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A novel trans-dimensional inversion algorithm to model deformation sources with unconstrained shape in finite element domains

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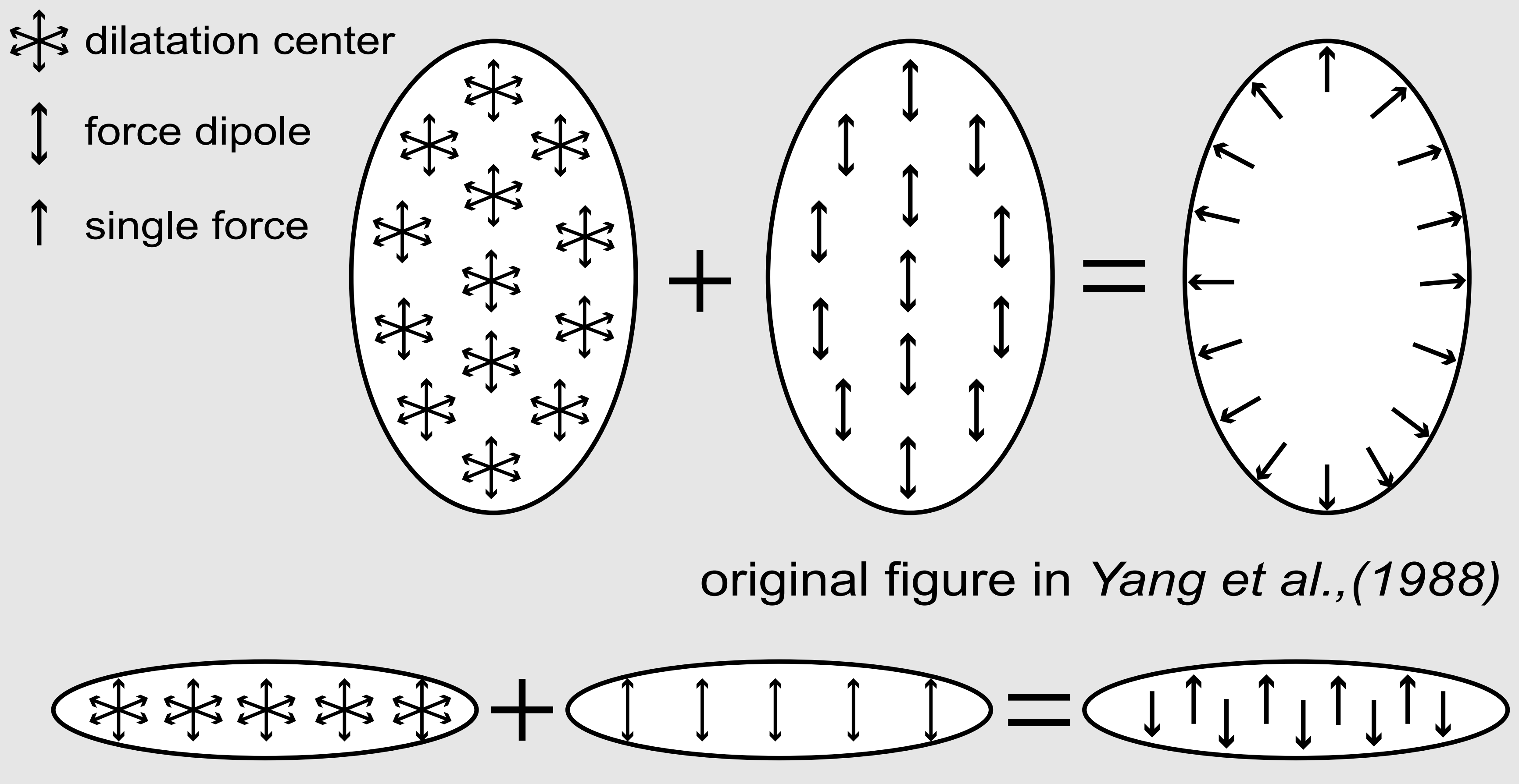
Design of a composite source method using FEM

- Deformation source modeling approaches typically rely on **a-priori shape assumptions**
- Attempts in literature simulating cavities as **aggregates** do not always fulfill continuum mechanics principles and are limited to elastic half-space, or use expensive re-meshing
- The stress field of a **uniform distribution of couples of forces** is equivalent to that caused by uniform normal stresses applied to the internal surface of a pressurized cavity (**Fig.1**)
- This concept is implemented in a **FEM mesh**, applying a **stress tensor** to the faces of cubic solid elements, creating an **elementary forward model** suitable to be assembled in a source of potentially any shape (**Fig.2**)
- We obtain a geometry-free source model, in a full FE space, allowing for **pre-computed solutions** on surface to be uniformly scaled with 6 scaling factors.

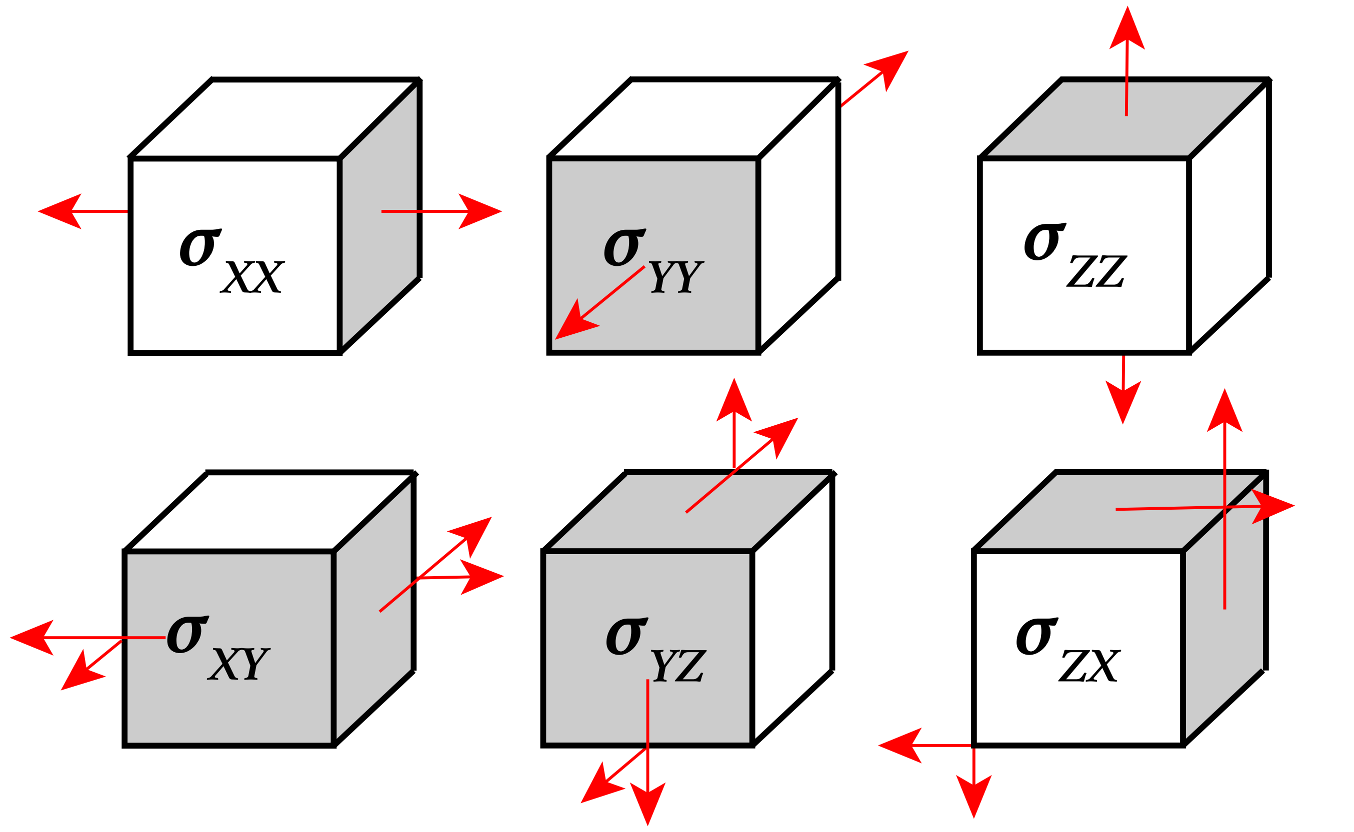
Fig. 1



original figure in *Yang et al.,(1988)*

original figure in *Segall.,(2010)*

Fig. 2 The elementary unit mechanism



Original figure in *Trasatti et al. (2008)*

$\sigma_{XX}, \sigma_{YY}, \sigma_{ZZ}, \sigma_{XY}, \sigma_{YZ}, \sigma_{ZX}$ *Unitary forces of 1 MPa are applied to the faces of each element*

$u_{XX}, u_{YY}, u_{ZZ}, u_{XY}, u_{YZ}, u_{ZX}$ *Computation of corresponding displacements on surface*

$U_{XX}, U_{YY}, U_{ZZ}, U_{XY}, U_{YZ}, U_{ZX}$ *Sum of contributions from each element in the assembly*

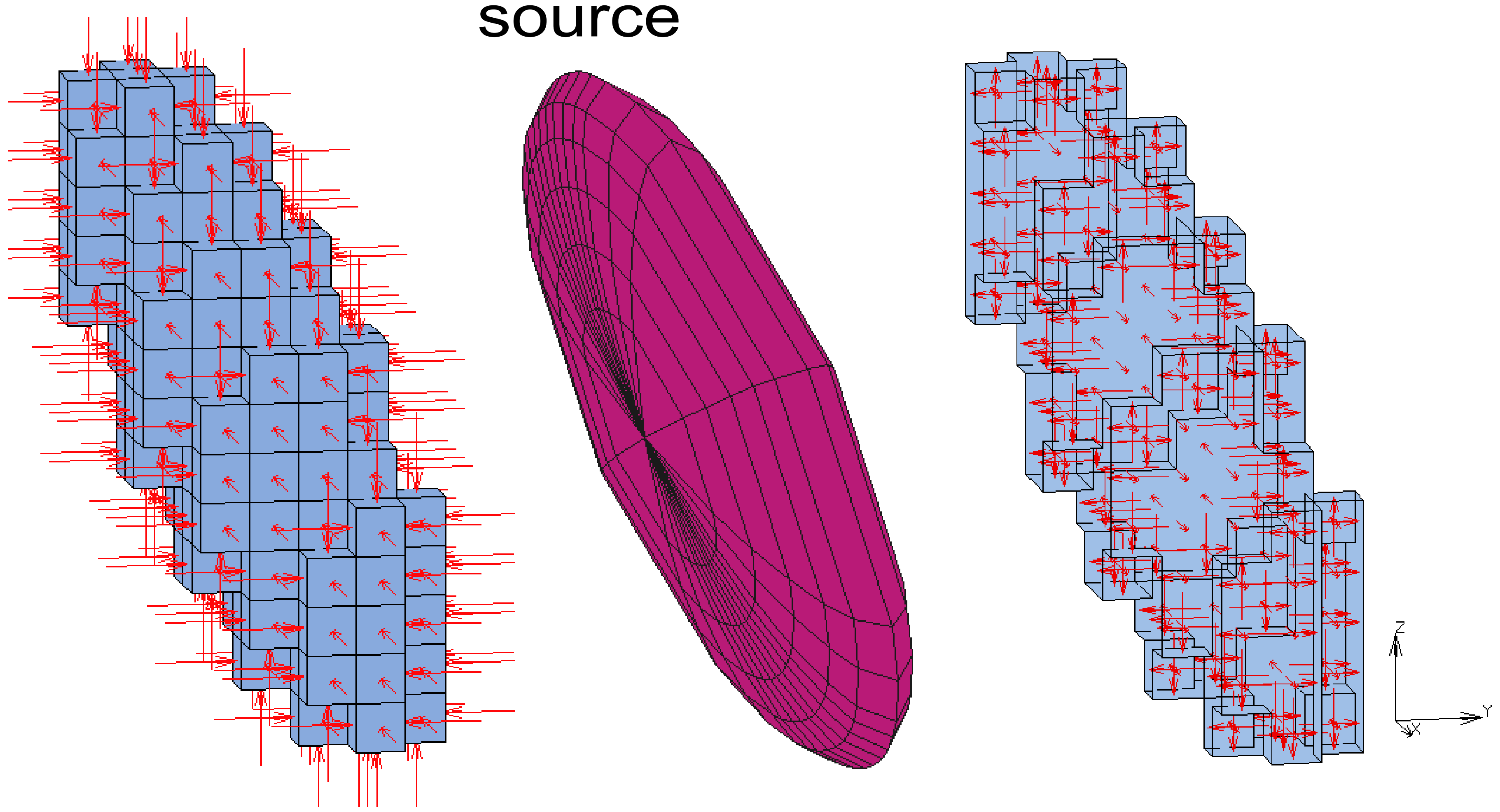
$s_{XX}, s_{YY}, s_{ZZ}, s_{XY}, s_{YZ}, s_{ZX}$ *Estimation of scale parameters to be uniformly applied to U_{ij}*

$$U_{tot}(x,y,z) = s_{XX}U_{XX} + s_{YY}U_{YY} + s_{ZZ}U_{ZZ} + s_{XY}U_{XY} + s_{YZ}U_{YZ} + s_{ZX}U_{ZX}$$

Synthetic testing and validation

Fig. 3

FEM assembly   analytical source   FEM cavity



- Synthetic tests prove the **equivalence with the deformation fields** produced by corresponding **cavities**, with uniform pressure applied to the boundaries Fig.3
- Sources with oblique symmetry axes (dip ≠ 90°, strike ≠ 0°) require also the shear components i.e. all 6 scaling factors (see example below)

FEM assembly vs analytical source

a = 2951 m (volume eq)   b/a = 0.333

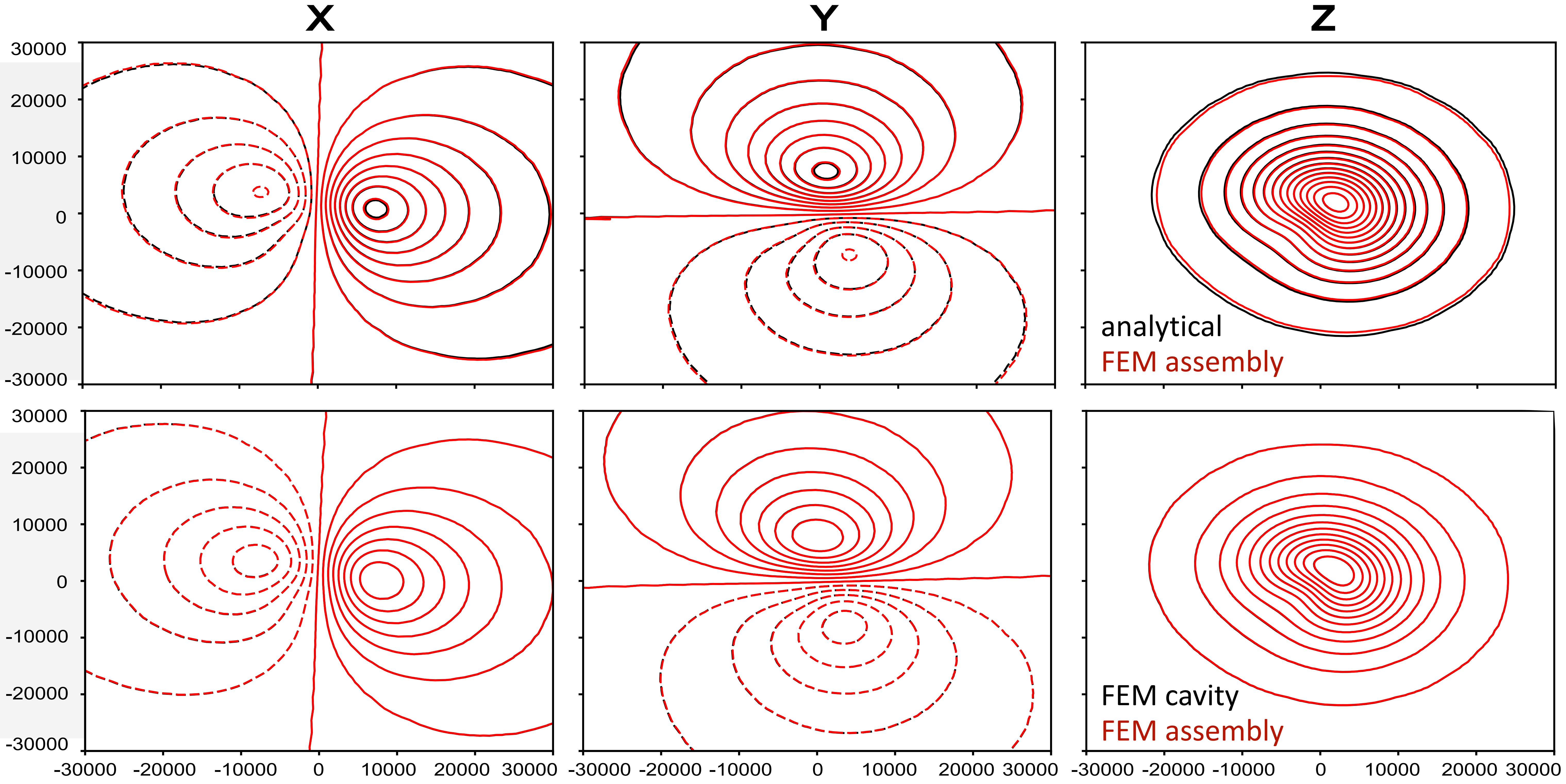
dip = 60°   Strike = 45°

Sxx = 2.654	Syy = 2.654	Szz = 2.155
Sxy = -0.095	Syz = 0.236	Szx = 0.237

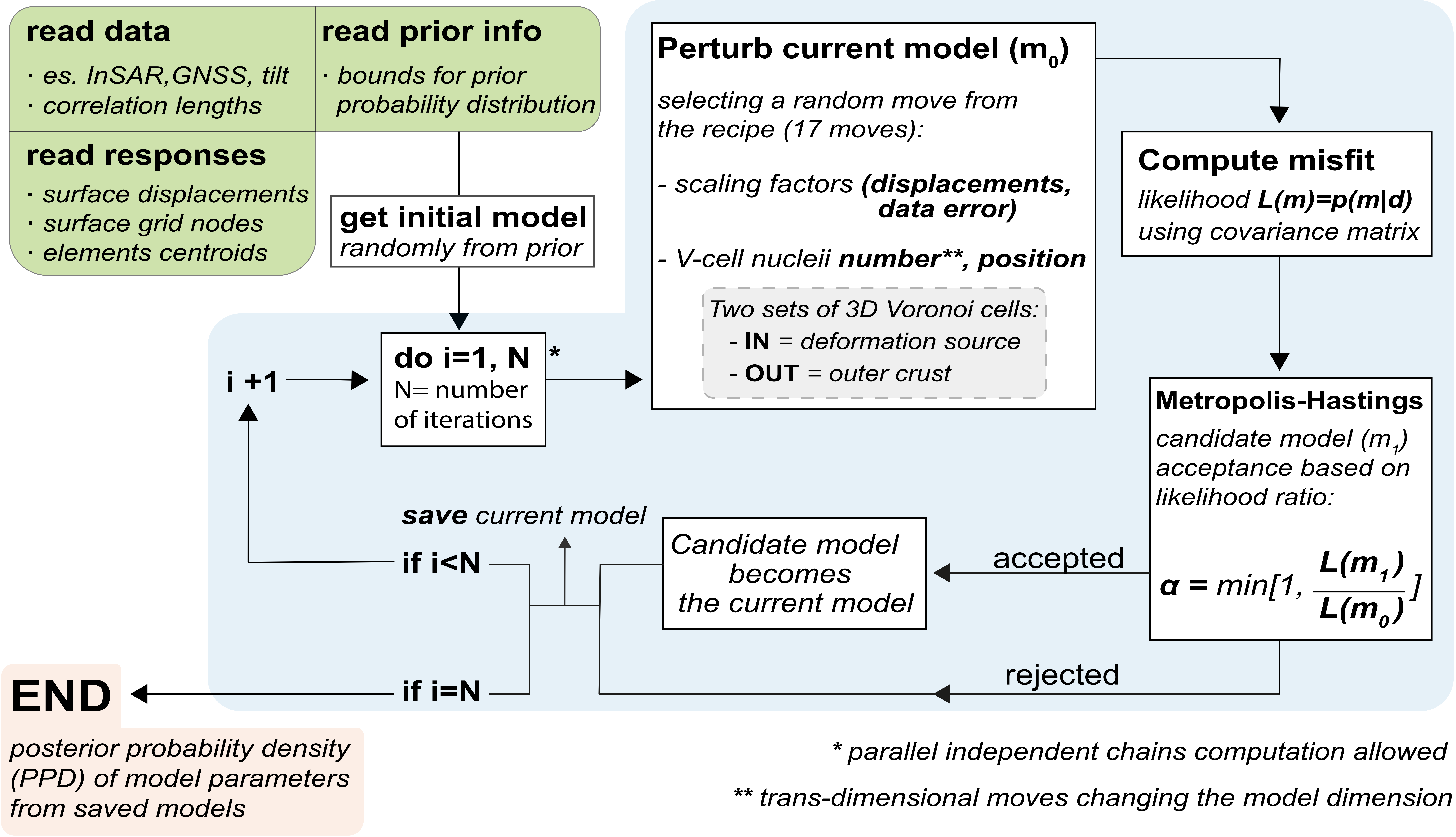
FEM assembly vs FEM cavity*

* pressure applied to cavity boundaries

Sxx = 2.755	Syy = 2.755	Szz = 2.172
Sxy = -0.153	Syz = -0.179	Szx = -0.179



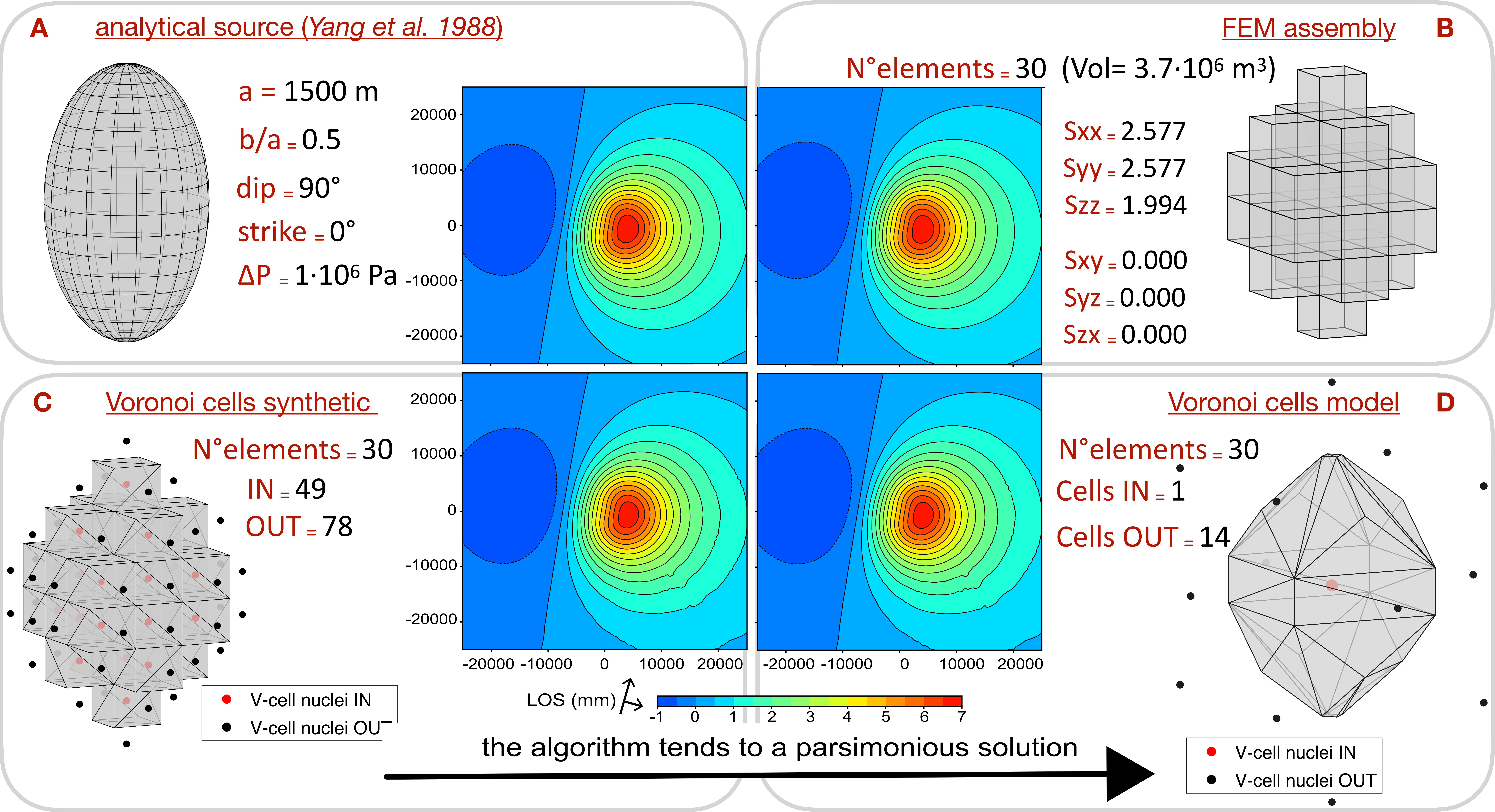
Inversion algorithm flowchart



* parallel independent chains computation allowed

** trans-dimensional moves changing the model dimension

Comparison of source configurations



Conclusions and final remarks

- Modeling **free of a-priori geometry assumptions**, source shape defined by the data
- Advantages of **FEM domain potential complexities** (topography, 3D fully heterogeneous)
- Based on **pre-computed** set of solutions to be scaled, improving **cost-efficiency**
- Supported by a sophisticated bayesian trans-dimensional inversion algorithm
- **Rigorous** in terms of continuum mechanics
- Work in progress: Application to Long Valley Caldera, CA
- Promising approach in the view of more realistic source representations (irregular shapes)

Essential References:

Segall, P. (2010). Earthquake and volcano deformation. In Earthquake and Volcano Deformation. Princeton University Press.

Trasatti, E., Giunchi, C., & Agostinetti, N. P. (2008). Numerical inversion of deformation caused by pressure sources: application to Mount Etna (Italy). Geophysical Journal International, 172(2), 873-884.

Yang, X. M., Davis, P. M., & Dieterich, J. H. (1988). Deformation from inflation of a dipping finite prolate spheroid in an elastic half-space as a model for volcanic stressing. Journal of Geophysical Research: Solid Earth, 93(B5), 4249-4257.