Anisotropy and history of the Earth's inner core: forward models and input from mineralogy

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Collaboration

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- **Ph. Cardin (ISTerre, Grenoble)**
- **R. Deguen (LGLTPE, Lyon)**

Université de Lille 1 Sciences et Technologies

Université Grenoble Alpes

Université de Lyon

cnrs dépasser les frontières

IUF institut universitaire de France

Earth's inner core

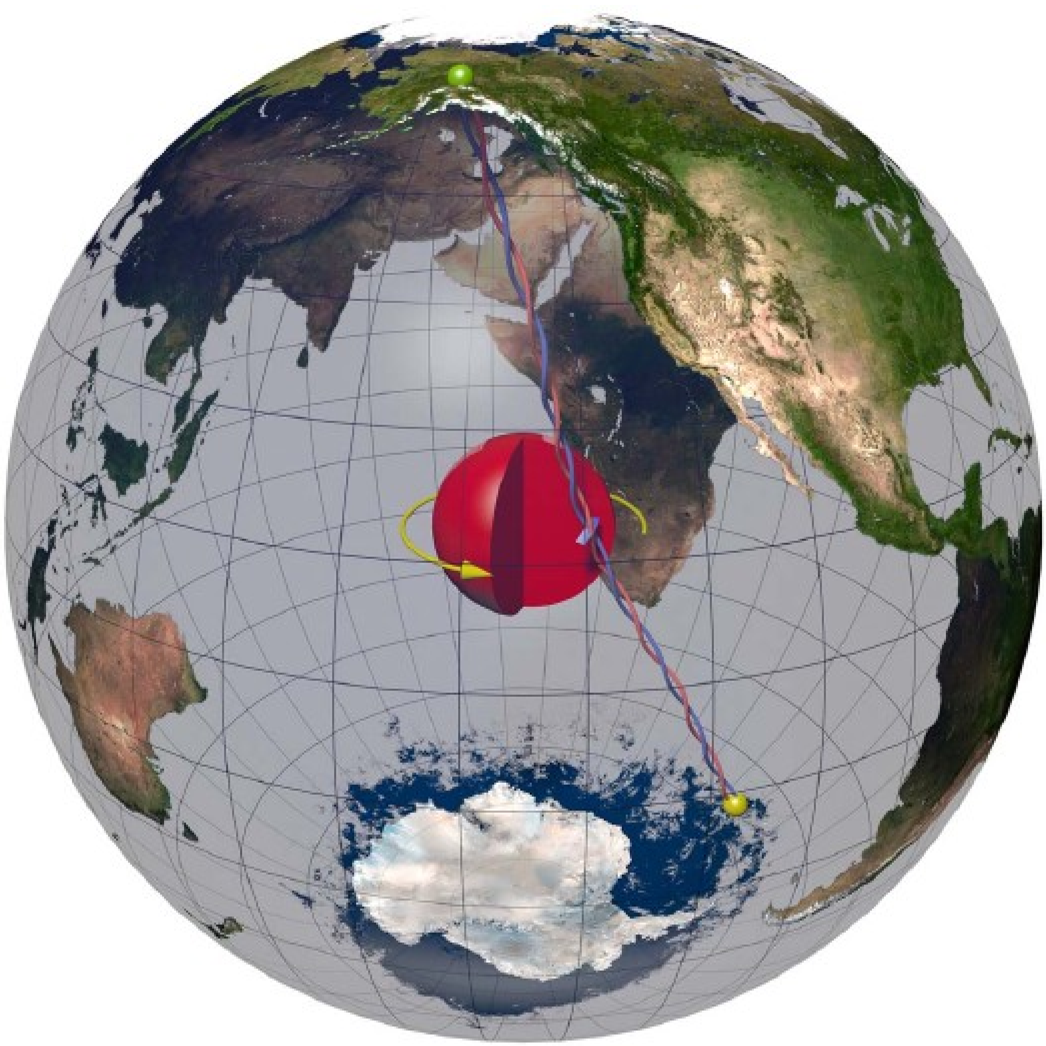
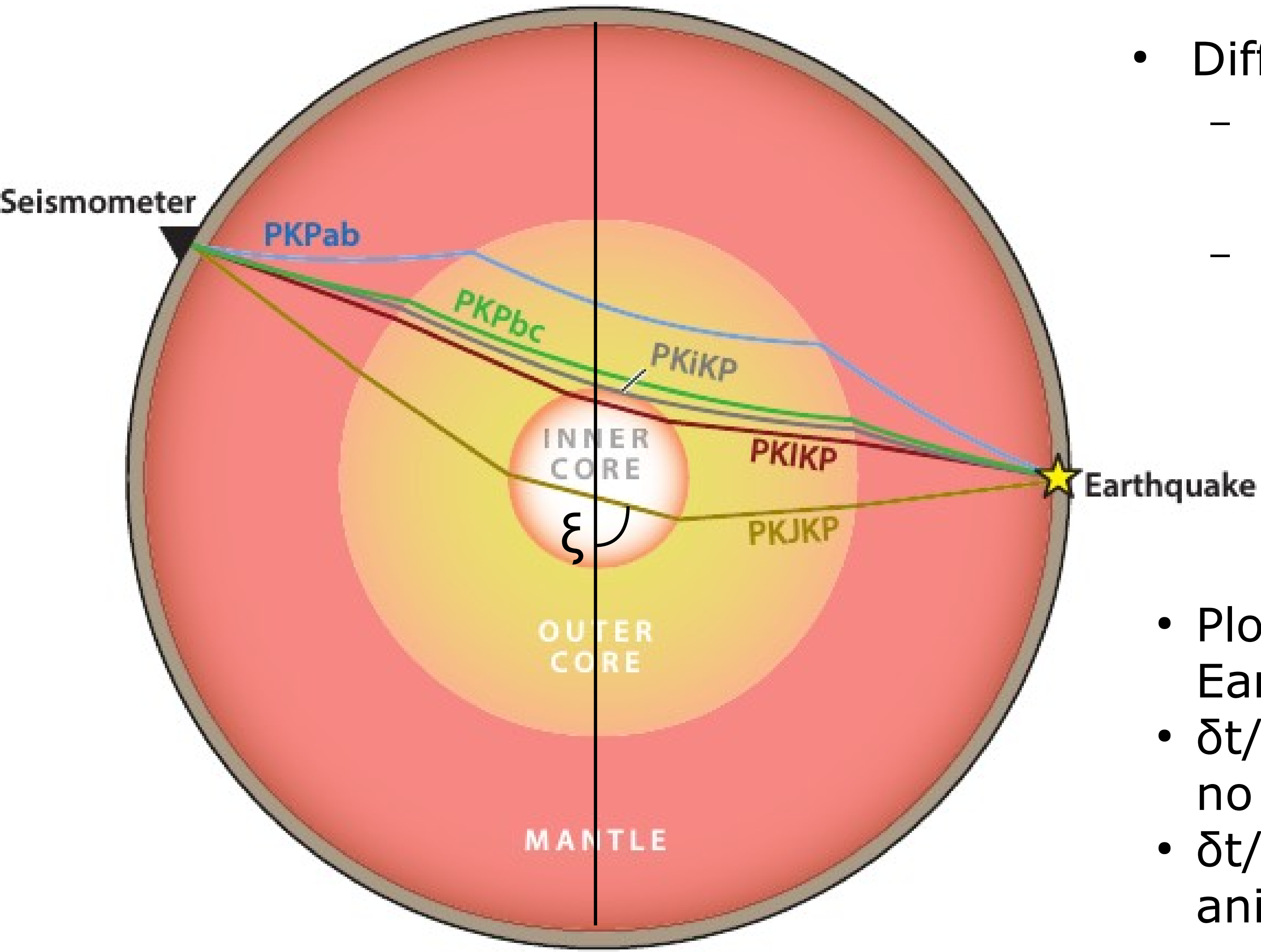


Illustration : Tkalčić, *Rev Geophys*. 2015

- 1220 km radius
- Crystallization of Fe-alloy due to Earth's cooling
- Pressure range: 330-365 GPa
- Temperature: ~6000 K
- Seismic anisotropy
  - North-South inner core P-waves faster than equatorial paths
- Complex structure:
  - Outer inner core isotropic
  - Inner inner core anisotropic
  - Stronger anisotropy in western hemisphere
  - Super-rotation: 0.3-1.1°/y (?)

Inner core anisotropy

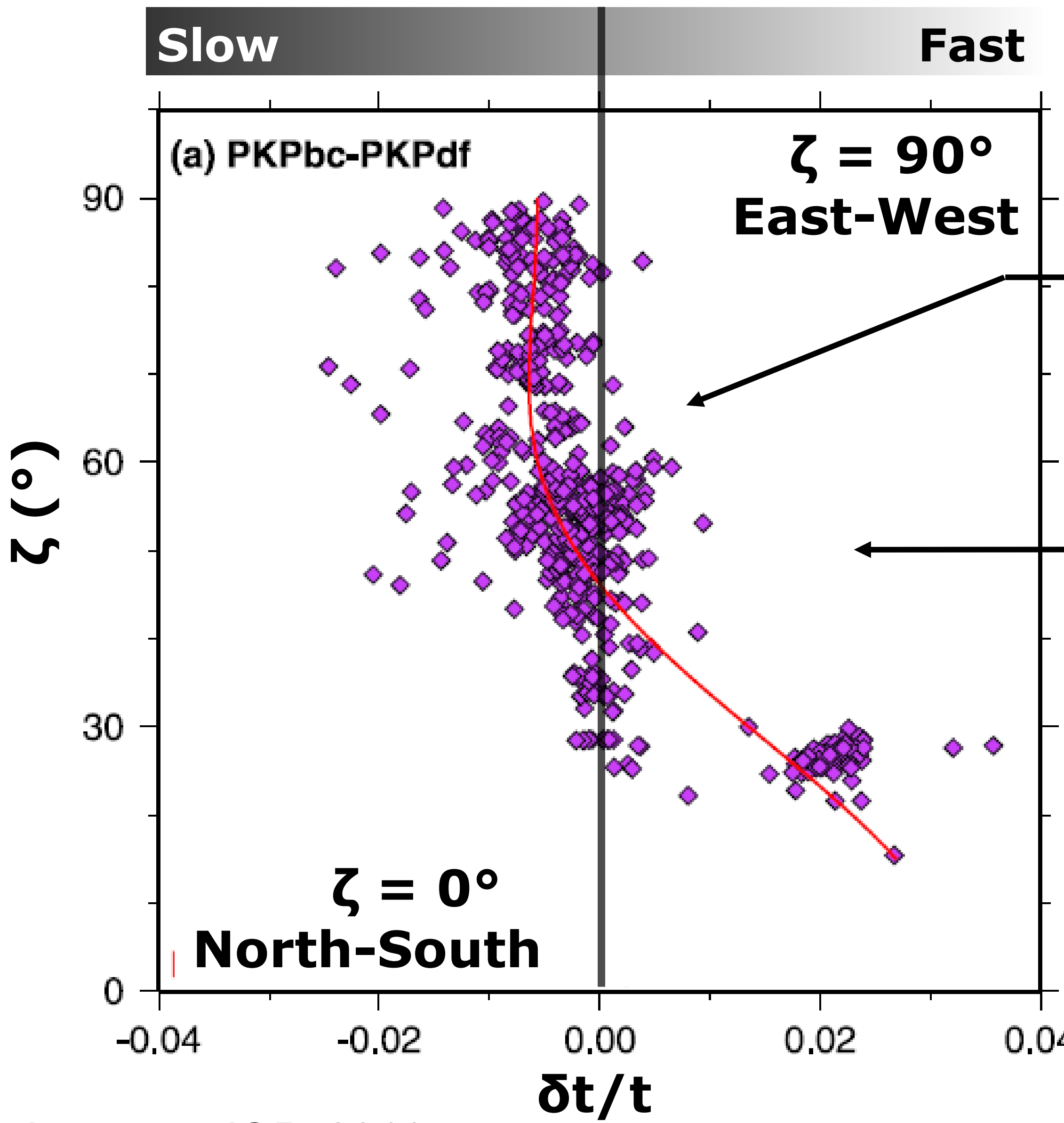


- Differential travel time δt:
  - PKIKP – PKiKP, or other combination
  - Cancels effects of mantle and crust

- Plot δt/t vs. ξ, angle to Earth rotation axis
- δt/t independent of ξ: no anisotropy
- δt/t depends on ξ: anisotropy

Illustration : Deuss, *Annu. Rev. Earth Planet. Sci*. 2015

Inner core anisotropy: measurement



Irving *et al*, *JGR* 2011

Seismic residuals

$$\frac{\delta t}{t} = \frac{s_{ray} - s_0}{s_0}$$

Where s_0 = average slowness in IC

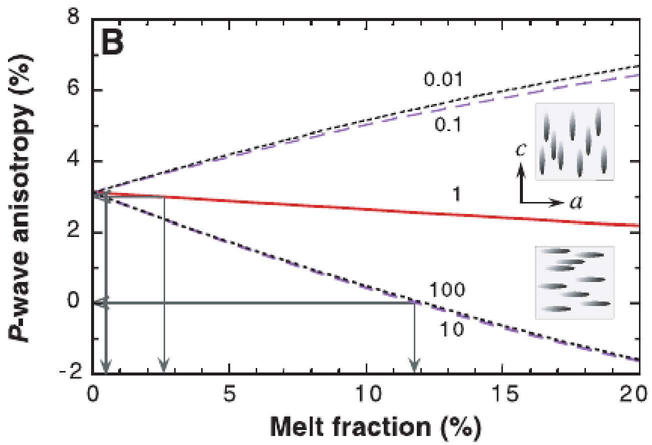
Fitting residuals (hyp : homogeneous IC)

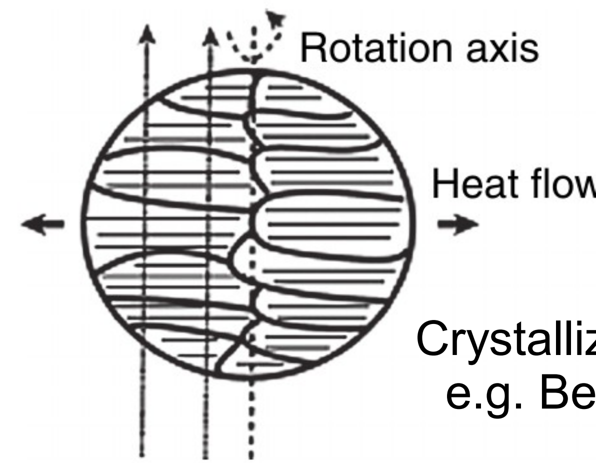
$$\frac{\delta t}{t} = a + b\cos^2\zeta + c\cos^4\zeta$$

Estimate of N-S anisotropy (b + c)
→ global anisotropy 3.8 %

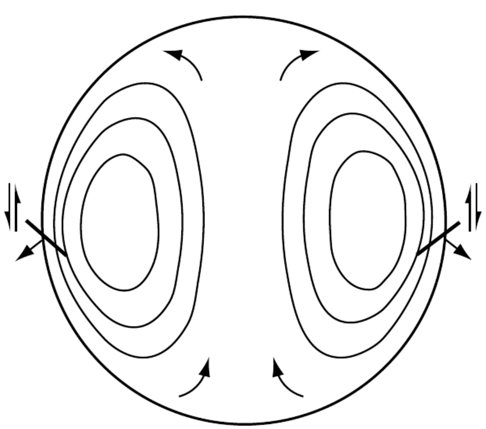
Inner core anisotropy
Global models

Melt inclusions
e.g. Singh et al, 2000

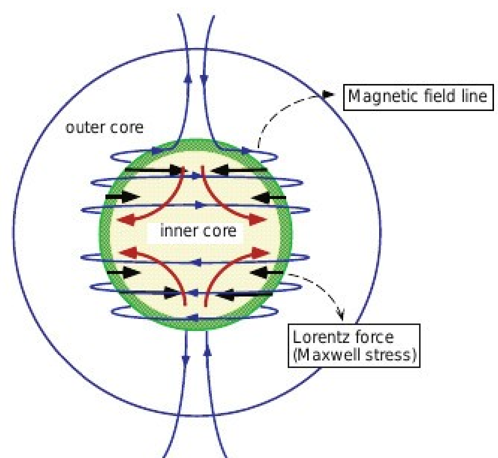




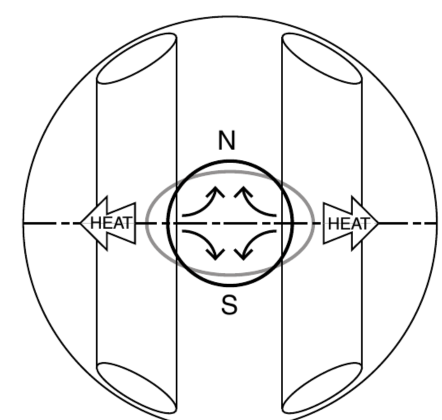
Crystallization textures
e.g. Bergman, 1997



Thermal convection
e.g. Jeanloz and Wenk, 1988

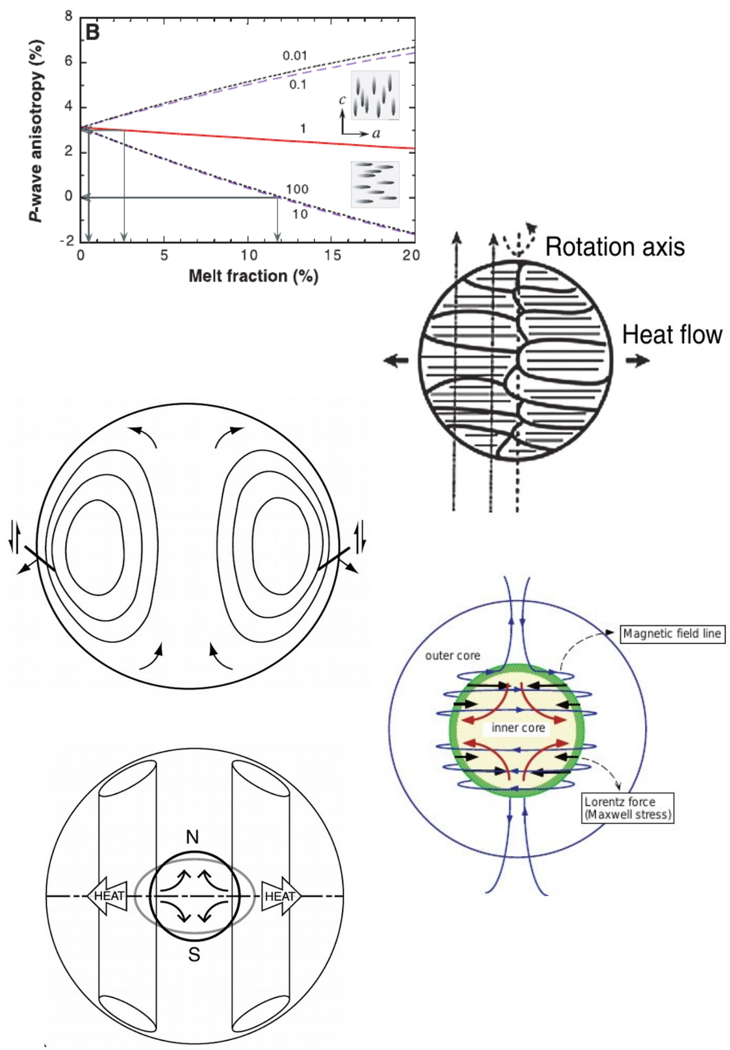


Outer core magnetic forcing
e.g. Karato 1993



Heat extracted from outer core
e.g. Yoshida et al 1996

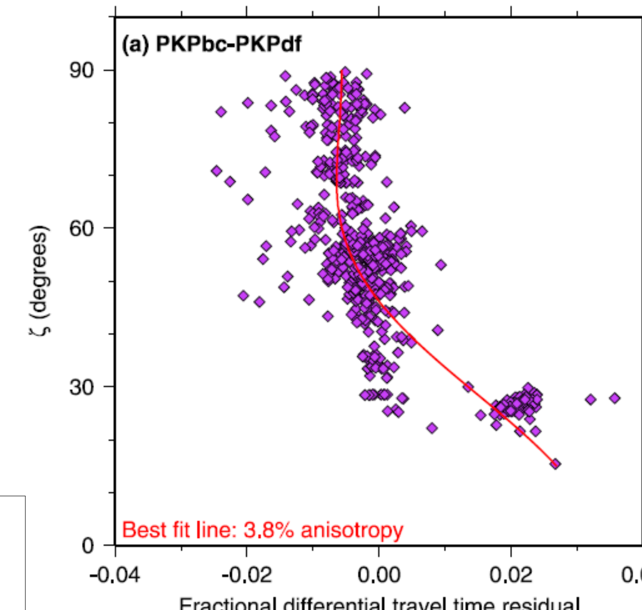
Implications



Models

Observations control on models

Implications for
- inner core present-day structure
- inner core history



Present-day seismic measurement (each dot is data)

Key questions for mineralogists

Crystal structure for inner-core Fe alloy (cubic or hexagonal)

Elasticity

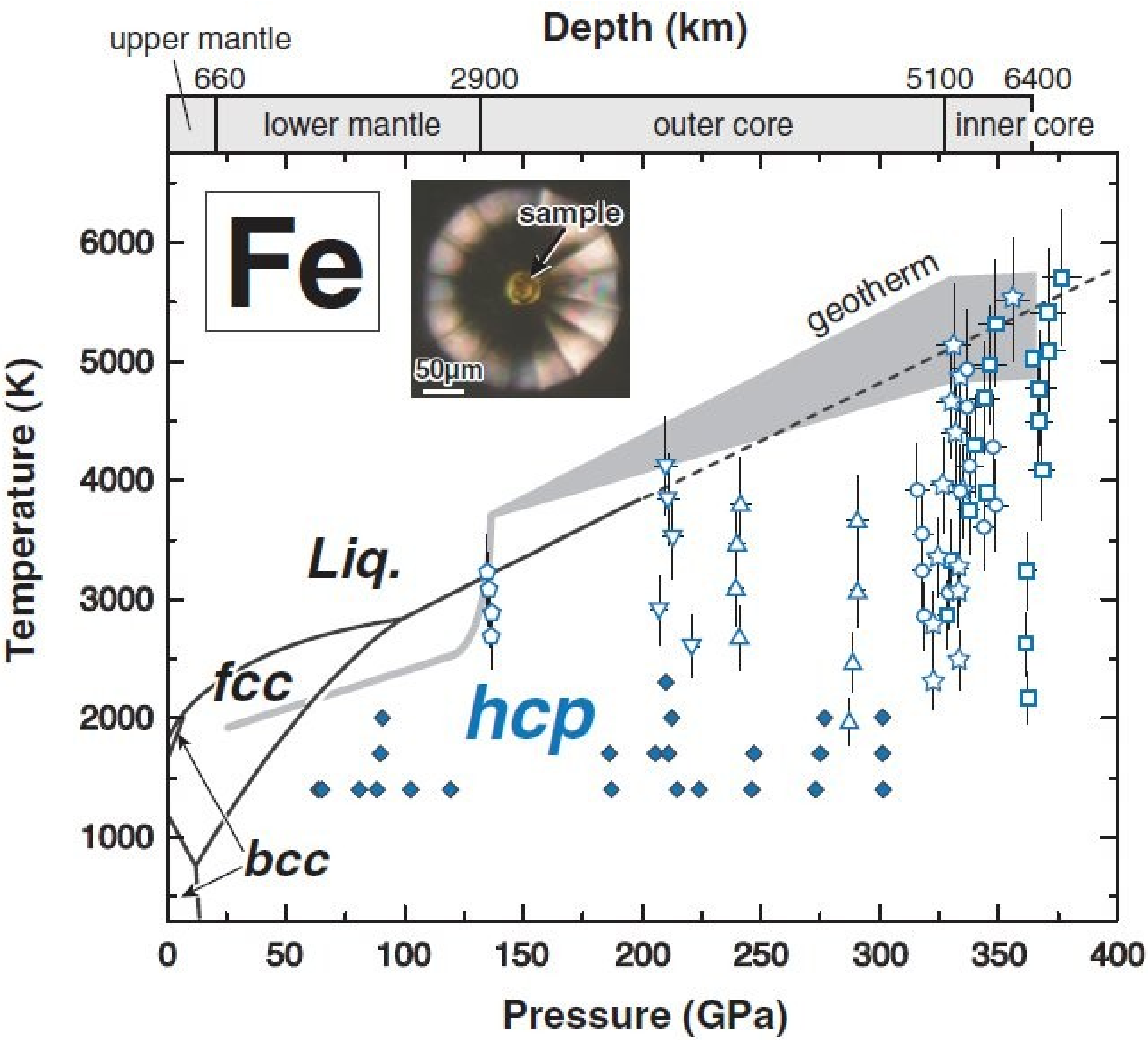
Mechanisms for crystal alignment

- Crystallization
- Plastic deformation

Numerical model for polycrystal behavior

- Model for crystal alignment
- Elasticity at polycrystal scale

High P/T phase diagram for pure Fe



Stable phase of pure Fe at core conditions is ***hcp***

But...

Impurities (light elements) may stabilize other phases such as ***fcc*** or ***bcc***

Tateno *et al*, *Science*, 2010

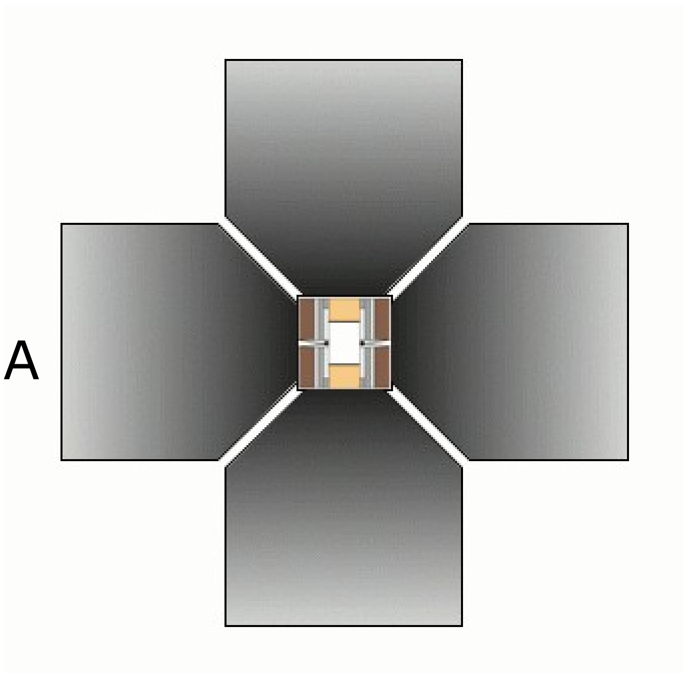
Deformation Experiments on hcp-Fe (old work)

Collaboration

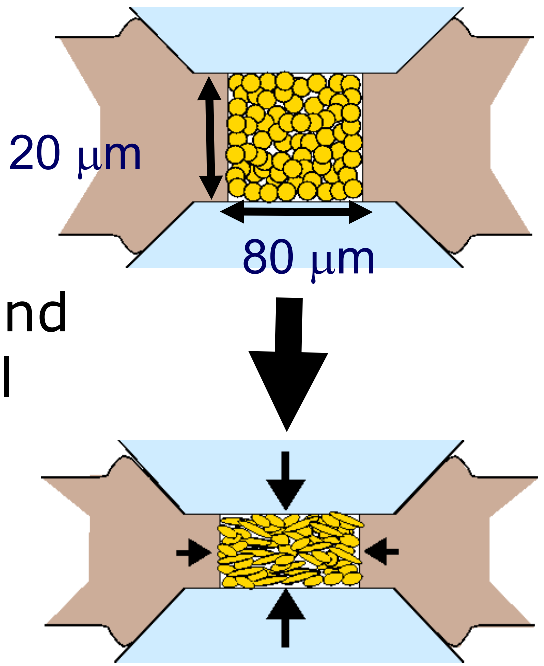
H.-R. Wenk (Berkeley), C.N. Tomé (Los Alamos), L. Miyagi (Utah), N. Nishiyama (Hamburg), Y. Wang (Chicago), and many others...

Plastic deformation at high pressure

D-DIA



Diamond anvil cell

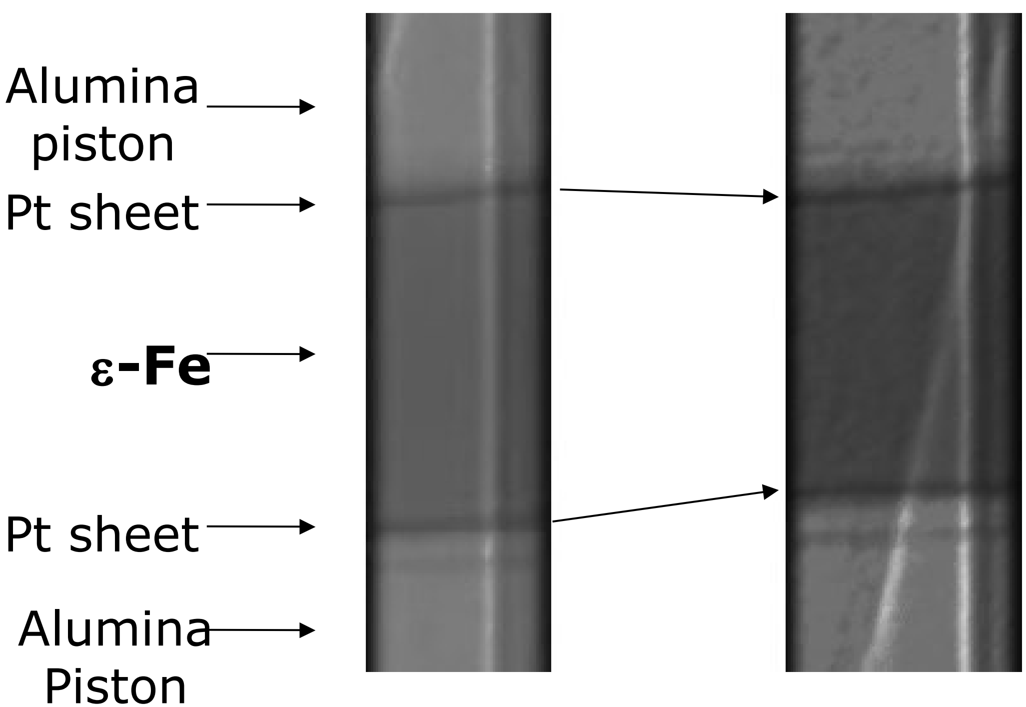


- Controlled axial deformation
- Axial or lateral compression
- Deformation cycling possible
- Constant pressure
- P_{max} ~ 20 GPa - T_{max} ~ 2000 K
- Samples: cylinders, ~mm diam.

- Un-controlled axial deformation
- Pressure increases with deformation
- P_{max} ~ 300 GPa at 300 K
- P_{max} ~ 50 GPa at 1500 K (resistive heating)
- Higher T with laser heating

In-situ measurements

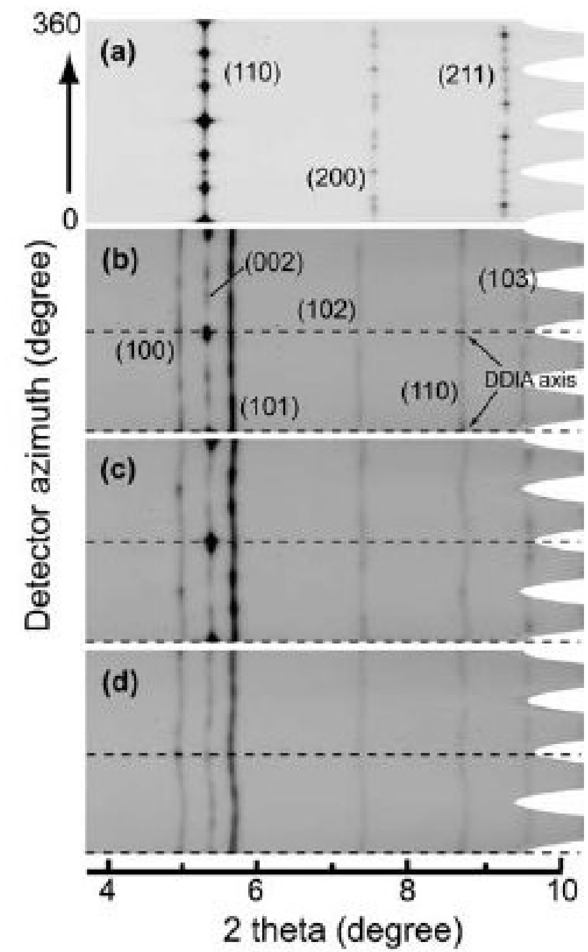
Synchrotron x-ray radiogaphy



T = 400 K
P = 17.0 GPa
t = 0
ε = 0

T = 400 K
P = 17.0 GPa
t = 11 h 37 min
ε = 10,7%

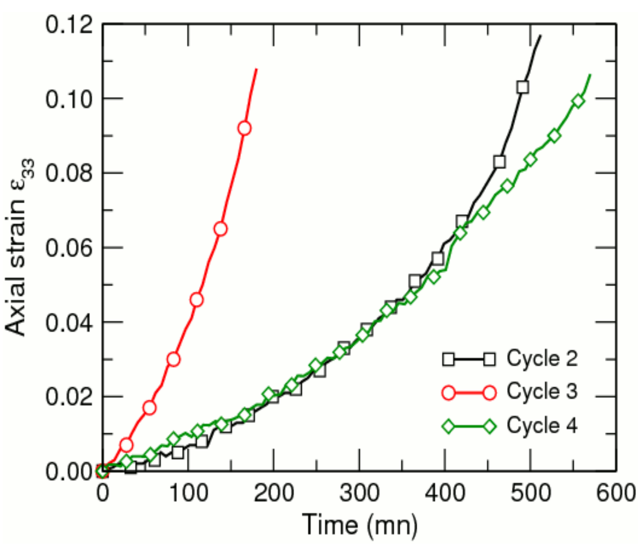
Synchrotron x-ray diffraction



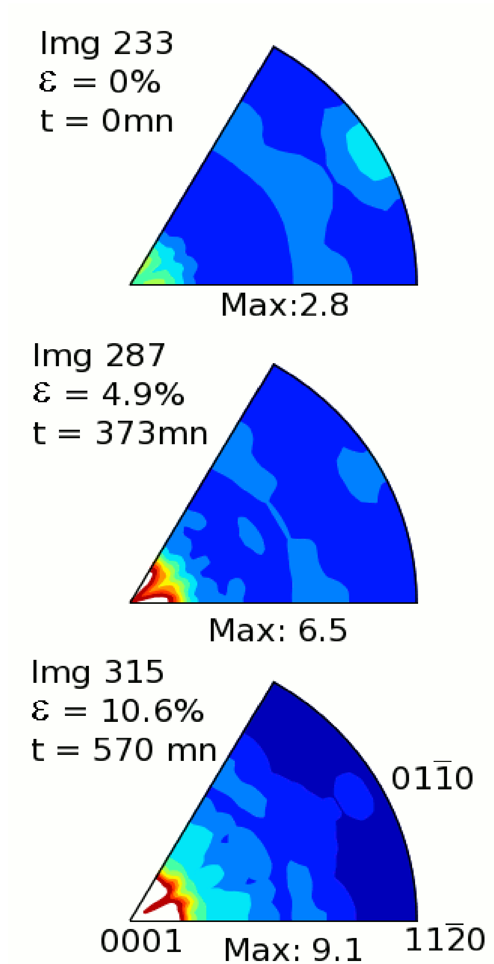
Experimental results

Hcp-Fe in the D-DIA
P ~ 17 GPa
T ~ 400-600 K

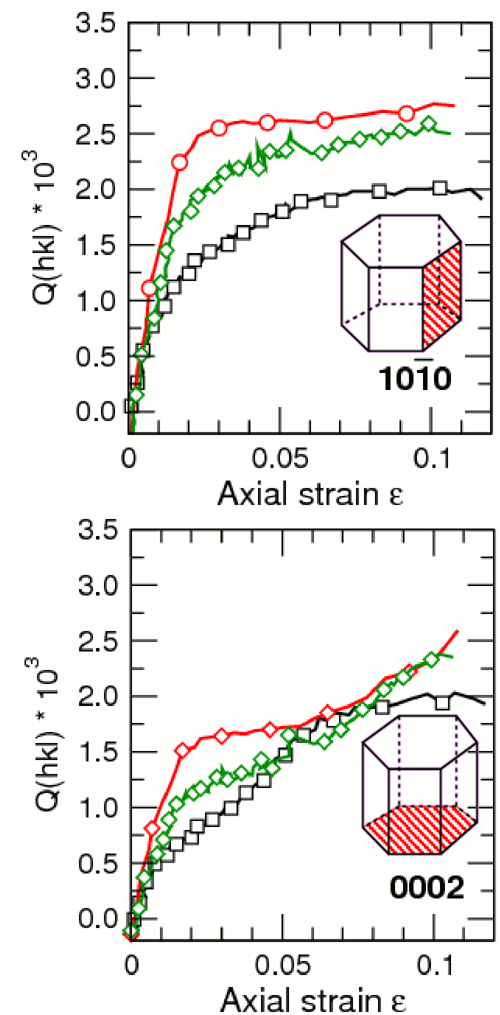
Macroscopic strain
vs. time



Polycrystal textures
vs. strain

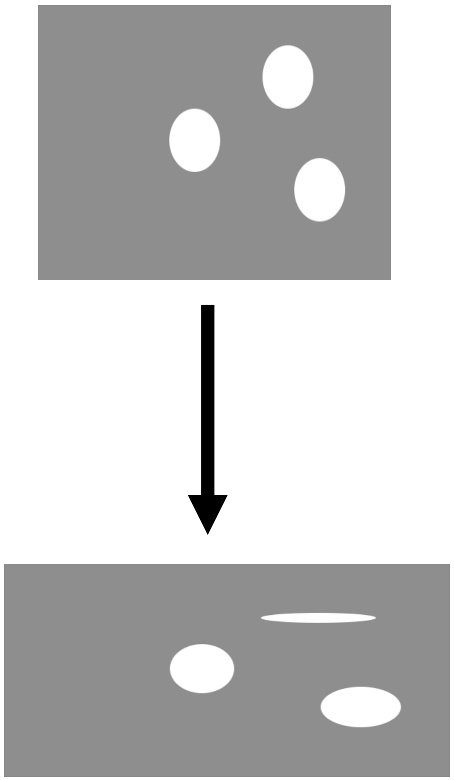


Microscopic vs.
macroscopic strain



Merkel *et al*,
Modelling Simul. Mater. Sci. Eng. 2012

Interpretation of experimental results
Polycrystal plasticity



Self-consistent polycrystal plasticity

- Iterative calculation
- Grain = ellipsoidal inclusion in homogeneous matrix

Parameters

- Sample phases
- Crystal structures
- Elasticity
- Plastic deformation mechanisms
- Deformation geometry

Approximations

- Elasto-plastic
- Visco-plastic
- Elasto-visco-plastic

Uses

- Interpretation of experimental data
- Modeling of polycrystal behavior

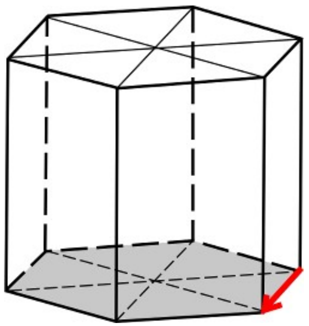
Codes : Los Alamos (EPSC, VPSC, EVPSC, C. Tomé, R. Lebensohn)
Paris (VPSC, O. Castelnau), etc

Results for hcp-Fe

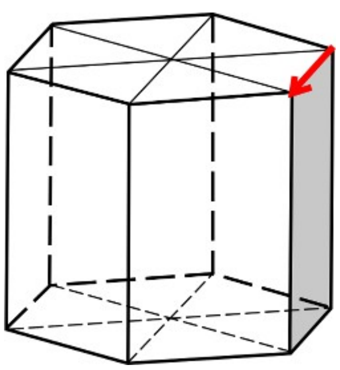
Plastic mechanisms for hcp-Fe

- 300 K, up to 200 GPa (DAC):
  basal slip + twinning dominant
- 17 GPa, up to 600 K (D-DIA):
  activity of pyramidal <c+a> increases
  less twinning
- 30 GPa, 2000 K (DAC)
  basal and pyramidal <c+a> slip
- Full self-consistent model of D-DIA experiments

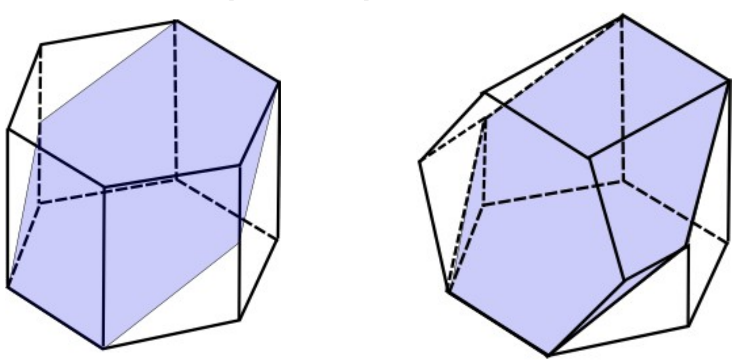
Basal slip



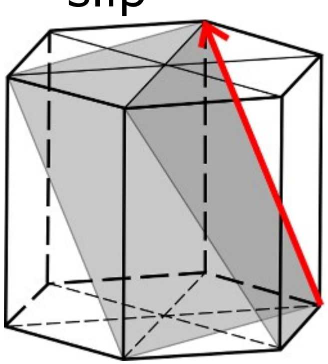
Prismatic slip



{$10\bar{1}2$} twins



Pyramidal <c+a> slip



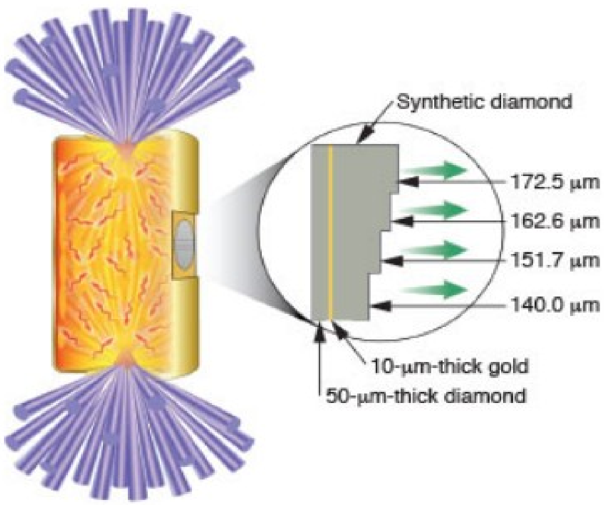
Wenk *et al* Nature, 2000
Merkel *et al* PEPI, 2004
Miyagi *et al* JAP, 2008
Merkel *et al* MSME, 2012

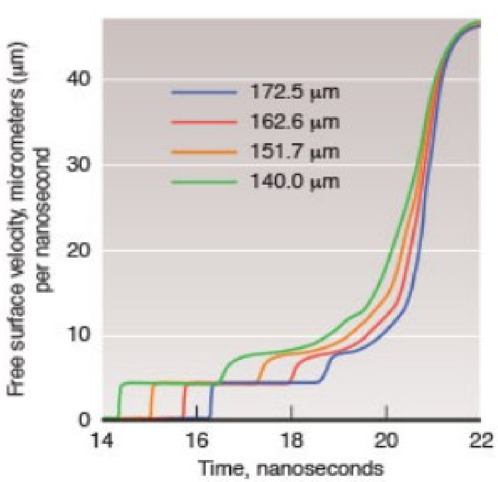
New Experiments
Dynamic compression of
of Fe Alloys

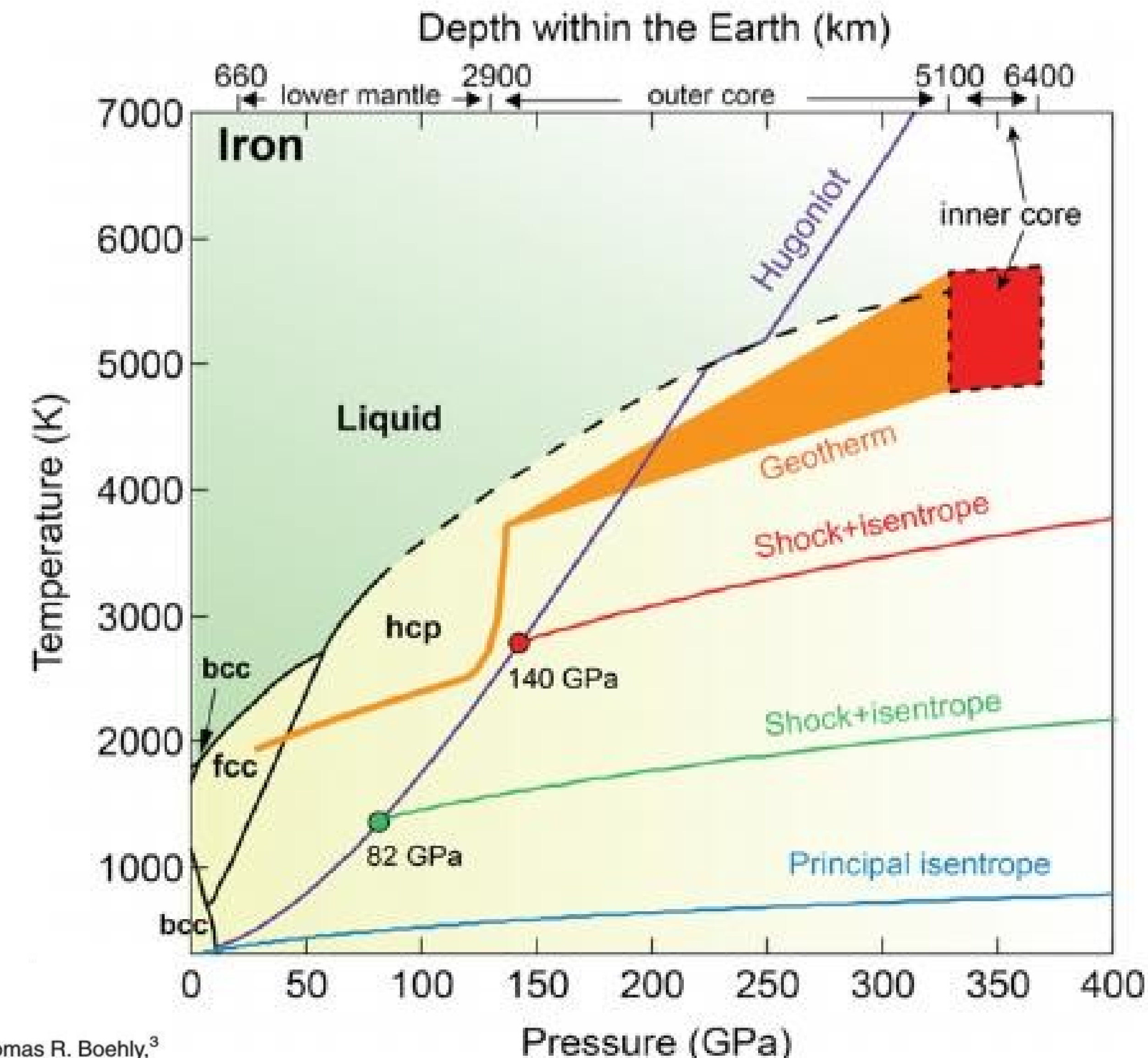
Collaboration

A. Gleason, C. Bolme (Los Alamos)
W. Mao (Stanford)

Laser Compression





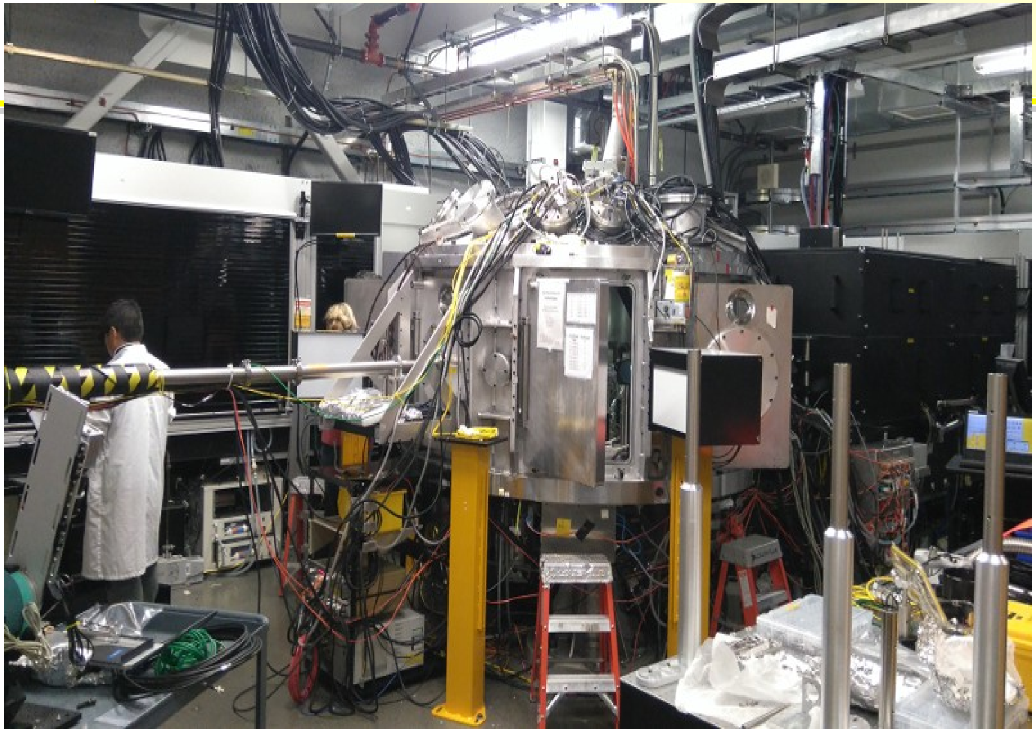


JOURNAL OF APPLIED PHYSICS **114**, 023513 (2013)

Ramp compression of iron to 273 GPa

Jue Wang,[1] Raymond F. Smith,[2] Jon H. Eggert,[2] Dave G. Braun,[2] Thomas R. Boehly,[3] J. Reed Patterson,[2] Peter M. Celliers,[2] Raymond Jeanloz,[4] Gilbert W. Collins,[2] and Thomas S. Duffy[1]

X-ray free electron laser + laser compression
In-situ plasticity studies



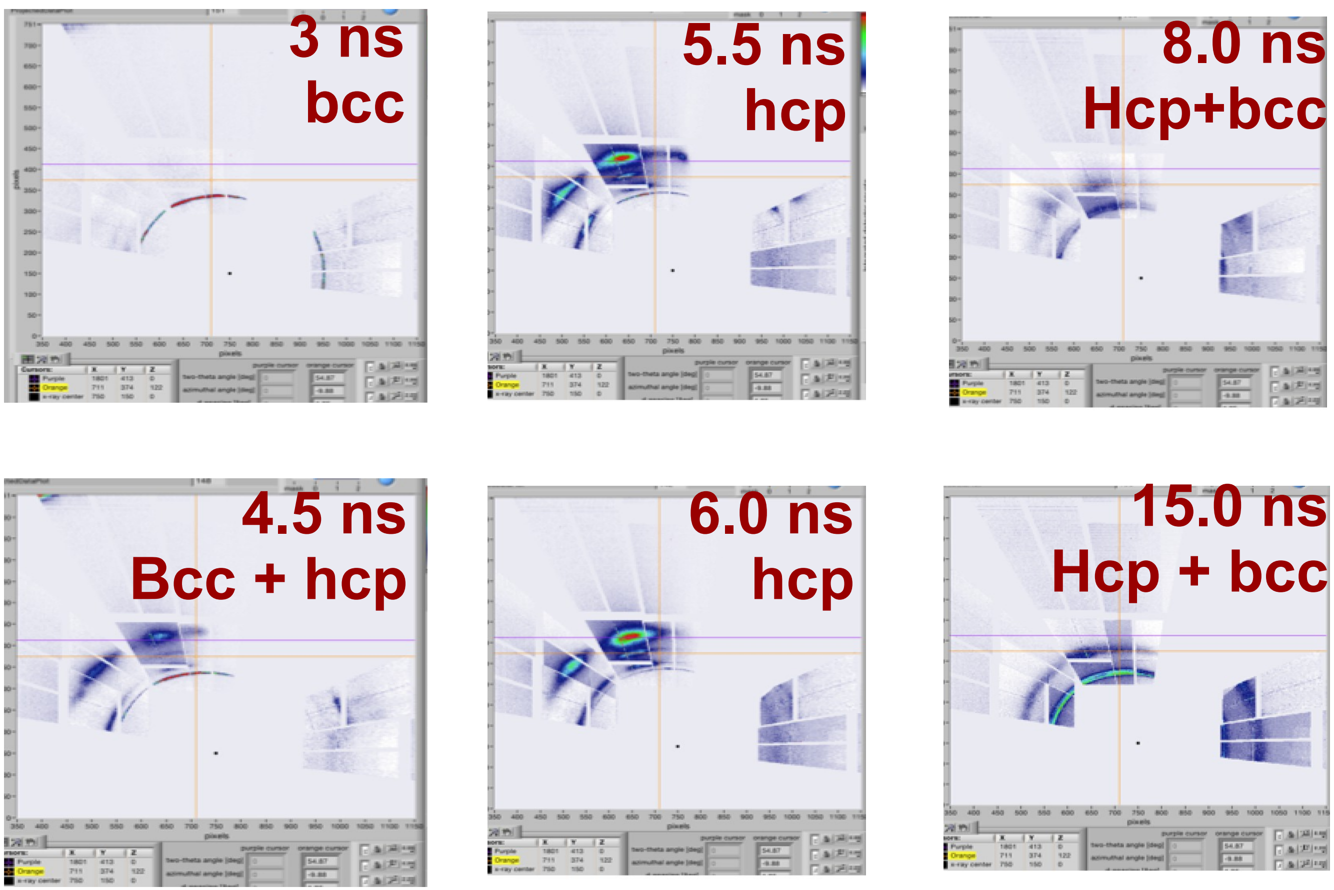
MEC beamline at
LCLS/SLAC, Stanford

Preliminary Analysis

Peak shock pressure: ~ 140 GPa

T ~ 2000-3000 K

Diffraction pattern at multiple times: before, during, and after the shock



In-situ x-ray diffraction

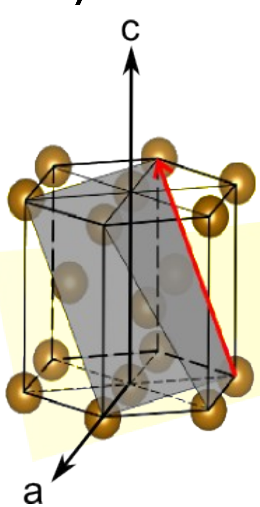
Evidences for

- Phase transition to hcp
- Full hcp
- Back-transformation to bcc

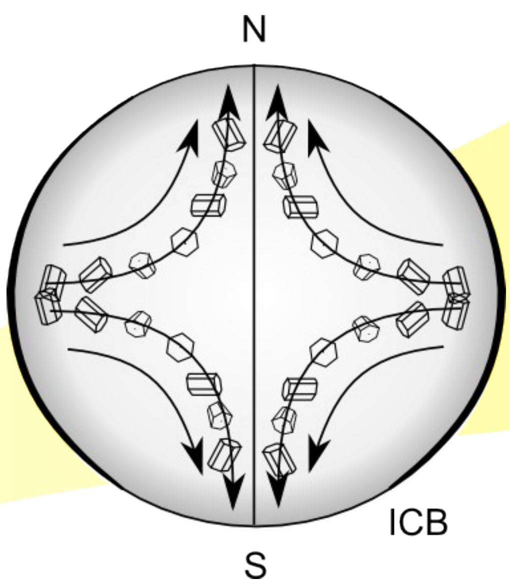
Inner Core Anisotropy Model

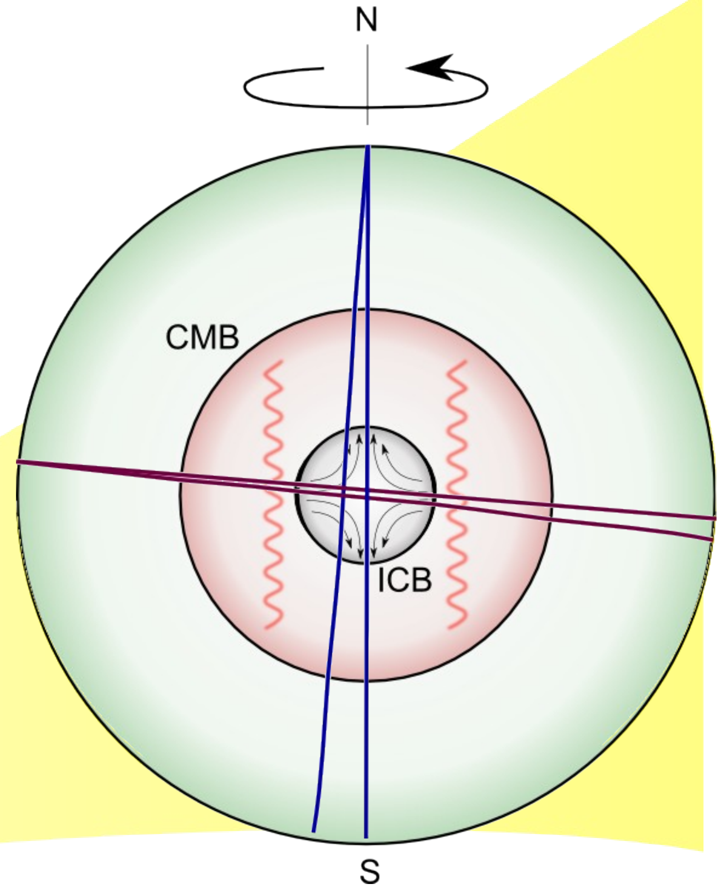
Inner core anisotropy
Multi-scale forward model

1 : Choose microscopic model for inner core Fe-alloy



2 : Build virtual inner core
- Dynamics
- Crystals orientations
- Local seismic velocities





3 : Present-day seismic response
- Virtual rays in virtual inner core
- Estimate anisotropy

Objectives

Literature

- Multiple models for inner formation, multiple choices for structure of inner core Fe-alloy, multiple sets of elastic moduli
- No integrated model of inner core anisotropy

This work

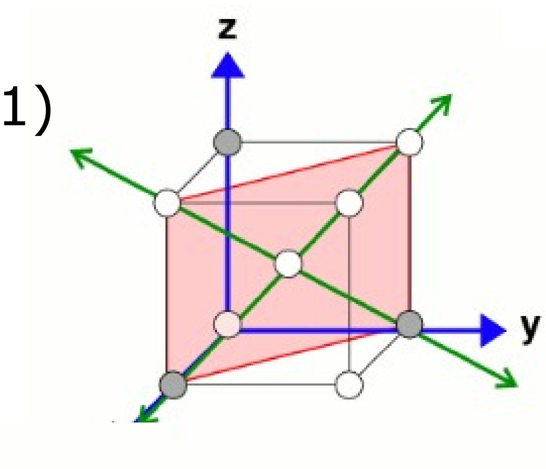
- Multiscale forward model:
  core formation geodynamical model
  single crystal deformation and elasticity
  seismic measurement simulation

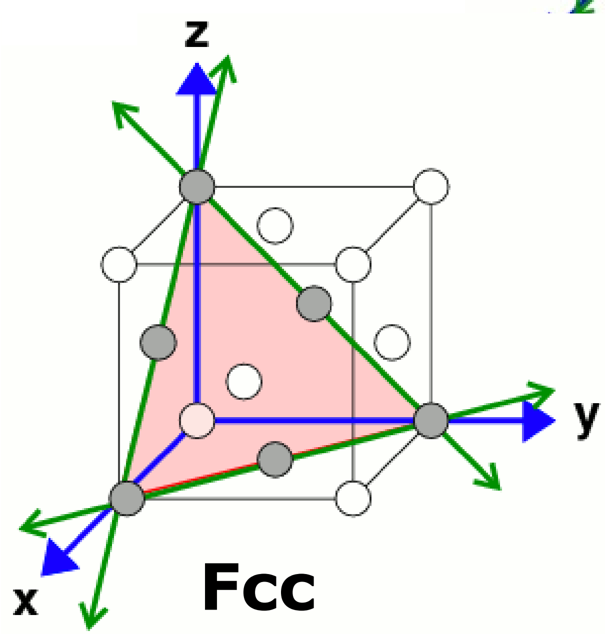
Objectives

- Can we even get 3% global IC anisotropy?
- Crystal structure, deformation, elasticity of IC Fe-alloy?
- What is driving inner core dynamics?

Single crystal: Fe structures

Bcc
Slip on (011)

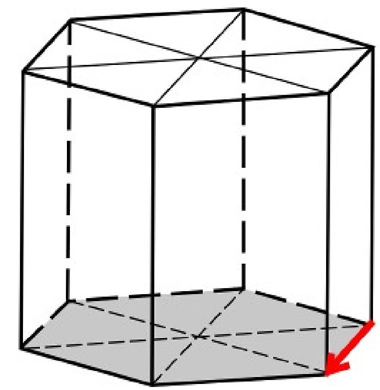




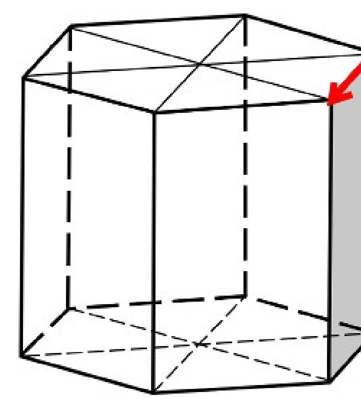
Fcc
Slip on (111)

Hcp

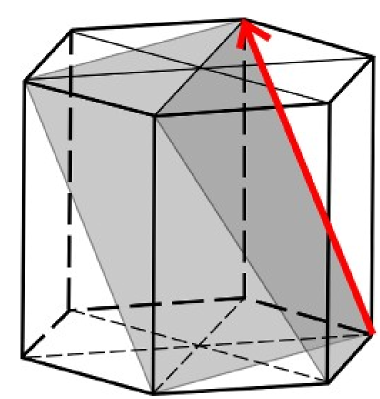
Basal slip



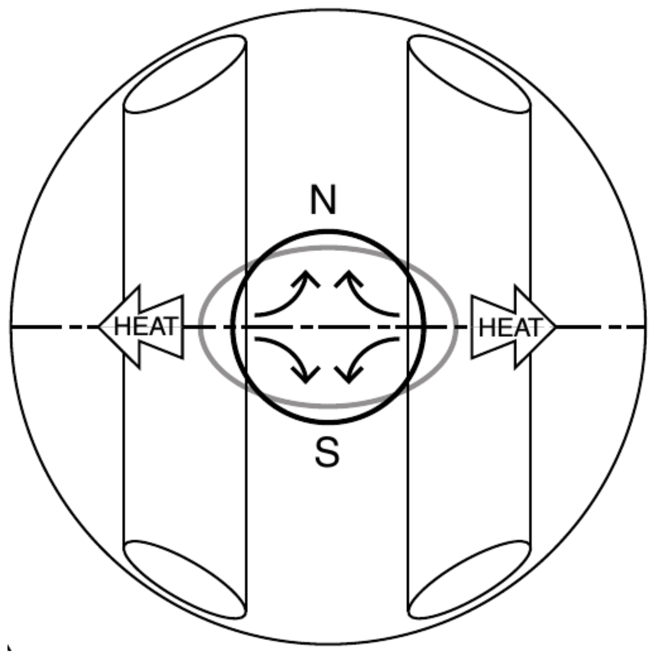
Prismatic slip



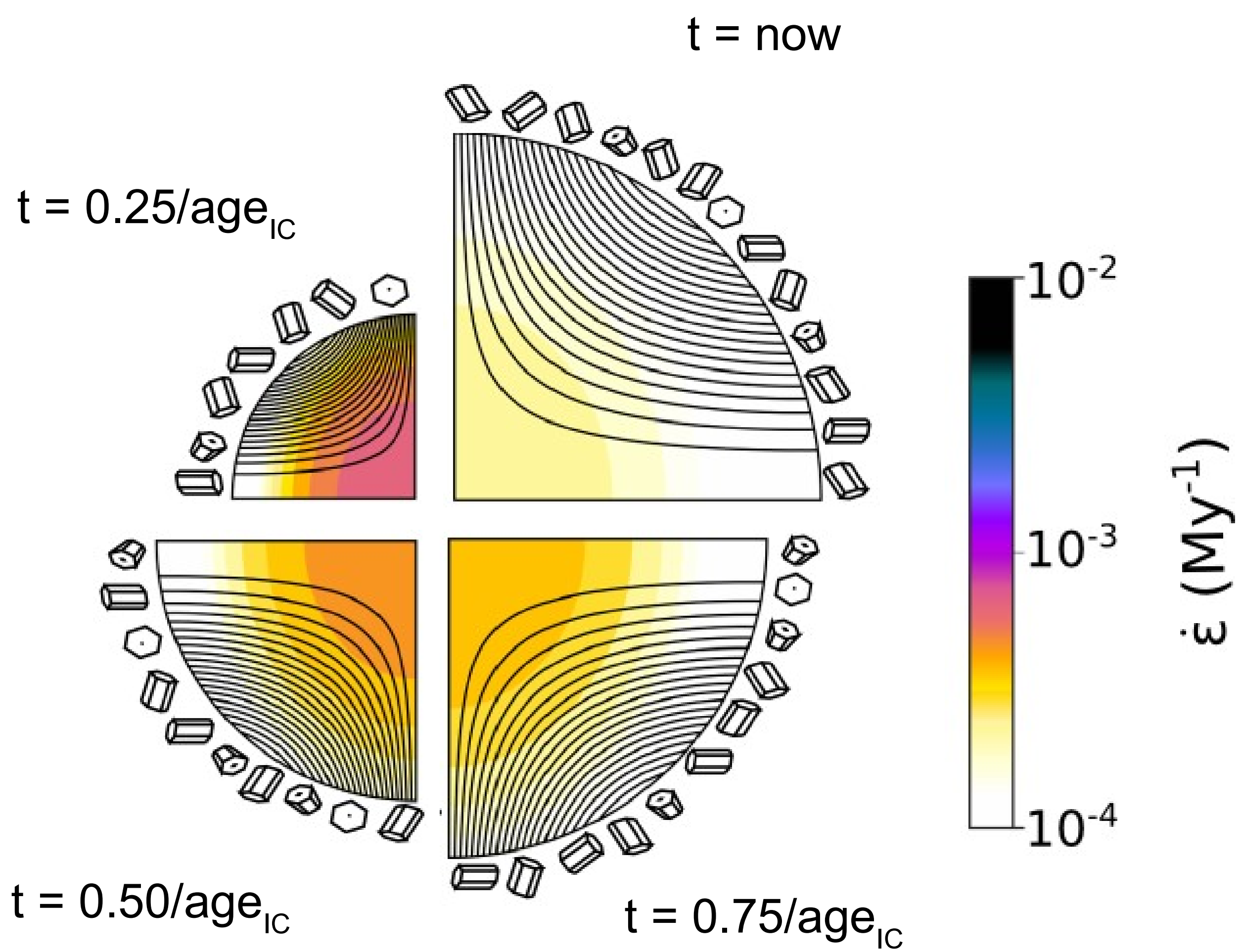
Pyramidal <c+a> slip



Core formation model
Preferrential growth at the equator

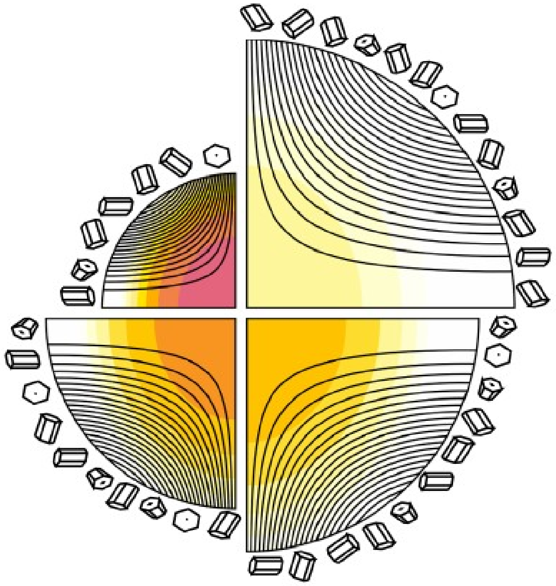


- Only model with large deformation (100%)
- Axisymmetric deformation
- Compatible with observations of a N-S component of seismic anisotropy

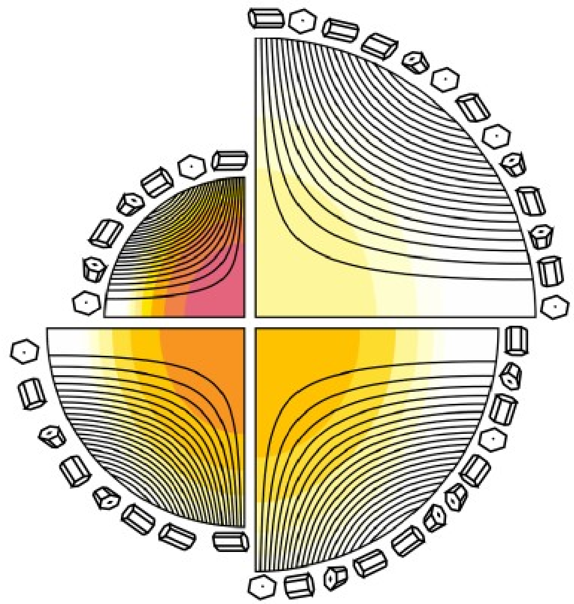


Yoshida *et al*, 1996

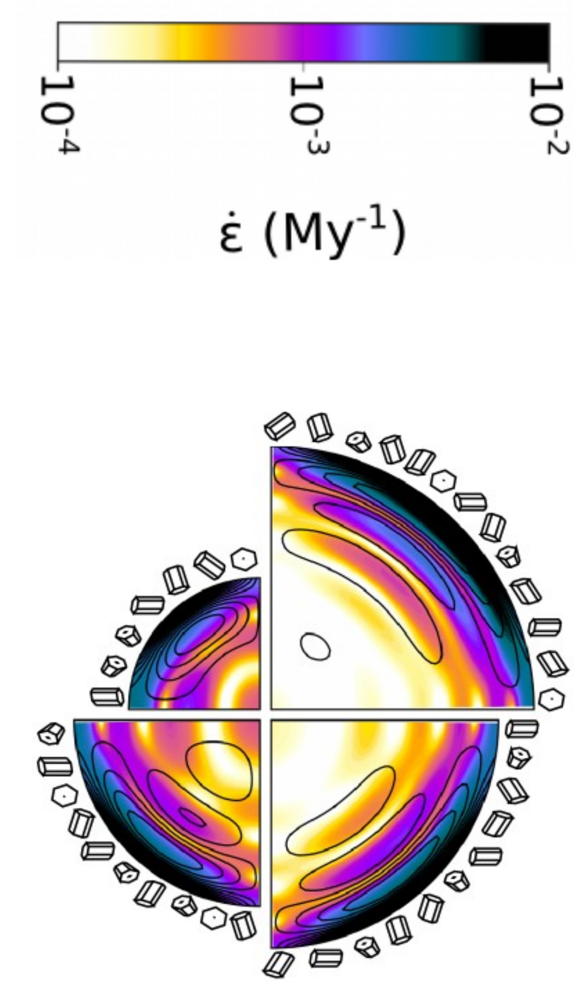
Extensions



Preferential growth
Random crystallization
Yoshida *et al*, 1996



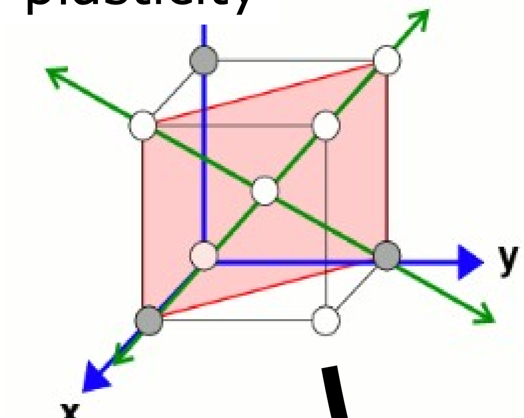
Preferential growth
Crystallization textures
Yoshida et al, 1996 +
Bergman *et al*, 1997



Preferential growth
with chemical stratification
Deguen *et al*, 2009

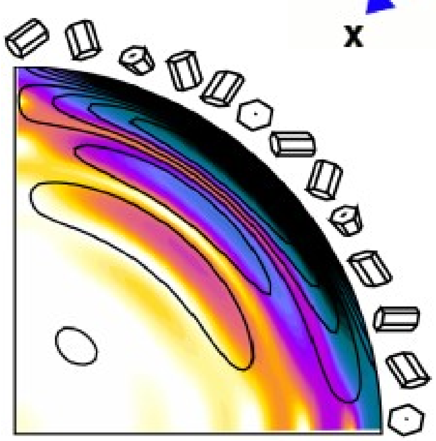
Virtual inner core

Crystal structure
Polycrystal plasticity

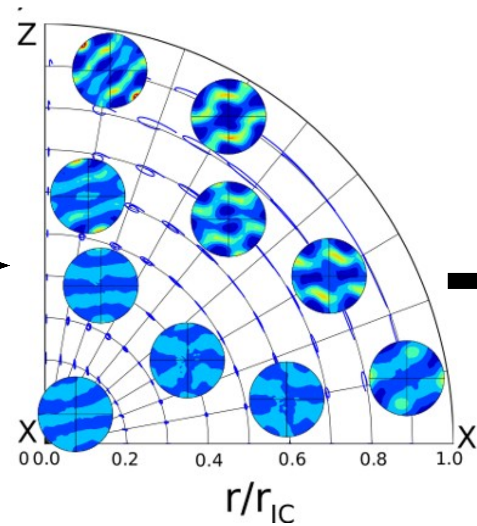


$$\begin{pmatrix} c_{11} & c_{12} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{12} & c_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{pmatrix}$$

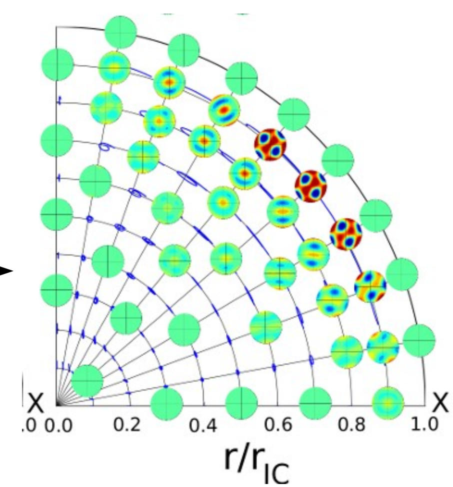
Elasticity



Core formation model



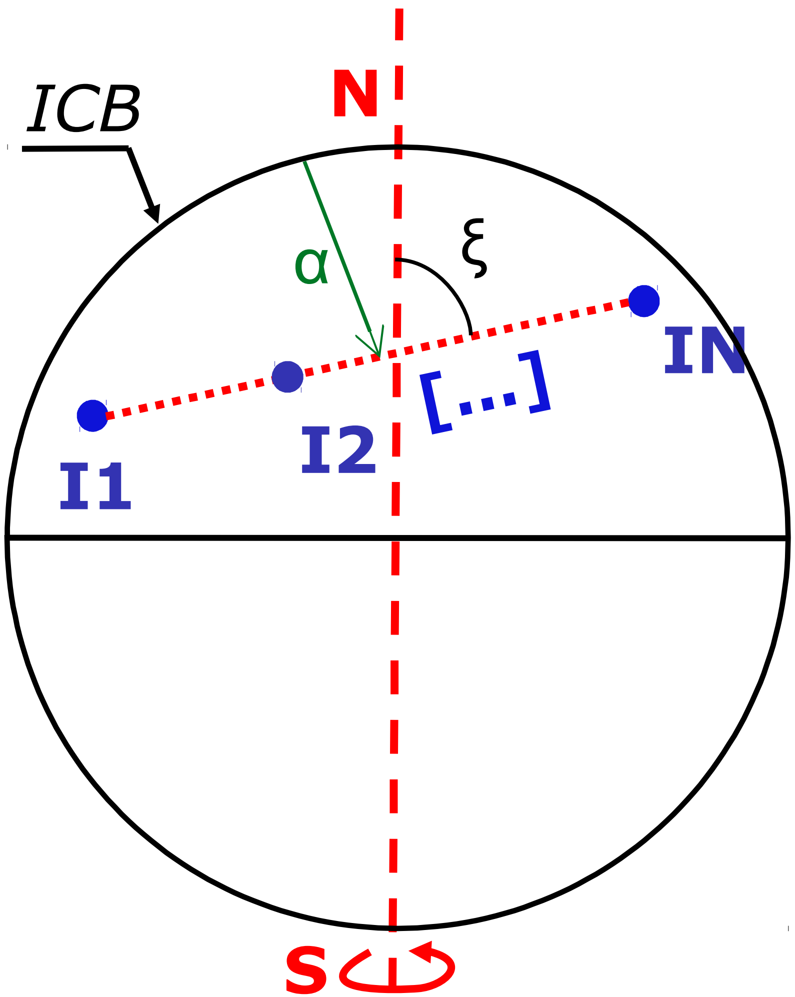
Present-day inner core textures



Present-day inner velocities

Lincot *et al*, *Geophys. Res. Lett*. 2015

Virtual inner core: seismic response



Procedure

- Choose random ray path
- Calculate velocity at each point along the ray
- Slowness: $<s> = 1/<V_P>$
- Seismic residual $\delta t/t=(<s>-s_0)/s_0$

Repeat 300 000 times...

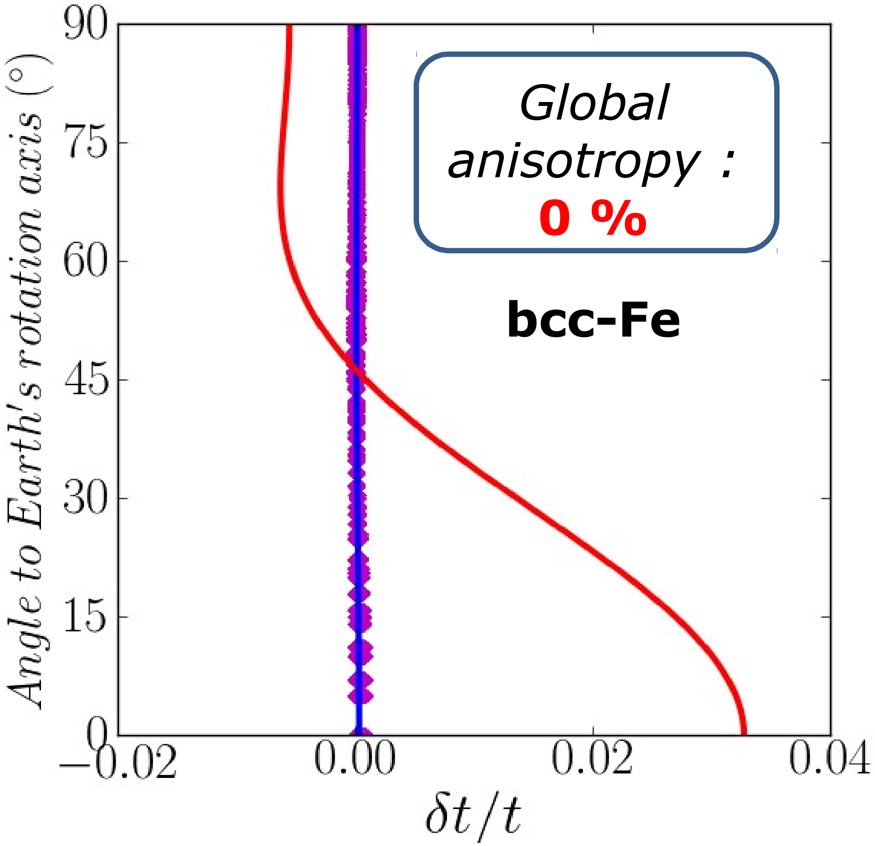
Plot results as seismologists do

- Residual vs.
  - Angle to rotation axis (ξ)
  - Depth of the ray (α)

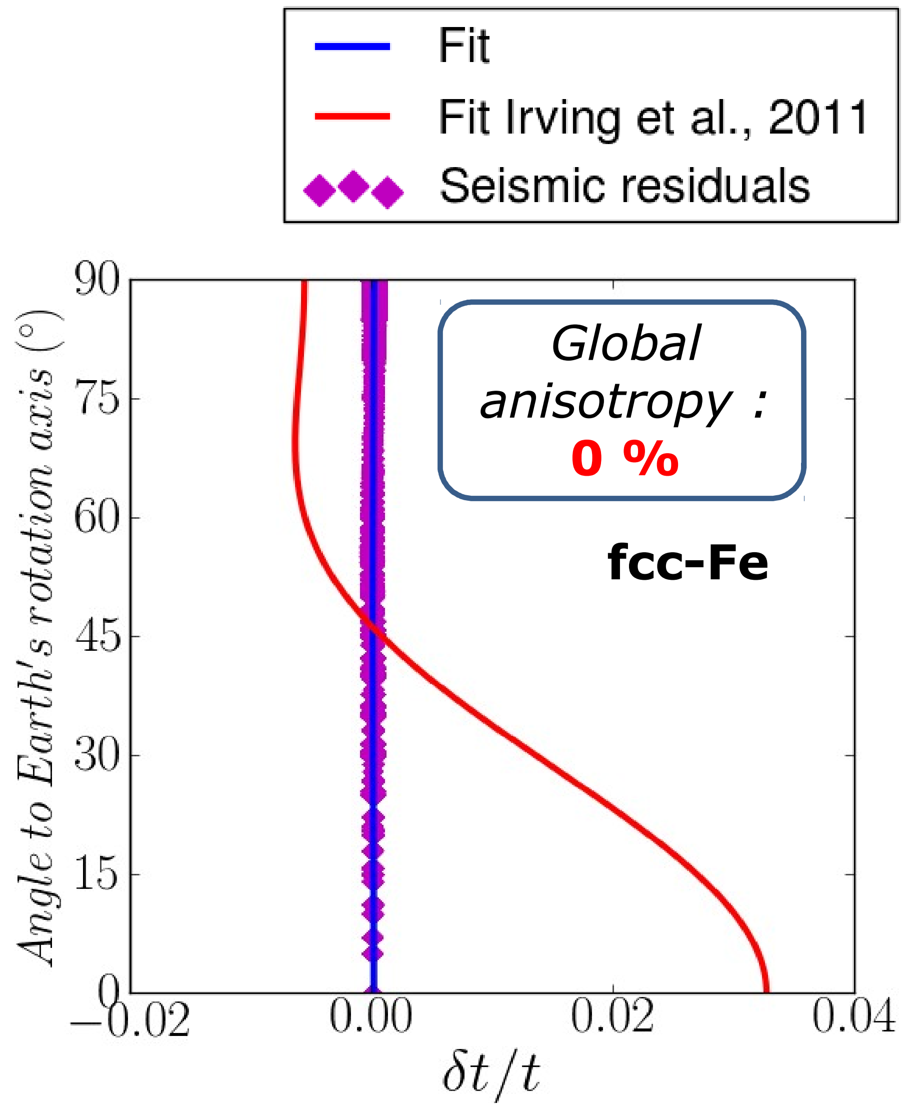
Lincot *et al*, *C.R. Geosc.* 2014

Virtual inner core seismic response Cubic-Fe

Cubic-Fe
Preferential growth at equator
No solidification texture
No chemical stratification



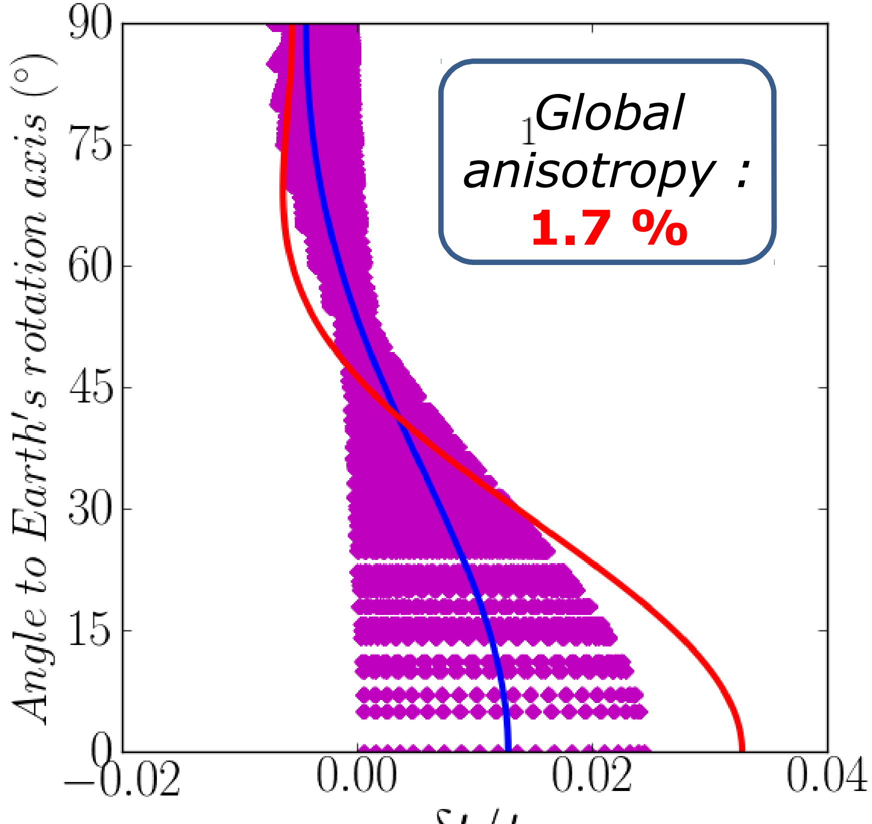
Elasticity
Vocadlo *et al* (2007)



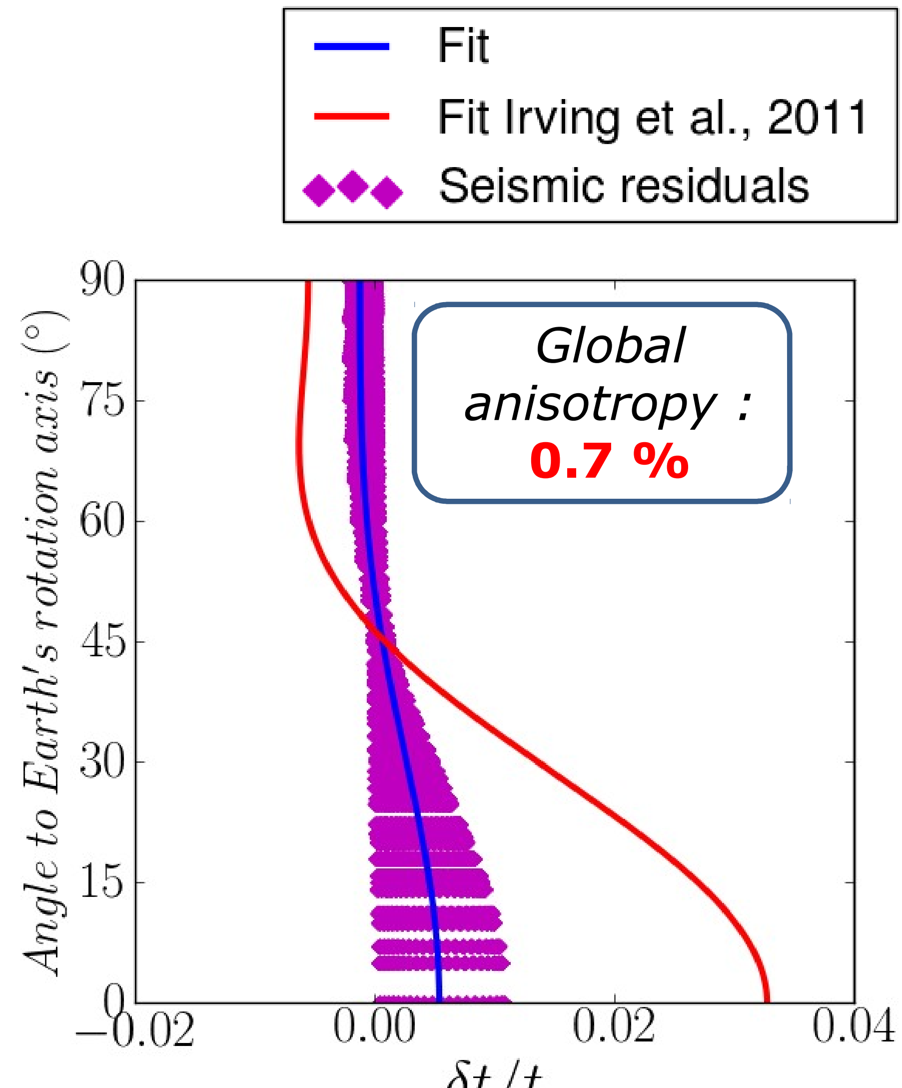
Elasticity
Vocadlo *et al* (2008)

Virtual inner core seismic response hcp-Fe

Hcp-Fe, dominant basal slip
Preferential growth at equator
No solidification texture
No chemical stratification



Elasticity
Steinle-Neumann *et al* (2001)



Elasticity
Vocadlo et al. (2009)

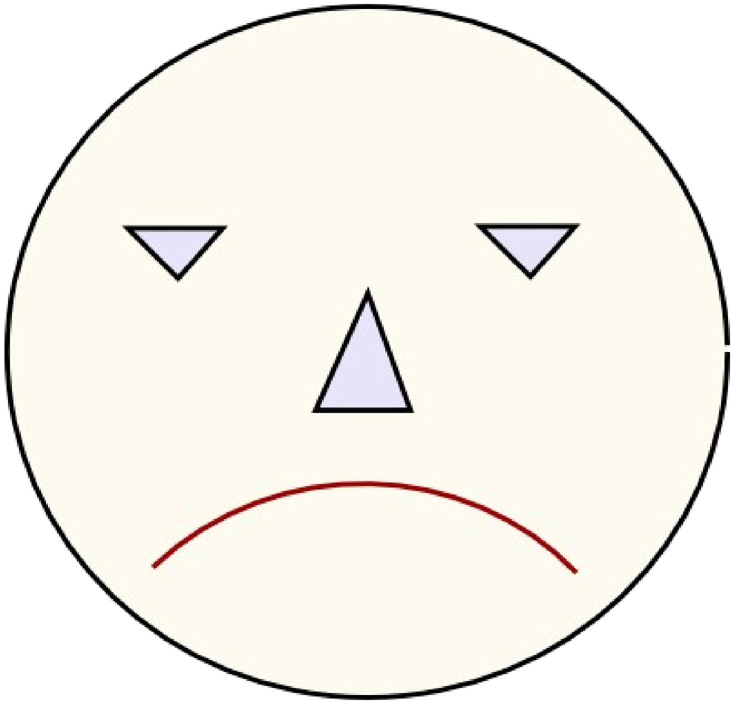
Core formation models

Core formation model

Deformation based on flow in core-formation model

Additions: stratification, crystallization textures

Elastic moduli from the literature

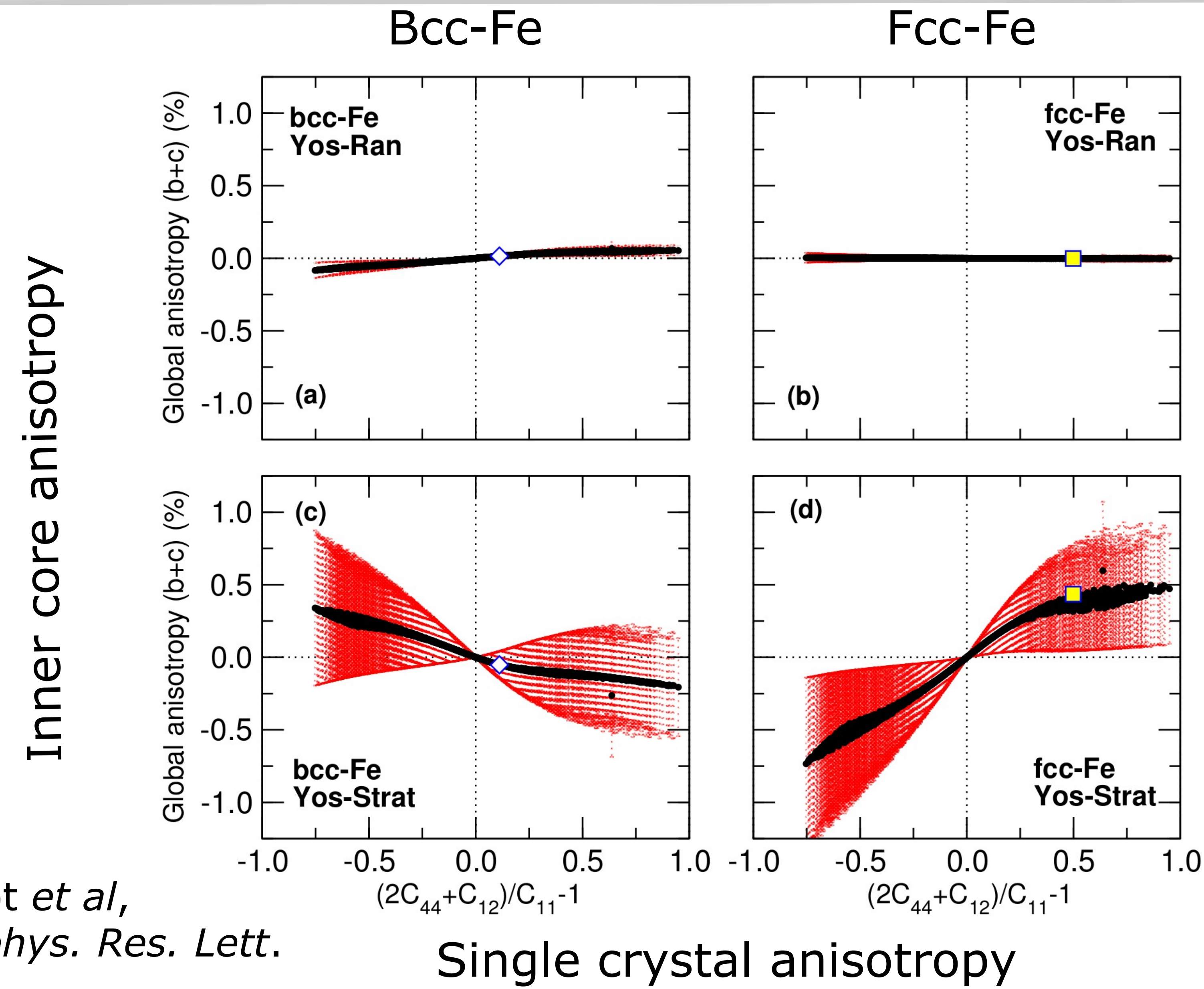


Lincot *et al*, *C.R. Geosc.* 2014

Extension of the work

- Difficult to get ~3% global seismic anisotropy
- Room for improvement:
  - Geodynamics :
    - locked (difficult to produce more deformation with a quadrupolar flow)
  - Choice of plastic mechanism
    - Multiple choices for hcp-Fe
  - Elasticity :
    - hcp-Fe : large panel of single crystal anisotropy
    - cubic-Fe : only a few models published
- Solution
  - Test multiple slip systems for hcp-Fe
  - Monte-Carlo search for elastic moduli: test all possible sets of elastic moduli for the inner core Fe-alloy

Results: cubic-Fe



Preferential growth at equator

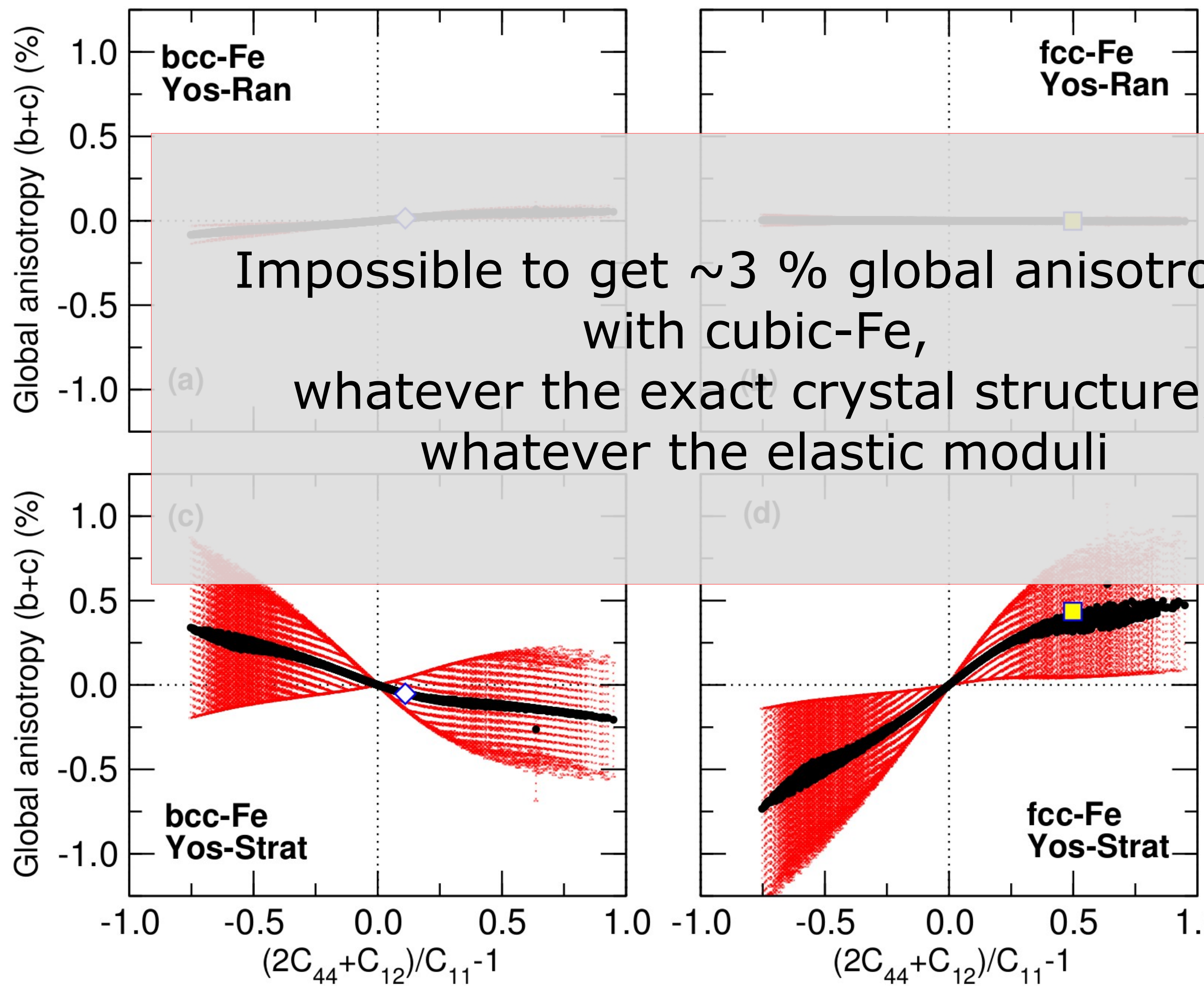
Preferential growth at equator
+
Chemical stratification

Lincot *et al*, *Geophys. Res. Lett*. 2015

Results: cubic-Fe

Bcc-Fe | Fcc-Fe

Inner core anisotropy



Single crystal anisotropy

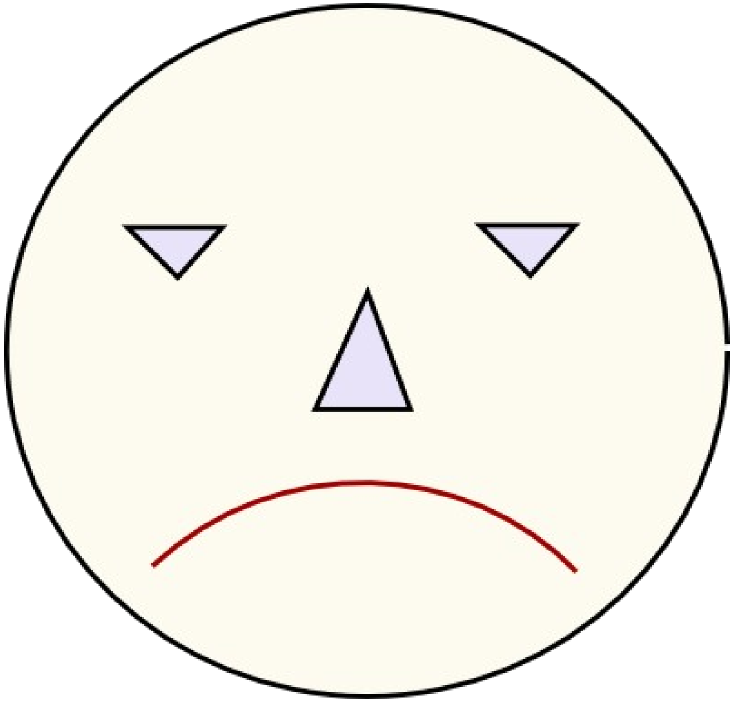
Impossible to get ~3 % global anisotropy with cubic-Fe, whatever the exact crystal structure, whatever the elastic moduli

Preferential growth at equator

Preferential growth at equator + Chemical stratification

Lincot *et al*, *Geophys. Res. Lett*. 2015

Cubic structure for Fe?



Lincot *et al*, *GRL* 2015

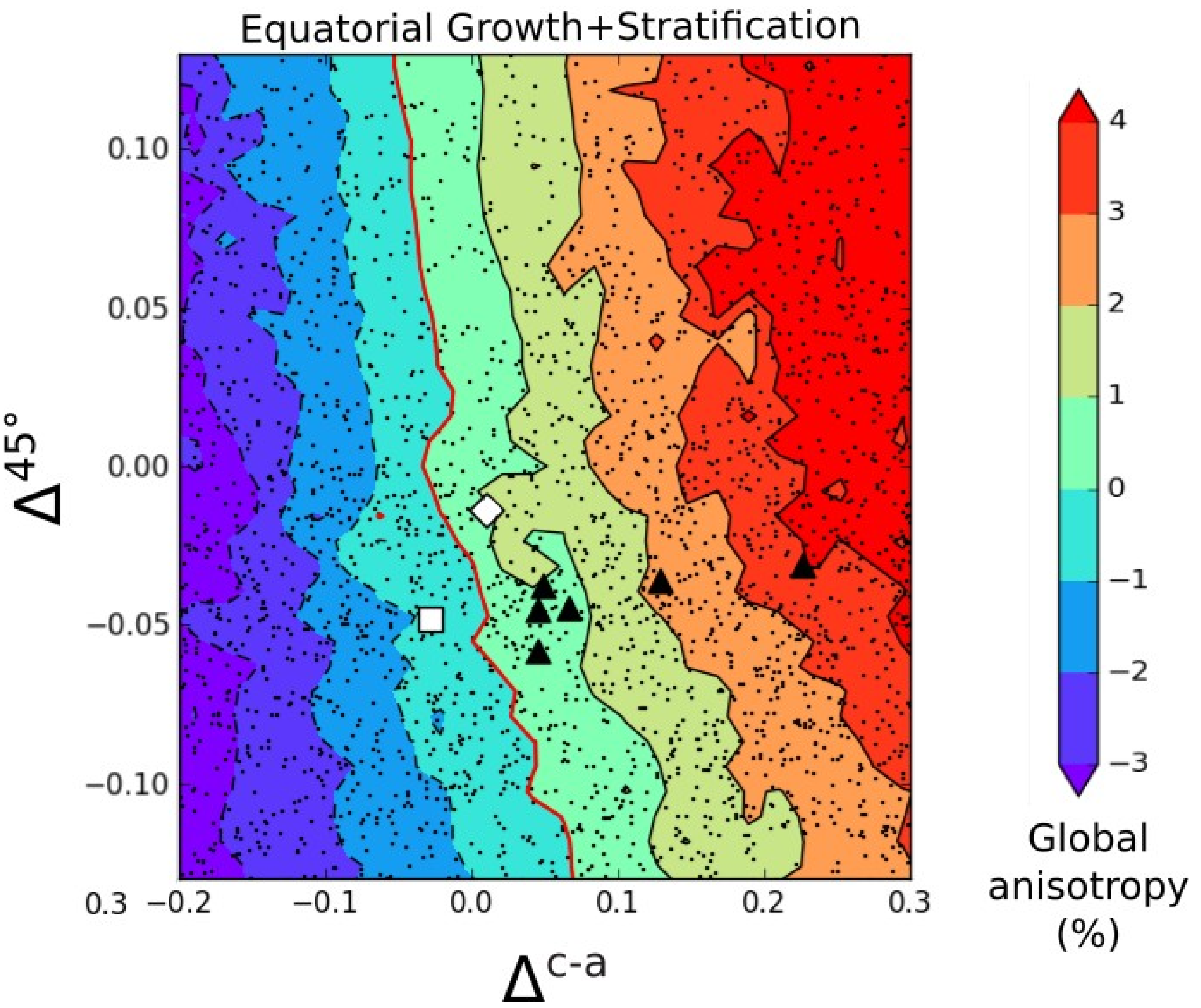
Global anisotropy results: hcp-Fe

Hcp-Fe

Preferential growth at equator with chemical stratification

Dominant pyramidal slip

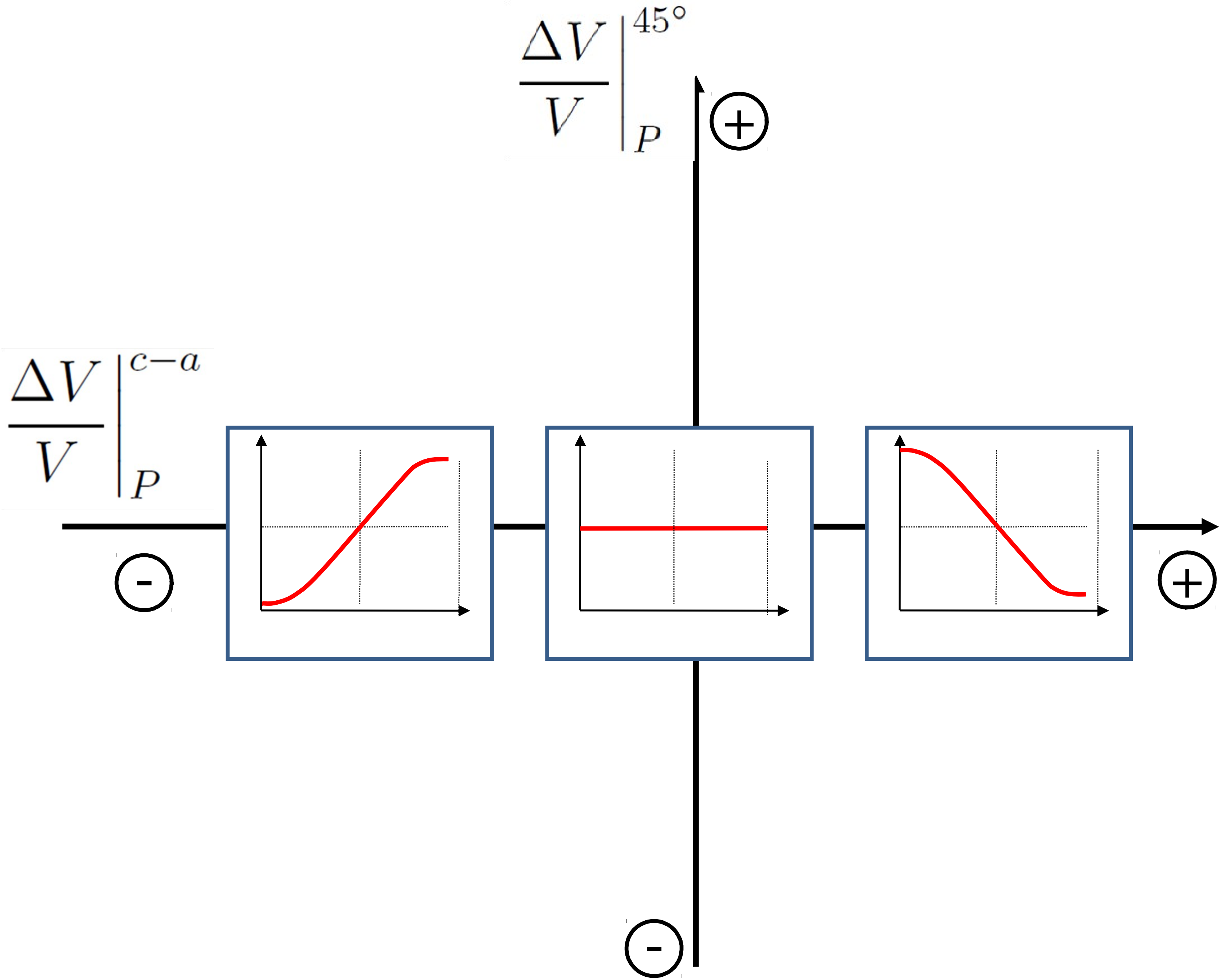
5000 sets of elastic moduli tested

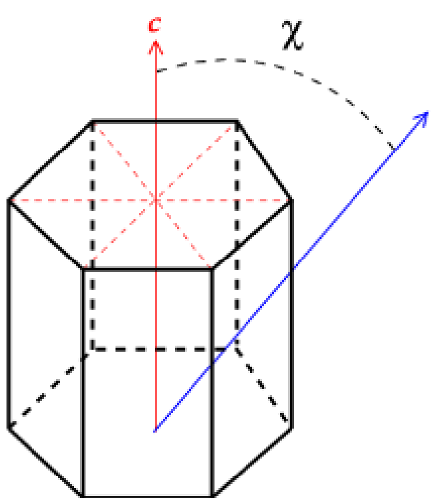


Lincot *et al*, *Geophys. Res. Lett*. 2016

Hcp elastic anisotropy parameters

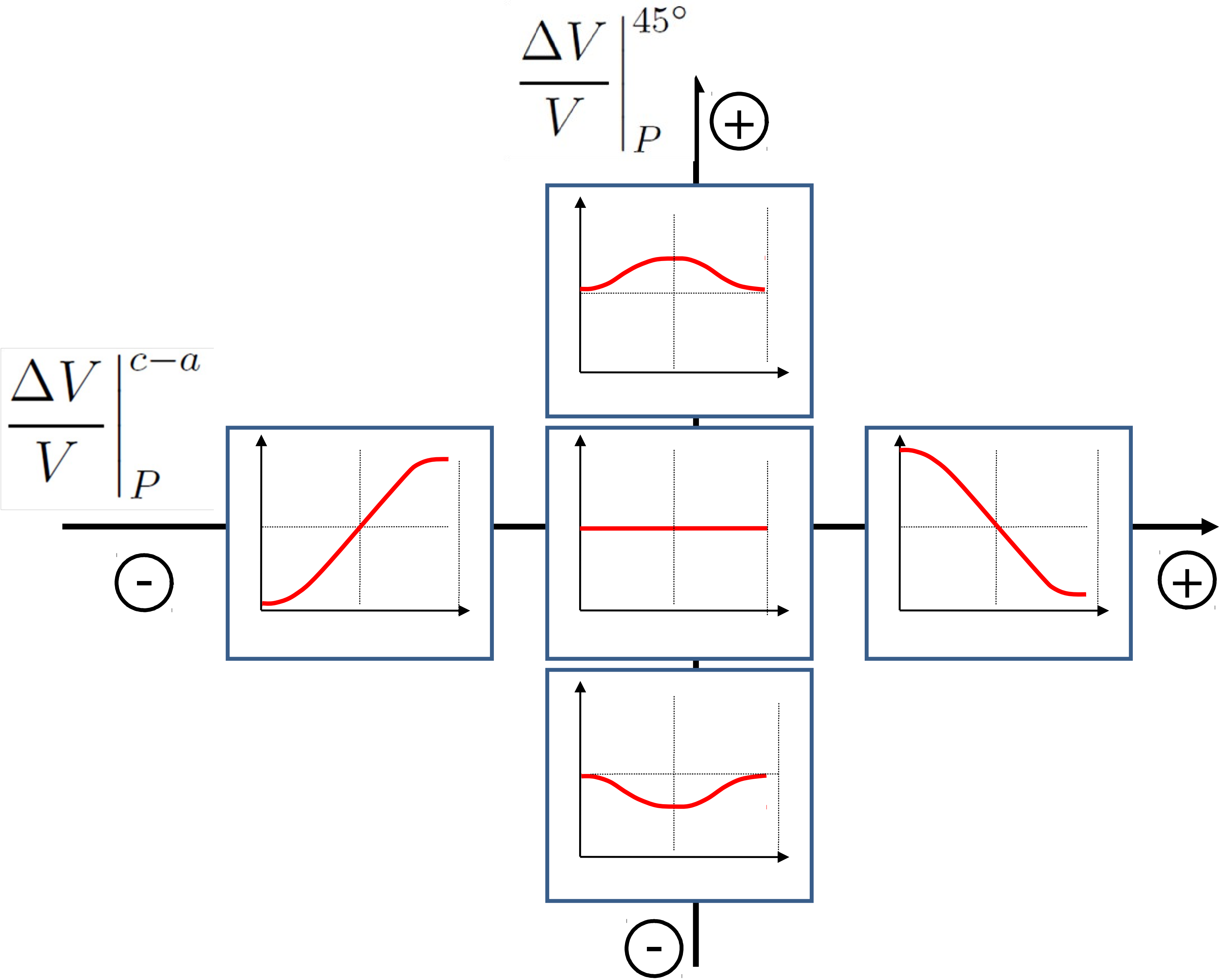
V_P vs. angle to c axis

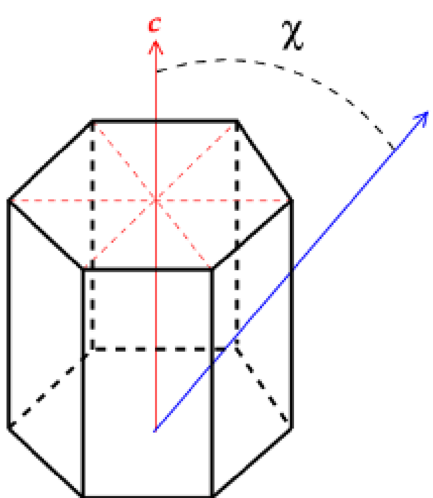




Hcp elastic anisotropy parameters

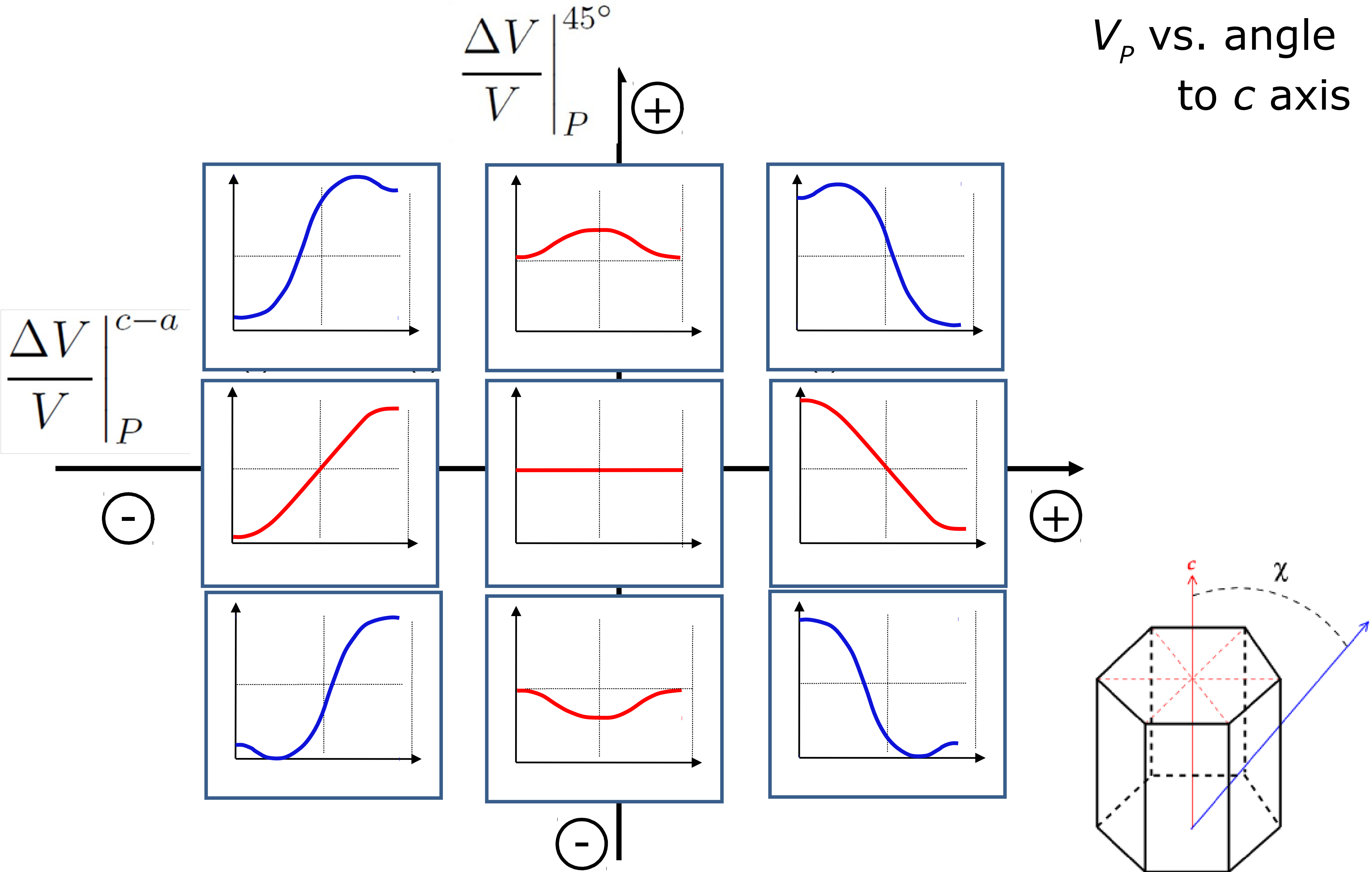
V_P vs. angle to c axis





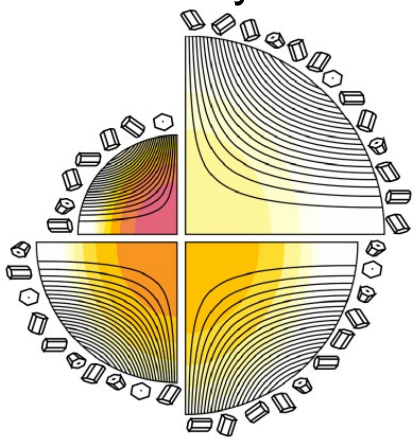
Hcp elastic anisotropy parameters

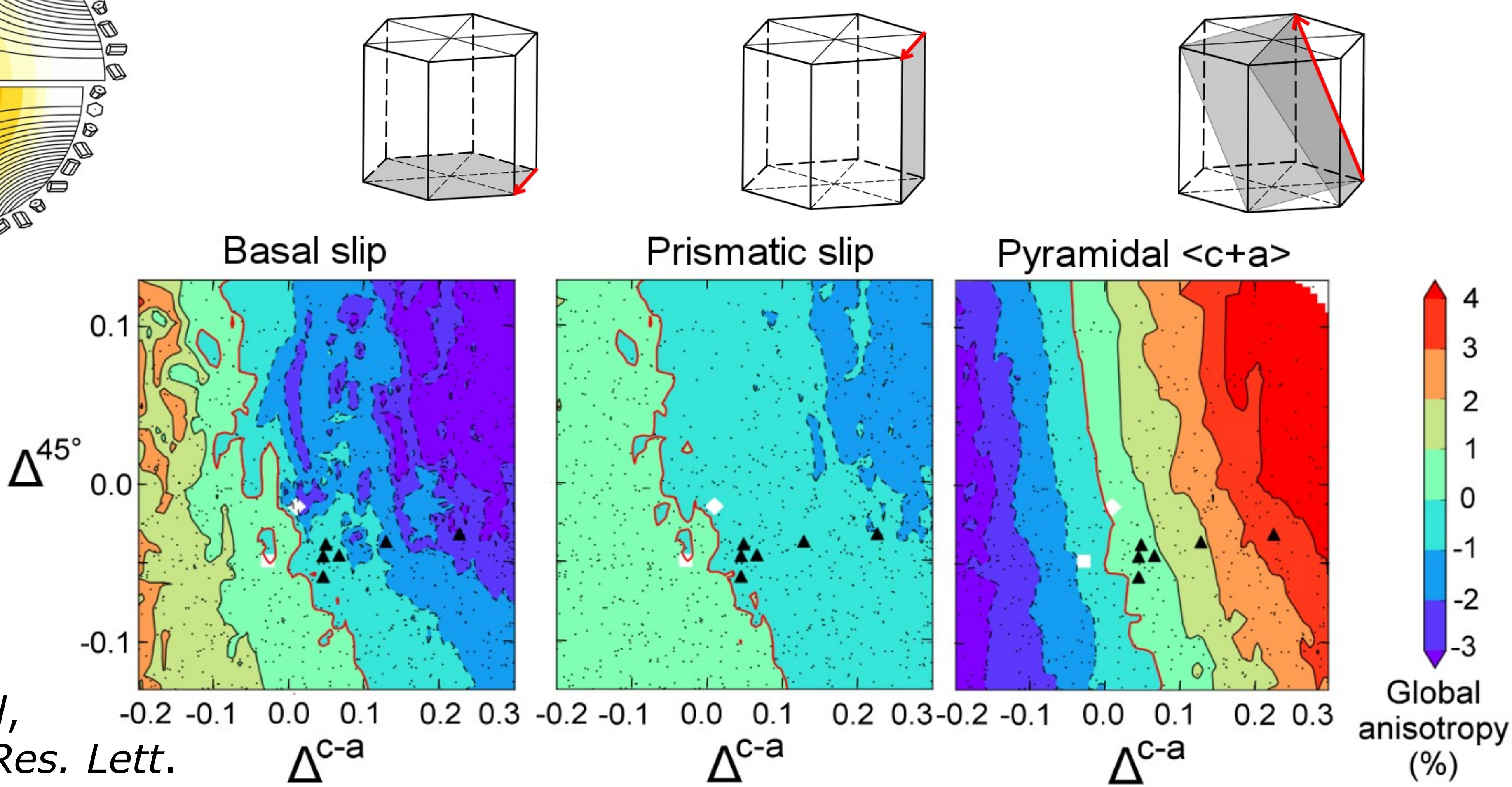
V_P vs. angle to c axis



Effect of dominant slip system

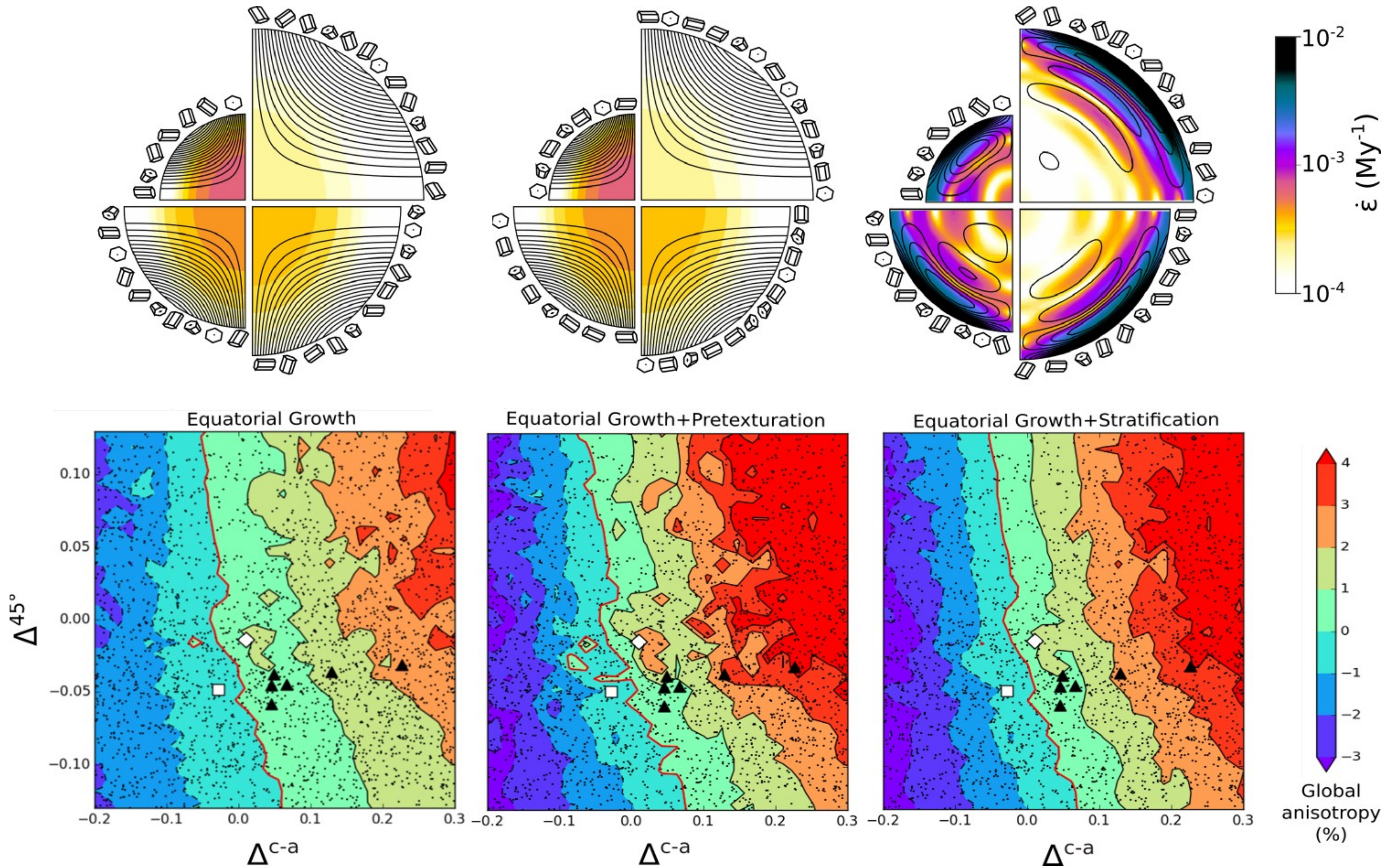
No stratification
Random crystallization

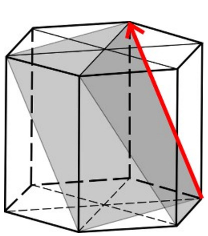




Lincot *et al*, *Geophys. Res. Lett*. 2016

Effect of inner-core formation model





Dominant pyramidal <c+a>

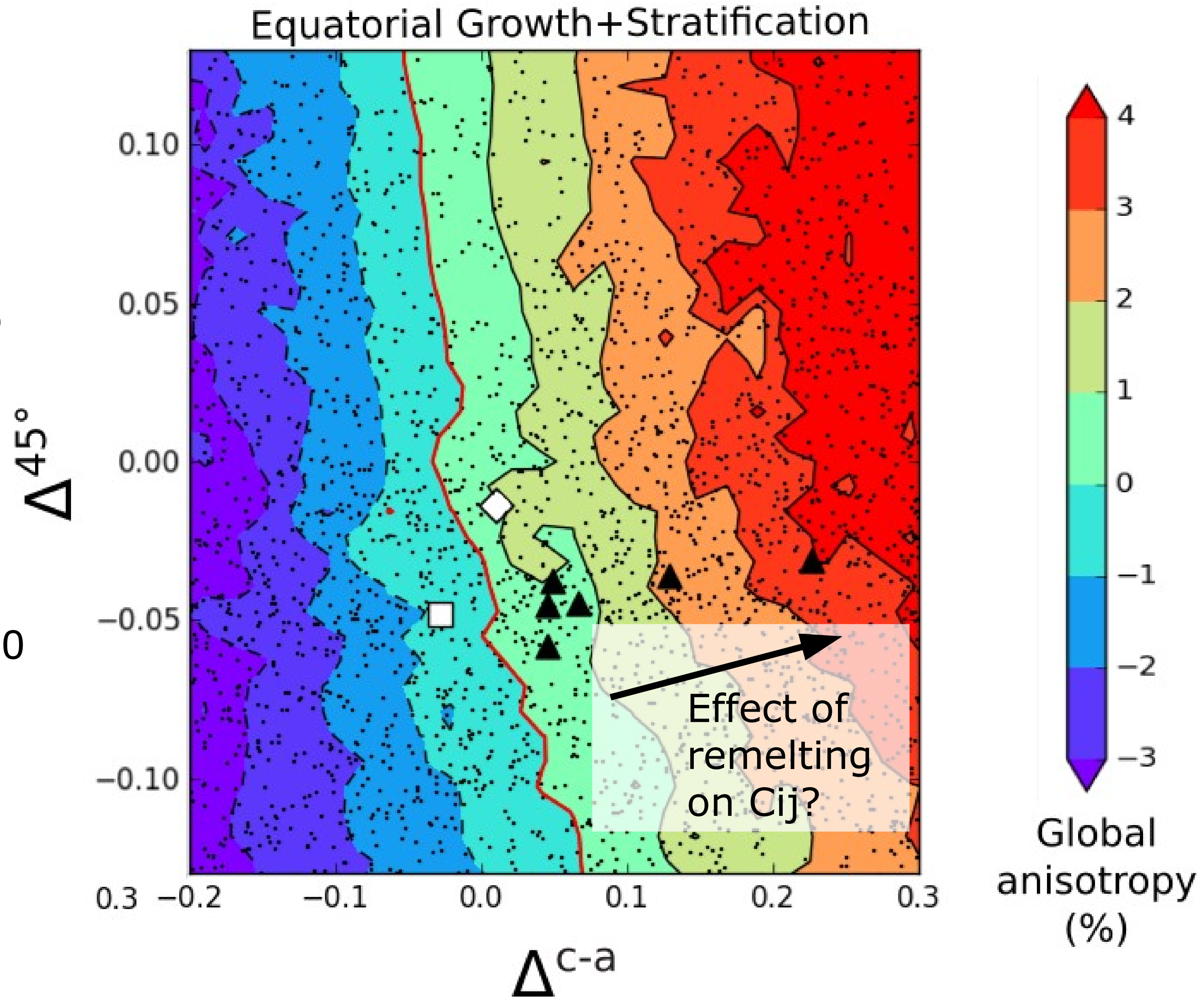
Global anisotropy results: hcp-Fe

Hcp-Fe

Preferential growth at equator with chemical stratification

Dominant pyramidal slip

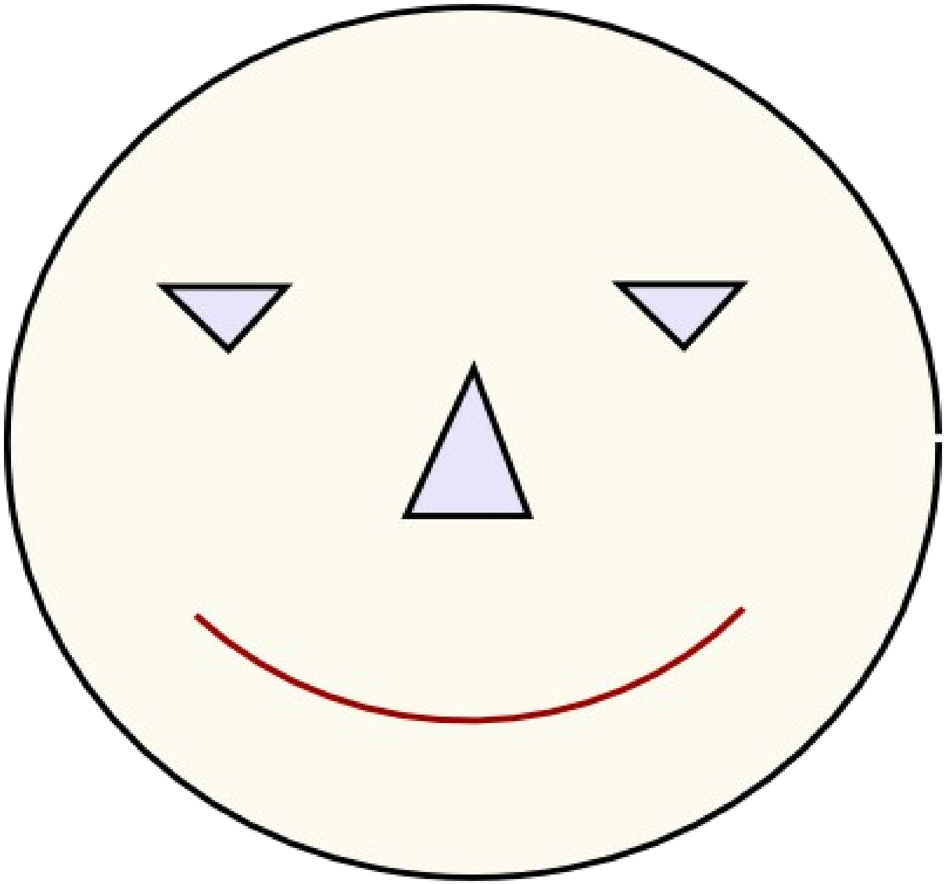
Squares:
Vocadlo et al, 2009
Diamond:
Sha and Cohen, 2010
Triangles:
Martotell *et al*, 2013



Lincot *et al*, *Geophys. Res. Lett*. 2016

Finally...

We have one!
...many, in fact...

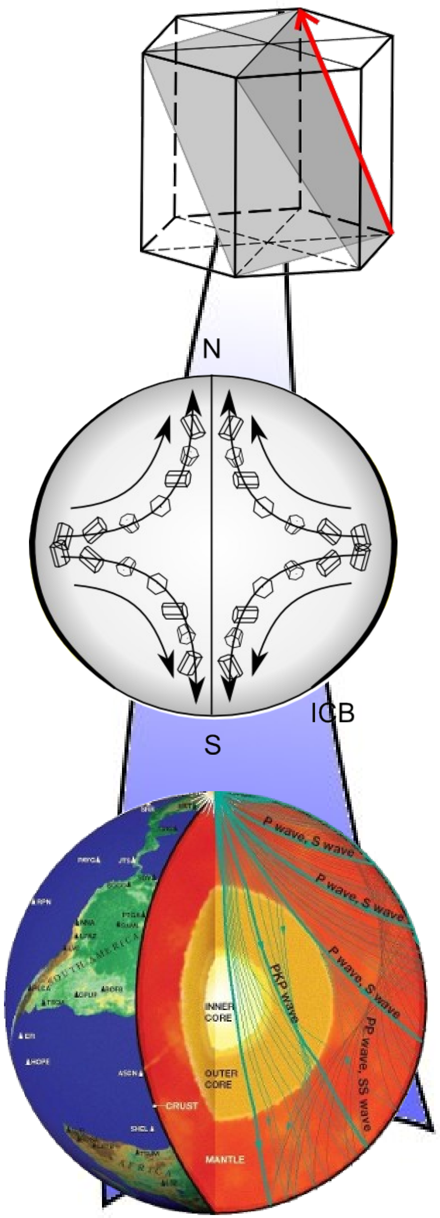


Lincot *et al*,
Geophys. Res. Lett.
2016

Take home messages

Not so straightforward to build inner core model with
3% global anisotropy:

- Simple core formation model
  Ex: preferential growth at equator + extensions
- Structure for Fe alloy
  Impossible with cubic structure
  Possible with hcp
- Dominant deformation by pyramidal slip
  Most efficient at aligning c-axes
- ~ 20% elastic anisotropy in the single crystal
  (depends on the core formation model)
- Details of inner-core history
  Can not discriminate at this point



Future works

Seismology

- Add new data points (e.g. virtual path from ambient noise)
- Publish actual residuals, with entry and exit points for the used paths

Mineral physics

- HP/HT phase diagrams of Fe-alloys
- Effect of HT on plastic deformation mechanisms
- Confirm crystallization mechanisms

Modeling

- Build virtual inner cores with full-field, direct models of seismic travel times
- Constrain inner-core history based on seismic measurements and input from mineral physics