UNIVERSITÀ DI PAVIA

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Pavia

International School
“Structure and Composition of the Lower Continental Crust”

Geophysical investigation of the LCC:
1. Tools and their limitations
2. Results and questions

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FNSNF
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FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

Introduction (warning?)

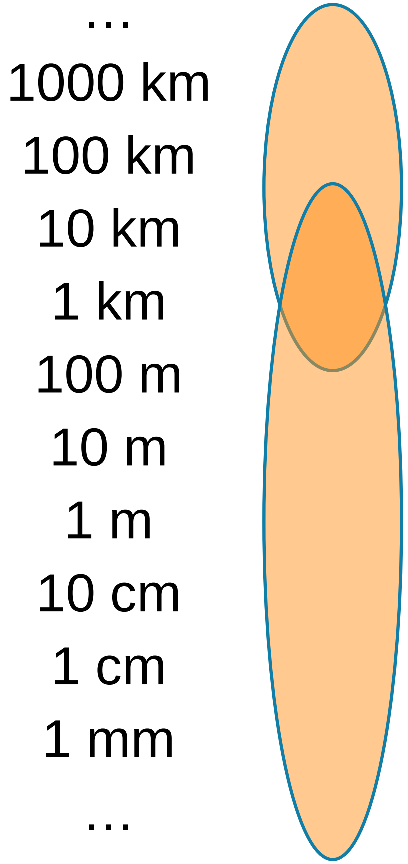
1. I’m a geophysicist. However, we should speak the same language:

   Ask your questions as they come!

2. Insights into what is possible and known, and what is NOT.
3. Working across the scales:

   ⇔ Sandra’s lectures.

4. Tools and results will be partly mixed.
5. Often indirect approach:
   - an *observation* is fit by a *model*,
   - we try to best constrain this model: *inversion*.



Tools and their limitations

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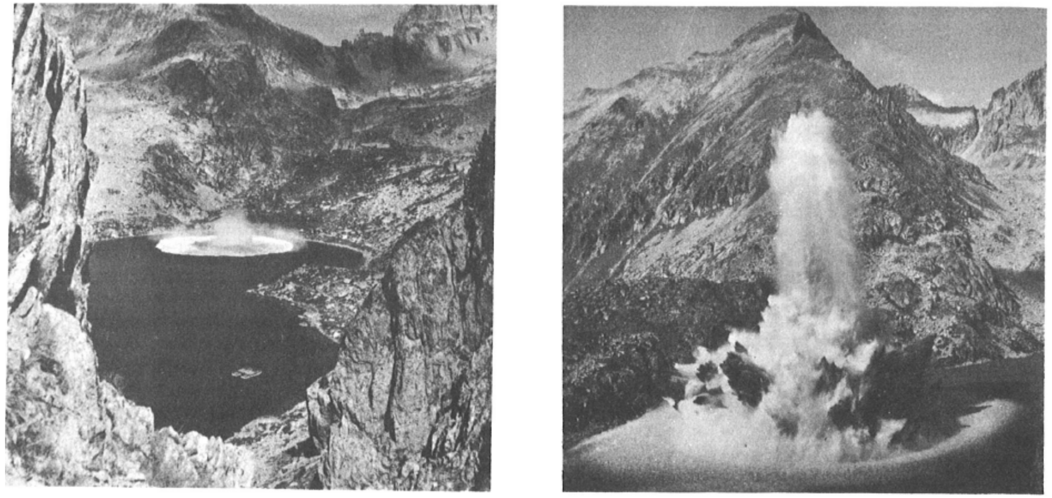
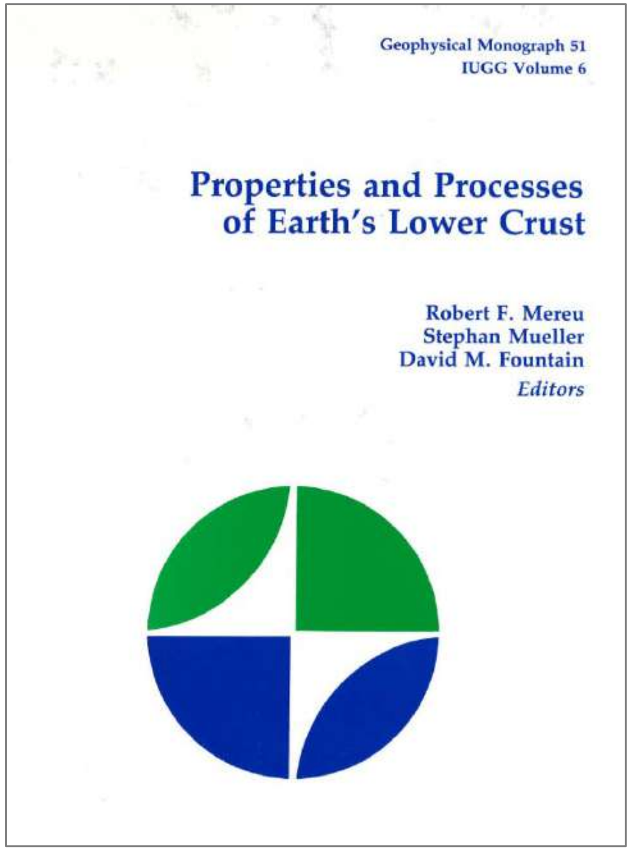
1. Seismology
    - active, passive, earthquakes
2. Potential fields
    - gravity, electromagnetics
3. Geothermics
4. Borehole geophysics
5. Remote sensing
6. Numerical modelling



FIGURES I.9
Explosions de 1 et 25 tonnes au Lac Nègre.

Labrouste, 1963

1989



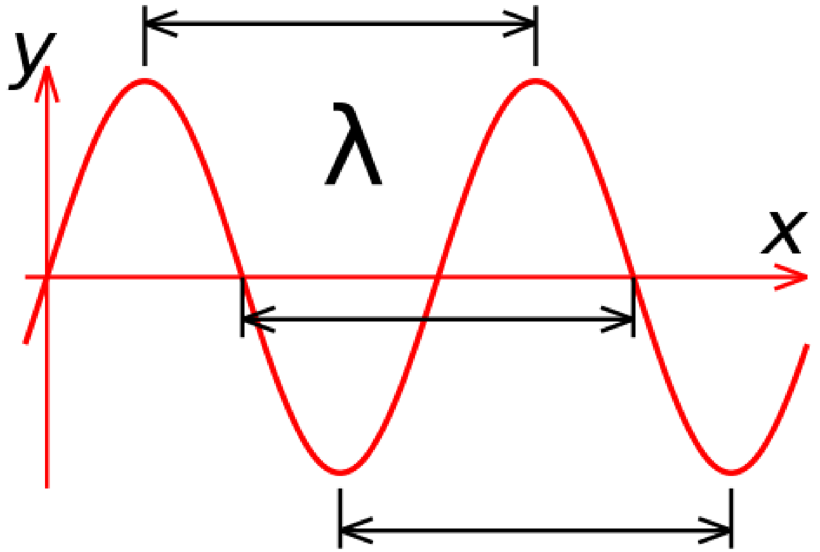
1. Seismology

- etymology: study of earthquakes
- generally: propagation of elastic waves
- active ~ : we generate the energy
- passive ~ : natural source
- what can we image?

  → resolution ~ λ/4

  (in theory…)

λ = v / f



v = λ * f

speed = wavelength * frequency

[m/s] = [m] * [1/s]

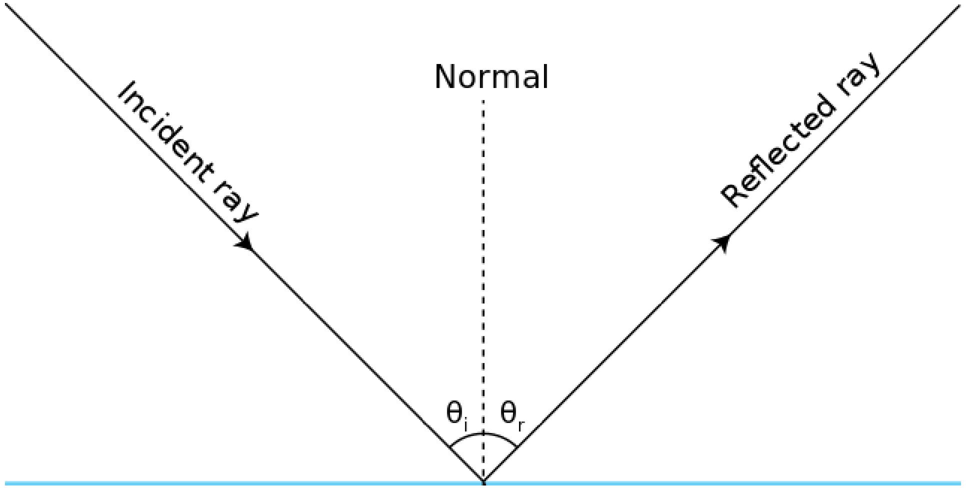
[Hz]

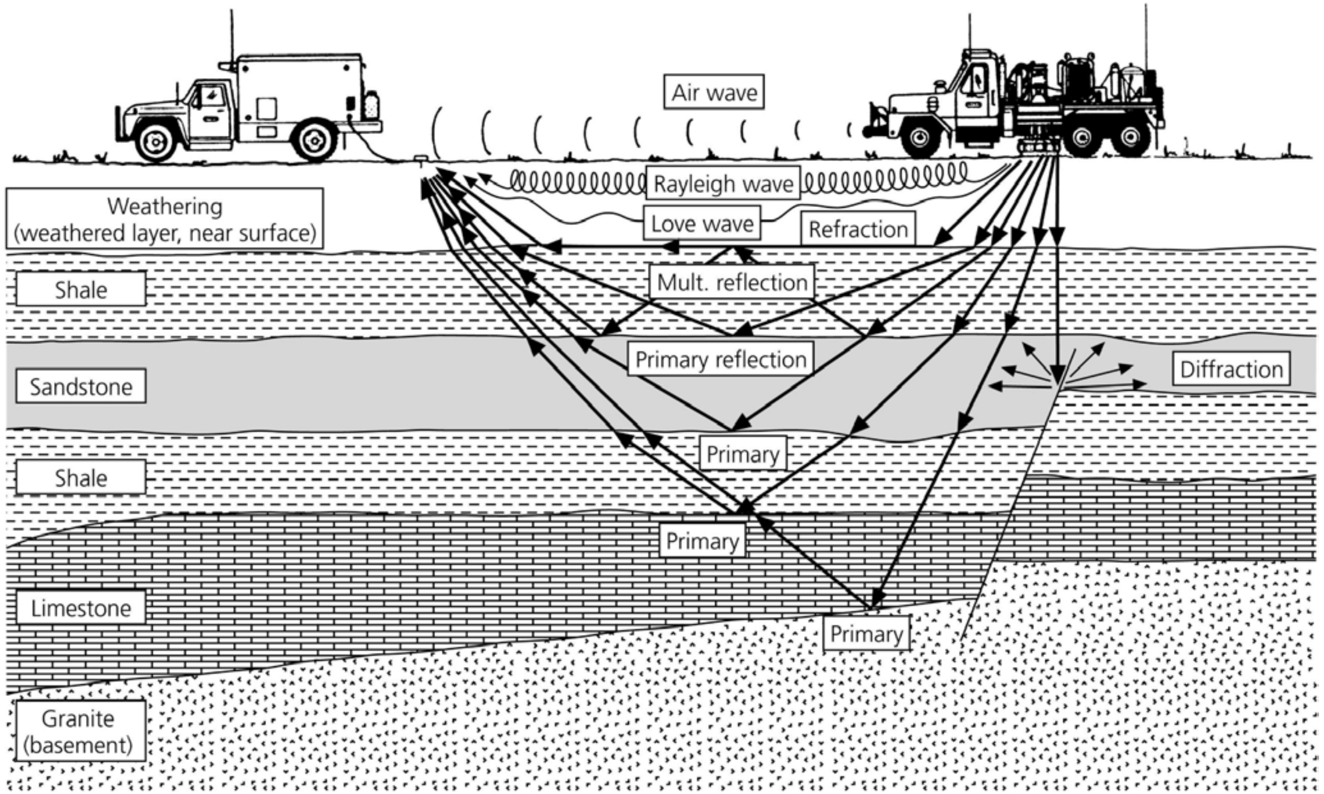
Active: Reflection seismics

active source: hammer, explosion, airgun, Vibroseis, weight drop, …

recording: geophones (2D, 3D)

wave **reflects** back from interface





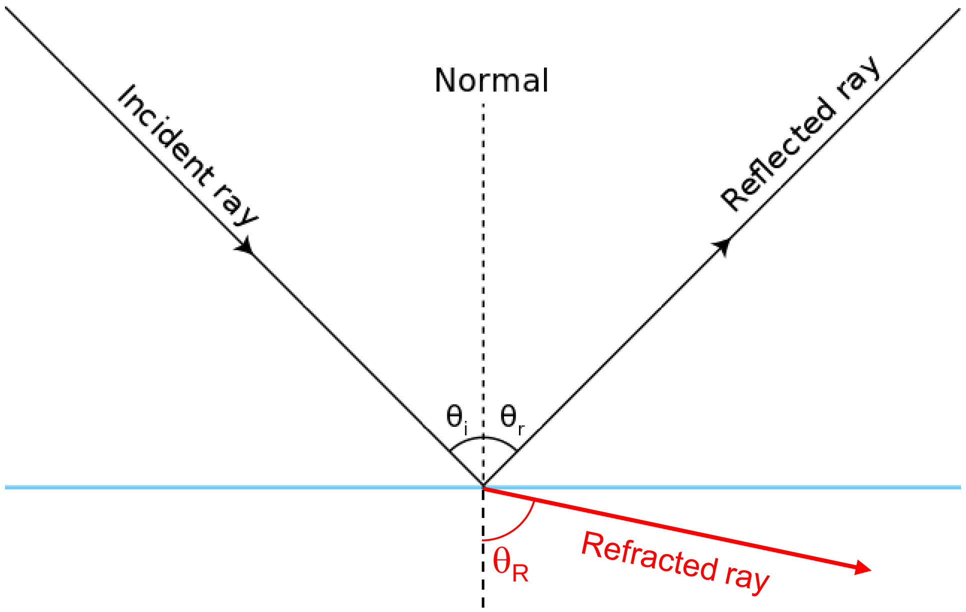
In: Stein and Wysession 2003, drawing with permission of Conoco

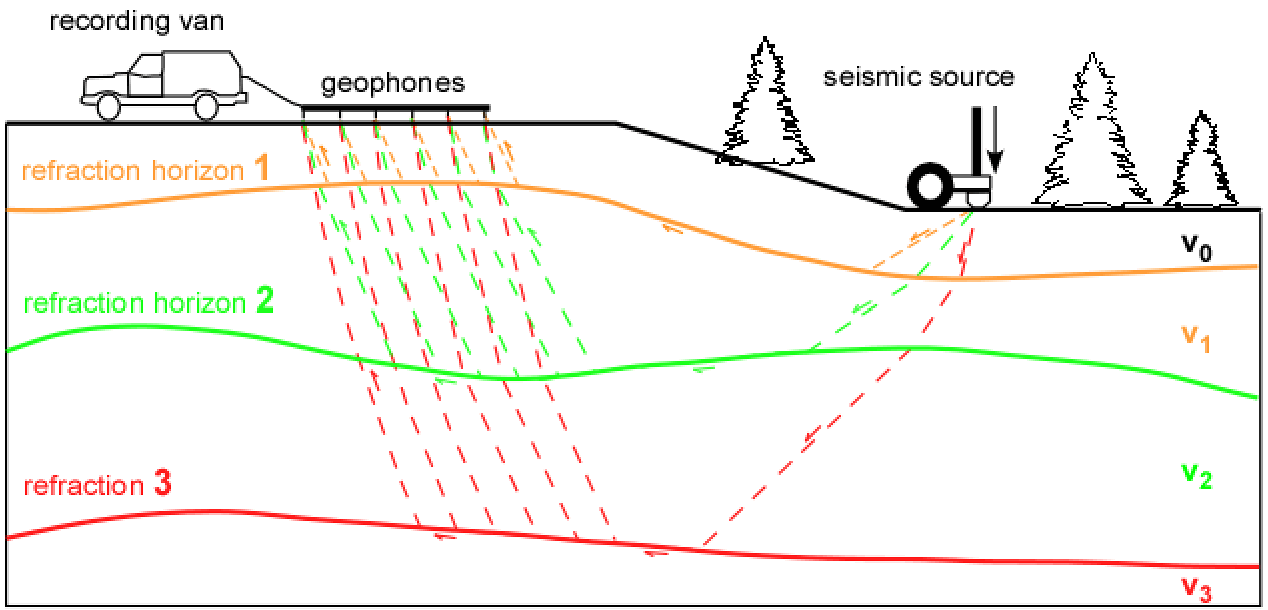
Active: Refraction seismics

active source…

geophones…

wave dives into next layer





NB: this is how A. Mohorovičić and V. Conrad identified the resp. interface (1909, 1925)

Active seismics in reality

- both reflected and refracted waves are recorded + noise + multilayer + dip + …
- simple sketch … → … sophisticated and heavy processing
- goal: structure, velocities, dip, physical properties
- examples:

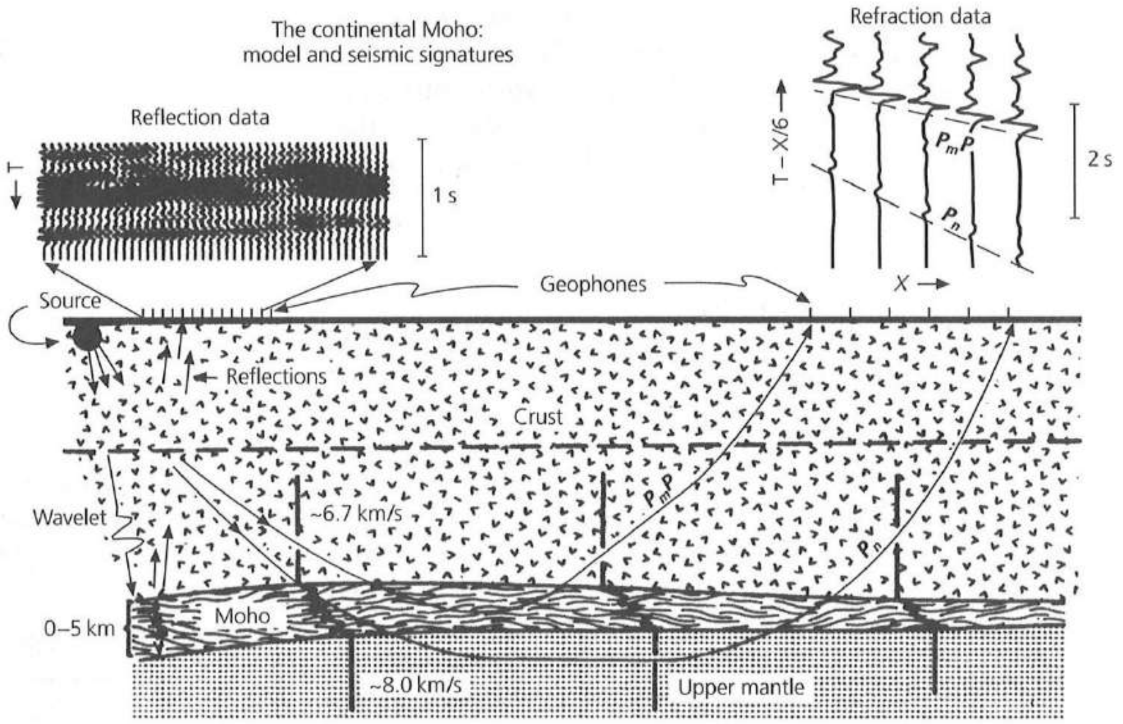


Fig. 3.2-21 Schematic model for the continental Moho as a laminated structure. Refraction studies using relatively longer wavelengths would show clear P_mP and P_n arrivals, whereas reflection studies using shorter wavelengths would show reverberations. (Braile and Chiang, 1986. *Reflection Seismology*, 257–72, copyright by the American Geophysical Union.)

Lower crust is reflective

- Australia, Eromanga Basin
- lower crustal lenticle

Finlayson et al. 1989

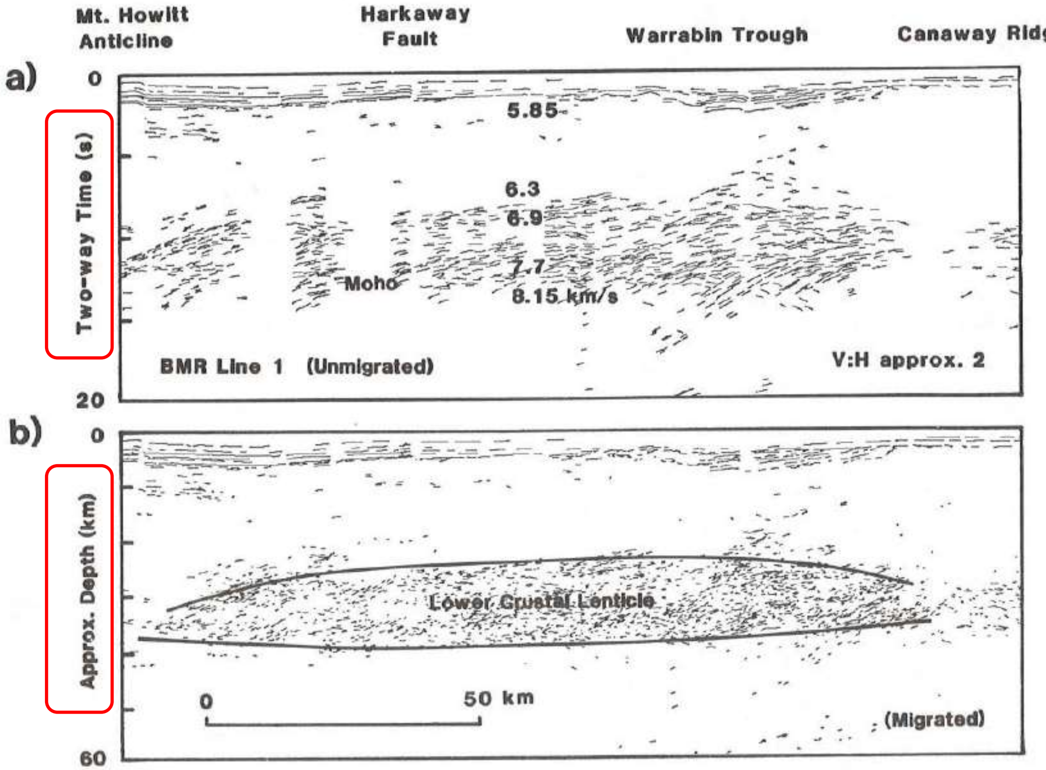


Fig.10. Digitized line diagram of reflectors along BMR Line 1 between the Mount Howitt Anticline and the Canaway Ridge: a) unmigrated data with velocity information derived from coincident seismic refraction data; b) migrated data converted to depth using an average crustal velocity of 6.0 km/s. The migrated data emphasize the reflections in a lower crustal lenticle.

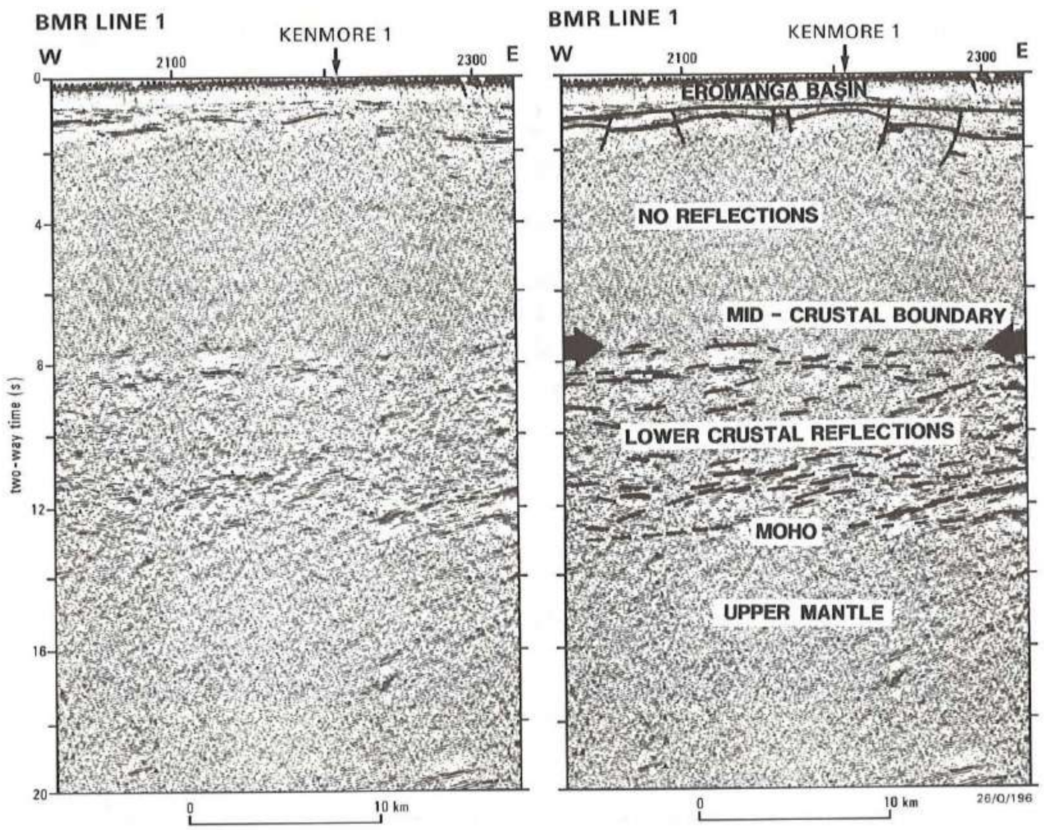


Fig.2. A 20 s reflection profile from BMR Line 1 west of the Warrabin Trough illustrating the characteristics of deep records from the central Eromanga Basin region. The upper crustal basement between about 2 and 8 s two-way time (TWT) is largely non-reflective or "transparent". There is a discontinuity at mid-crustal depths and many reflections from the lower crust. Below the interpreted Moho at 13 s there is a marked decrease in the amplitude and continuity of reflections.

Lower crust is reflective

- S. Germany, P and S waves
- layered v-model from lab data
- laminated lower crust
- compositional layering

Holbrook 1989

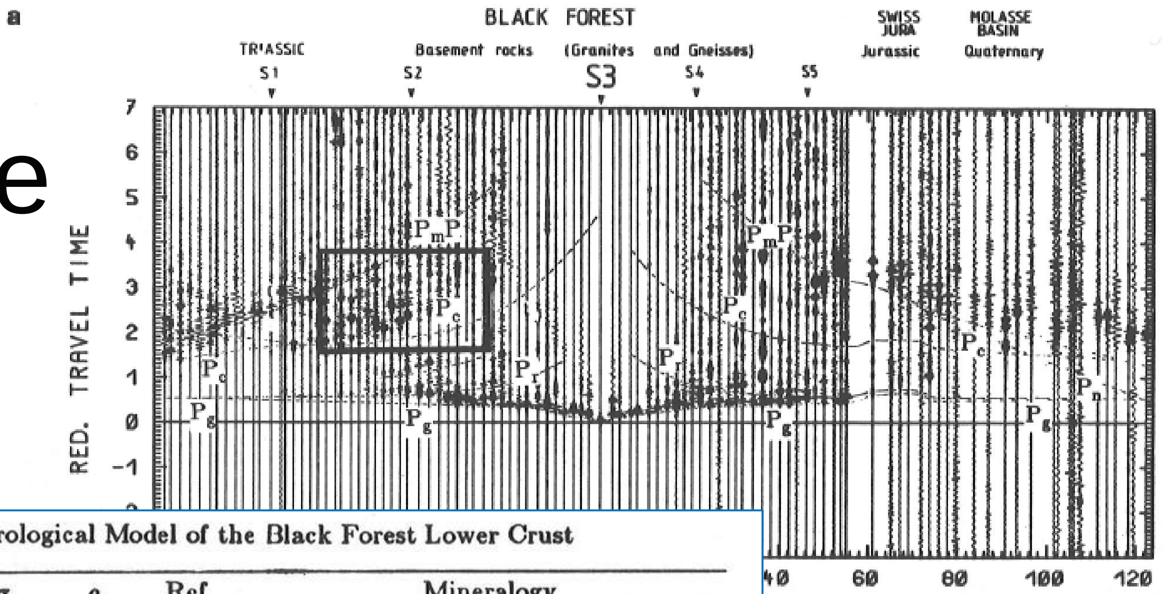
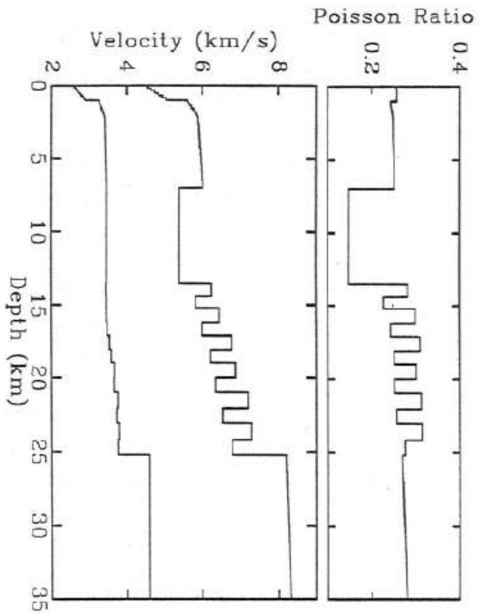


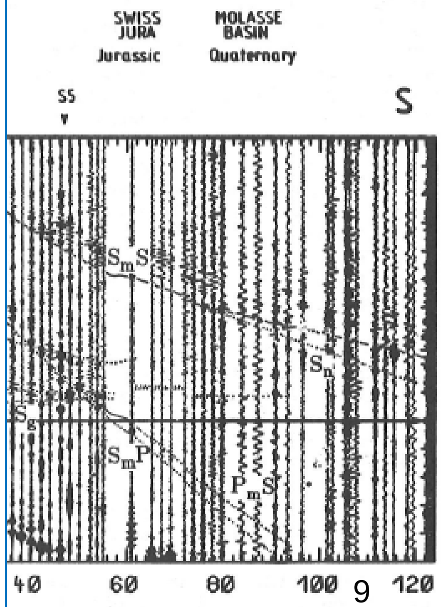
TABLE 1. Detailed Petrological Model of the Black Forest Lower Crust

Layer	h	v_p	v_s	σ	ρ	Ref	Mineralogy
1	0.9	6.27	3.45	0.28	2.71	h	Granite (qtz-biot-fspar)
2	0.8	5.83	3.46	0.23	2.63	a	Granite (fspar-qtz)
3	1.0	6.47	3.46	0.30	2.73	b	Gabbro-anorthosite Granulite
4	0.9	6.00	3.49	0.24	2.74	a	Diorite
5	1.0	6.78	3.55	0.31	2.78	f	Gabbro-anorthosite Granulite
6	0.9	6.24	3.59	0.25	3.03	c	Gabbroic Granulite (plg-cpx-biot)
7	1.0	6.89	3.67	0.30	3.08	c	Hornblende Granulite (hbl-plg-cpx)
8	1.0	6.36	3.66	0.25	2.93	g	Quartz Diorite
9	1.1	7.23	3.77	0.31	3.08	a	Garnet gabbroic pyriclasite(plg-px-gnt)
10	1.0	6.55	3.74	0.26	2.95	d	Al-rich Gneiss (qtz-gnt-sil)
11	1.1	7.31	3.80	0.31	2.99	e	Gabbro (plg-cpx-opx)
12	1.0	6.80	3.78	0.28	3.07	f	Gabbroic Granulite (plg-cpx-opx)
Tot	11.7	6.60	3.63	0.28	2.90		

a. Brooks, 1985
b. Christensen and Fountain, 1975
c. Chroston and Evans, 1983
d. Fountain, 1976; and Burke, 1987
e. Kroenke et al., 1976
f. Manghnani et al., 1974
g. Simmons, 1964
h. Simmons and Brace, 1965

Twelve-layer compositional layering model of the Black Forest lower crust used to calculate reflectivity synthetic of Fig. 3b. Explanation: h= thickness of layer(km), v_p= P-velocity (km/s), v_s= S-velocity (km/s), σ= Poisson's ratio, ρ= density (*GMCC*), Ref= source of velocity data.





ETH Working Group 1991

Western & Central Alps

Processed, interpreted cross-sections

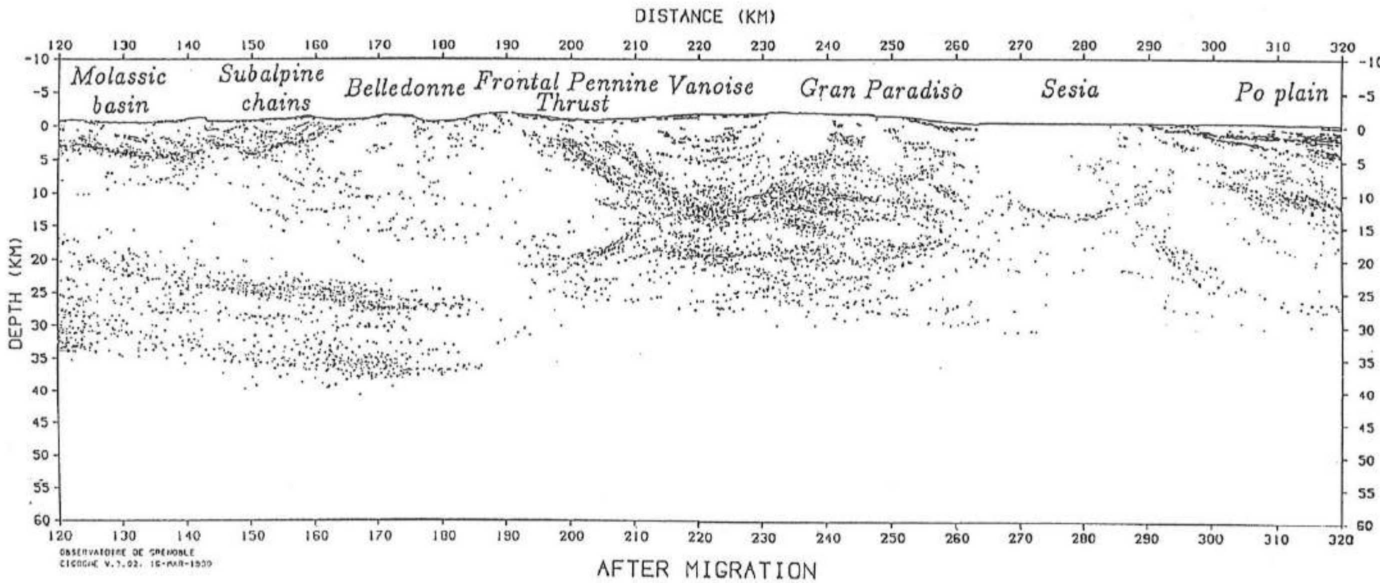
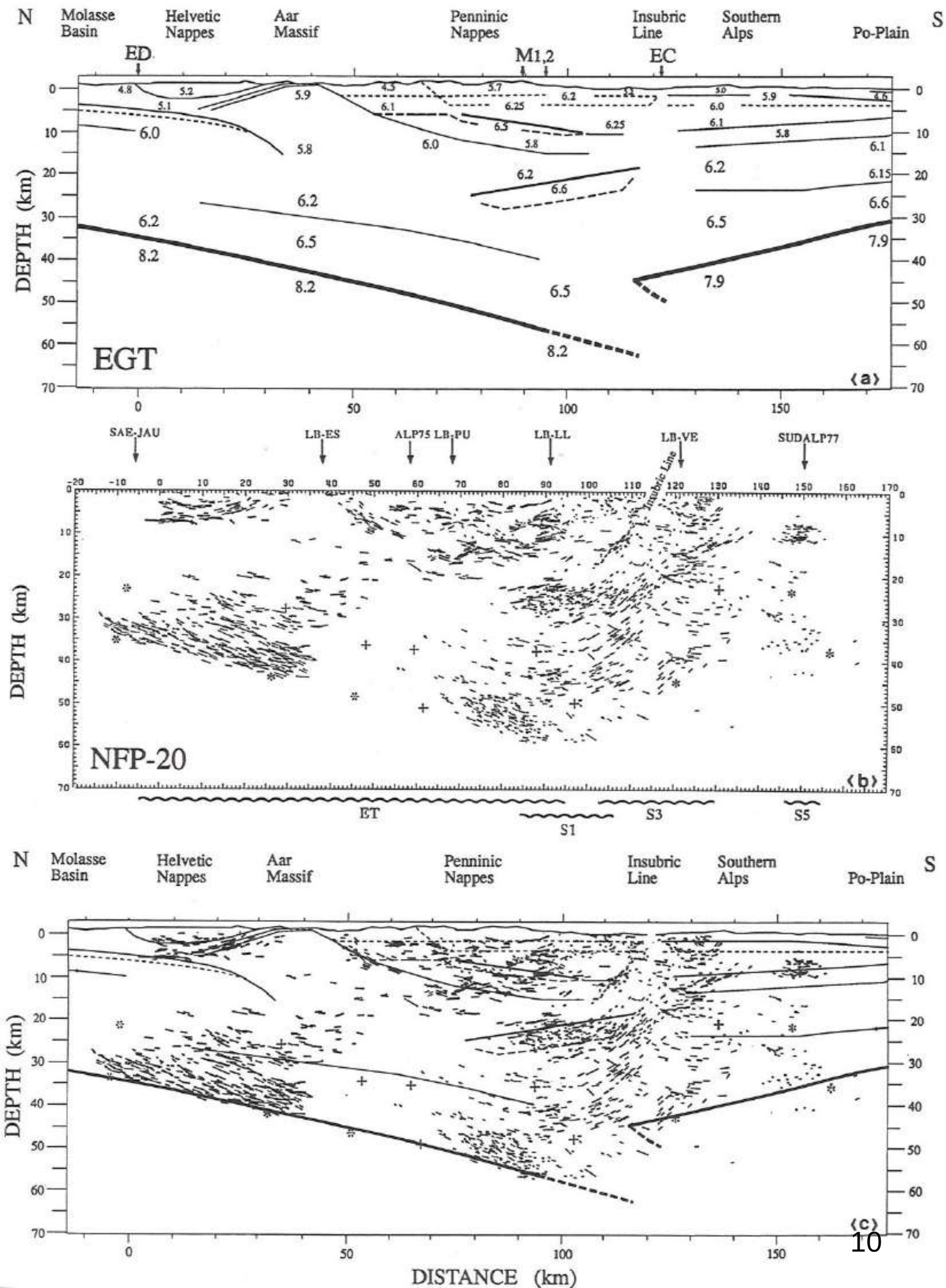


Fig.6 Unmigrated time section (a) and migrated depth section (b) of the line-drawing of the ECORS-CROP Alps profiles between the Belledonne Massif and the Po Plain.

Sénéchal & Thouvenot 1991



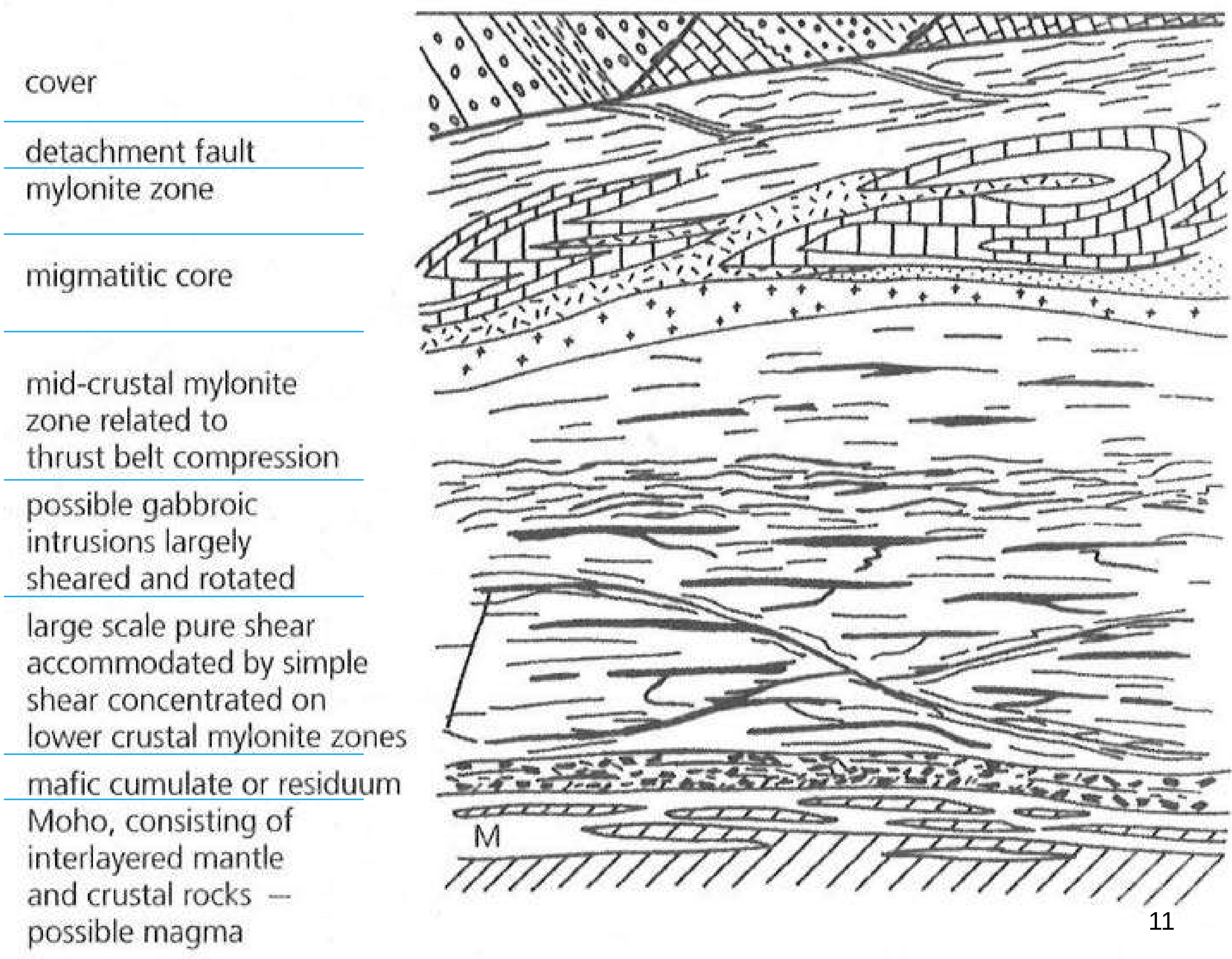
Basin & Range

Smithson 1989

Interpretative cross-section

- Cenozoic extension:
- deep crust: granulite
- LC: mylonites +

  3-km mafic cumulate
- sharp Moho ± p. melt
- crust:
  - ~50% mafic
  - ≤25% m. underplating



Minnesota

Interpretative cross-section

- Archean crust
- weak to no reflections
- “compressional shearing erased earlier structures”
- Moho is compositional, not layered

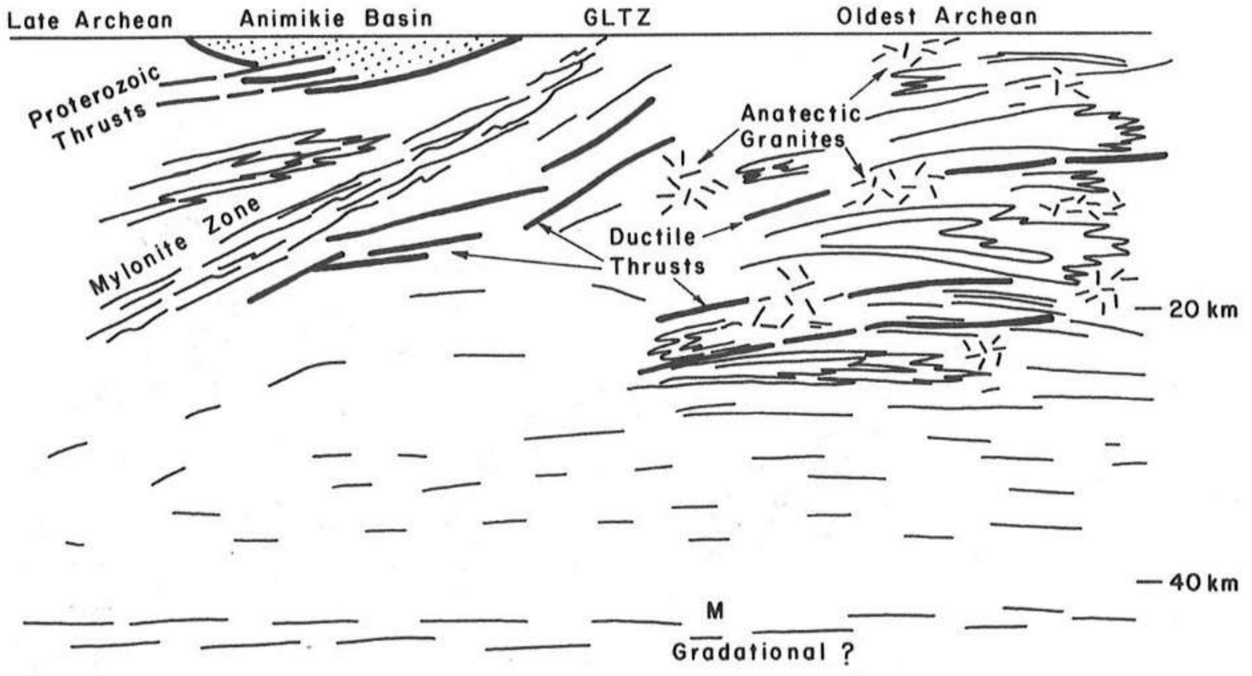


Fig. 5. Interpretative cross section of Archean crustal structure in Minnesota showing suture, Animikie basin and ancient gneiss terrain. Archean basement is remobilized along discrete thrusts to deform supracrustal rocks in Animikie basin. Complex, moderately dipping suture zone (GLTZ = Great Lakes Tectonic Zone) can be followed geophysically to about 20 km. Oldest Archean crust passes from a thick (approx. 30 km) stack of nappes interspersed with anatectic granites into a subhorizontal tectonic regime in lowermost crust about a gradational Moho.

Smithson 1989

Geological models

…drawn from / after seismics

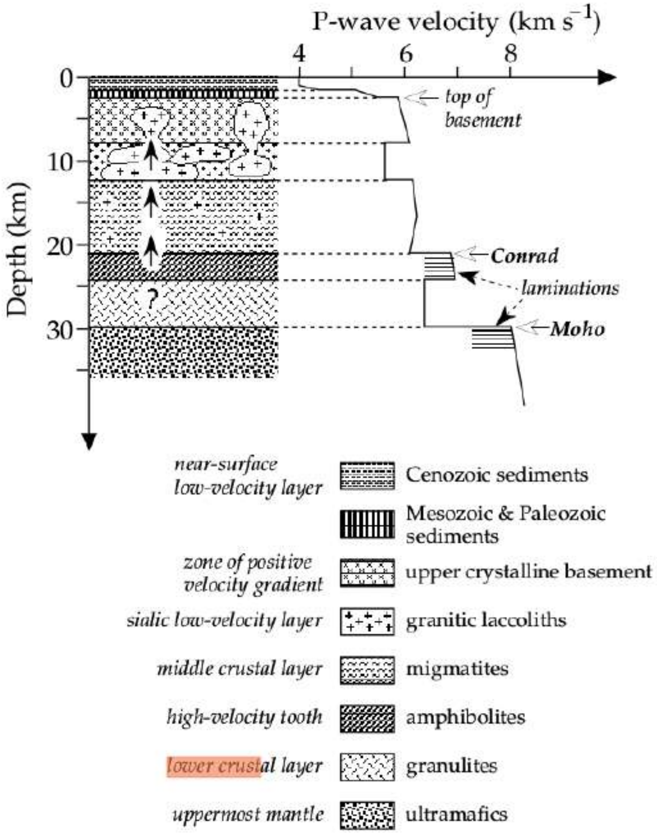


Fig. 3.86 Generalized petrological model and P-wave velocity–depth profile for continental crust (after Mueller, 1977).

Müller et al. 1977

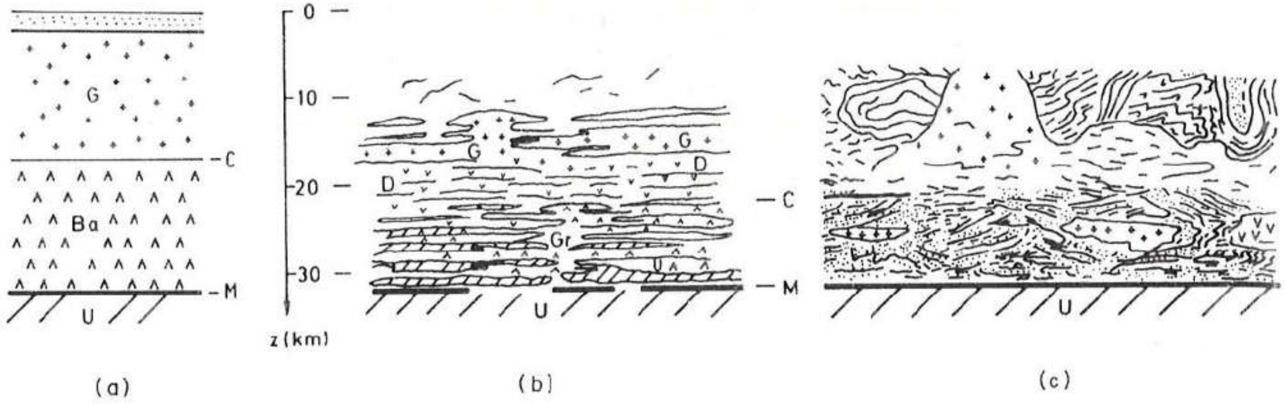


Fig. 5.1 Structural–compositional models of the continental crust. (a) Classical view, (b) model of Meissner (1967), and (c) model of Smithson (1978); G, granitic; D, dioritic; Ba, basaltic; Gr, gabbroic–granulitic; U, ultramafic; C, Conrad; and M, Moho.

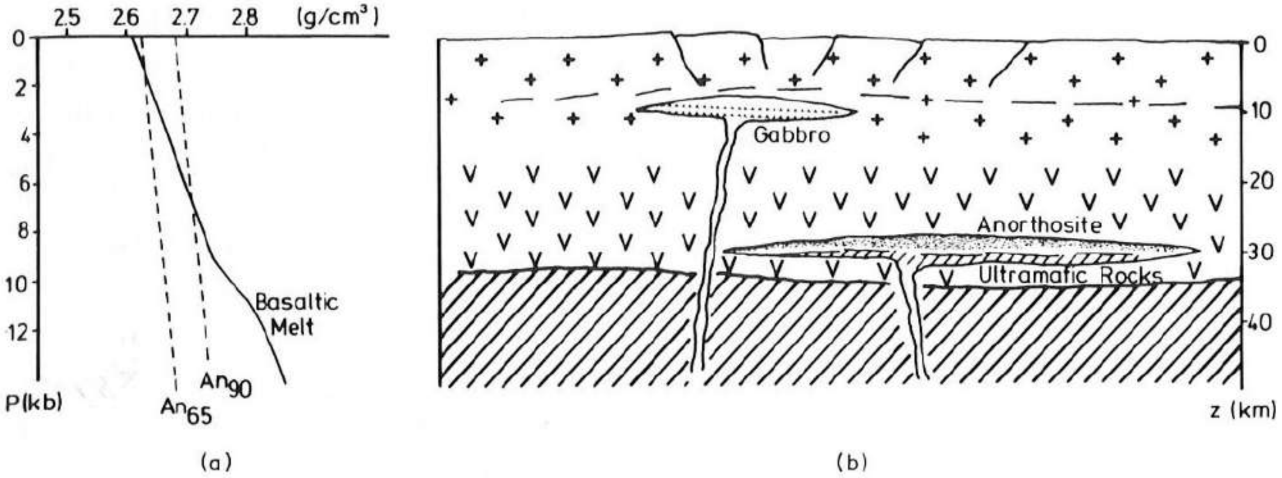


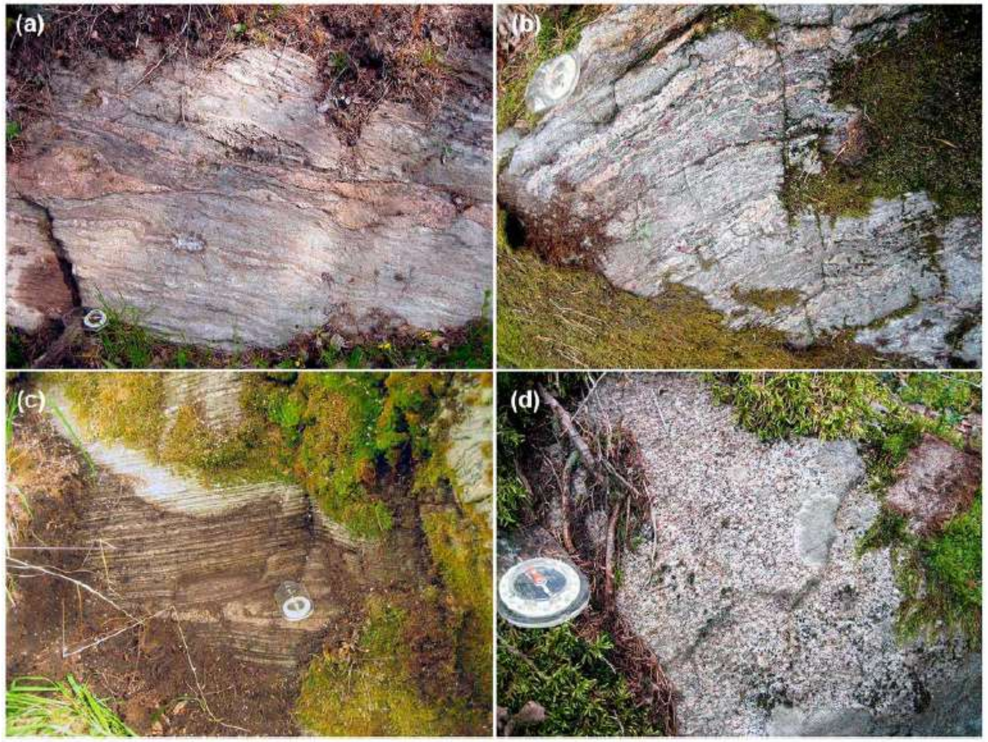
Fig. 5.7 Two different products of differentiation. (a) Density–pressure relationship for an olivine tholeiitic melt and plagioclase with different percentage of anorthite and (b) intrusions into lower crust with formation of plagioclase-rich rocks with ultramafic cumulates. Upper crust contains gabbroic cumulates. [After Kushiro (1980).]

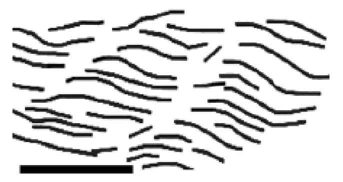
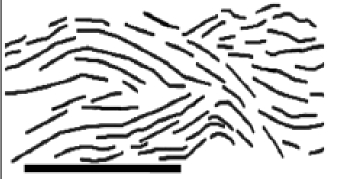
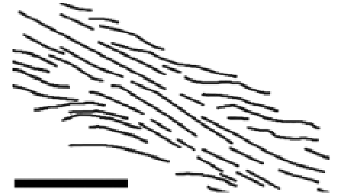
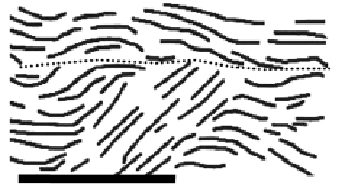
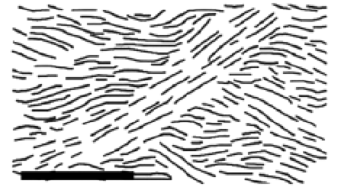
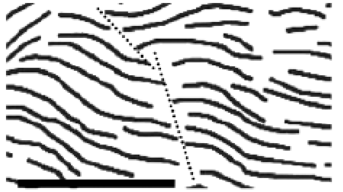
in Meissner et al. 1986

Torvela et al. 2013

More recently:

- Finnish Reflection Experiment
- seismic *attributes* + seismic *facies*
- mid-crustal deformation



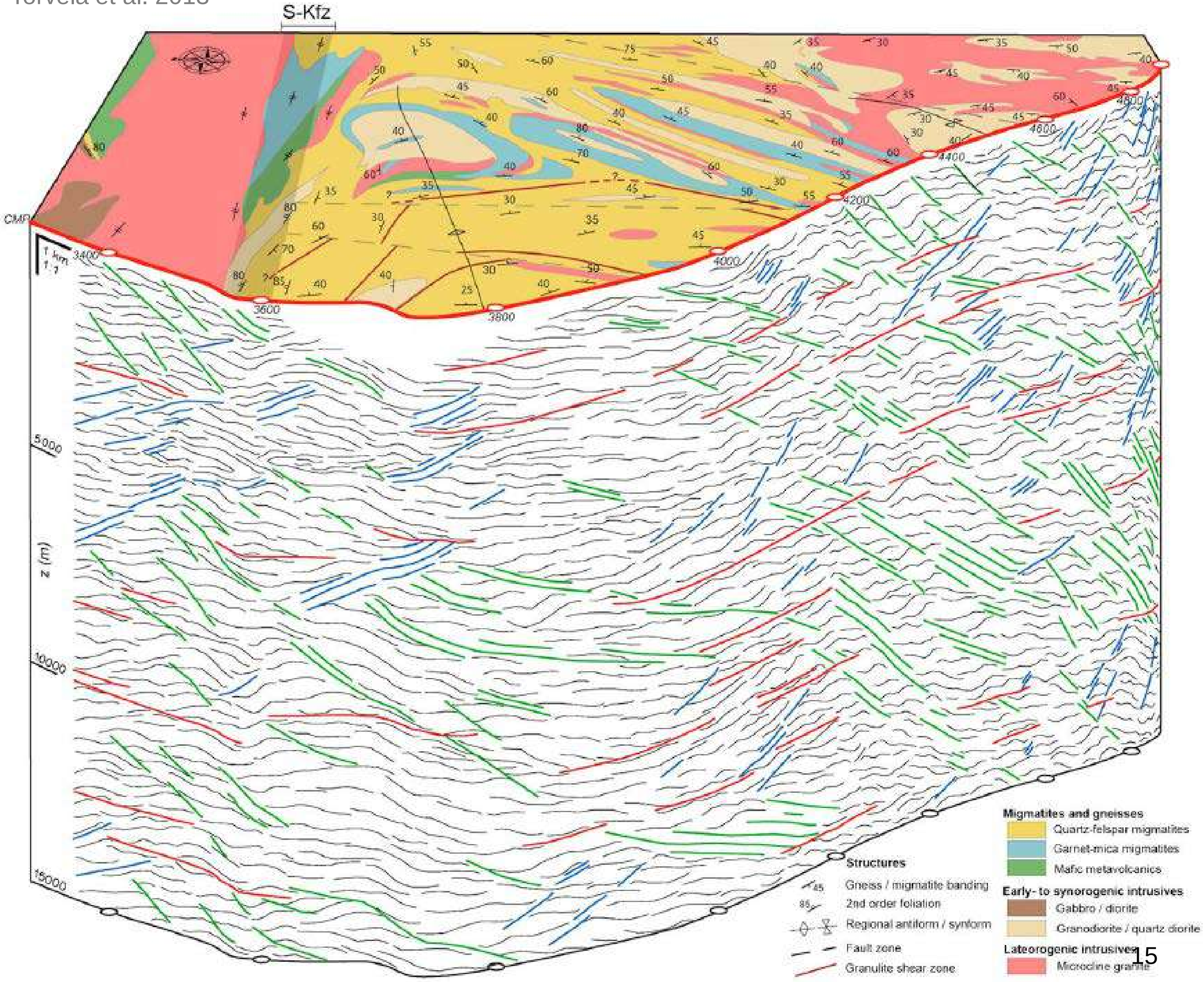
Seismic facies class		Description	Interpretation
SF1		Subhorizontal, sigmoidal reflections with terminations aligned into moderately dipping, relatively straight, non-reflective or weakly reflective zones	*Main S-C' facies:* S-C' structure, with the wavy reflections defining the C'-planes and the non-reflective / weakly reflective zones (and sometimes SF3) representing S-planes
SF2		Sets of converging reflections, often separated by straight, moderately dipping reflections	*Fold facies:* recumbent, isoclinals folds bounded by extensional/transtensional shear zones (i.e. the folds are affected by the S-C' folding and shearing)
SF3		Straight, moderately dipping reflections, flanked by reflections (of SF1/SF2) bent into (sub)parallelism with the straight reflections	*Shear zone facies:* Extensional / transtensional shear zone; some of these show higher energies (amplitudes) than others and may contain dykes. Often form an inherent part of the S-C' structures.
SF4		Various reflection types terminating along a non-reflective or weakly reflective, subhorizontal zone (marked with a stippled line)	*Detachment facies:* A subhorizontal detachment accommodating some of the overall extensional/ transtensional strain
SF5		Reflection assemblages showing characteristics of two or more of the other classes	*Complex facies:* interpretations vary
SF6		Reflections within SF1-SF5 terminating abruptly onto steeply dipping/subvertical, non-reflective planes (marked with stippled lines)	*Fault facies:* late, brittle faults cutting the ductile structures

More recently:

- shear zone
- shear zone
- detachment

→ attributes and facies are tools to help interpretation

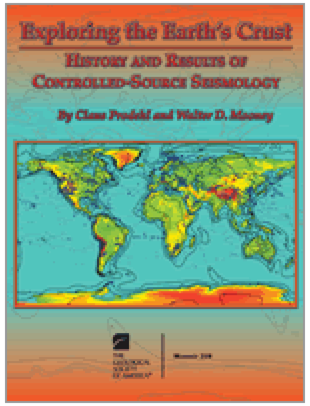
Torvela et al. 2013



Reflective lower crust interpretation

Copying expressions from papers:

- strain-induced fabric, ductile shear zones, extensional plastic flow ➔ Deformation
- layering: igneous, lenses of partial melt, compositional ➔ Structure
- free fluids, fluid-filled cracks ➔ Fluids



Seismics in your region of interest?

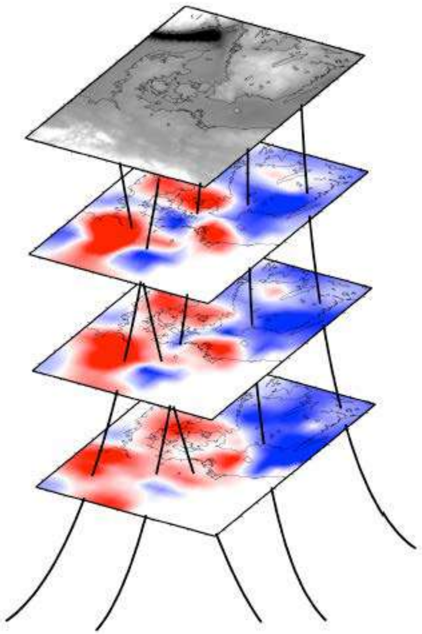
Exploring the Earth's Crust: History and Results of Controlled-source Seismology

Claus Prodehl and Walter D. Mooney

GSA Memoir 208, 764 pp, 2012, doi: 10.1130/MEM208

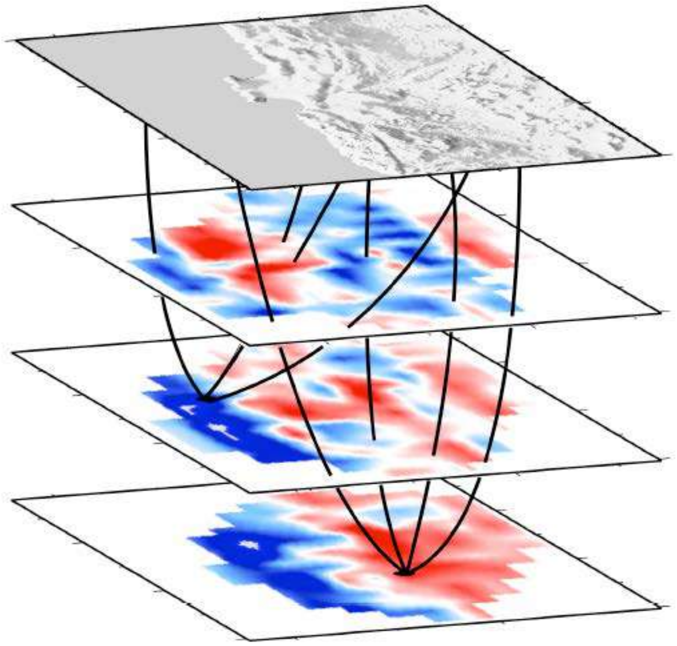
Passive: earthquake tomography

Arrival time of seismic waves → velocity anomalies in the Earth



distance = velocity * time

it depends....   *unknown*   *observed*

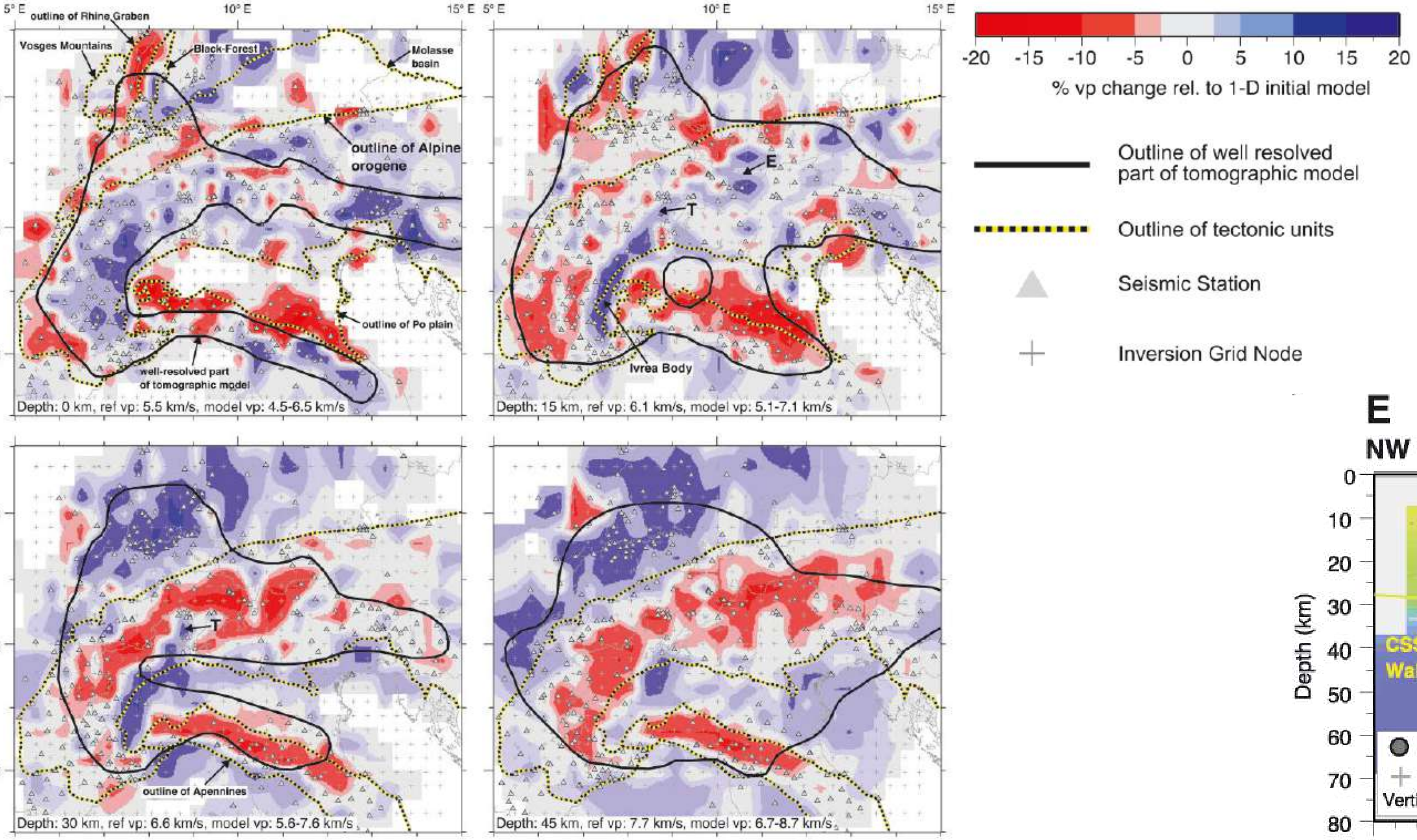


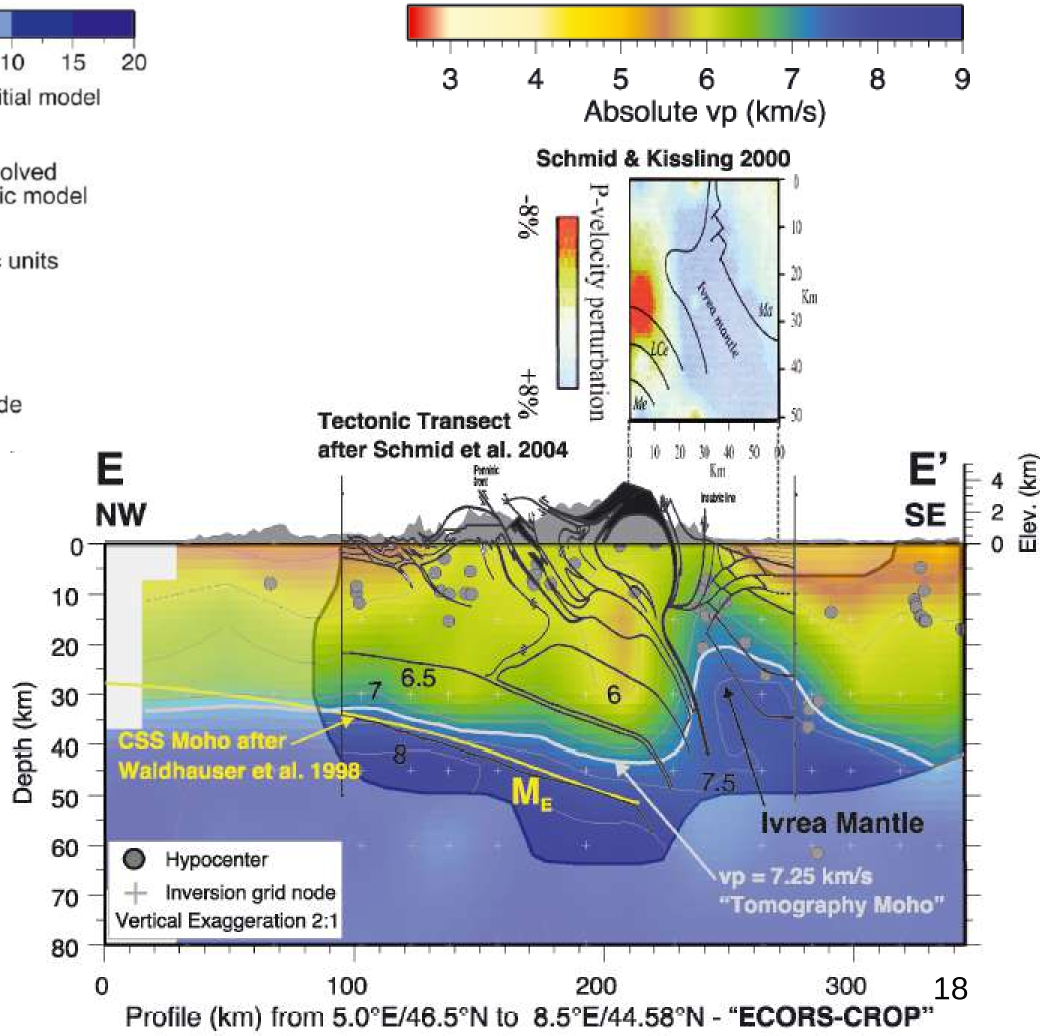
teleseismic tomography:
inversion for velocities

local earthquake tomography:
joint inversion for vel. and eqk. origin

Alps local earthquake tomography

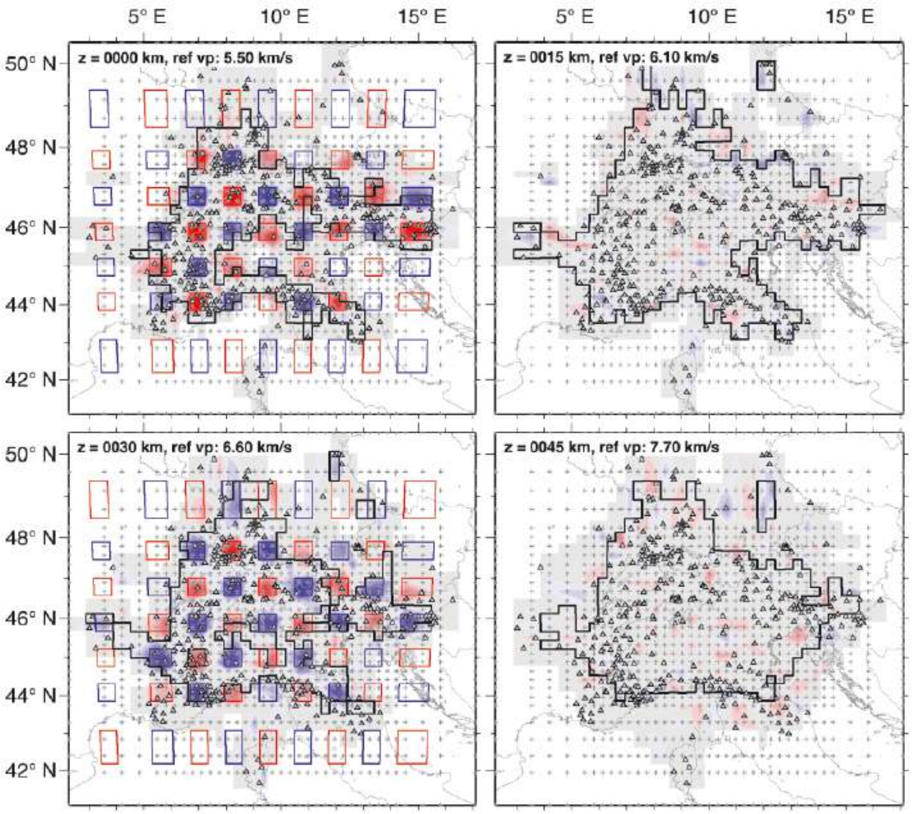
Diehl et al. 2009

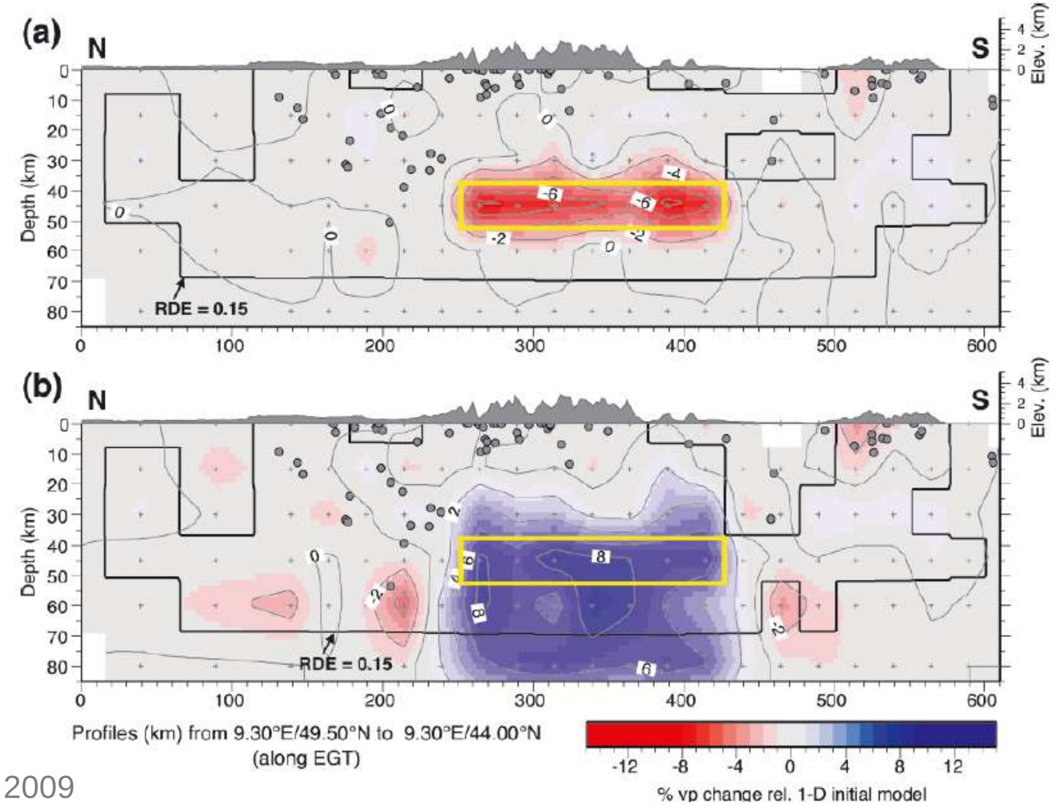




Credibility?

Not everything on a tomographic image is real !!!





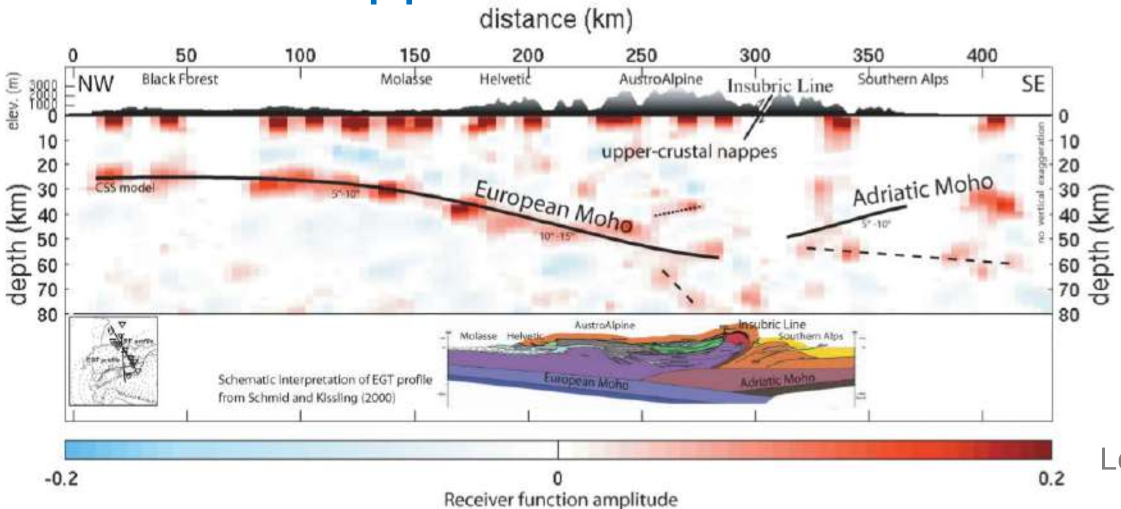
Diehl et al. 2009

Resolution test: alternating +/– anomalies

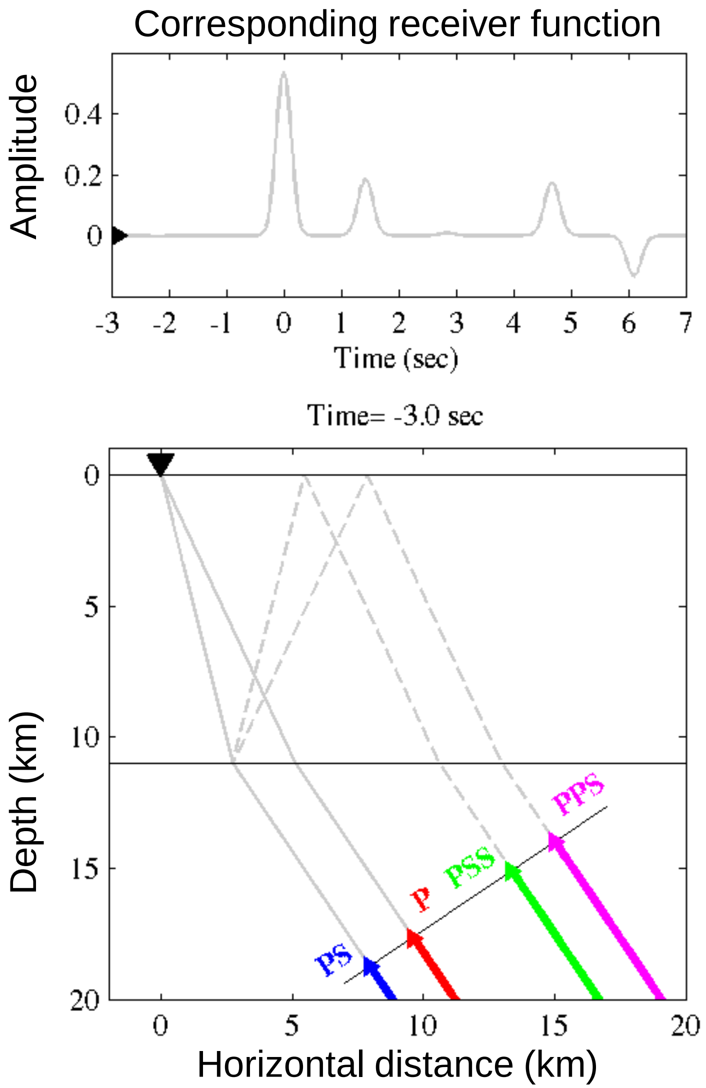
Synthetic test: artificial structures

Passive: receiver functions

- converted waves at a discontinuity
  P-to-S conversion   Moho, …
- result:
  - depth of sharp velocity changes (+, –)
  - average Vp/Vs of crust (low: felsic, high: mafic, fluids?)
- 1D, 2D, 3D applications

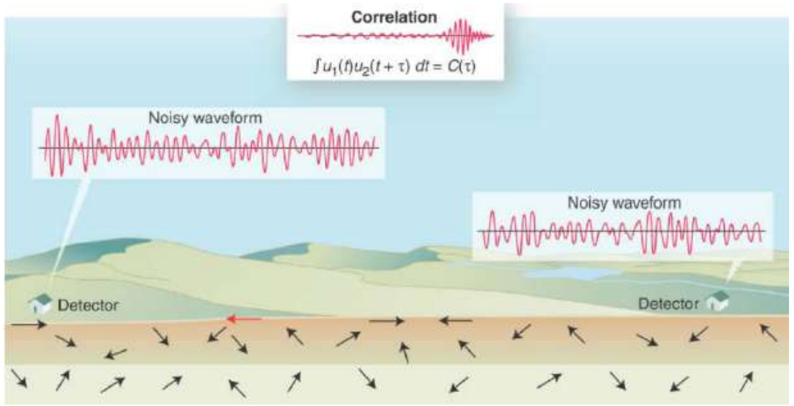


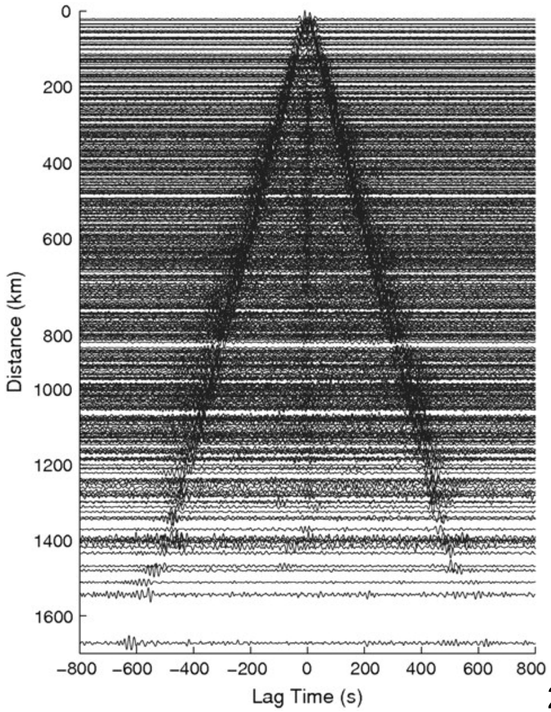
Lombardi et al. 2008



Passive: overview

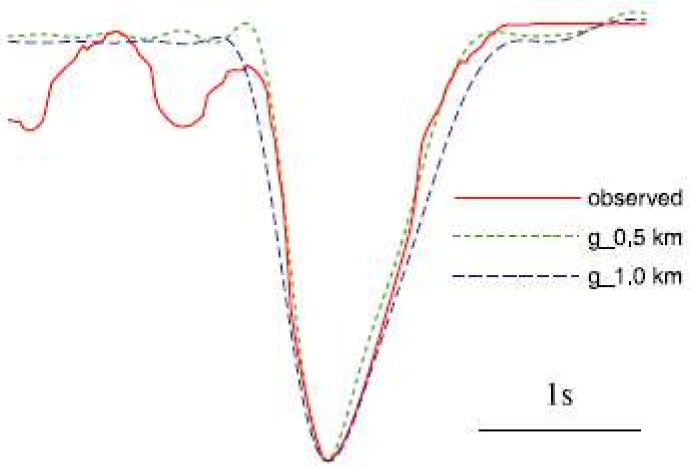
- tomography (direct body waves): bulk velocity anomalies
- receiver functions (body wave conversions): sharp interfaces
- surface wave tomography: usually coarse resolution
- ambient noise tomography:
  - bulk Vs
  - may reach LC if array is large
- shear-wave (SKS) splitting:
  - anisotropy, e.g. olivine CPO
  - depth is usually poorly constrained



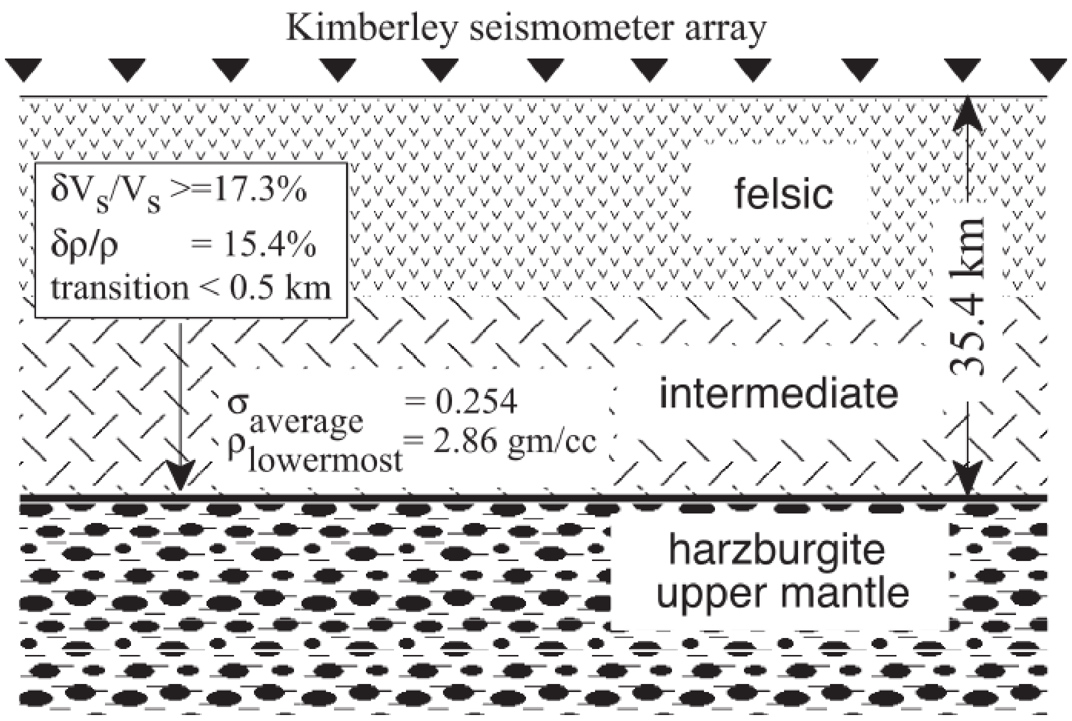


How thick is the Moho?

- Kaapvaal craton, Kimberley
- thickness of velocity-gradient is frequency dependent



James et al. 2003



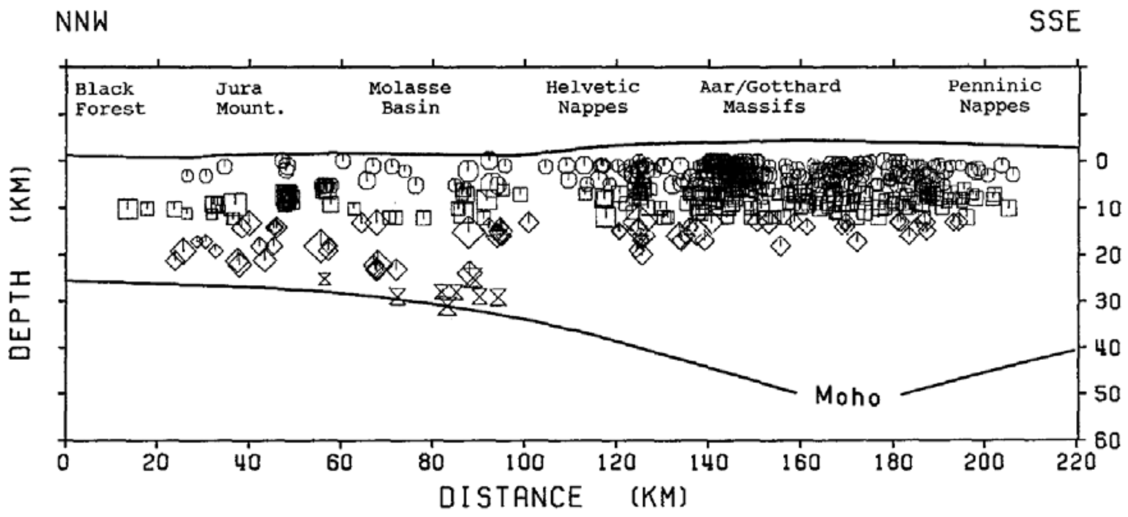
- Moho: <2 km everywhere, locally <0.5 km

Earthquakes:

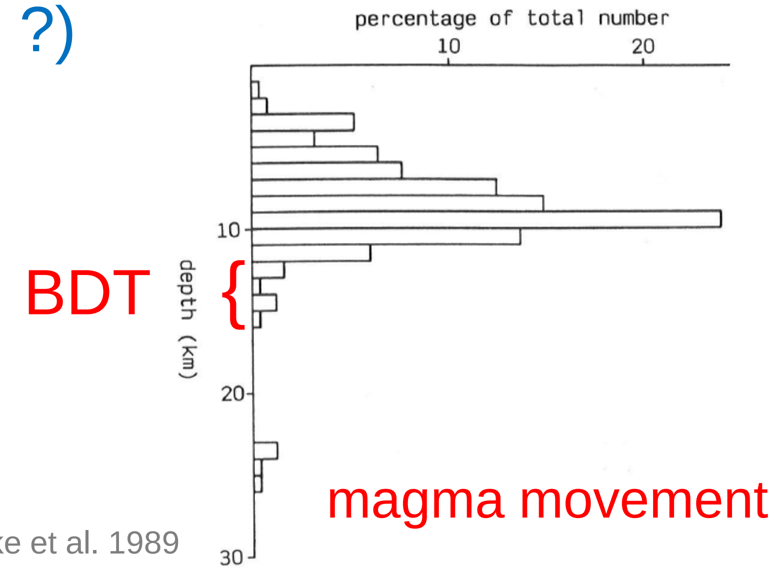
“Sudden brittle failure.” (?)

See discussions on: e.g. Jackson et al. 2004 Geology and citing papers

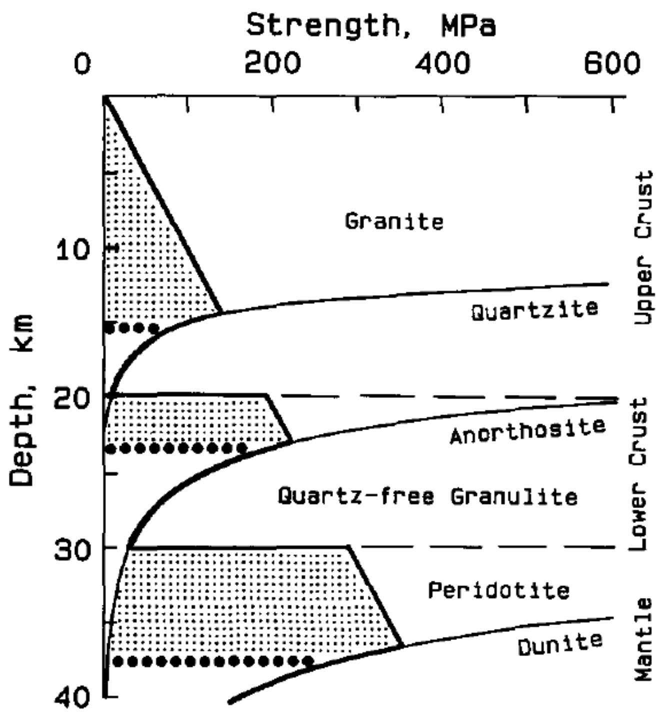
- depth: most events are in the upper crust, but…
- rheology: lower crust is usually aseismic, but…
- temperature (≤ 600°C ?)



Deichmann 1992



Cooke et al. 1989



Earthquakes: energy budget and rock record

- generation of: waves cracks heat
- energy partitioning: ~1/3 2/3

	waves	cracks	heat
generation of:	waves	cracks	heat
energy partitioning:	~1/3		2/3

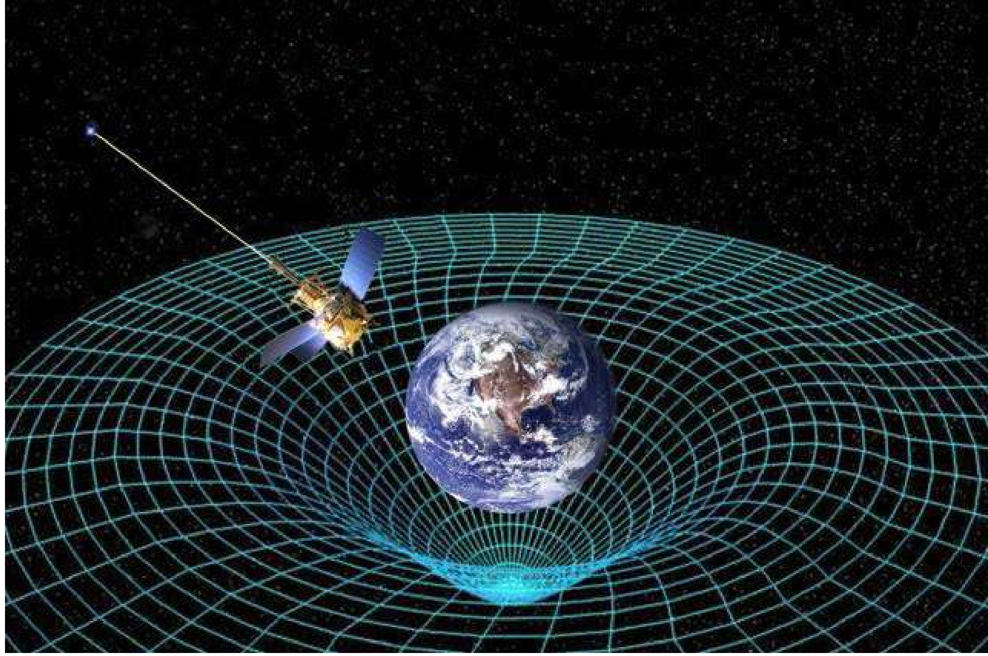

http://www.lpl.arizona.edu/~rlorenz/pseud.html

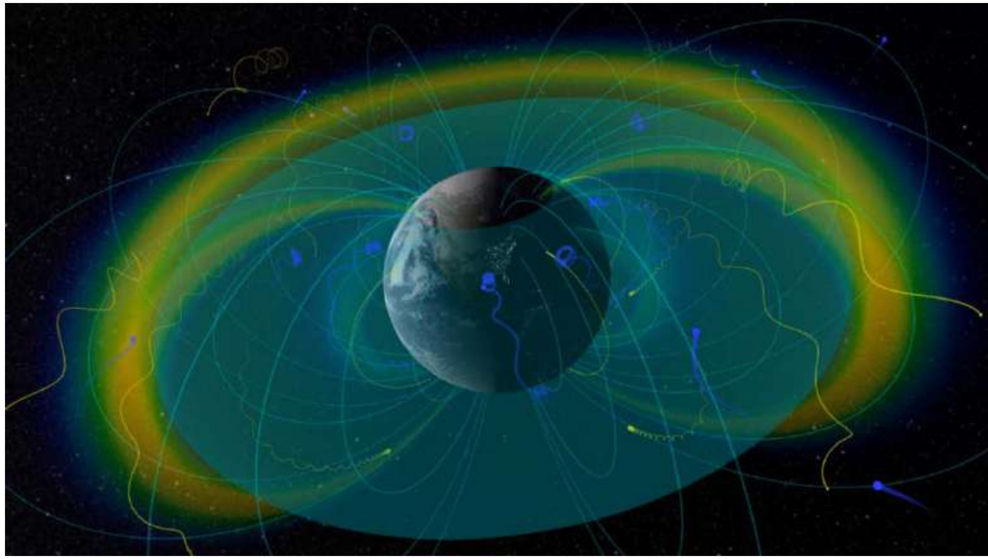
2. Potential fields

Gravitational and electromagnetic interactions can be modelled using potentials (→ maths) and functions (→ harmonic functions) satisfying the same equation (→ Laplace equation).

(Hm… what does this mean?)

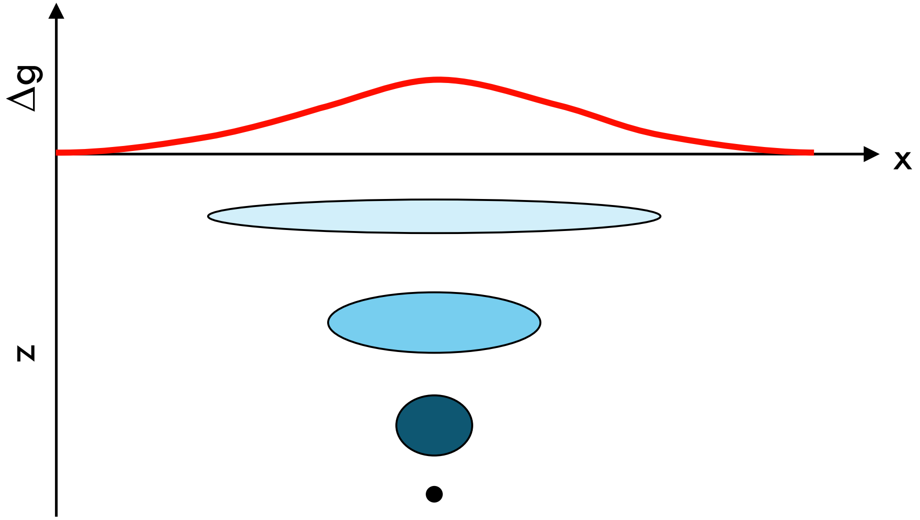
Gravity and EM methods share similarities.





Characteristics

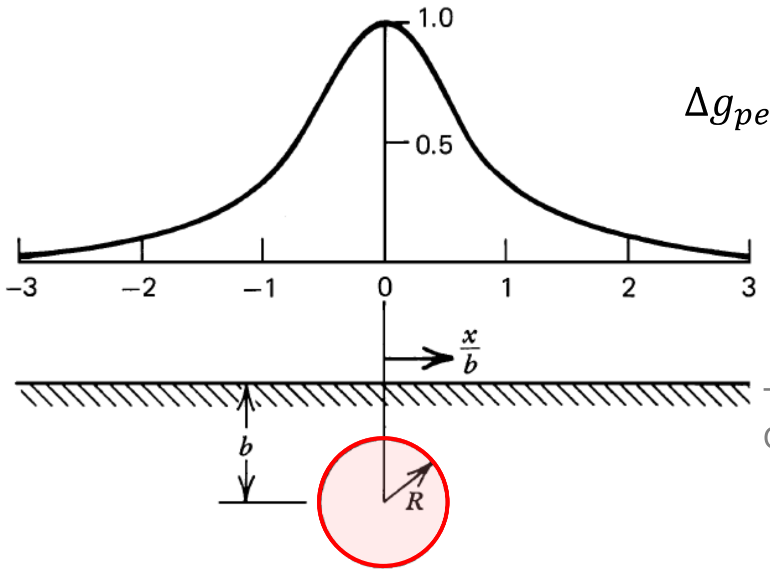
- ☺ wide range of applications
- ☺ measure of gradients
- ☹ non-unique



Remedy ☺ : use other datasets, too!

(general recommendation)

Example: gravity



$$\Delta g_{peak} = \frac{4\pi G R^3 \, \Delta\rho}{3b^2}$$

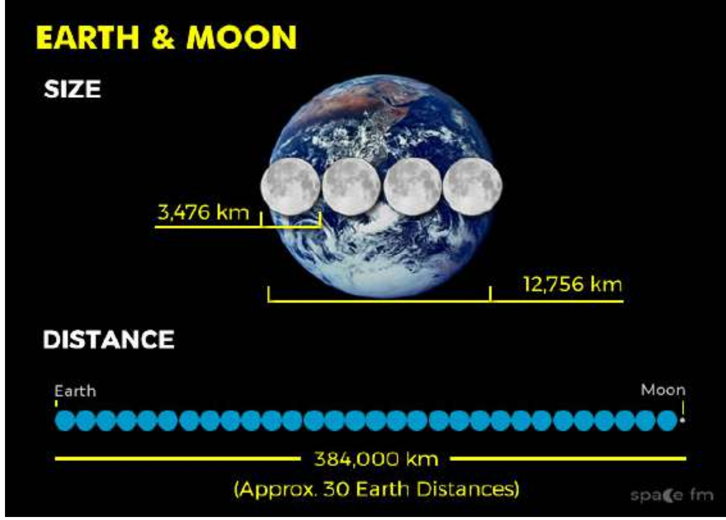
Turcotte & Schubert
Geodynamics

same Δg_{peak} for:

R [km]	Δρ [kg/m3]	b [km]
1	100	2
1	25	1
0.5	100	0.7
0.5	800	2

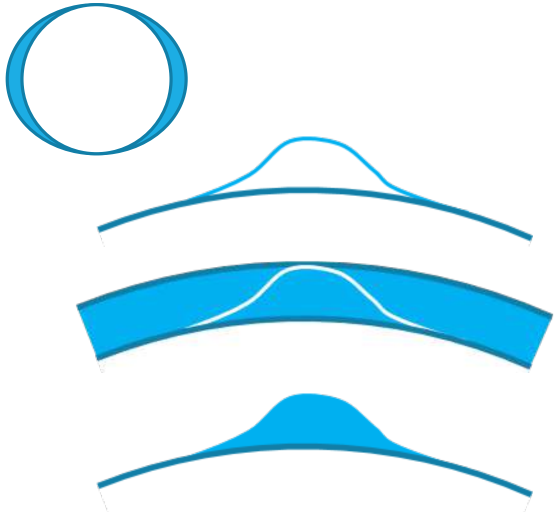
Gravity anomalies

- the “most precise” geophysical measurement *(~5 ppb)*
- whole Earth → local anomalies



384’400 ± 0.02km

- measurement — g_{OBS}
- latitude corr.
- elevation corr. — free-air anomaly
- plateau corr.
- terrain corr. — Bouguer anomaly

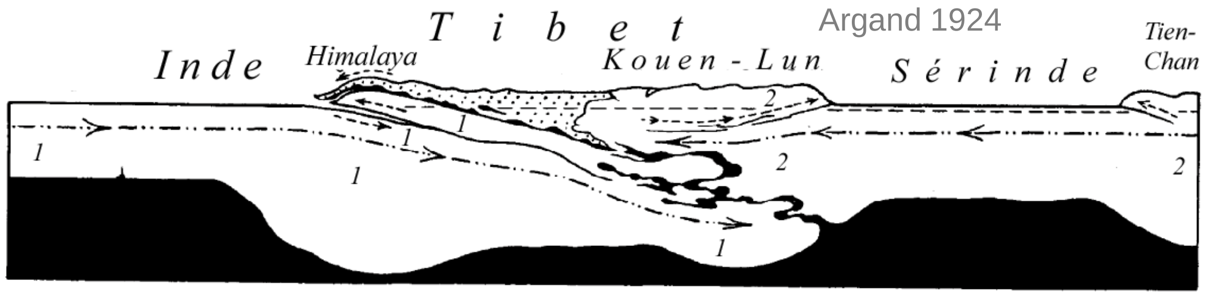


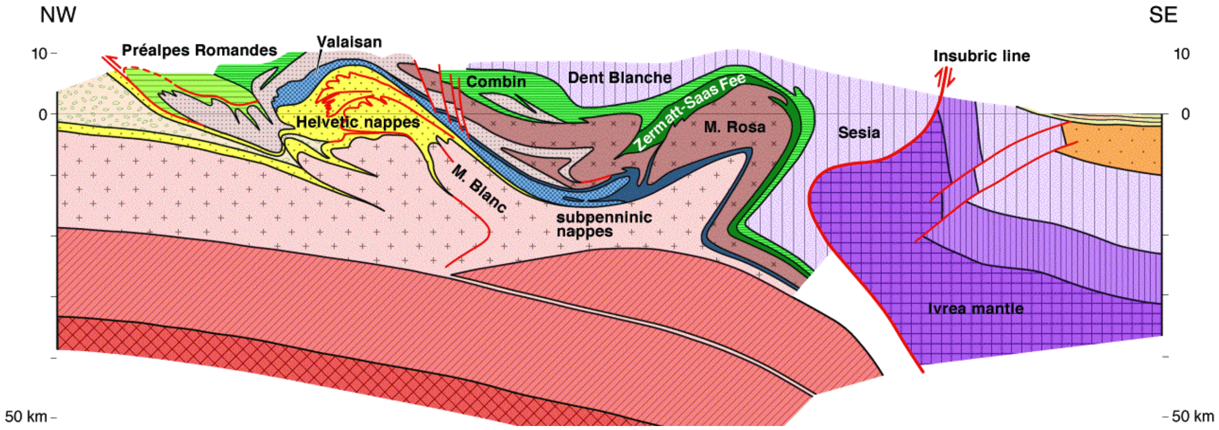
Bouguer Anomaly

all effects are reduced to sea-level

denser body: BA positive

lighter body: BA negative





https://tecto.earth.unibas.ch//Members/Schmid/alps/schmid_html/fig3b_large.html

Electromagnetic methods

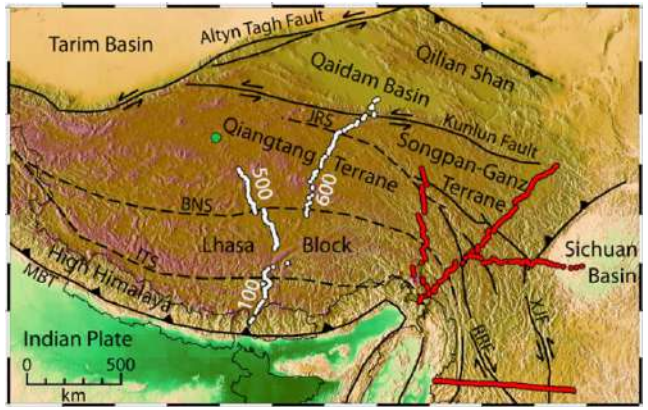
- interaction of **E** and **M** fields
- usually near-surface applications
- problem: noisy environment

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho \, dV$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{l} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{l} = \mu_0 \left(\iint_{\Sigma} \mathbf{J} \cdot d\mathbf{S} + \varepsilon_0 \frac{d}{dt} \iint_{\Sigma} \mathbf{E} \cdot d\mathbf{S} \right)$	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$

wikipedia

- main deep-reaching method: **MT**
  - magnetotellurics, 1 mHz-100 kHz
  - Earth's natural field (Earth is 10^{10} better conductor than atmosphere)
  - penetration depth $\propto \sqrt{\text{resistivity} \cdot \text{period}}$
  - sources of interest: fluids: aqueous, brine, partial melt
    graphite and other conductive materials

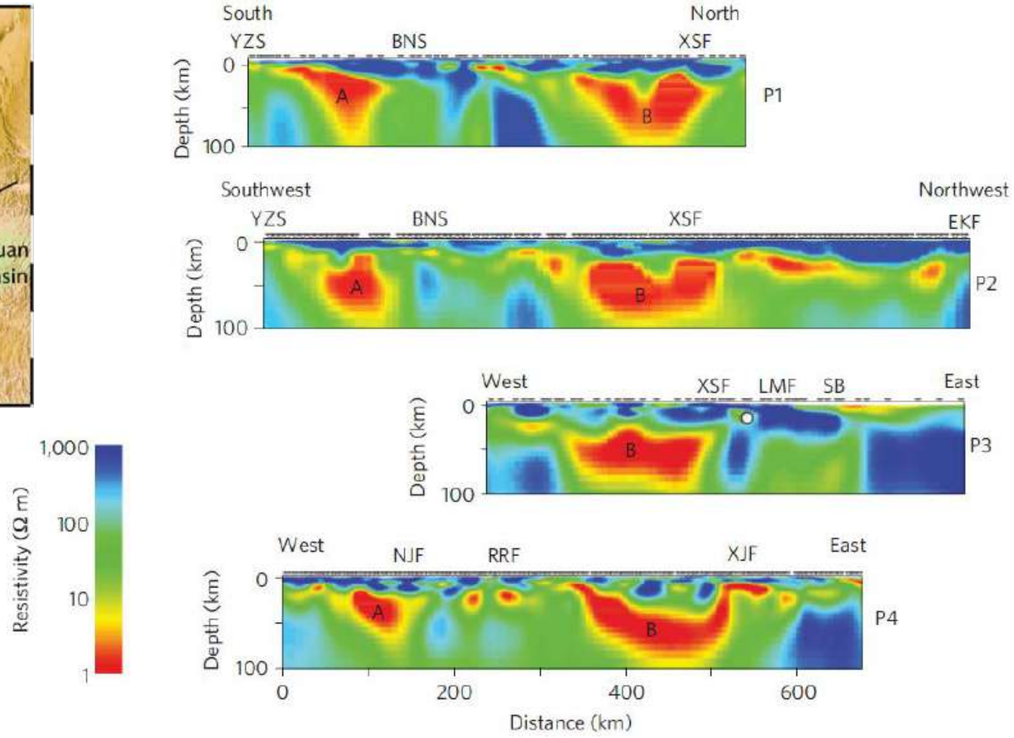
Partial melt in



Seismics: reflective bright spots

(Low-Velocity Zones)

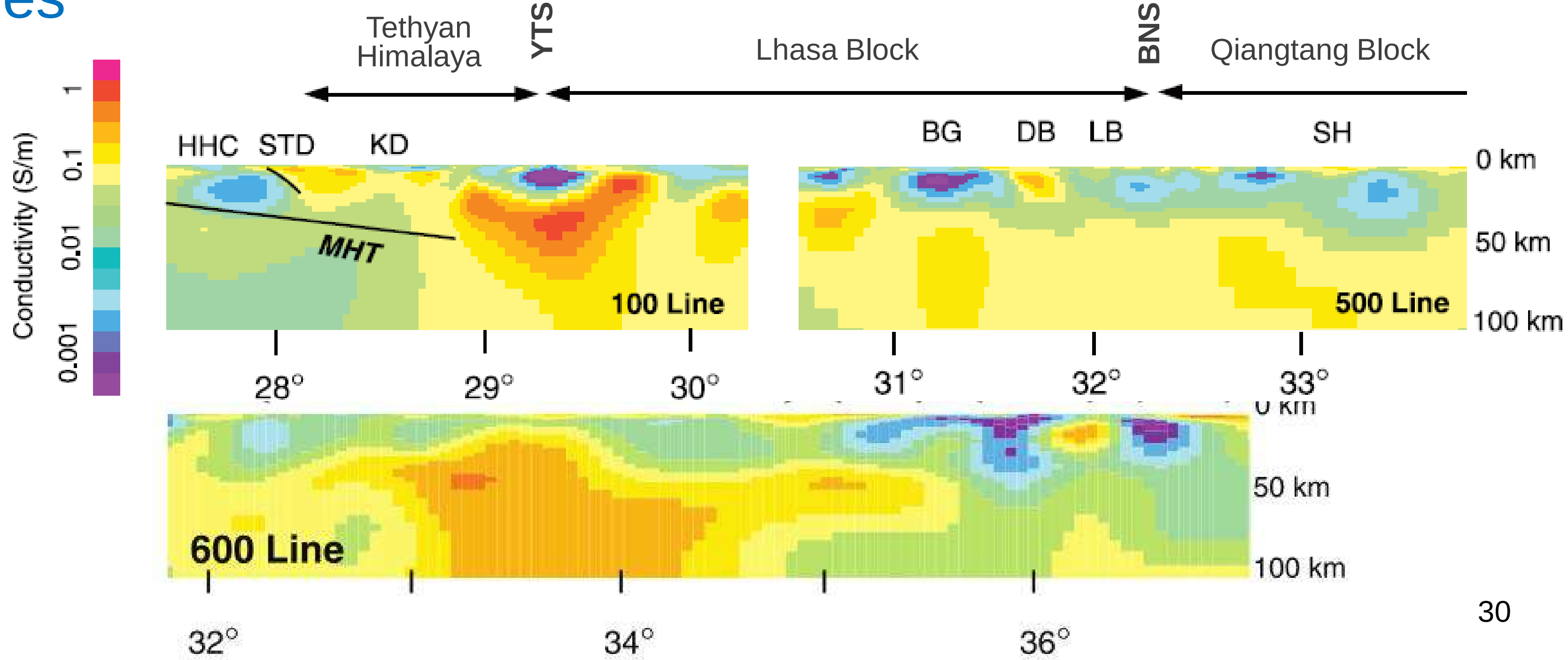
Rippe & Unsworth 2010
Bai et al. 2010
Wei et al. 2001



MT: high conductivity zones

→ "widespread partial melt"

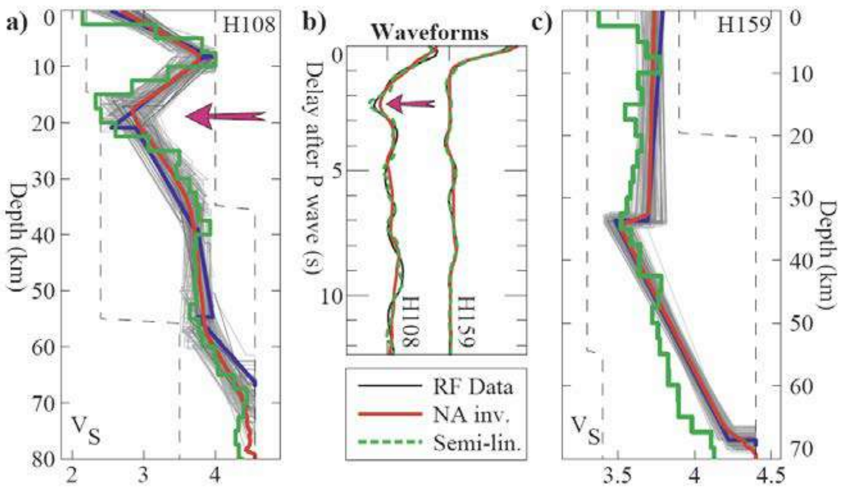
→ "channel flow"

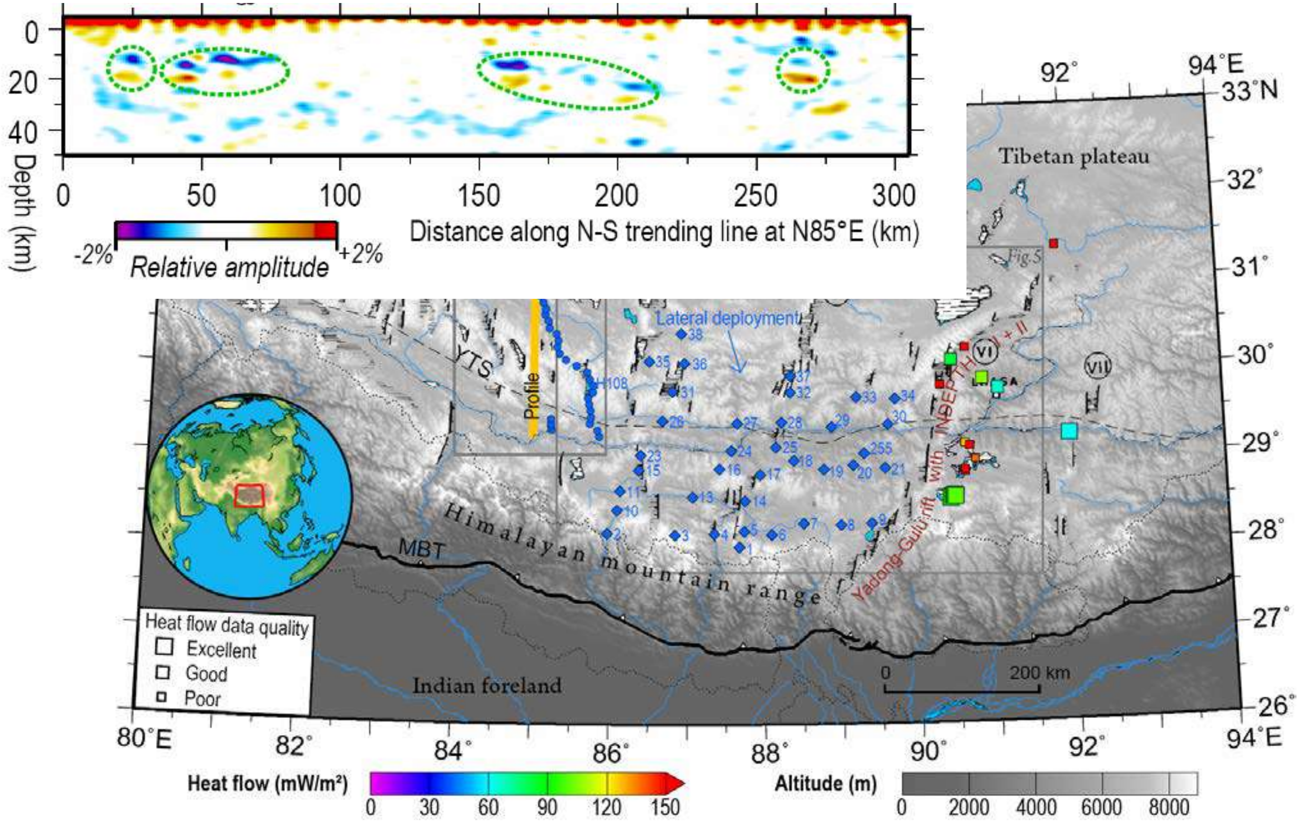


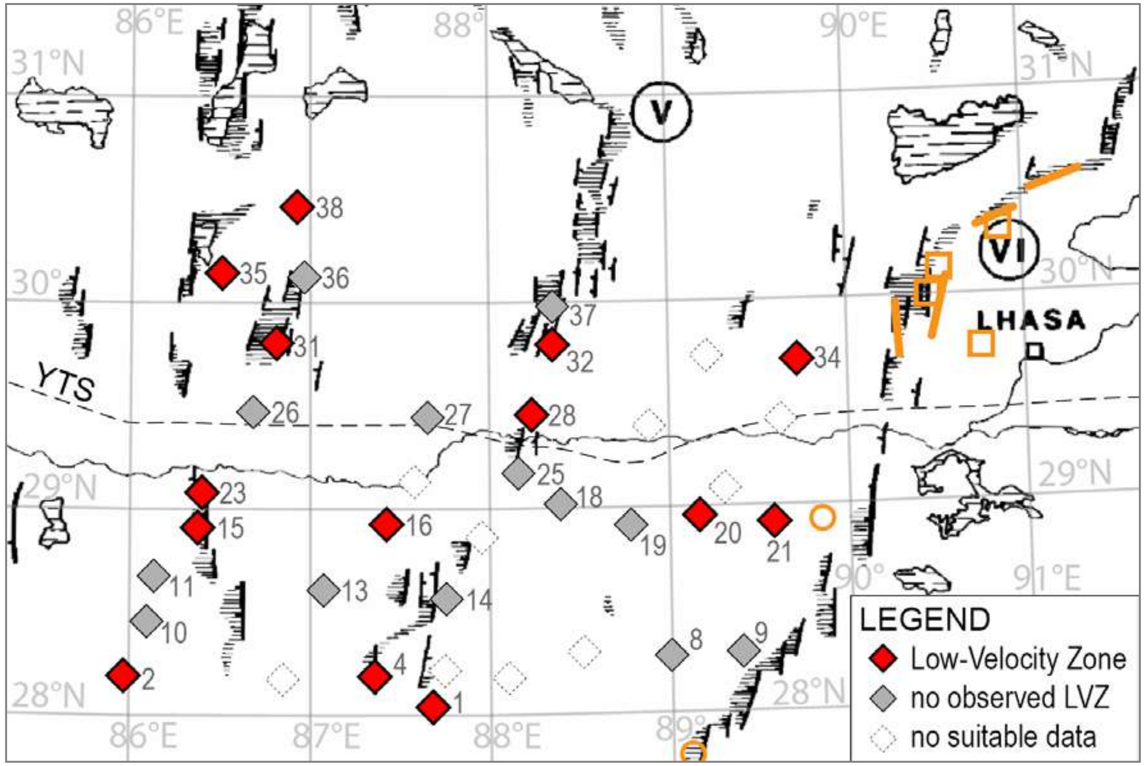
Hetényi et al. 2011

Partial melt in Tibet

Discontinuous LVZs and regular crustal Vp/Vs question the viability of the channel flow model







Melt?

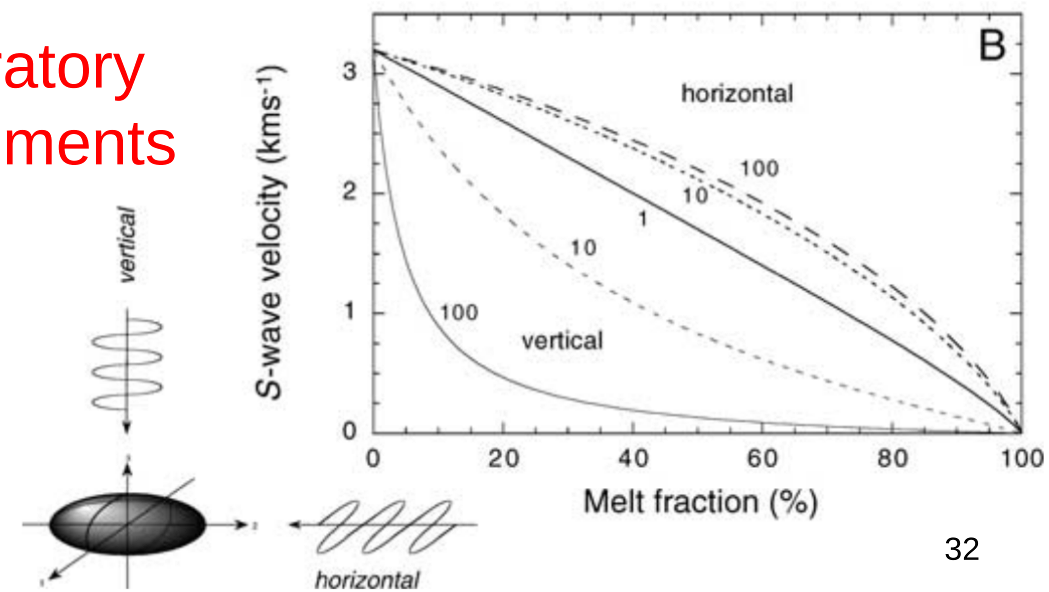
Sandra asked how melt could be recognized geophysically?

A few thoughts:

- need significant volume — upscaling
- very likely needs to be interconnected
  - conductivity
  - drop in Vs
  - properties depend on shape

} laboratory experiments

Taylor & Singh 2002



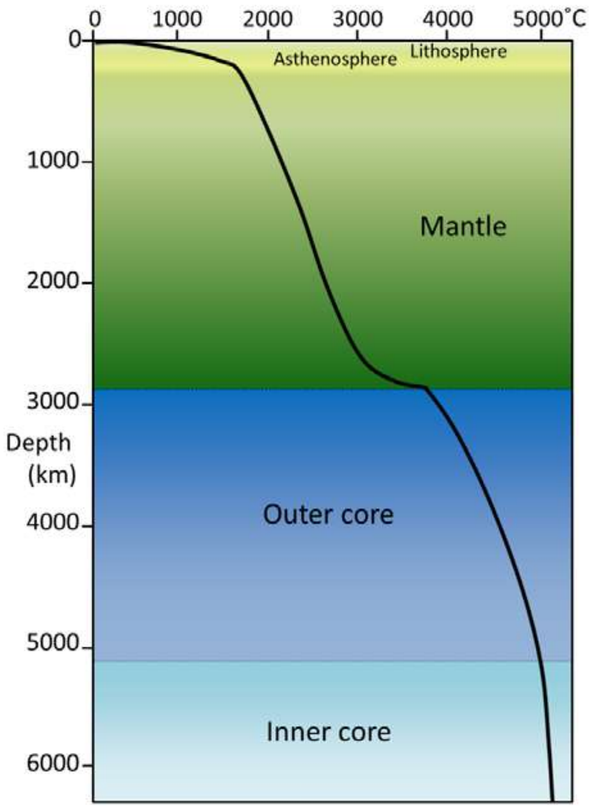
3. Geothermics

T : (probably) the most important and the least constrained parameter in Earth

- radioactive decay of ^{232}Th, ^{238}U, ^{40}K, ^{235}U
- lithosphere
- crust: <1% volume, ~25% heat production
- heat flow [mW/m²]: it is integrated, difficult to measure
- rocks: heat production, heat conduction, heat capacity

  μW / m³ | W / m K | J / kg K

- How about the LCC?



https://opentextbc.ca/geology

Geothermics

The LCC is a small contributor

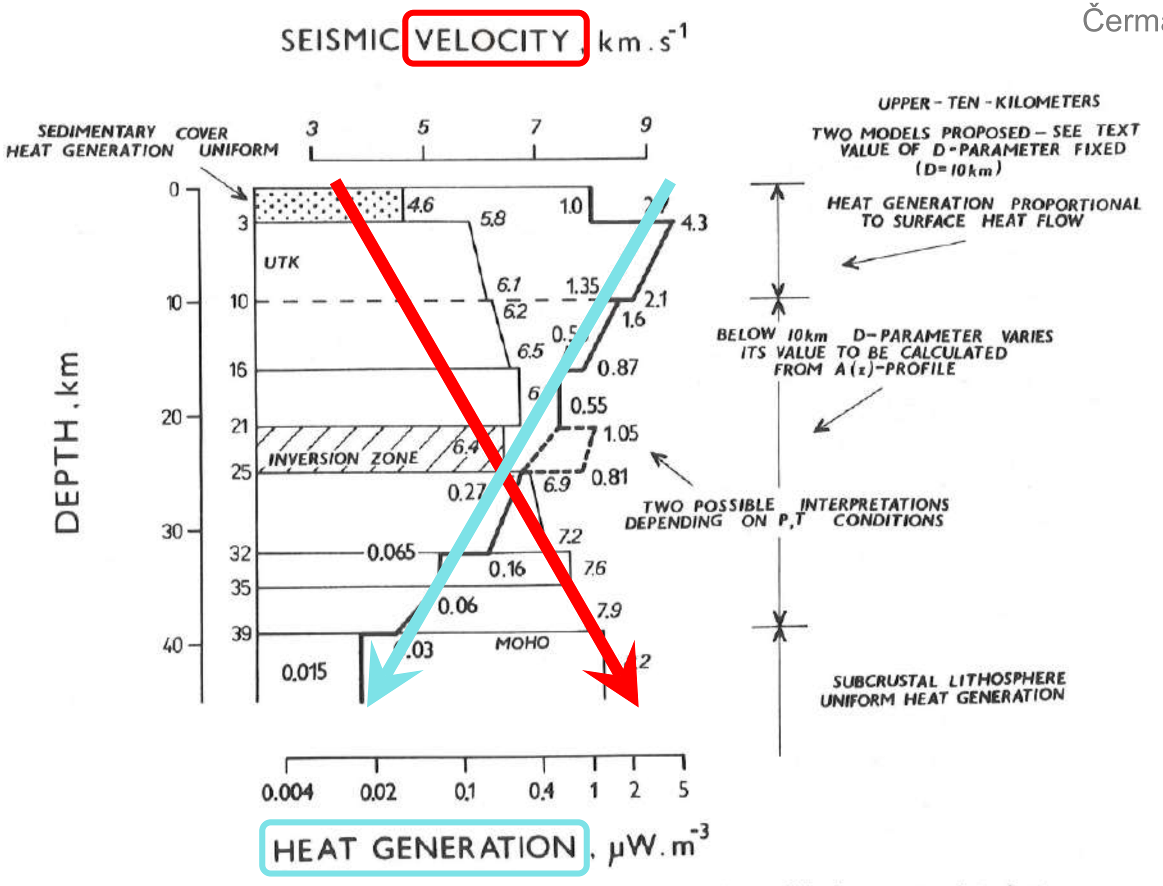
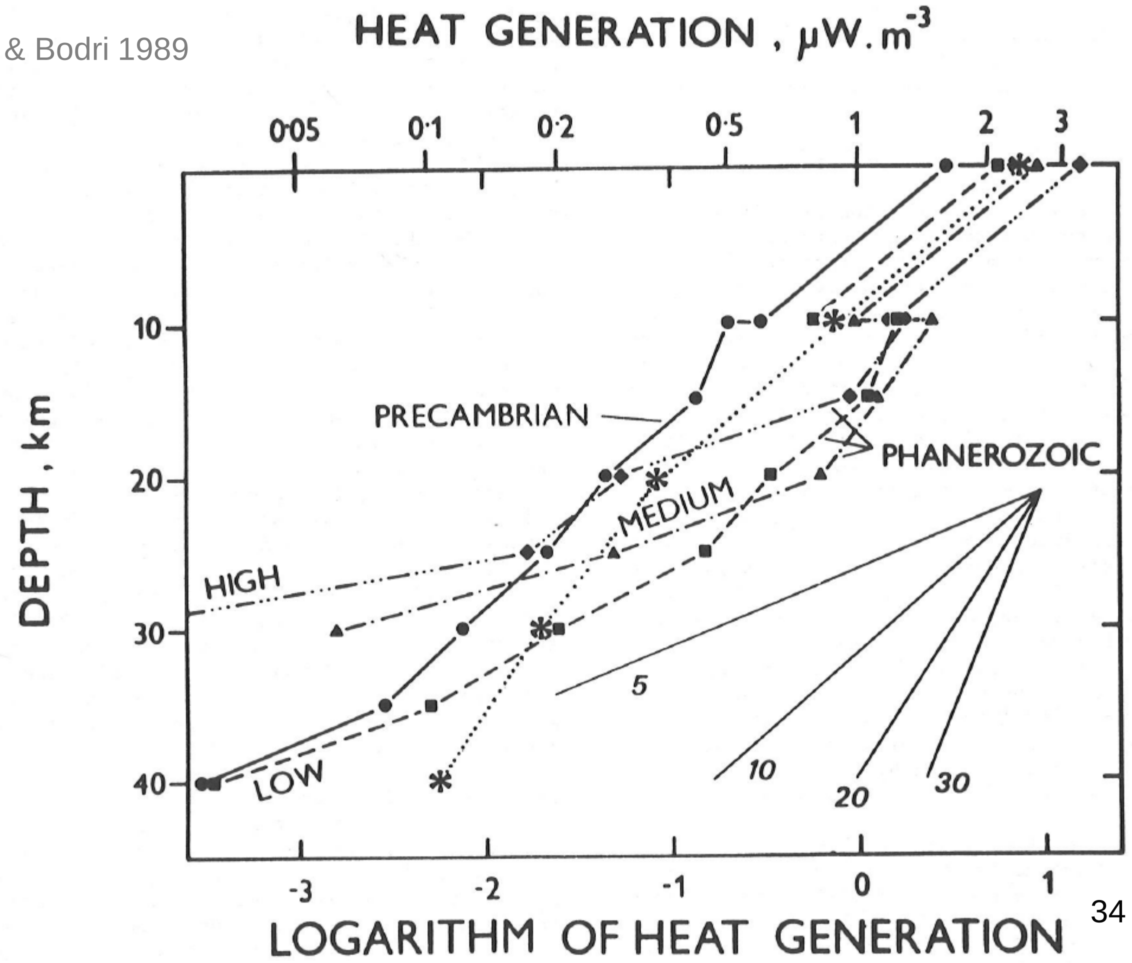


Fig.2. An example of how the seismic velocity versus depth profile is converted to heat production versus depth profile (see text),

Čermák & Bodri 1989

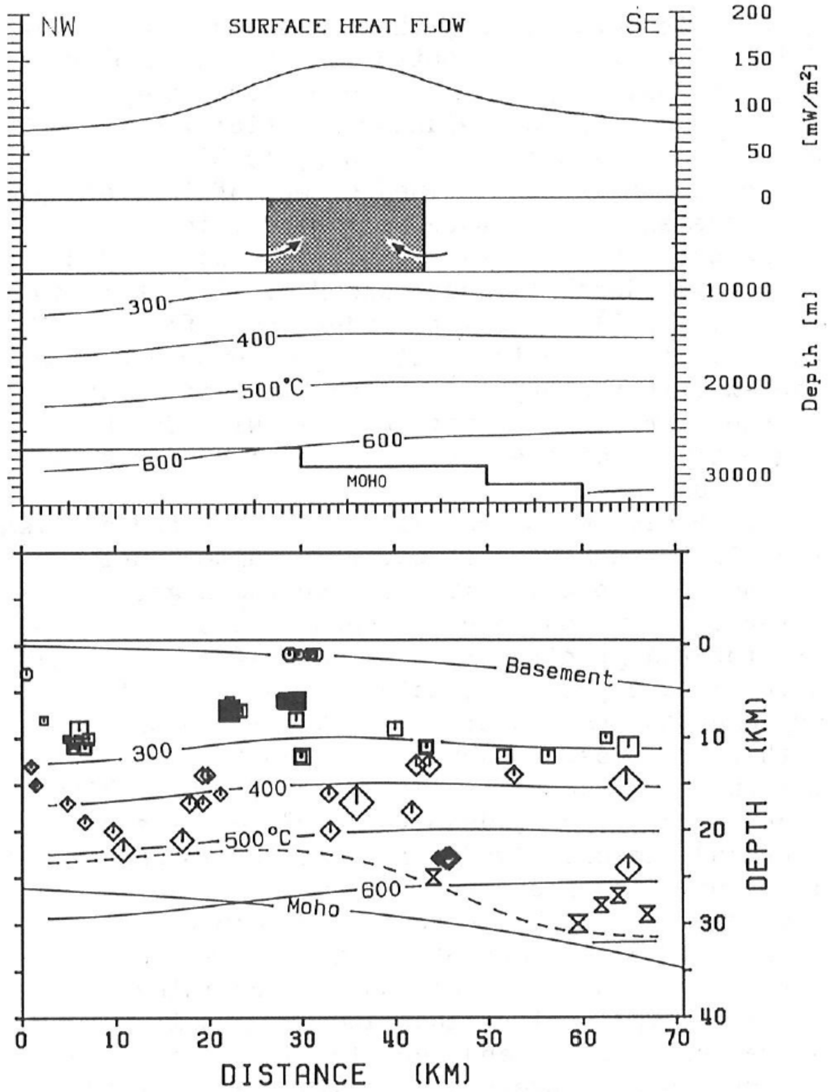


Northern Alpine foreland

Seismicity and geothermics

- events in the LCC
- good data, advanced modelling
- brittle above ~~450°C~~

  600°C !!!



Deichmann and Rybach 1989

4. Borehole geophysics

- Kola superdeep hole: 12’262 m
- drill exposed LCC

DIVE
Drilling the Ivrea-Verbano zonE

- rich choice of methods…

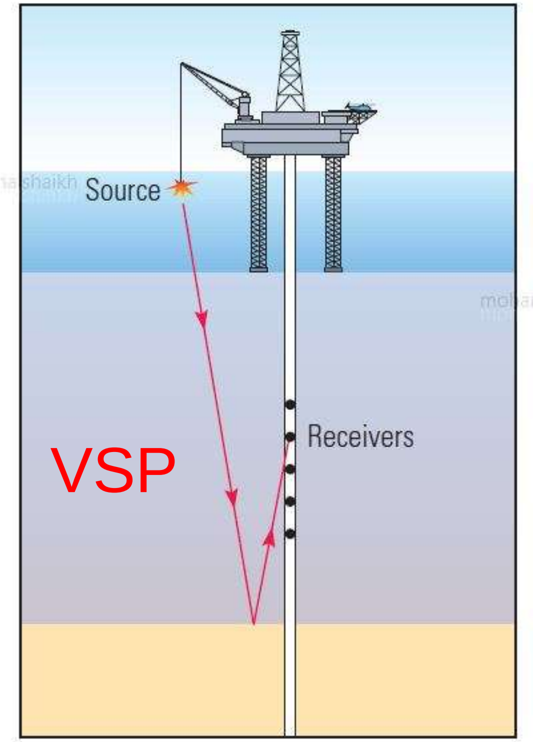
wikipedia

- electical resistivity
- gamma rays, neutron
- sonic waves
- caliper, optical televiewer
- T, pH, oxygen, redox
- …

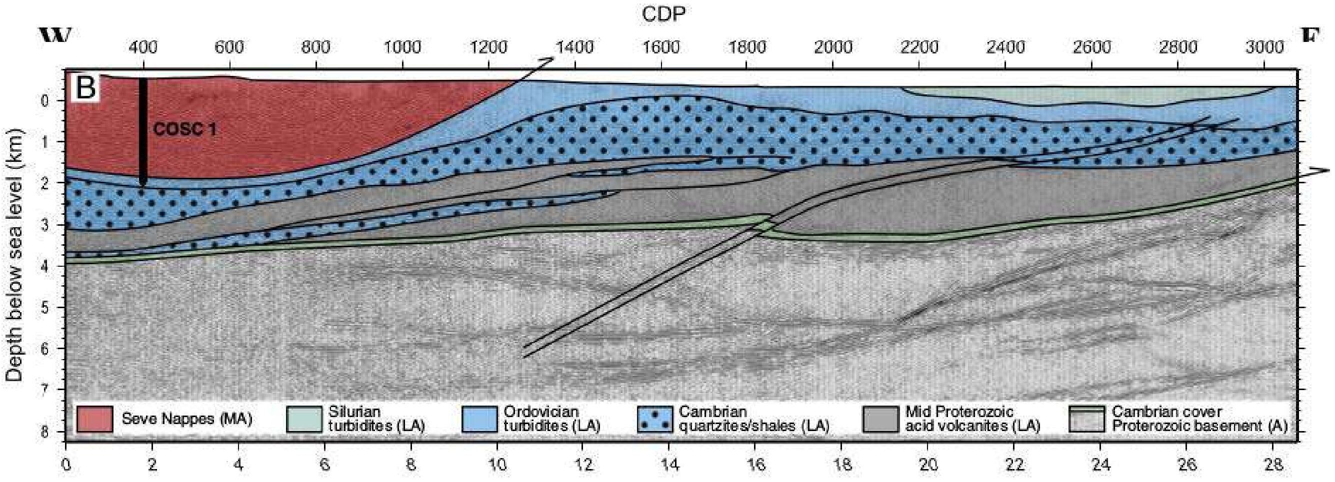
- velocity, density
- clay, fluid, H content
- stress
- permeability
- porosity
- …

COSC-1 and anisotropy

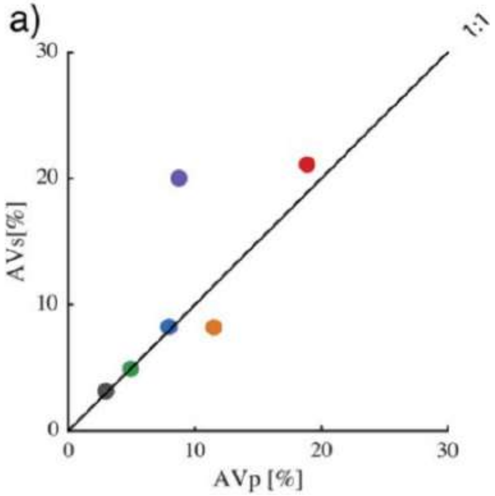
- Collisional Orogeny in the Scandinavian Caledonide, hole 1
- active seismic profile + migration
- seismic properties of cored rock samples: anisotropy

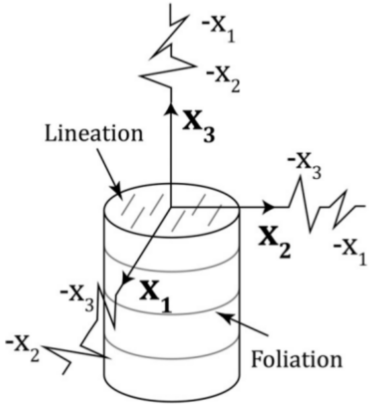


https://wiki.seg.org/wiki/Borehole_geophysics



Hedin et al. 2012



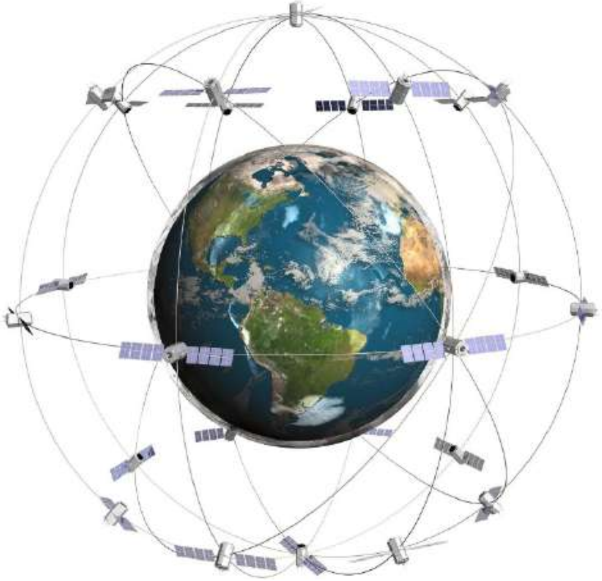


Wenning et al. 2016

5. Remote sensing

Monitoring Earth surface deformation

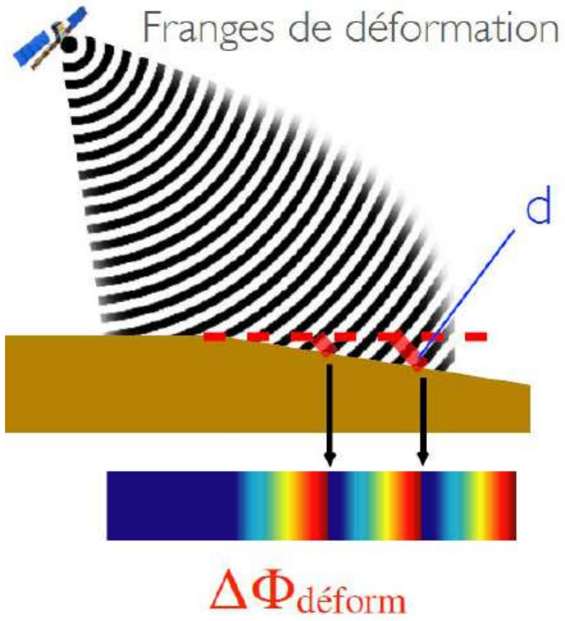
GNSS

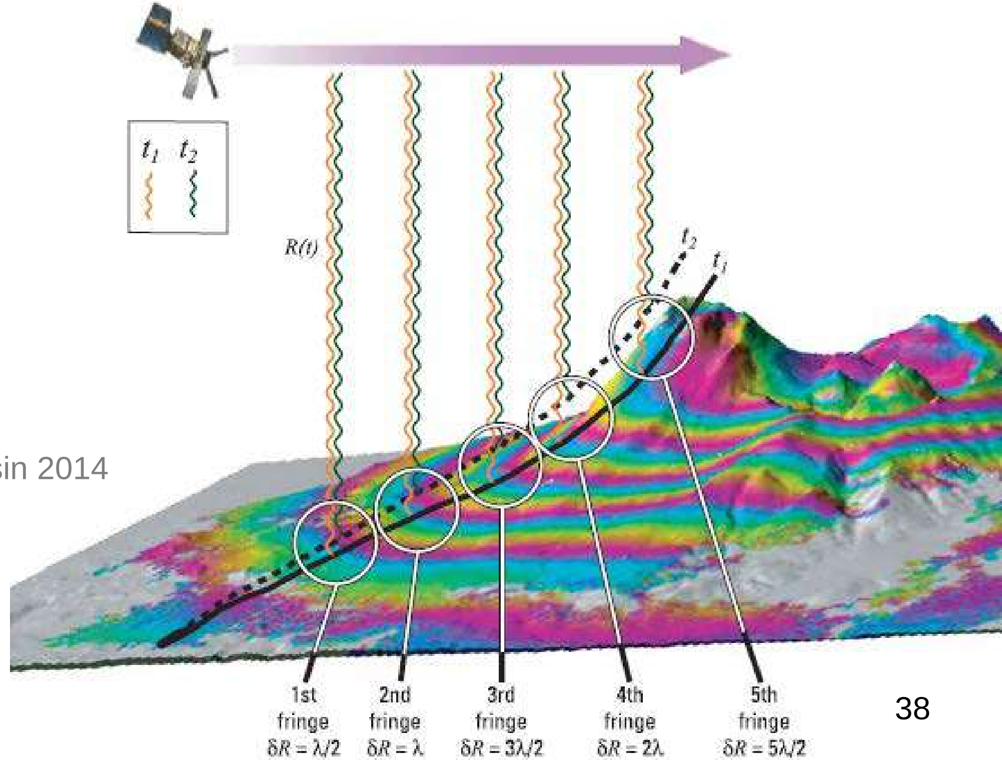


- <mm accuracy positioning (optimally)
- relative motion of a point, 3 components
- permanent or campaign measurements

InSAR

- ~mm-cm accuracy
- relative deformation map
- regular scans
- high spatial resolution



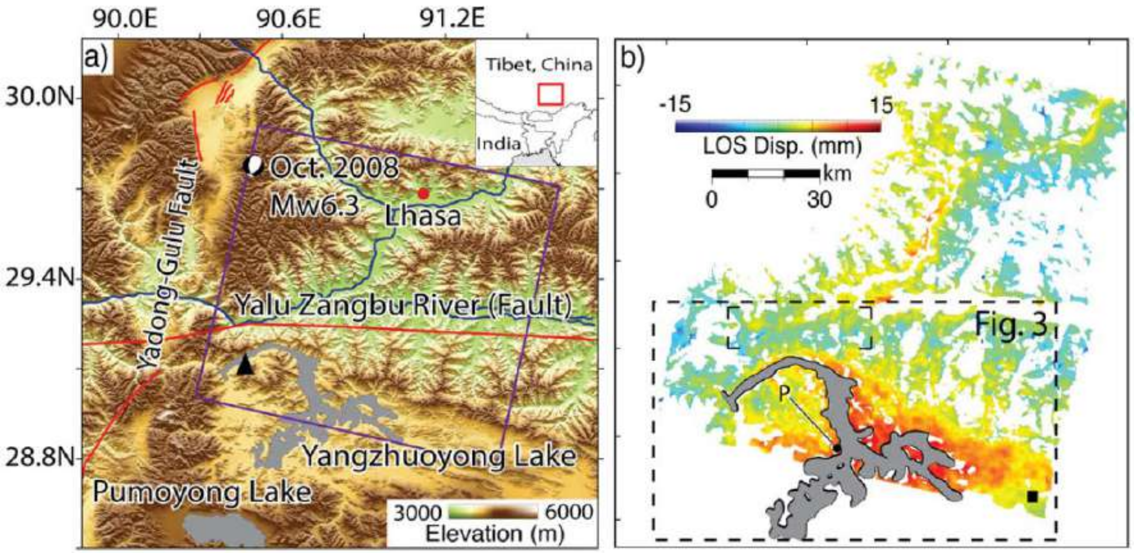


Lu and Dzurisin 2014

Inferring rheology

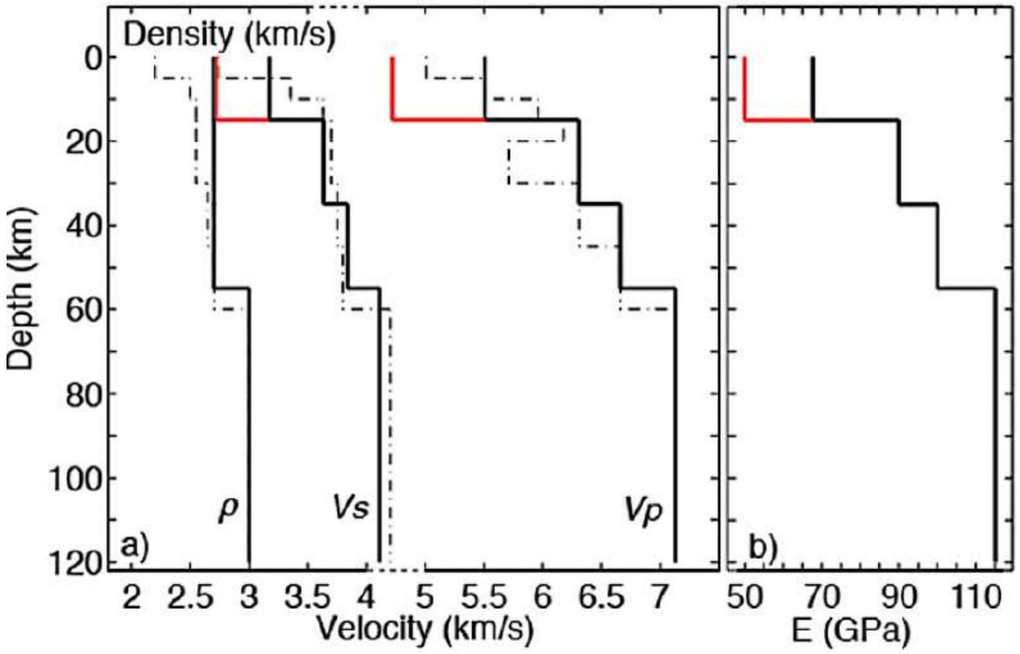
Lake water loss causes surface rebound

- lake level: –3 m
- numerical simulations of physical properties
- upper crustal Young modulus 50±9 GPa, lower than seismologically inferred
  → fluids, rock damage

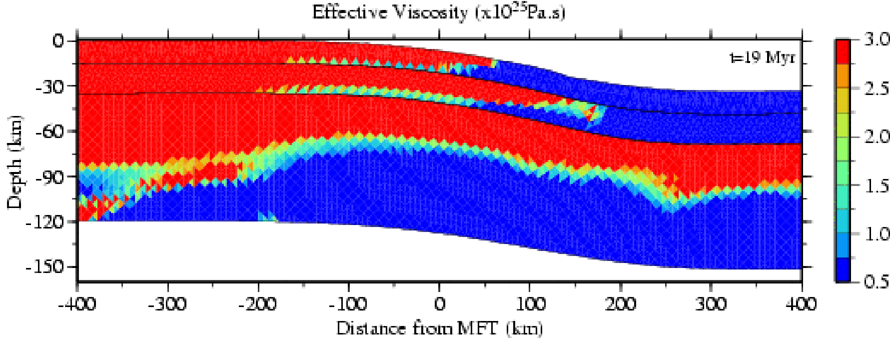


Zhao et al. 2016

2003–2010 map
ENVISAT InSAR



6. Numerical modelling



Set up a model to test scenarios, explain observations:

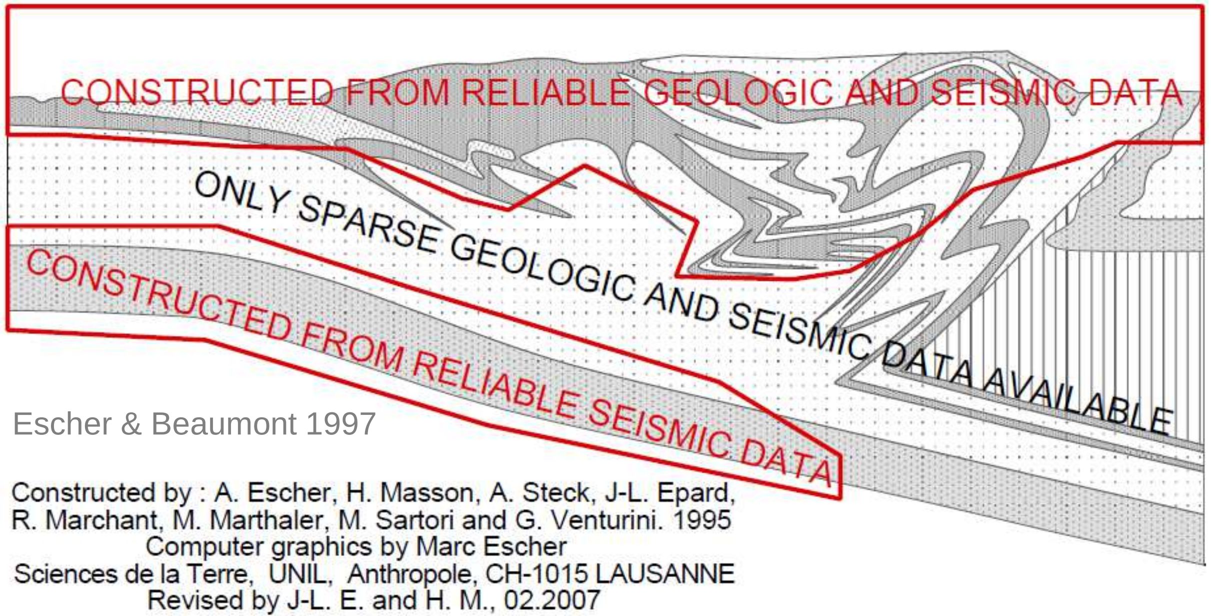
- discipline: physical ± chemical ± …
- approach: thermo-kinematic, thermo-dynamic, …
- implementation: finite-difference, finite element, …

- post-seismic creep of the lower crust to fit surface deformation
- rheology of the lithosphere to explain plate flexure

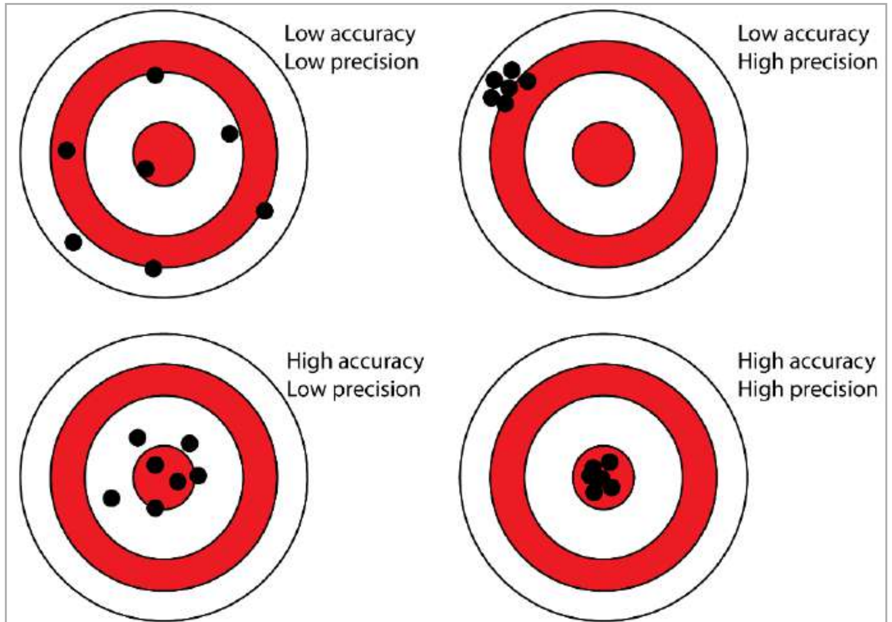
- the limitation is your imagination (and computer affinity?)

Conclusions

- Many geophysical tools are standard analyses, some applicable to the LCC
- Tendency: 2D + isotropic → 3D + anisotropic media
- Main limitations: depth, resolution, temperature
- There are many unknowns → strong need to combine several methods

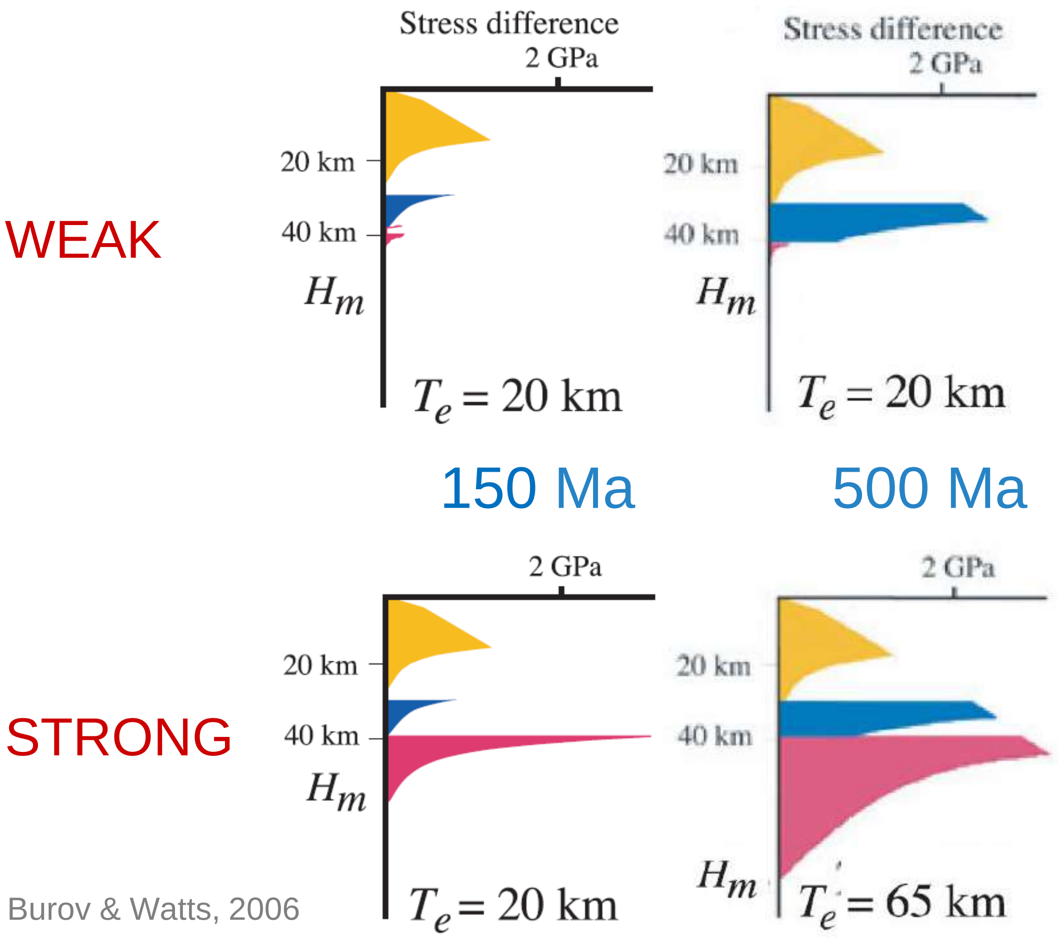


Escher & Beaumont 1997



6. Numerical modelling: rheology and flexure

Debate on rheology: the long-term strength of the mantle



Burov & Watts, 2006

Table 1. Summary of the previous estimates of the EET in the Himalayan-Tibetan region by different methods and authors.

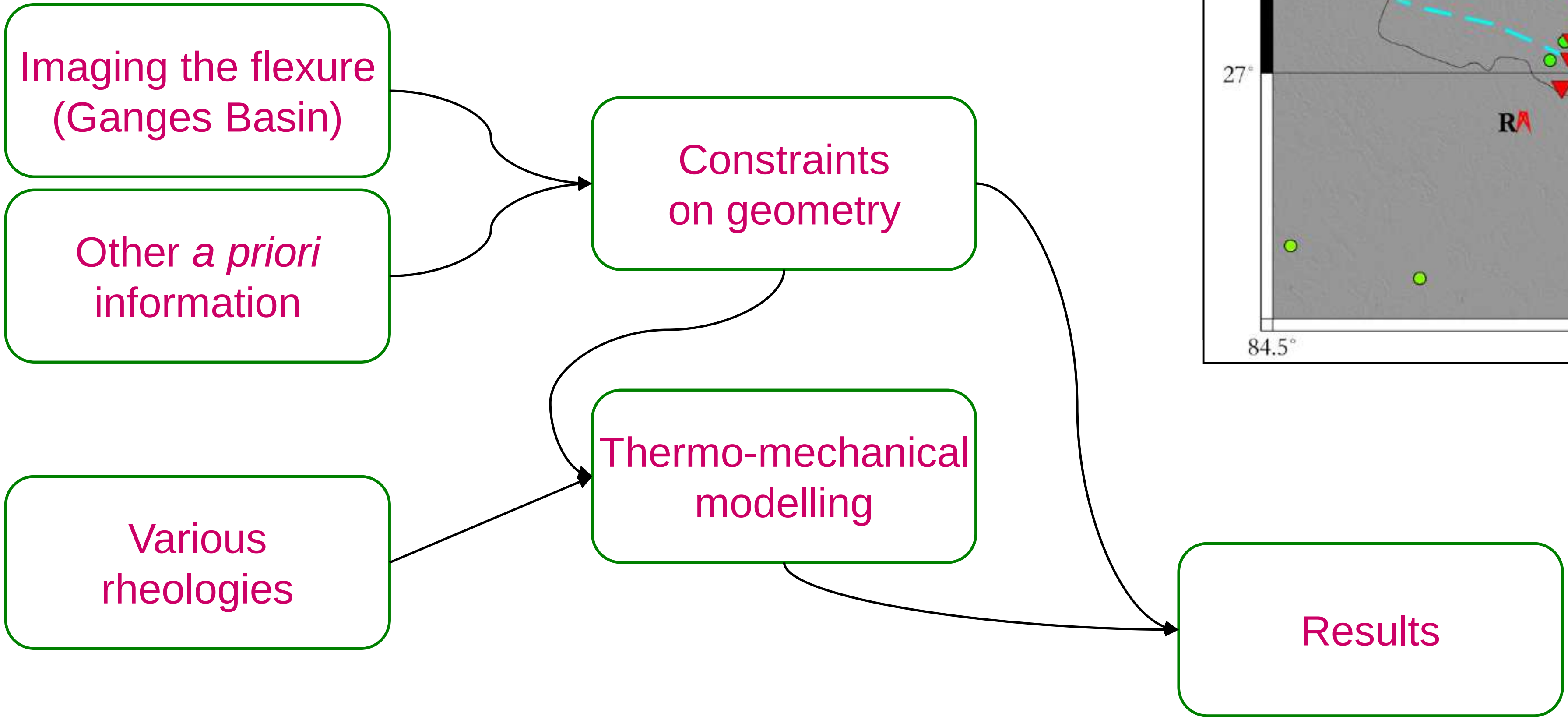
EET (km)	Method or concept	Authors
80–110	Elastic plate, Bouguer anomaly	Lyon-Caen & Molnar (1983) Karner & Watts (1983)
90 India 30–45 Tibet	Bouguer anomaly, Variable EET	Jin *et al.* (1996)
42	Free-air anomaly and topography coherence	McKenzie & Fairhead (1997)
40–50 India 30 Tibet	Thermomechanical modelling, Viscoelastoplastic rheology	Cattin *et al.* (2001)
36.5	Seismogenic and elastic thickness similarity ('crème brûlée')	Jackson (2002); based also on Maggi *et al.* (2000)
60–70	Integrated brittle, elastic and ductile strength ('jelly-sandwich')	Watts & Burov (2003); Burov & Watts (2006)

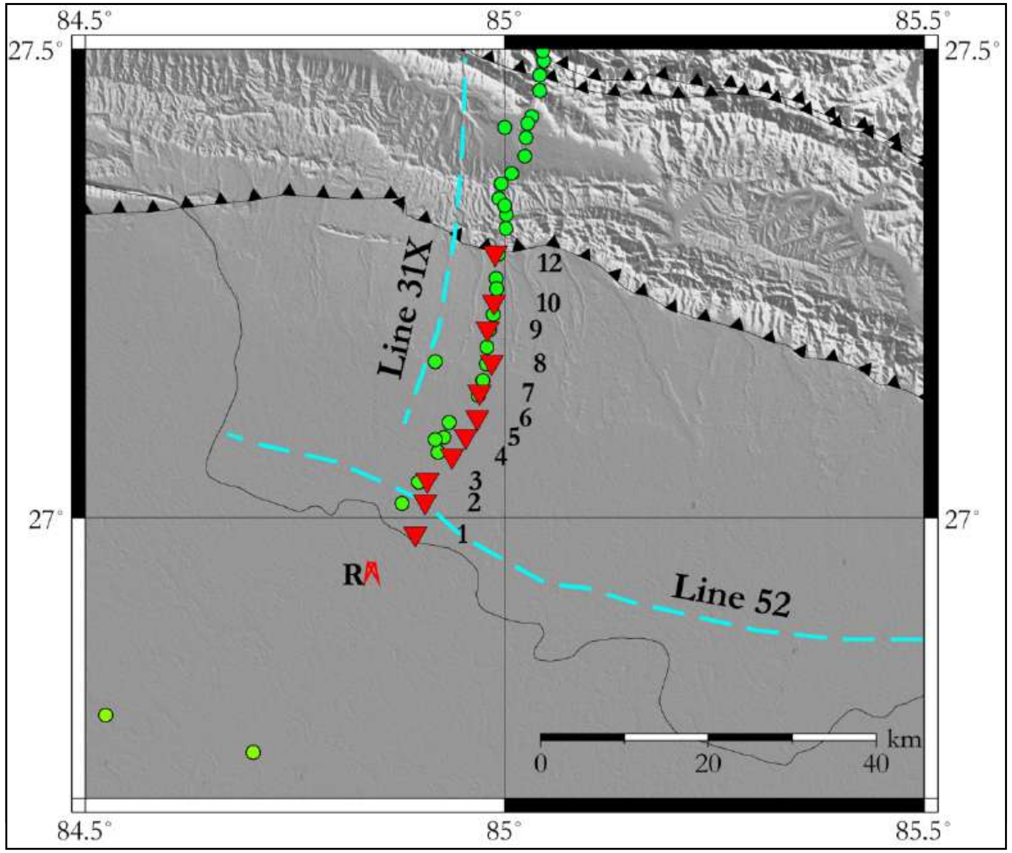
We need proper plate geometries

Hetényi et al. 2006

Flexure of the India plate

Approach and geometries

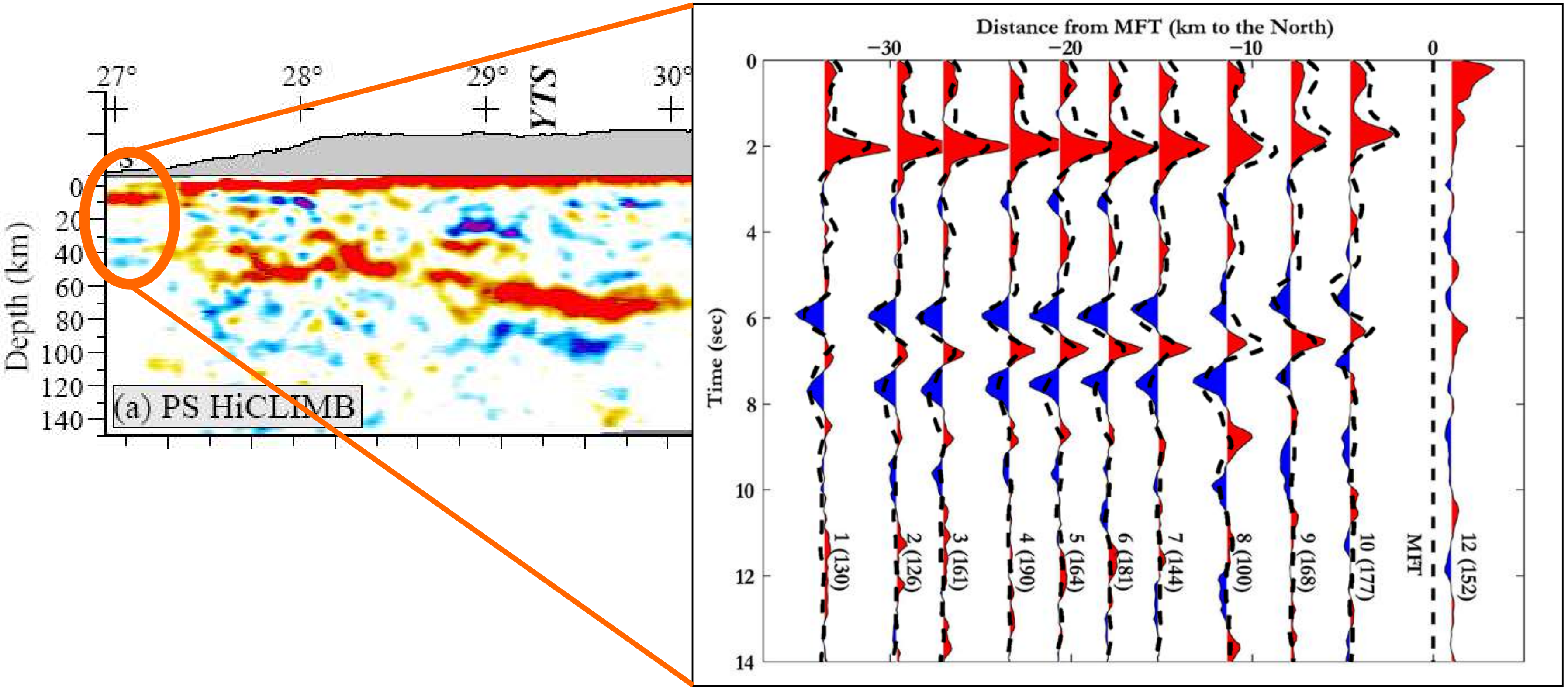




Hetényi et al. 2006

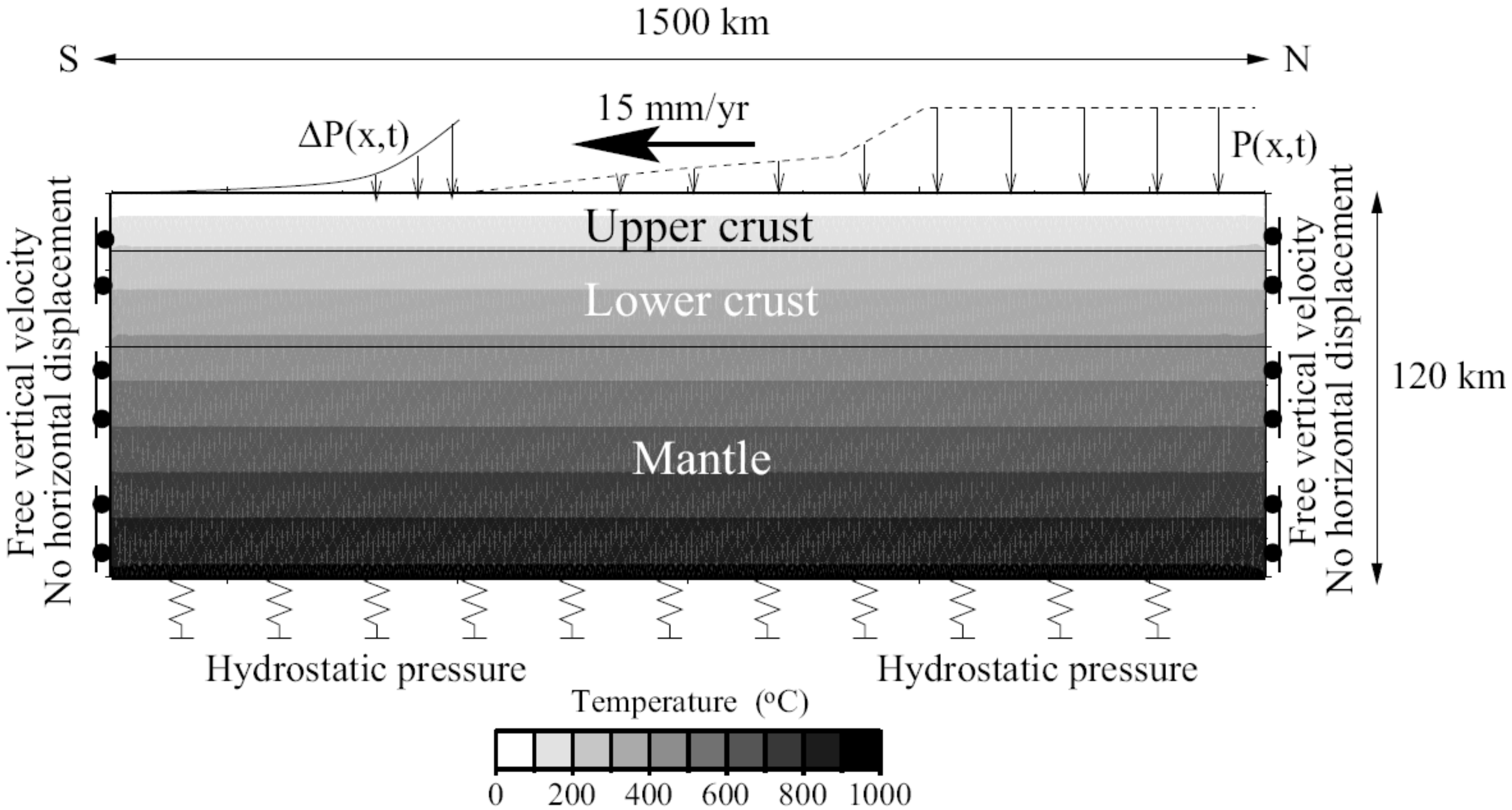
Imaging the flexure

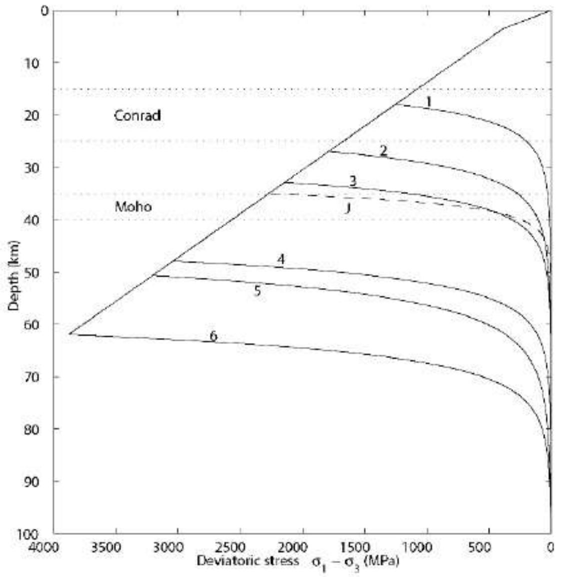
Receiver function imaging: Moho, foreland basement (4.5 km), plate dip



Thermo-mechanical modelling

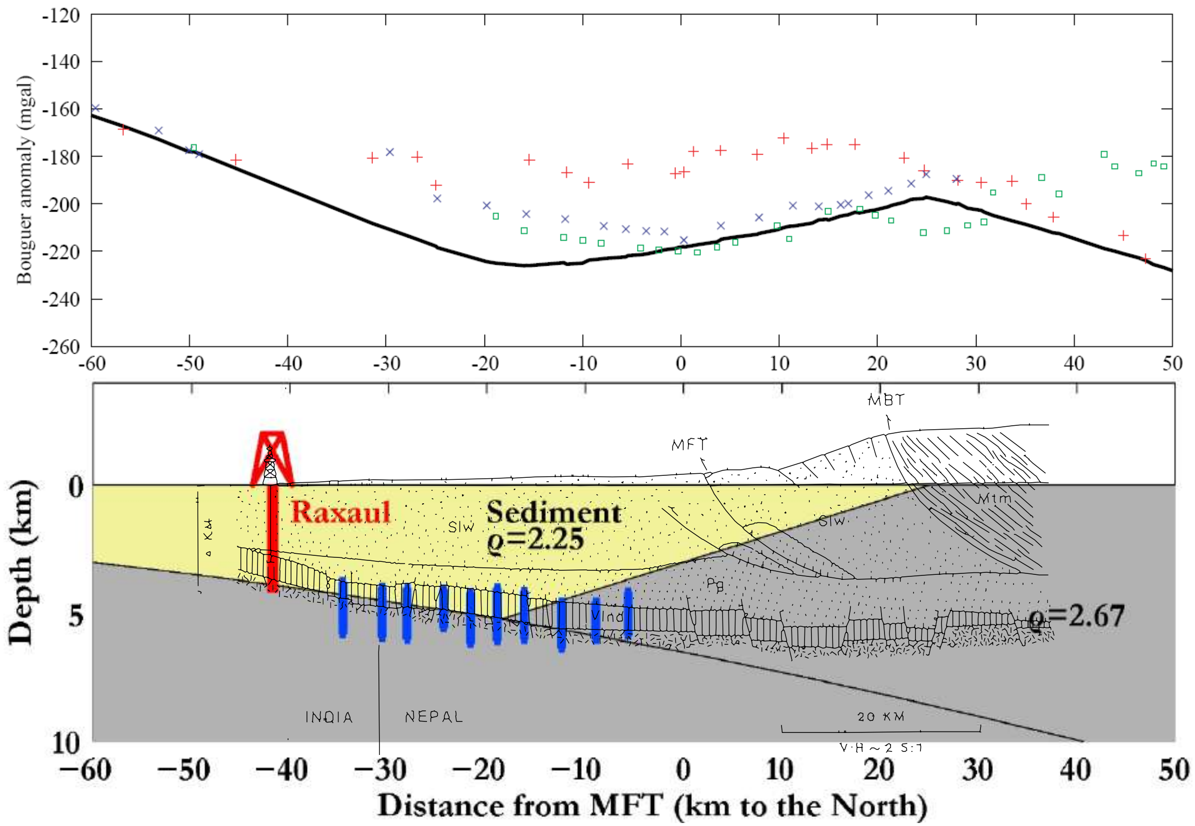
- bending of the India plate: shortening, vertical load, various rheologies
- assessing results based on geometry and gravity anomalies

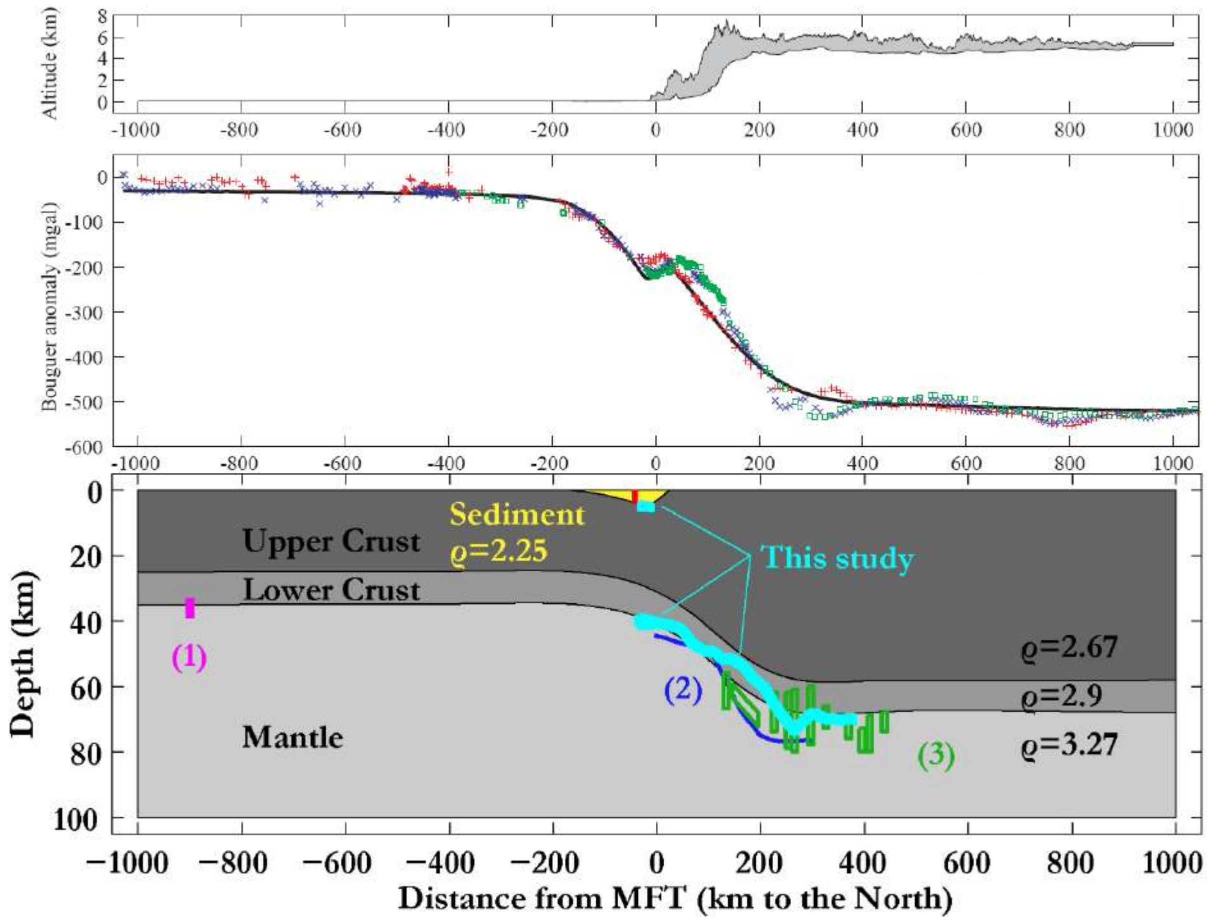




Hetényi et al. 2006

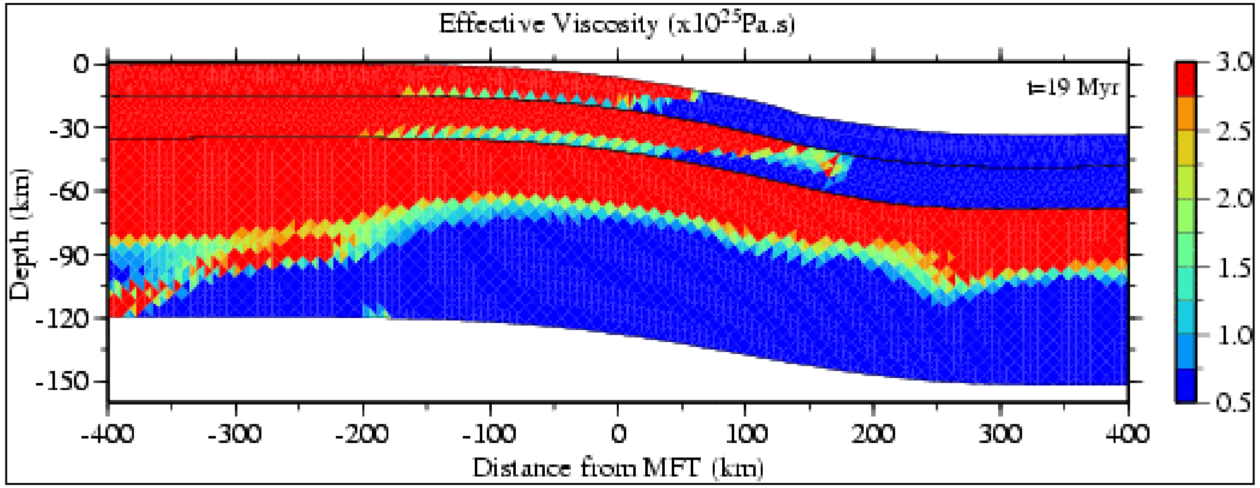
Results and constraints on geometry



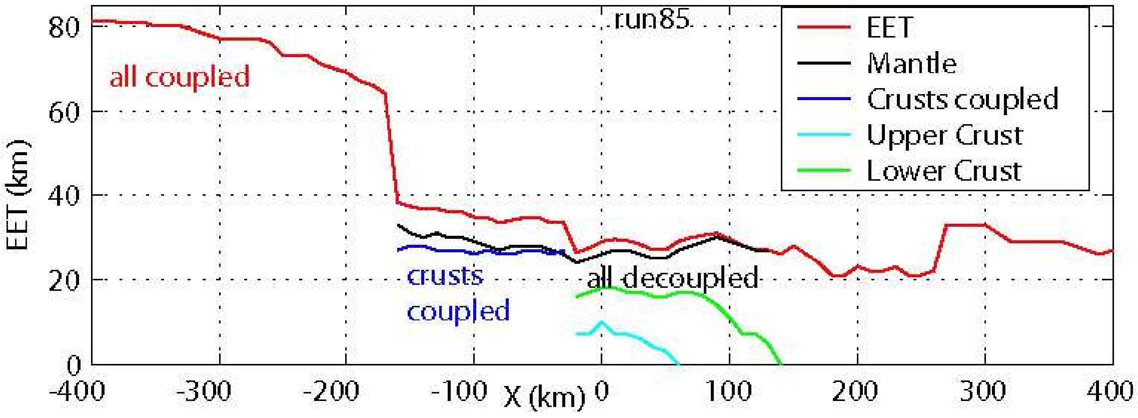


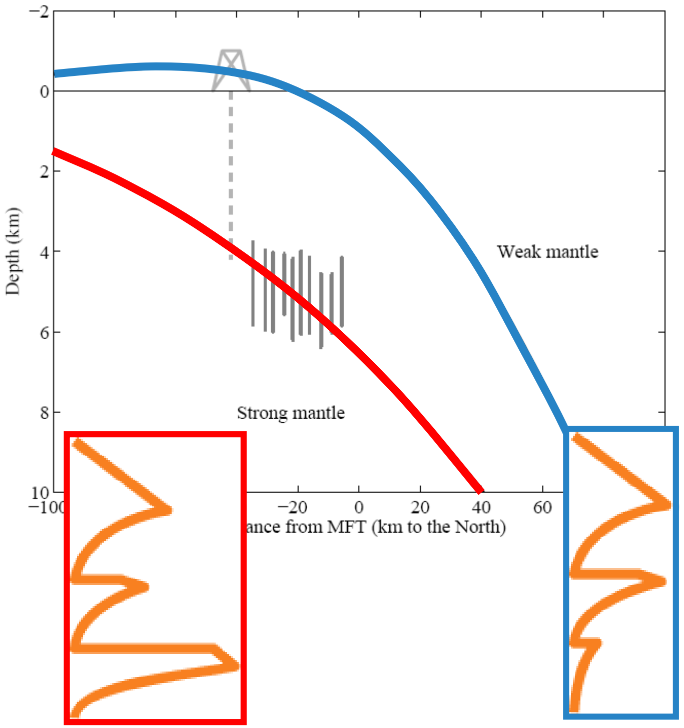
Hetényi et al. 2006

Effective elastic thickness – conclusions



- decoupling and drop of EET from S to N
- weight of the plateau held by the mantle
- “weak mantle” rheology fails





Hetényi et al. 2006