel

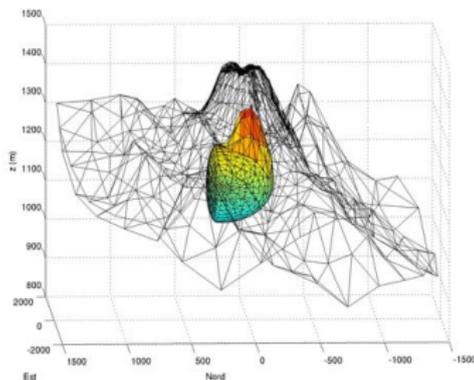
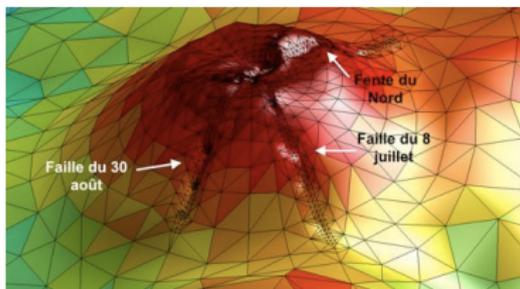


Synthèse Réseau Extensométrie (tout)

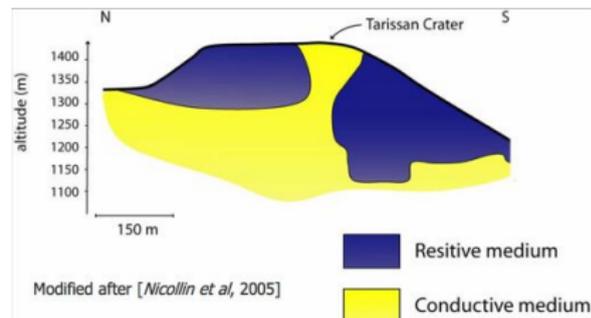
23-Jan-2010 02:55:37 -4 - Etat 000 % - Acquisition:070 % - M - 3 mois
 WEBOS © 2010, DVSU-IPUG



Soufrière : un vrai cas tridimensionnel



[Jacob et al., 2005 ; Beauducel et al. [in prep.]

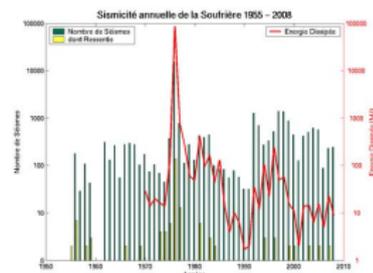
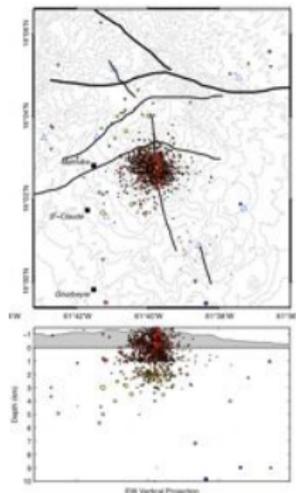
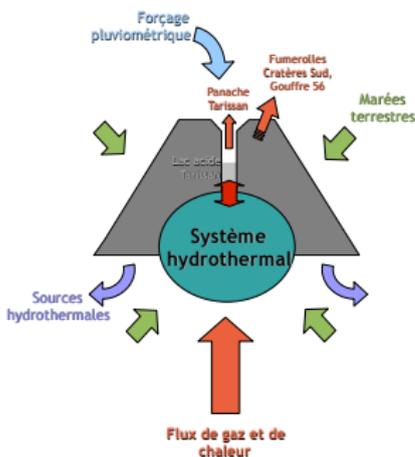


Modified after [Nicollin et al, 2005]

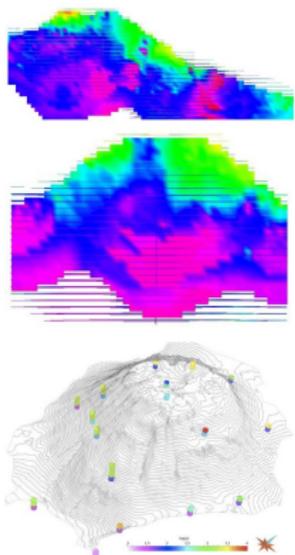
Modélisation élastique 3D

- ▶ Bonne reproduction des observations (source superficielle et inversion de la profondeur des fractures)
- ▶ Source compatible avec zones identifiées par tomographie électrique

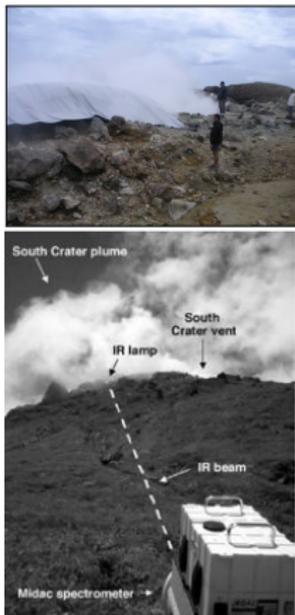
Soufrière : système hydrothermal



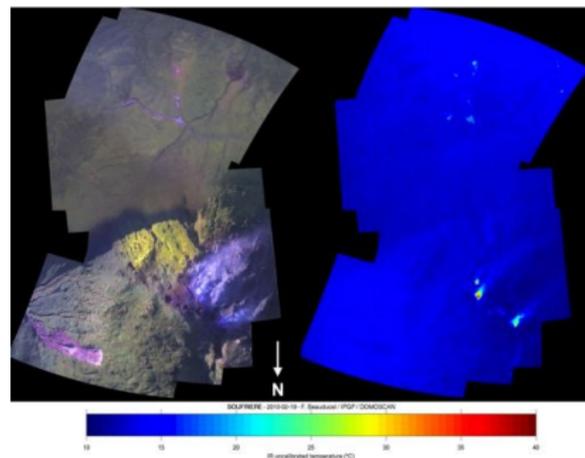
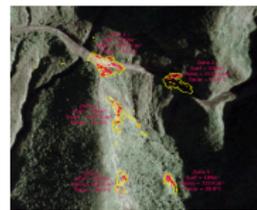
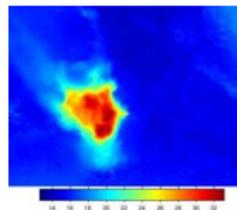
Soufrière : tomographies et mesures de flux



[Nicollin et al., 2005]



[Bernard et al., 2006]



[Beauducel & Gaudin, 2010]
Beauducel et al. [in prep.]

Surveillance opérationnelle

Missions d'un observatoire volcanologique

- 1 Surveillance du volcan actif :
 - comprendre les phénomènes
 - détecter un changement de comportement
 - l'évaluer en terme de potentiel éruptif
 - informer les autorités responsables
- 2 Recherche fondamentale en géosciences
- 3 Information préventive et divulgation des connaissances en géosciences

⇒ **Observer et mesurer...**

... pour **comprendre, prévoir et prédire.**



Surveillance opérationnelle : quels outils ?

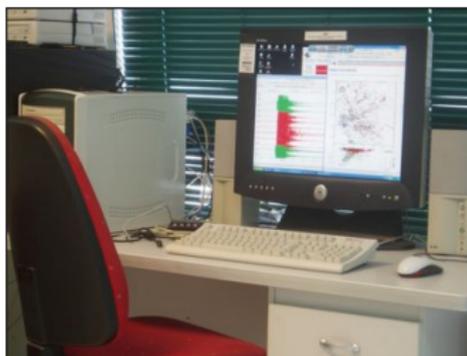


Objectifs

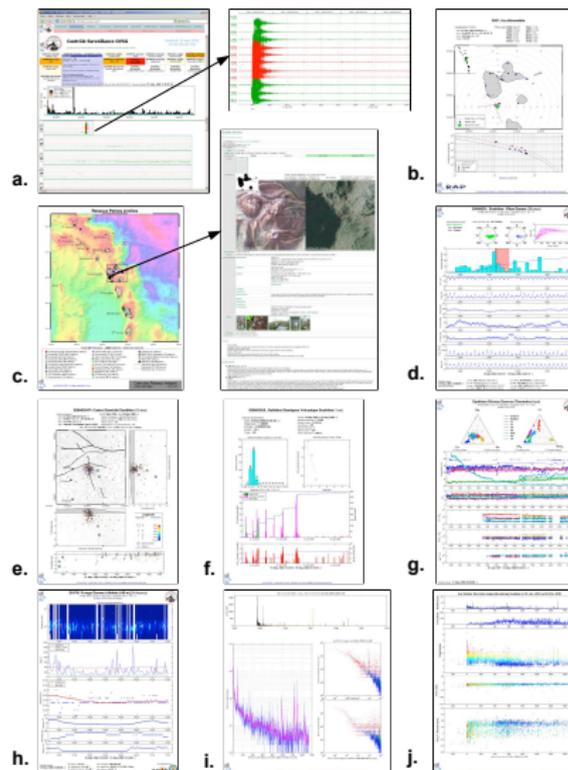
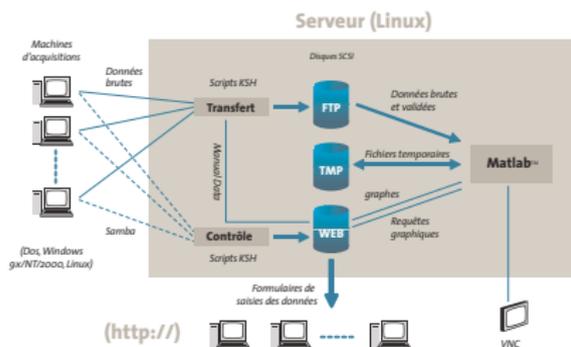
- ▶ **Temps-réel** : accès instantané à l'ensemble des données, toutes disciplines, dans une optique d'aide à la gestion de crise
- ▶ **Archivage** : centralisation des données et méta-données
- ▶ **Partage** : accès à un niveau d'information unique, télé-surveillance, support aux collaborations



Webobs : solution effective



[Beauducel et al., 2010]



Conclusions

Déformations : vers un modèle prédictif temps-réel ?

- ▶ Modélisation **tridimensionnelle** avec **discontinuités** permet parfois d'expliquer le premier ordre
- ▶ Le champ de déformations est **unique** : nécessité de valider et d'intégrer les différentes techniques au travers des modèles
- ▶ Objectif de la modélisation : détermination des structures et des **paramètres physiques** associés (ΔV , ΔP), les seuls comparables aux autres modèles disciplinaires (géophysique et géochimique)
- ▶ Seule une modélisation réaliste permettra une quantification des paramètres et d'aborder les problèmes de prédiction
- ▶ Approche pluridisciplinaire indispensable : vers un "volcan numérique" ?

Références

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