Recent Advances and Road Ahead for Global Seismology

(Opportunities and Challenges for Next Decade)

Rob van der Hilst

Massachusetts Institute of Technology

“The future ain’t what it used to be” (Yogi Berra)

"The future ain't what it used to be" (Yogi Berra)

Or is it?

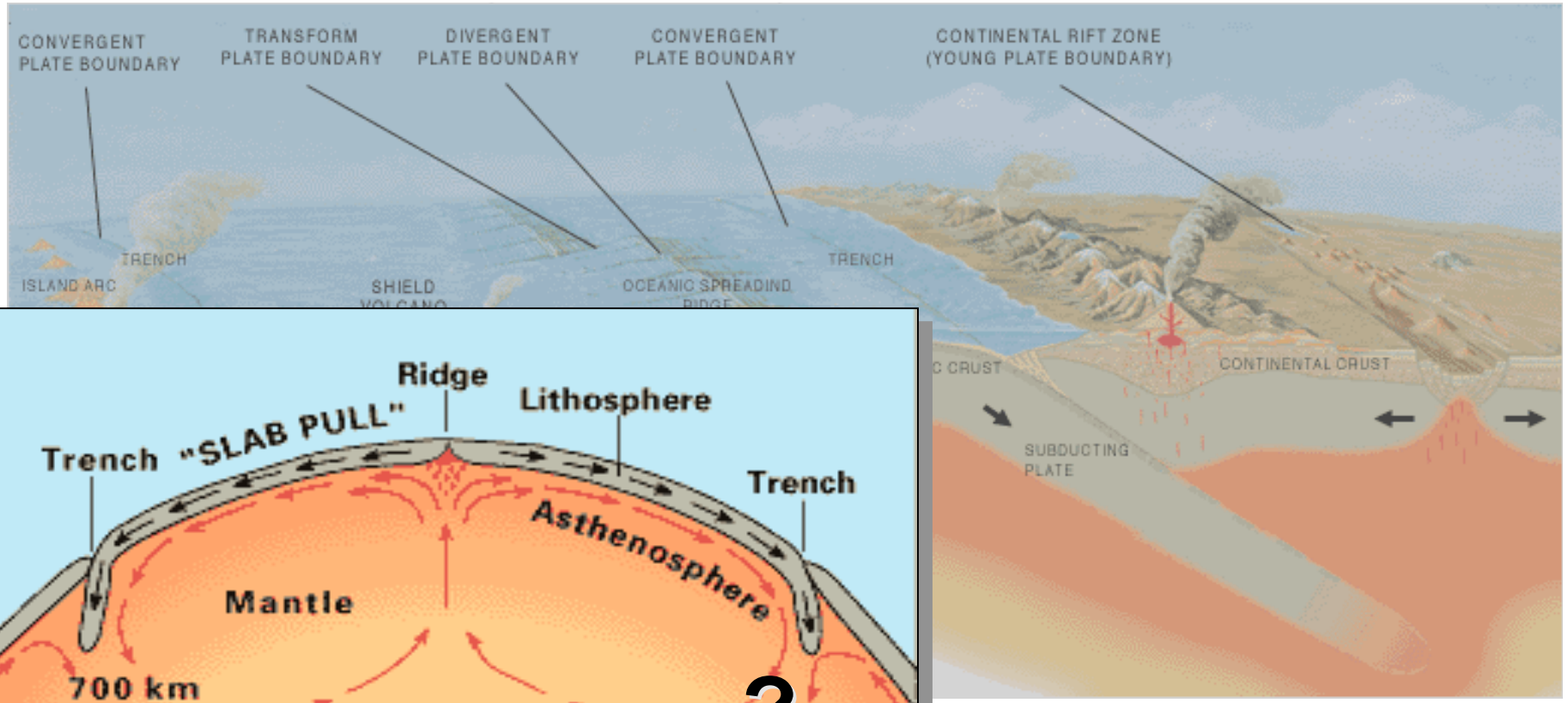
Some of the Grand Challenges of yesteryear continue to motivate our research

But over last decade unprecedented data access, technical and theoretical innovation, and crosscutting research have increased our understanding of the inner workings of planet Earth.

Some old questions remain and new questions are forming.

Over next decade: spectacular opportunities → much progress expected:
- New (and better) data sets are coming on line in rapid pace
- New *types* of signal (formerly known as noise) are being recognized and used
- Better theory, methods, and computation schemes are being developed
- Rapid developments in related fields (e.g., mineral physics, satellite technology)

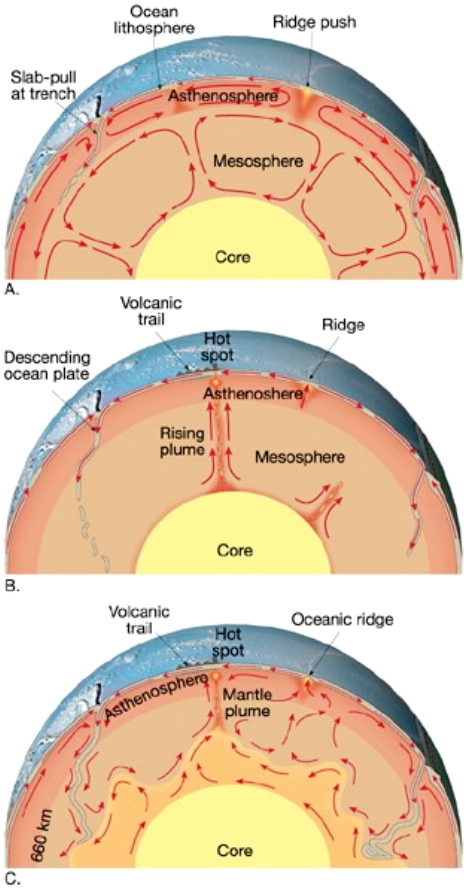
But keep open mind for the unexpected!



Grand Challenge:

How does Earth work?
How do deep processes relate to what happens at the surface?

Recent Advances: Scale and Nature of Mantle Convection

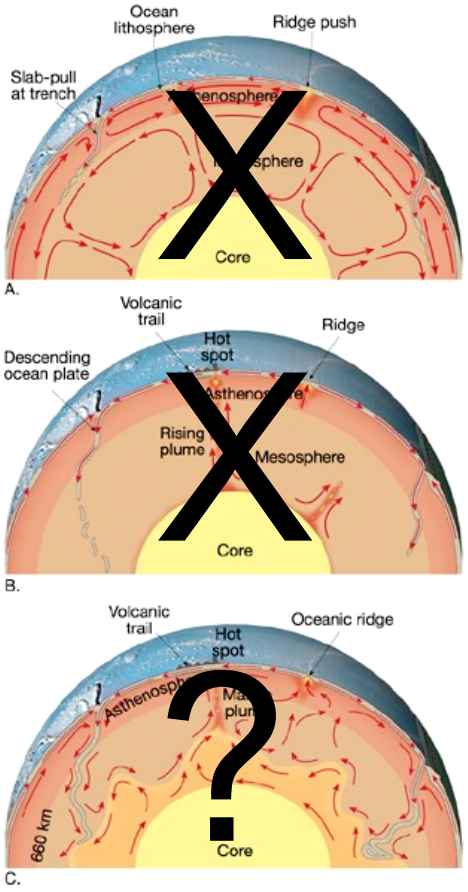


Convective layering at 660 km discontinuity?
(thermal convection in layers of different composition)

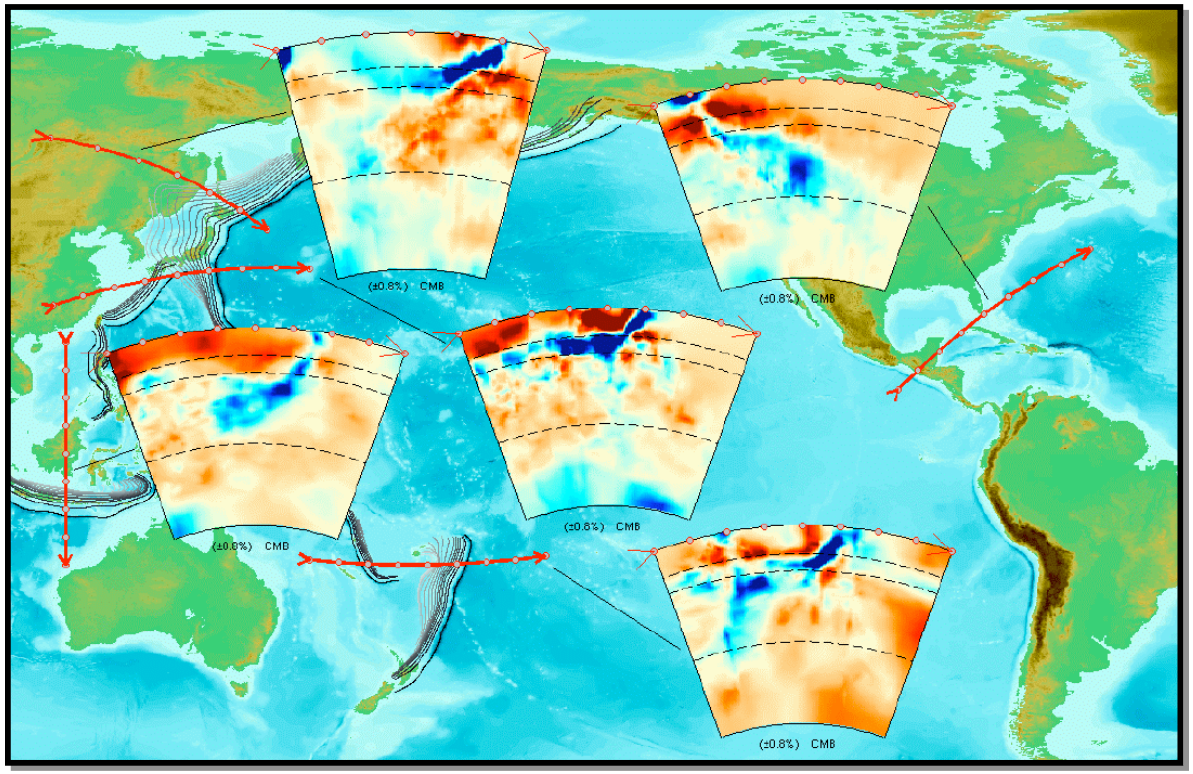
Unobstructed whole mantle convection?
(thermal convection in compositionally homogeneous mantle)

Somewhere in between?
(thermo-chemical convection with more complex flow patterns)

Recent Advances: Scale and Nature of Mantle Convection



Growing consensus on long wavelength structures and on "hybrid" form of convection

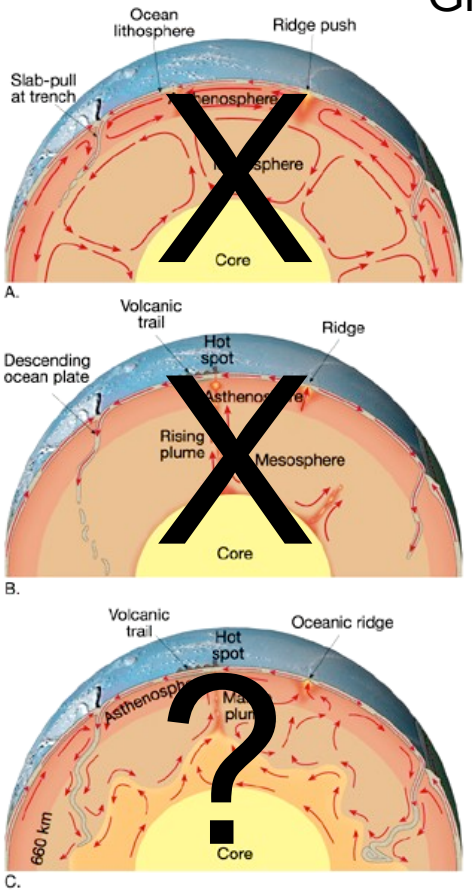


(Karason & Van der Hilst, 2000)

→ neither strong layering nor simple whole mantle convection
→ local and (probably) transient layering

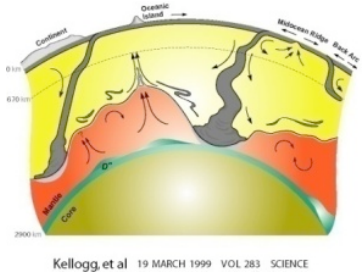
Questions: Mass flux upper-lower mantle? Relationship plate motions—style of subduction/fate of slab? Scales of heterogeneity and flow patterns? Origin and control of such scales? Anisotropy?

Recent Advances: Scale and Nature of Mantle Convection



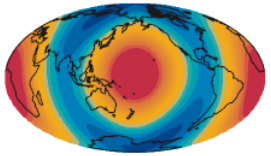
Growing consensus on presence of compositional heterogeneity

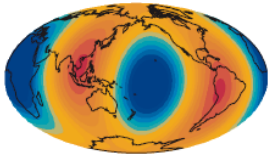
Anomalous wavespeed ratios
(Su & Dziewonski, 1997; Kennett et al., 1998; Saltzer et al., 2001; Houser et al., 2006; …)



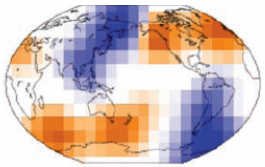
Wavespeed-density aniti-correlation
(e.g., Ishii & Tromp, 1999; Trampert et al., 2004; …)

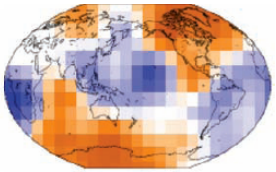
Temperatures inferred from different wave types inconsistent
(e.g., Cammarano & Romanowicz, 2007; …)


Shear speed


density

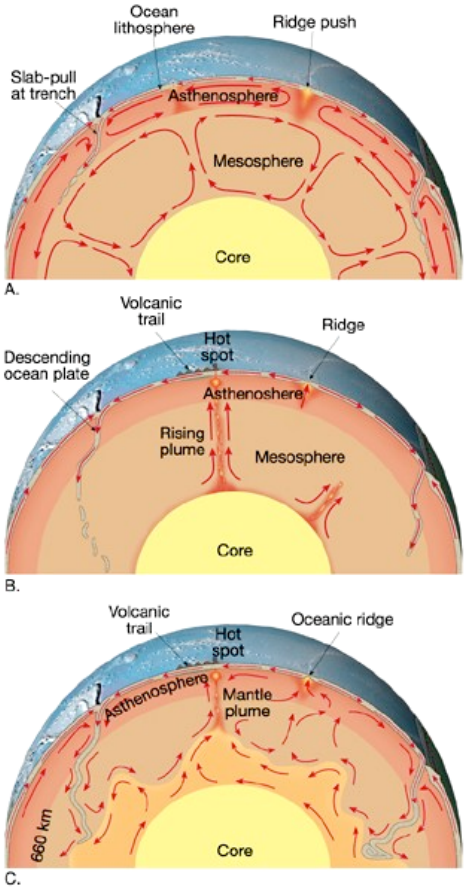
Sharp edges of many deep mantle structures
(e.g., Wen, 2001; Sun et al., 2007; …)


Temperature

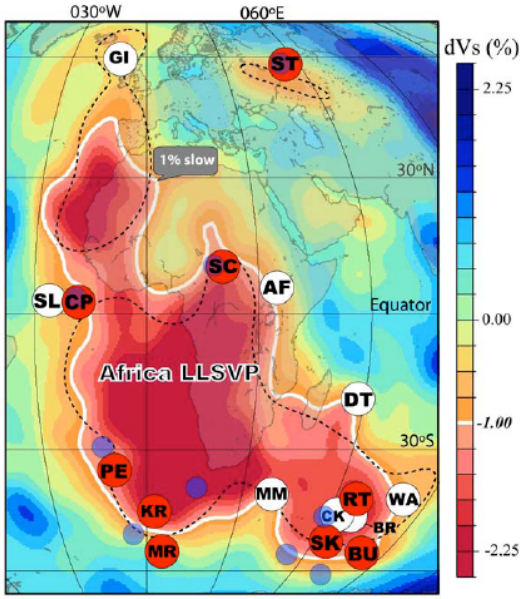

Iron

Questions: What *is* the compositional variation? Its origin and evolution? “Water”? Relative importance thermal vs. compositional effects? Length scales of thermal vs. compositional heterogeneity?

Recent Advances: Scale and Nature of Mantle Convection



Deep compositional domains may be ancient: do they stabilize or are they stabilized by the large scale patterns of mantle flow?

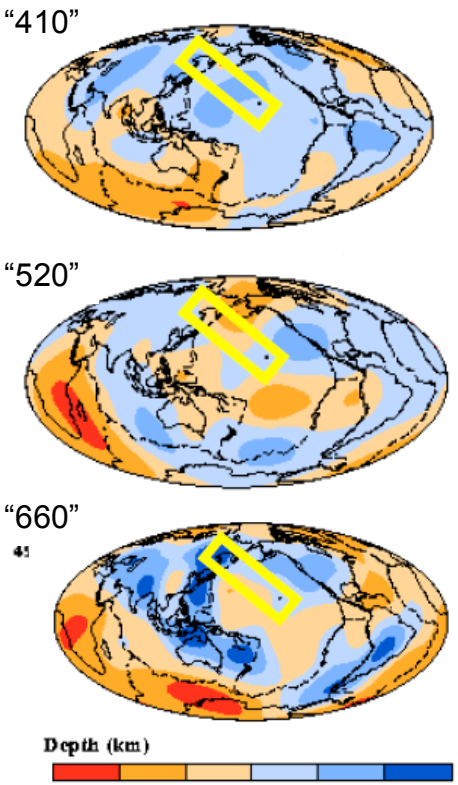


Relationship between LIPs (Large Igneous Provinces) and LLSVPs (Large Low Shear wave Velocity Provinces)?

Torsvik, Steinberger, Cocks, Burke Longitude: Linking Earth's ancient surface to its deep interior (in press EPSL 2008).
NB others have observed similar relationships between large scale deep mantle anomalies and (presumed) small scale upwellings (e.g., Garnero, Thorne, and co-workers.)

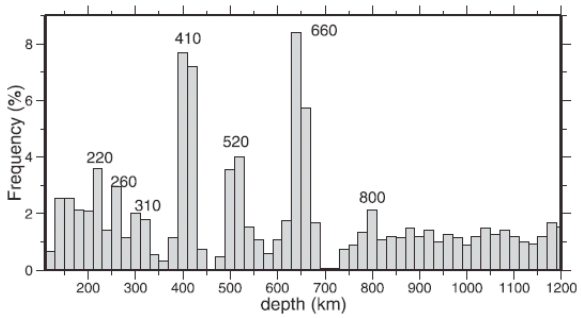
Recent Advances: Interfaces and Boundary Layers (TZ)

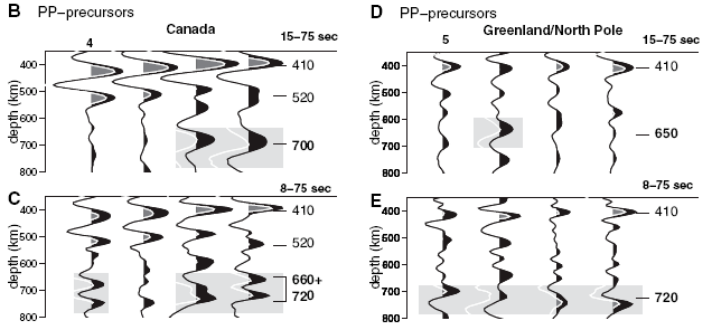
Long wavelength mapping continues; new studies of topography and interface character



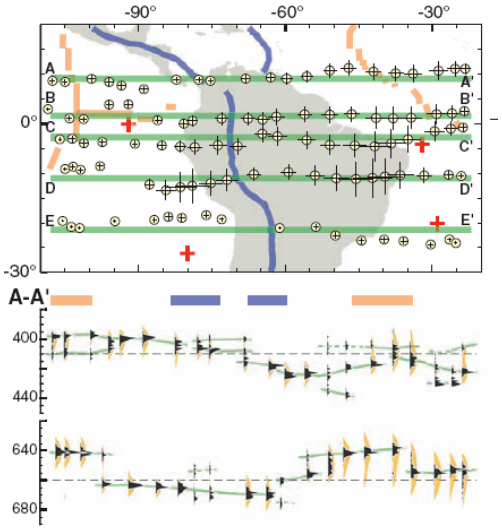
e.g., Flanagan and Shearer,1998;
Gu & Dziewonski, 2002; Reif et al., 2002

Deuss & Woodhouse (2002)





Deuss et al (2006)



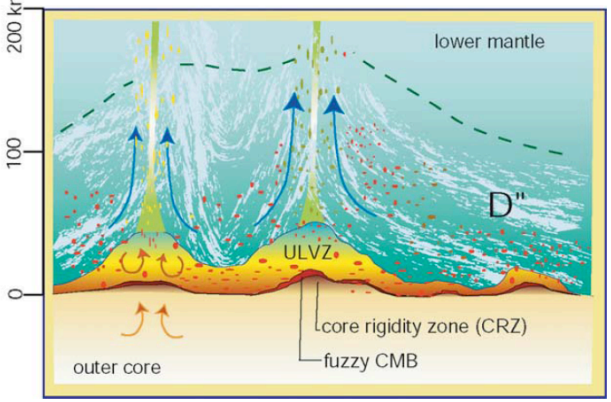
Schmerr and Garnero (2007)

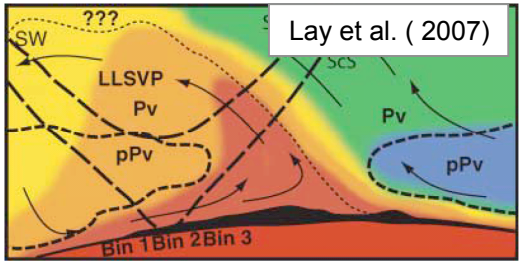
Questions: Are there more (global) interfaces? Can we improve accuracy? (Horizontal) wavelength of topographies? Degree of correlation? Effects of composition and "water"/melt? Temperature, composition, and water content at and along interfaces?

Recent Advances: Interfaces and Boundary Layers (D")

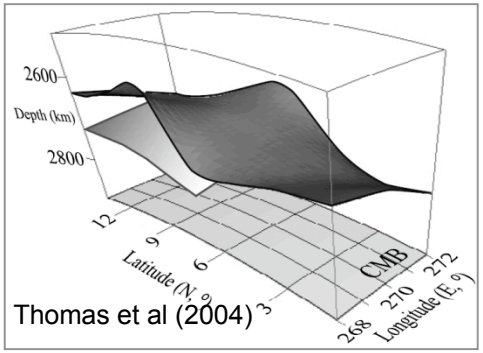
Seismologists have been discovering remarkable complexity near base of the mantle (anisotropy, ULVZs, multiple interfaces, steep lateral gradients, pPv lenses, …).

Garnero (2000)





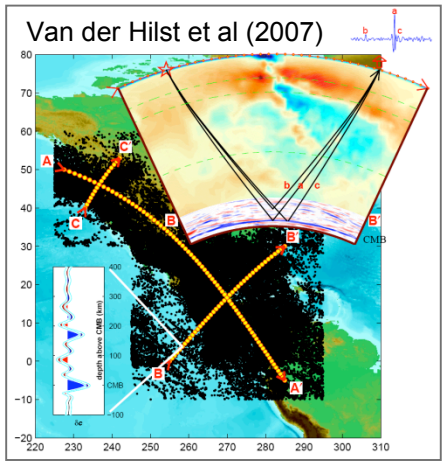
Lay et al. (2007)

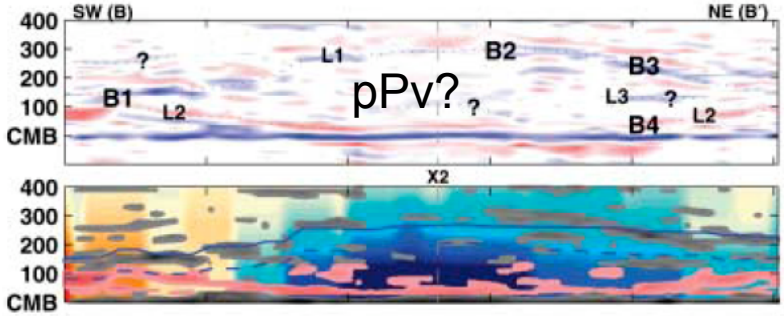


Thomas et al (2004)

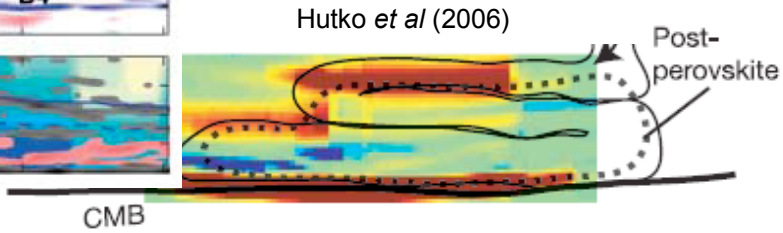
Even estimates of temperature near CMB!

Van der Hilst et al (2007)





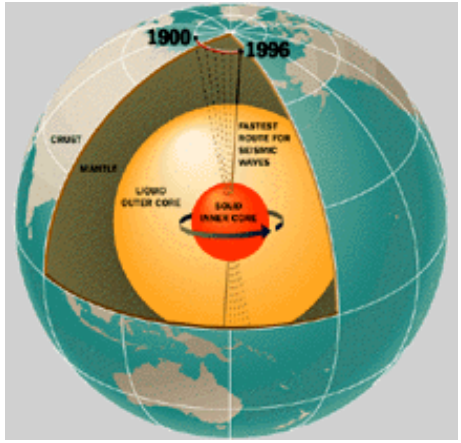
Hutko *et al* (2006)

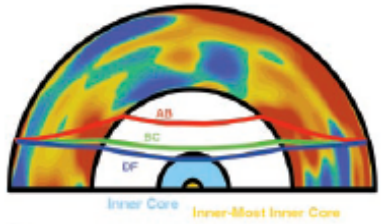


Questions: How real are these structures? Can we improve accuracy? Can we constrain heat flux from core into mantle?

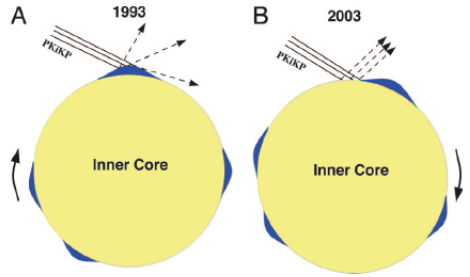
Recent Advances: Inner Core

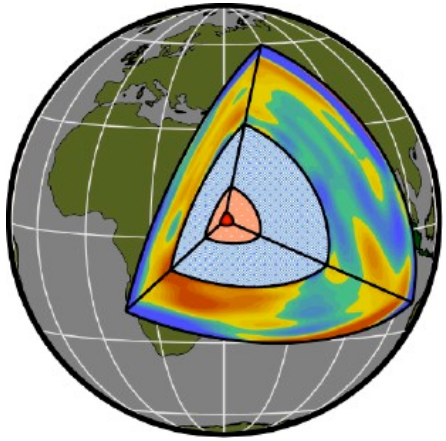
New constraints on heterogeneity, anisotropy, rotation rate … seismologists even found an INNER inner core (What will they find next? An inner-inner-inner core? The long lost NSF budget increase?)



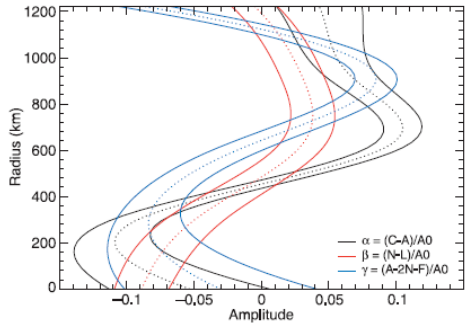


Ishii and Dziewonski (2002)





Beghein and Trampert (2003)

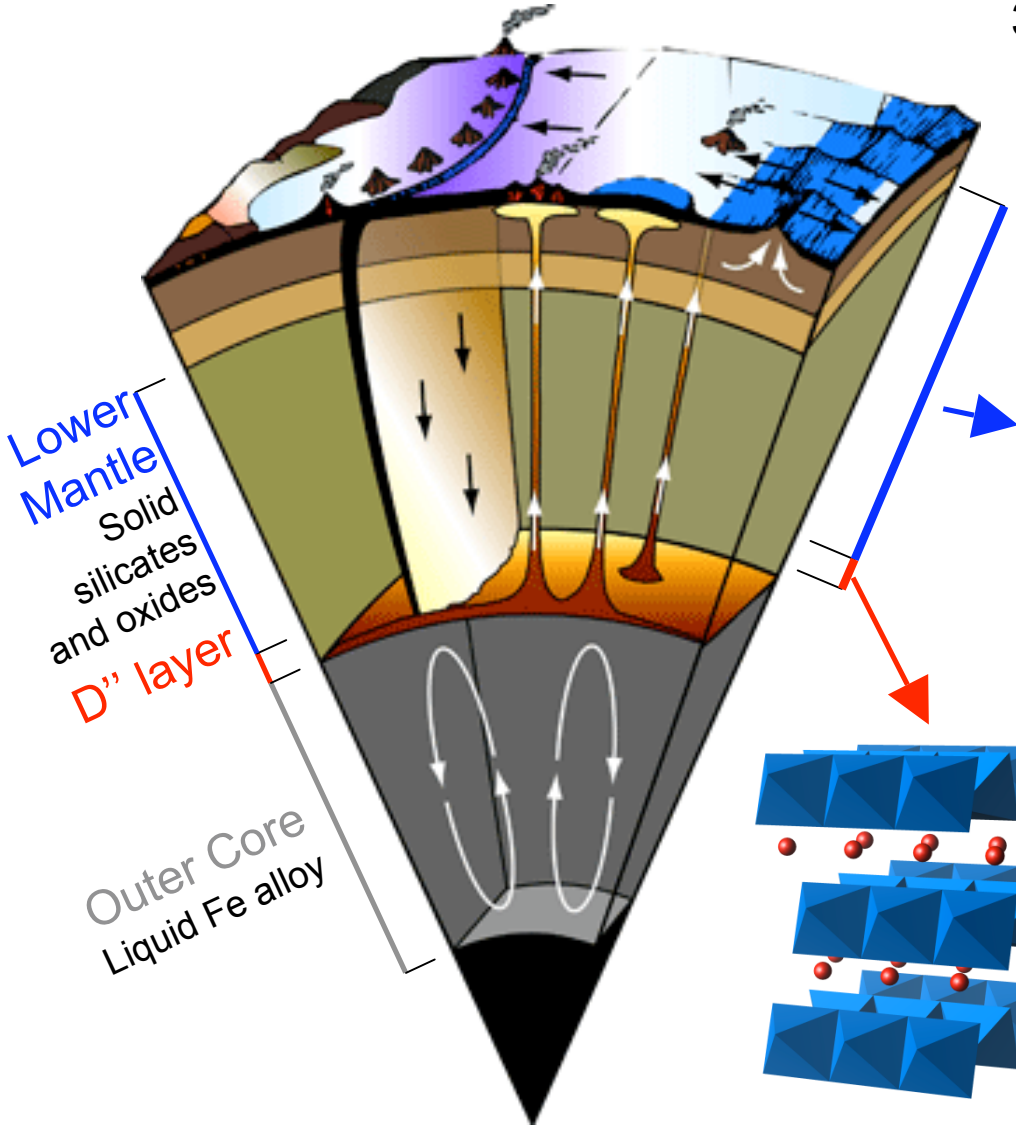


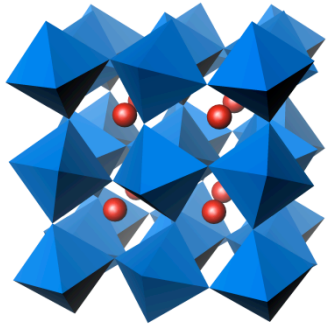
ICB topography? (Cao et al., 2007)
ICB growth? (Wen, 2006)

Outstanding issues: Rigidity/anelasticity of IC; Lateral heterogeneity and radial structure; Nature of ICB? Can growth be detected? Role in stabilizing geomagnetic field? Timing of formation and growth history?

Parallel Developments: Mineral Physics

1- Post-Perovskite Transition
2- Changes in spin-state of iron
3- Consideration of more complex compositions (SiO2, MgO, FeO + Fe2O3, Al2O3,CaO, … + effects of water) → **new transitions? → new materials?**



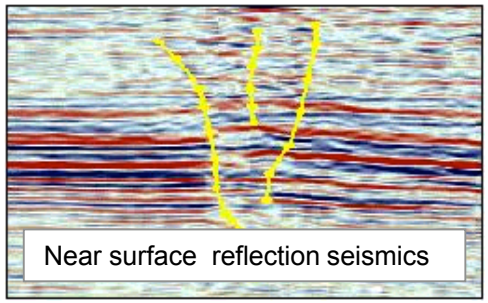


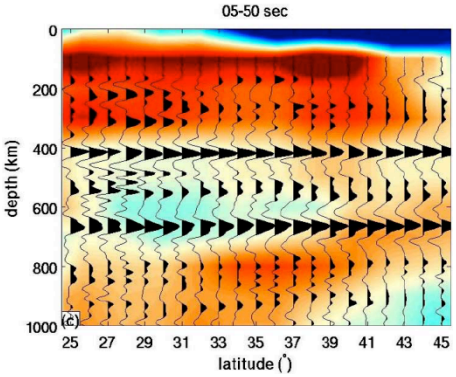
Perovskite

Post-perovskite

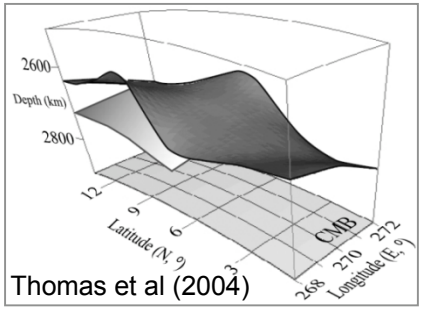
Technical Developments: Deep Earth "Exploration Seismics"

With access to massive data volumes and big computers
→ New inverse scattering/migration methods

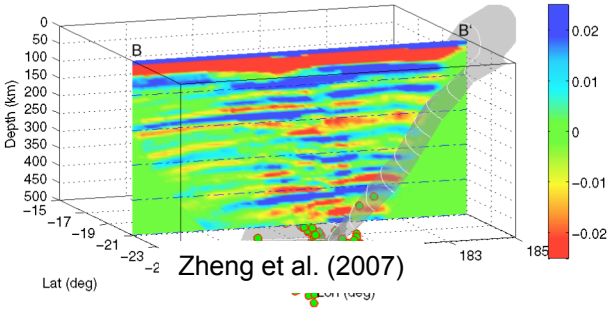




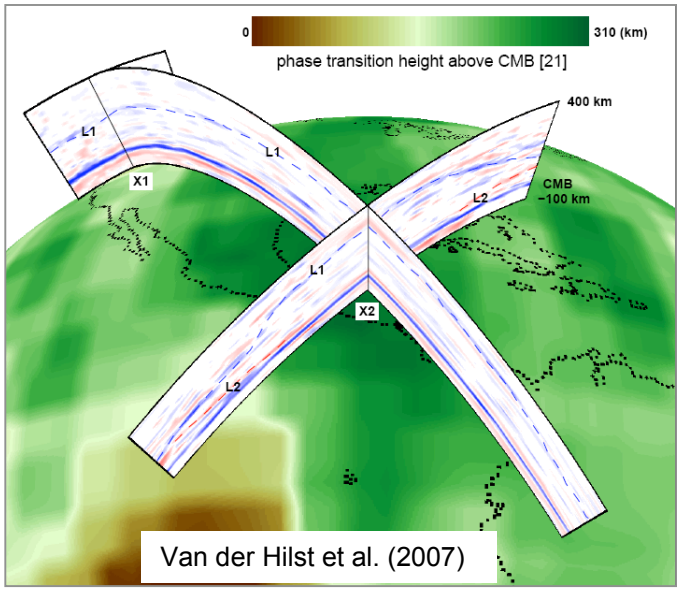
Cao et al. (in preparation)



Thomas et al (2004)

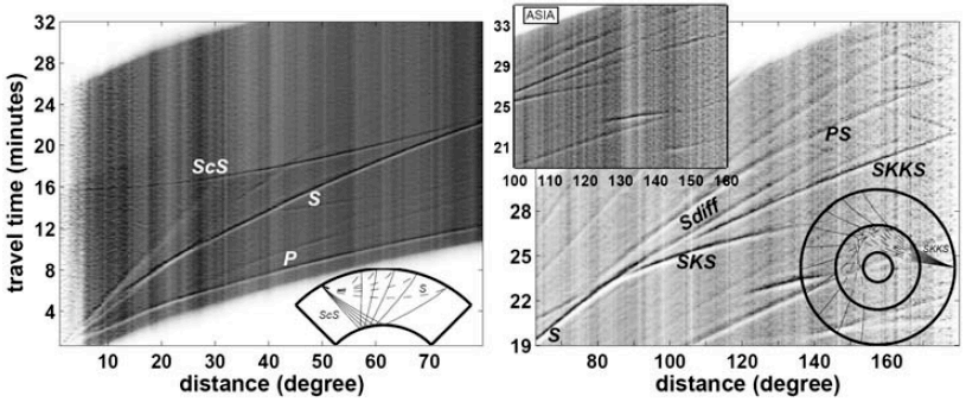


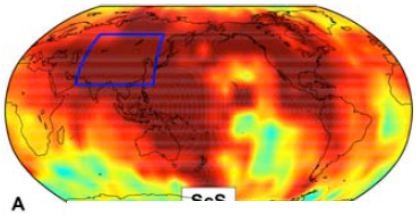
Zheng et al. (2007)



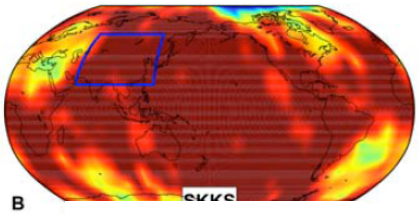
Van der Hilst et al. (2007)

Is global scale D'' imaging within reach?





ScS

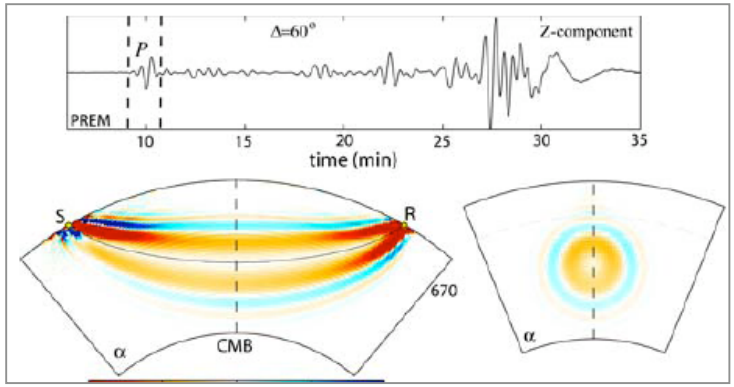


SKKS

Technical Developments: Theory and Computation

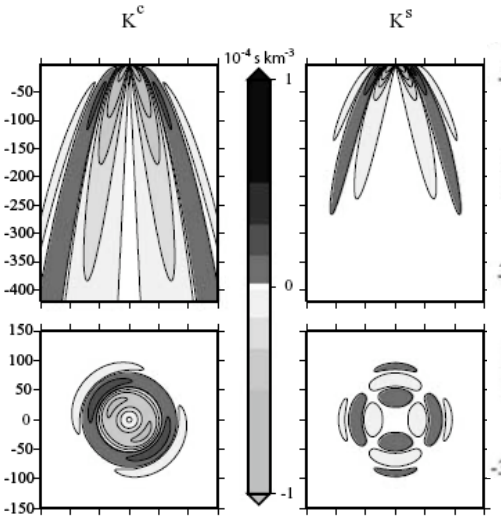
Finite Frequency Wave Propagation and Inversion (ray theory → full wave dynamics)

Transmission

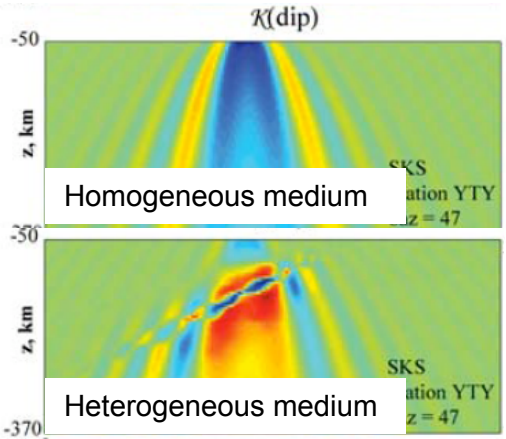


Dahlen et al (2000); Zhao & Jordan (2006)

Shear wave splitting

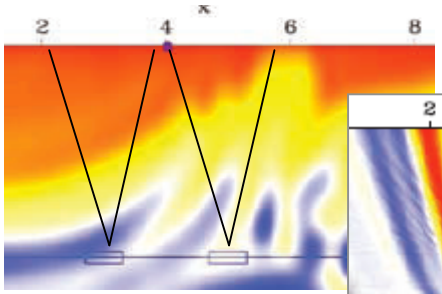


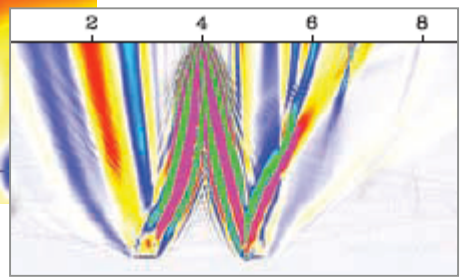
Favier & Chevrot (2003)



(adjoint method)
Long et al. (2008)

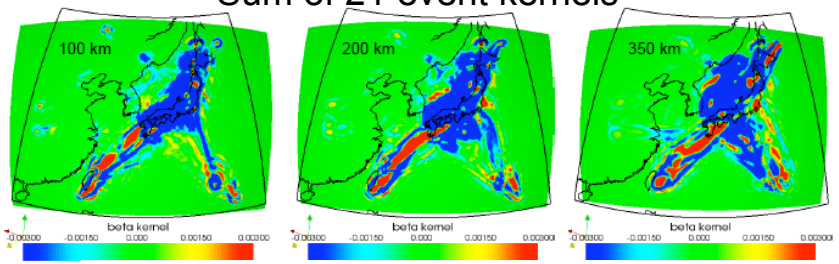
Reflection





De Hoop et al (2006)
(adjoint)

Sum of 21 event kernels

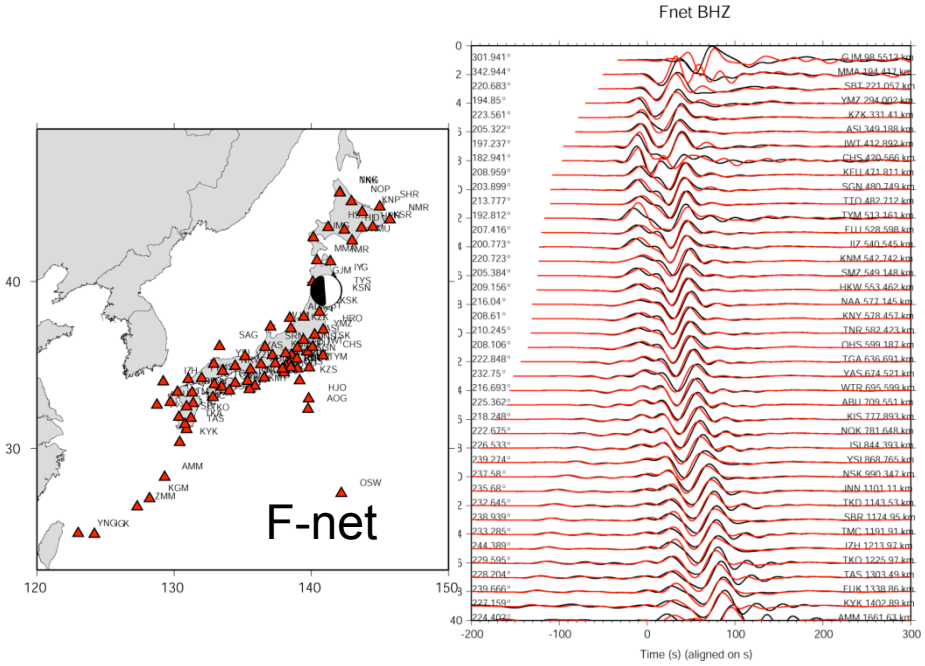


Chen, Tromp (in preparation) – SEM/adjoint

Technical Developments: Theory and Computation

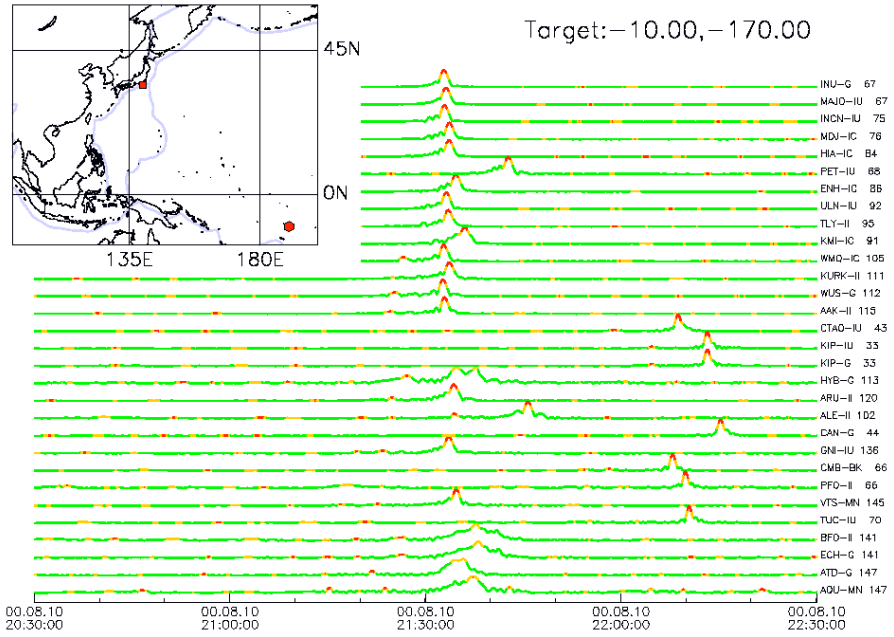
With modern computer power, massive (forward modeling) calculations becoming feasible.

Accurate synthetics in 3-D media: e.g. Spectral Element Method (Komatitsch, Tromp, …)



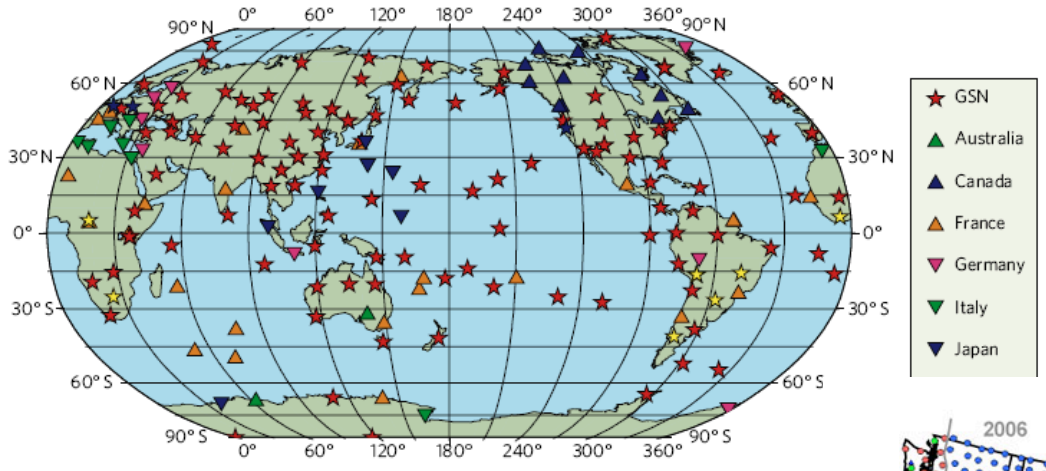
3D SEM (red) Synthetics vs Data (black)

Iterative forward model for event location (e.g., Ekstrom et al)



New Observations: Data and Types of Data

Ever growing networks and data sets; Continuing to improve international coordination



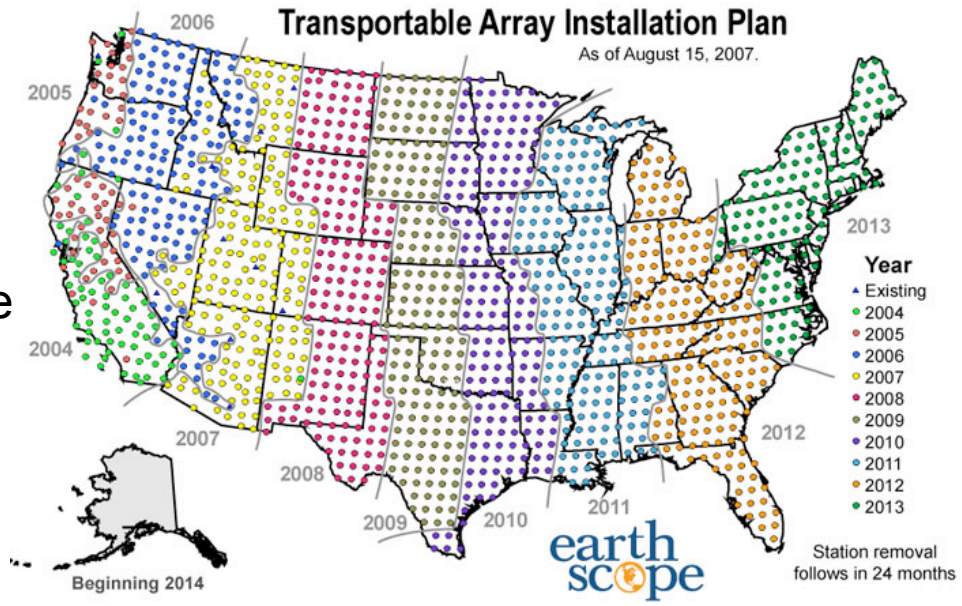
Global Broadband Digital Seismic Network (Oct 2007)

+ dense networks elsewhere in the world (Europe, China, Japan, …)

+ expand OBS network and bring on-line

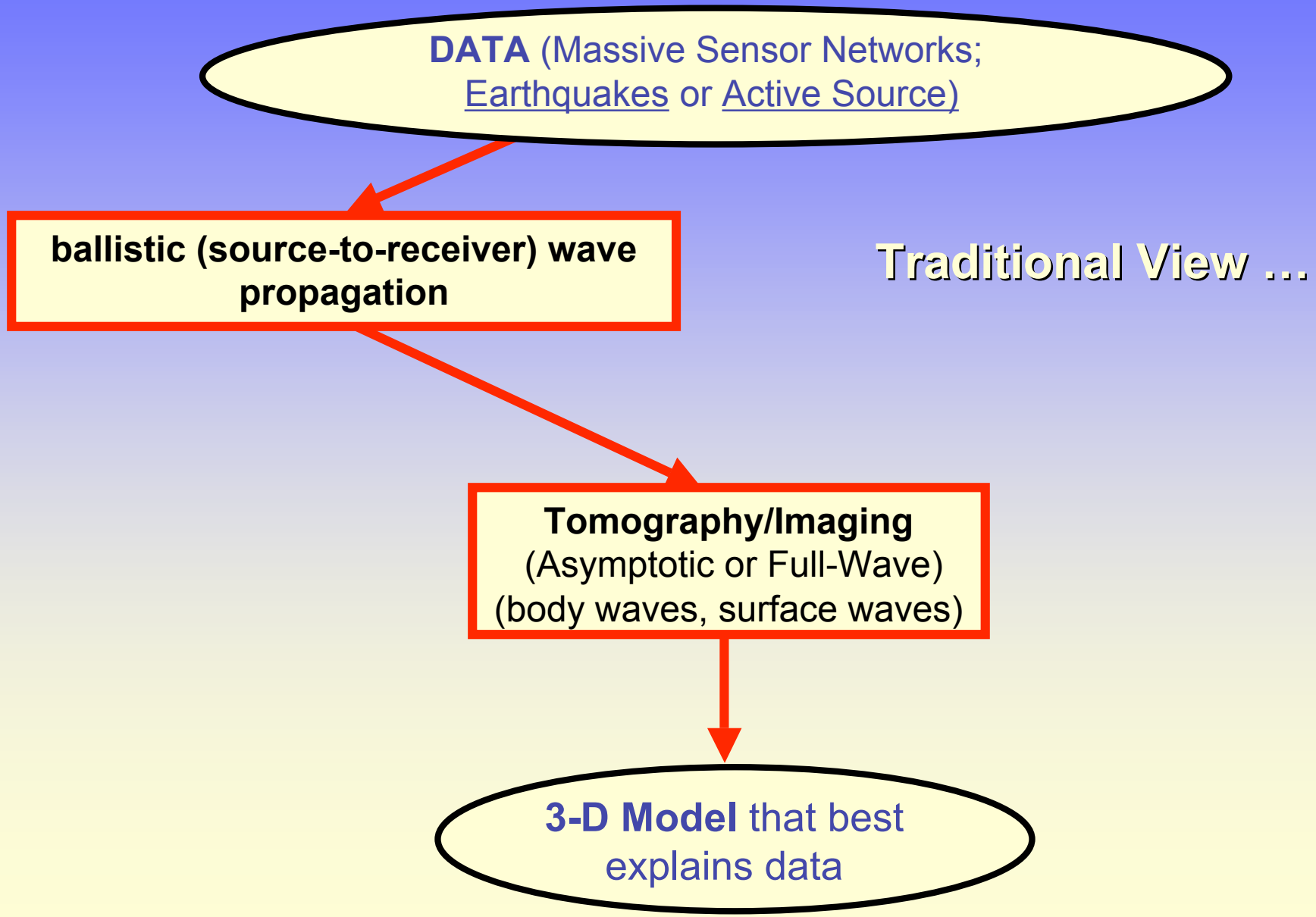
+ new sensors? Fleet of buoys? Millions of cheap, disposable (biodegradable) sensors deployed from airplanes?

USArray



New Era in Array Seismology

New Observations: Data and Types of Data



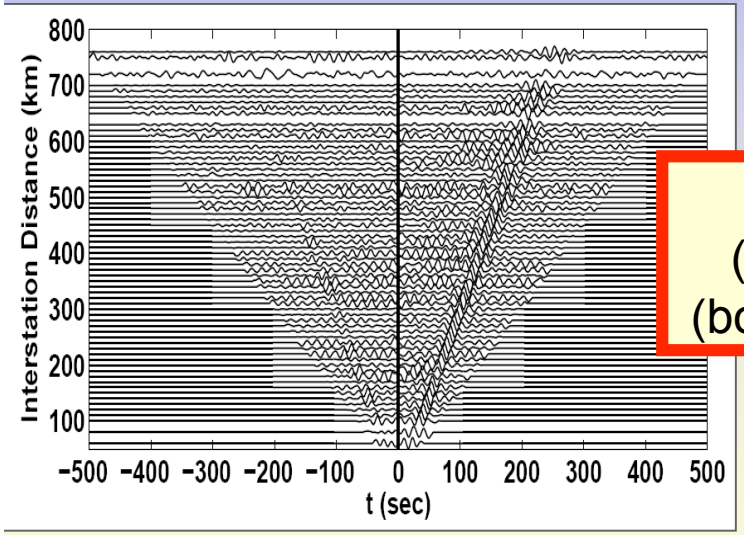
Traditional View …

New Observations: Data and Types of Data

DATA (Massive Sensor Networks; background noise)

create data by means of interferometry/cross-correlation

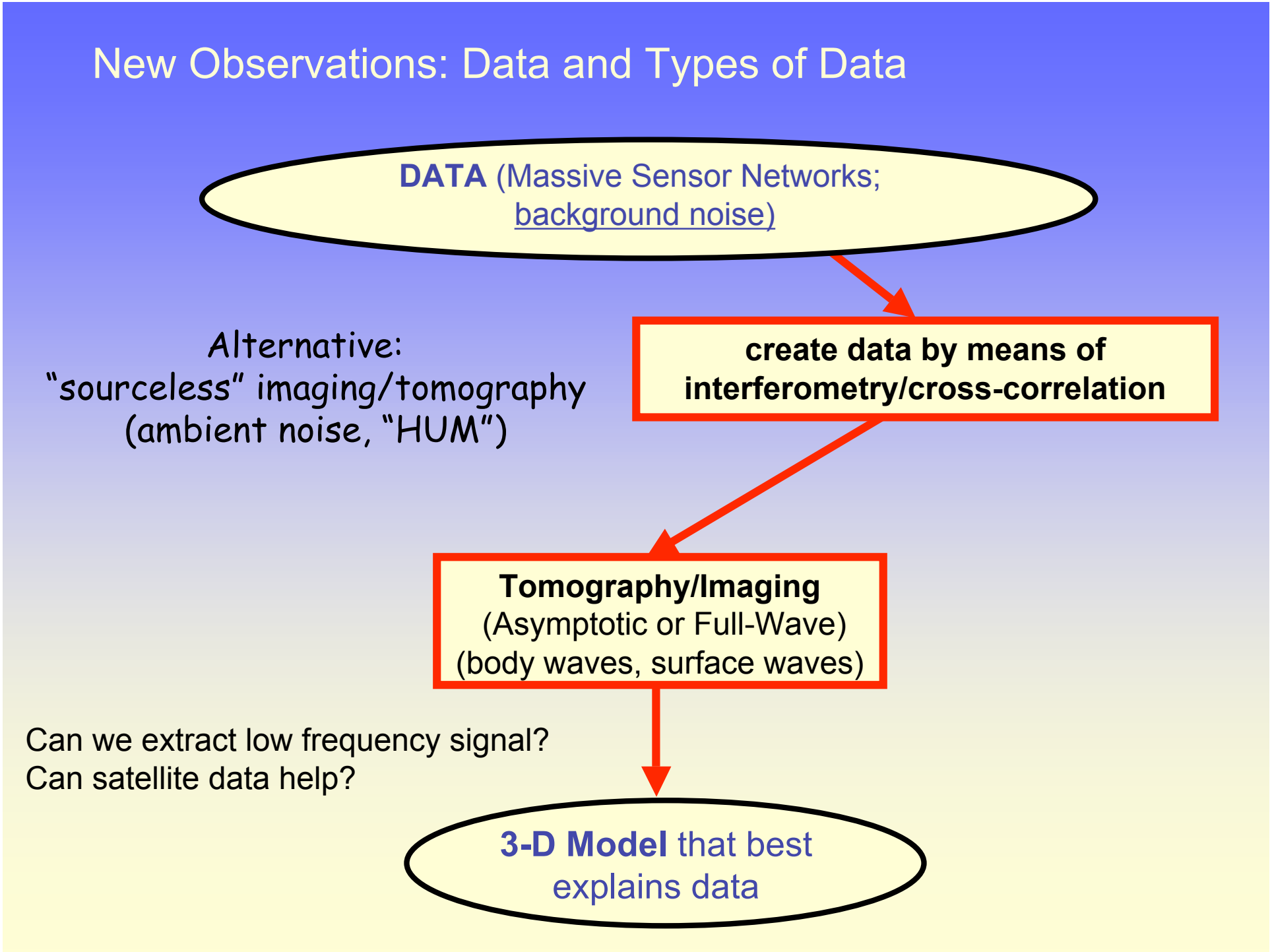
Alternative:
"sourceless" imaging/tomography
(ambient noise, "HUM")



Tomography/Imaging
(Asymptotic or Full-Wave)
(body waves, surface waves)

3-D Model that best explains data

New Observations: Data and Types of Data



Building on these recent advances – and with seismology as integral part of concerted, multi-disciplinary effort – we must address following challenges:

1: *Multi-scale thermo-chemical convection – relation to near-surface deformation*

- Scales of heterogeneity and flow patterns? Origin/control of such scales (plates? mantle?)
- Nature and scale of convective return flow? Can we (finally) image “plumes”?
- Can we put tighter constraints on composition and temperature? Water?
- Relative contributions temperature vs. composition?
- Longevity of deep mantle domains and effect on overall convection pattern?
- Scale and pattern of anisotropy?

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2: *Temperatures at and mass/heat flux across interfaces and boundary layers*

- Continue to explore for hitherto unknown interfaces.
- Characterize interfaces or edges of structure more precisely.
- Determine lateral variations in depth with more accuracy and over larger geographical regions in order to constrain temperature, composition, melt, ...
- Can we constrain temperature and thermal gradients at base of the mantle?
- What is the ICB? Its topography? Can we measure changes in time (growth?)

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3: *Monitor and measure change in Earth's deep interior*

- Recent discovery of tremors begs question: are there other such processes that can be detected through processing of massive amounts of data?
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- Can we detect in the Terrabytes of modern data subtle signals that point to hitherto unknown sources (e.g., astrophysics approach)?

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Road Ahead: What is needed?

Observations:

- Increase global data coverage
- International coordination for better access to existing data
- Expand Ocean Bottom Seismometer network, integrate with other data bases
- New types of data and sources: push limits of interferometry (ambient noise, “HUM”)
- New types of data: will satellite technology ever be precise enough to do “normal mode seismology” from space?
- New types of sensor

Theory and Methods:

- Full wave methods for tomographic inversion and model validation
- Industry type data processing: inverse scattering with (very large) data sets
- Improve accuracy of constraints on deep Earth’s structure

Cross-disciplinary integration:

- Explicit incorporation elasticity data for complex compositions/mineralogies
- 3D Reference Model (seismology, mineral phys.) Grand Challenge or Tool?
- Design new probes, with physically more meaningful parameters
- Integration with gravity and magnetic missions like GRACE, GOCE, CHAMP for detection and monitoring of slow (sub-seismic) processes in Earth’s deep interior

Keep open mind (serendipity and “small science” works!)

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