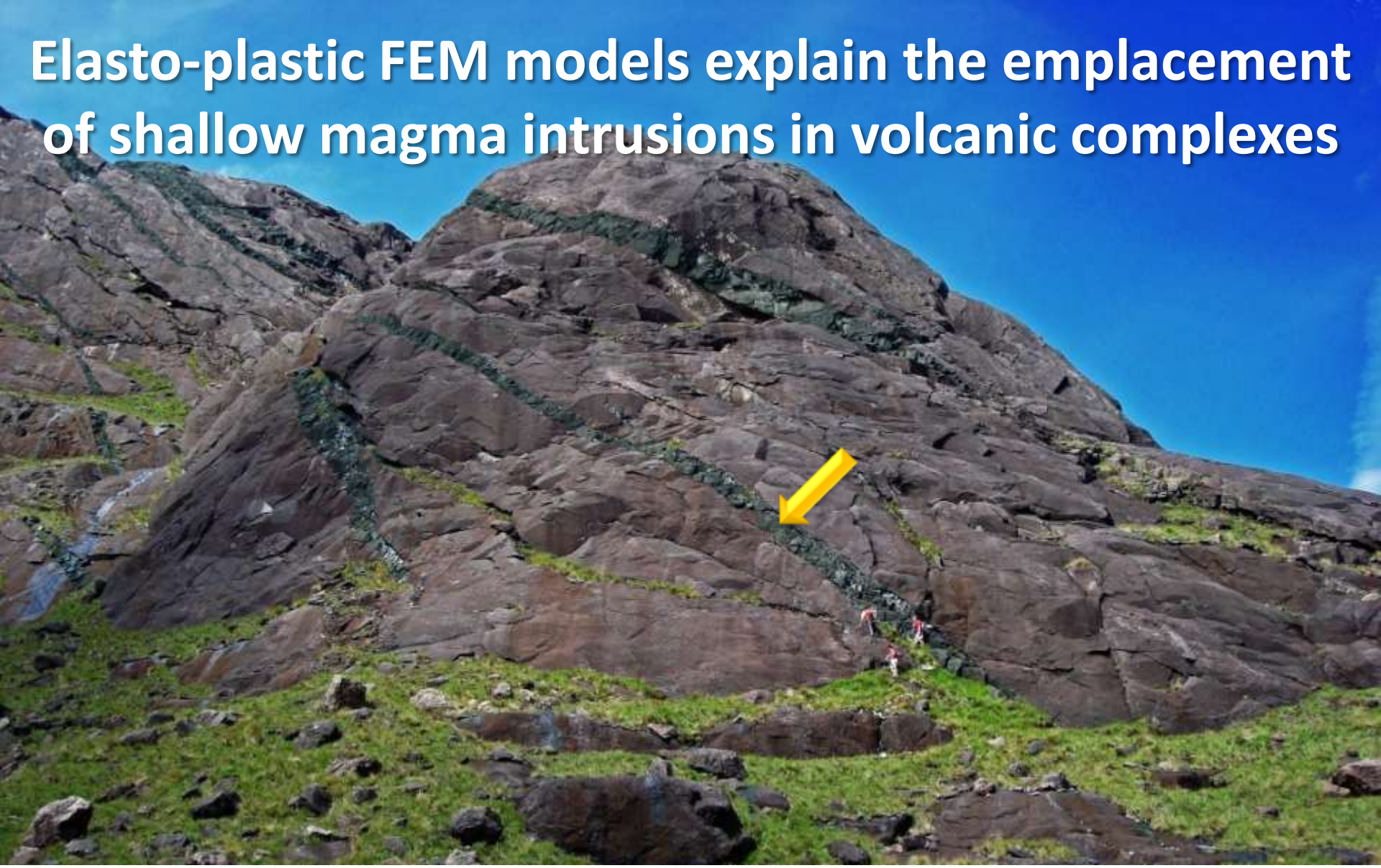
Elasto-plastic FEM models explain the emplacement of shallow magma intrusions in volcanic complexes

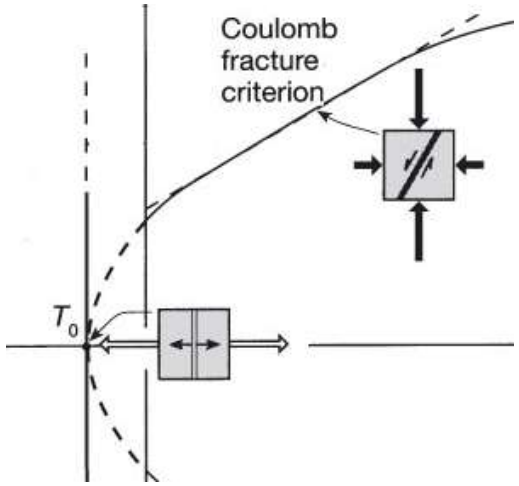


Andrea Bistacchi

University of Milano Bicocca - Structural Geology Lab

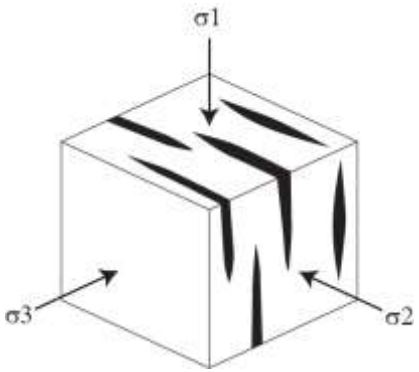
Excerpt from the Proceedings of the 2012 COMSOL Conference in Milan

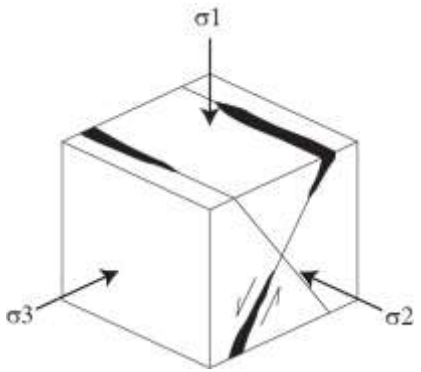
For non-geologists → magma intrusions are proxies for stress field

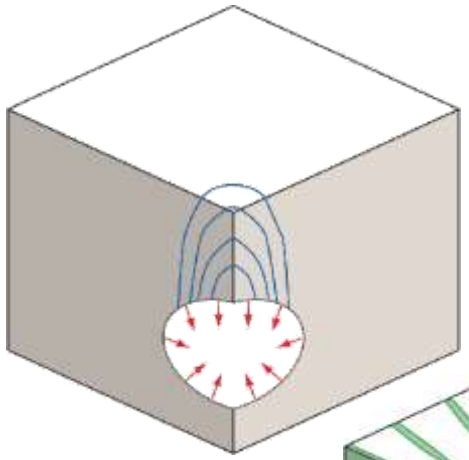


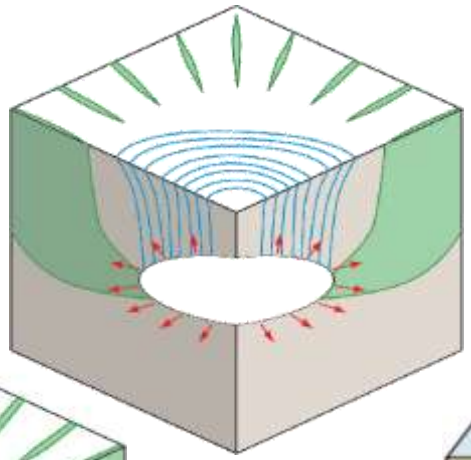
compressive stresses > 0

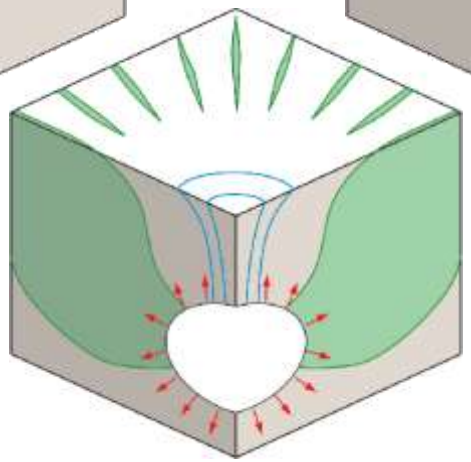
$\sigma_3 < \sigma_2 < \sigma_1$

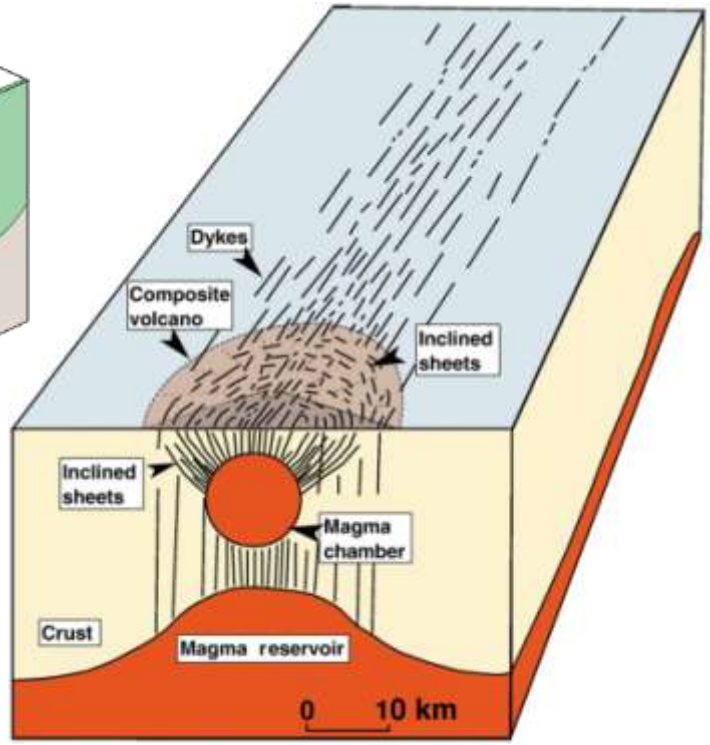








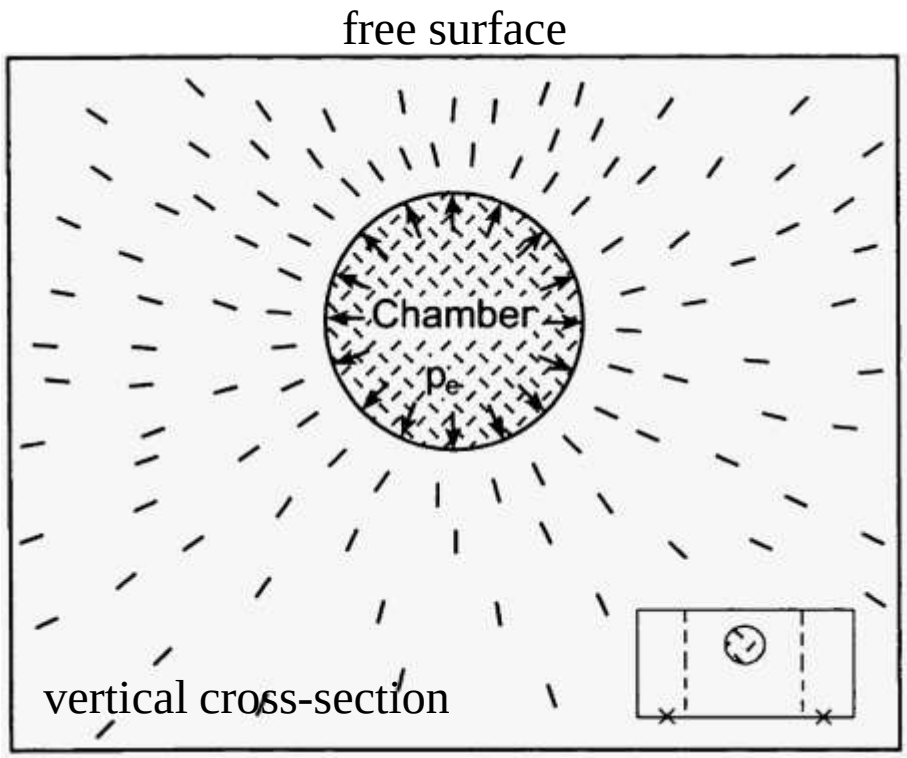




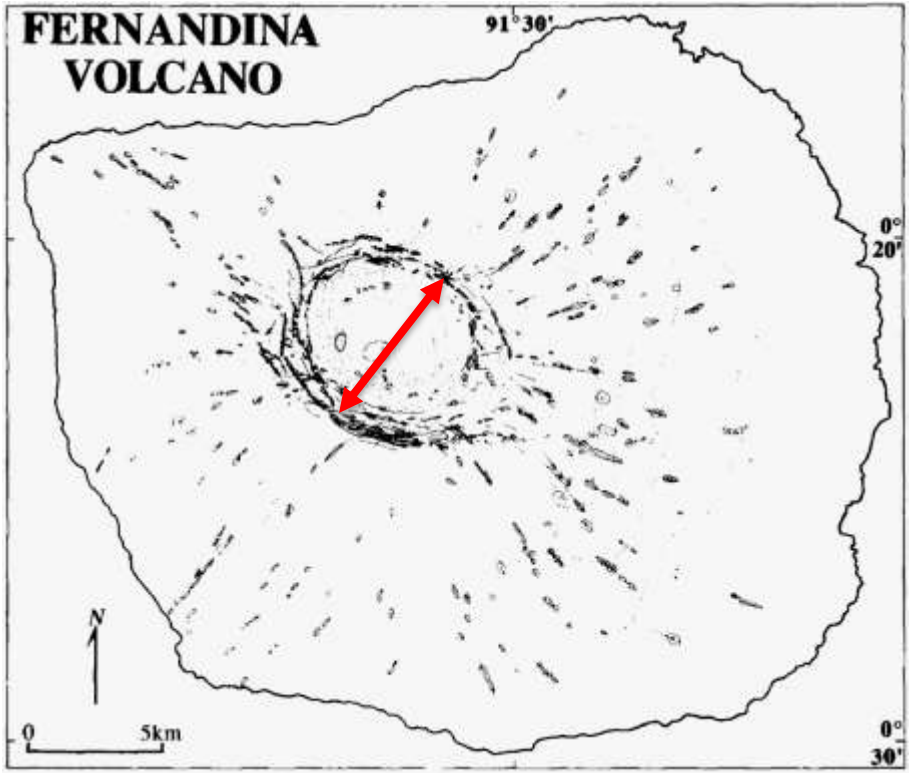
Cone-sheets: a modeling paradox?

<u>Models</u> → cone-sheets predicted everywhere under small magma overpressure.

<u>Nature</u> → cone-sheets not always present and only in axial region, then switch to radial dikes.

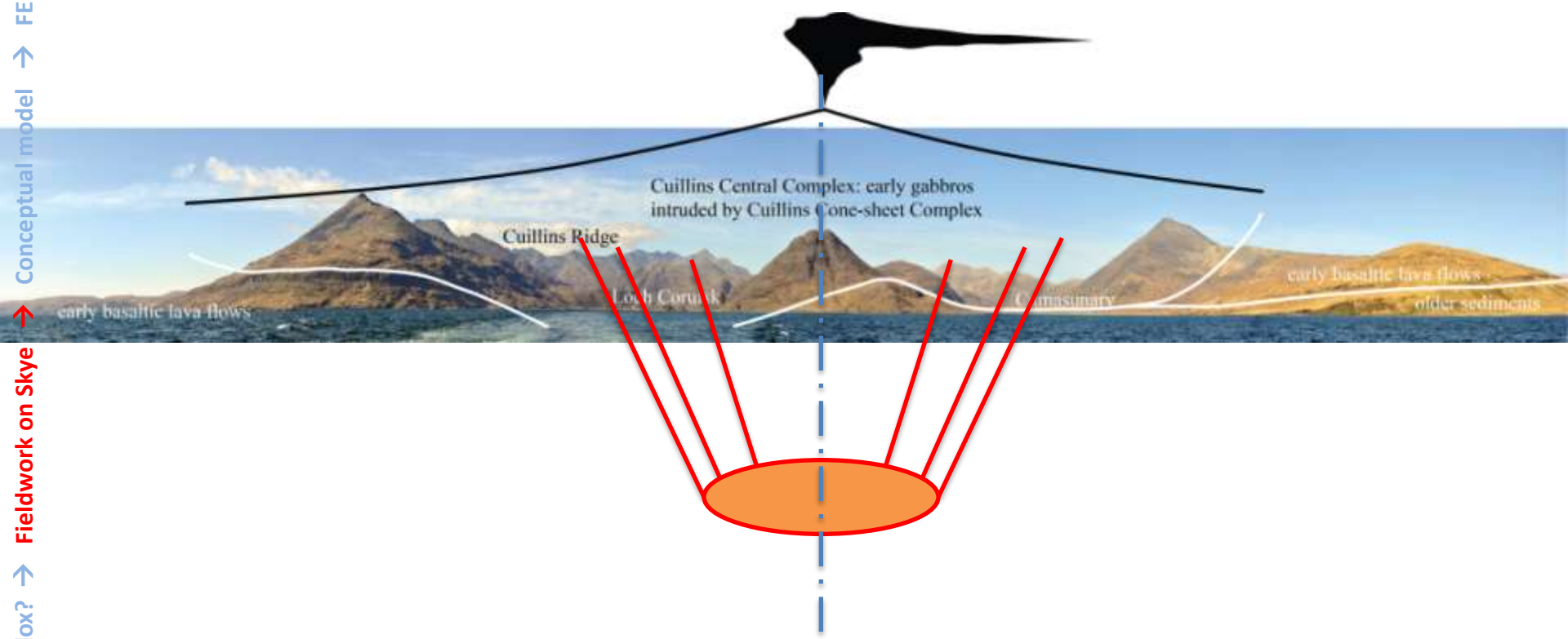


2D BEM or FEM model of a spherical magma chamber with overpressure. σ_1 directions shown in a vertical cross-section (review in Gudmundsson, 2006).



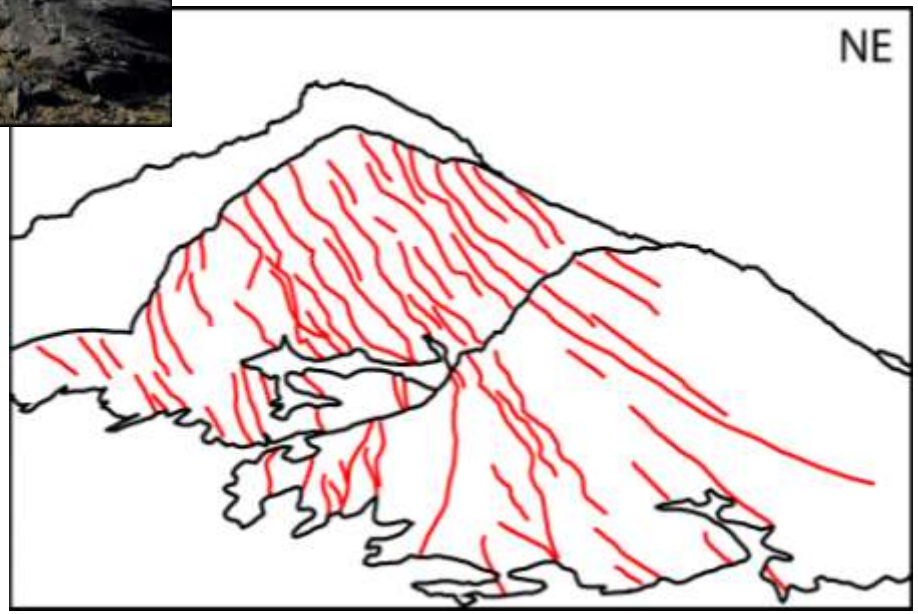
Radial dykes and cone-sheets (inward-dipping circumferential dykes) on Fernandina, Galapagos, map view (Chadwick & Dieterich, 1995).

Cone-sheets of the Isle of Skye

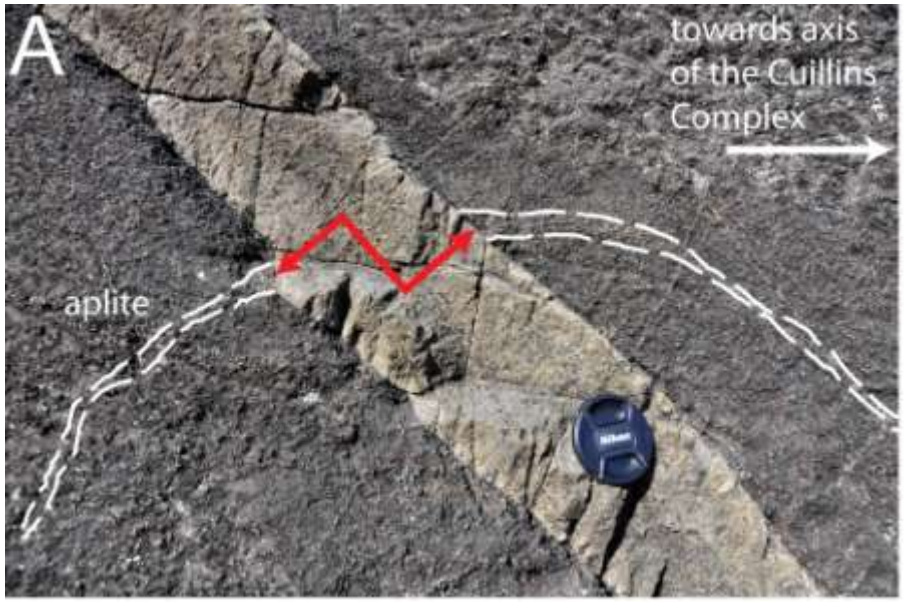


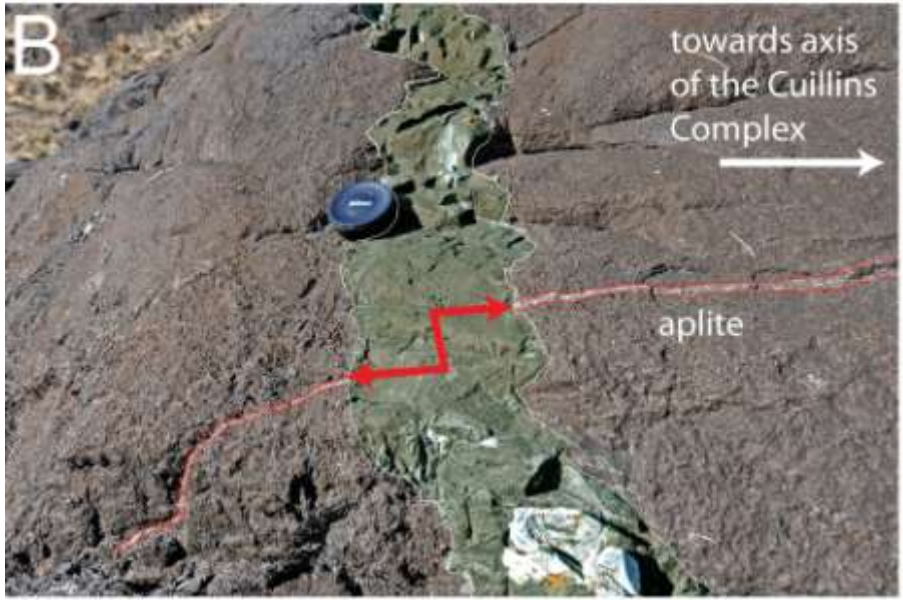
Bailey et al., 1924; Anderson, 1936.

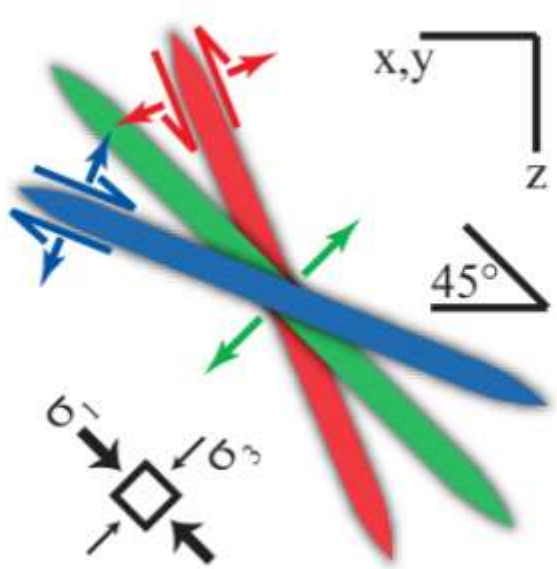
Cone-sheets of the Isle of Skye



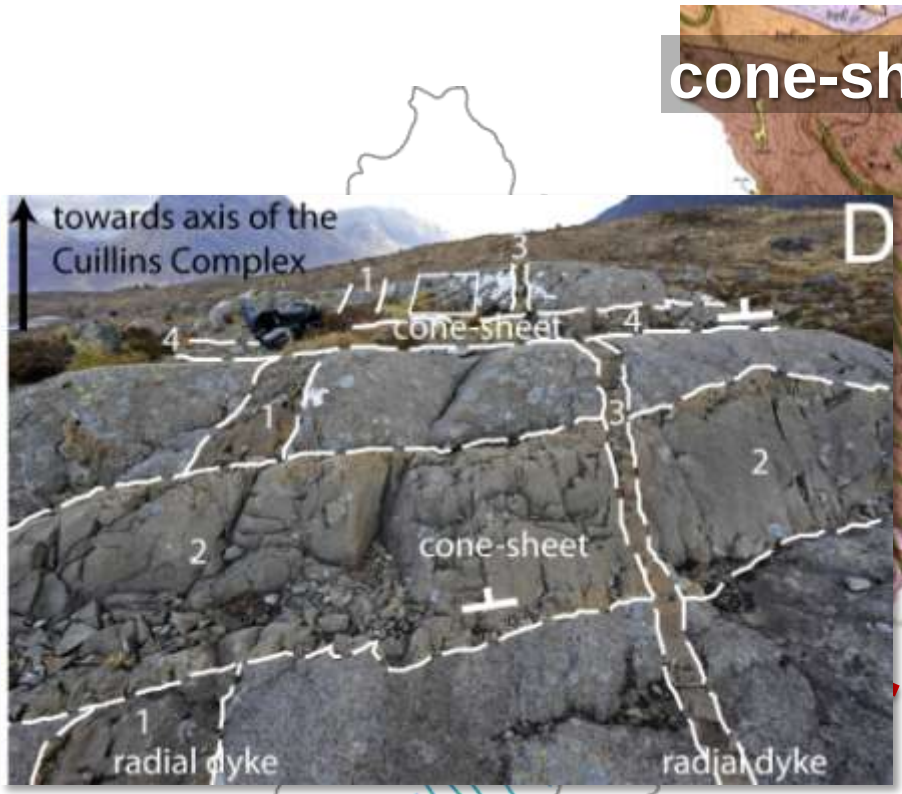
Cone-sheets of the Isle of Skye



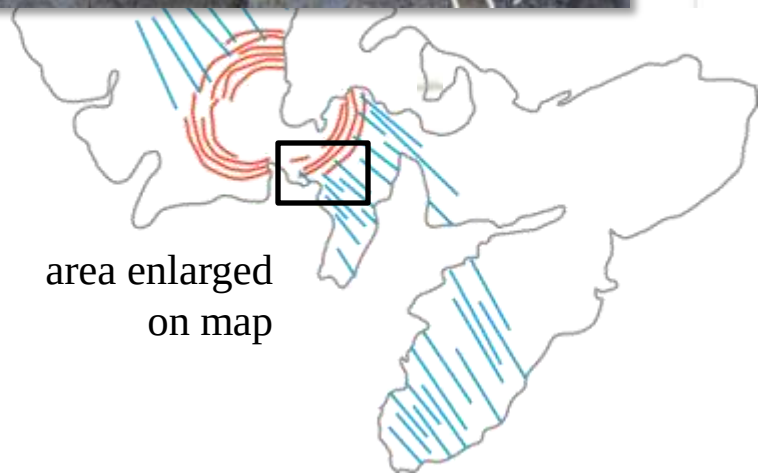




Cone-sheets "critical" distance

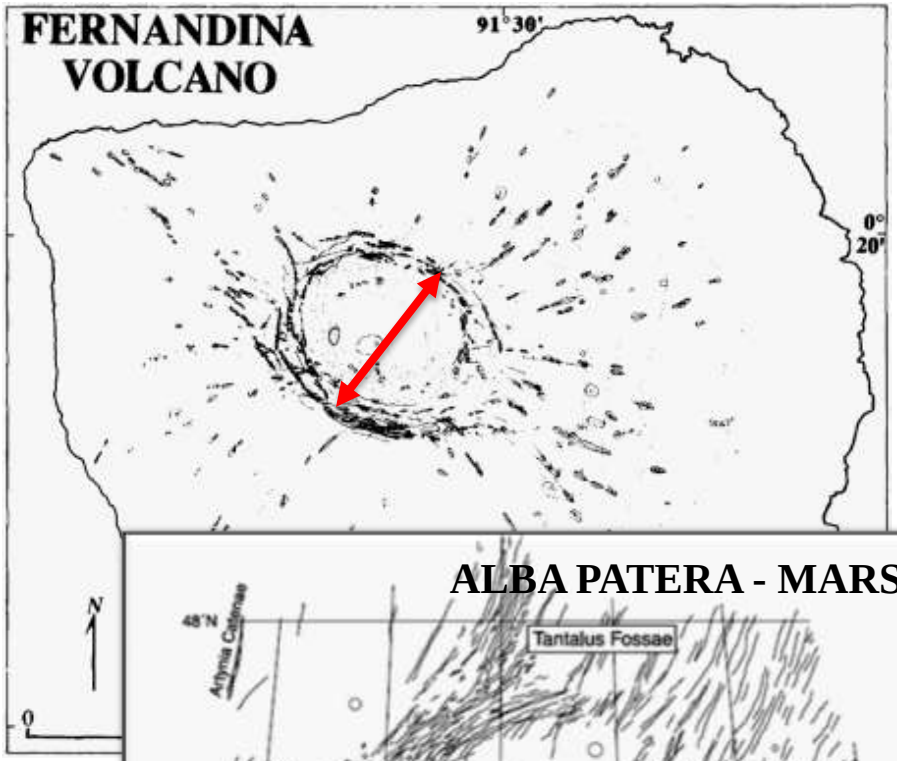


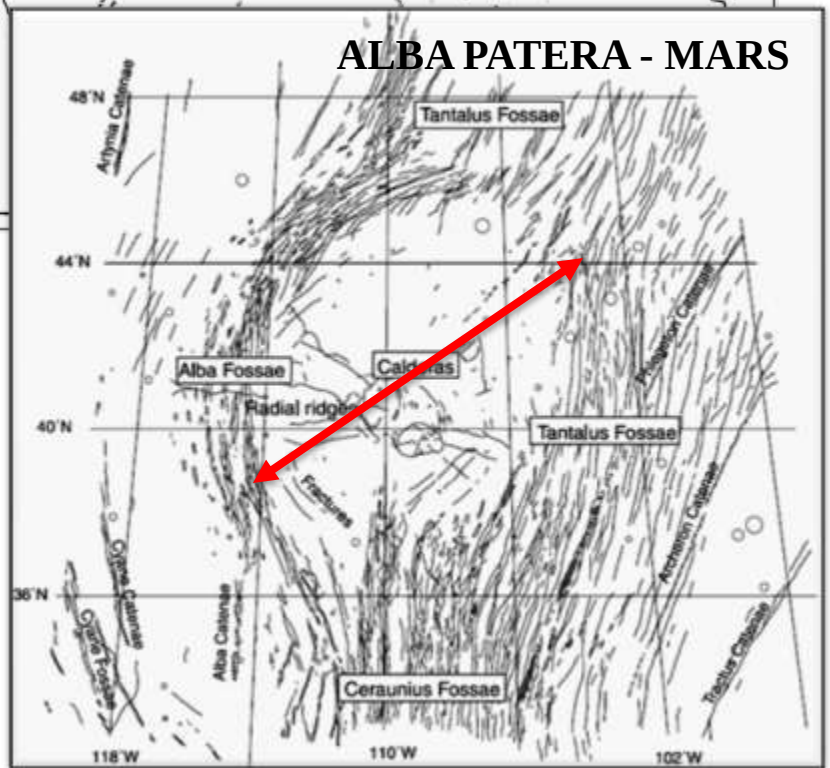
(British Geological Survey, 2005)



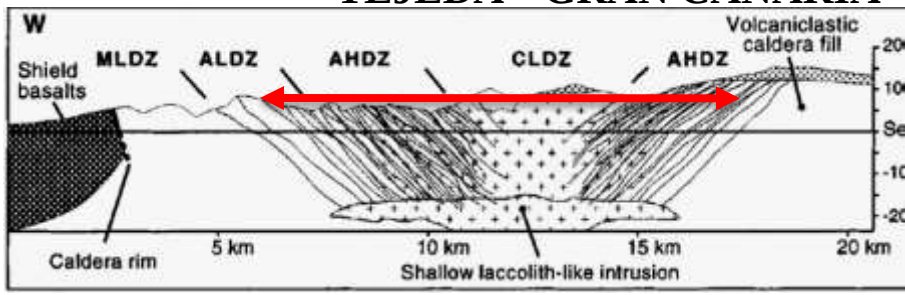
area enlarged
on map

Cone-sheets "critical" distance

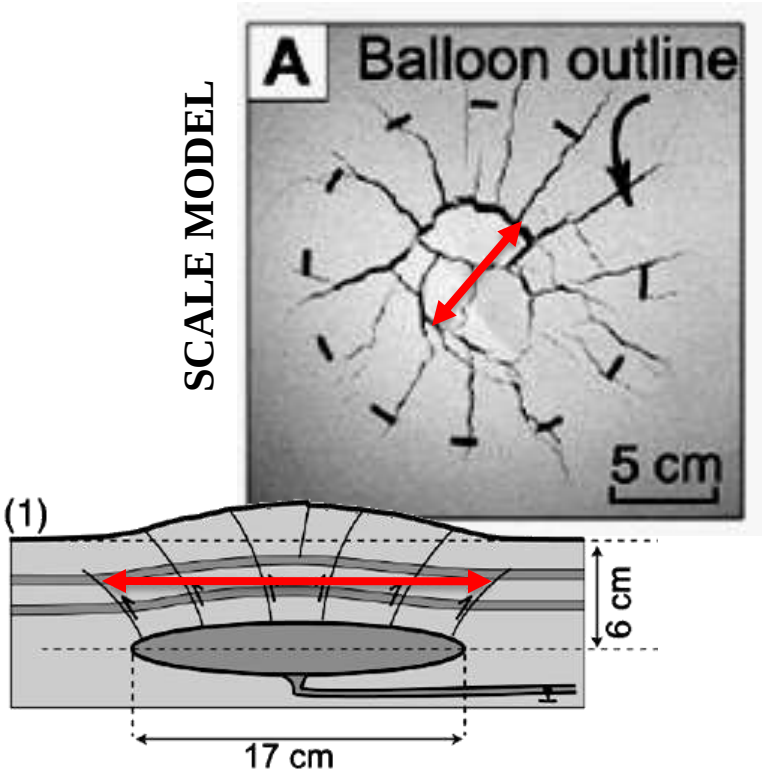




TEJEDA – GRAN CANARIA

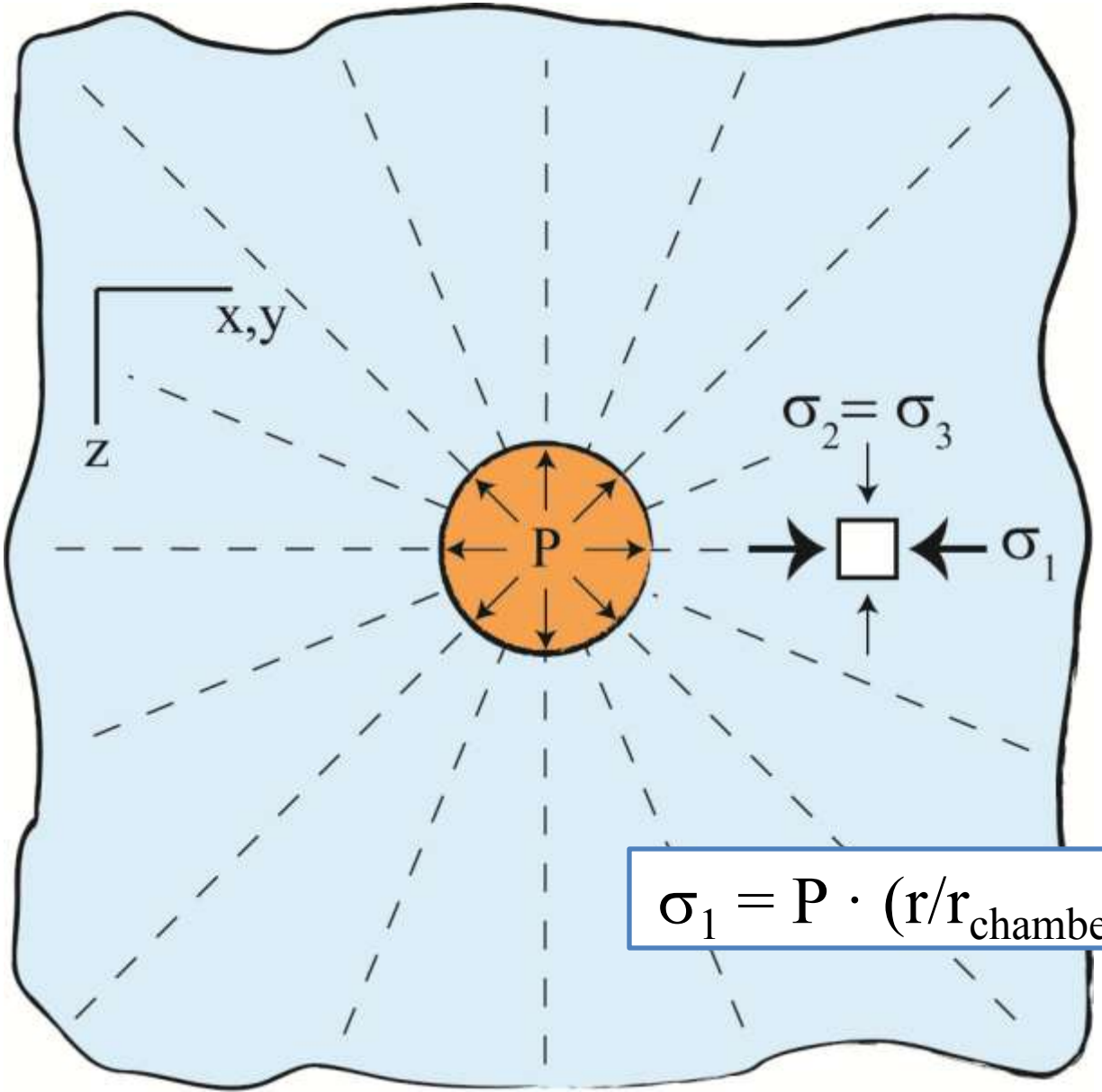


SCALE MODEL



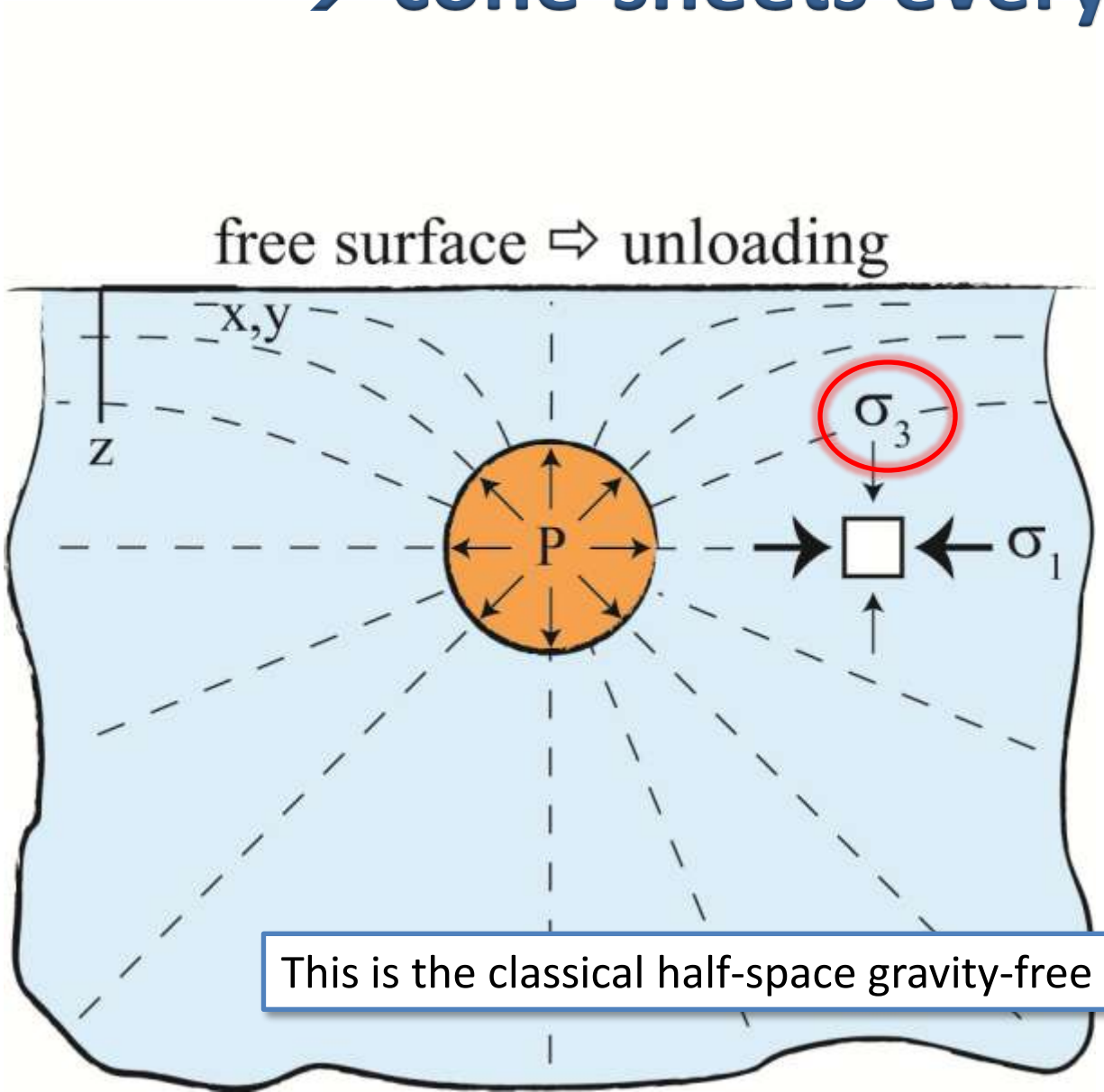
(Chadwick & Dieterich, 1995; Cailleau, Walter, Janle & Hauber, 2003 ; Schirnick, van den Bogaard & Schmincke, 1999; Troll, Walter & Schmincke, 2002)

Conceptual model: pure overpressure…



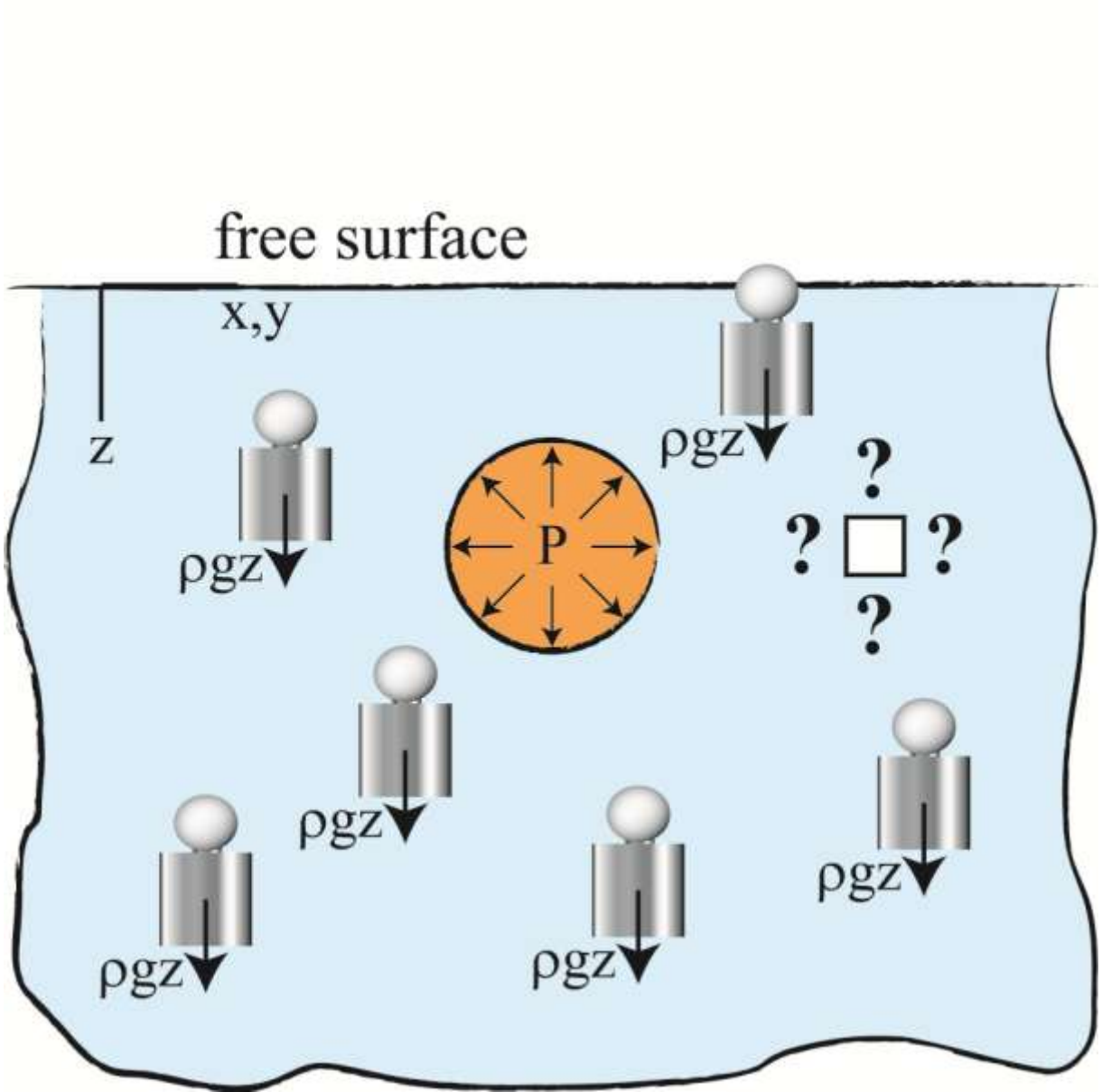
$$\sigma_1 = P \cdot (r/r_{chamber})^2$$

Conceptual model: the classic model → cone-sheets everywhere

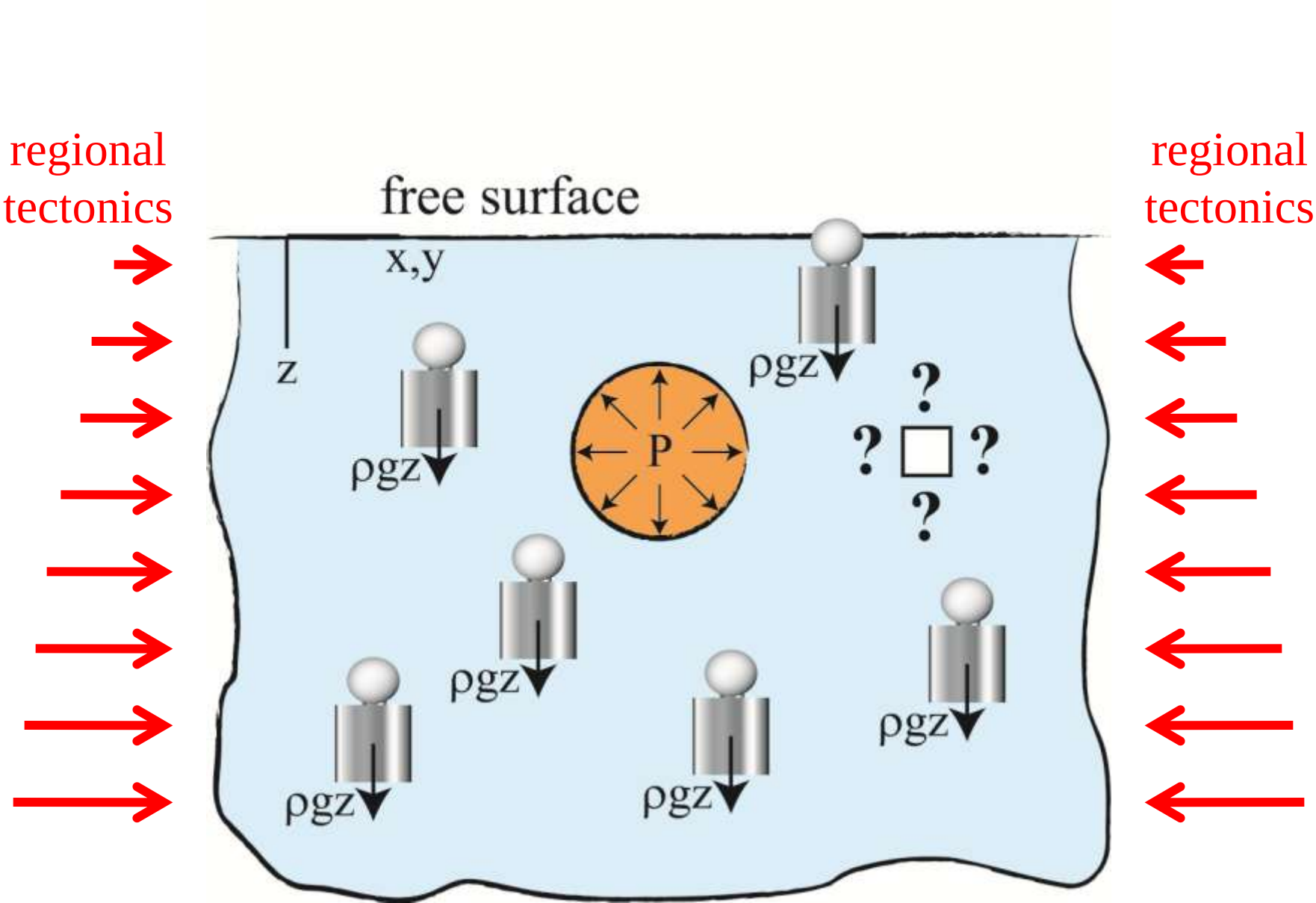


This is the classical half-space gravity-free elastic model

Conceptual model: gravity…



Conceptual model: … and tectonics



Finite Element Method modeling

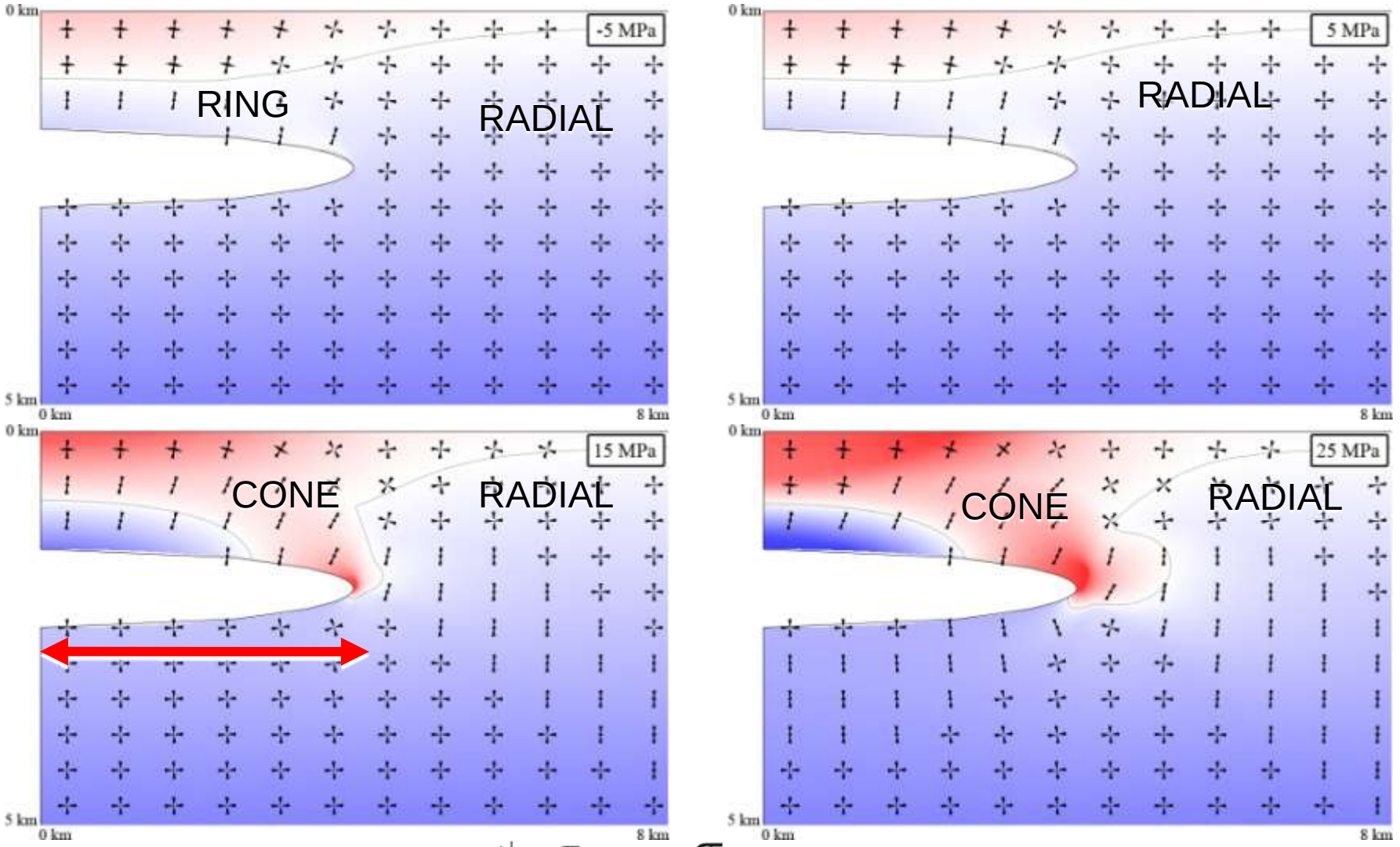
The question we are asking to FEM models is: “Does the complex **interplay** of magma overpressure, effect of a free surface, gravitational body load, and regional tectonics may produce the observed **switch** from cone-sheets to radial or “regional” parallel dikes? And under what **conditions**?

Model “ingredients”:

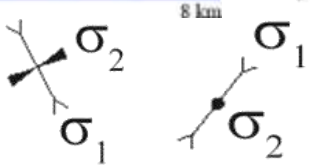
- solve equilibrium equations for displacements under body loads (**gravity**) and mixed BC’s (**magma pressure**, **tectonics** and zero displacements)
- geometry: **2D axial-symmetric** or **3D**
- material: homogeneous isotropic **elasto-plastic** Drucker-Prager
- nonlinear parametric solver (COMSOL Multiphysics®)
- improved 3D visualization with gOcad®

FEM modeling results - 1

2D axisymmetric: increasing overpressure in an oblate chamber



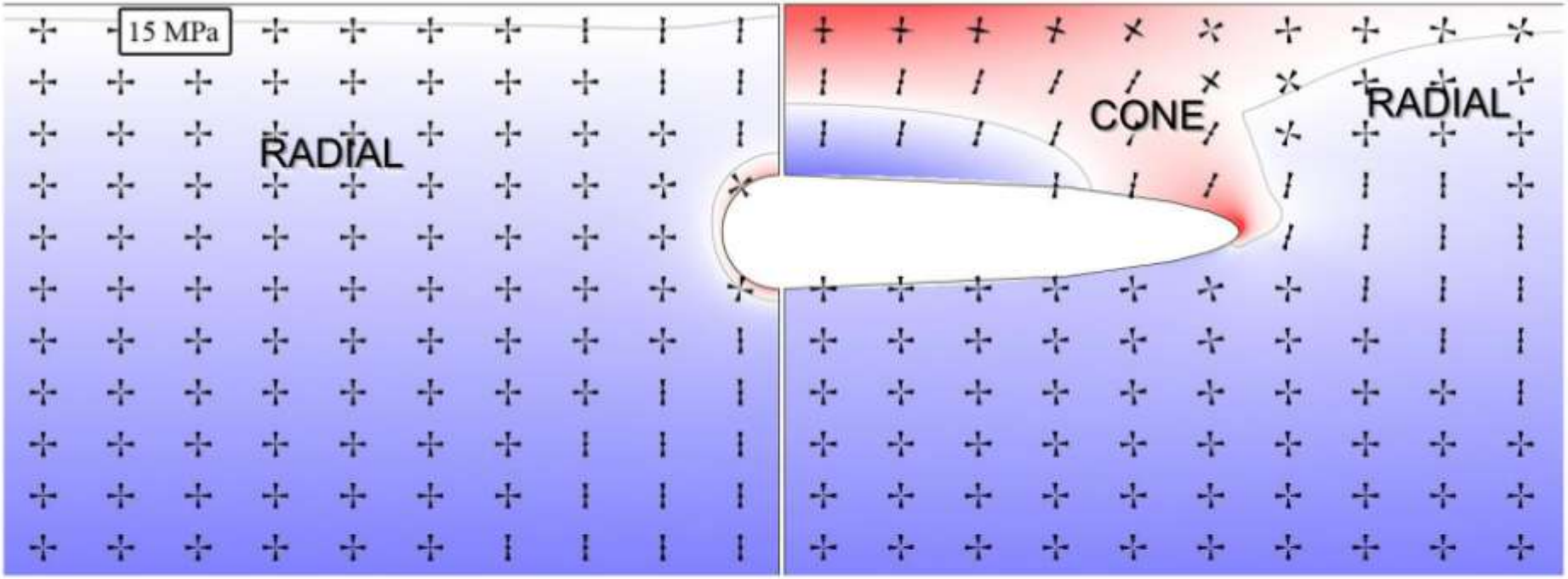
stress axes ↔ dykes:



red → σ_3 is tensional

FEM modeling results - 2

2D axisymmetric: spherical vs. oblate chamber



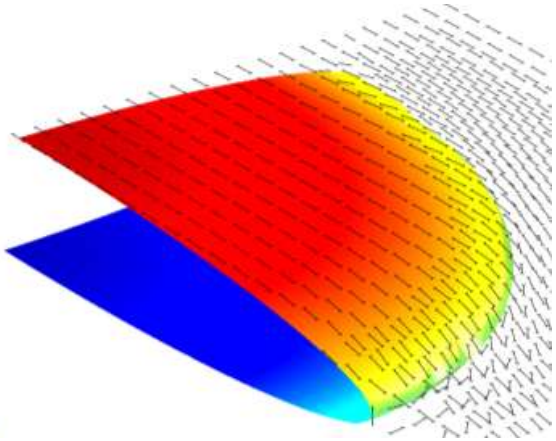
→ spherical magma chamber not compatible with cone-sheets

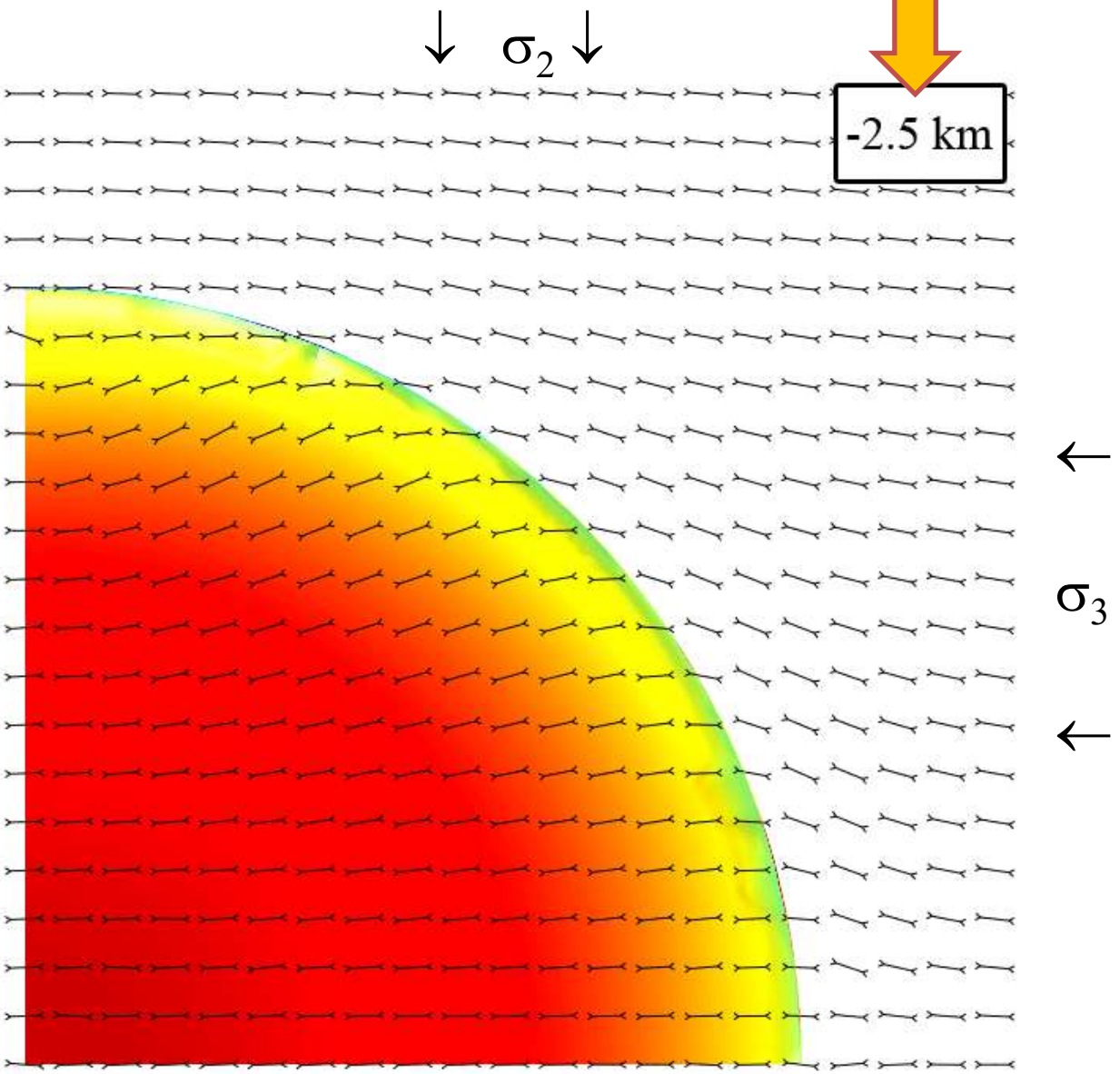
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance

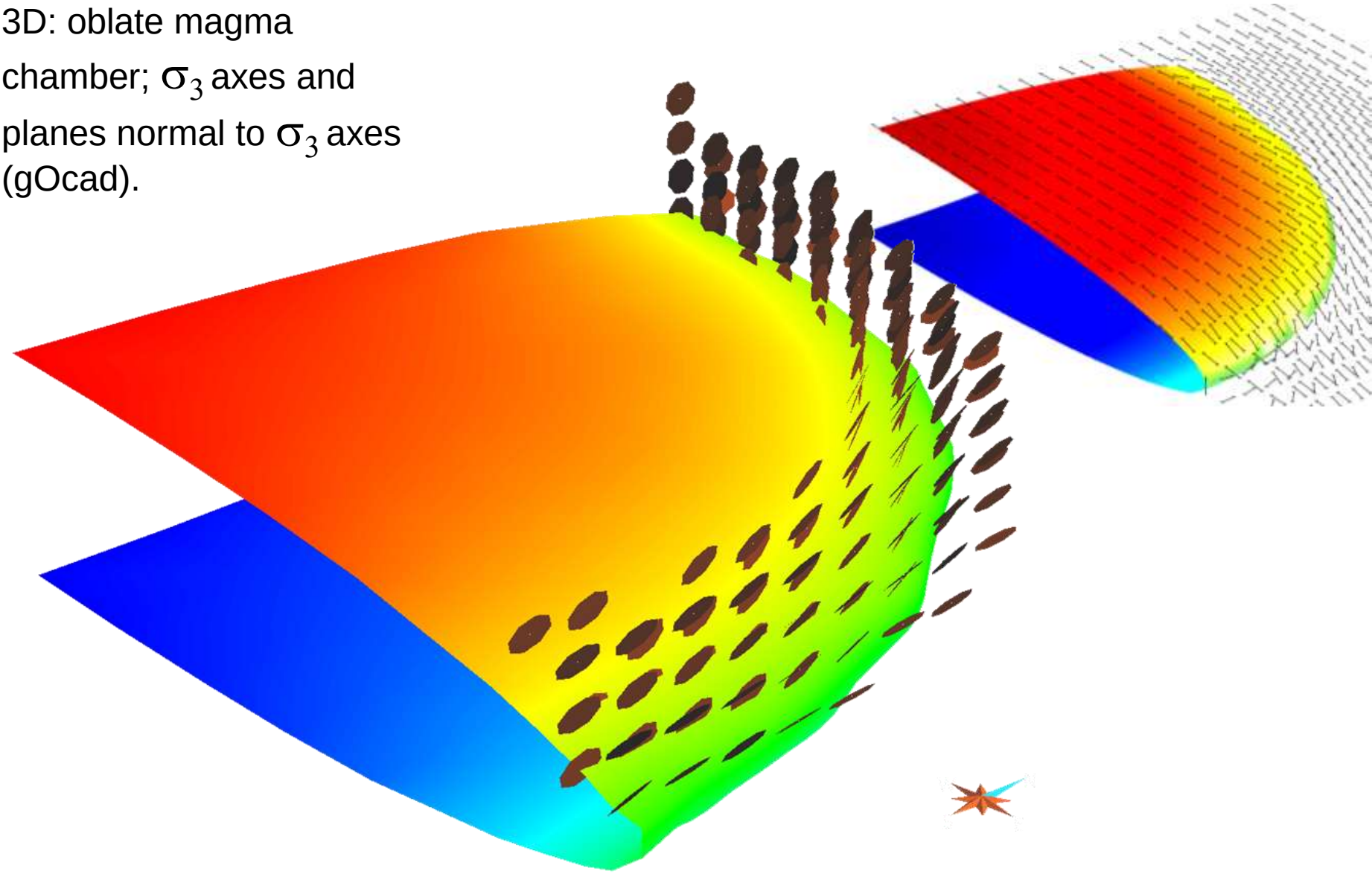




[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

FEM modeling results - 4

3D: oblate magma chamber; σ_3 axes and planes normal to σ_3 axes (gOcad).



[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

Conclusions

- 2D axisymmetric **elasto-plastic** models with **gravity** explain scale models, 3D models with **tectonics** explain field examples.

- An **oblate** magma chamber is required for cone-sheet development. The cone-sheet annular region depicts the **diameter** of the magma chamber.

- Possible applications include:
  - to infer the **shape and dimensions of shallow magma chamber**.
  - to infer the **tensional state** of the system.

Earth and Planetary Science Letters 339–340 (2012) 46–56

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

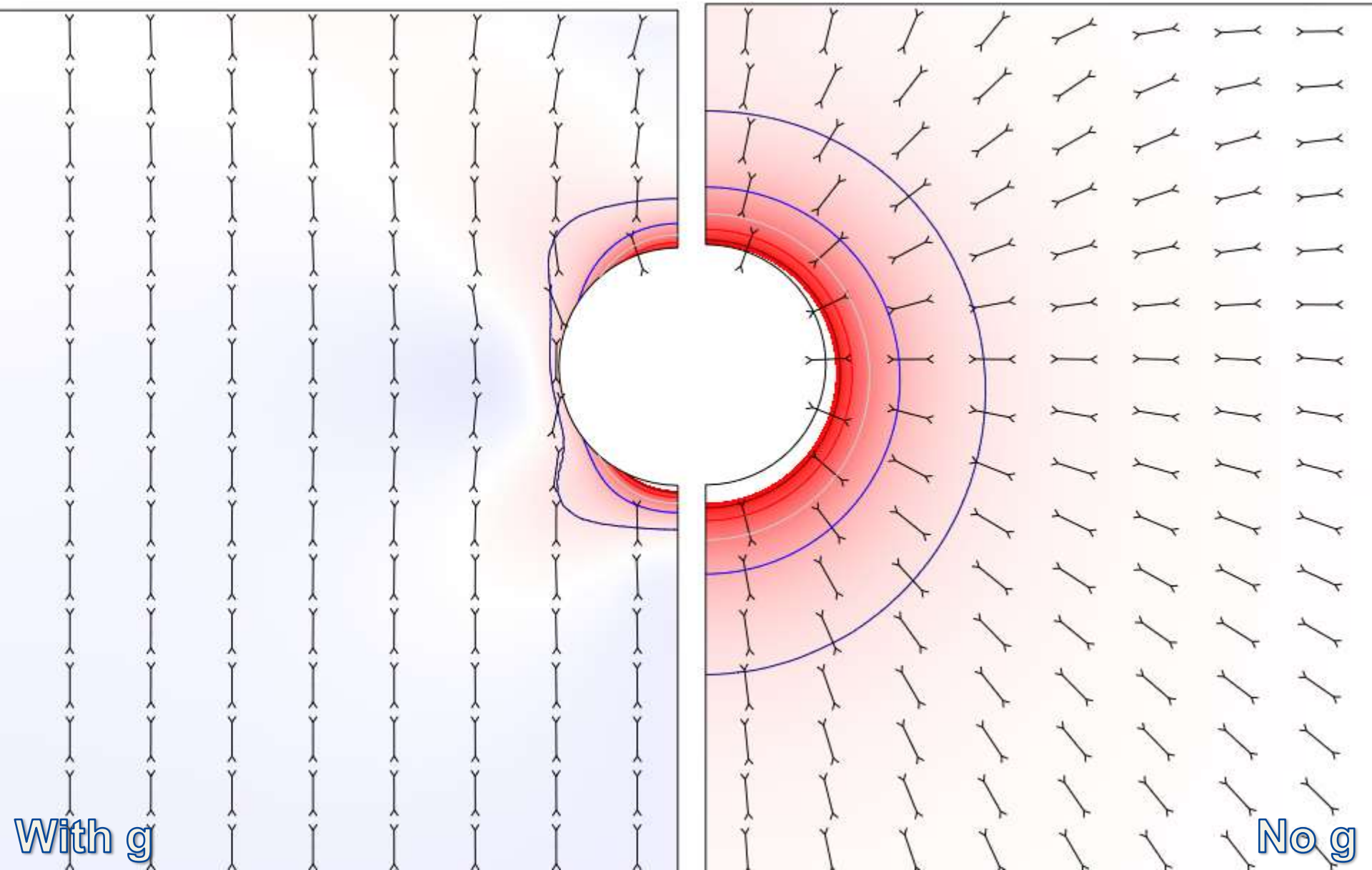
journal homepage: www.elsevier.com/locate/epsl

The association of cone–sheets and radial dykes: Data from the Isle of Skye (UK), numerical modelling, and implications for shallow magma chambers

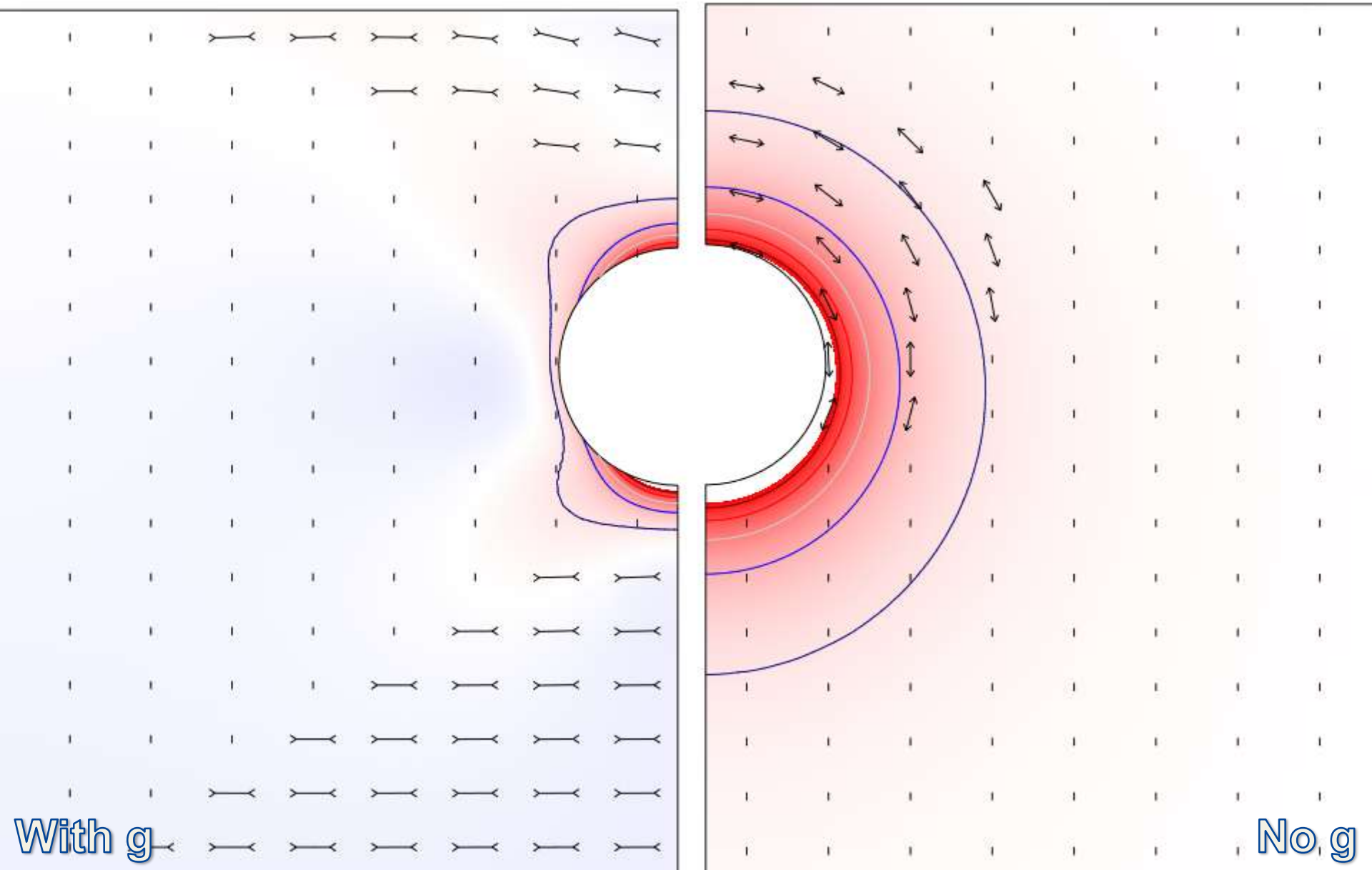
Andrea Bistacchi [a,*], Alessandro Tibaldi [a], Federico A. Pasquarè [b], Derek Rust [c]

[a] *Dipartimento di Scienze Geologiche e Geotecnologie, Università degli Studi di Milano Bicocca, Italy*
[b] *Dipartimento di Scienze Chimiche e Ambientali, Università degli Studi dell'Insubria, Italy*
[c] *School of Earth and Environmental Sciences, University of Portsmouth, UK*

Elastic: with or without gravity σ_1



Elastic: with or without gravity σ_3

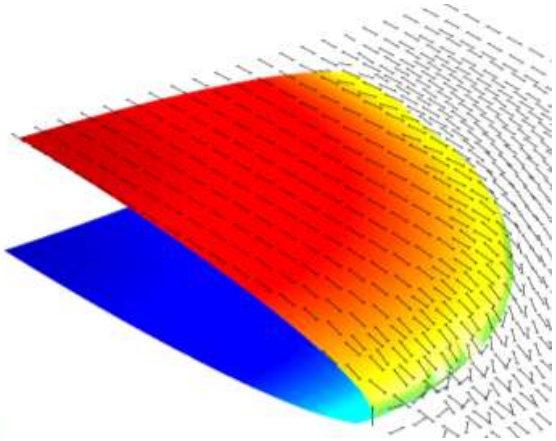


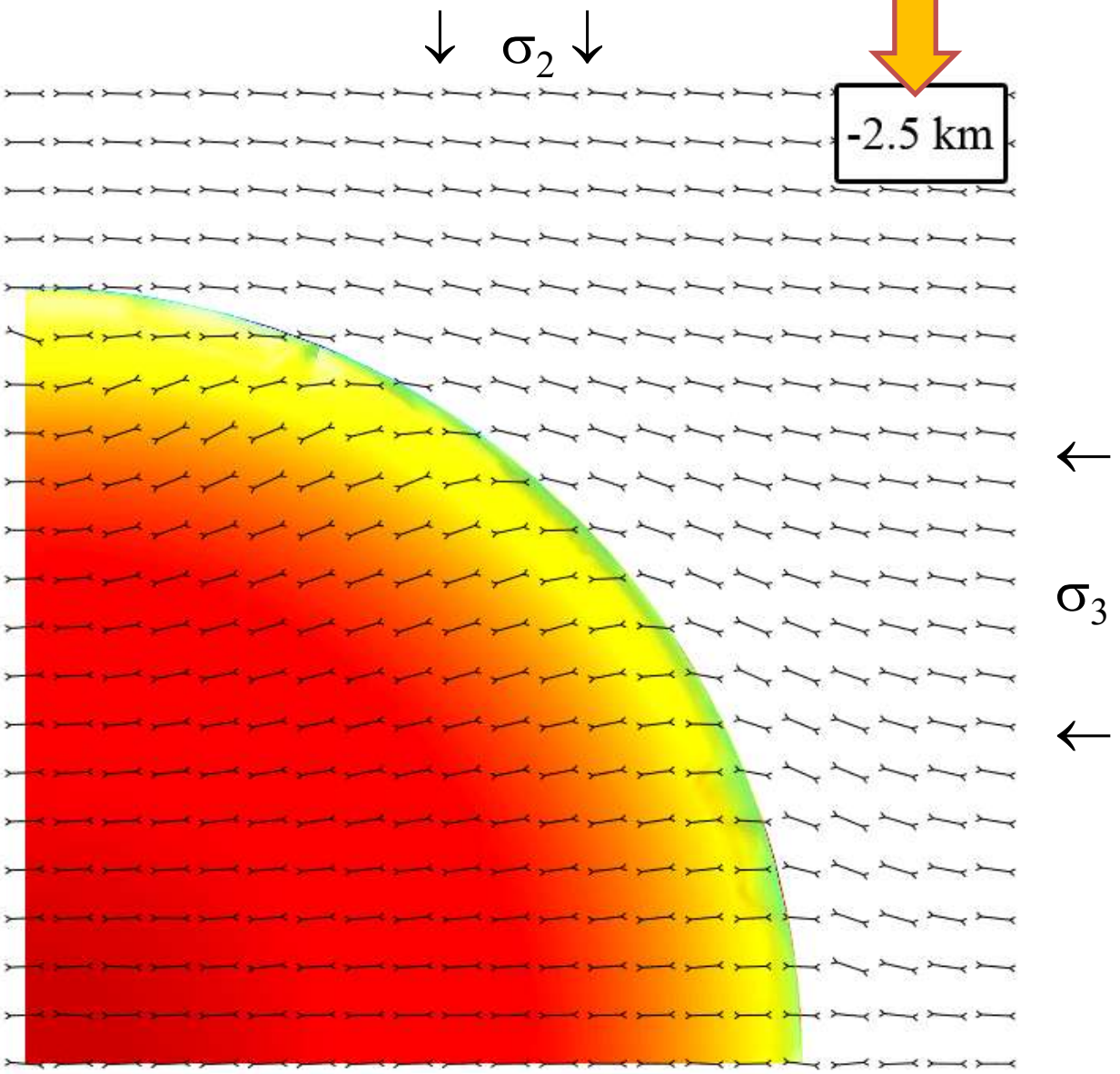
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





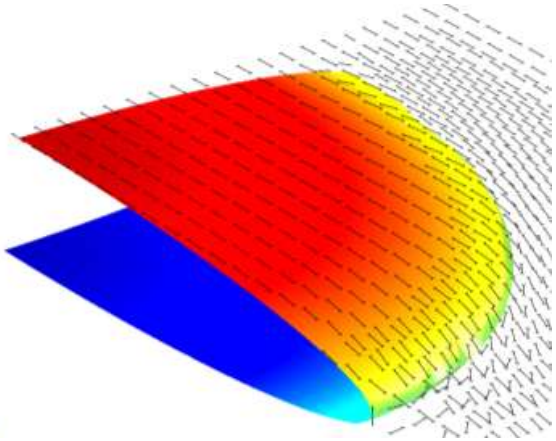
[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

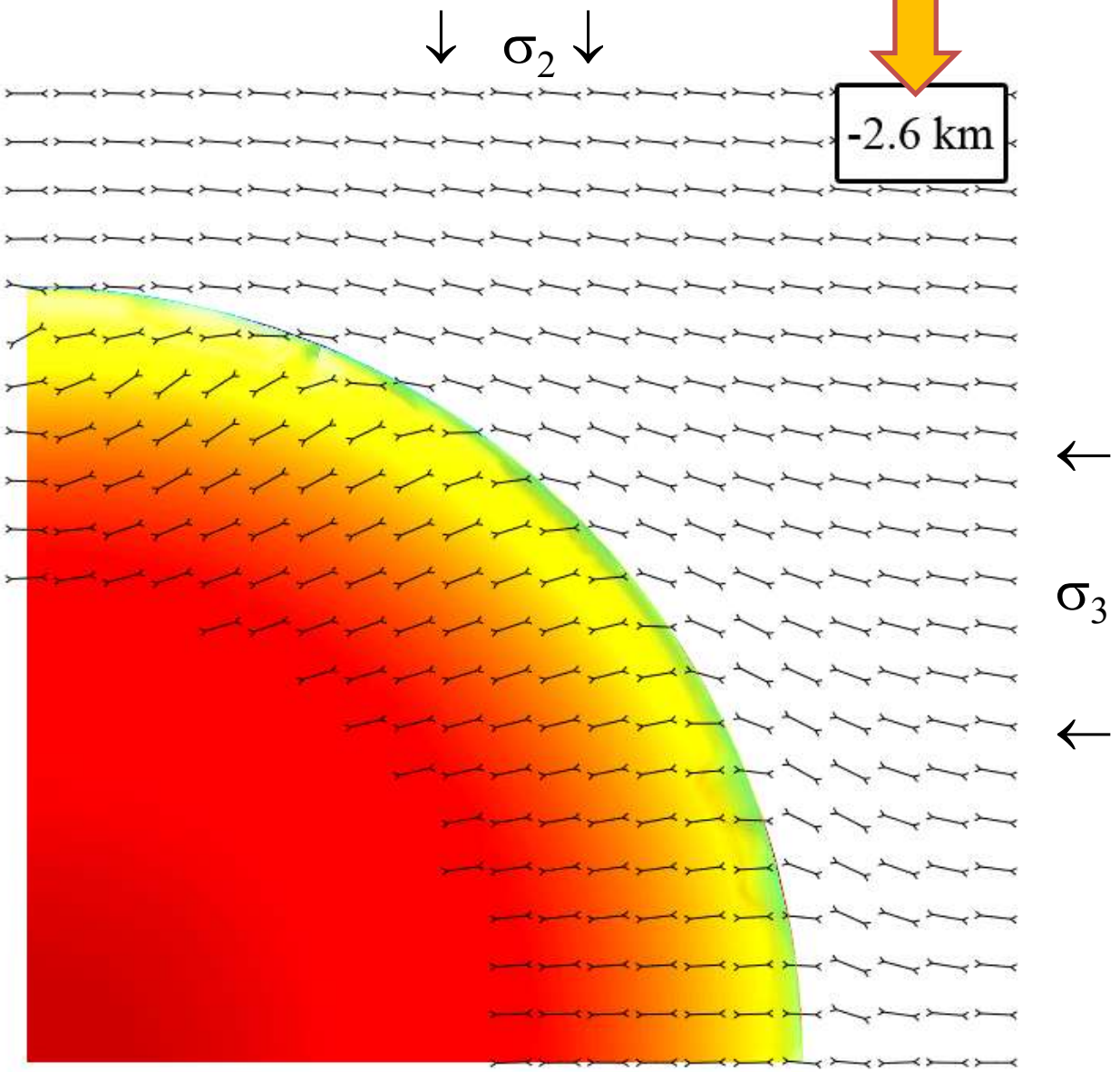
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





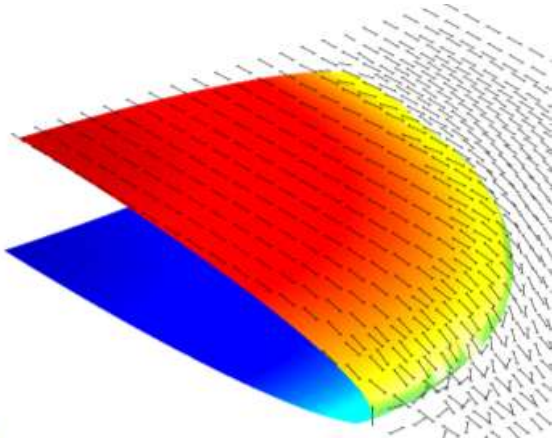
[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

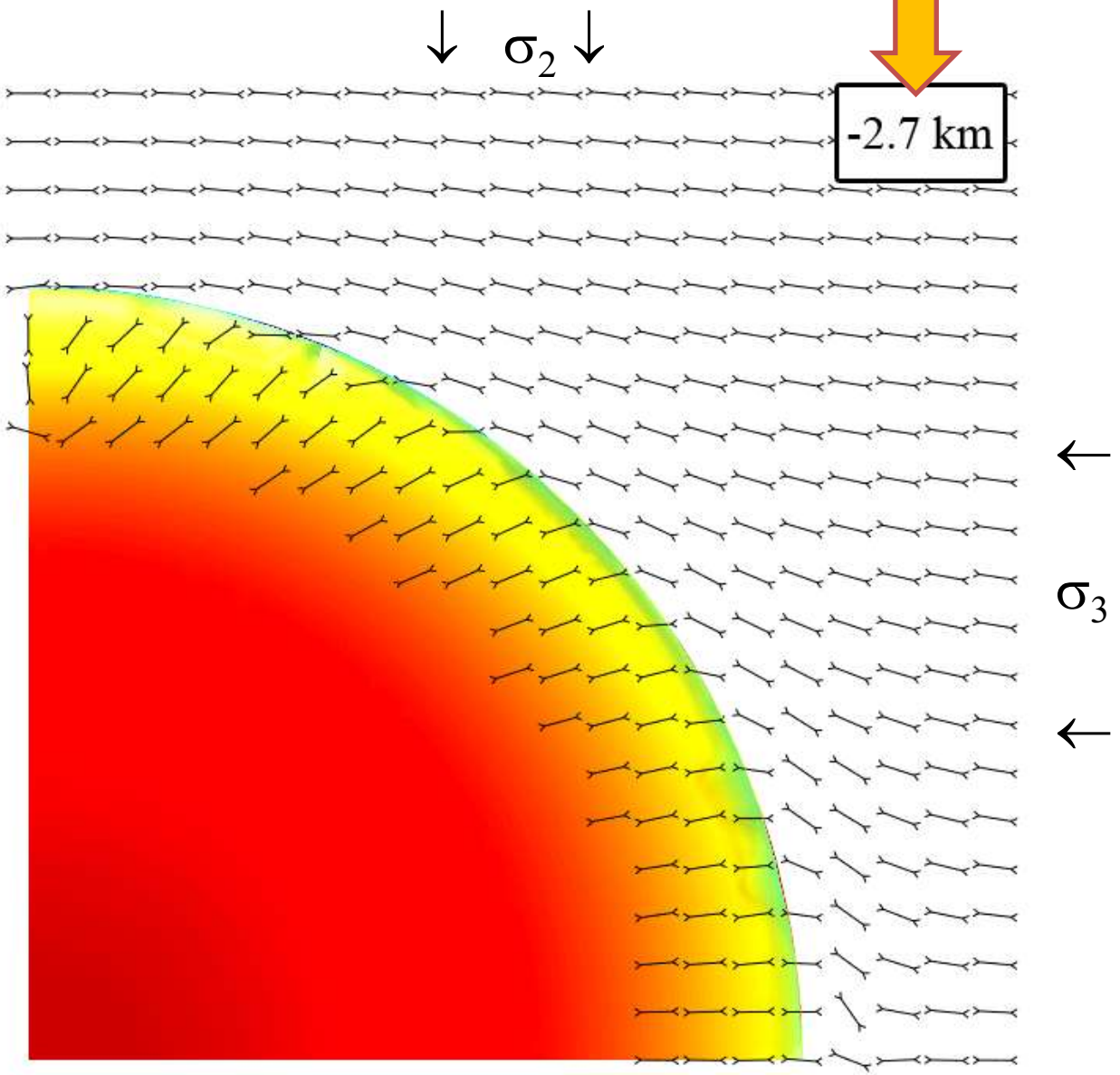
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





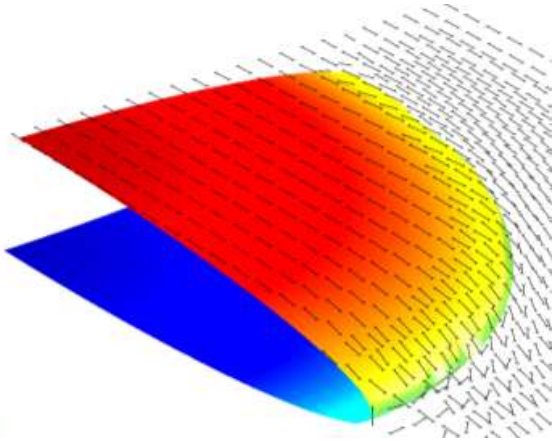
[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

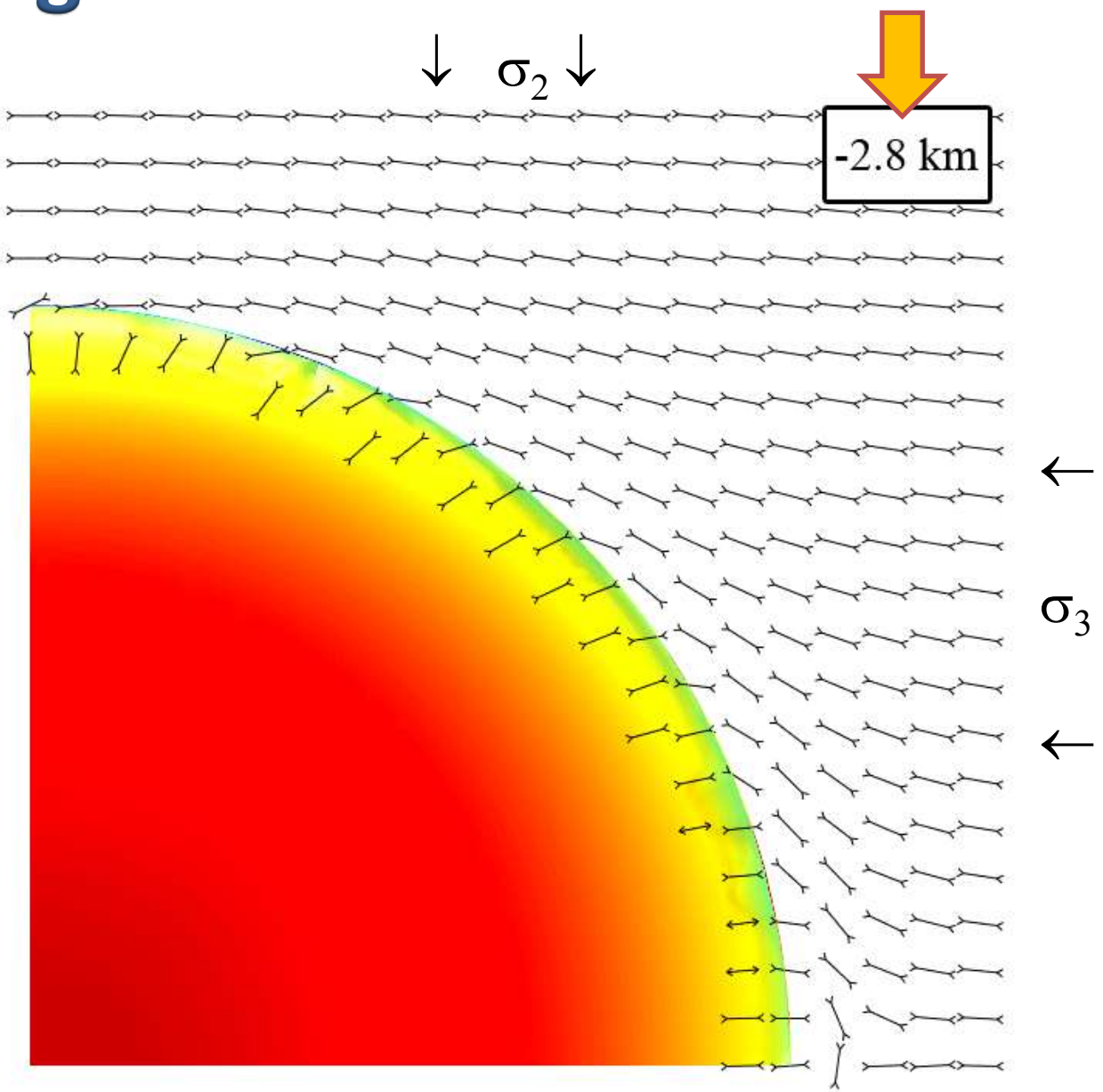
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





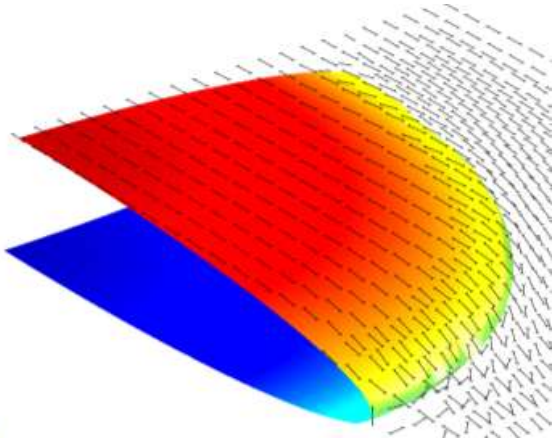
[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

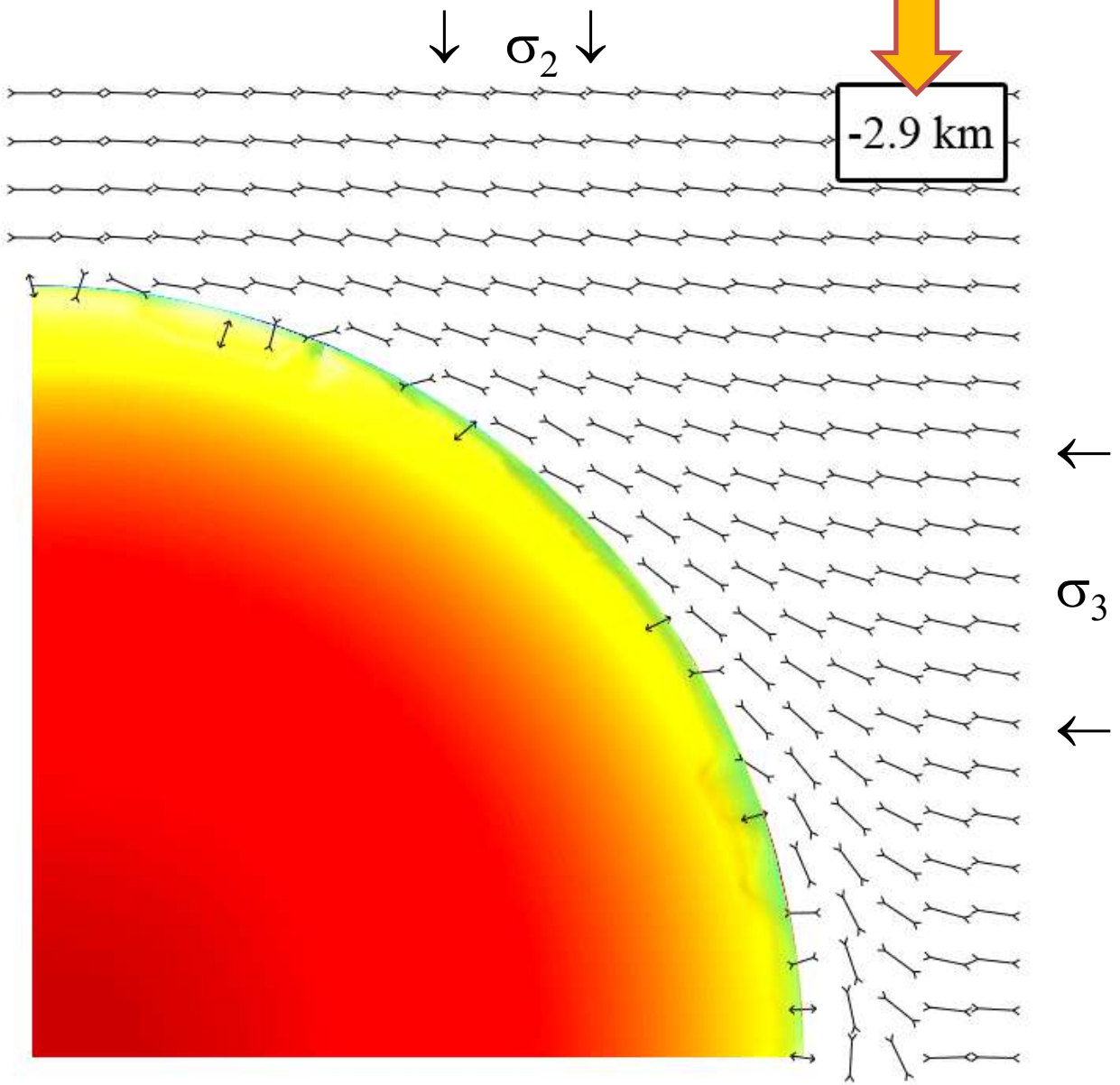
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





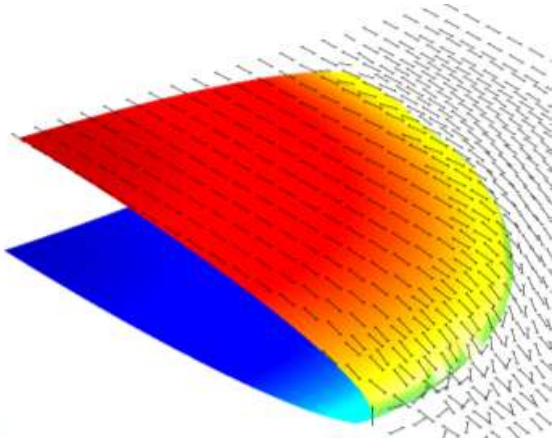
[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]

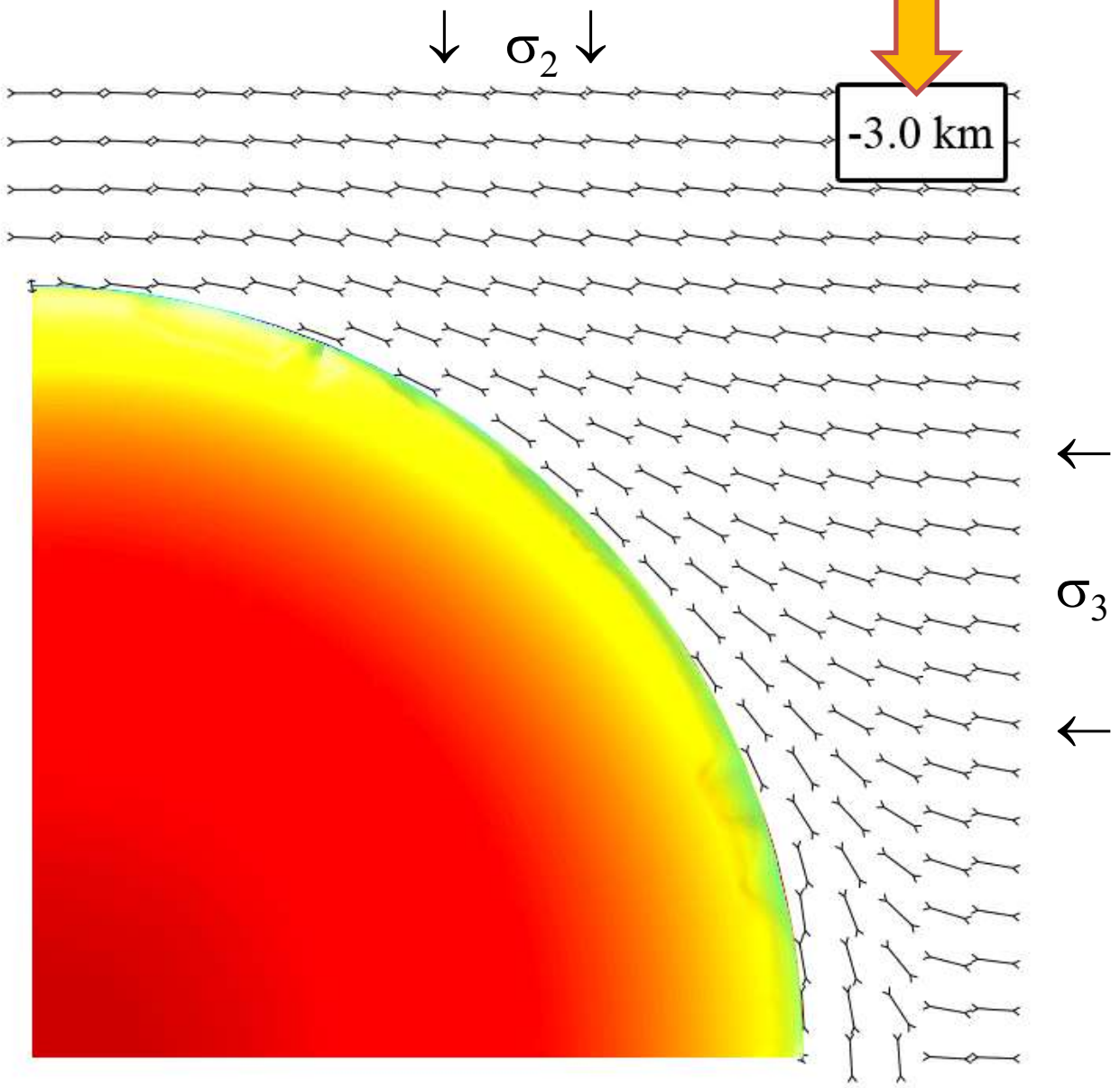
FEM modeling results - 3

3D: oblate magma chamber seen from above, at increasingly deep slices; only σ_3 is shown.

→ cone-sheets above magma chamber

→ parallel dykes after a threshold distance





[Static visualization is not really satisfying. If you are interested, I have 3D models on my laptop.]