A practical Short Course on Inversion of geodetic data using the toolbox DefVolc

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EUROVOLC

Requirements

1) To complete the workshop, you require the following:

- a linux laptop
- a recent version of the mesher gmsh
  http://gmsh.info/
- matlab Runtime v9.5, compatible with matlab2018b
  https://fr.mathworks.com/products/compiler/matlab-runtime.html
- The provided uncompressed archive with executable, and examples

1) To run your computation on UCA Clusters and get updates about new versions, please register on defvolc web site http://www.opgc.fr/defvolc/. Ask me (valerie.cayol@uca.fr) for a project code

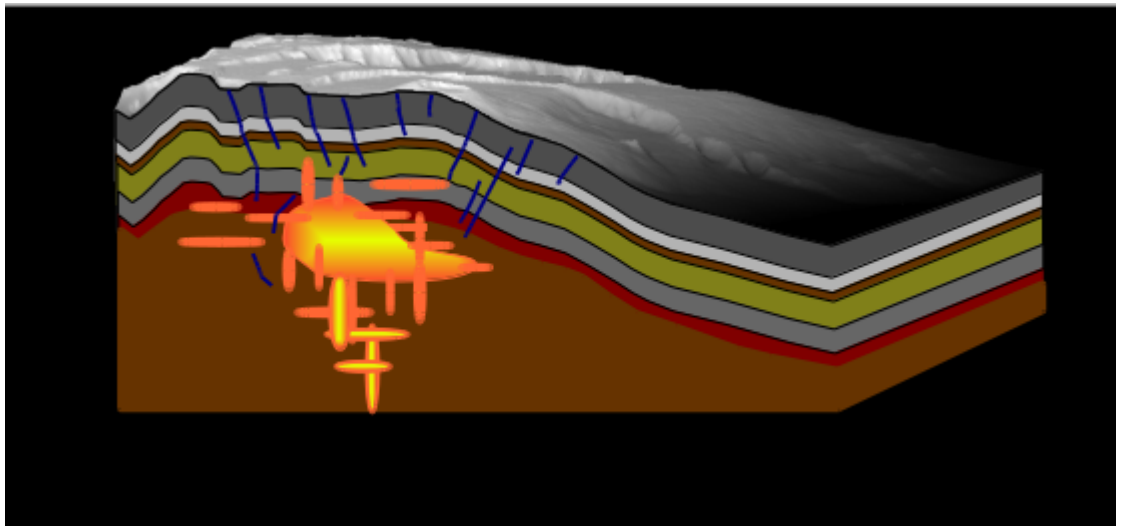
Objective

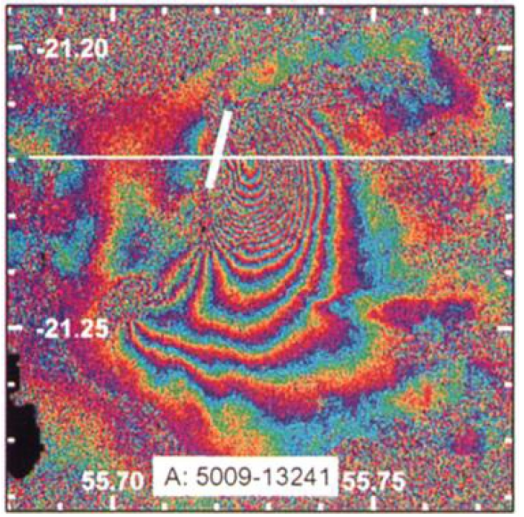
The purpose is to provide you with enough information so that you can confidently apply DefVolc to your particular inversion problem

- Inform you on the theory DeVolc is based on;
- Guide you through the use of DefVolc for you inversions of deformation data of volcanoes and faults
- Explain to you the functionalities
- Teach you about the files generated

Beyond too simple models

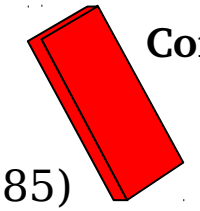
Reality





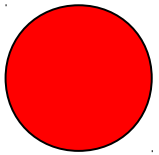
Models

Analytic Models



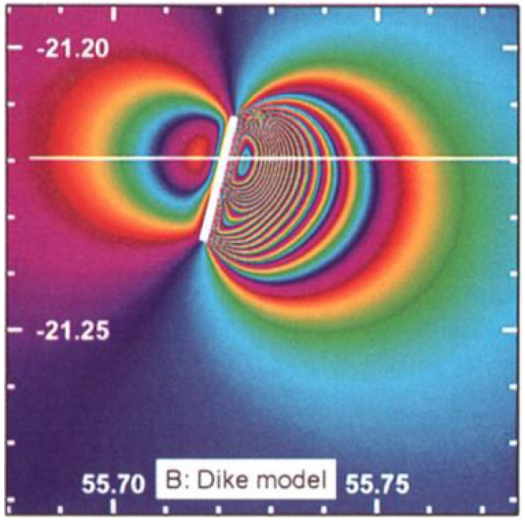
Constant displacements

(Okada, 1985)



Overpressures

(Mogi, 1958)



(Sigmundsson et al., GRL, 1999)

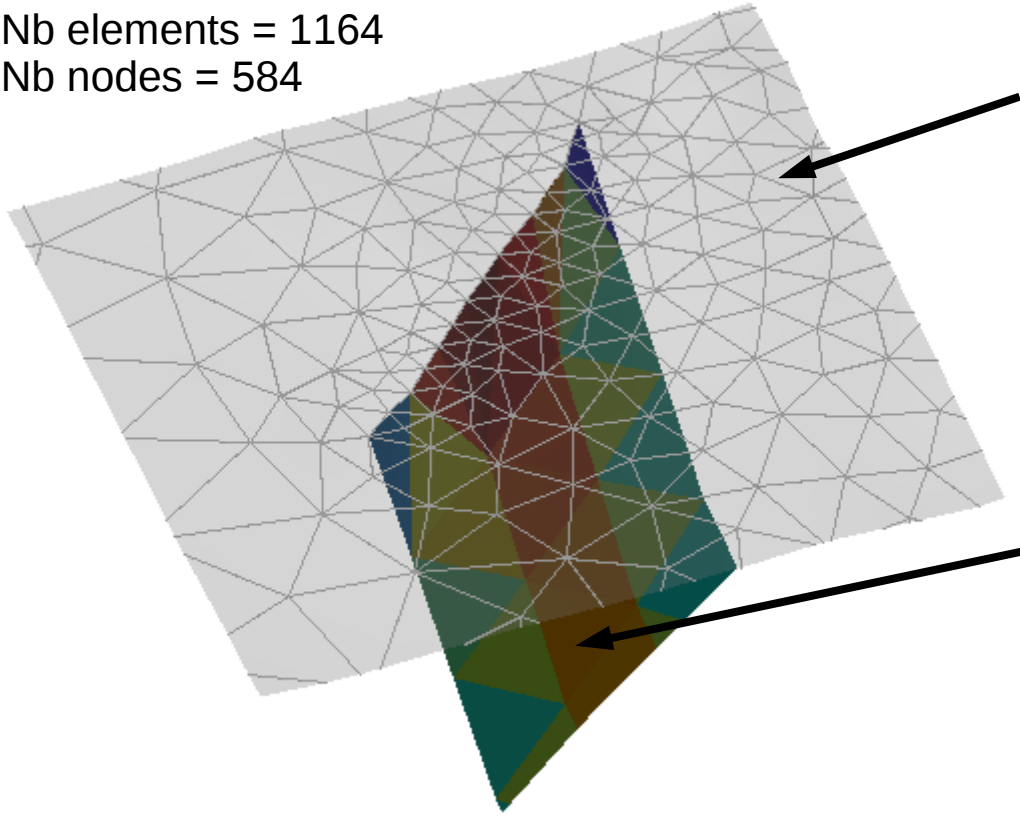
→ **InSAR data call for more realistic modelds**

Modelling with a 3D Mixed Boundary Element Method

(Cayol and Cornet, Int.J. Rock Mech. & Min. Sc., 1997)

- **3D Numerical method**:
  - **Realistic topographies**
  - **Any number and geometry of faults and pressure sources**
  - **treats more than one source appropriately**
- **Assumptions**:
  - **the volcano is elastic, homogeneous and isotropic**
  - **dikes, faults reservoirs are submitted to constant stress changes**
- **Method: combination of two types of boundary element methods**

Nb elements = 1164
Nb nodes = 584



Direct method (Cruse, Computers and struct., 1974)
Linear elements: solutions at nodes -> efficient and precise

Displacement discontinuity method (Crouch Starfield, 1983)
Constant elements: solutions at centroid

Modelling with a 3D Mixed Boundary Element Method

(Cayol and Cornet, JGR, 1998)

- **3D Numerical method**:
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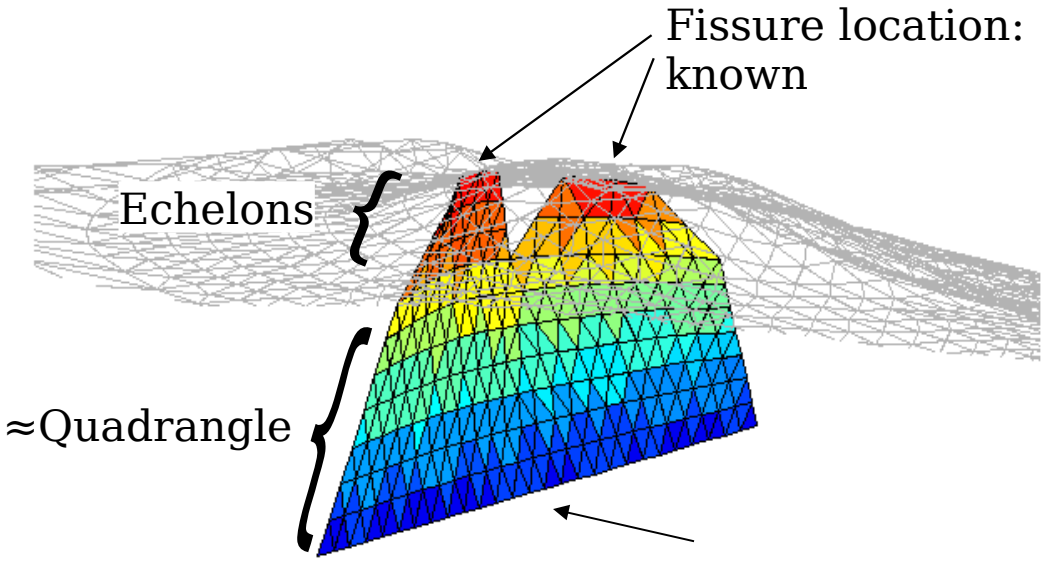
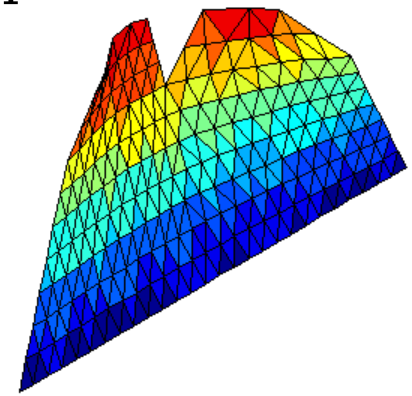


Parameters :
Position and location of the quadrangle bottom line:
6 à 8 parameters +
a pressure

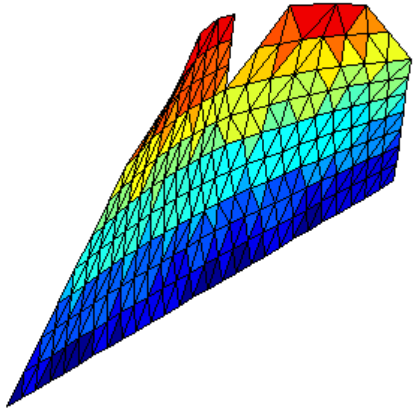
3 D Boundary element modelling

6 geometrical model parameters for a dike connected to the surface

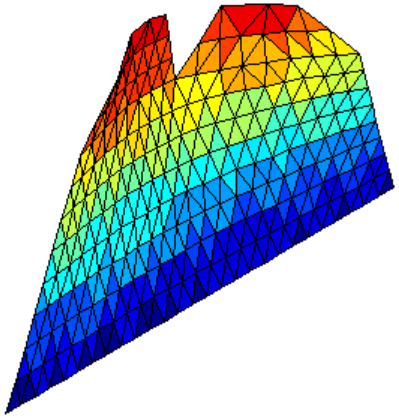
1. Dip



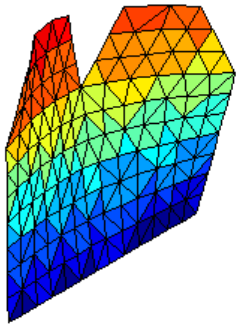
2. Shear



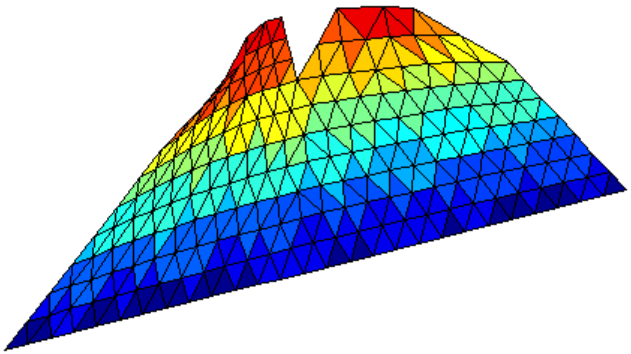
3. Botelv



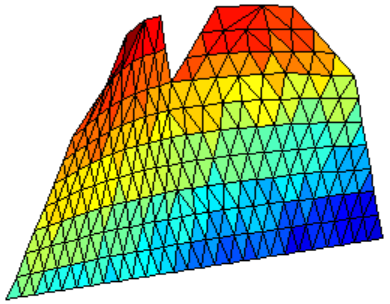
4. Botlen



5. twist

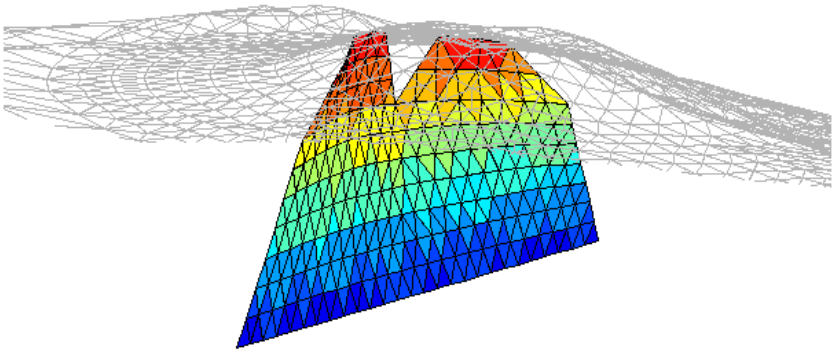


6. Botan

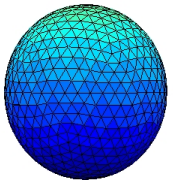


Available sources

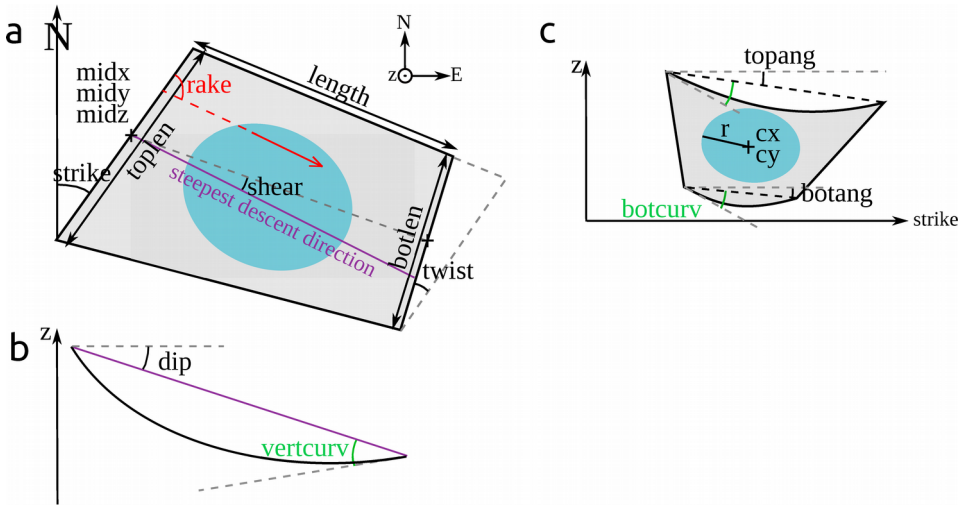
Dikes or faults



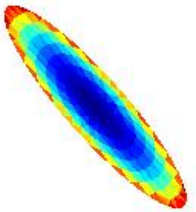
Massive Reservoirs:



Curved quadrangular sources



Planar ellipsoids



Non-linear inversions with a Neighborhood Algorithm

(Fukushima et al., JGR,2005)

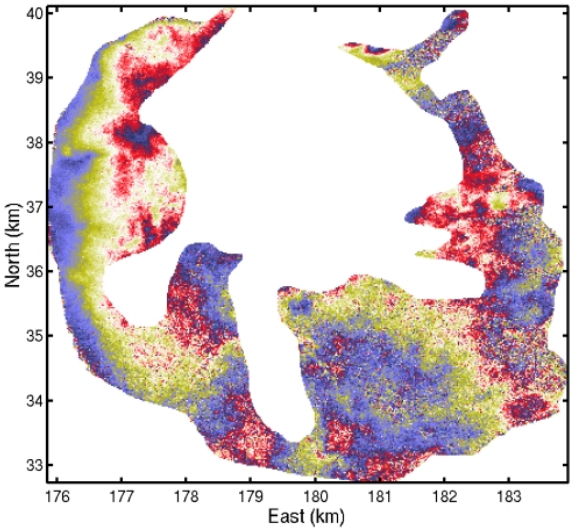
A misfit function which is taking the data noise correlation into account is used:

$\chi^2 = (\mathbf{u}_o - \mathbf{u}_m)^T C_d^{-1} (\mathbf{u}_o - \mathbf{u}_m)$ where $\mathbf{u}_o$, **LOS observed displacements**

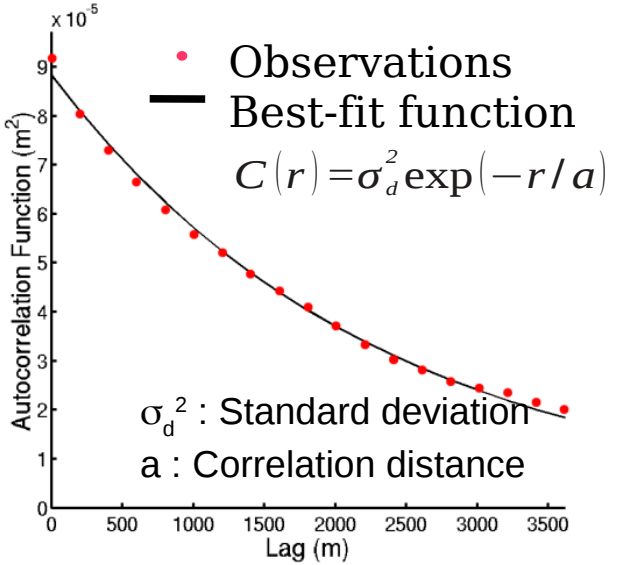
$\mathbf{u}_m$ **, LOS modelled displacements**

$\mathbf{C_d}$**, Covariance matrix (full matrix)**

Autocorelation function: statistical characteristics of randomly correlated data



Undeformed area



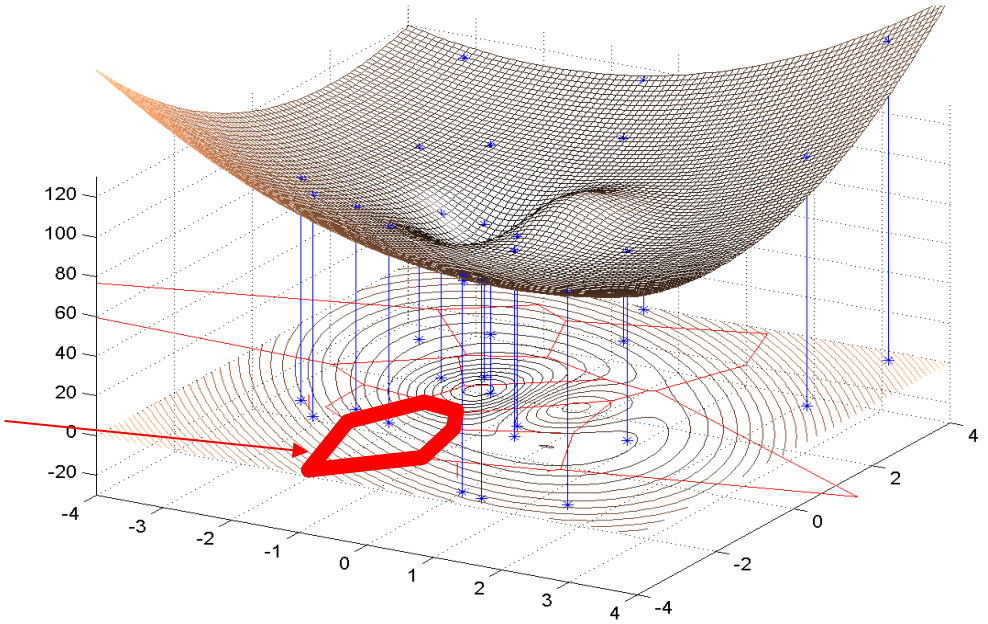
Knowing the distance between pairs of points, r, elements of C_d are computed

NA-MBEM: non-linear inversions with a Neighborhood Algorithm

(Fukushima et al., JGR,2005)

- **Near-neigborhood non linear inversion** (Sambridge, JGI, 1999a) **to invert for geometrical parameters**

Voronoi cell (neighborhood): region closest to a point than any other point



Misfit function in a two parameters space

- **Linear inversions of pressure and data shift**
- **Appraisal of model using Bayesian inference → confidence intervals and trade-offs between parameters** (Sambridge, JGI, 1999b)
- **Synthetic test → parameters are well resolved within confidence intervals**

NA-MBEM: non-linear inversions with a Neighborhood Algorithm

(Fukushima et al., JGR,2005)

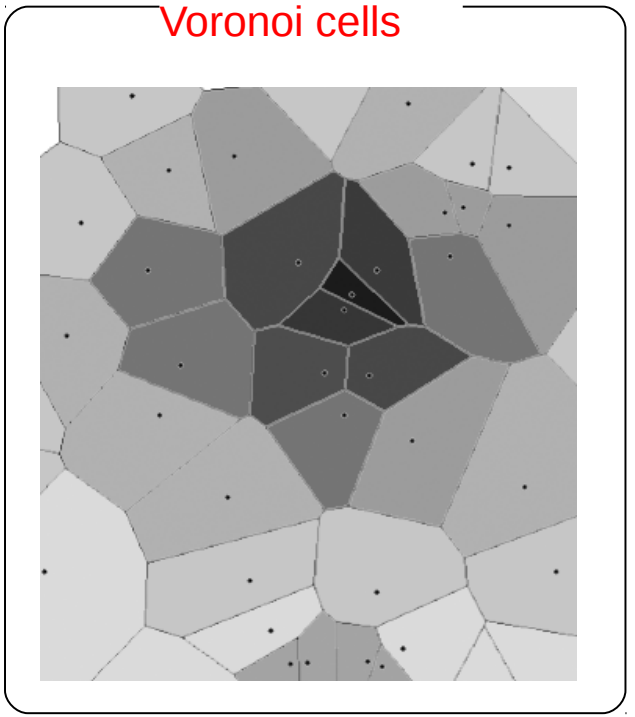
Appraisal stage

(Sambridge, GJI, 1999)

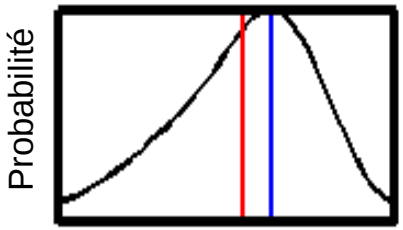
Use of models determined at the search stage

Posterior probability density function (PPD) = k exp (- χ^2 / 2)

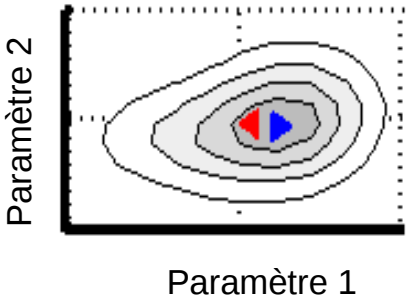
Neighbourhood:
Voronoi cells



Model uncertainties are characterized by marginal PPDs



1D marginal PPD:
Confidence intervals,
mean model



2D marginal PPD:
Trade-offs

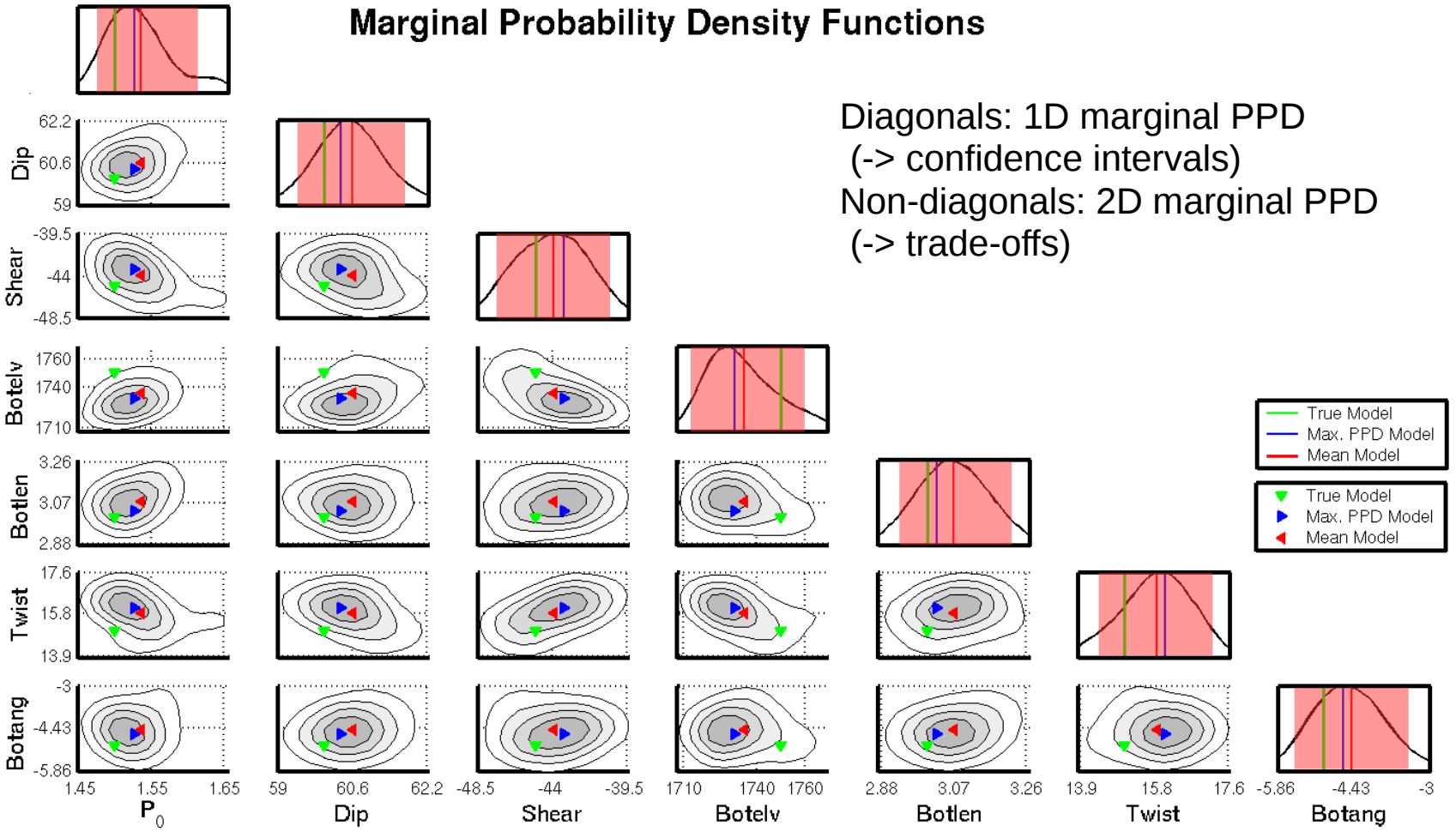
→ **Range of plausible models**

NA-MBEM: Inversions combined with 3D models

(Fukushima et al., JGR,2005)

Synthetic tests

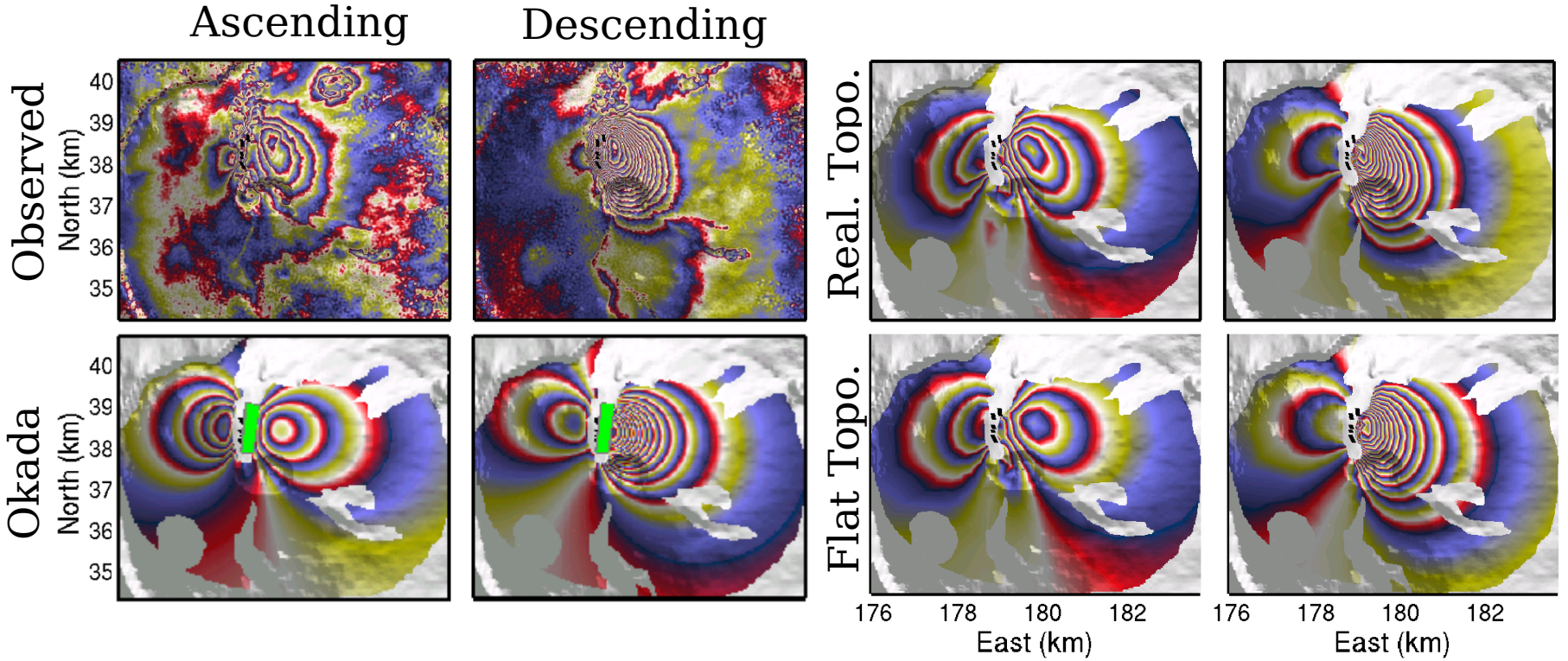
95% confidence intervals

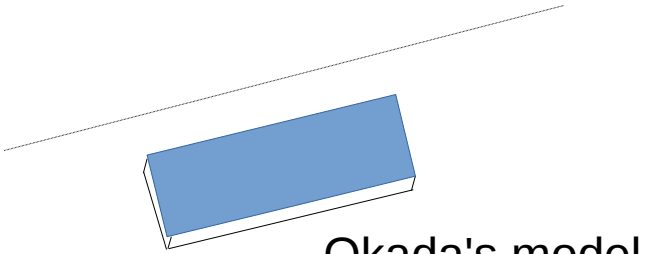


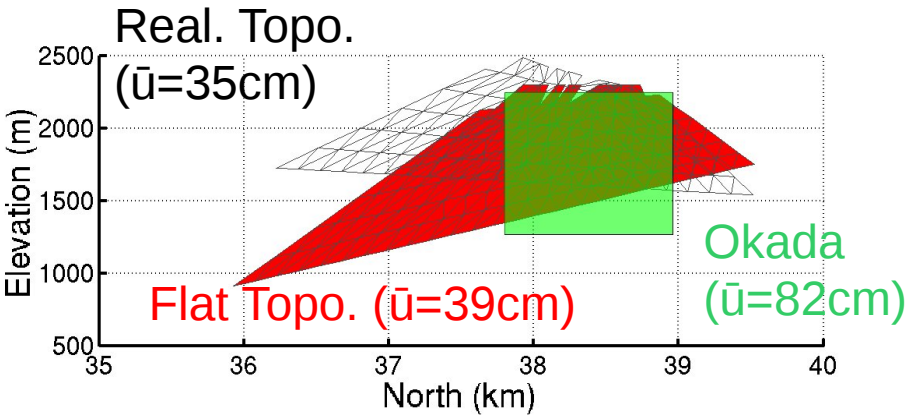
→ **The initial model is within the confidence intervals bounds**

Why taking topography into account ?

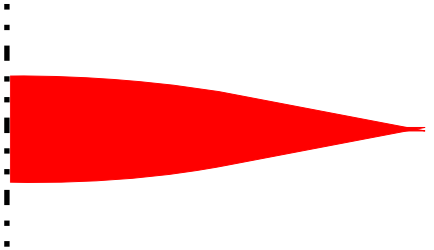
(Fukushima et al., JGR,2005)



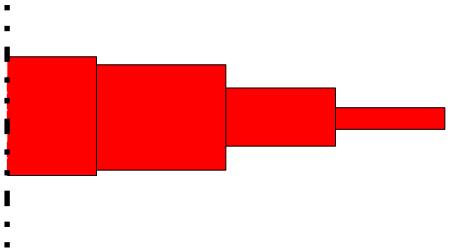




Pressure versus displacement boundary conditions

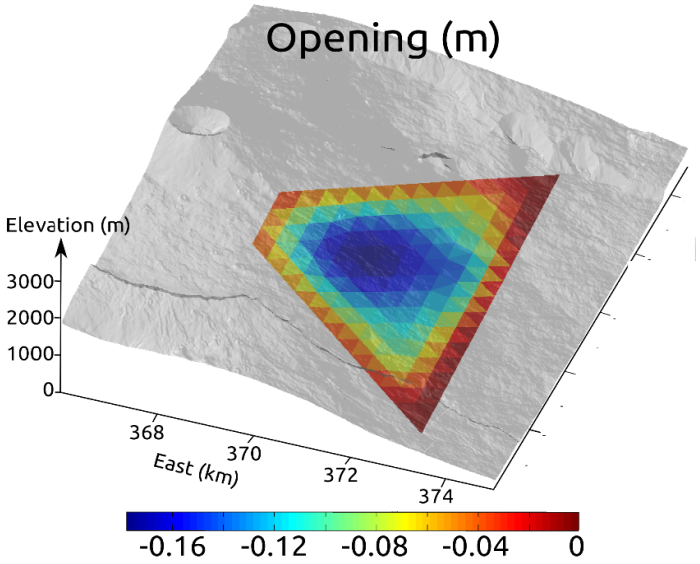


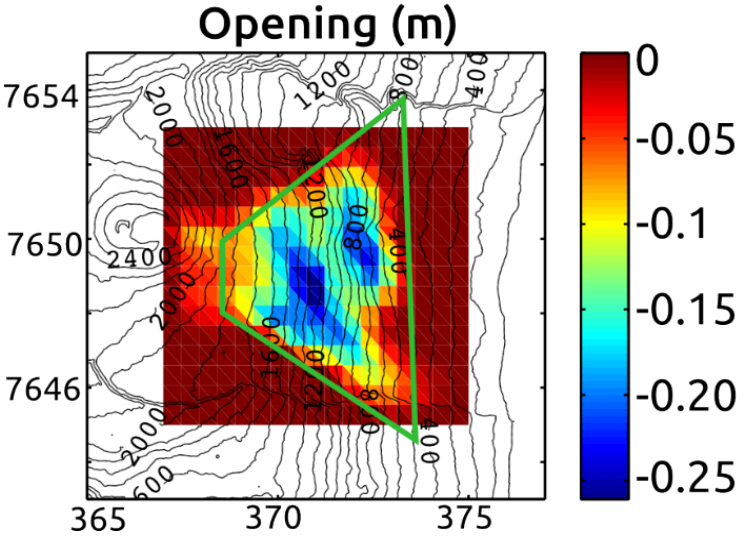
Pressure boundary condition



Displacement boundary condition : kinematic models

Inverted openings





~ 5 % of inverse models

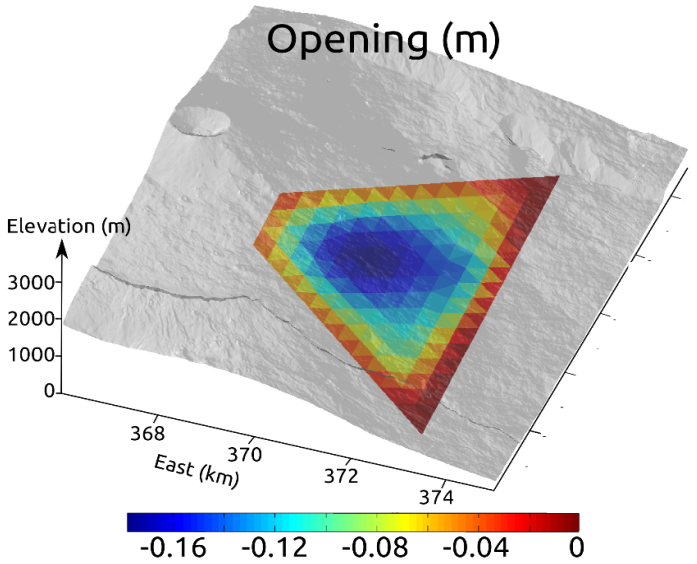
~ 95 % of inverse models

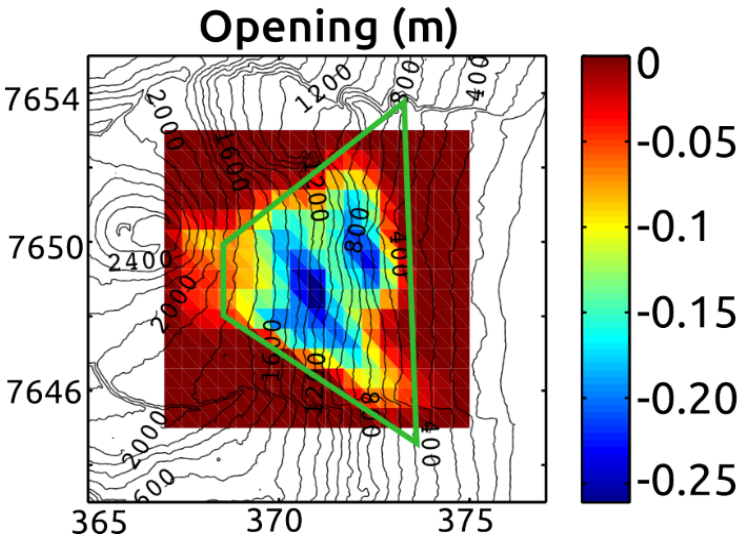
Pressure versus displacement boundary conditions

Pressure boundary condition

Displacement boundary condition

Inverted openings





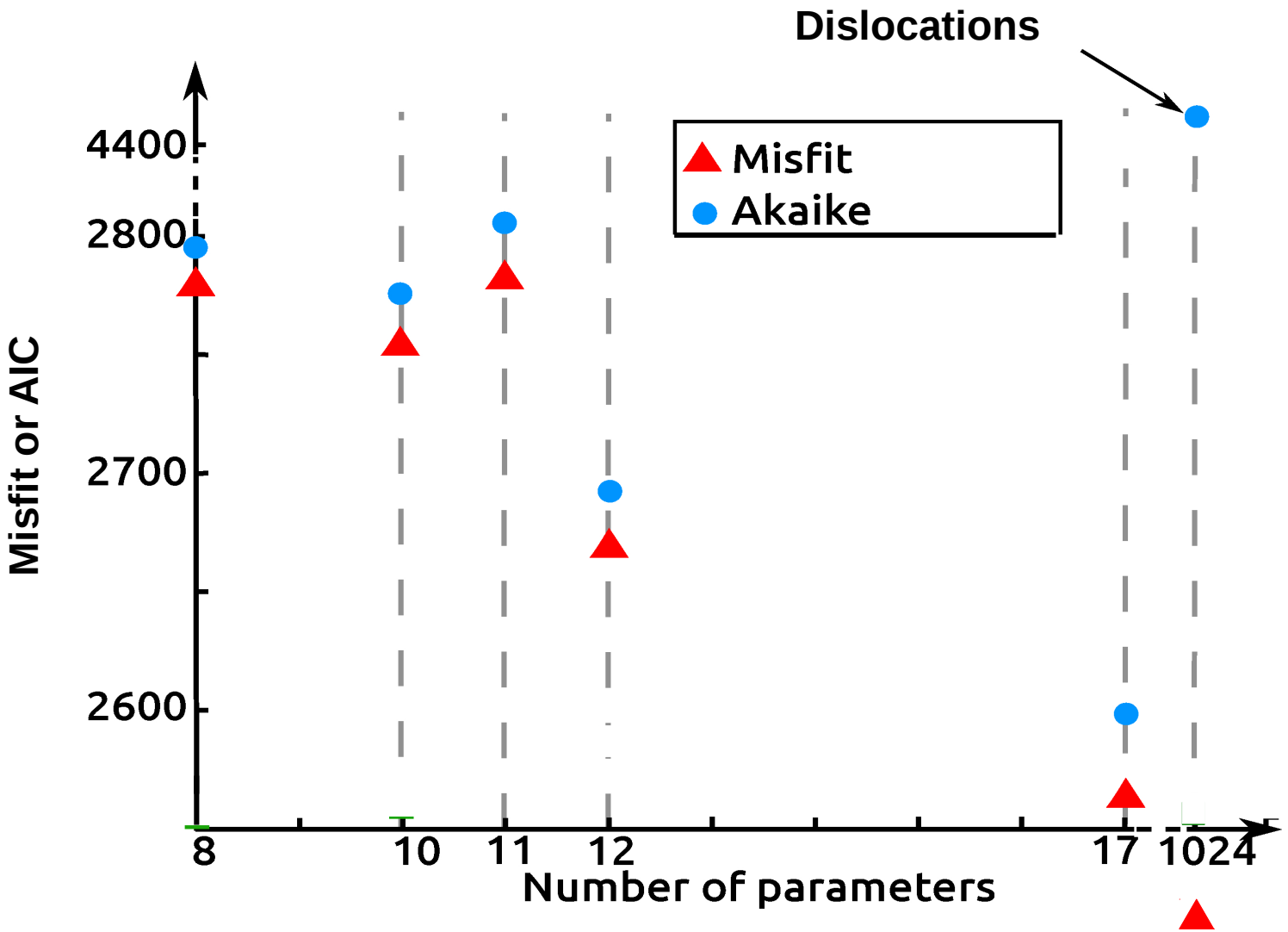
One parameter

500 parameters

→ **Stress boundary conditions models require less inversion parameters**

AIC, misfit versus number of parameters for post-eruptive displacements

Most likely = lowest AIC = $2*k + \chi^2 + cst$ with k = number of parameters and χ^2 = misfit



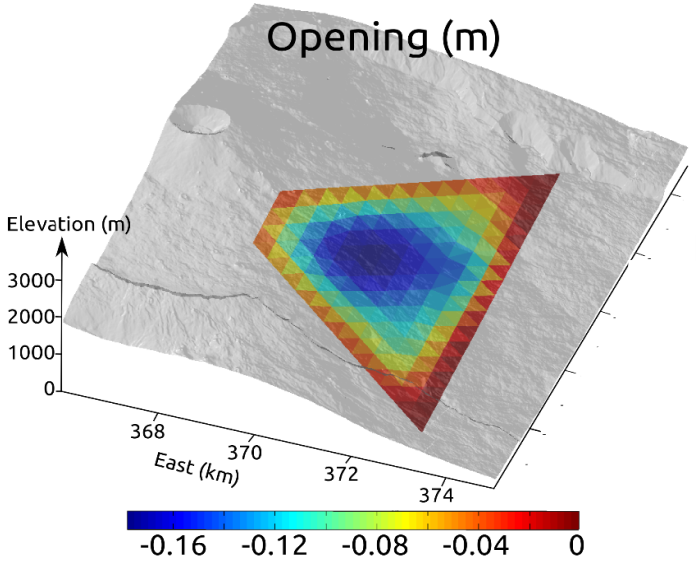
Inverting for stress leads to more likely models than inverting for dislocation amplitudes

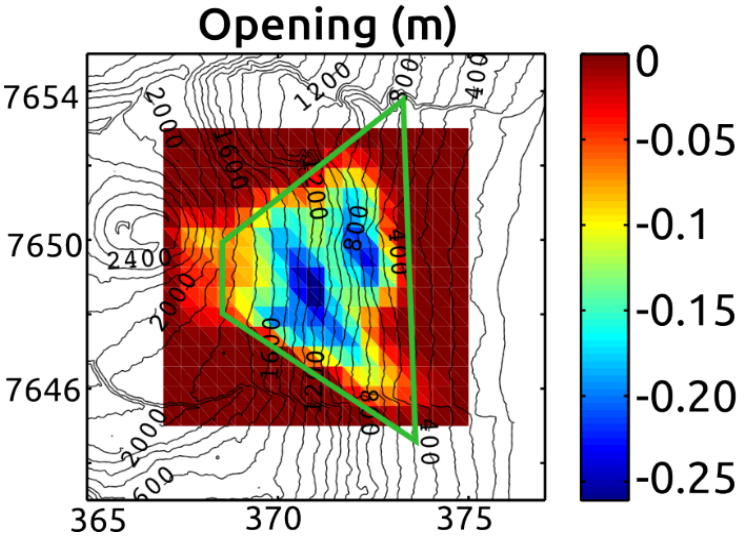
Stress versus displacement boundary conditions

AIC = 2*k + χ^2 + cst with k = number of parameters and χ^2 = misfit

Pressure boundary condition **Displacement boundary condition**

Inverted openings





One parameter

$\chi^2 \approx 2784$

AIC ≈ 2800

500 parameters

$\chi^2 \approx 2300$

AIC ≈ 3300

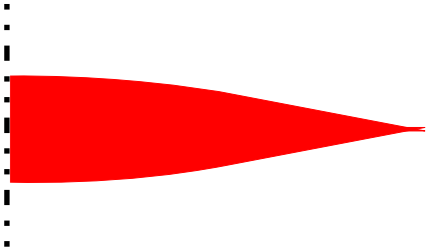
→ **Stress boundary conditions models require less inversion parameters**

→ **Inverting for stress leads to more likely models than inverting for dislocation amplitudes**

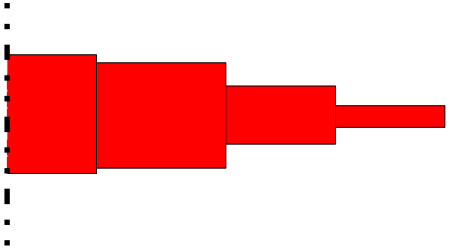
Pressure versus displacement boundary conditions

Field observation

Models



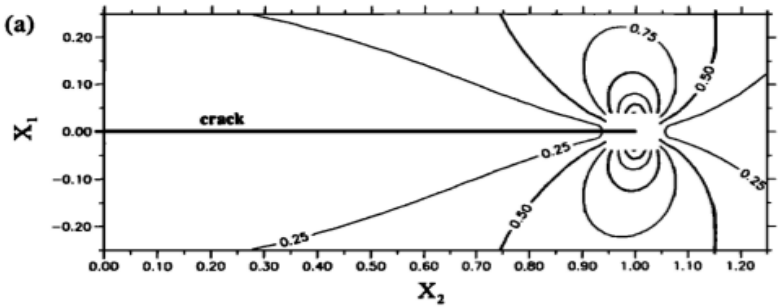
Pressure boundary condition

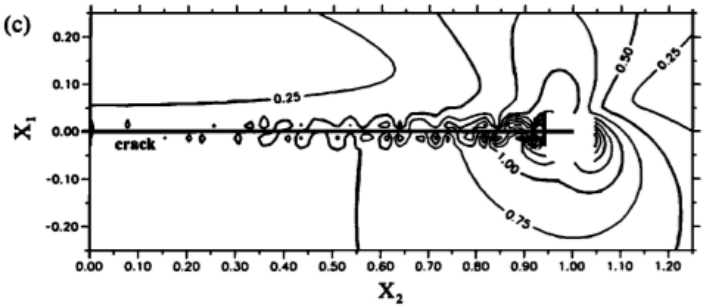


Displacement boundary condition : kinematic models

Fracture stress

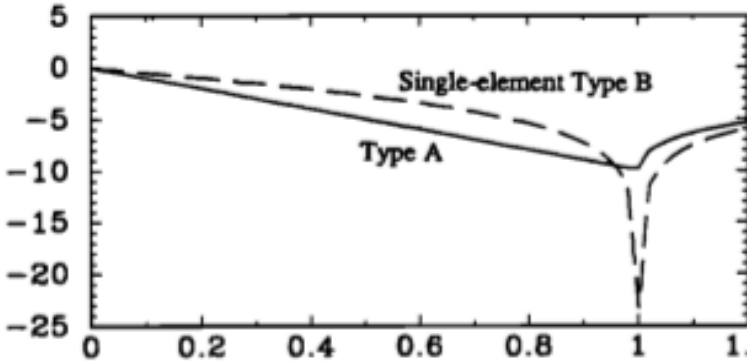
More stress singularities

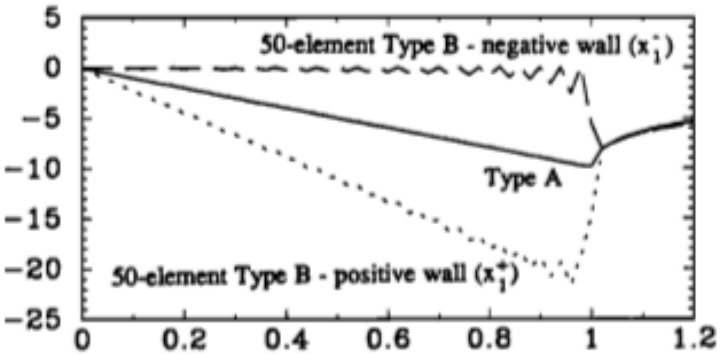




Fracture shear displacement

Too small shear displacements



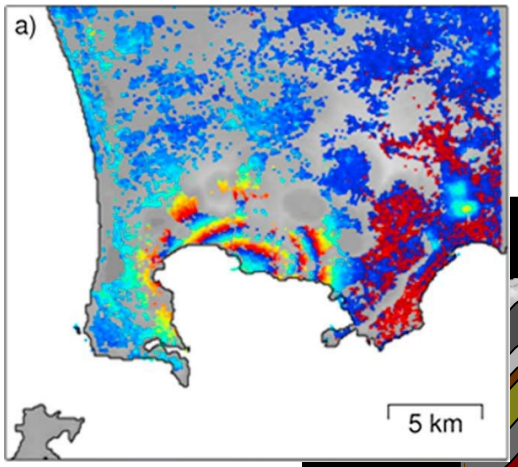


(Zeller and Pollard, JGR, 1992)

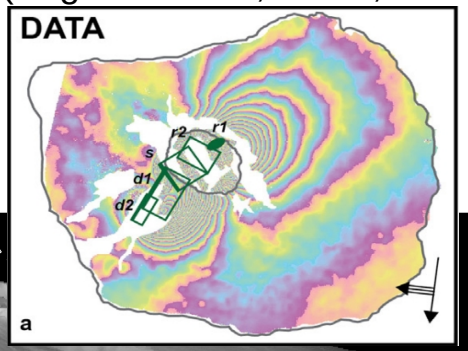
→ **Stress boundary conditions models are closer to the physics**

Stress boundary condition models are more informative

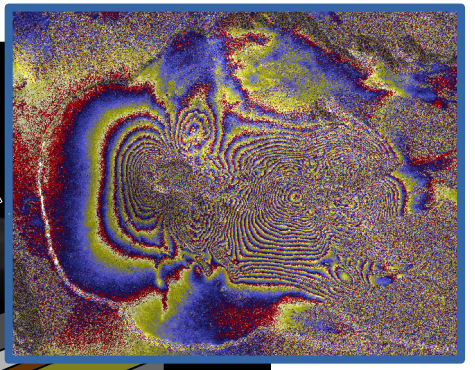
Hydrothermal systems
(Camacho et al., JGR, 2011)

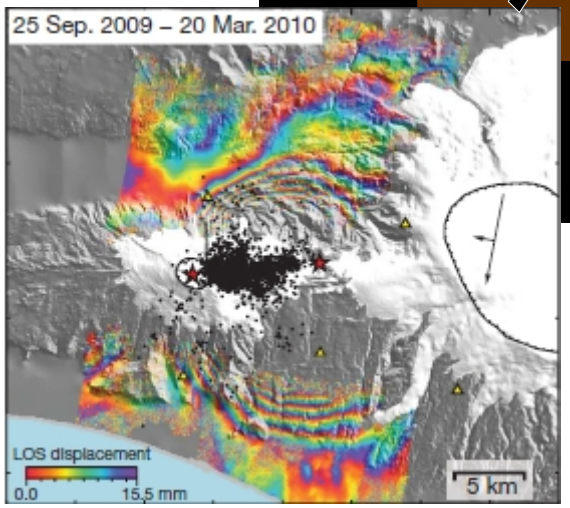


Intrusion pathways
(Bagnardi et al., EPSL, 2013)

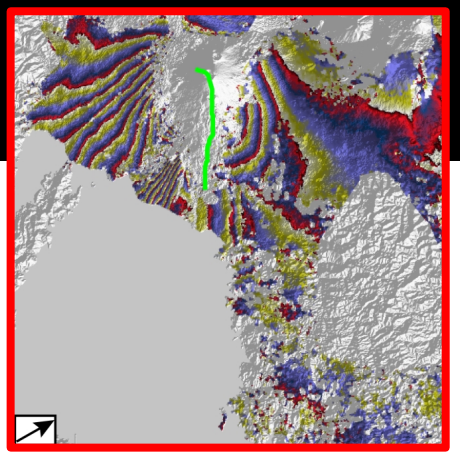


Flank slip mechanism
(Tridon et al., JGR, 2016)

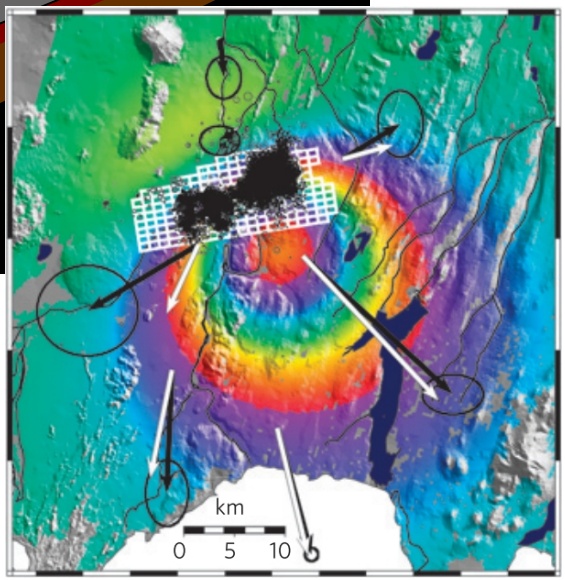




Magma reservoirs
(Sigmundson et al., Nature, 2010)



Rift extension drive
(this study)

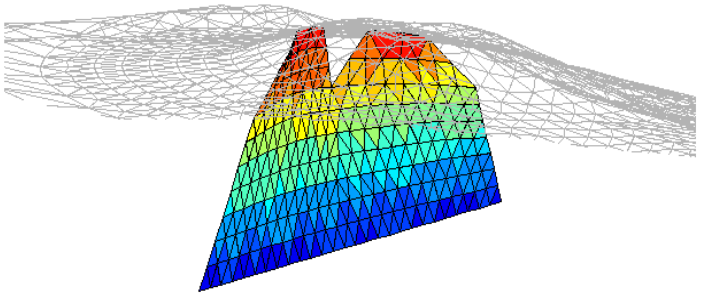


Glacier retreat influence
(Hooper et al., Nat. Geos, 2011)

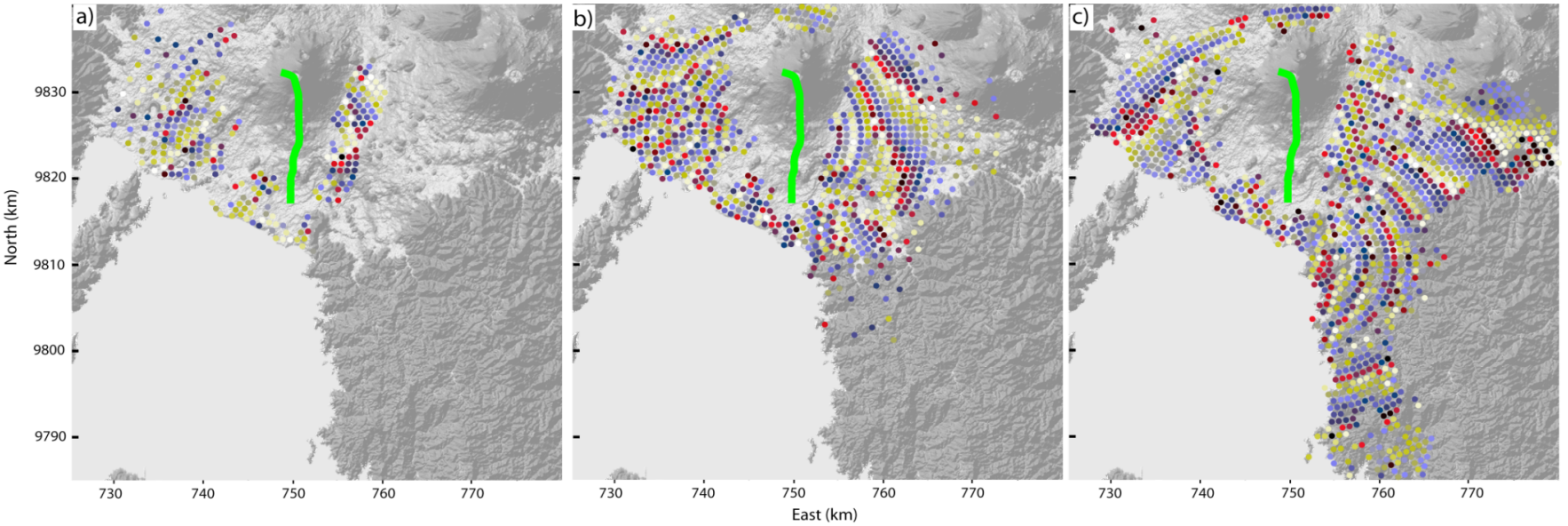
Faster inversion: 1. Interface

Launching inversions requires many steps

- model (dike, spherical source, etc) and parameter ranges
- fissures coordinates
- topography file



- data undersampling
- covariance matrix C_d computation

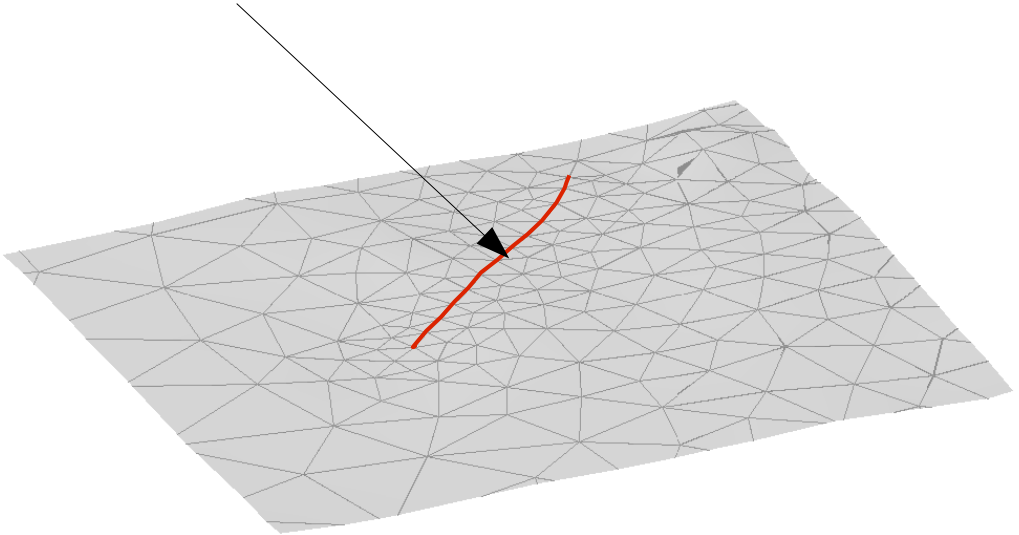


→ **the user is guided through the steps**

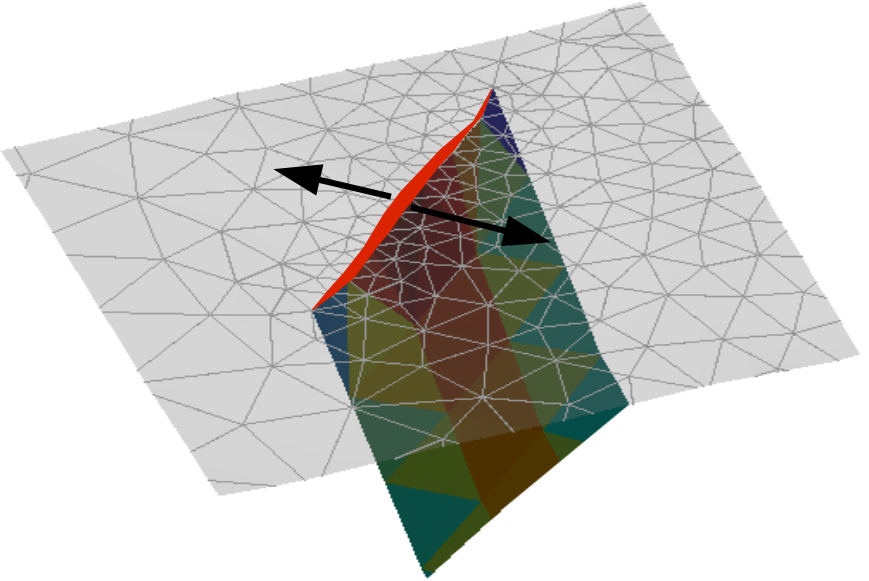
Faster inversion: 1. Interface

The steps can be imbricated: Eruptive fissures required for topography mesh

Eruptive fissure



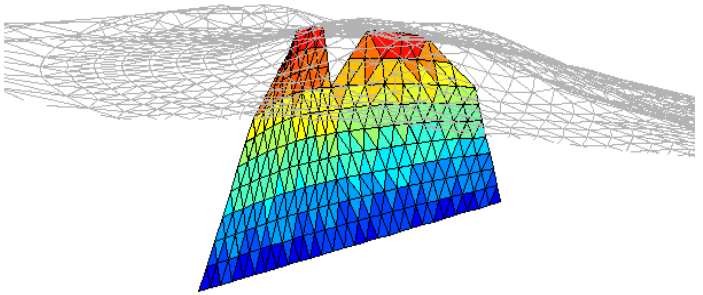
Discontinuity at fissure $\mathbf{D = u^{+} - u^{-}}$



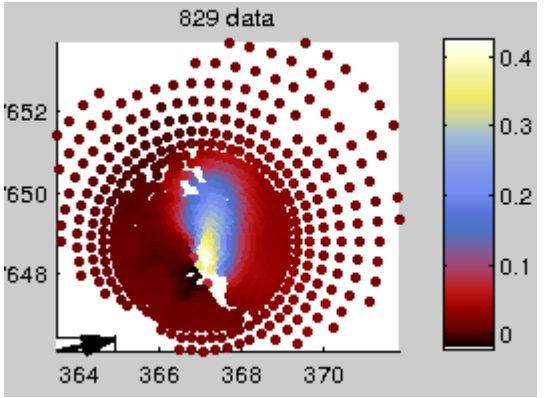
Faster inversion: 1. Interface

Imbricated

ex : Eruptive Fissures



Topography and source mesh

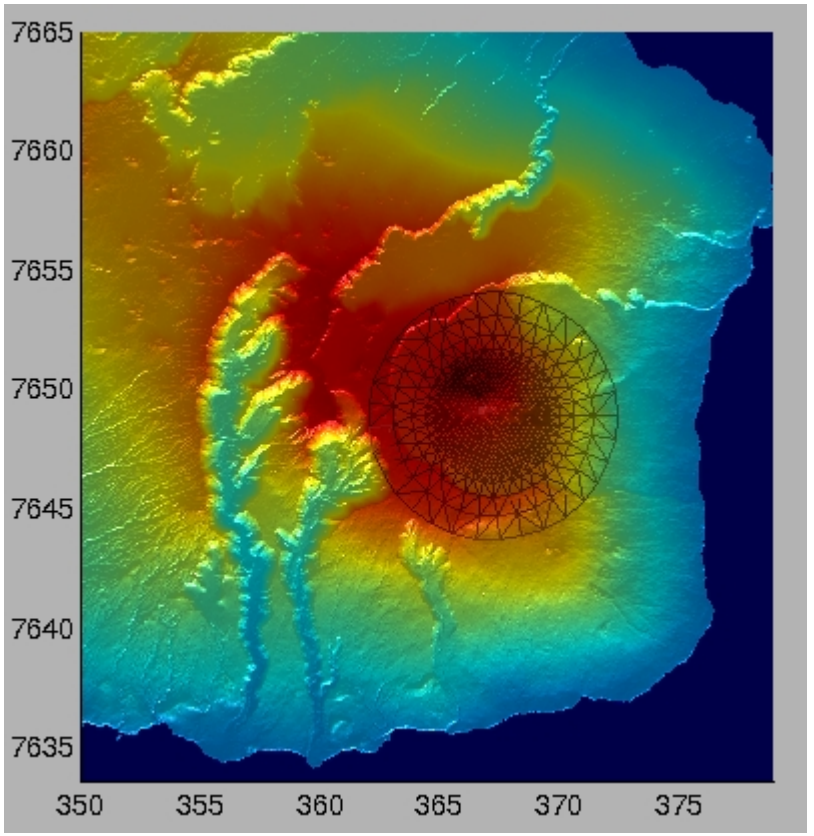


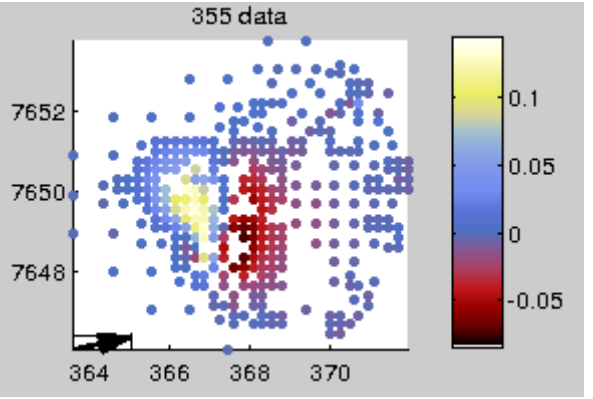
Undersampling

→ **Imbricated steps are implicitly taken into account**

Faster inversion: 1. Interface

Need for a graphical control



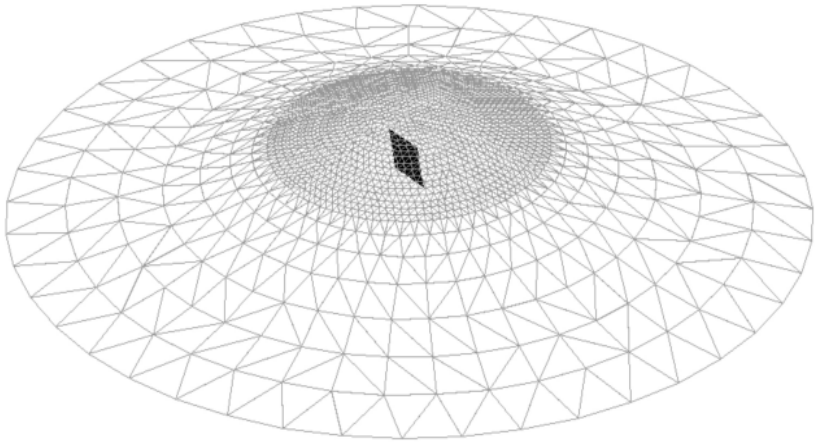


For undersampling parameters

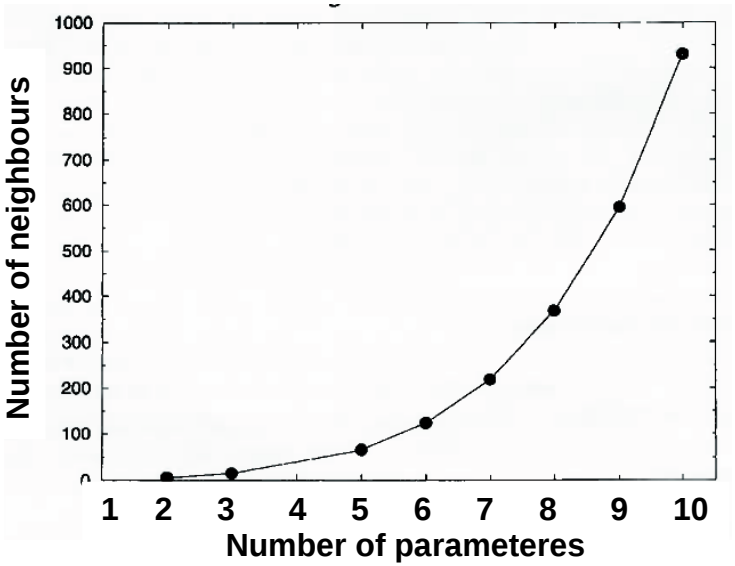
→ **Graphical control**

Faster inversion: 1. Interface

Rules of thumbs to use



Extension of topography mesh with respect to fracture size

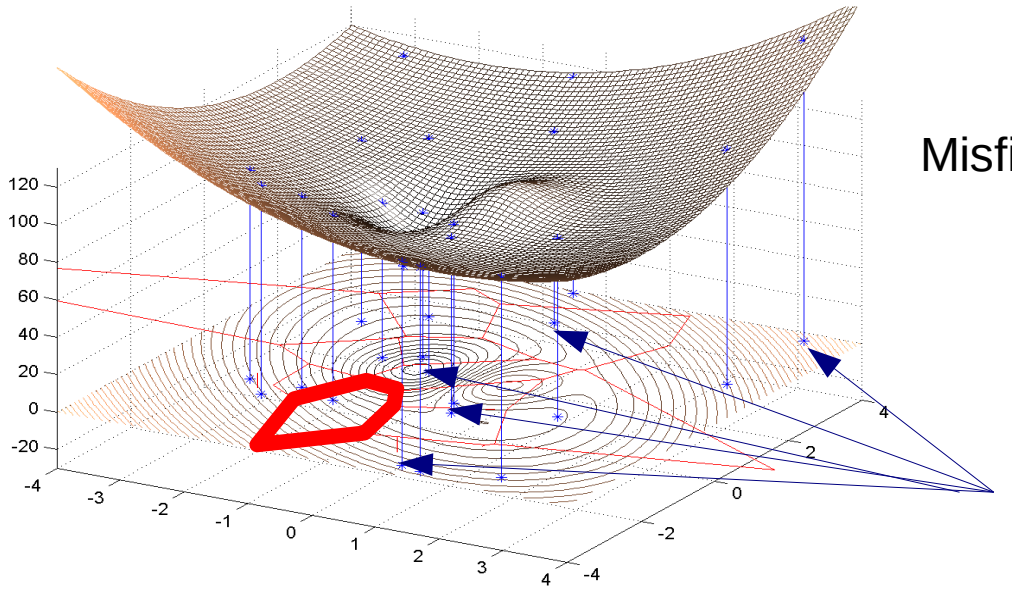


Number of forward models at first iteration is a function of the sources and the associated number of parameters

(Sambridge, 1998)

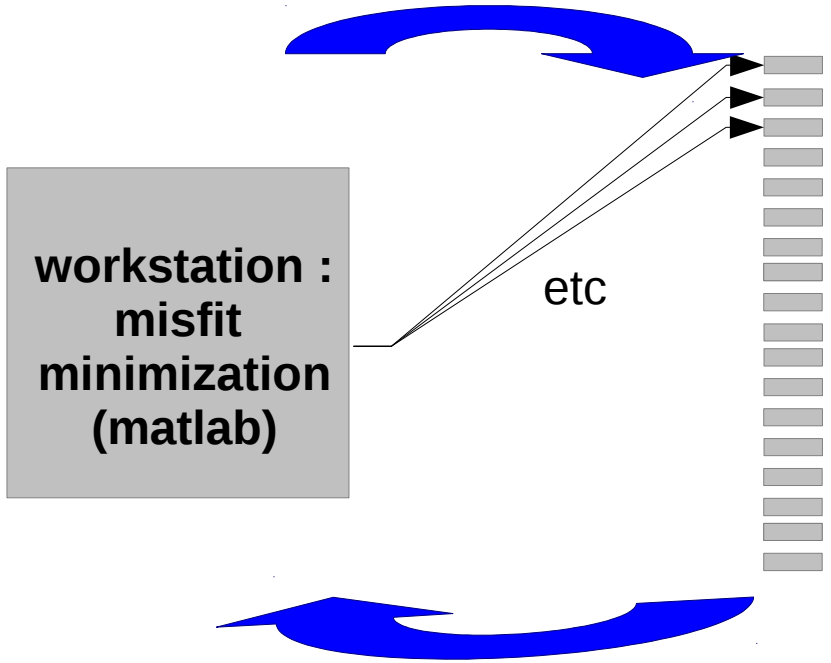
→ **Implicitely proposed**

Faster inversion: 2. Forward models parallelization



Misfit minimization

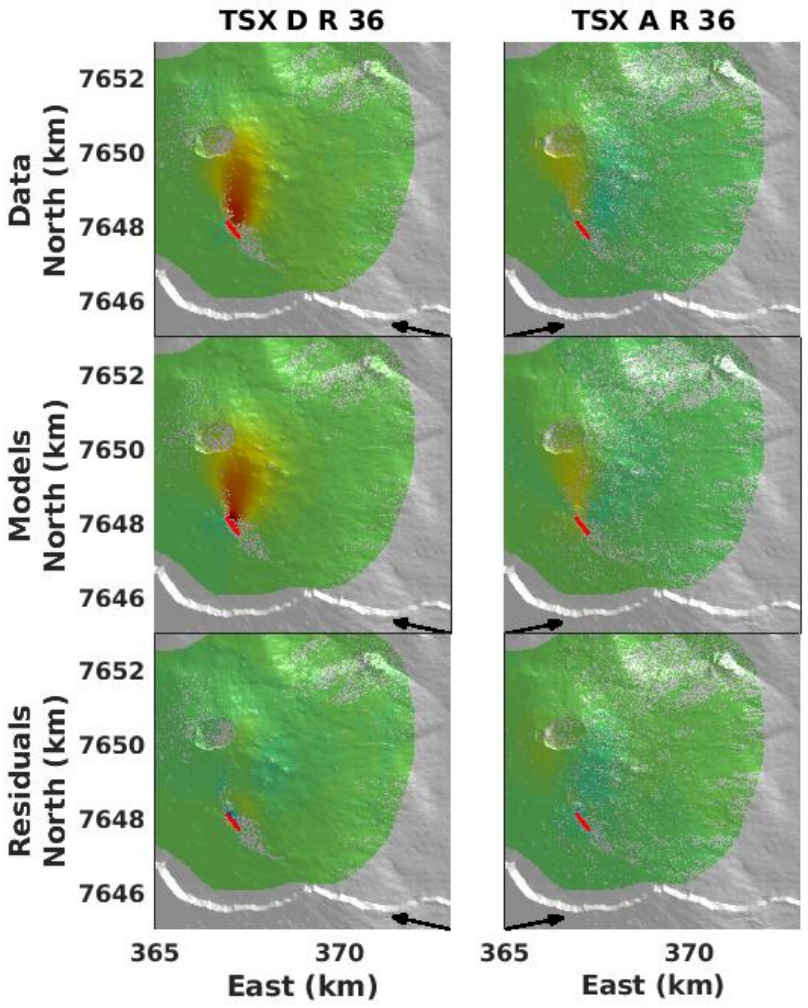
np simultaneous forward models



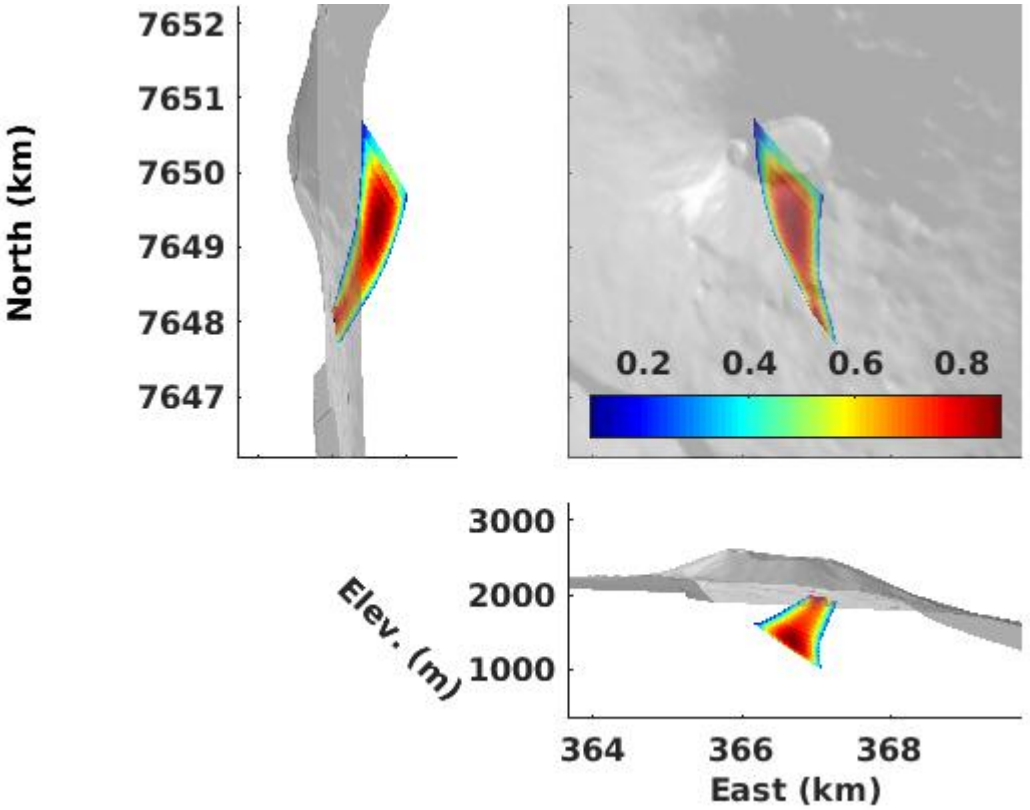
Cluster (>50 processors) : forward models computation (C)

50 times faster (6 hours against two weeks)

Example of the Oct. 2010 Piton de la Fournaise eruption



A sill that turns into a dyke ?



50 processors of a cluster : from a few weeks to a few hours (here 4 hours for a 9 parameters model)

Folder organization

```
cayol@empmetlmv004:~/MATLAB/DEFVOLC/MDIS2019/MDISaDistribuer$ ls *
launch_DefVolc  run_launch_DefVolc.sh

Data:
PdF_Oct2010_MDIS

Inversions:
PdF_Oct2010_MDIS

Manuels:
bord.eps  DefVolcShortCourse.odp  Fissure.jpg                  MindMapSteps.jpg  planarEll.jpg
bord.jpg  err_eff_bord.jpg        manuelutilisationDEFVOLC.pdf  MindMapSteps.odg  topo.tif

Utils_compiled:
bmp2raw              mergemask              run_bmp2raw.sh      run_meshtest.sh  savemask
demflipud            meshtest               run_demflipud.sh    run_r42grdb.sh
interf2tif           r42grdb                run_interf2tif.sh   run_sarflip.sh
maskfromcoh          readme.txt             run_maskfromcoh.sh  run_savemask.sh
mccExcludedFiles.log requiredMCRProducts.txt run_mergemask.sh   sarflip
cayol@empmetlmv004:~/MATLAB/DEFVOLC/MDIS2019/MDISaDistribuer$
```

Required files (Data folder)

- A custom file that users yould make, named INSAR.txt, containing the information on the satellite, orbit, radar wavelength, LOS

```
cayol@empmetlmv004:~/MATLAB/DEFVOLC/defvolc_gitlab/Data/PdF_Oct2010_MDIS$ more INSAR.txt
Satellite Pass Looking Track Wavelength RADARLOOK_X RADARLOOK_Y RADARLOOK_Z
S1 A R 144 0.056 -0.66 -0.17 0.73
TSX D R 036 0.031 0.59 -0.13 0.80
TSX A R 036 0.031 -0.54 -0.11 0.83
CSK A R 15 0.031 -0.73 -0.18 0.66
ALOS2 A L 55 0.236 0.89 0.14 0.44
```

- Interferograms,binary files of floating point numbers (‘float32’ in matlab), coded on 4 bytes. Extension should be .r4, .nvi, .unwr
- An envi type header file for the interfergram (see files *.hdr joined), having the same name as the corresponding interferogram and a .hdr extension.
- Masks, binary files coded on a byte as unsigned integer (‘uchar’ in matlab), with 0 values for masked data and 1 values for visible data. Same dimension as interferograms
- A dem file, with a surfer type header, binary file of floating point numbers (‘floats’ in matlab), coded on 4 bytes. Extension should be .grd

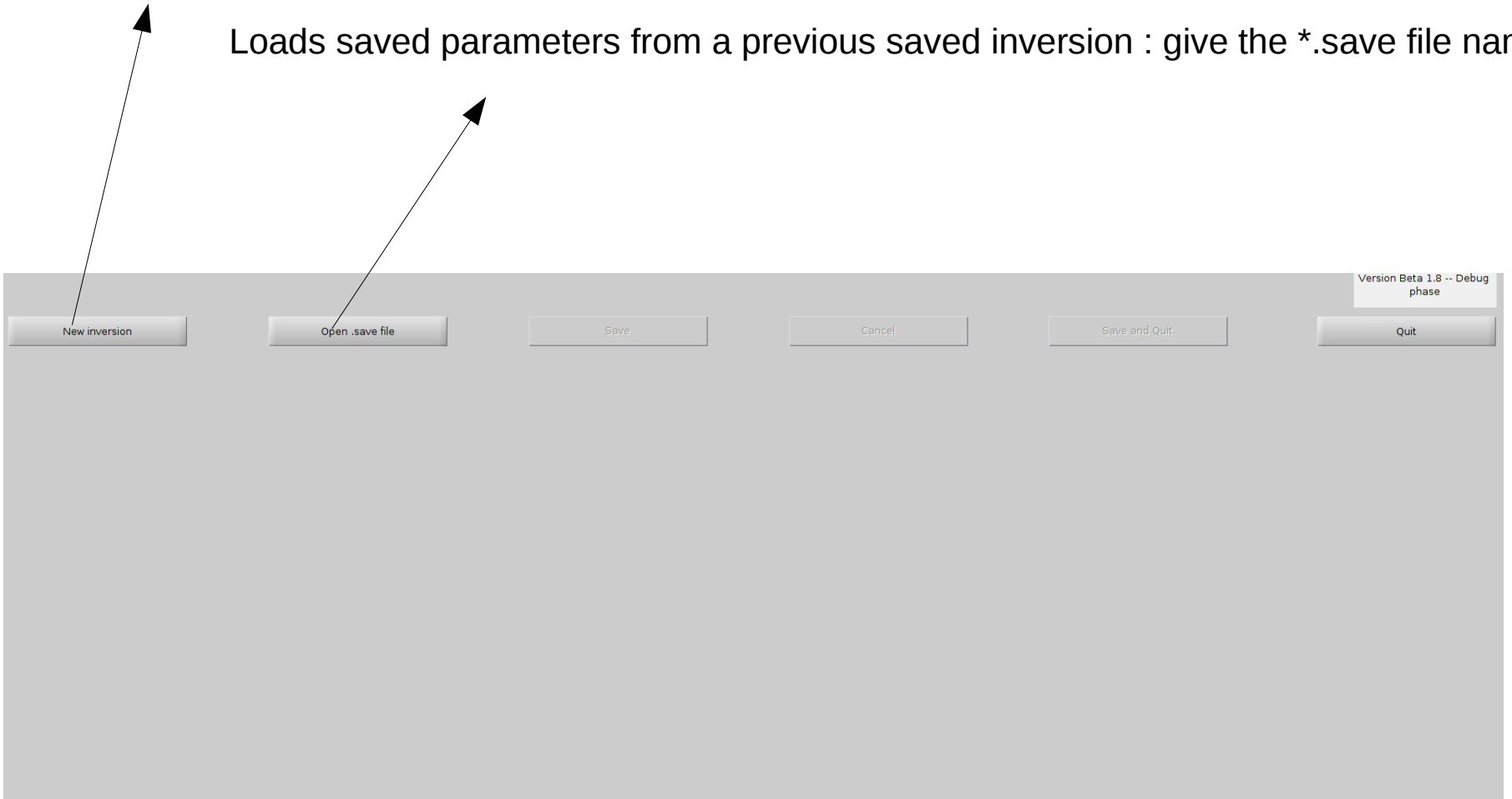
Launching the compiled interface

From a terminal, do

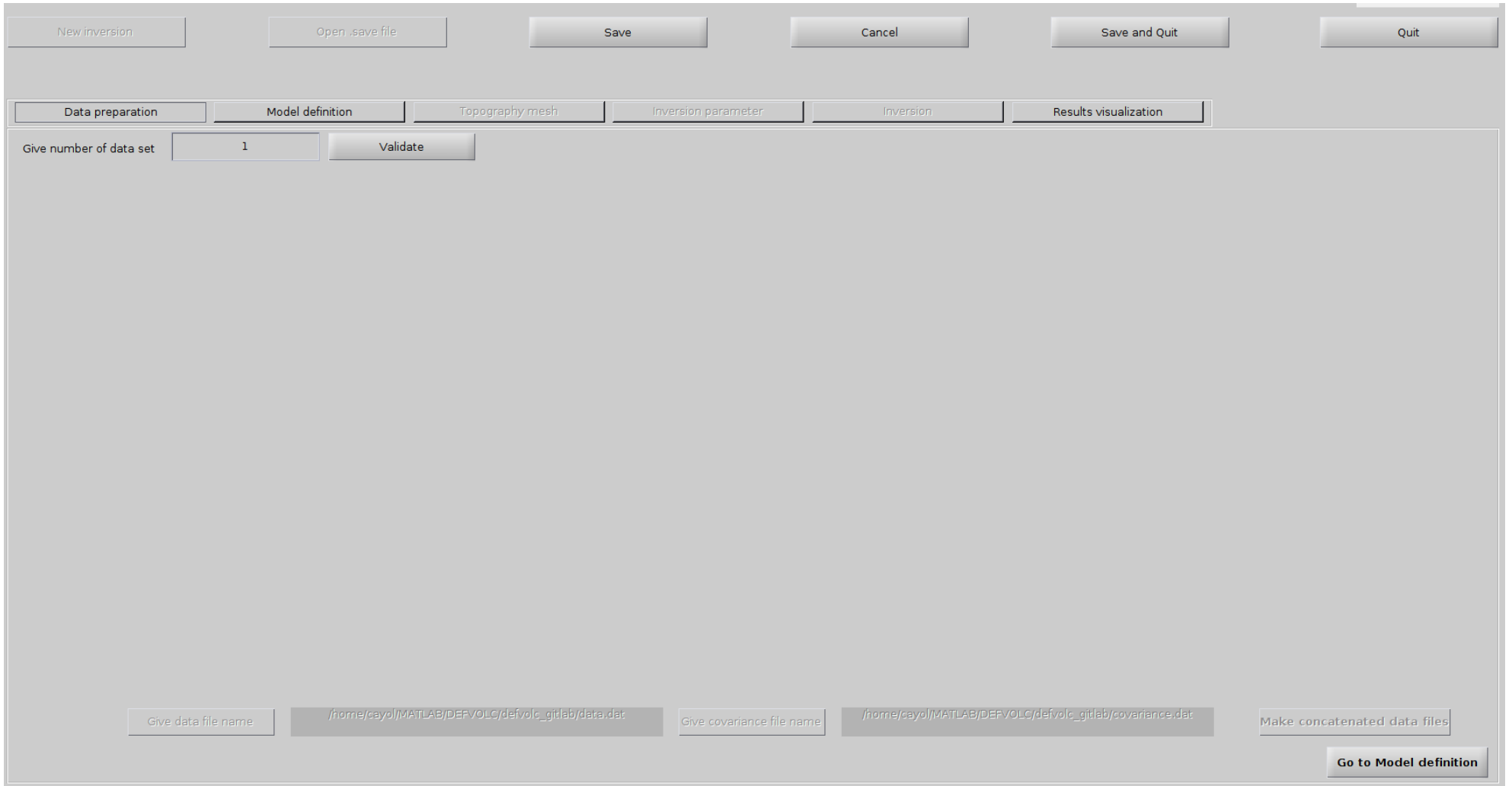
```
cayol@empmetlmv004:~/MATLAB/DEFVOLC/MDIS2019/MDISaDistribuer$ ./run_launch_DefVolc.sh /usr/local/MA
TLAB/2018b/v95
```

Asks for the inversion directory : give a folder name in the Inversions directory, /Inversion/Rundir

Loads saved parameters from a previous saved inversion : give the *.save file name

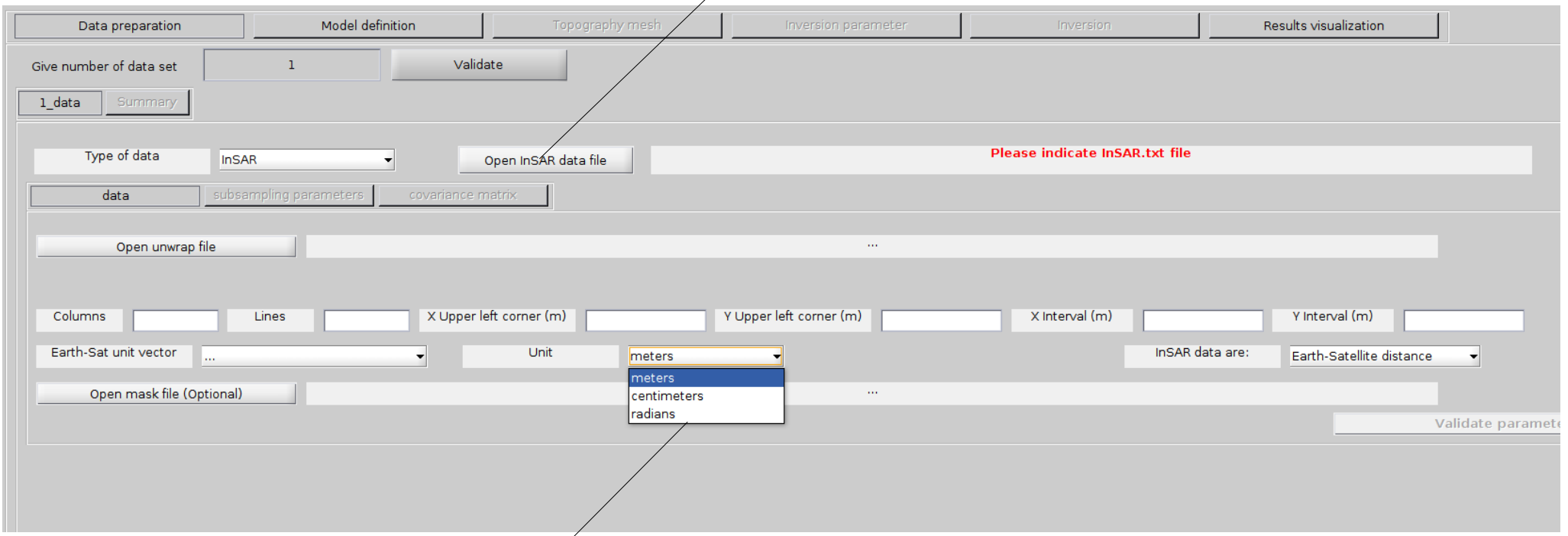


6 Steps


New inversion
Open .save file
Save
Cancel
Save and Quit
Quit
Data preparation
Model definition
Topography mesh
Inversion parameter
Inversion
Results visualization
Give number of data set
1
Validate
Give data file name
/home/cayol/MATLAB/DEFVOLC/defvolc_gitlab/data.dat
Give covariance file name
/home/cayol/MATLAB/DEFVOLC/defvolc_gitlab/covariance.dat
Make concatenated data files
Go to Model definition

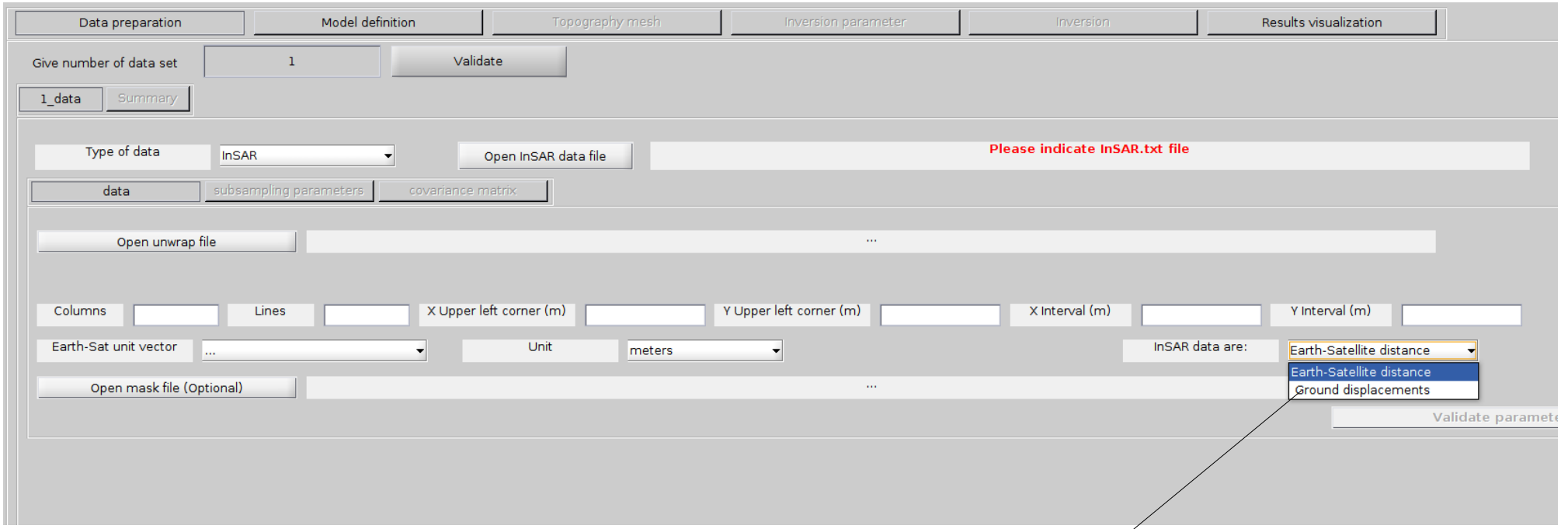
Data subsampling: options for InSAR data

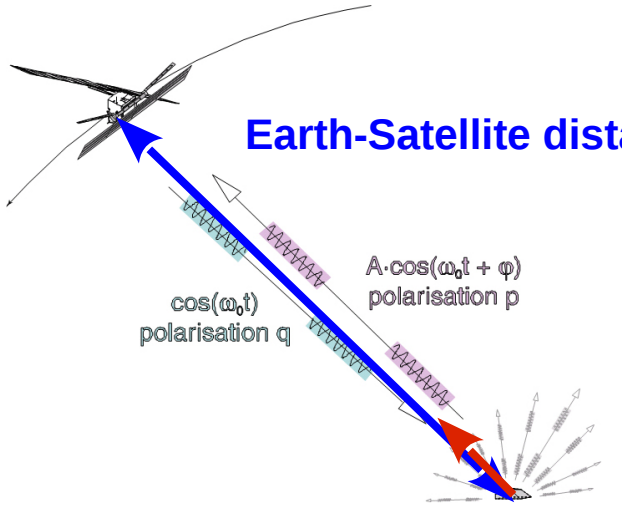
Given once for all interferograms



Depends on your InSAR data

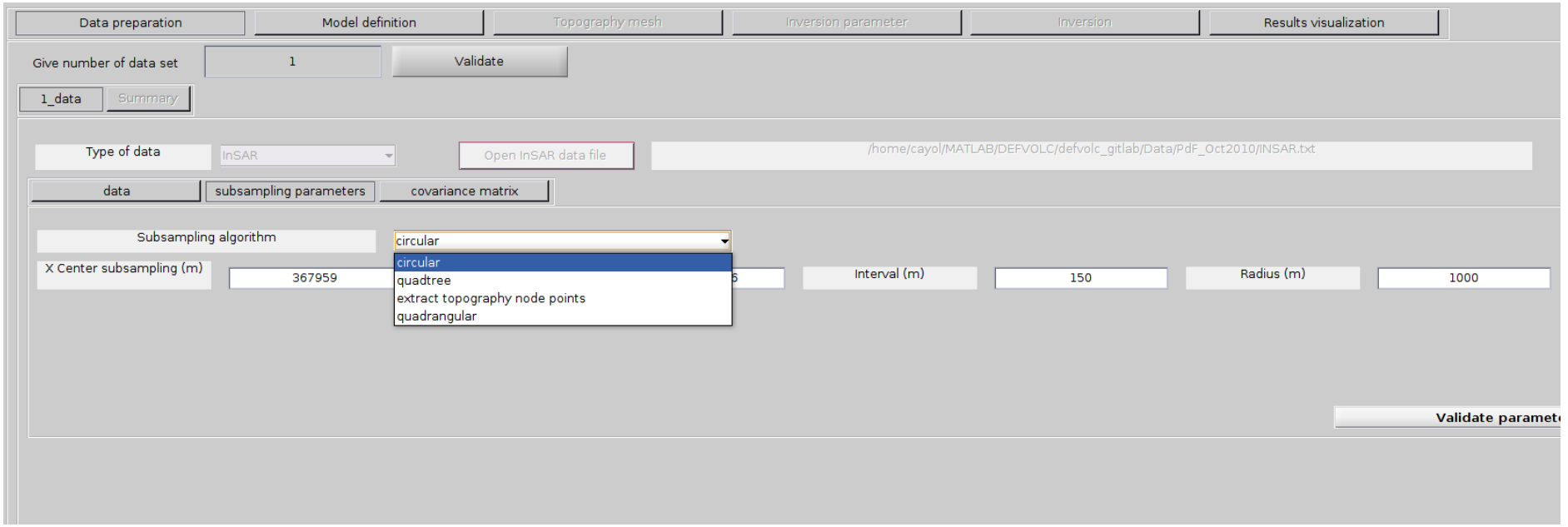
Data subsampling: options for InSAR data



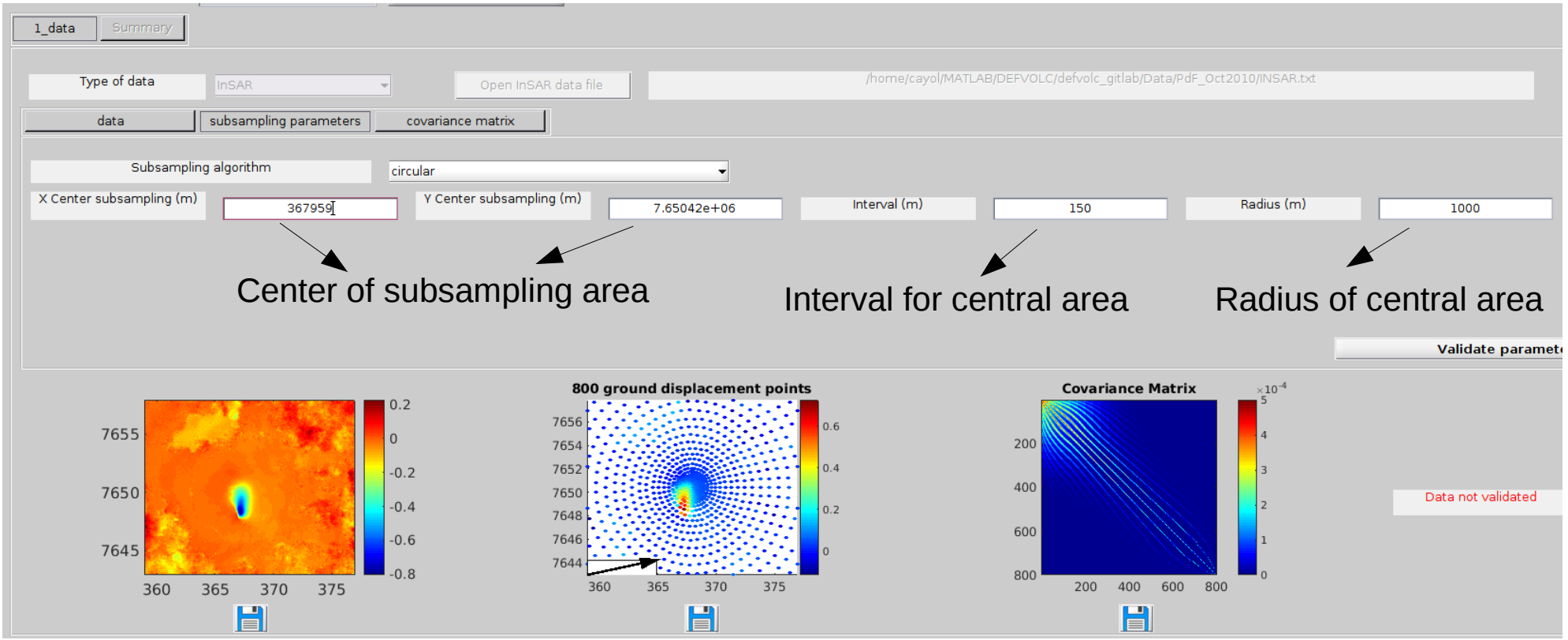


Earth-Satellite distance change = - Ground displacement

Data subsampling: 4 subsampling options for InSAR data



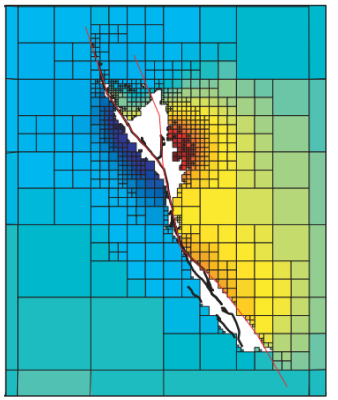
Data subsampling: circular subsampling option



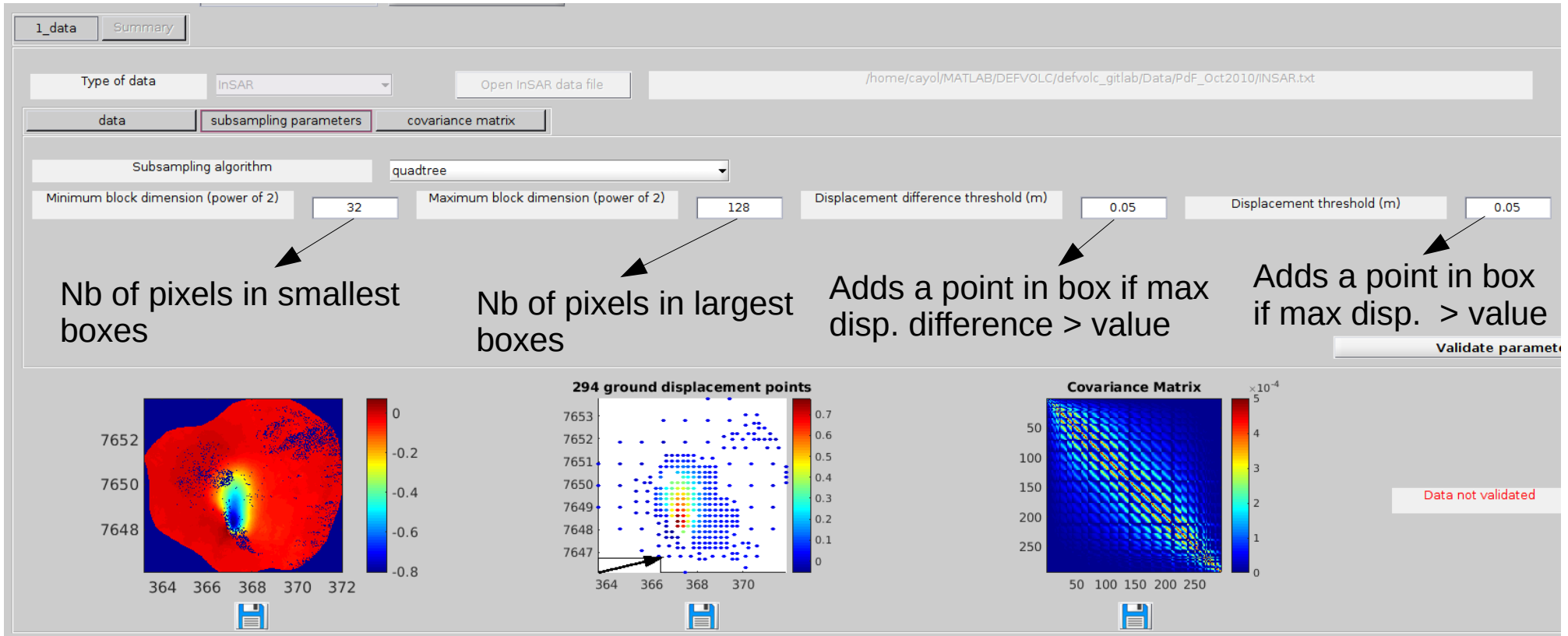
Data subsampling: quadtree subsampling option

For the quadtree decomposition method see Welstead, S. T. (1999), *Fractal and Wavelet Image Compression Techniques*, 232 p. and

basinc principle: Incrementally devides cells depending on the displacement gradient and absolute value

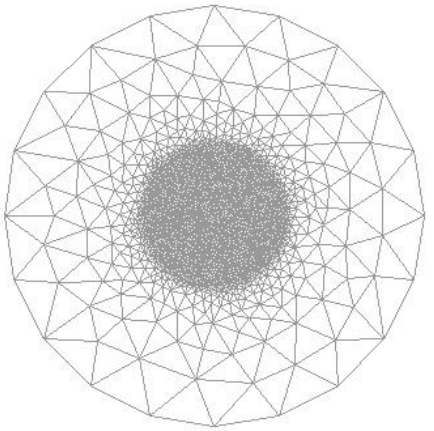


Jonsson et al., *BSSA*, 2002



Data subsampling: at topography mesh node points

Previously created topography mesh



1_data | Summary

Type of data: InSAR | Open InSAR data file

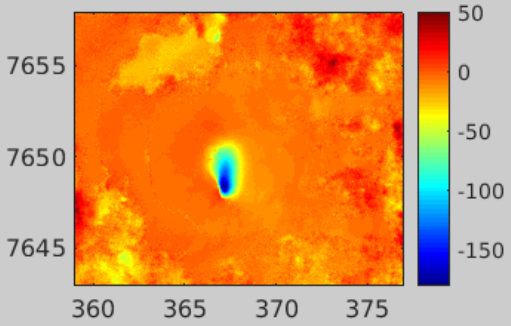
data | subsampling parameters | covariance matrix

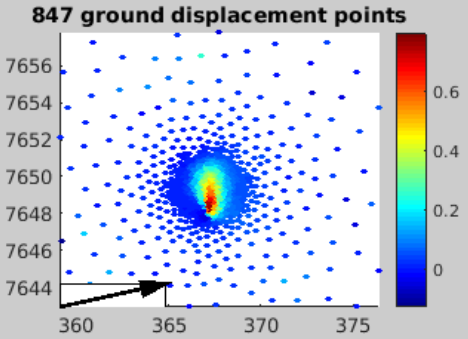
Subsampling algorithm: extract topography node points

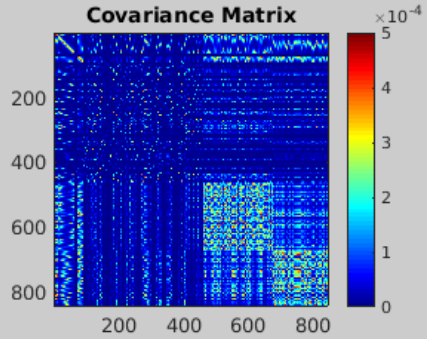
Open topography mesh file: /home/cayol/MATLAB/DEFVOLC/defvolc_gitlab/Inversions/PdF_Oct2010_MDIS/topo.ex3

Columns: 2400 | Lines: 2000 | Shift of topography mesh along X (m): 367232 | Shift of topography mesh along Y (m): 7649310

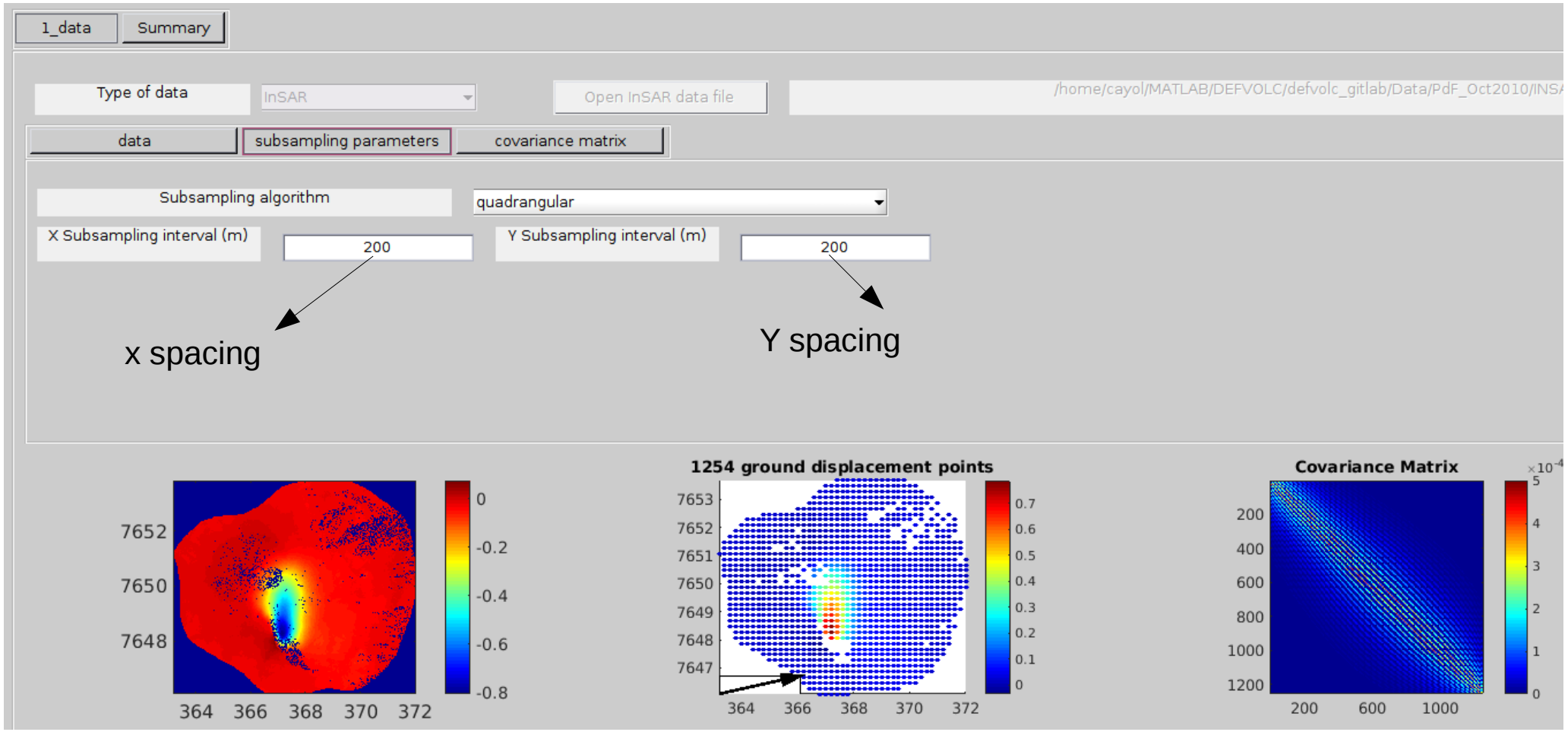
To be read from a previous param.input file (X0, Y0)





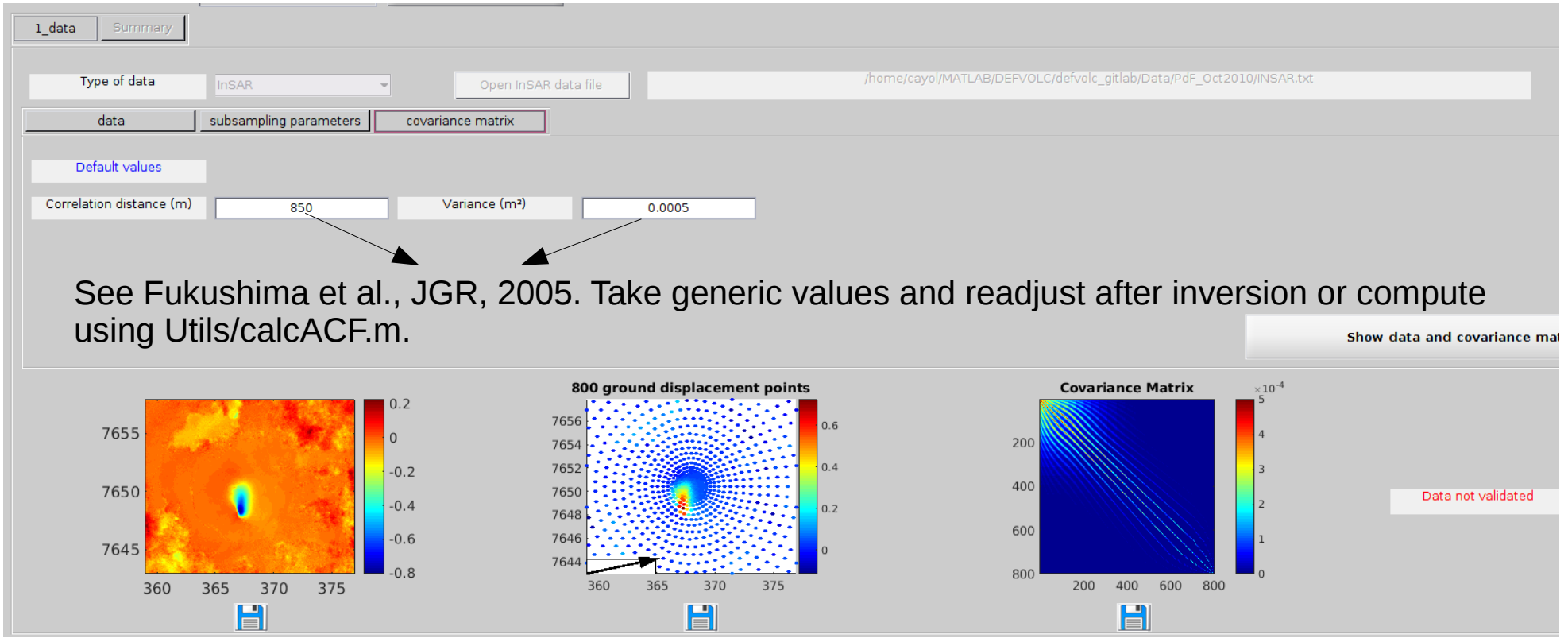


Data subsampling: regular subsampling option



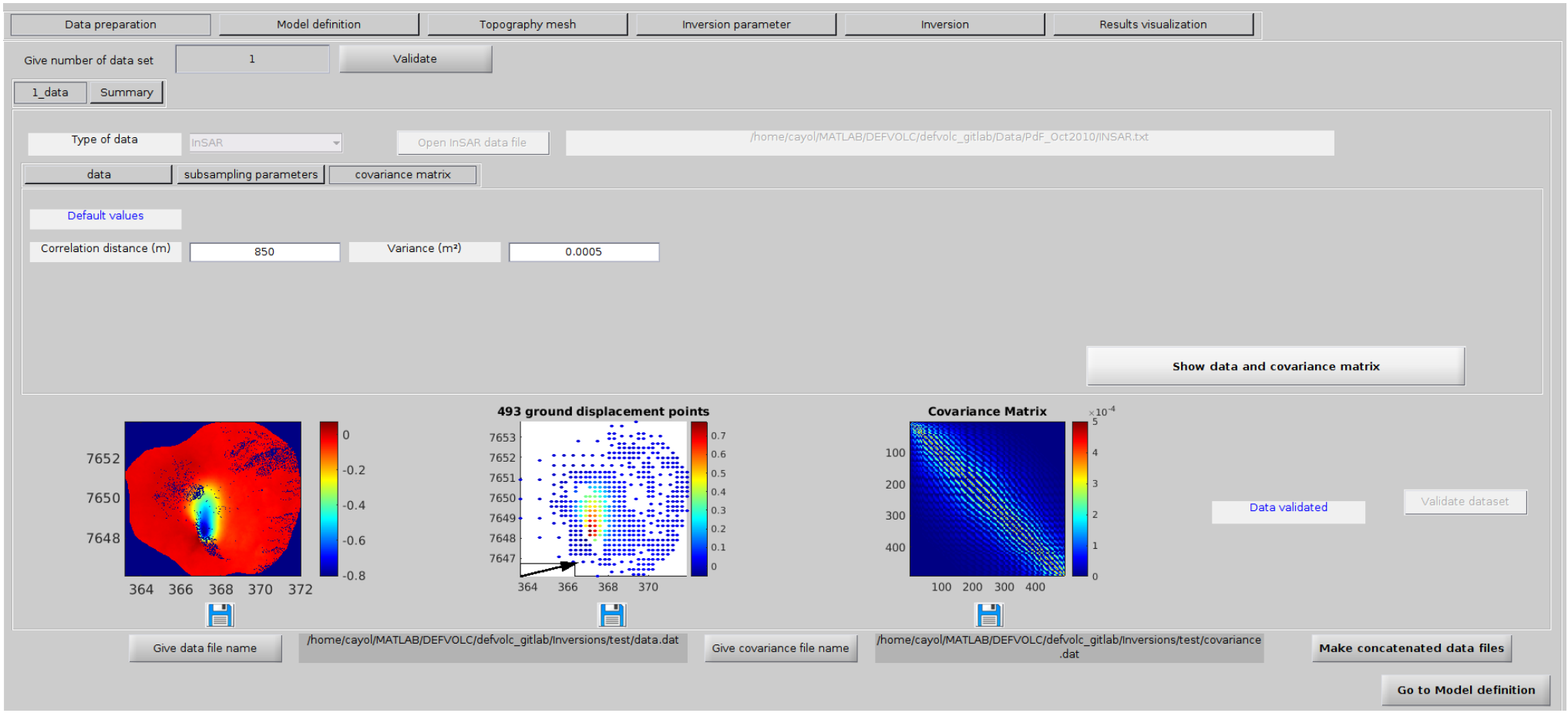
Data subsampling: covariance matrix

Independant from the subsampling method



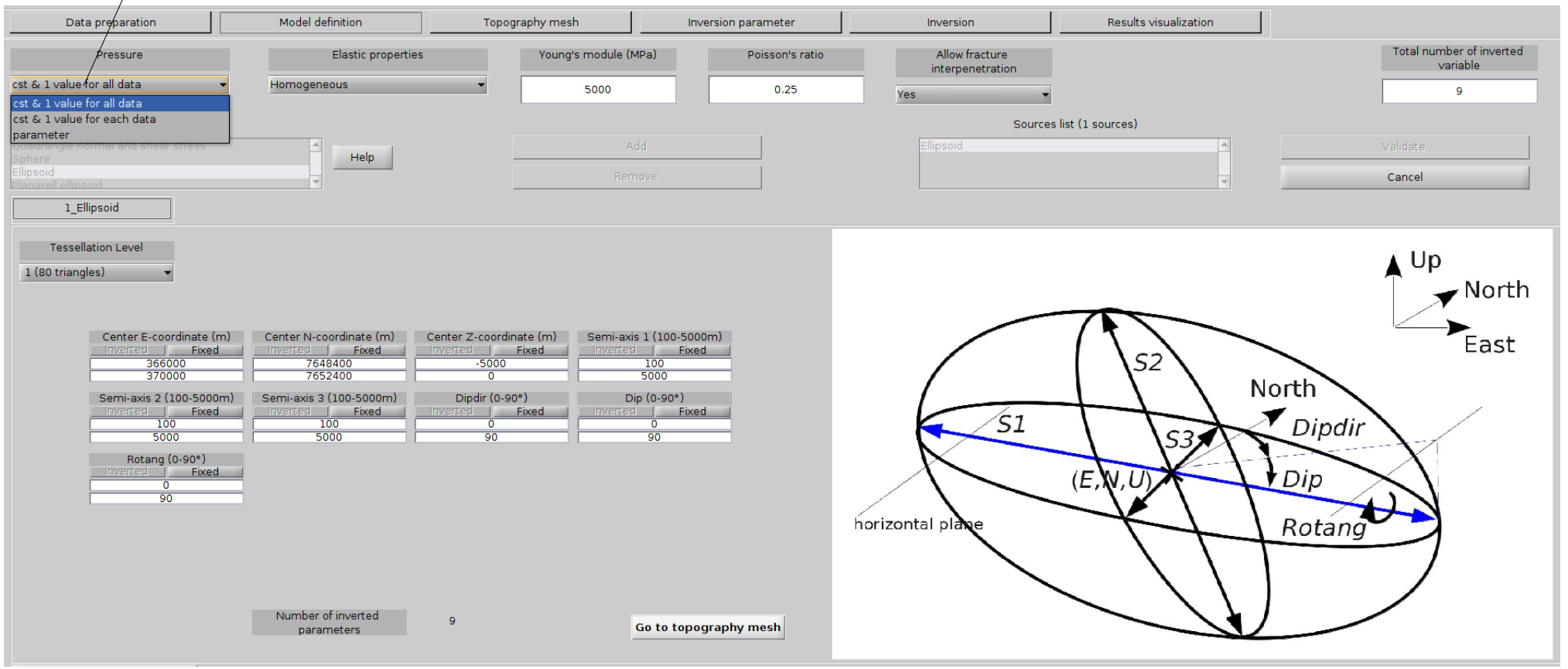
Data subsampling: creating data and covariance files

To create the data (/Inversions/RunDir/data.dat) and covariance (/Inversions/RunDir/covariance.dat) binary files, you need to validate each dataset and press "**Make concatenated data files**". Names can be changed, but the extension has to be *.dat.



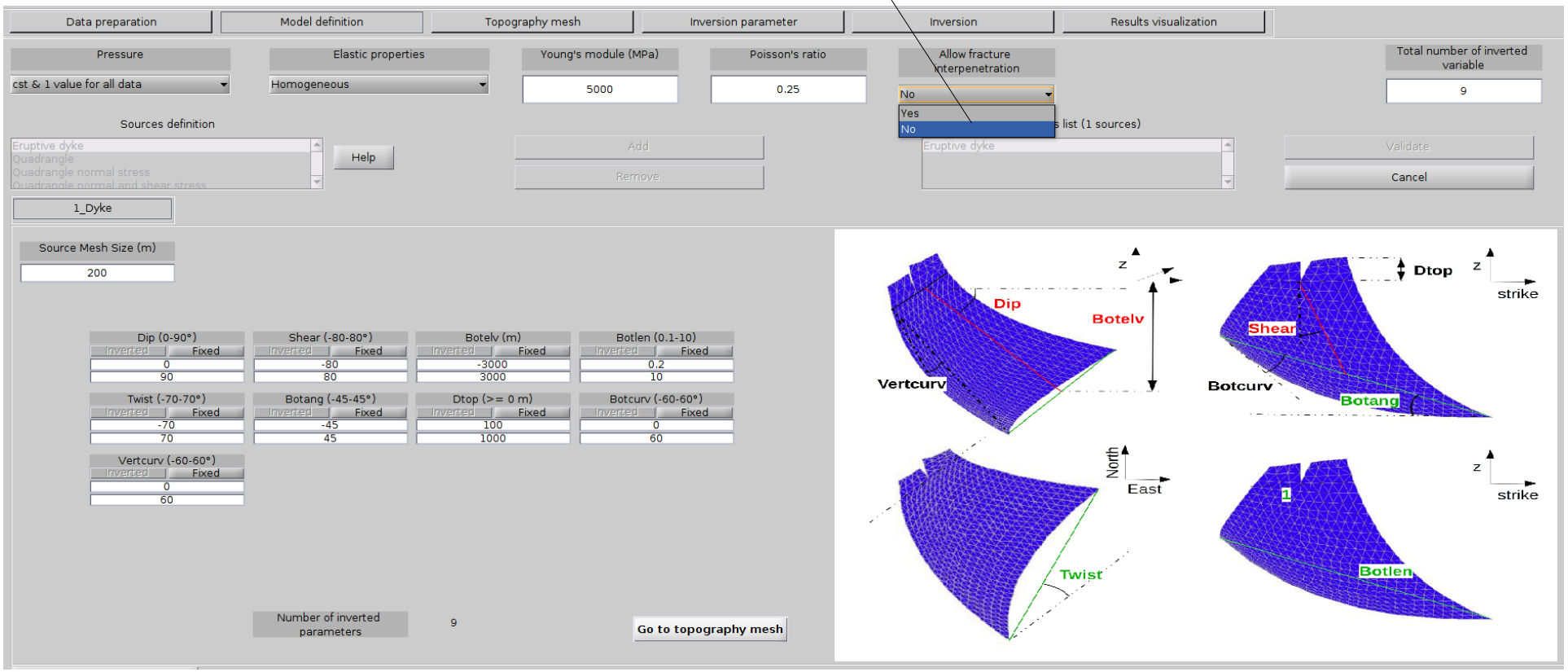
Sources definition:
Stress determination

cst and 1 value for all data : Stress changes (Overoressures, shear stress drops) are linear parameters. The stress change value minimizing the misfit on all the data is determined.
cst and 1 value for each data : Stress changes are also linear parameters, but their value is ajusted to minimize the misfit of each data set is determined
parameter : Stress changes are linear parameters



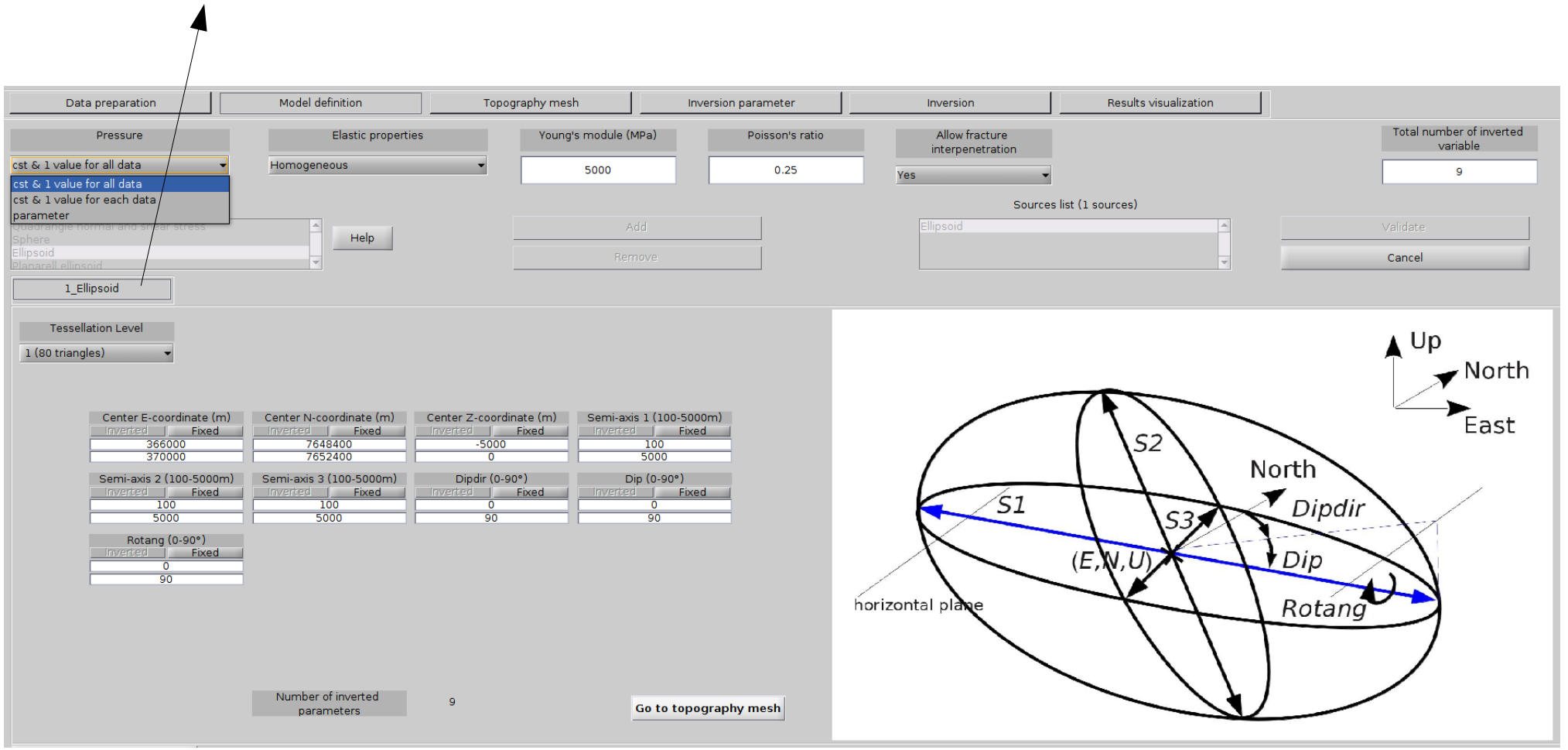
Sources definition: fracture interpenetration

Yes : The default value. Mathematical solutions allows for fracture interprenetration. This solution might be unphysical if the fracture was initially closed.
No : A solution is determined that solves the linear boundary element problem provided **$D = u^+ - u^- > 0$**. This is a constrained optimization problem. See Cayol, V., T. Catry, L. Michon, M. Chaput, V. Famin, **O. Bodart** et al., JGR, 2014, for algorithm.



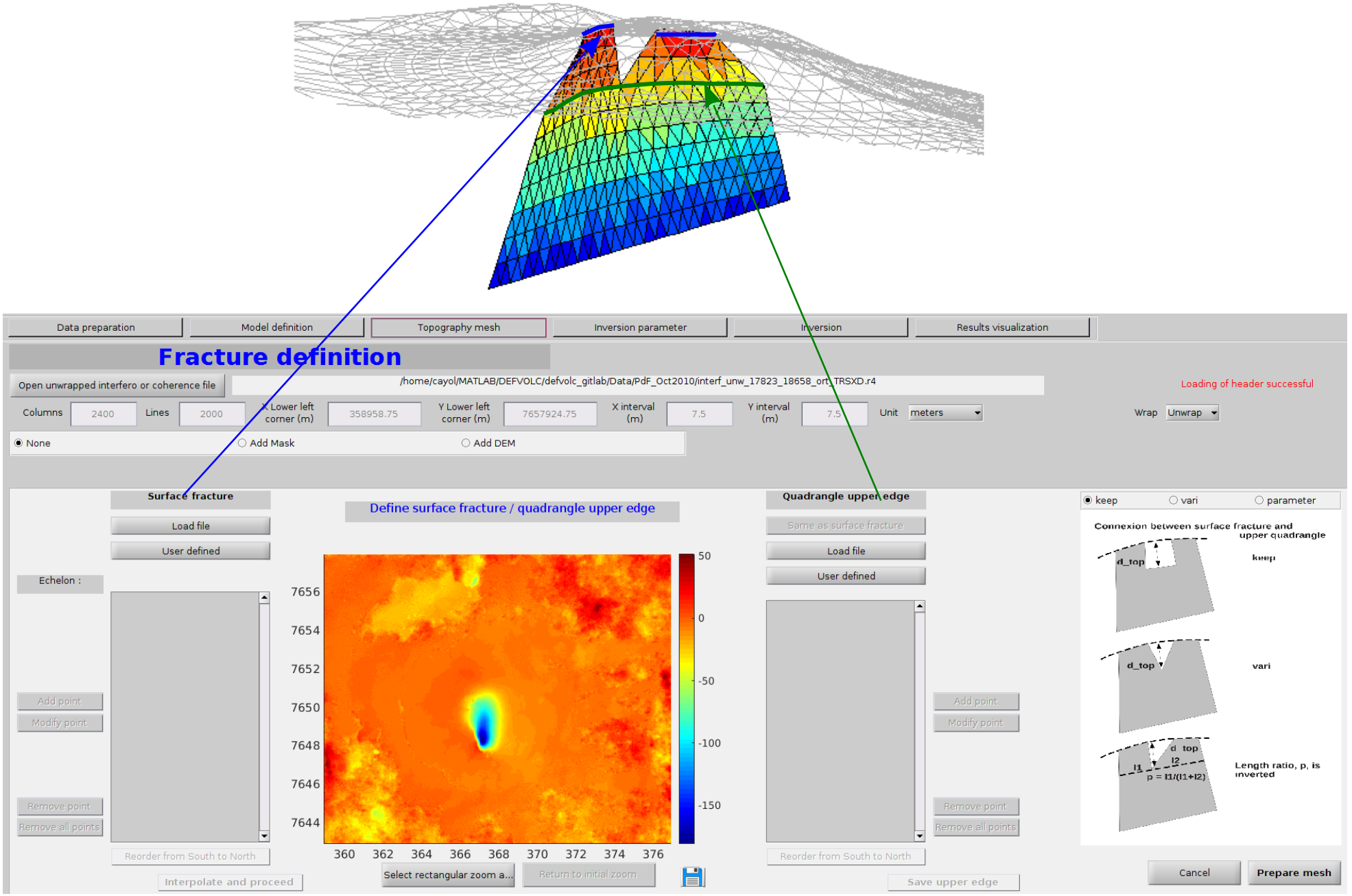
Sources definition:
Default source location

For blind sources, the default source location range corresponds to the data center ± 2 km



Topography Mesh: case of an eruptive dyke

Two fractures are required a surface fracture and a quadrangle upper edge

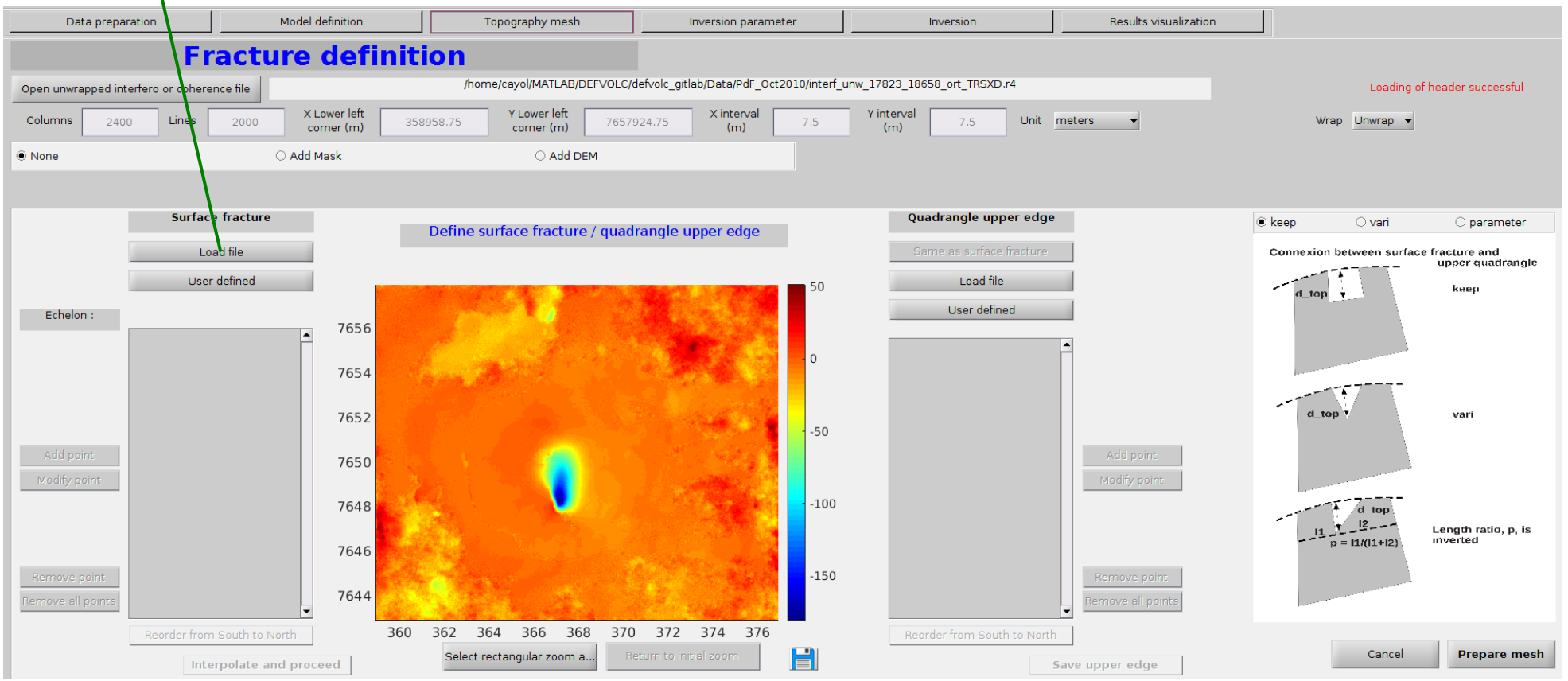


Topography Mesh: case of an eruptive dyke

Load File: The surface fracture (fract_a.dat) can be loaded from a file.

```
cayol@empmetlmv004:~/MATLAB/DEFVOLC/defvolc_gitlab/Inversions/test$ more fract_a.dat
5 1
367573.80 7647642.30
367505.01 7647709.75
367433.72 7647774.57
367358.67 7647833.67
367303.40 7647912.60
4 1
367123.20 7647948.70
367046.17 7648022.34
366974.70 7648101.16
366907.00 7648183.00
```

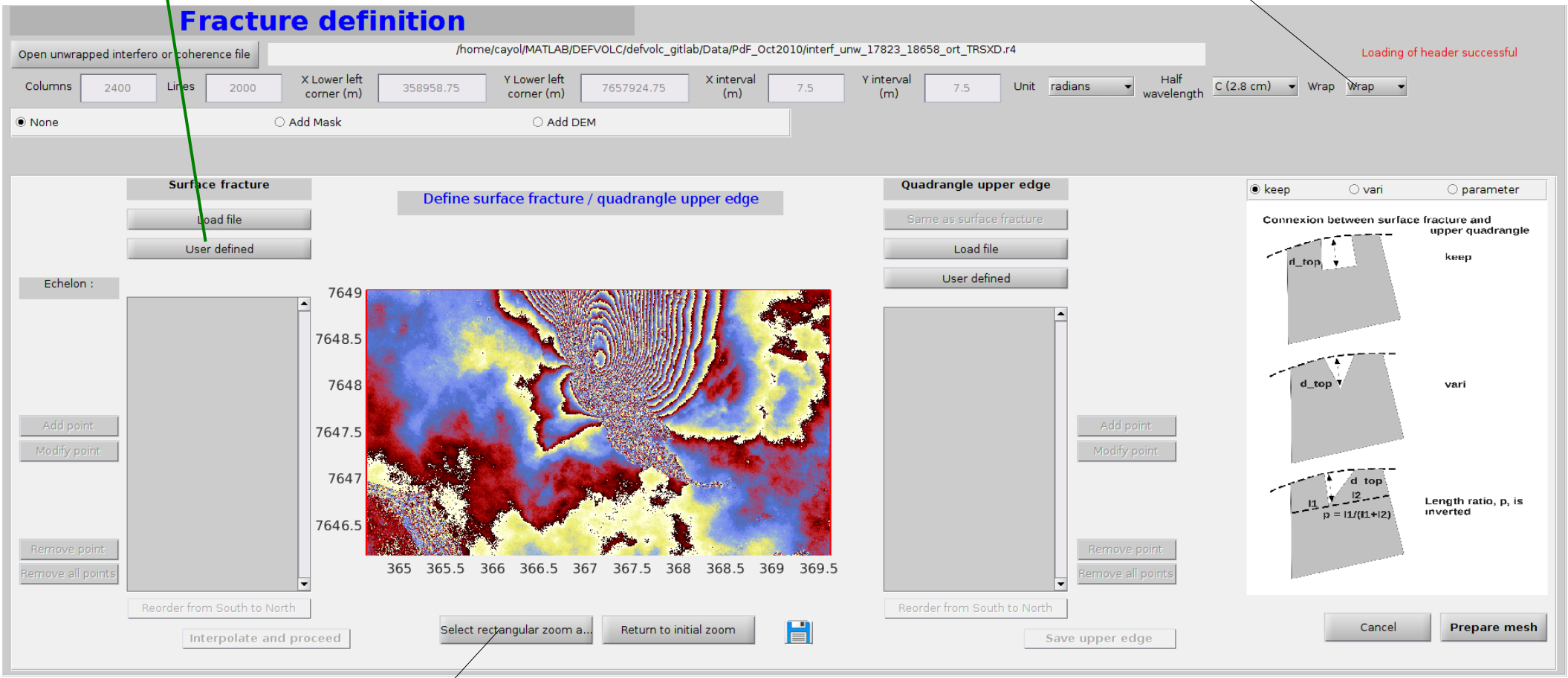
A file of east and north coordinates (meters), constructed from observatory data for instance.
Each fissure (here there are two) starts with the number of points used to define the fissure + a “1”



Topography Mesh: eruptive fissure

User defined: defined from the data by clicking

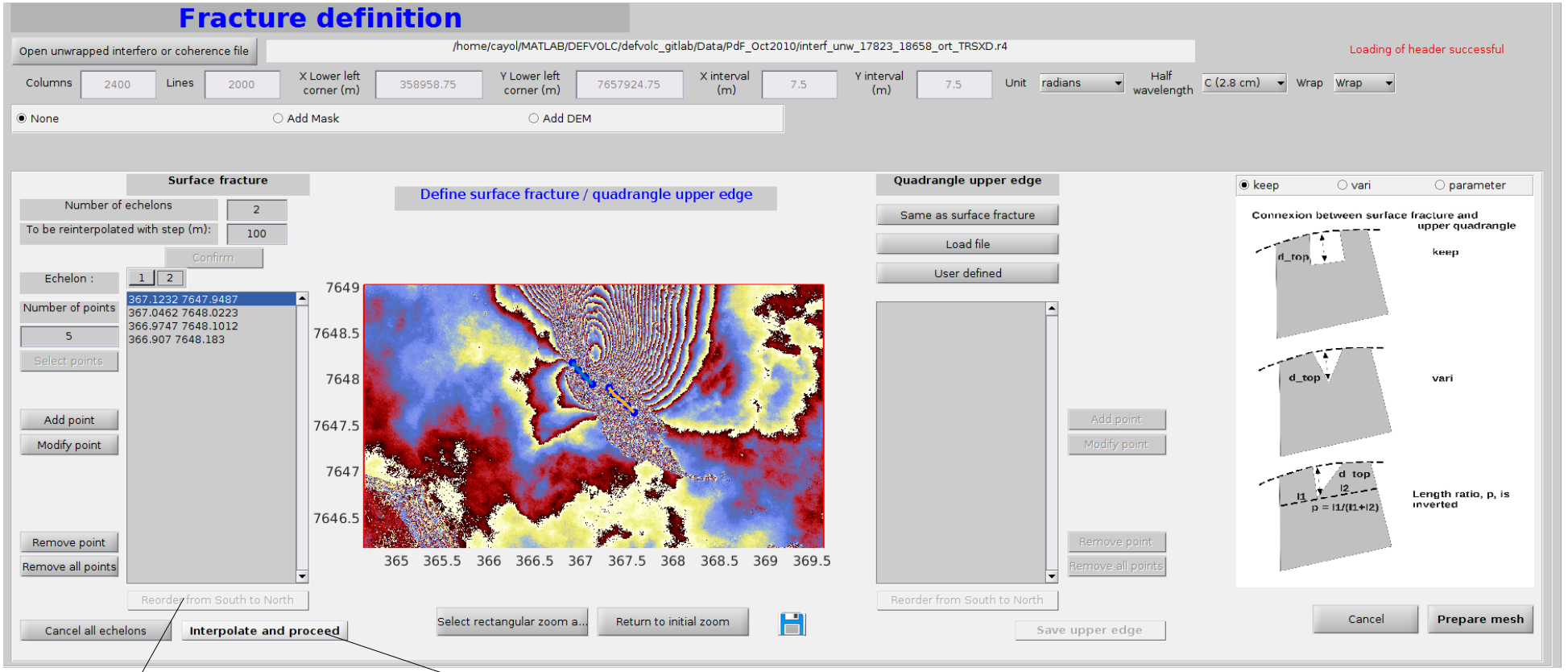
Possibility to see the data wrapped



Possibility to zoom

Topography Mesh: eruptive fissure

User defined: defined from the data



Dips are positive for eastward dipping fractures provided the fissures are defined from South to North

Interpolate to regular spaced points and save in fract_a.dat

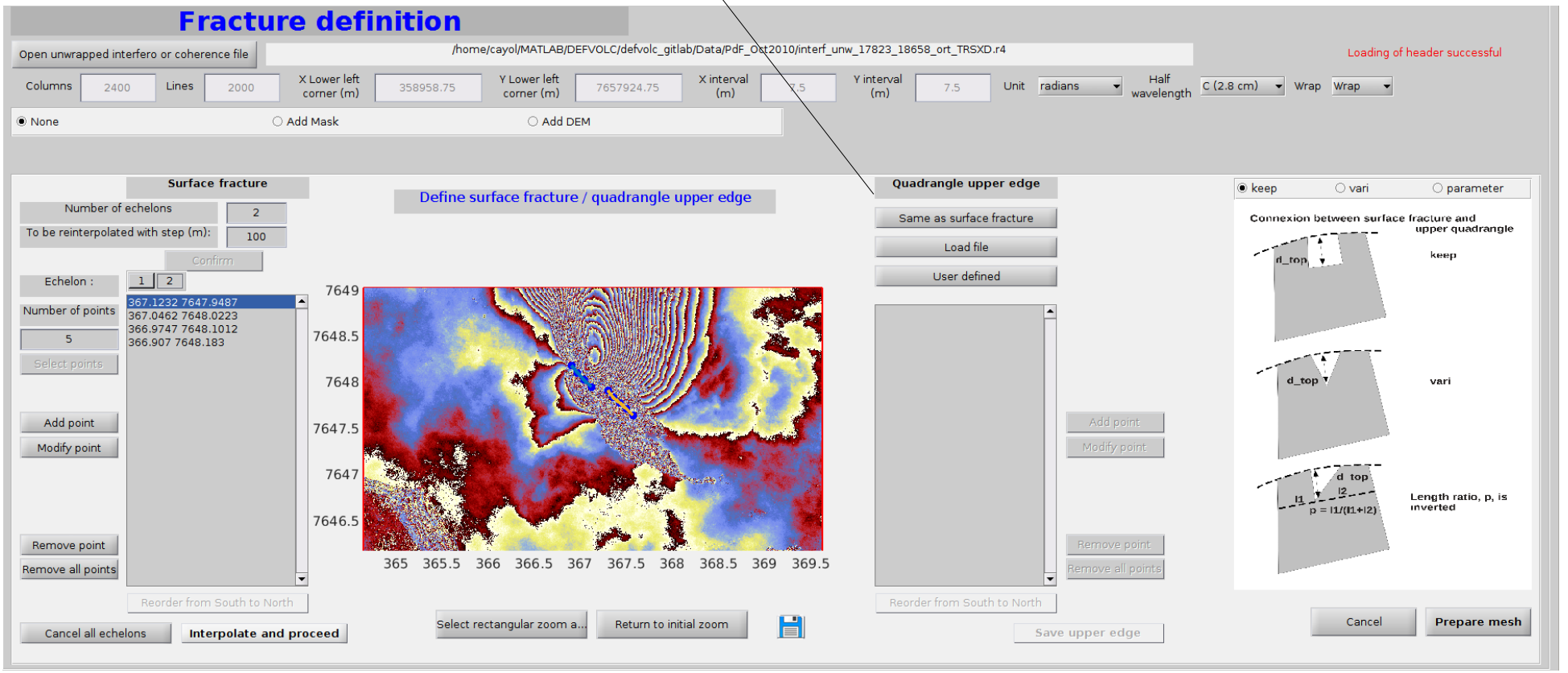
Topography Mesh: quadrangle upper edge

Same as surface fracture

Load file: loaded from a file having a list of East and North coordinates (in m)

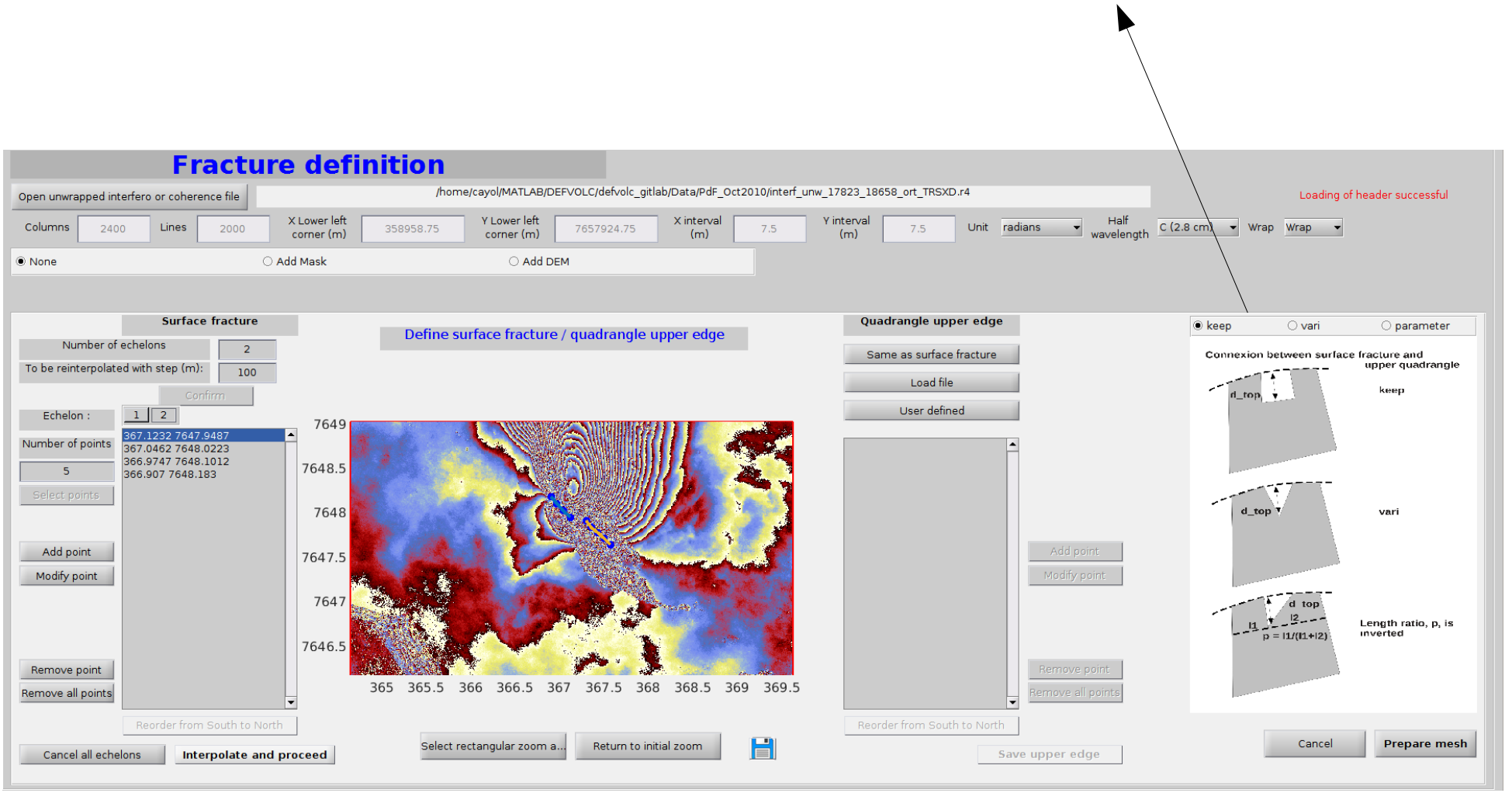
```
cayol@empmetlmv004:~/MATLAB/DEFVOLC/defvolc_gitlab/Inversions/test$ more fract_b.dat
367428.1          7647662.9
367369.1          7647746.6
367293.6          7647815.9
367219.2          7647886.3
367147.1          7647959.1
367077.3          7648034.2
367006          7648107.7
366918.1          7648160.4
```

User defined: define the fracture by clicking

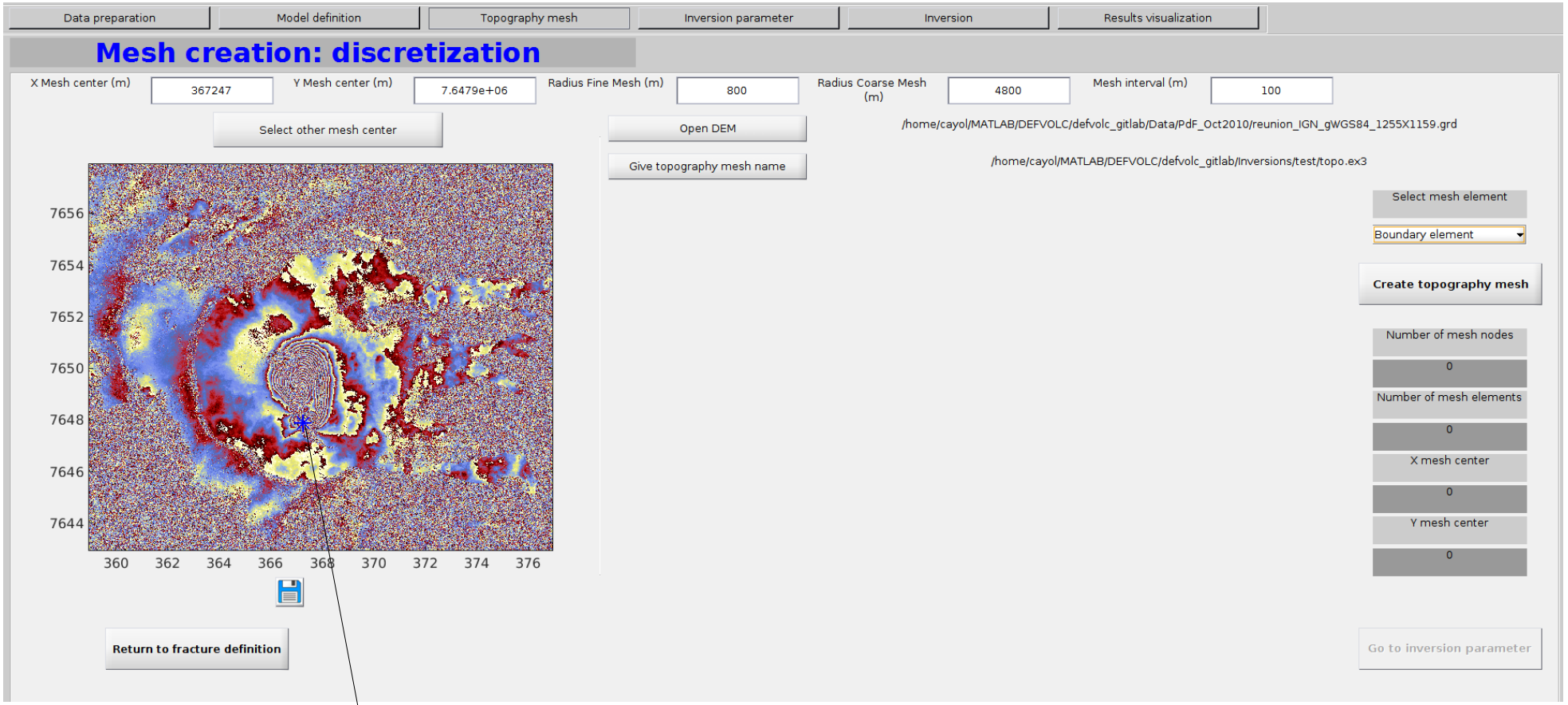


Topography Mesh: quadrangle upper edge

3 types of connections between the surface fracture and the quadrangle upper edge



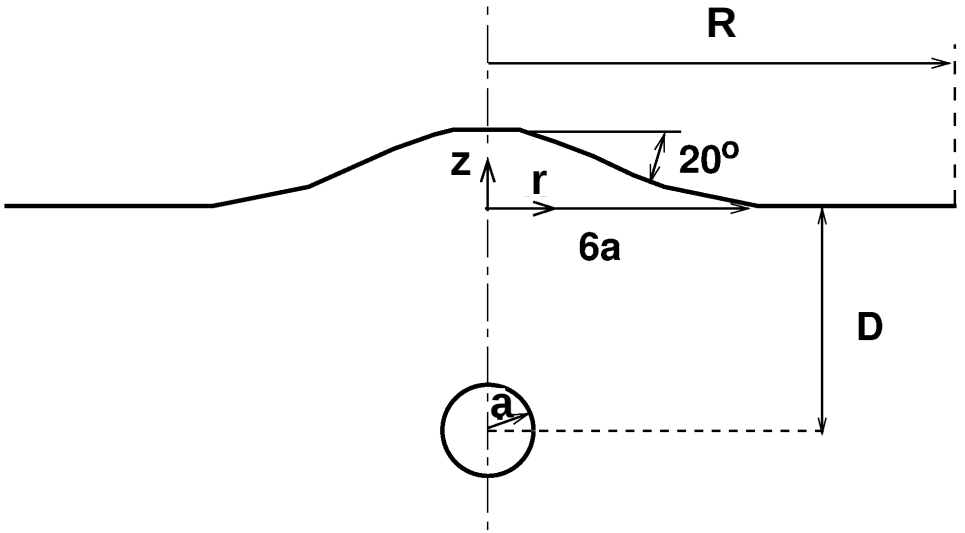
Topography Mesh: quadrangle upper edge

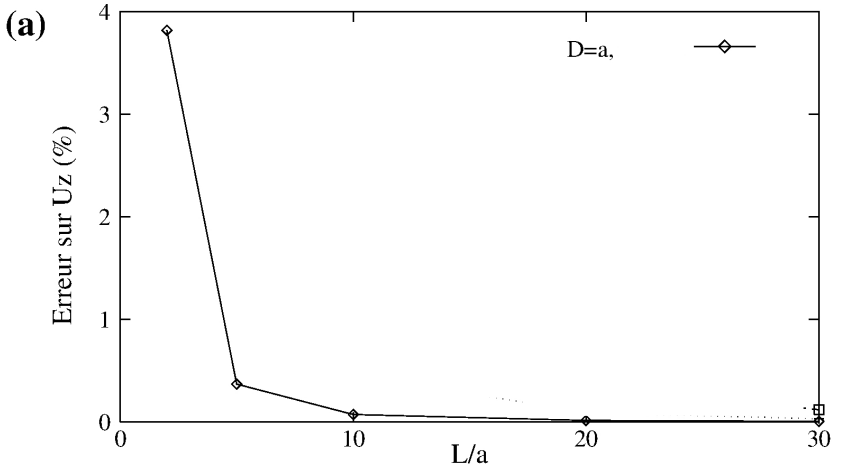


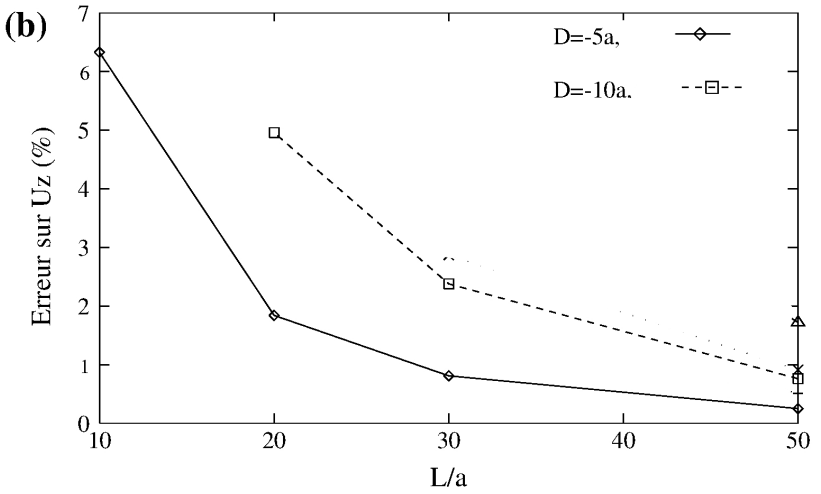
Default mesh center location is the centroid of eruptive fissures (fract_a.dat)
An other mesh center can be determined

Rule of thumb for edge effects

Rule of thumb: no edge effect for topography mesh radii > five times the source dimension
Practically :







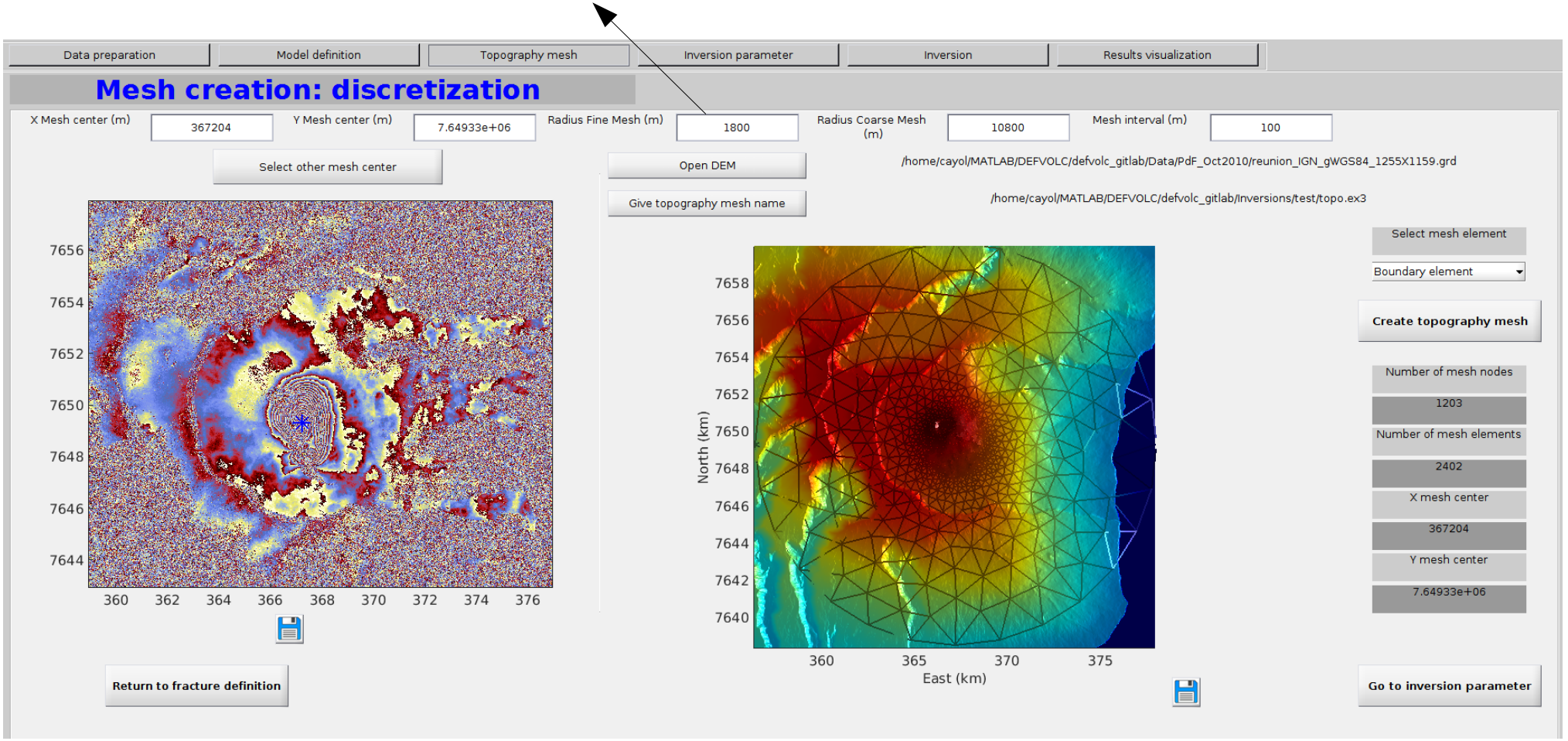
For sources at the ground surface (fissural dykes, this rule applies (Err Uz ~ 0.5%)

For sources at D>5a, it is better to have L>10a (Err Uz = 6% for D = 5a)

(Cayol, PhD, 1996)

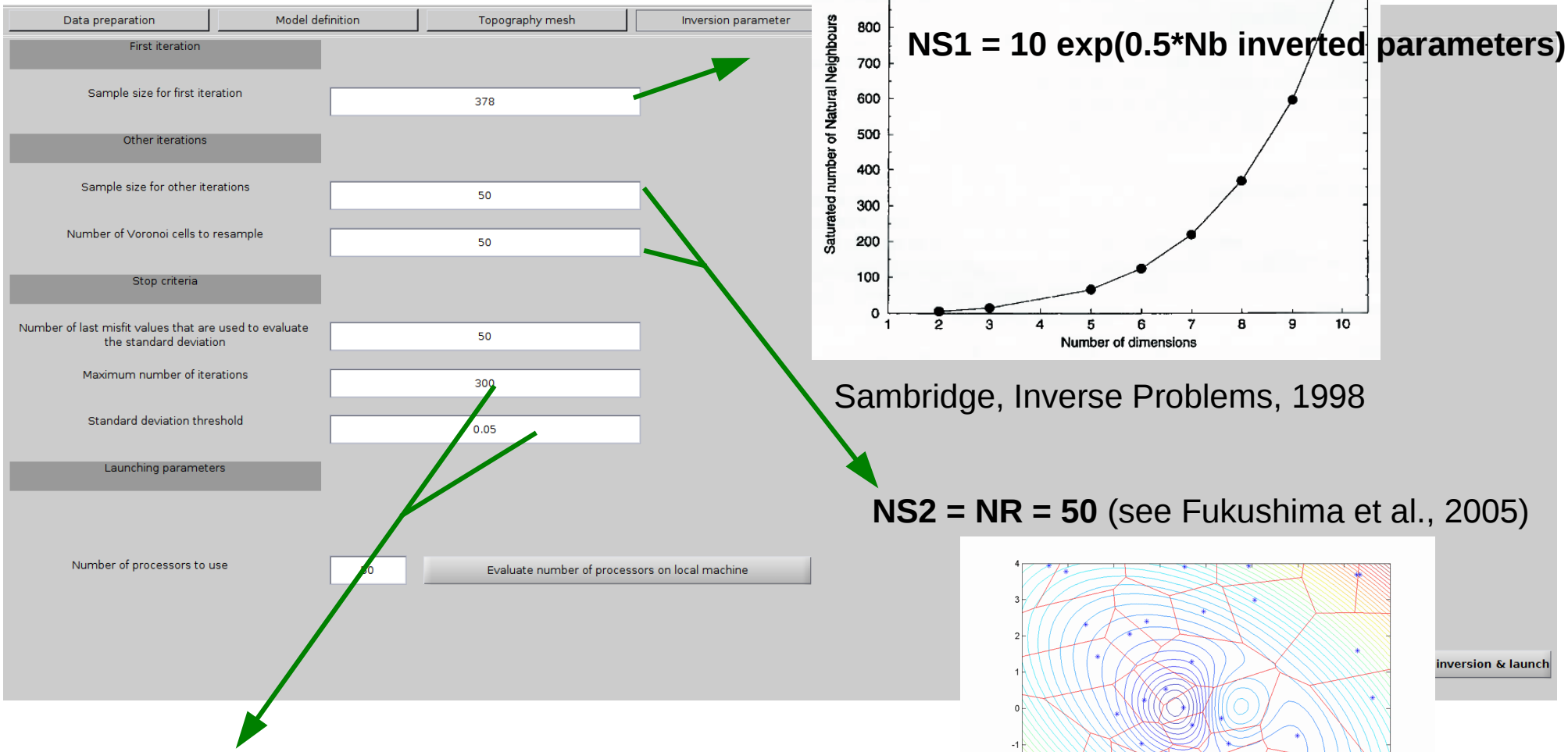
Topography Mesh: Mesh creation when eruptive fracture

Default **Radius fine mesh** is 2*distance between mesh center and most distant fissure point
Default **Radius coarse mesh** is 6*times the **Radius fine mesh**



Generates a topography mesh file with a default name /Inversions/RunDir/topo.ex3.
Name can be changed, but the extension has to be .ex3

Inversion parameters



NS1 = 10 exp(0.5*Nb inverted parameters)

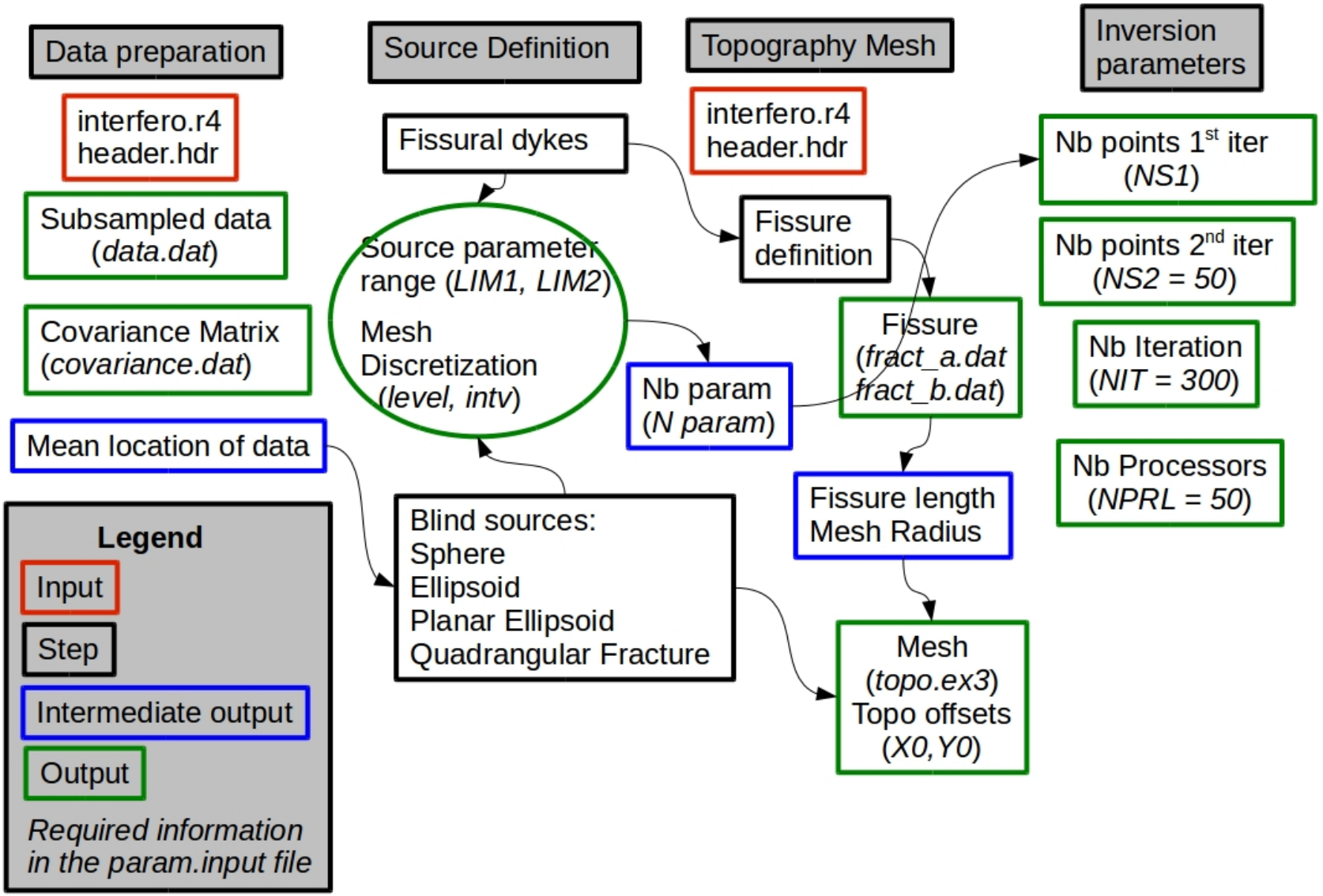
Sambridge, Inverse Problems, 1998

NS2 = NR = 50 (see Fukushima et al., 2005)

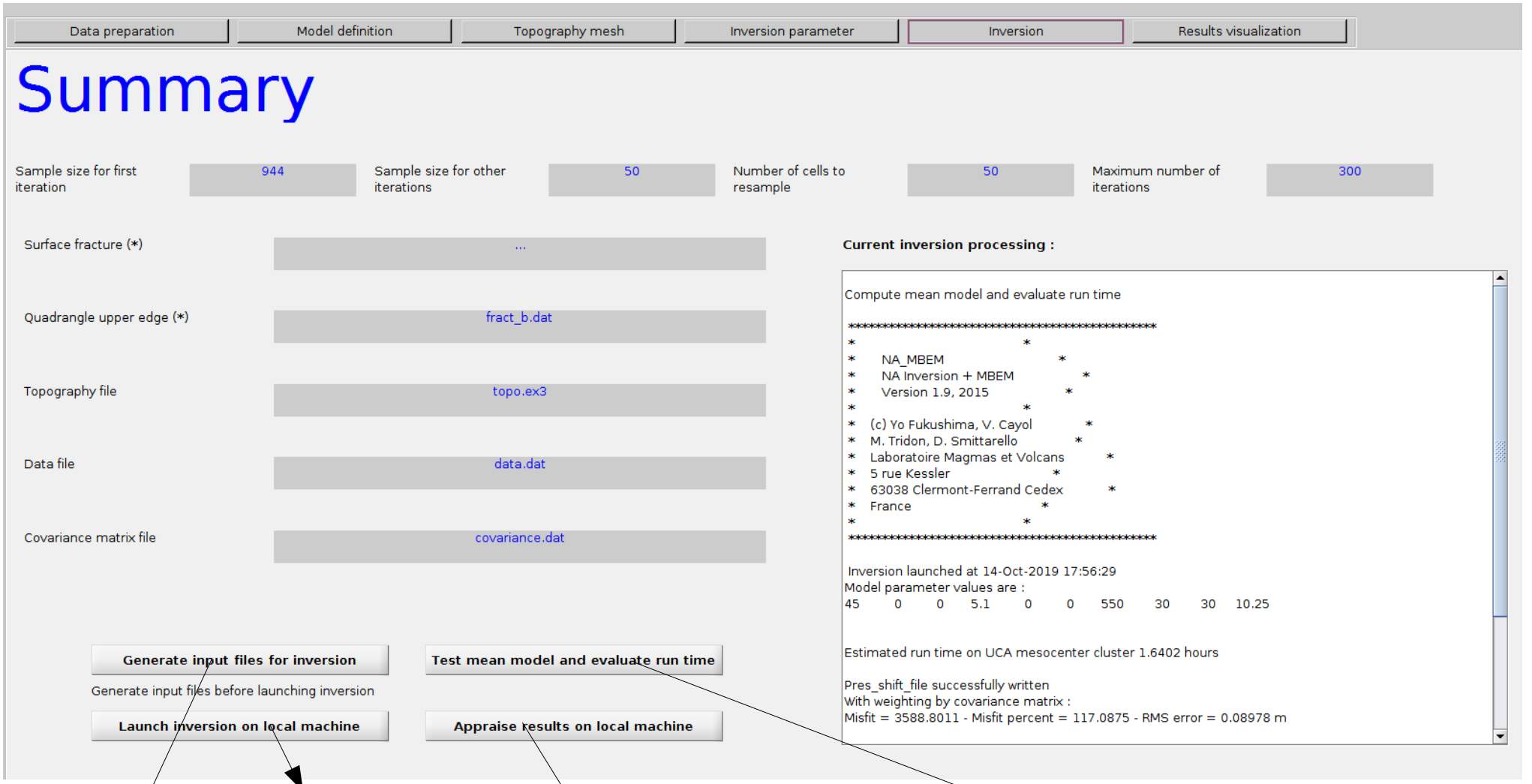
Iterations stop when one of the following criteria is reached :

- maximum number of iterations
- standard deviation of the misfit
- standard deviation on the parameters normalized by their search interval

Summary flow chart for the 4 steps of inversion preparation



Inversion and appraisal



Runs inversion corresponding to files in ~/Inversion/RunDir/
A binary file named **result.nares** is created, as well as an ascii file with boundary displacement of the best model (/inversion/RunDir/**best_mode.res**)

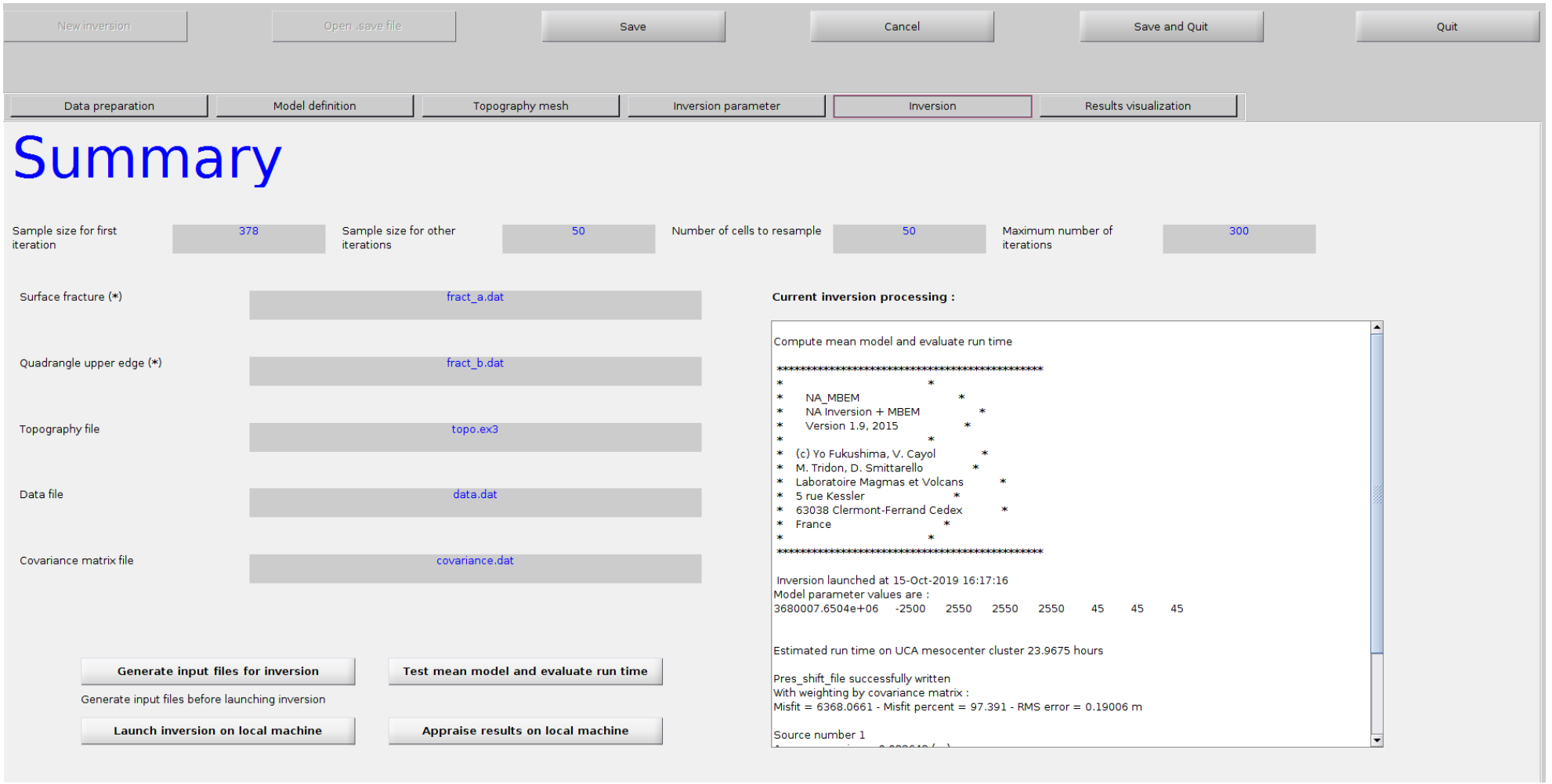
Generates ~/Inversion/RunDir/param.input file

- Runs computation of mean model
- Prints meshes, openings, shear displacement, displacement vectors, Model-Data-Residuals at subsampled points.
- Based on this forward model, evaluates inversion duration

After the inversion has been completed, runs the appraisal.
A file named **resamp_result.nares** is crated

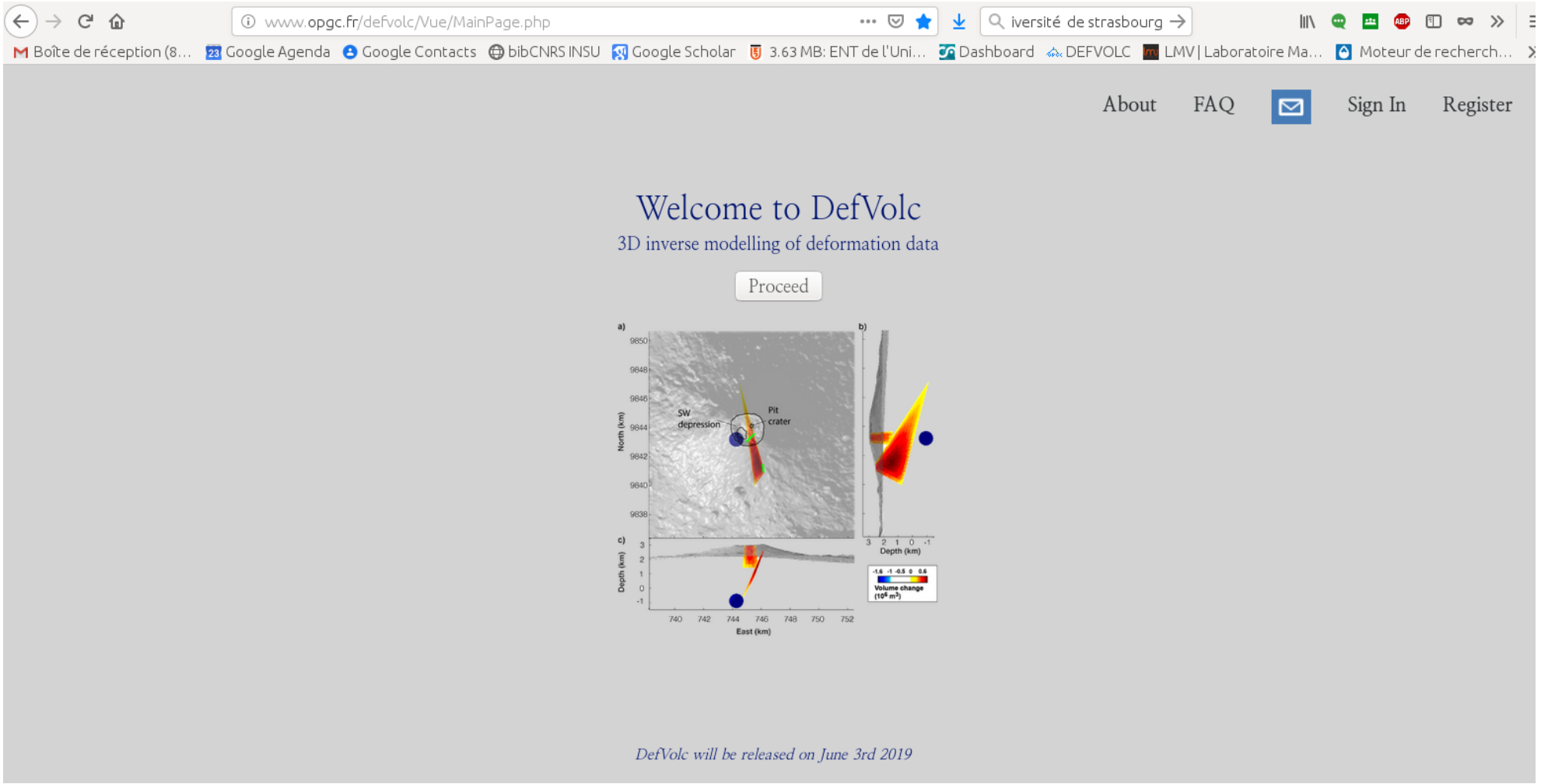
Saving the different steps

At any moment, the different steps can be saved in an ascii file. The default save file is names /Inversions/RunDir/date_time.save

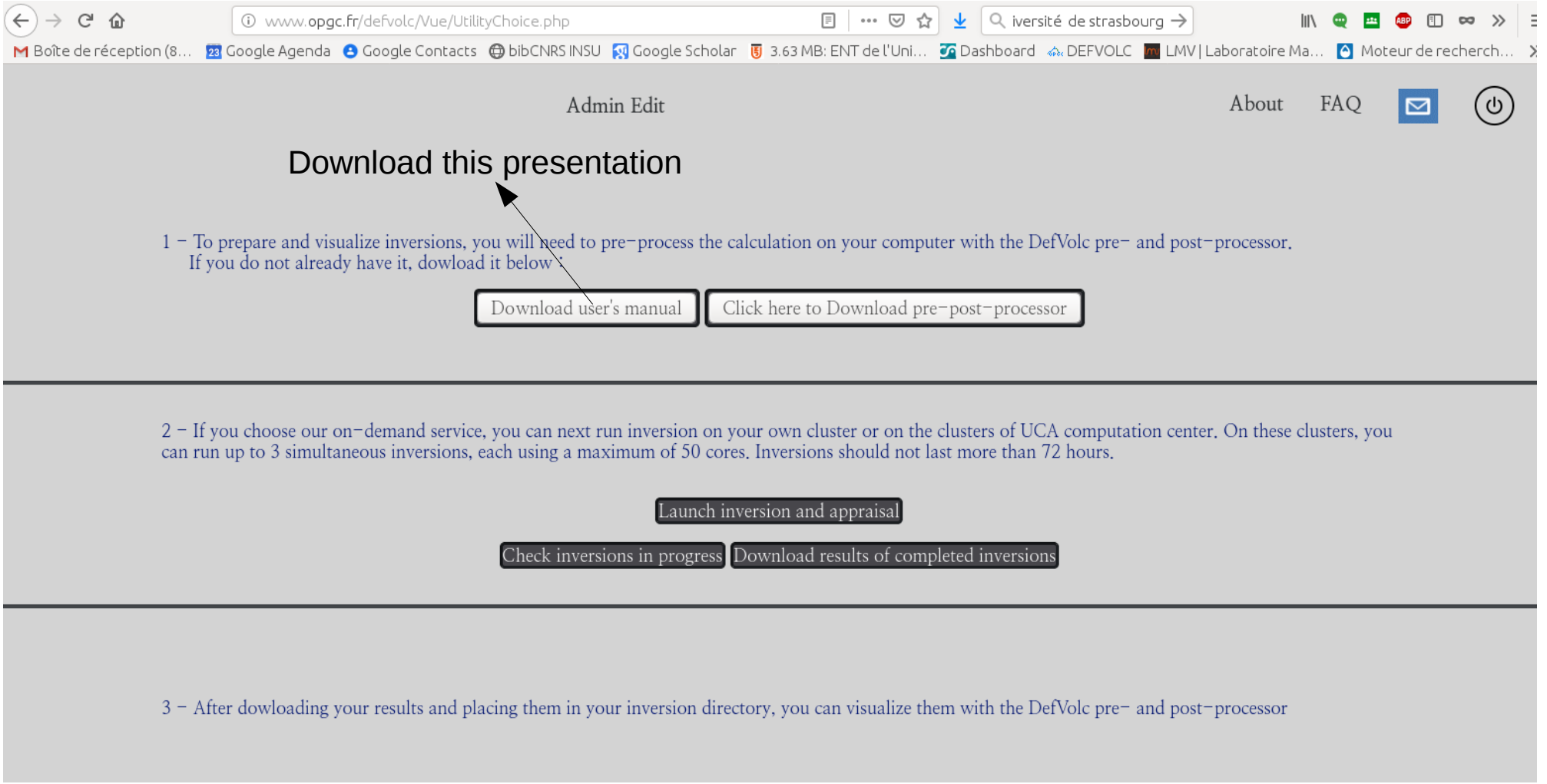


Running inversions and appraisal on the UCA clusters

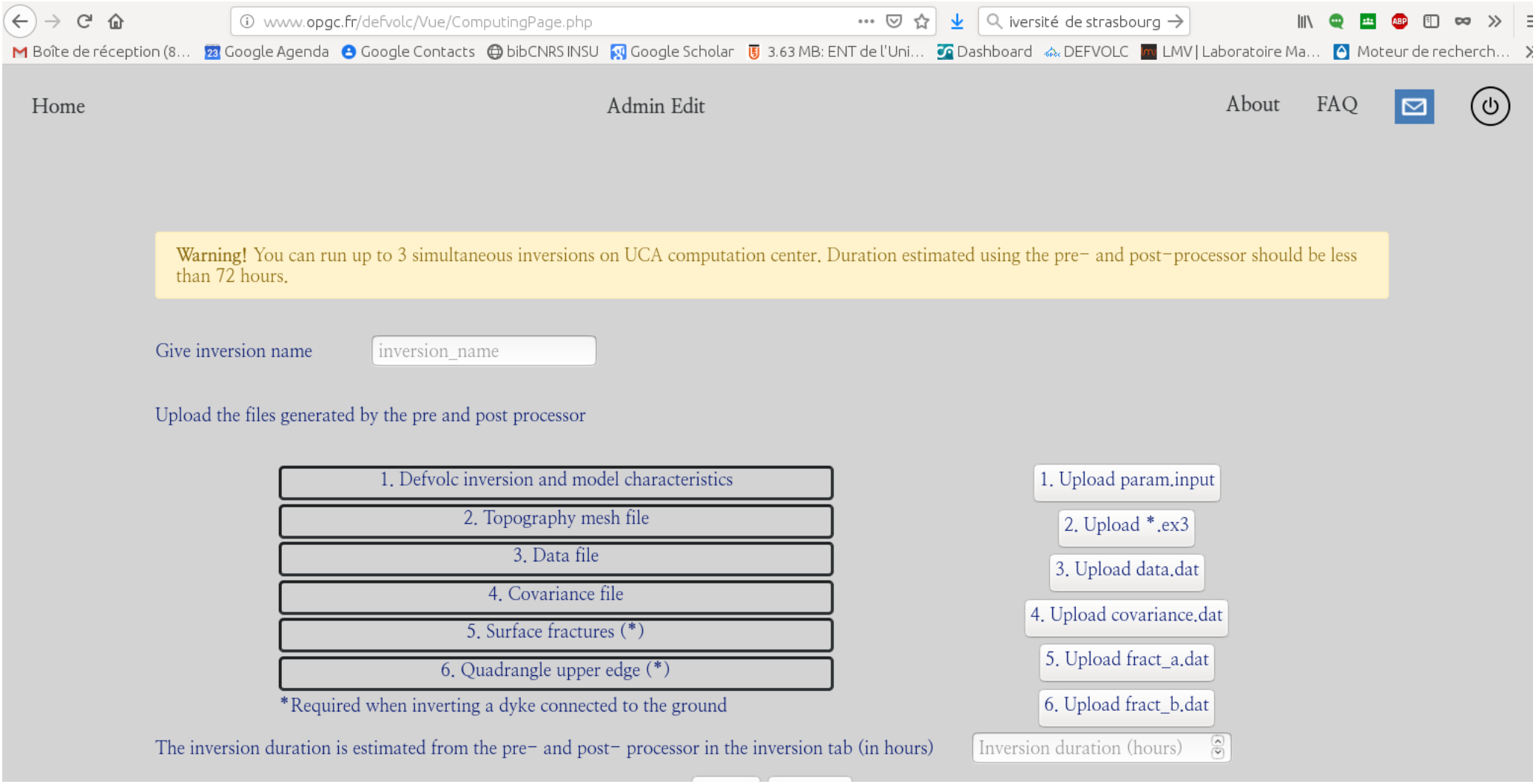
Register on defvolc at http://www.opgc.fr/defvolc/



Running inversions on the UCA clusters



Launch inversion and appraisal



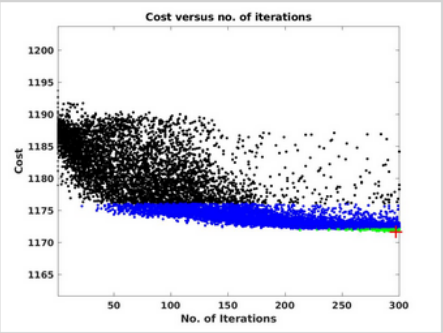
Check inversion in progress

www.opgc.fr/defvolc/Vue/PageResultInProgress.php

Home | Admin Edit | About | FAQ

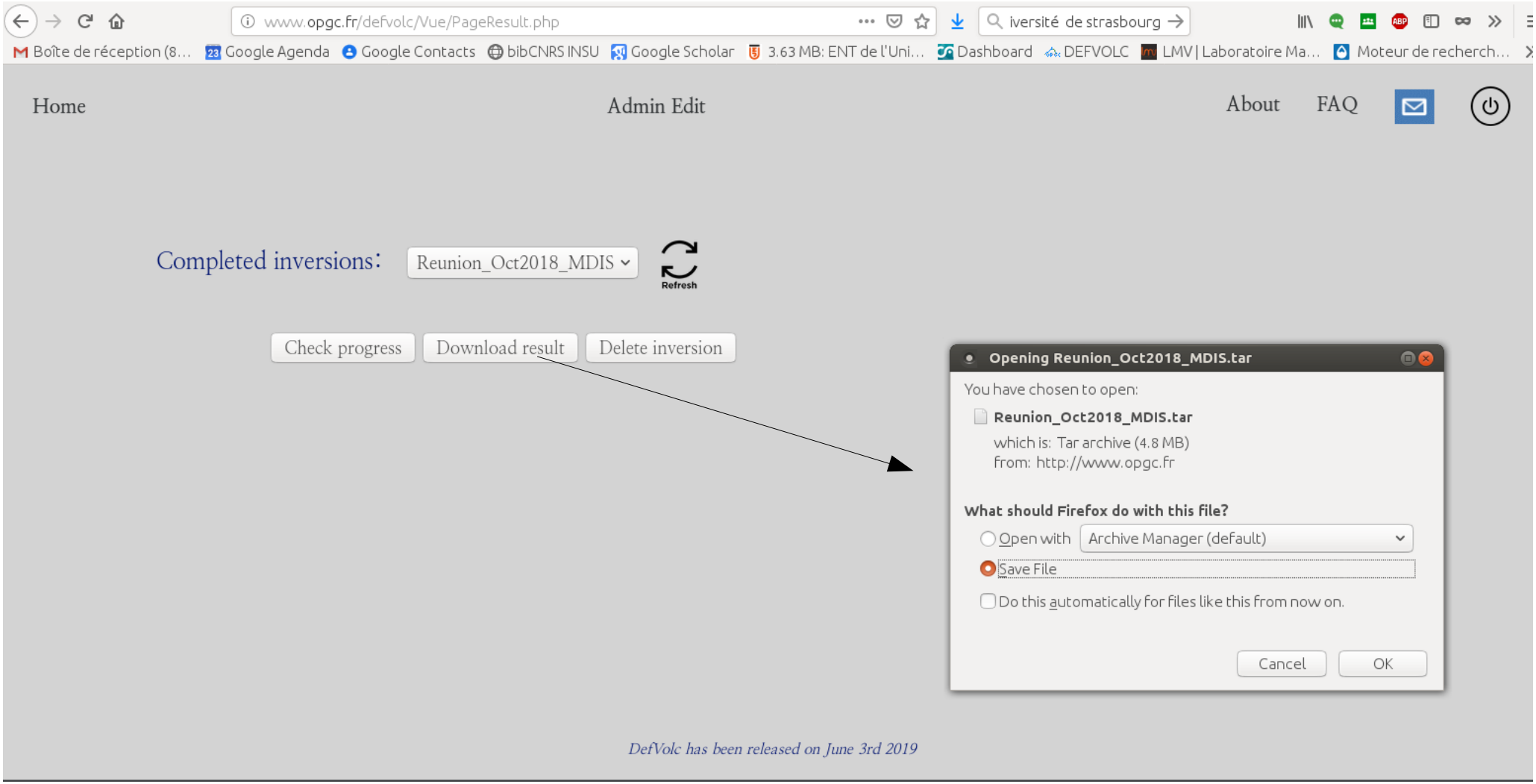
Inversions in progress: Test_MDIS_10Oct Inversion failed or interrupted.

Check progress | Continue | Download temporary result | Delete inversion



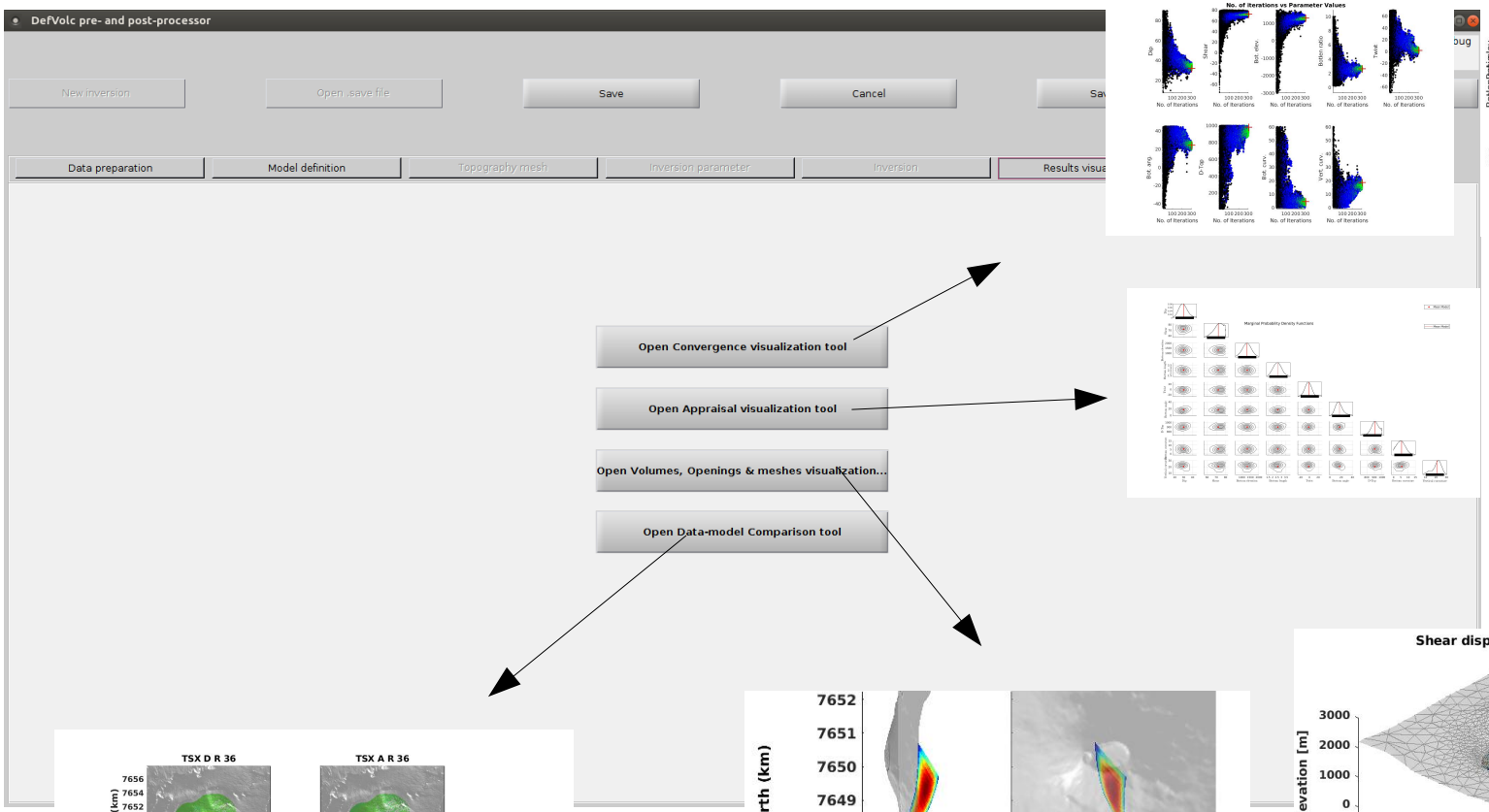
DefVolc has been released on June 3rd 2019

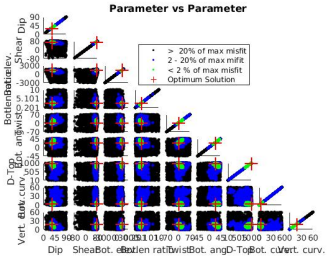
Download results of completed inversions



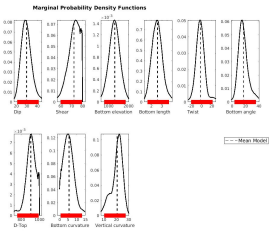
Result visualization

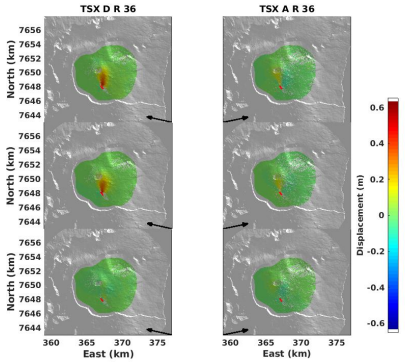
Independant from the other steps: can be used to visualize a previous inversion

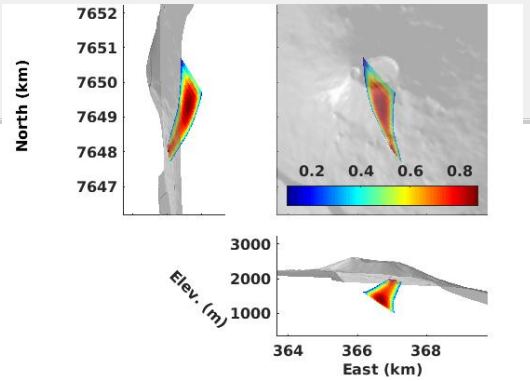


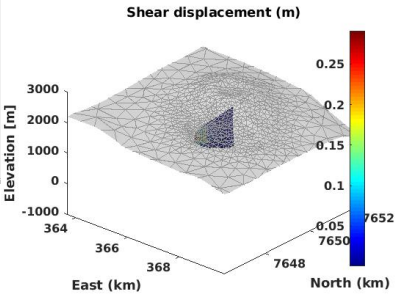


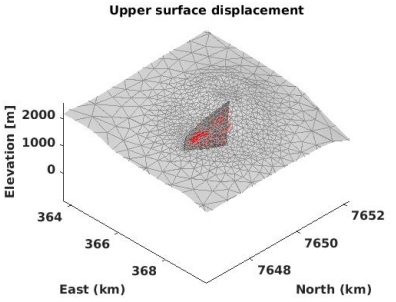
etc



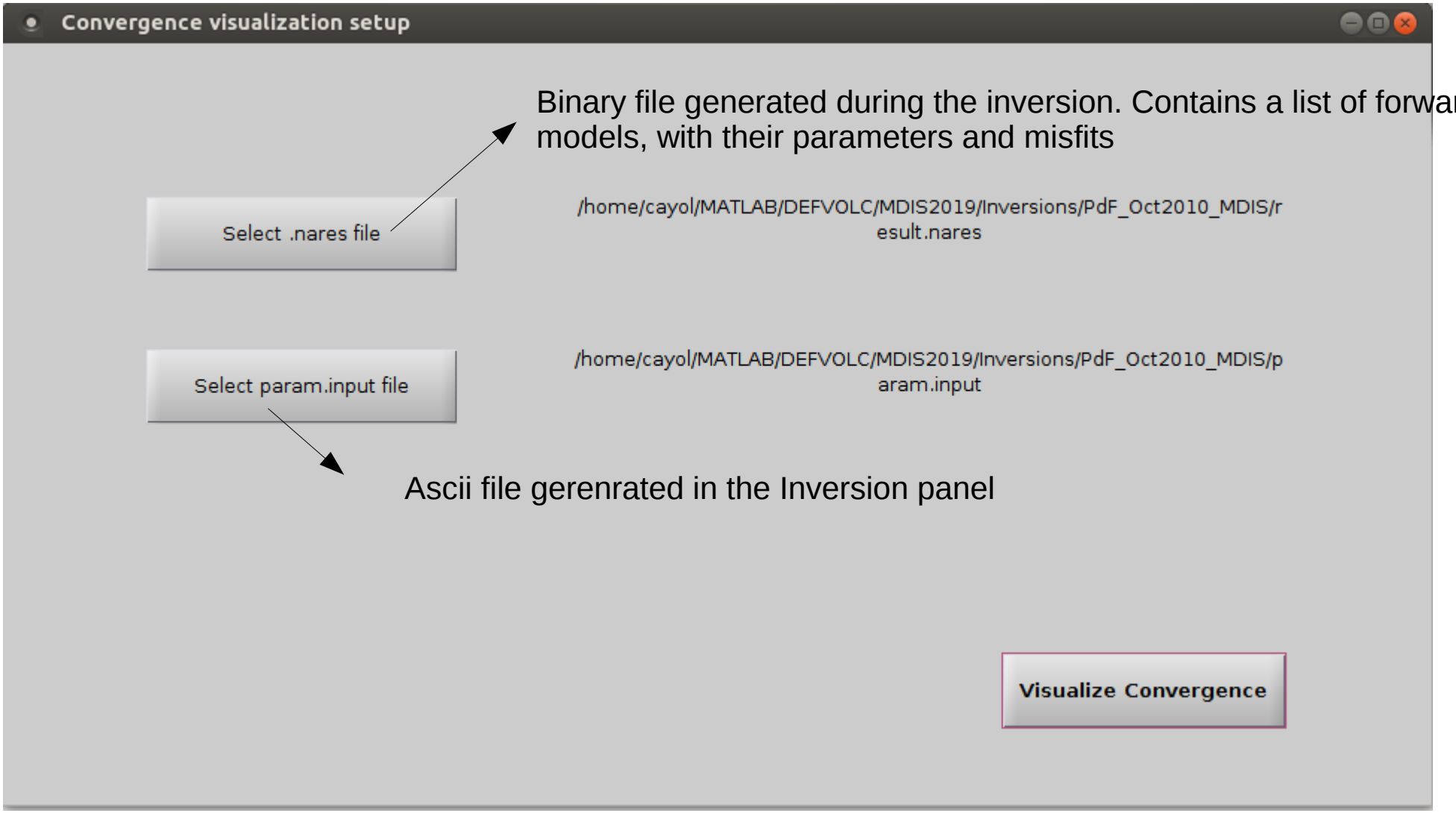




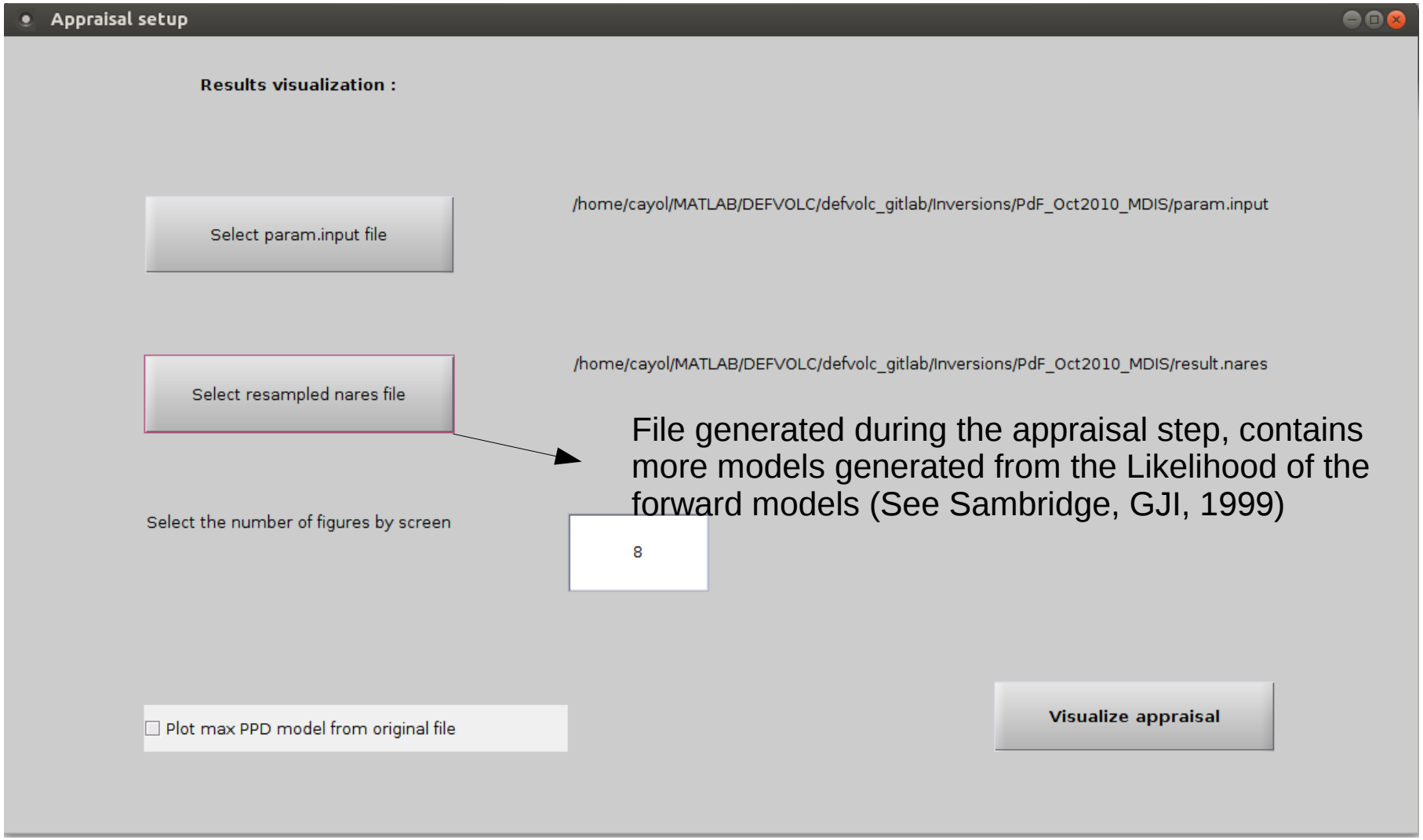




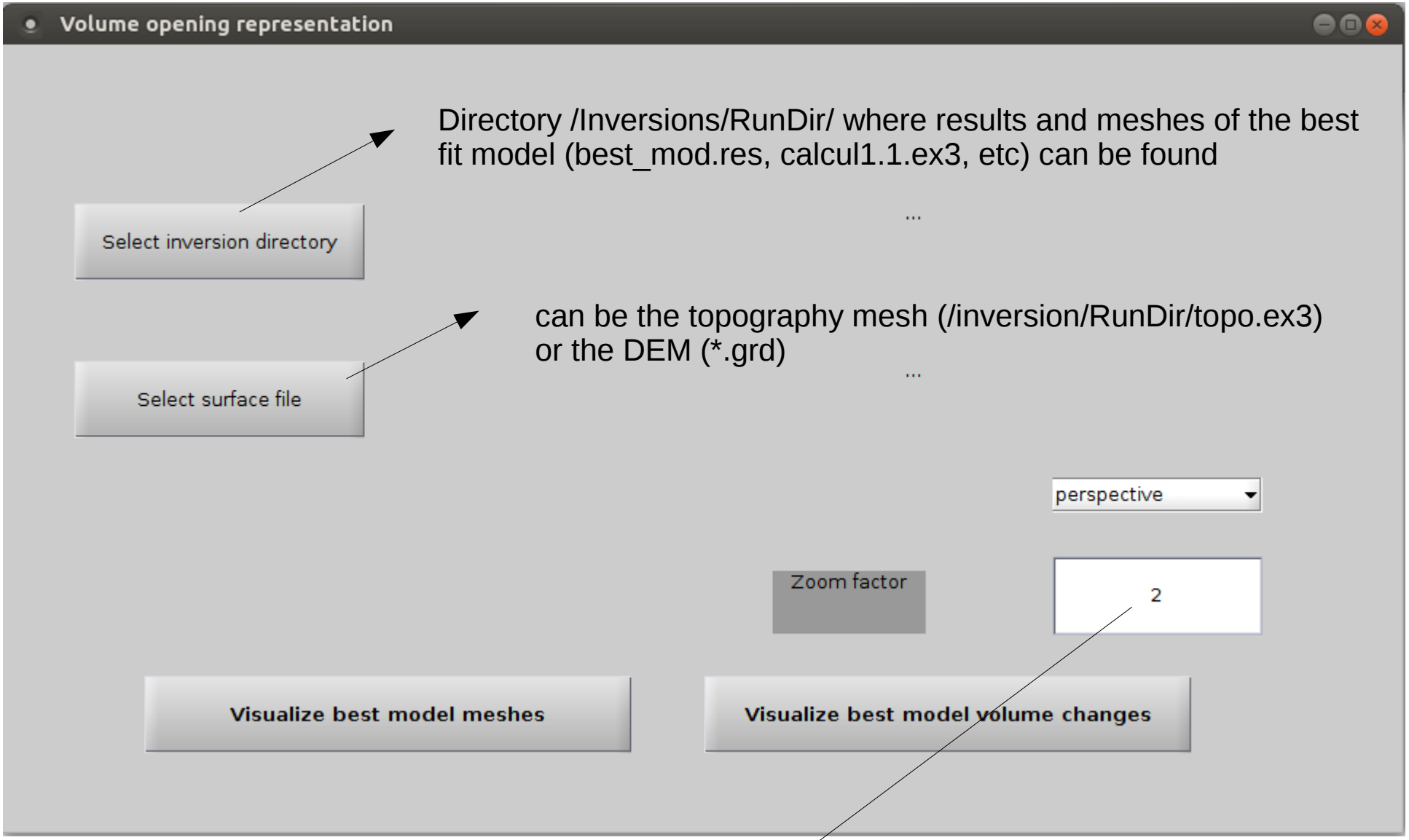
Result visualization: convergence visualization



Result visualization: Appraisal visualization



Result visualization: Volume opening representation



The higher this number the larger the ground surface extension

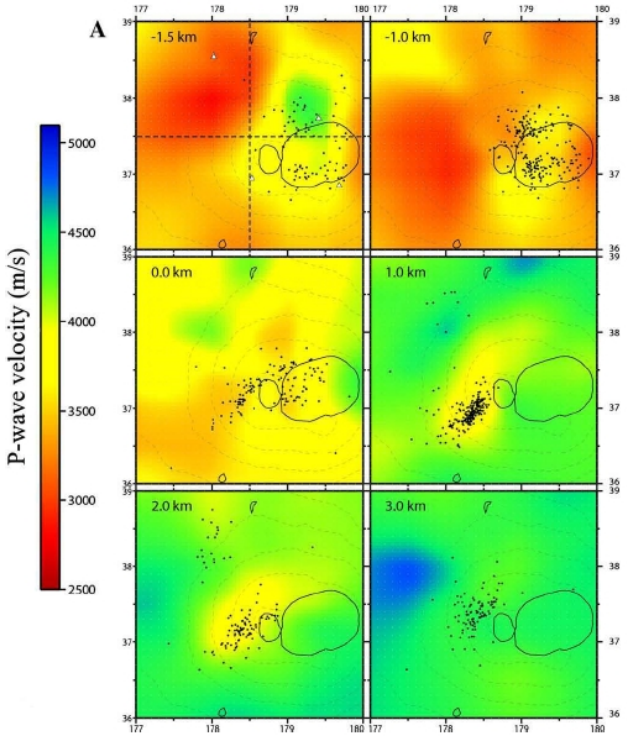
Result visualization: data – model comparison

Ascii file where the different steps have been saved (*.save). From this file the data characteristics are determine

Ascii file corresponding to best-fit model (Inversion/RunDir/best_model.res), containing boundary displacement

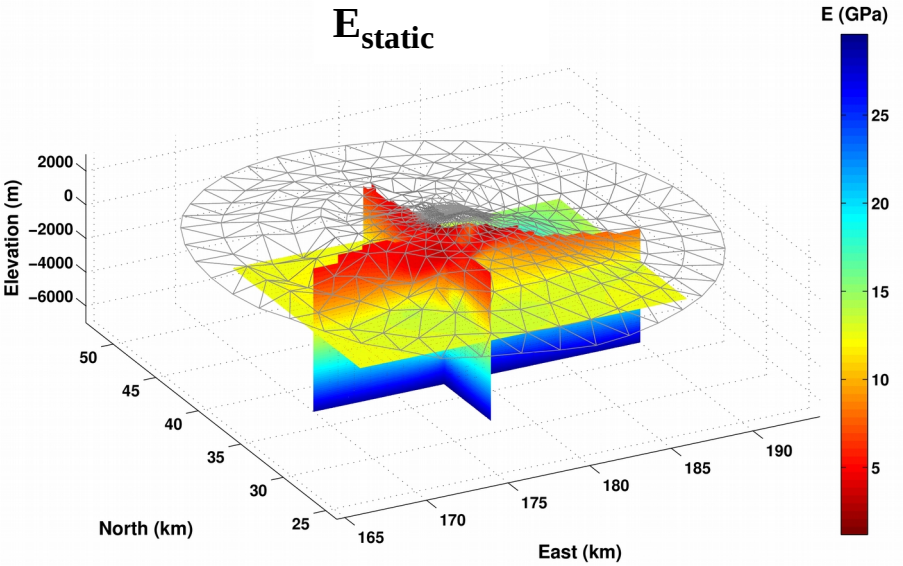
Fictitious domain for fractures in heterogeneous media
Application to Piton de la Fournaise volcano

P-wave velocity model (Prono et al., JVGR, 2009)

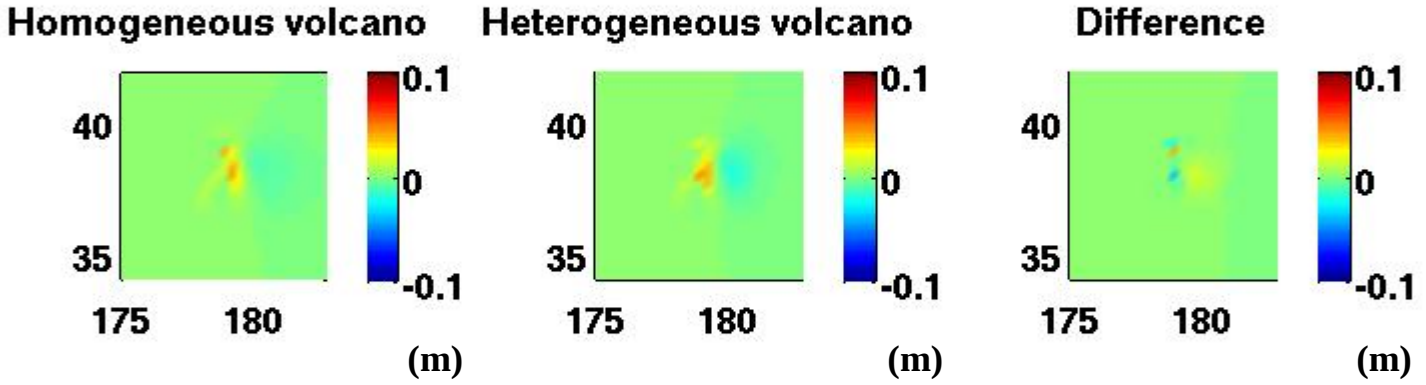


E_{dyn}, ρ , ν = f (V_p)
(Brocher, BSSA, 2005)

E_{static} = f (E_{dyn},P)
(Adelinet, GRL, 2010)



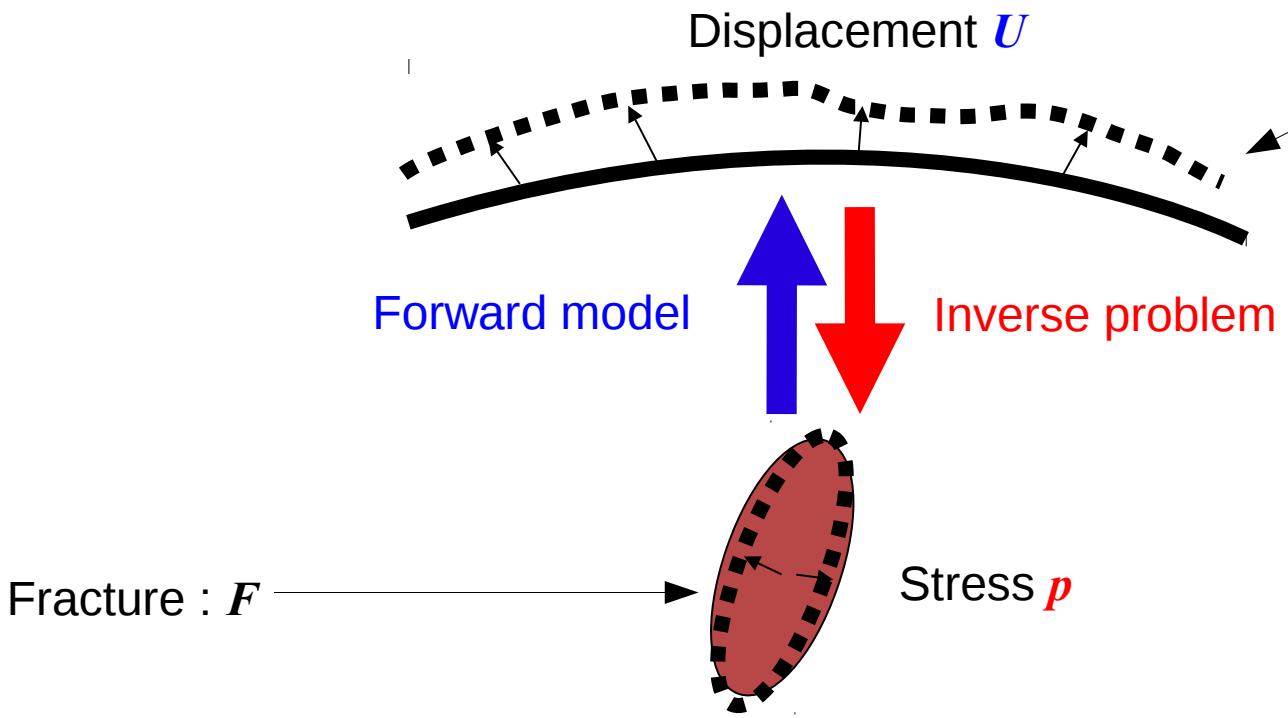
Comparaison des déplacements de la surface



52 % de différence

Determination of stress distributions on fractures

Bodart, Cayol, Dabaghi, and Koko, 25DD proceedings



Observed surface displaceme,

Minimisation of a misfit

$$J(p)=\int_G (U-U_{obs})^T C^{-1} (U-U_{obs})^T + \alpha \int_F p^2$$