UNIVERSITÀ DI PAVIA

International School
"Structure and Composition of the Lower Continental Crust"

09.10.2019.
Pavia

Geophysical investigation of the LCC:
2. Results and questions
A) Himalayas
B) Ivrea zone

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The underthrusted Indian lower crust: Geophysical constraints on eclogitization

György HETÉNYI

with Celso ALVIZURI, Kristel CHANARD, Lukas P. BAUMGARTNER, Frédéric HERMAN, Rodolphe CATTIN, Fabrice BRUNET, Laurent BOLLINGER, Jérôme VERGNE, John L. NÁBĚLEK, Michel DIAMENT

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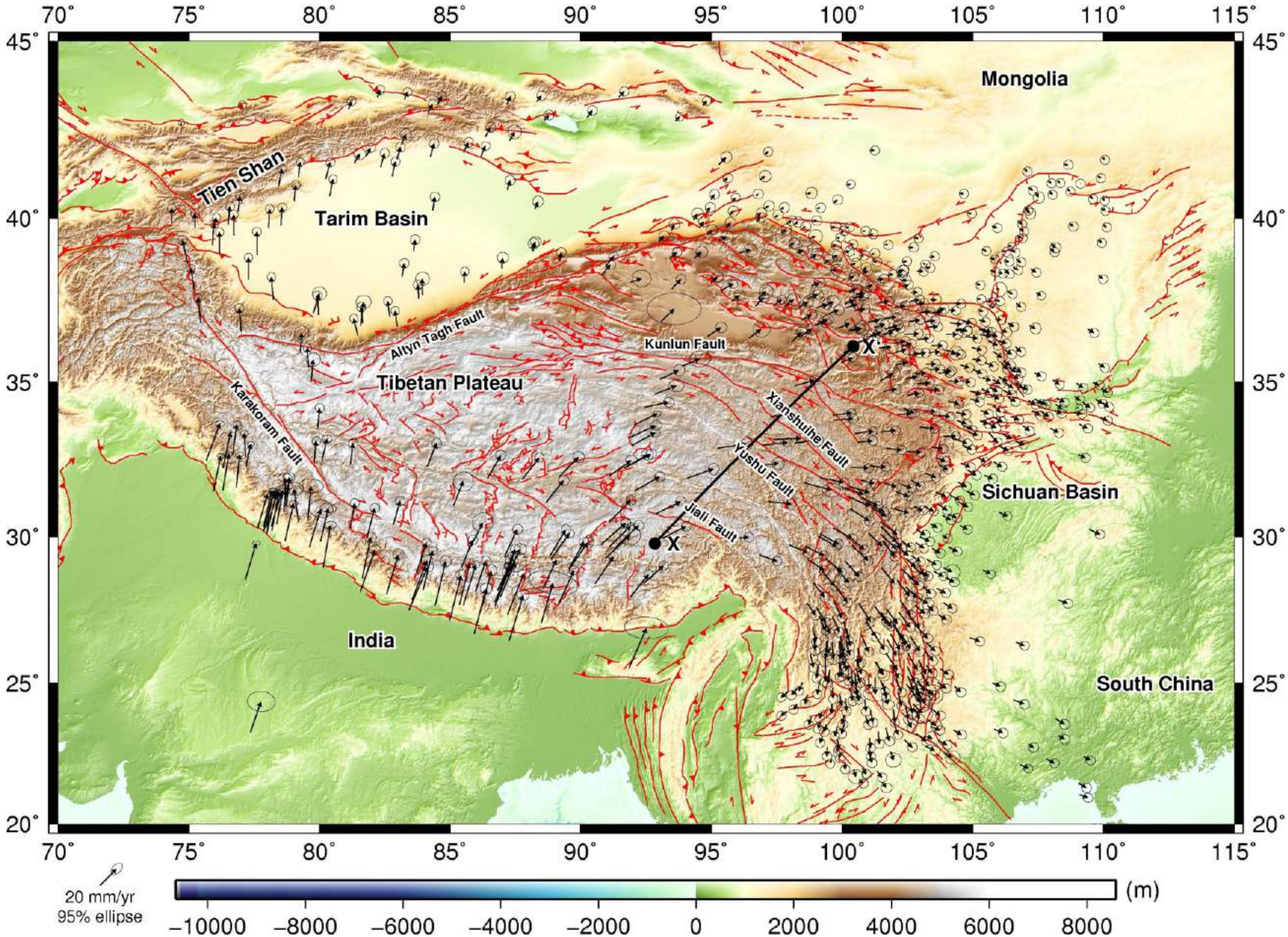
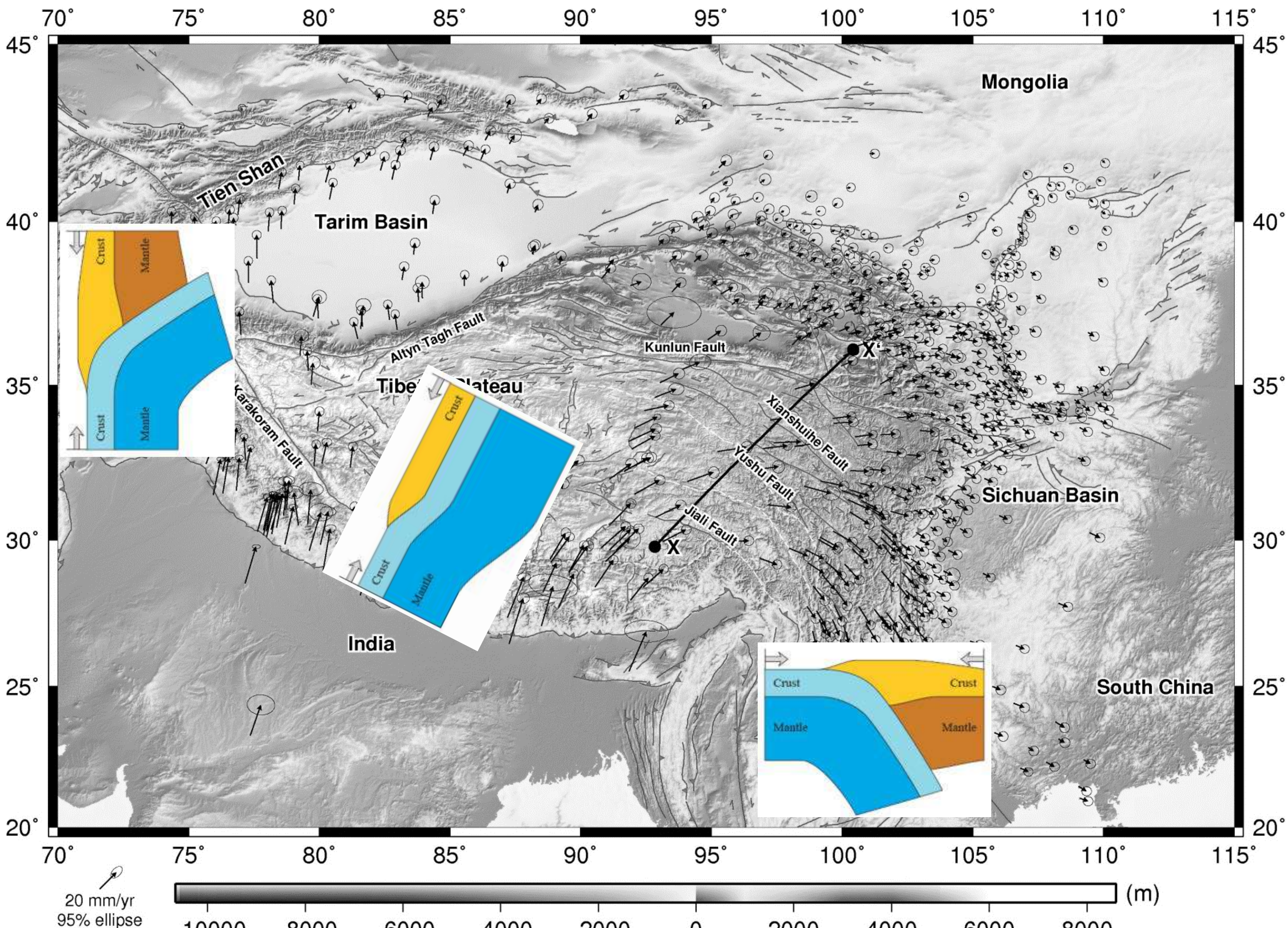
The Himalaya-Tibet-… orogenic system

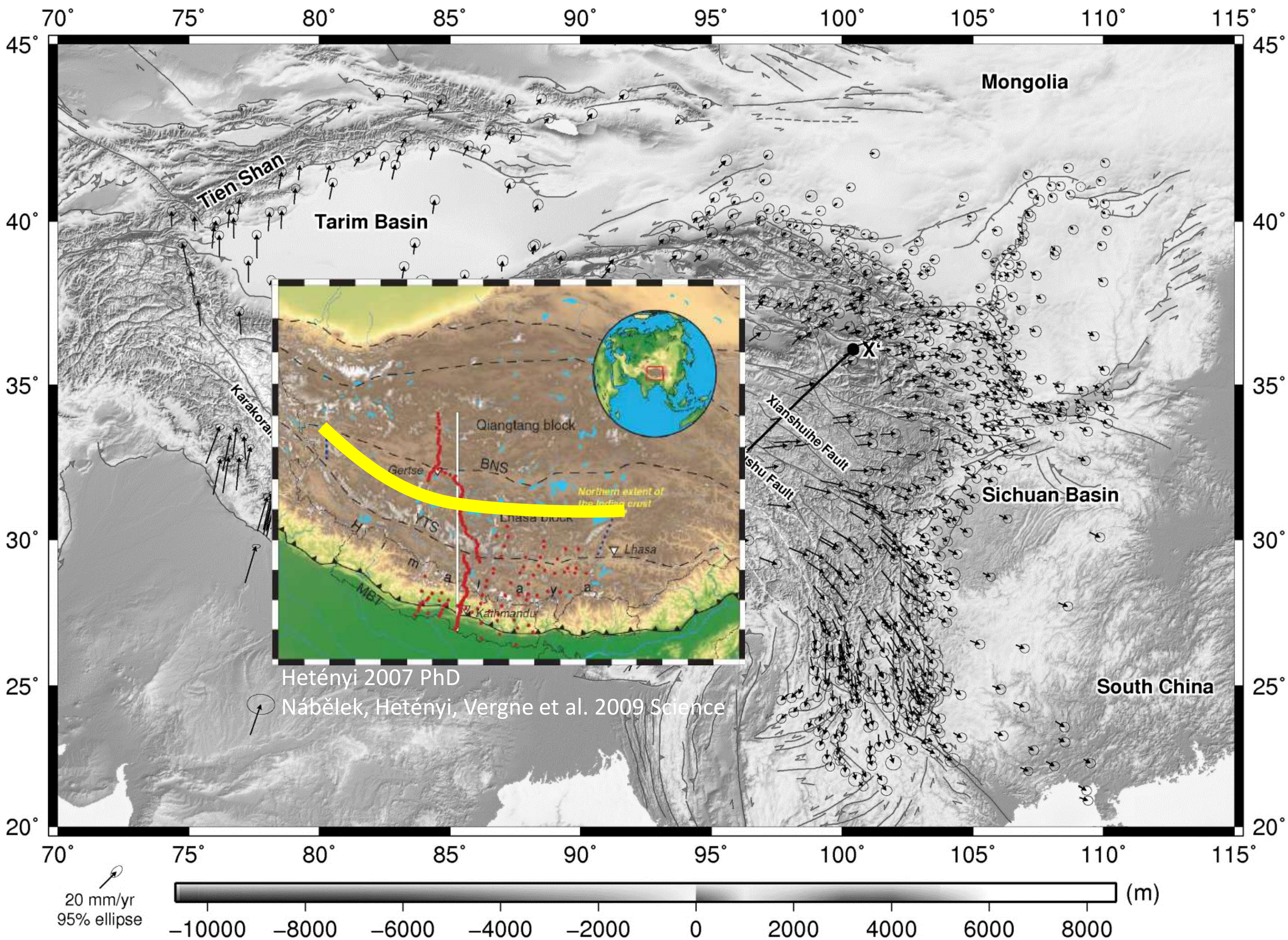


Elliot et al. (COMET), GPS: Gan et al. 2007 JGR

The Himalaya-Tibet-… orogenic system

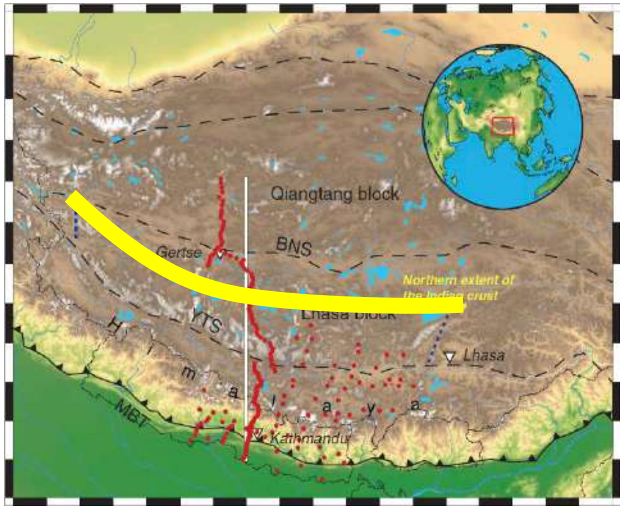


The Himalaya-Tibet-... orogenic system



Hetényi 2007 PhD
Nábělek, Hetényi, Vergne et al. 2009 Science

Cross-section view



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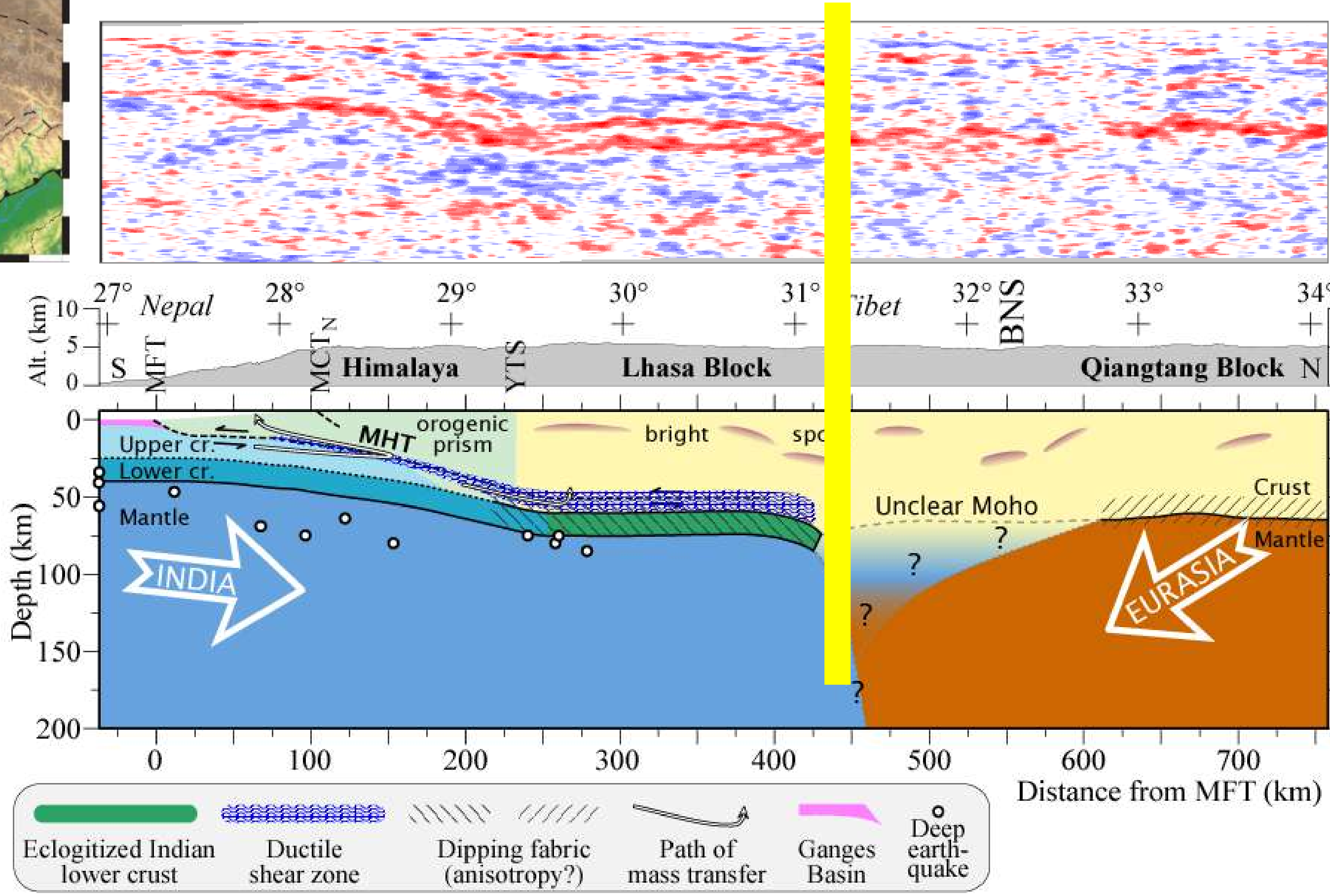
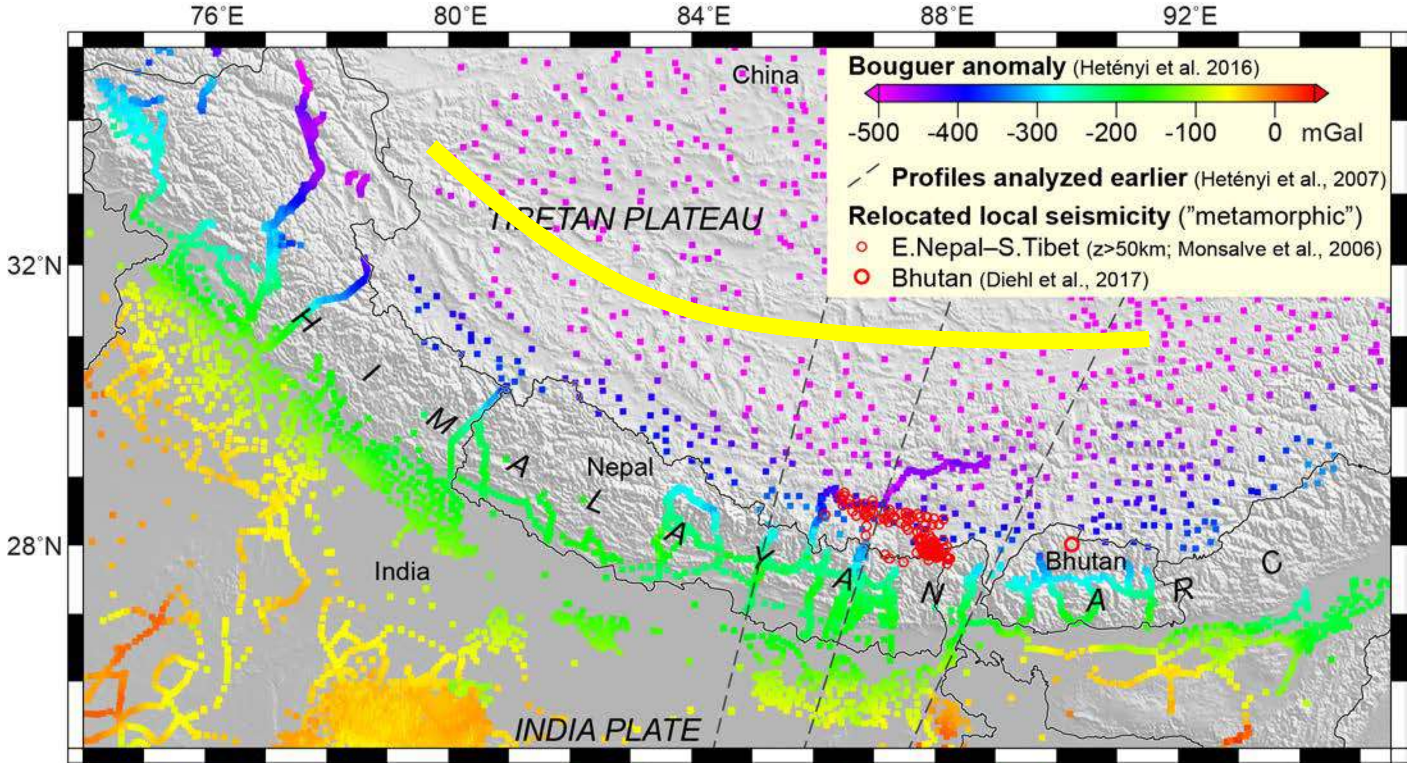


Outline

- Introduction
- The importance of <u>local</u> data
- Geophysical constrains on the Indian lower crust (ILC)
- Metamorphic earthquakes



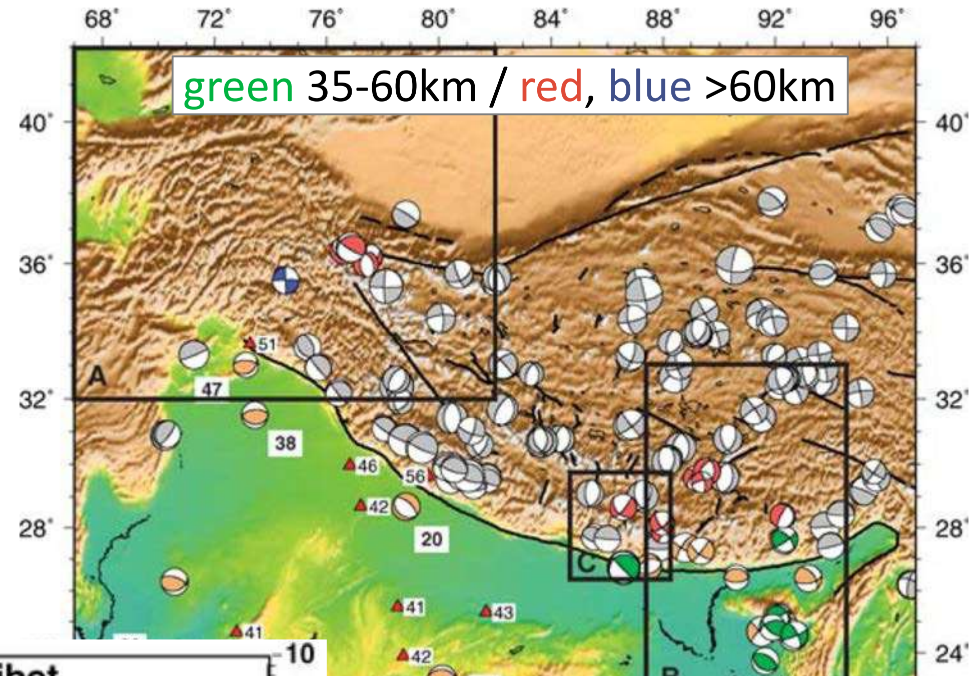
Chanard et al. in review

Local data: Moho depth

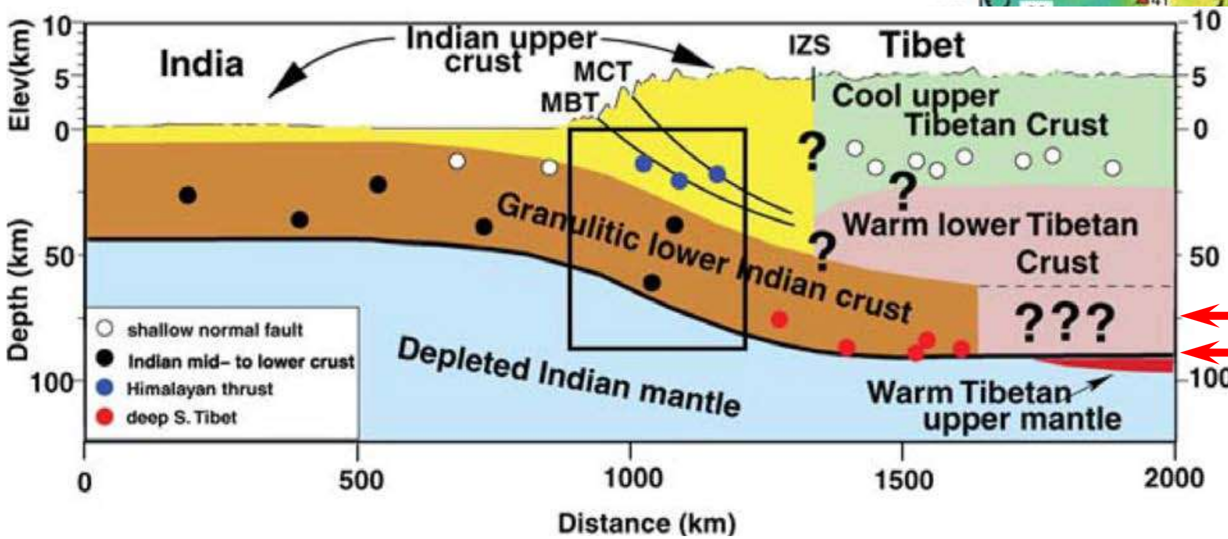
Are the rare deep earthquakes in Tibet in the mantle or the lower crust?

~26 events 1963-2001 M~4.8-6.4 Chen and Yang 2004 Science Priestley et al. 2008 GJI

- debate on rheology
- projections vs. local Moho depths
- different locations and contexts: (too) ambitious to give unique explanation for all events



Priestley et al. 2008 GJI

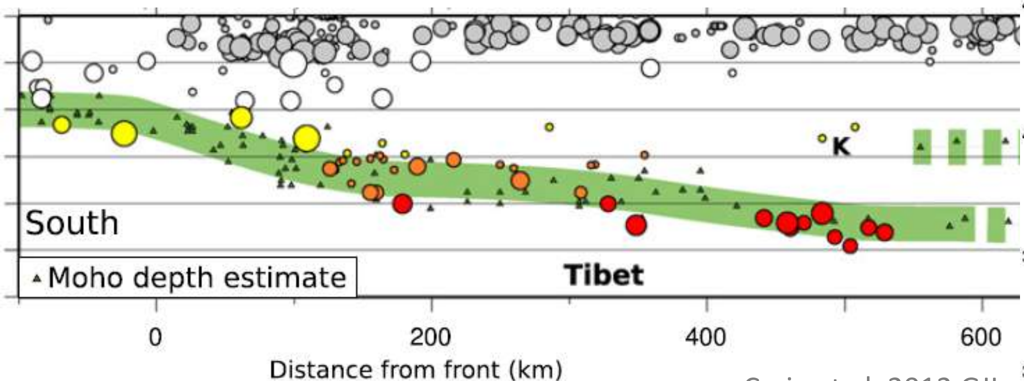


data: 75 ± 5 km

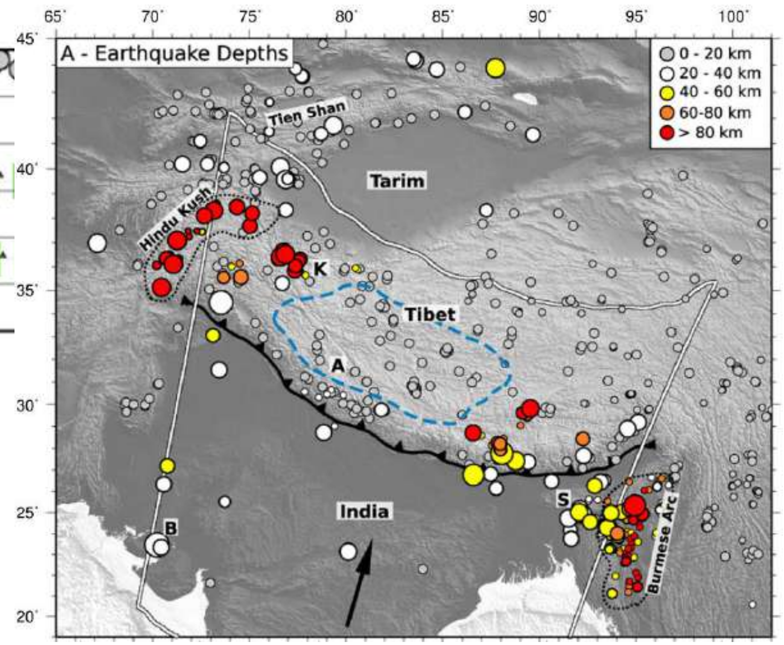
90 km: schematic

Local data: Moho depth

Are the rare deep earthquakes in Tibet in the mantle or the lower crust?

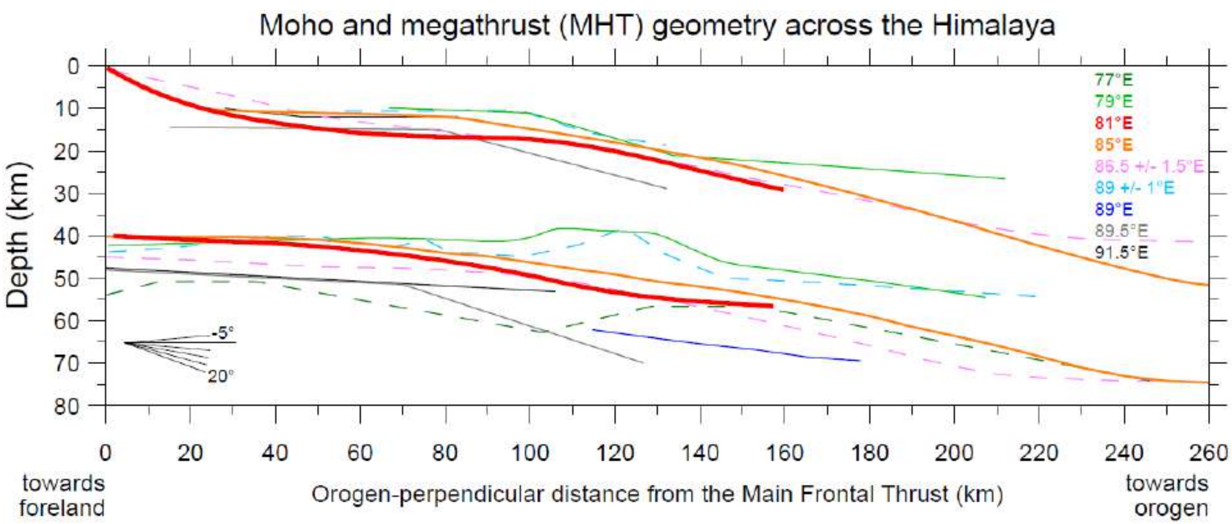


Craig et al. 2012 GJI



- large area → 3D structure

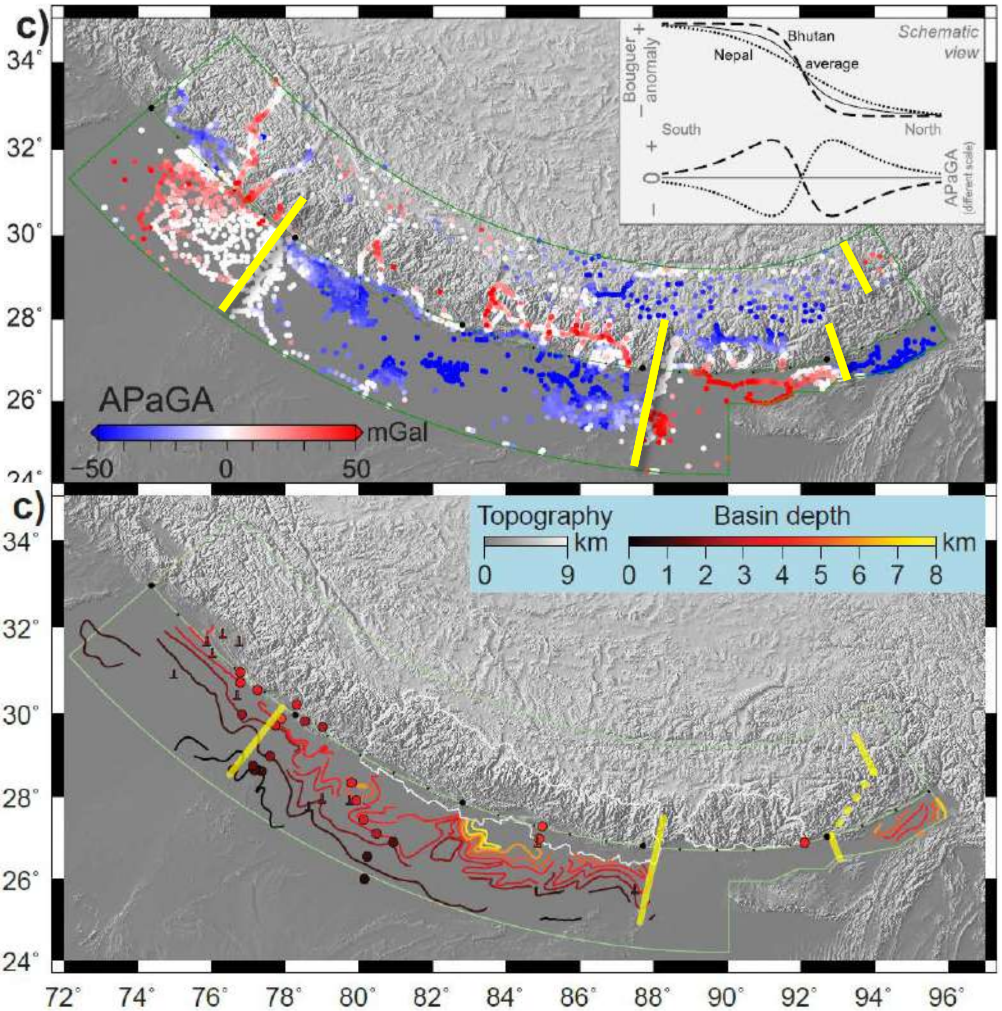
Subedi et al. 2018 GRL



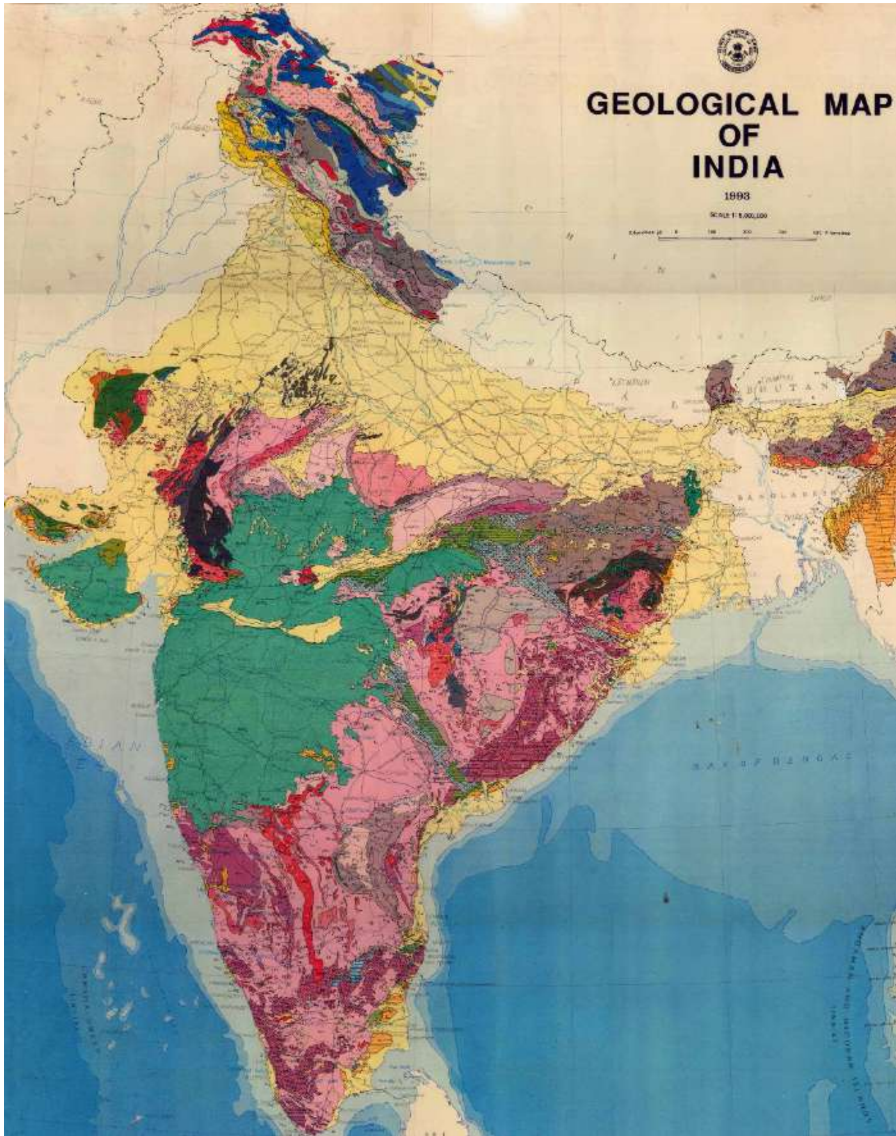
Local data: Geological variability

- segmentation of the Himalaya, inherited from the India plate

Hetényi et al. 2016 Sci Rep



Dasgupta et al. 1993



Local data: Dry Indian lower crust?

nature COMMUNICATIONS

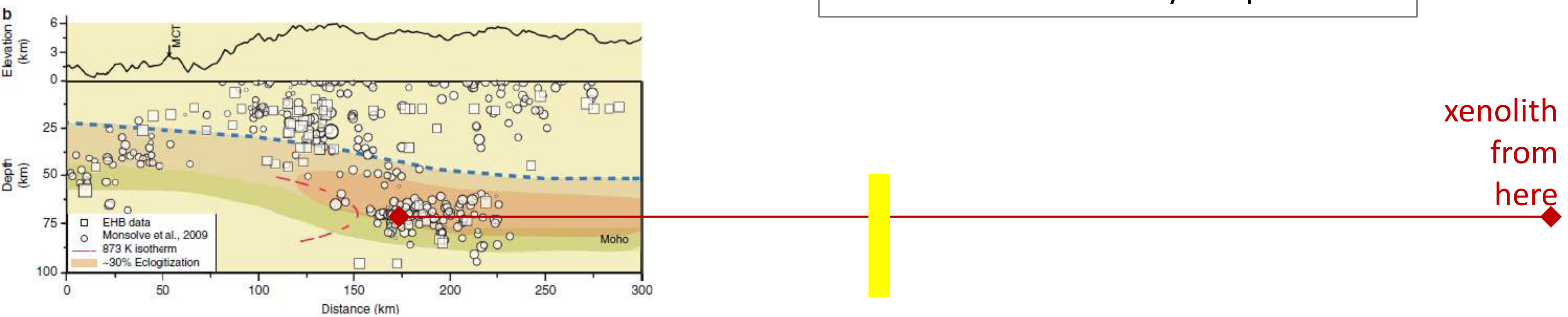
ARTICLE

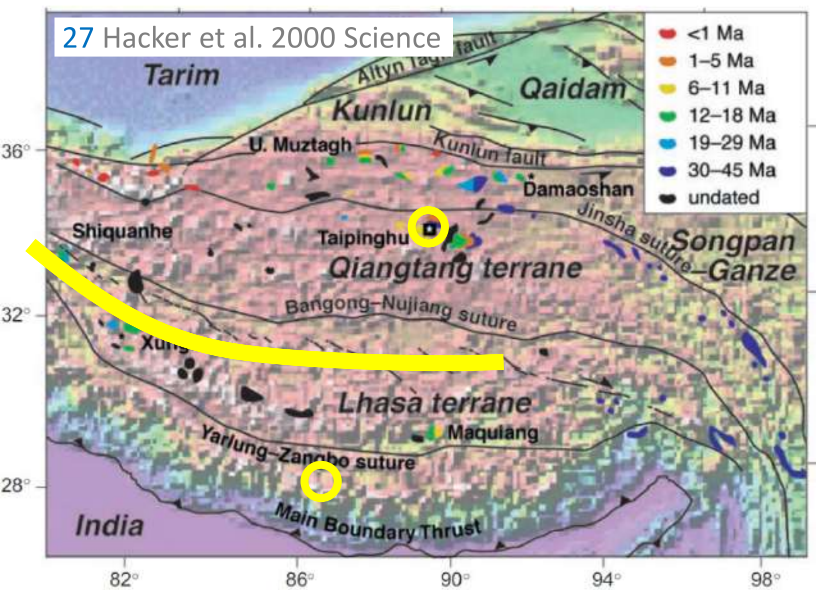
DOI: 10.1038/s41467-018-05964-1 OPEN

Lower-crustal earthquakes in southern Tibet are linked to eclogitization of dry metastable granulite

Feng Shi[1,2], Yanbin Wang[2], Tony Yu[2], Lupei Zhu[3], Junfeng Zhang[1], Jianguo Wen[4], Julien Gasc[5], Sarah Incel[5], Alexandre Schubnel[5], Ziyu Li[3], Tao Chen[1], Wenlong Liu[1], Vitali Prakapenka[2] & Zhenmin Jin[1]

Xenolith samples from Tibet suggest that the Indian lower crust lacks hydrous minerals[27], making dehydration embrittlement less likely to operate.

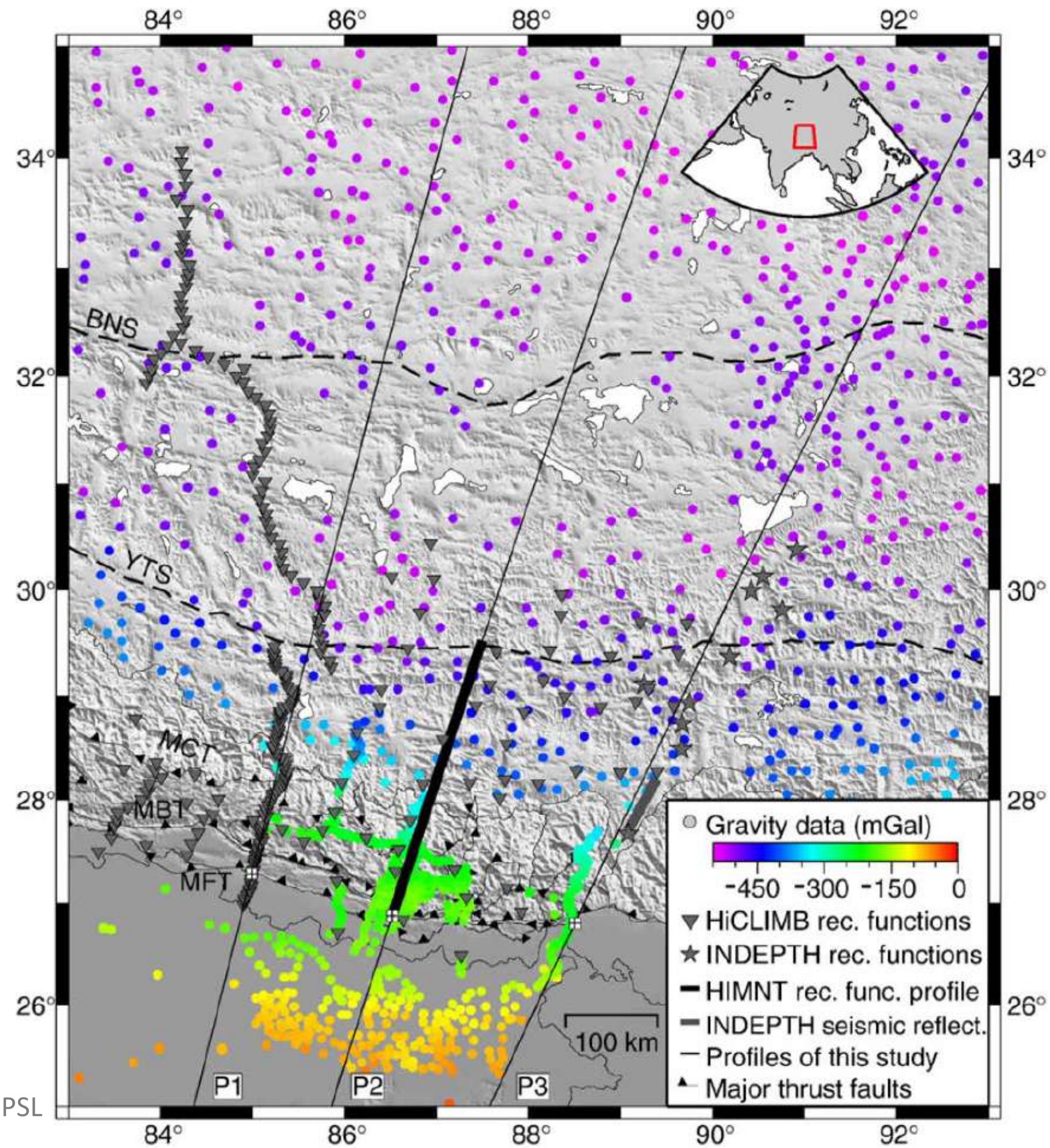




- xenolith sample from >600 km to N, region without underthrusting ILC
- to date we have no relevant sample of underthrusted Indian lower crust

Geophysical constraints on the Indian lower crust

- Central Himalaya
- Seismological data
  → structure geometry
- Thermo-kinematic and petrological modelling
  → T, P, chem. → ρ
  ⇔ gravity data
- Can we constrain
  - Water content?
  - Reaction kinetics?



Hetényi et al. 2007 EPSL

Approach

- Central Himalaya

- Seismological data
  → structure geometry

- Thermo-kinematic and petrological modelling
  → T, P, chem. → ρ
  ⬄ gravity data

- Can we constrain
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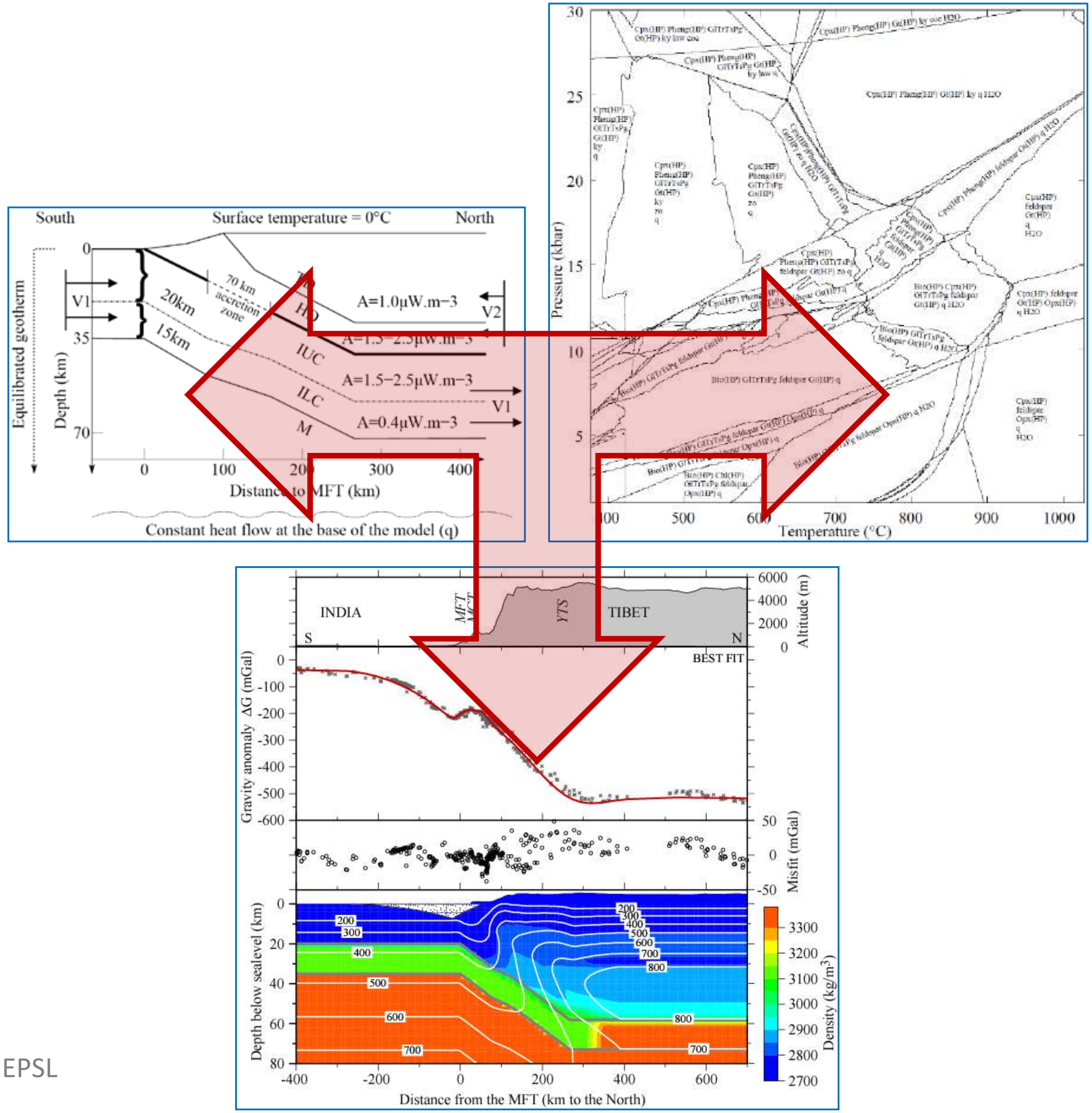
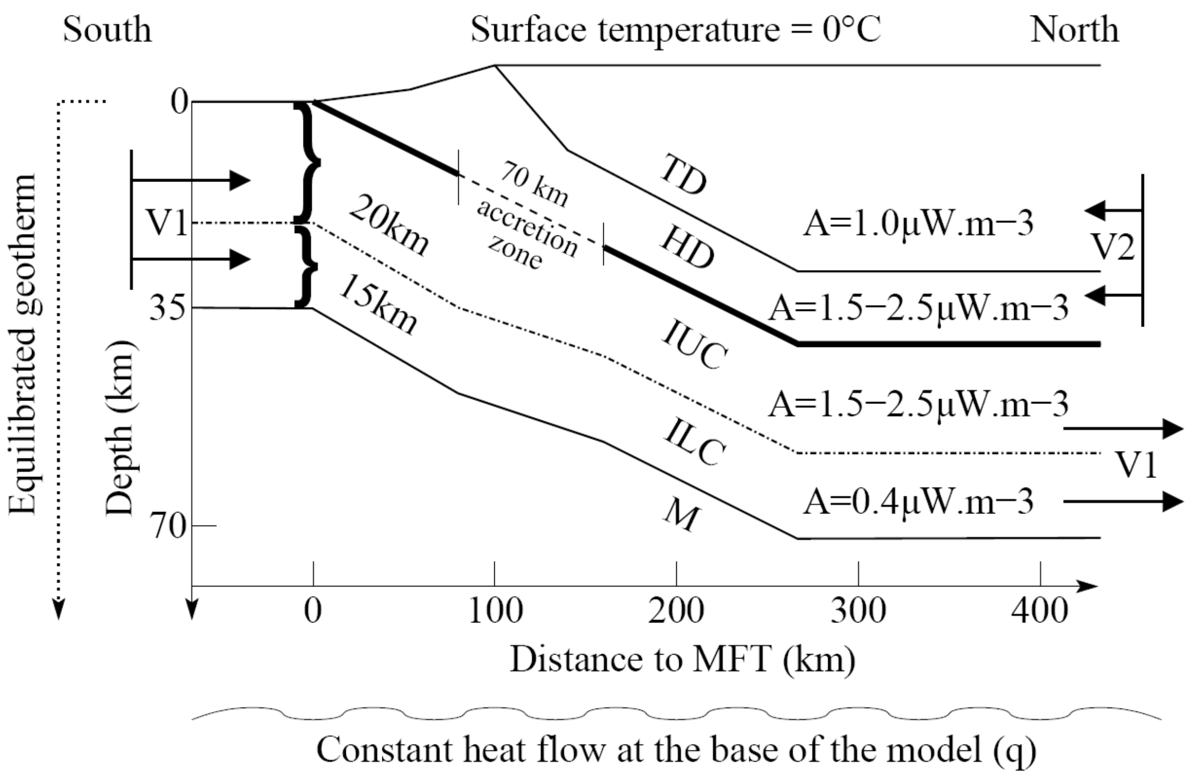


Hetényi et al. 2007 EPSL

Numerical models and varied parameters

Thermo-kinematic model

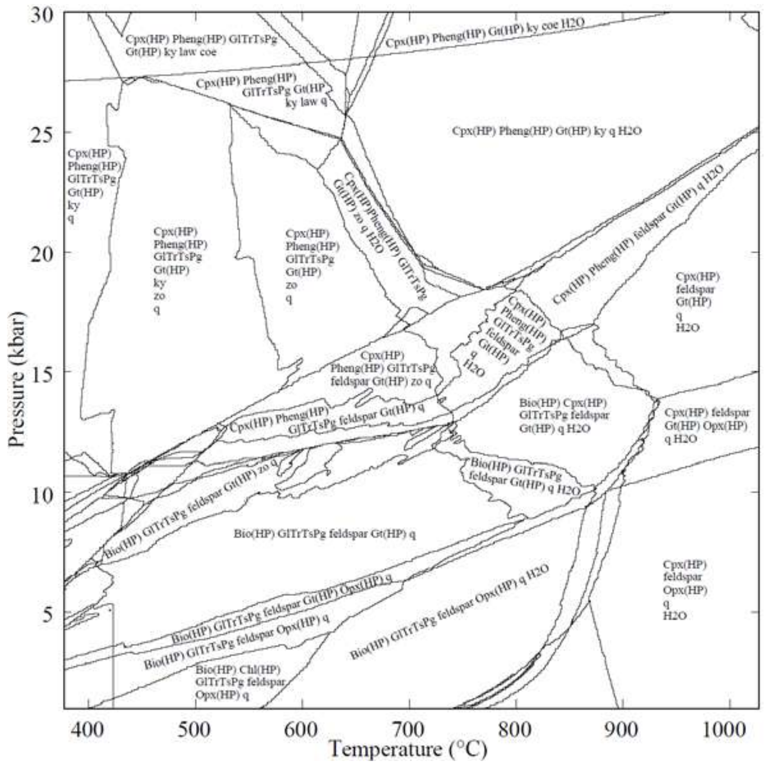
Following Henry et al. 1997; Bollinger et al. 2006

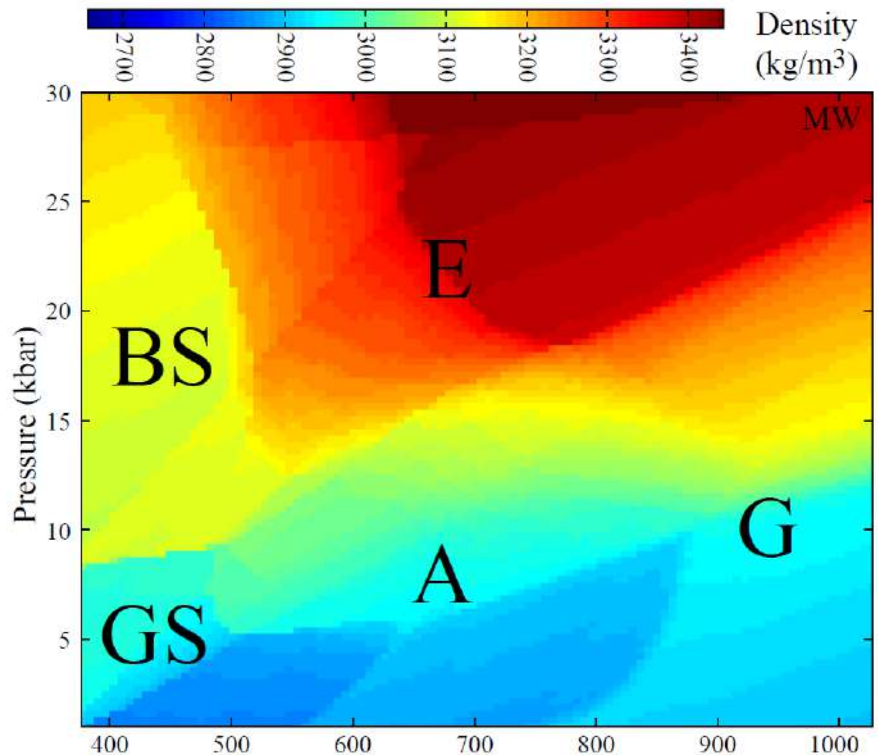


- ***FEAP***: finite-element heat advection-diffusion eq.
- geometries, convergence rate are fixed
- radiogenic heat production ***A***, basal heat flow ***q*** are varied ⇔ thermal field reproduces large field datasets

Numerical models and varied parameters

Petrogenetic grids Connolly 2005





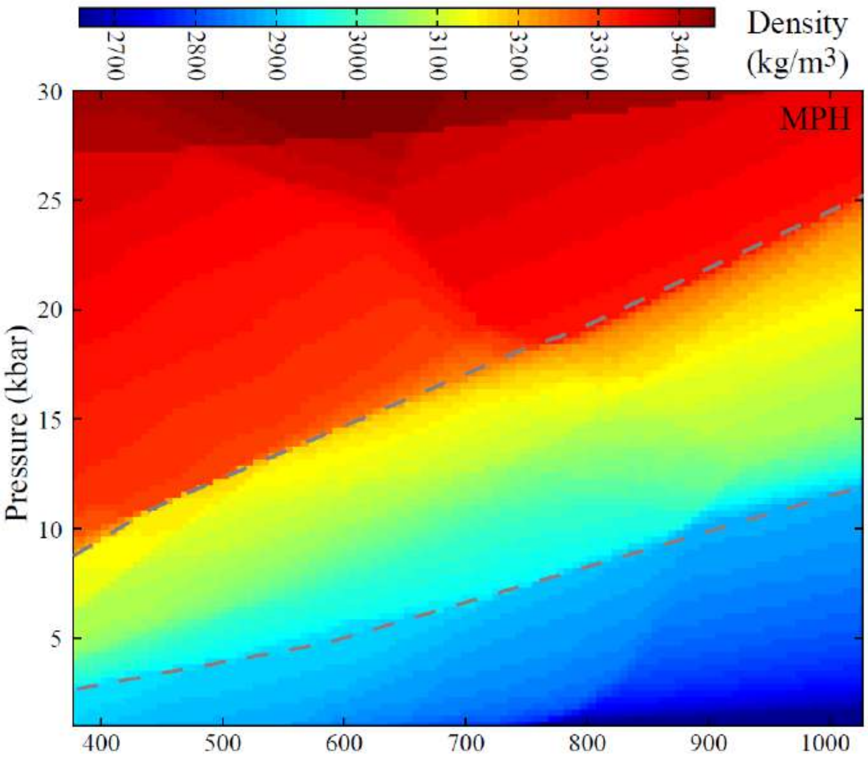
- ***Perple_X***: Gibbs energy minimization
- mineral composition is fixed: average continental lower crust

Rudnick and Fountain 1995
Rudnick and Gao 2003

- solid solution phases are fixed
- water content is varied:
  - **wet** (all hydrous minerals), **partially hydrated** (amphibolitic), **dry** (granulitic)

Numerical models and varied parameters

Petrogenetic grids Connolly 2005



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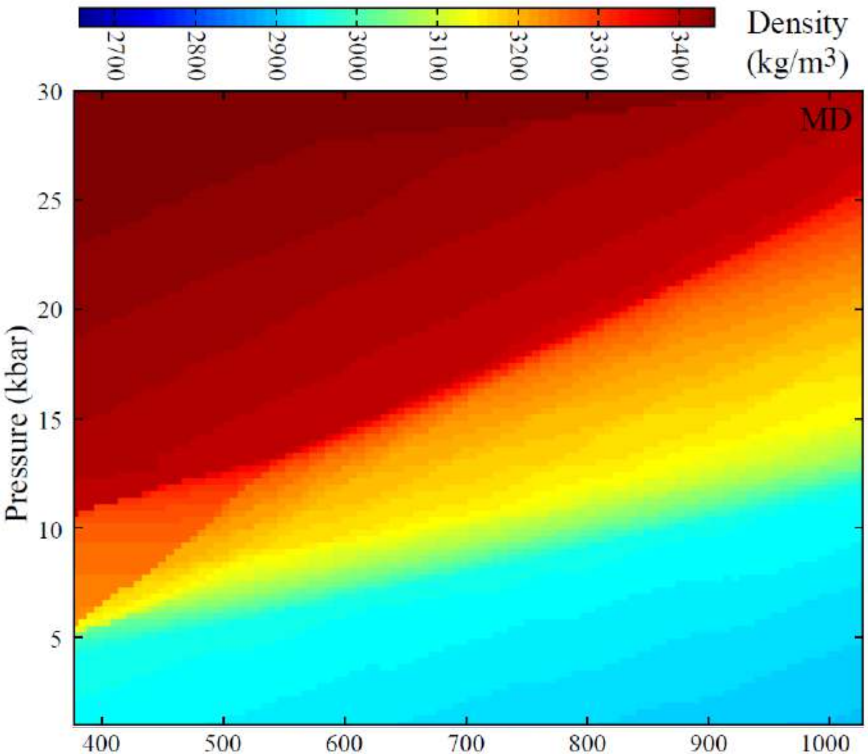

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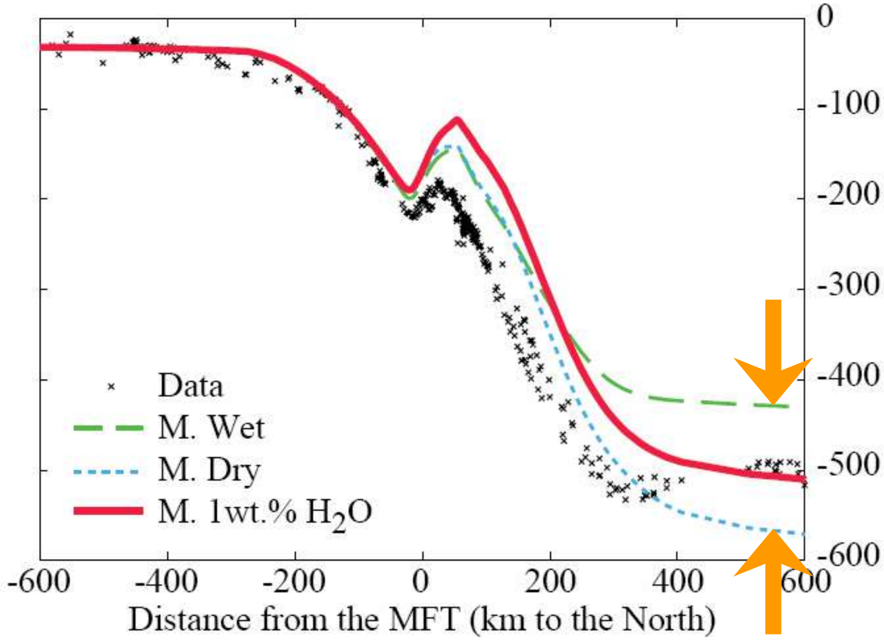
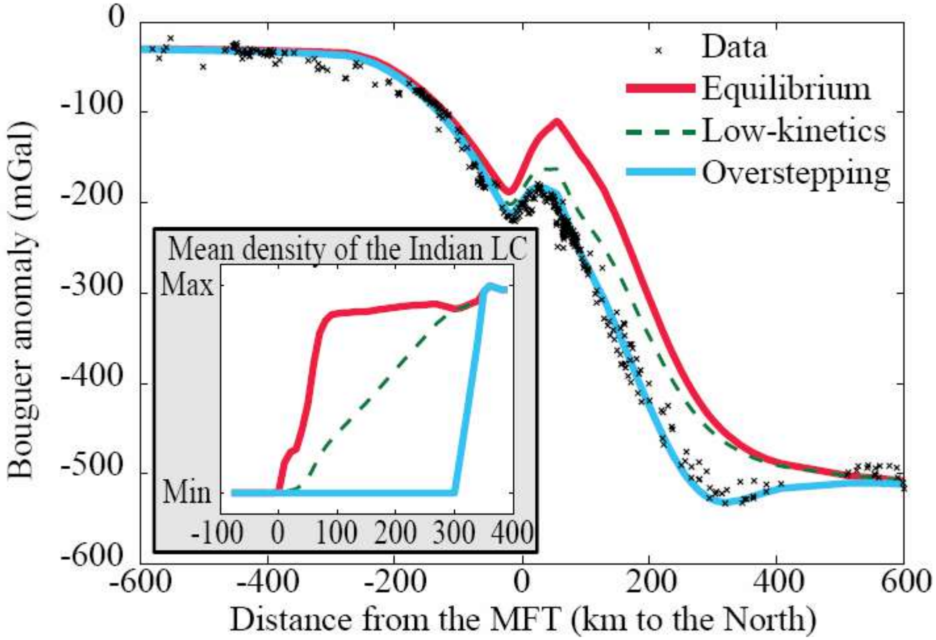
Constraining model results

- temperature at key locations ⇔ ***A*, *q***
- gravity anomalies:
  - far-field fit
    - ✓ partially hydrated
  - along-profile variations
    - ✘ misfit in the region of interest
- eclogitization kinetics:
  - ✘ equilibrium
  - ✘ sluggish kinetics
  - ✓ delay





Hetényi et al. 2007 EPSL

Reaction kinetics – the role of water

A

Lack of free water

↓

Overstepping of the plag-out reaction

B

Significant ΔT + free water

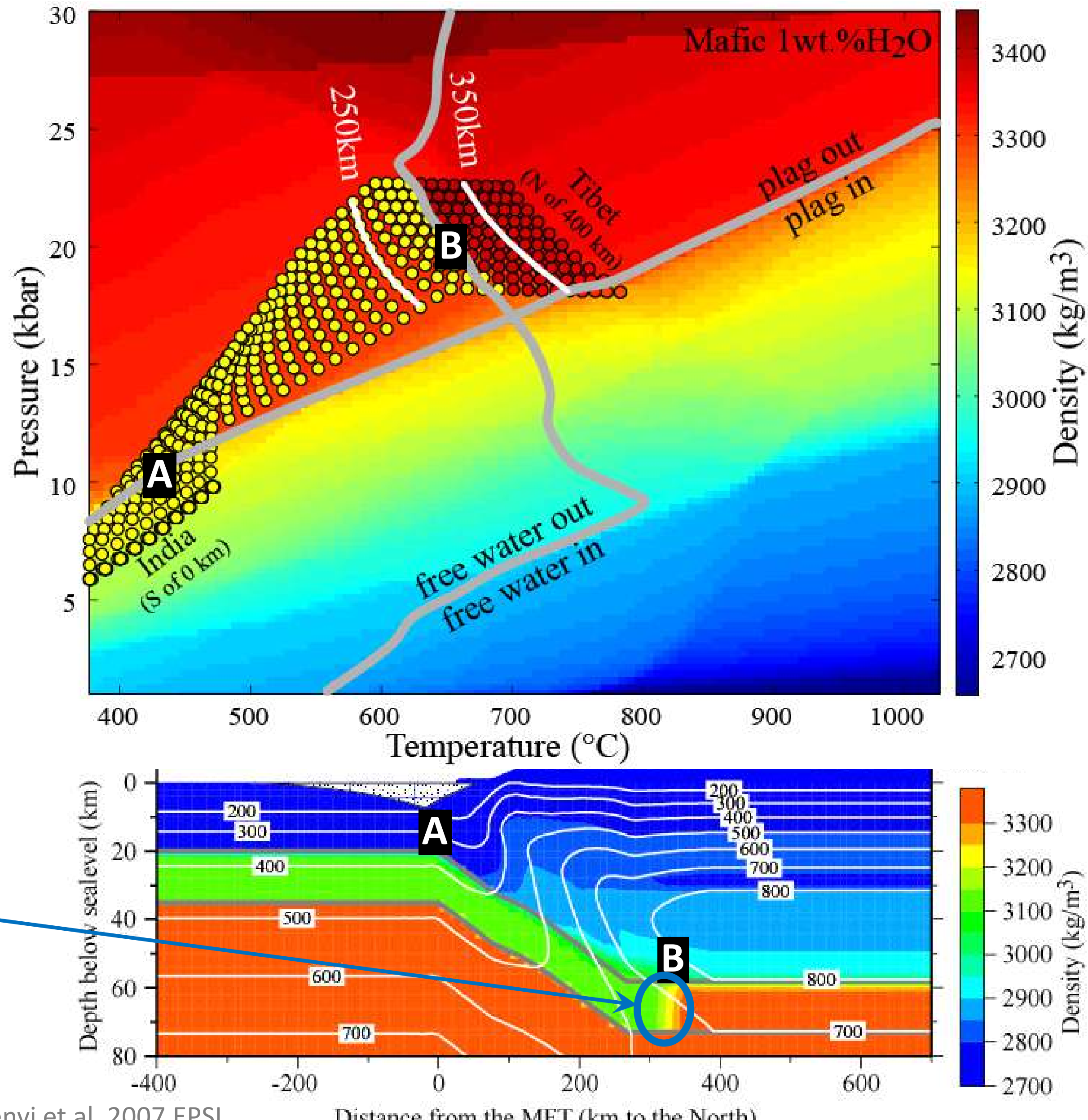
↓

Rapid eclogitization

+

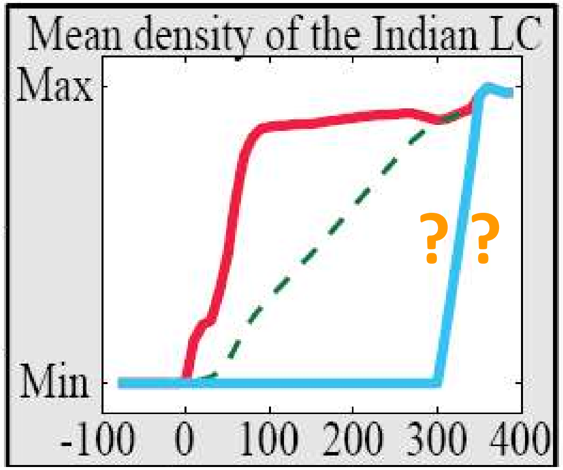
Localized microseismic activity

Monsalve et al. 2006 JGR



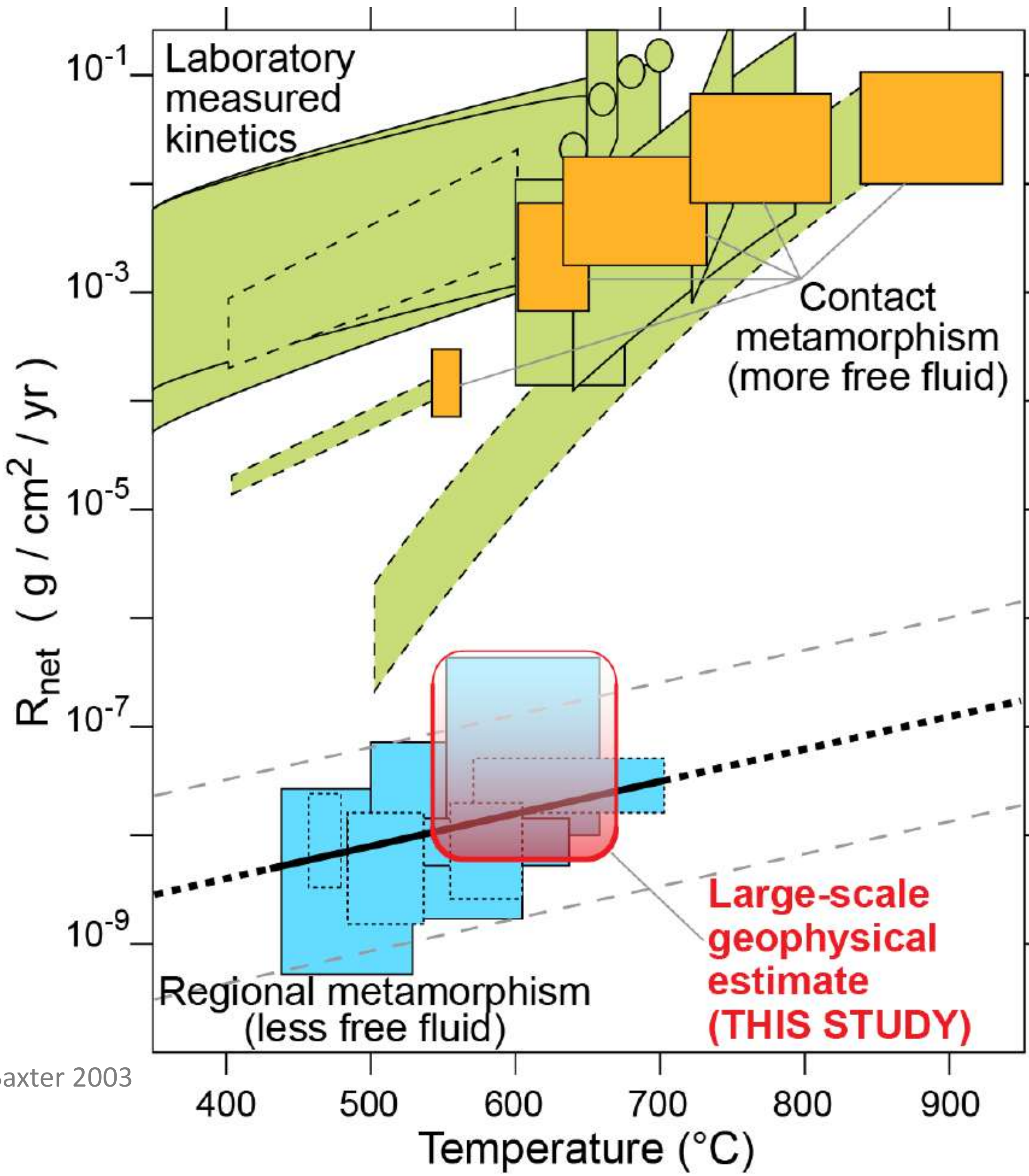
Hetényi et al. 2007 EPSL

Update on effective reaction rate



- overstepping well-constrained
- slope ~ kinetics →

Chanard et al. in review



after Baxter 2003

Conclusion 1

Indian lower crust partially hydrated

- various local datasets and coupled modelling

Question 2

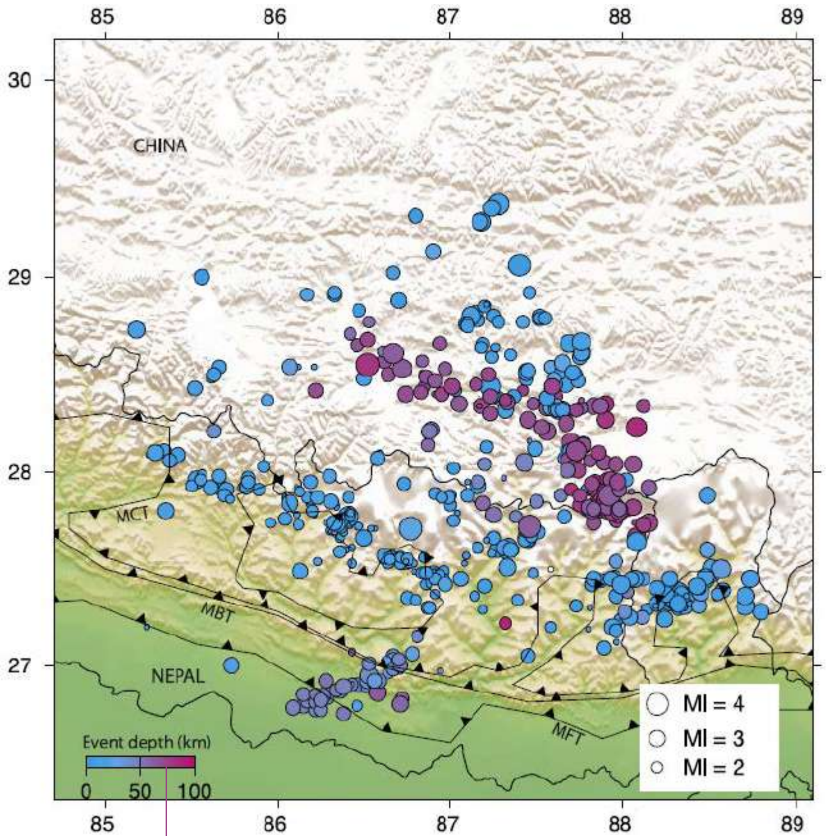
What are those earthquakes?

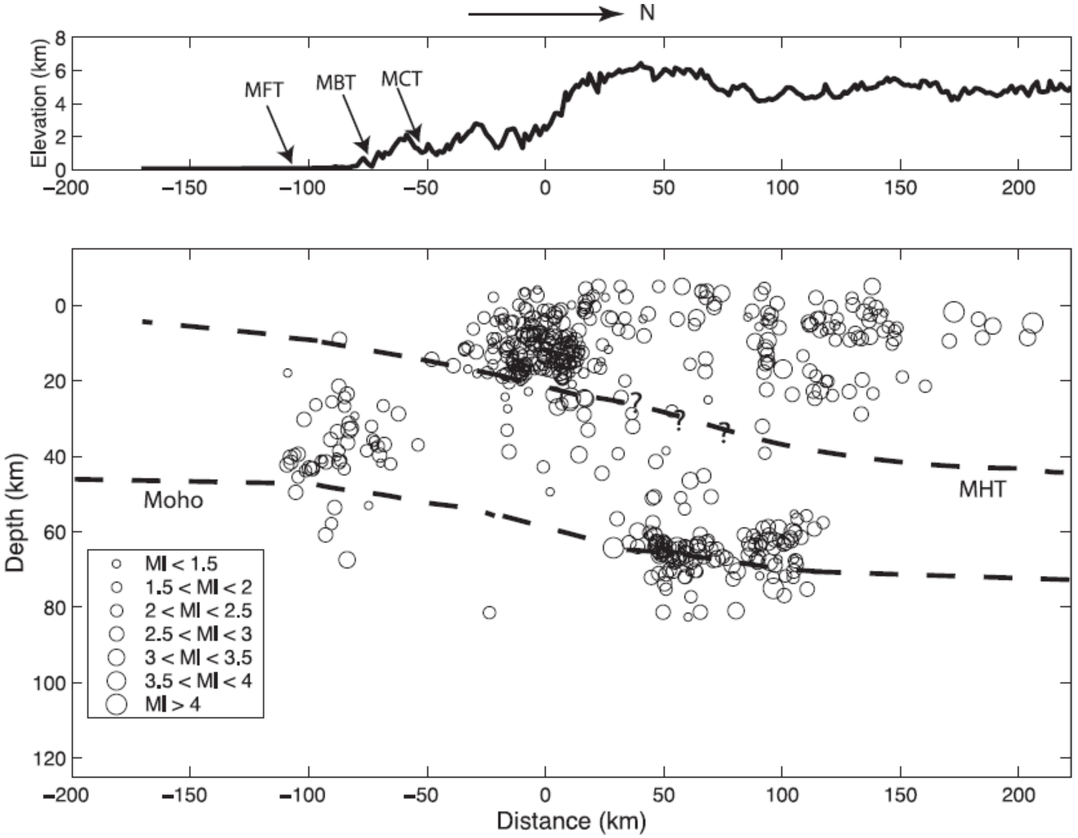
- hard to have brittle rupture at those temperatures
- what relation to metamorphism?

Himalayan deep-crustal earthquakes

Original figures of the relocated earthquakes

Monsalve et al. 2006 JGR





deep

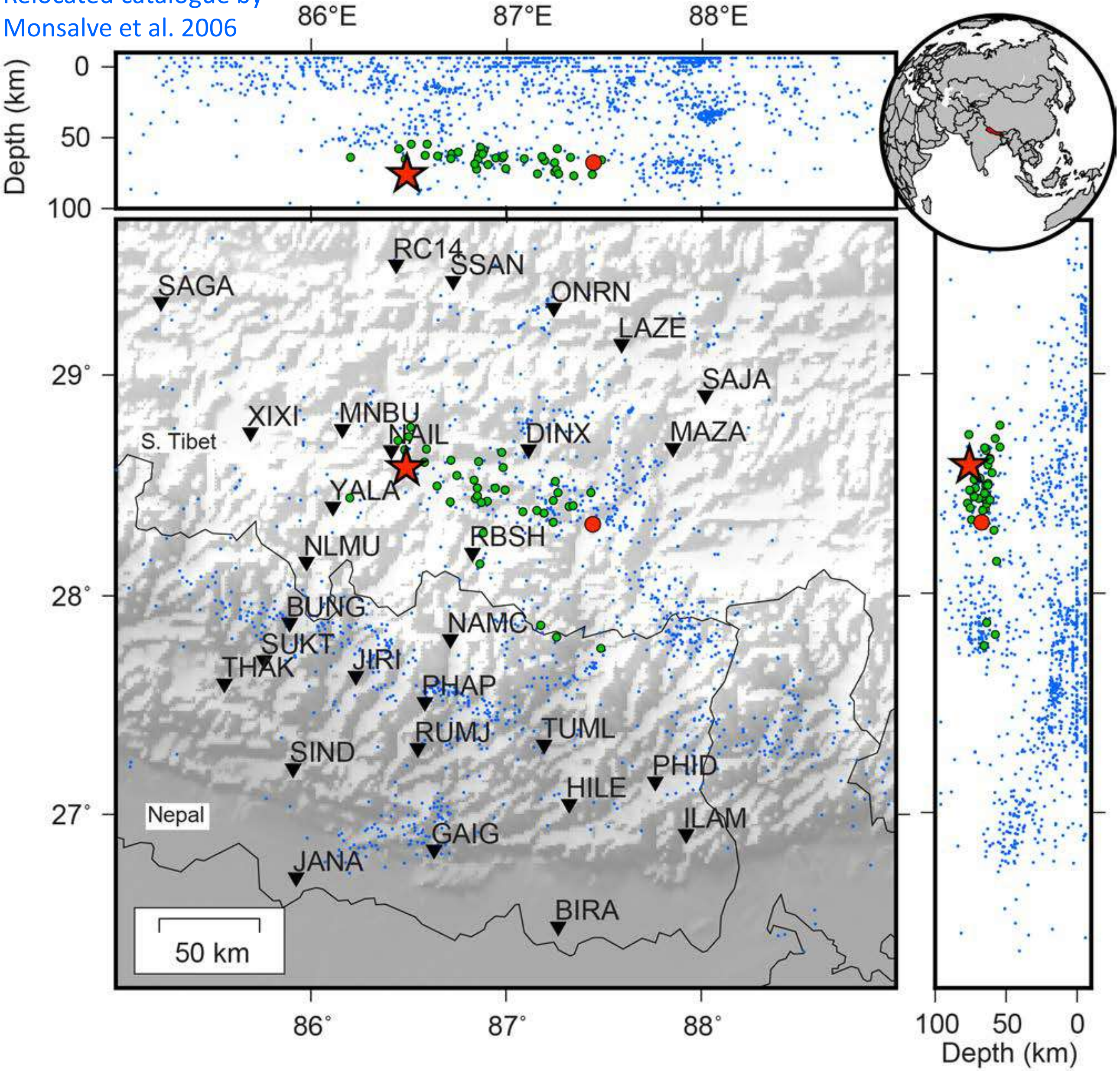
relatively small

in the Indian lower crust

Himalayan deep-crustal earthquakes

Alvizuri and Hetényi, 2019

Relocated catalogue by Monsalve et al. 2006



M~4 eqk. at 76 km

Possible causes:

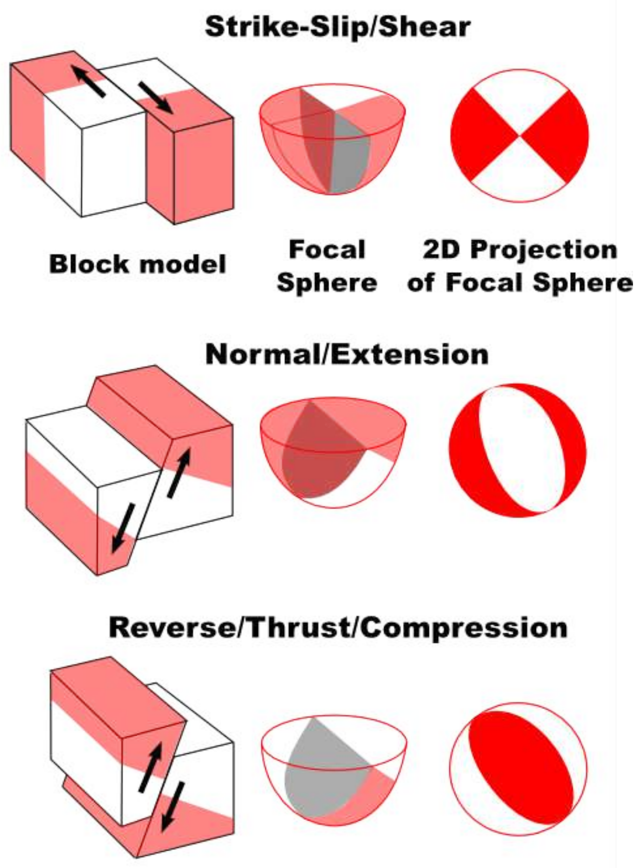
- tectonic? flexure?
- metamorphic?
  - thermal runaway?
  - anticrack?
  - dehydration embrittlement?

Methodology: full-moment-tensor analysis

- Seismic moment tensor: physical mechanism at the source

modified from Alvizuri et al. 2018 JGR

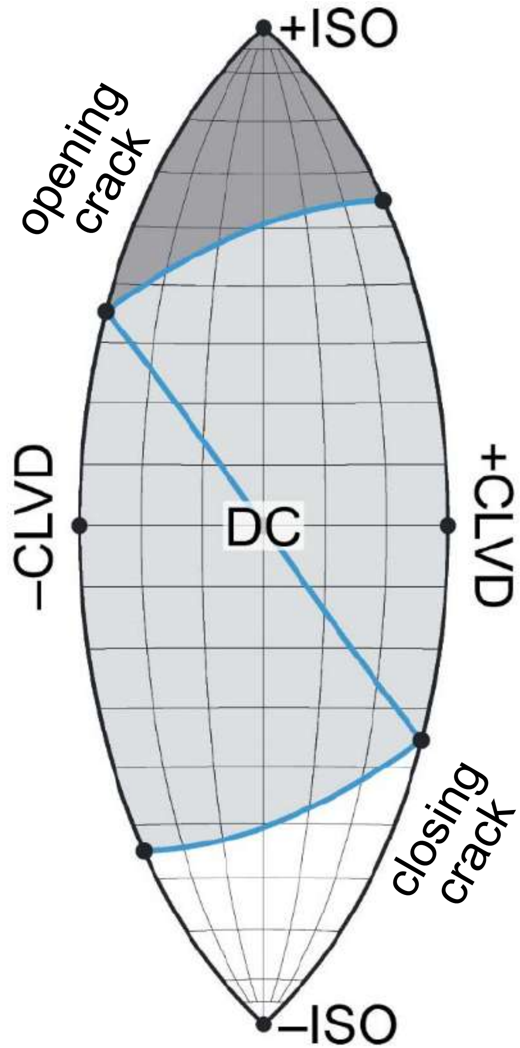
double-couple



CLVD

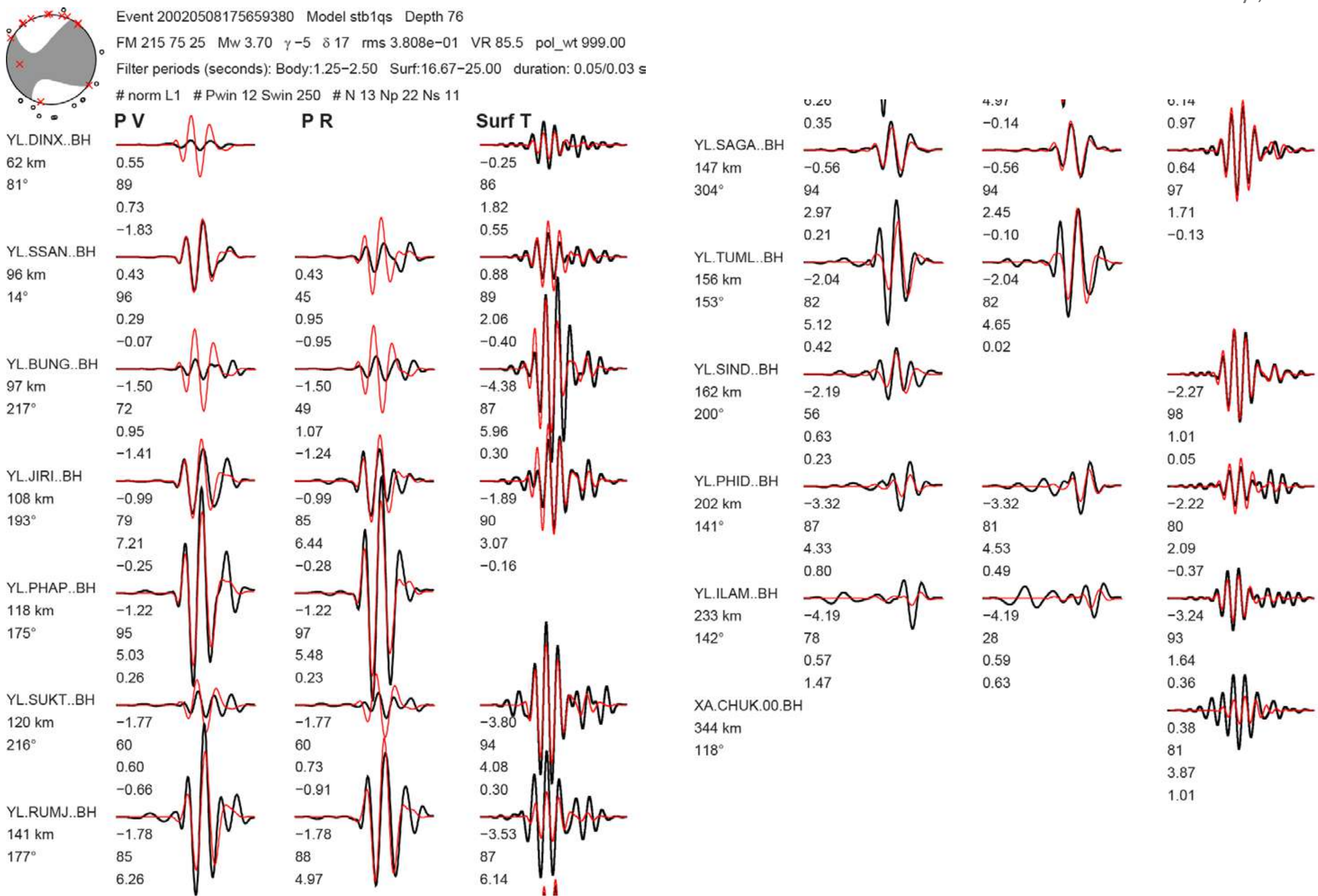
isotropic

the Lune



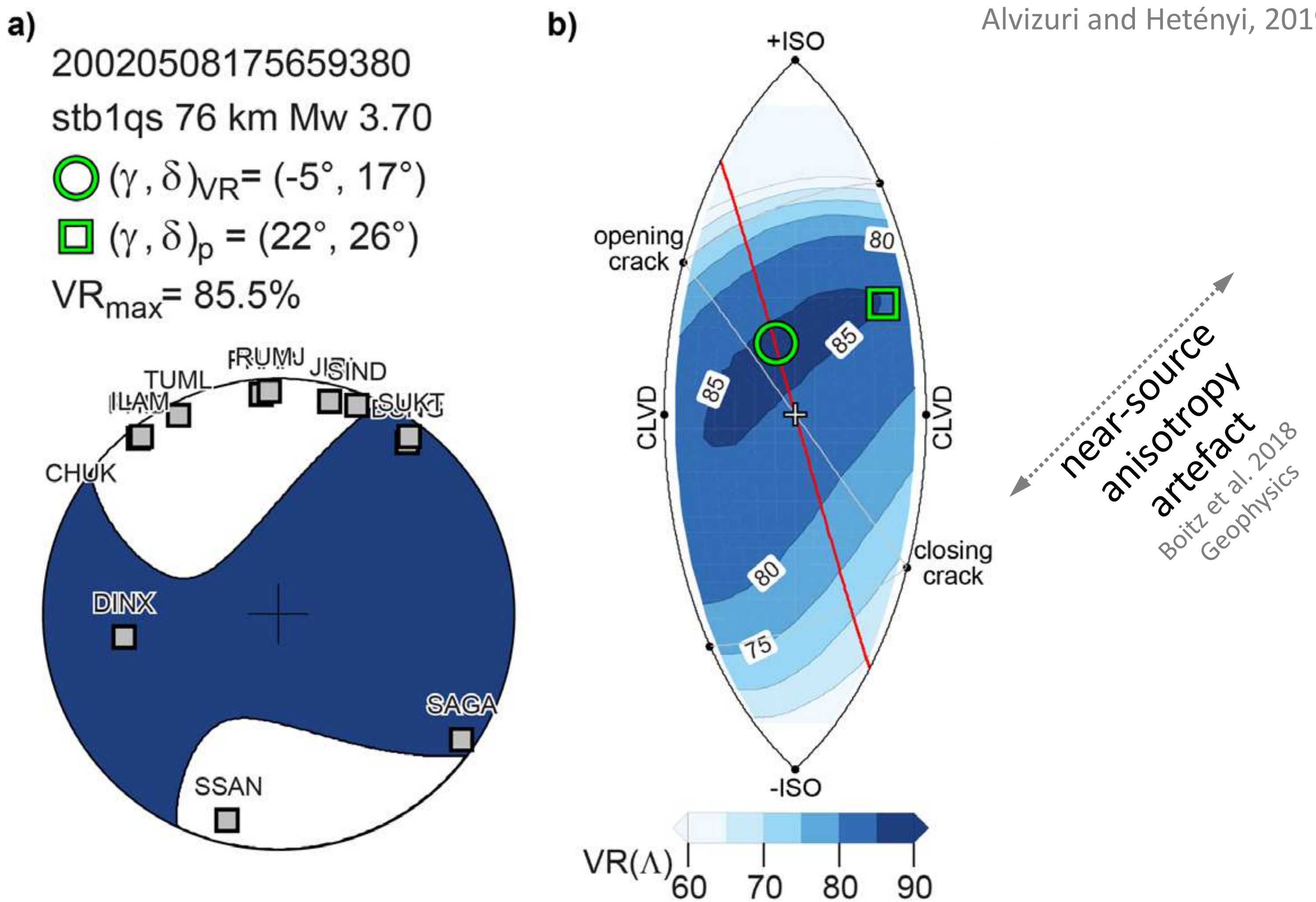
Meticulous scrutinizing of waveform fits…

Alvizuri and Hetényi, 2019



Full-moment-tensor and uncertainty

Alvizuri and Hetényi, 2019



Best-fit moment tensor

Fit-map on lune

Best-fit solution away from DC towards opening crack + uncertainty

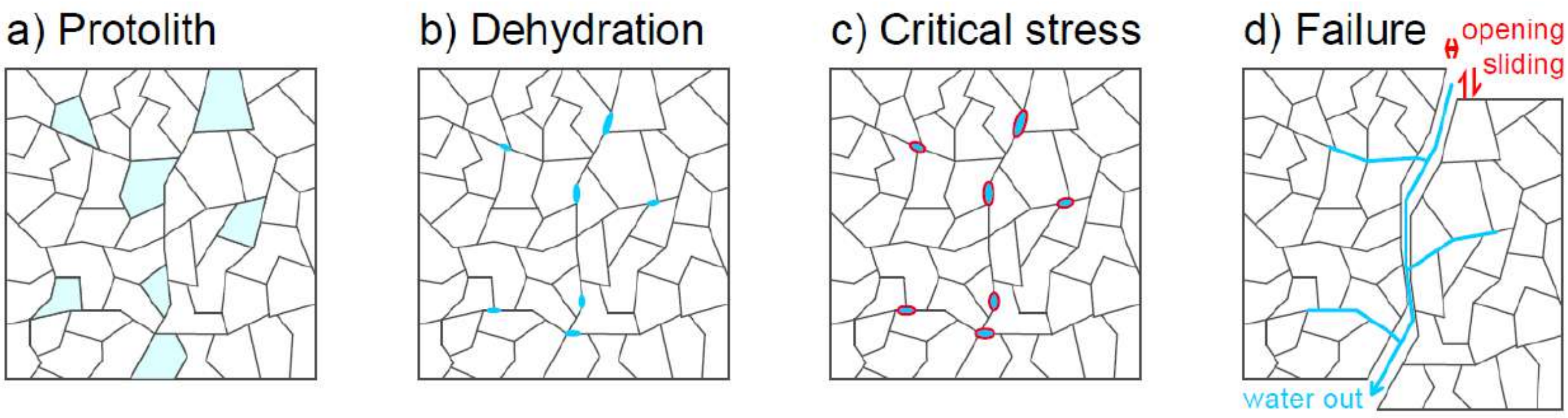
Interpretation

tectonic (DC) $\Delta V=0$

thermal runaway $\Delta V\sim 0$

anticrack $\Delta V<0$

dehydration embrittlement $\Delta V>0$



- lower crustal protolith reaches dehydration P-T conditions
- small amounts of H_2O accumulates in pores
- increased pore pressure creates fractures (smaller, then larger)
- final large fracture opens to evacuate H_2O and also slips during eqk.,

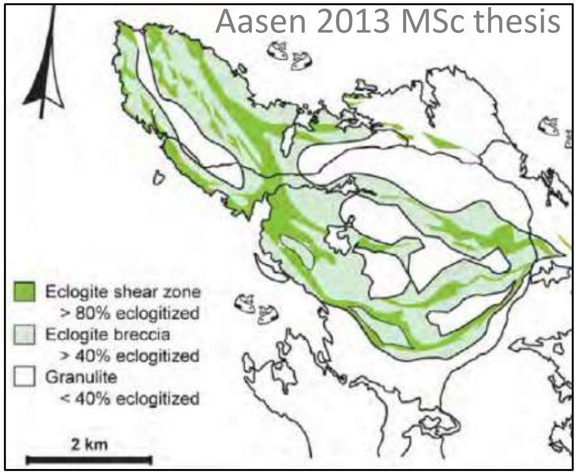
  including/through damage (see Ben-Zion et al.)

Comparison to palpable geological examples?

- Bergen Arcs?

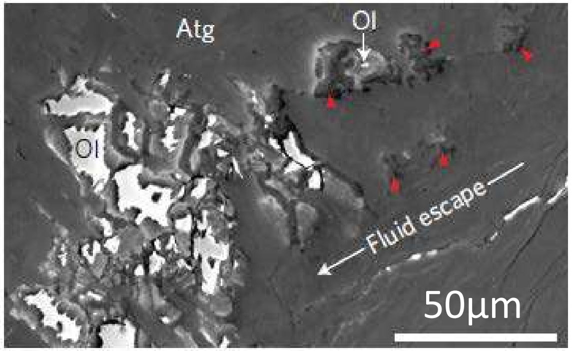
Austrheim et al. 1996 EPSL

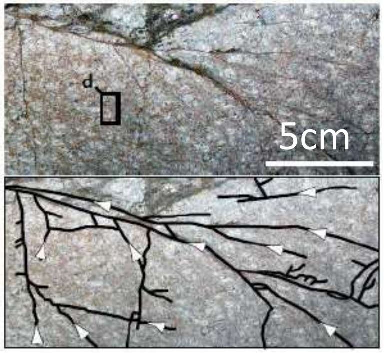
  - pseudotachylytes, but *dry granulite* → *eclogite* needs external fluids
  - imaginary event across Holsnøy ~ magnitude 4

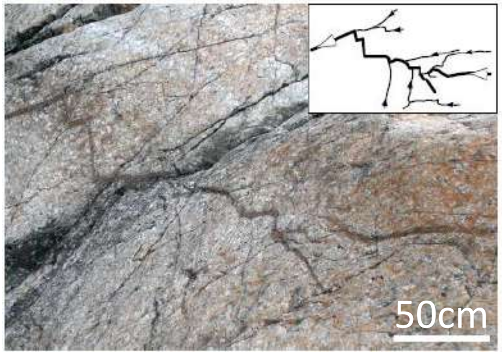


Alvizuri and Hetényi, 2019

- W. Alps?
  - µm-m documentation of dehydration–evacuation, but → thermal runaway







Plümper et al. 2017 Nat Geosci

Comparison to laboratory experiments?

- Serpentinized peridotite: dehydration reactions drive stress-transfer
  → acoustic emissions
- hydrated rock ☺, but oceanic crust (and different experimental P)

Ferrand et al. 2017 Nat Comm

Other experiments ("but"):

- Incel et al. 2017: lawsonite-blueschist, *lws* survives the reaction and keeps H_2O
- Wang et al. 2017: for mantle transition zone earthquakes
- Shi et al. 2018: dry rocks, T higher by 150°C
- Incel et al. 2019: dry granulite, higher P, higher T
- …

Proposal for an experiment:

- continental lower crustal composition
- various amounts of H_2O
- cross at ca. 650°C / 2 GPa
- slow deformation rate

Conclusions 1 & 2

Indian lower crust partially hydrated

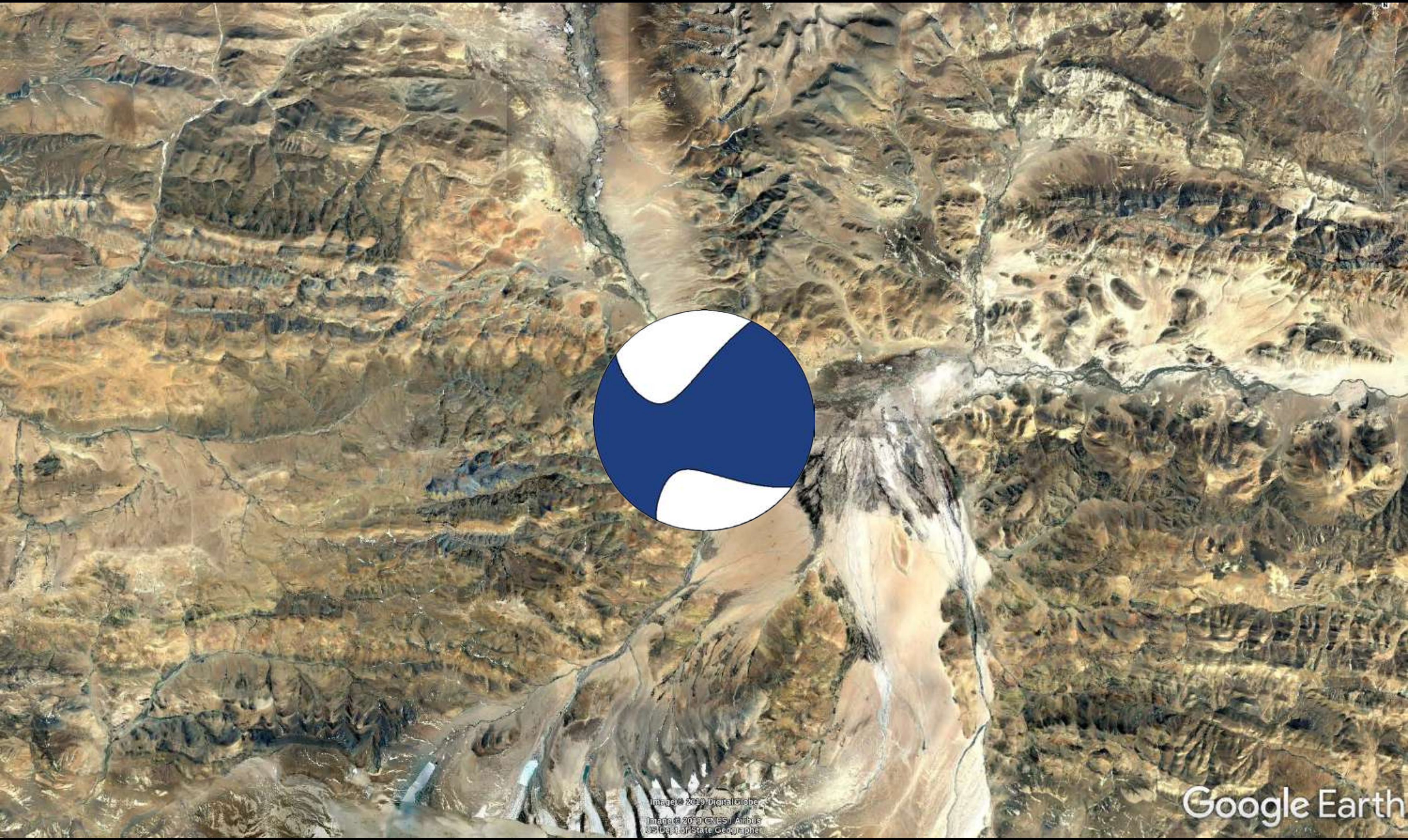
Metamorphic earthquakes related to dehydration

- local events and data – *not* a generalization for the Tibetan Plateau

"Dehydration embrittlement changes the mechanical properties of the crust, and extends the depth of the brittle rupture domain to that of the deepest hydrated phases"
(Raleigh & Paterson 1965)

Deep crustal, intermediate depth, deep earthquakes

- dehydration embrittlement? transformational faulting? thermal runaway?
- prevailing mechanism depends on P, T, chemistry & reactions, H_2O, …



Metamorphic earthquake in the Indian lower crust beneath southernmost Tibet

Old and new geophysical results on the Ivrea body

György HETÉNYI

with Matteo SCARPONI, Ludovic BARON, Théo BERTHET, Jarka PLOMEROVÁ, Stefano SOLARINO, Mattia PISTONE, Luca ZIBERNA, Alberto ZANETTI, Andrew GREENWOOD, Othmar MÜNTENER

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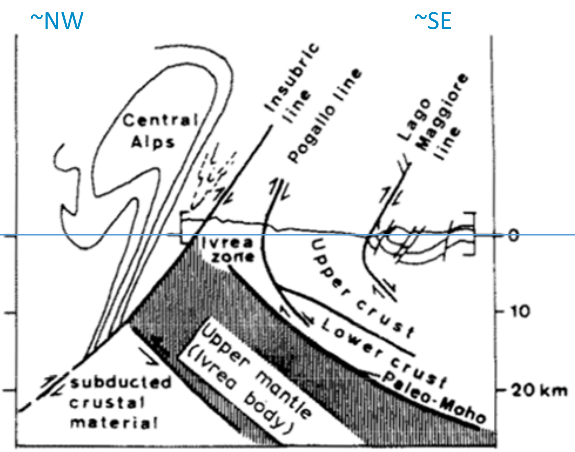
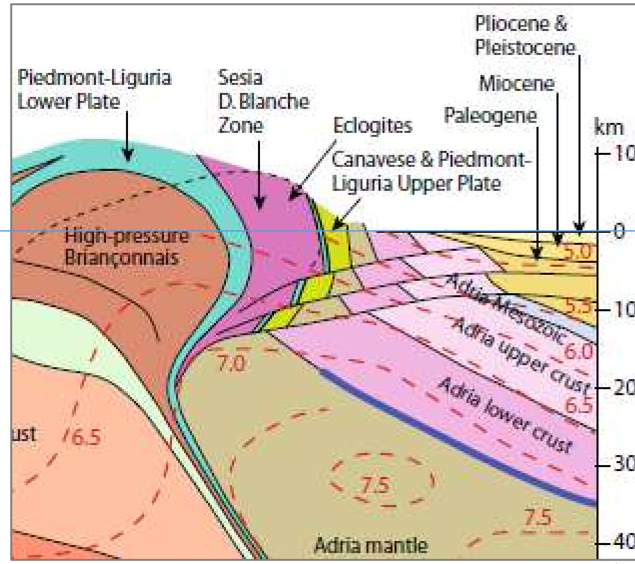
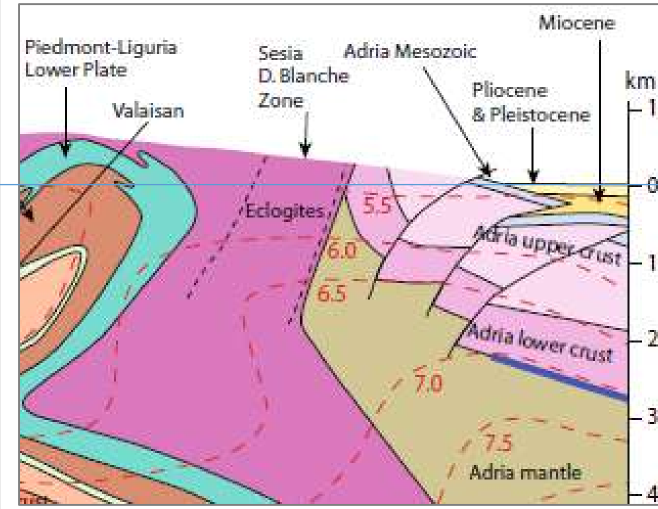
Geological situation of the IVZ at depth



Zingg et al. 1990

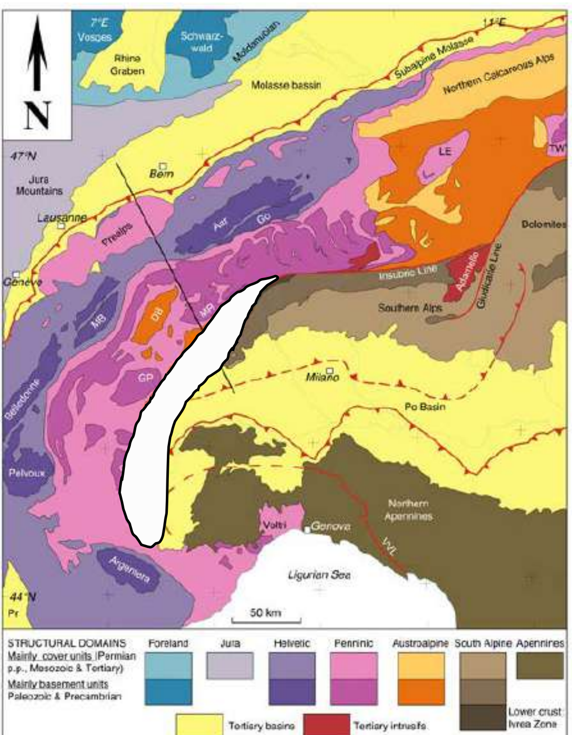


ECORS-CROP (southern IVZ)



Schmid et al. 2017

NFP20W (central IVZ)



www.virtualexplorer.com.au

Ivrea-Verbano Zone vs.
Ivrea geophysical body

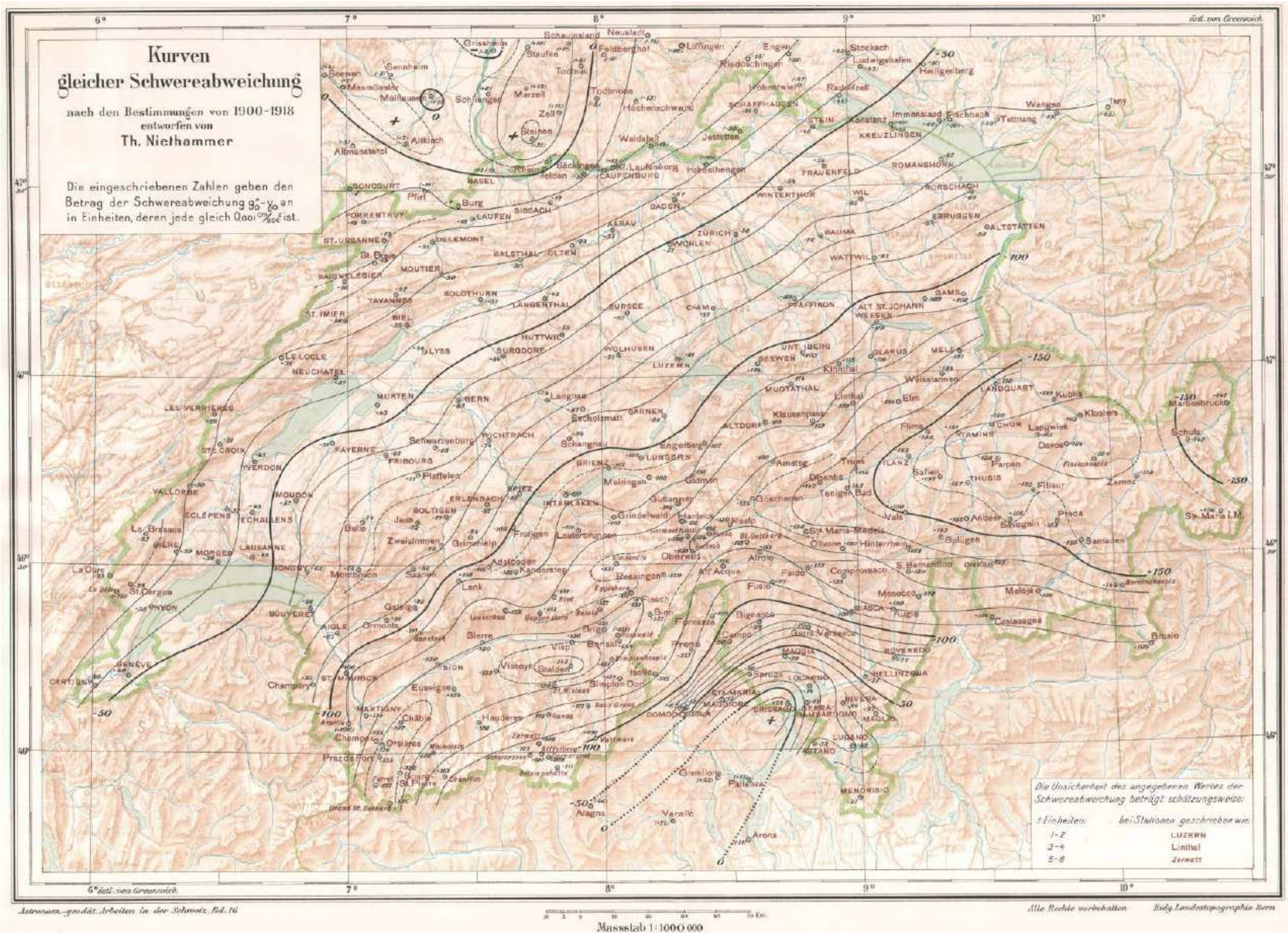
How deep is the Moho?

(“Can we drill it?”)

Gravity

First observation

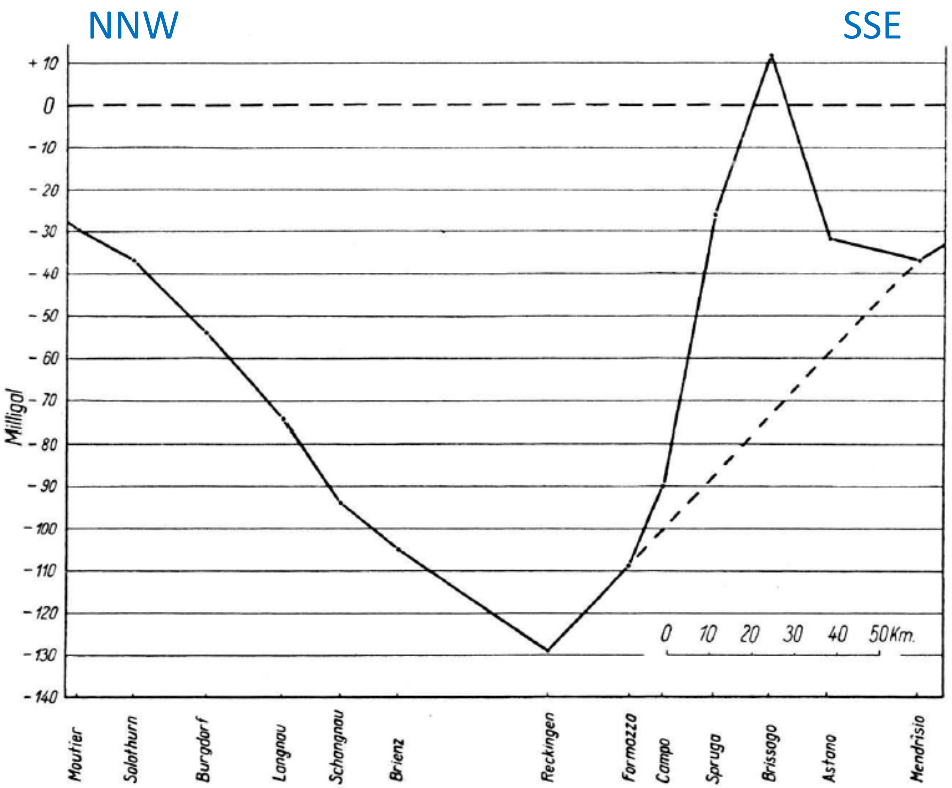
Niethammer 1921

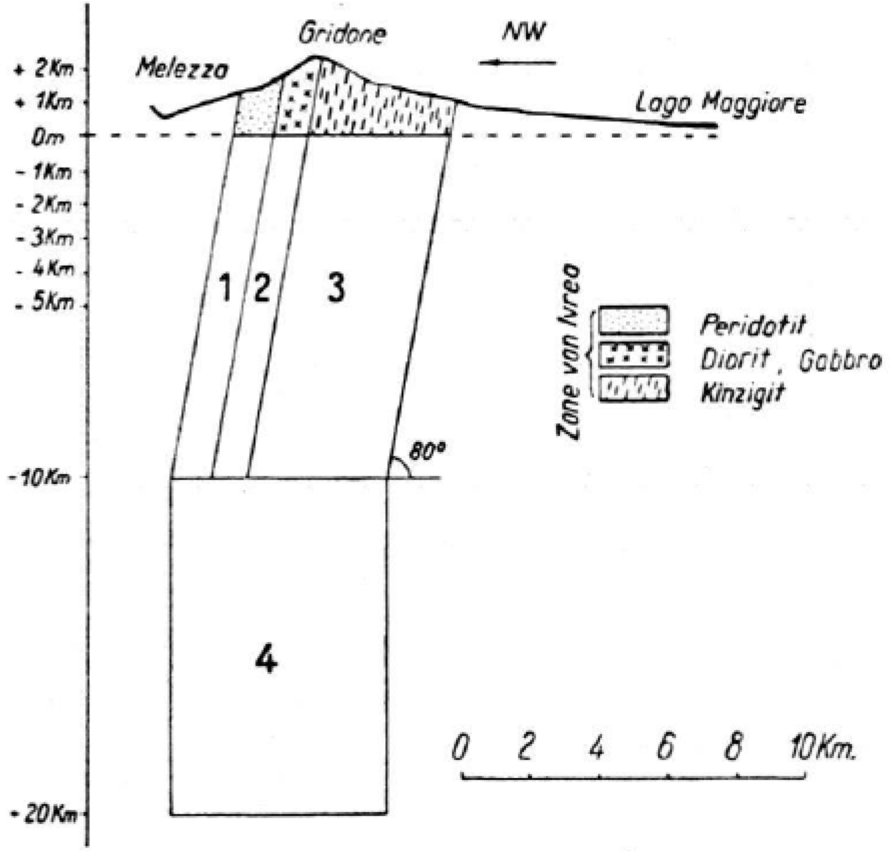


Gravity

First model

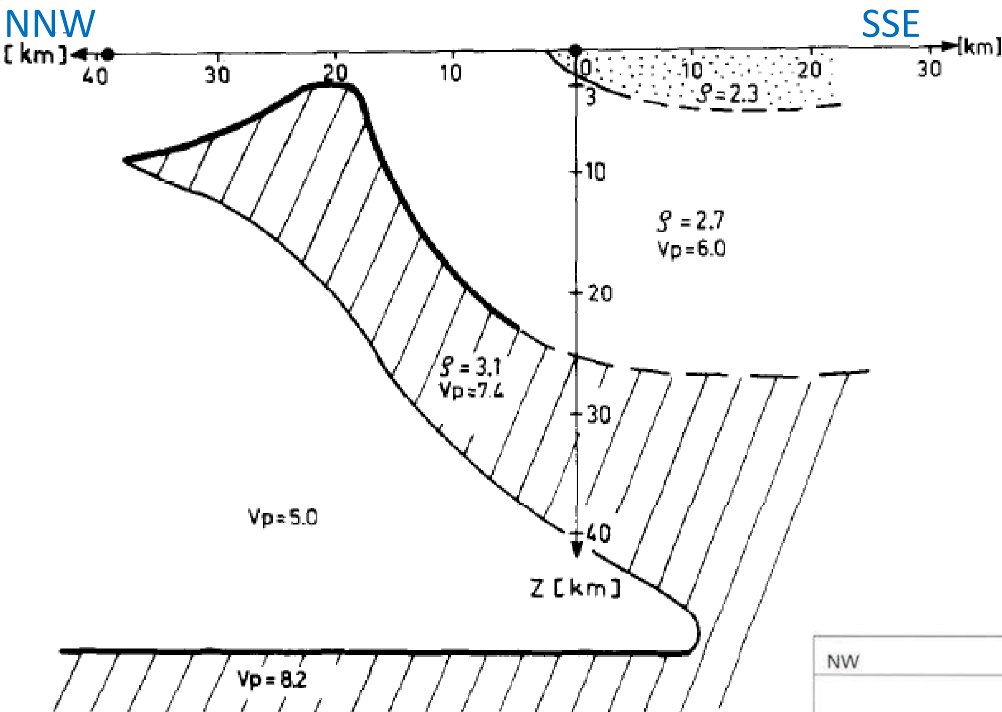
Niggli 1946





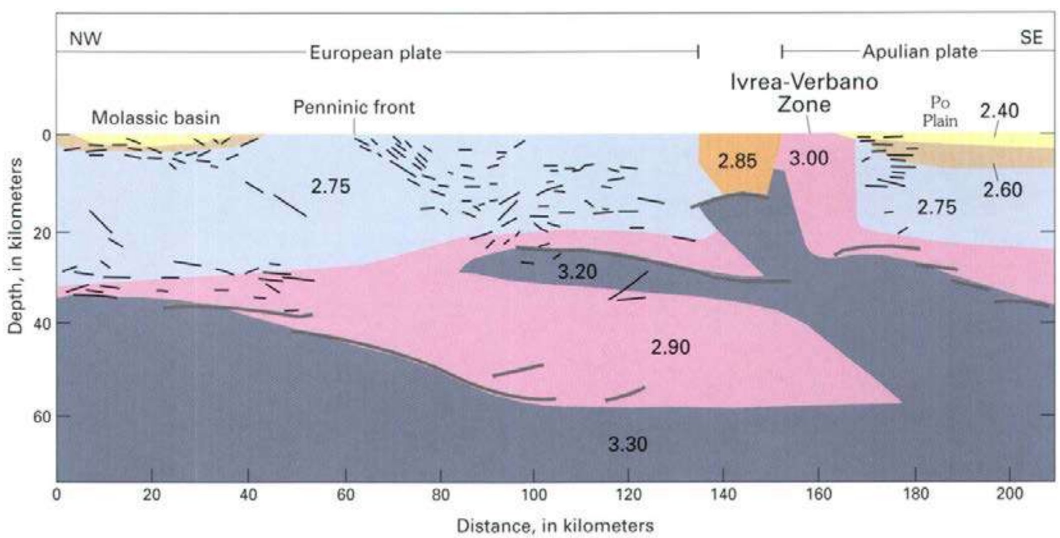
Gravity + Seismics

Combined density and P-wave velocity models



Coron 1963, Berckhemer 1968

ECORS-CROP
e.g. Nicolas et al. 1990



Gravity

3D models

- the simplest possible   Kissling 1984

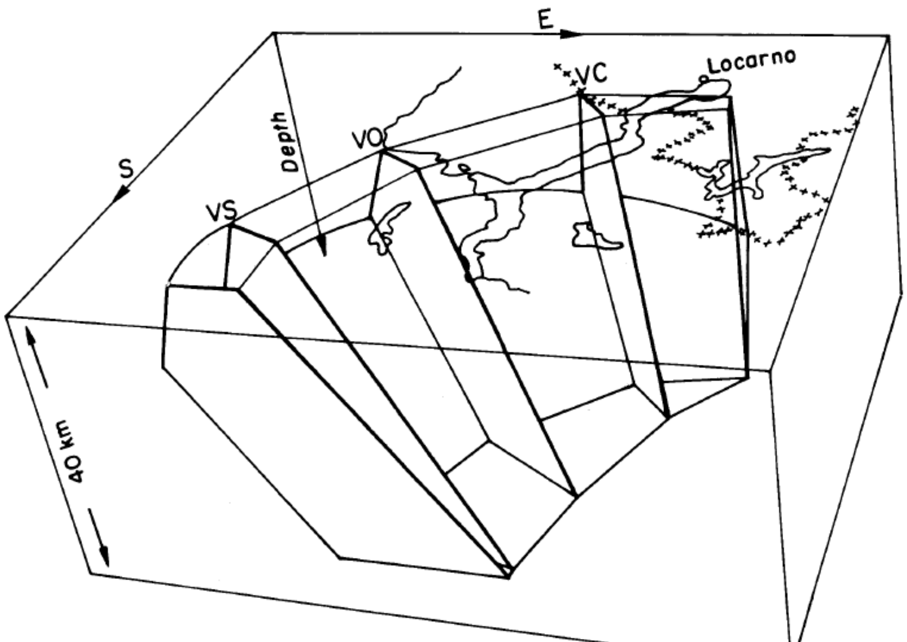
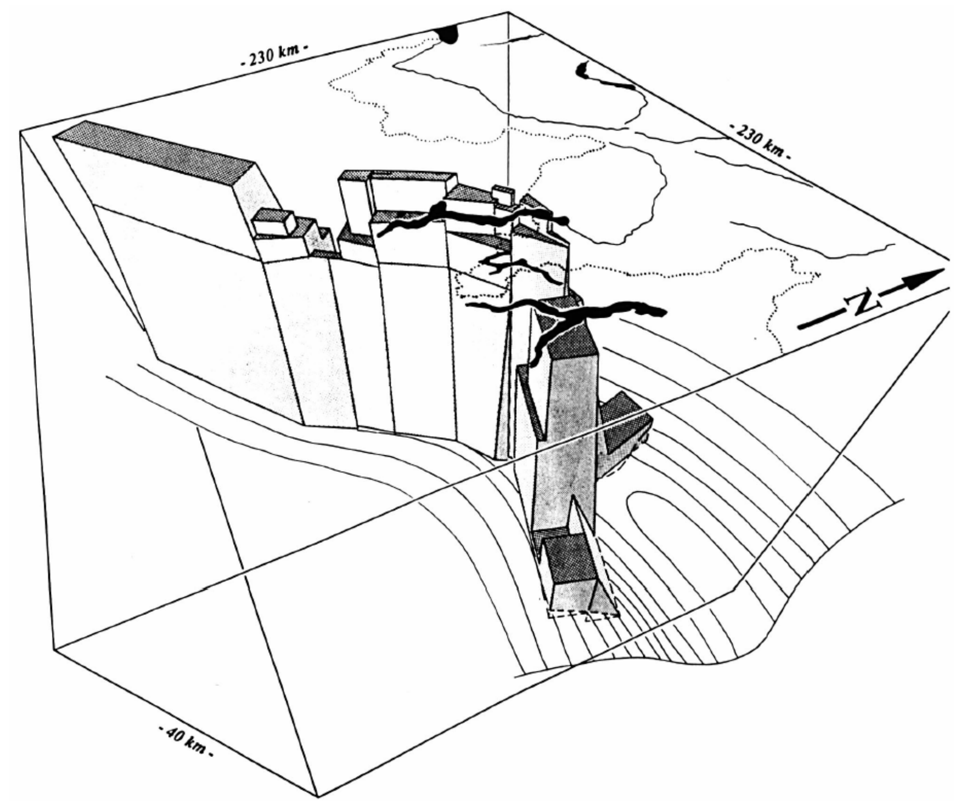


Figure 6: Three-dimensional model of the northern Ivrea body with cross sections along: VS = Val Sesia, VO = Valle d'Ossola, VC = Val Cannobina.

- multi-body   Bürki 1989



Gravity – summary:

ρ ~ 3000 kg/m^3 at surface

ρ ~ 3100 kg/m^3 at < 5 km

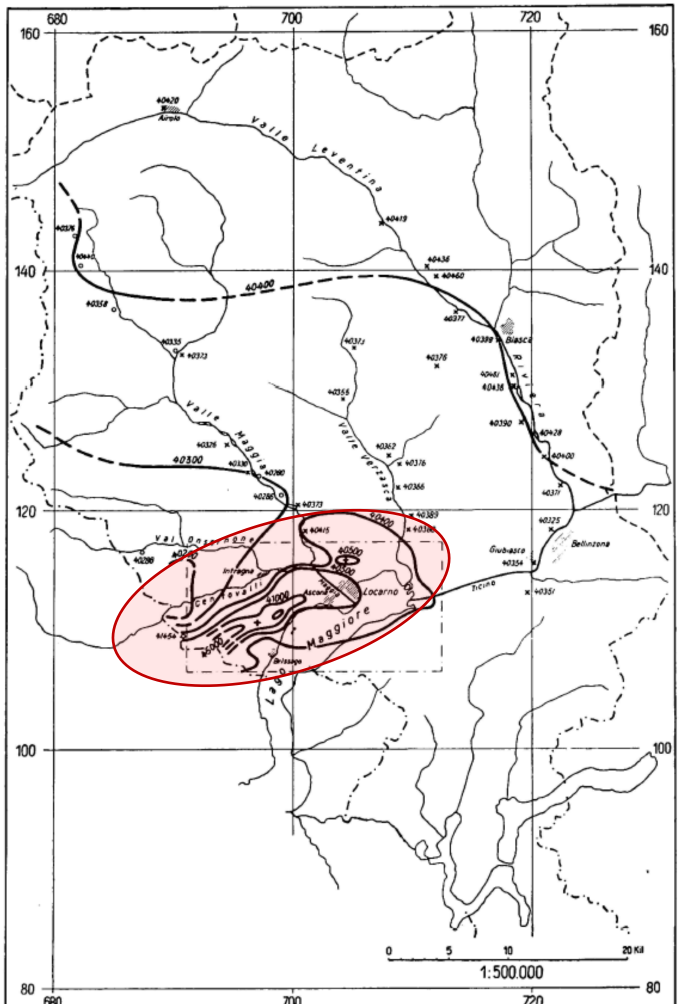
ρ ~ 3300 kg/m^3 at ~10 km

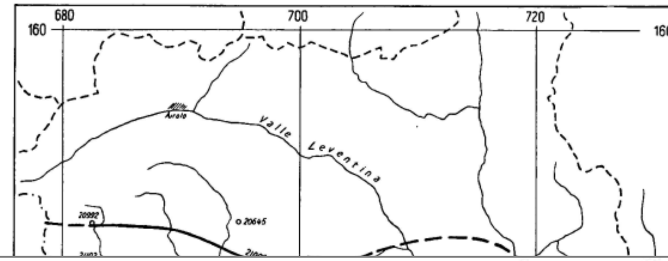
All models assume *constant* density difference!

Magnetics

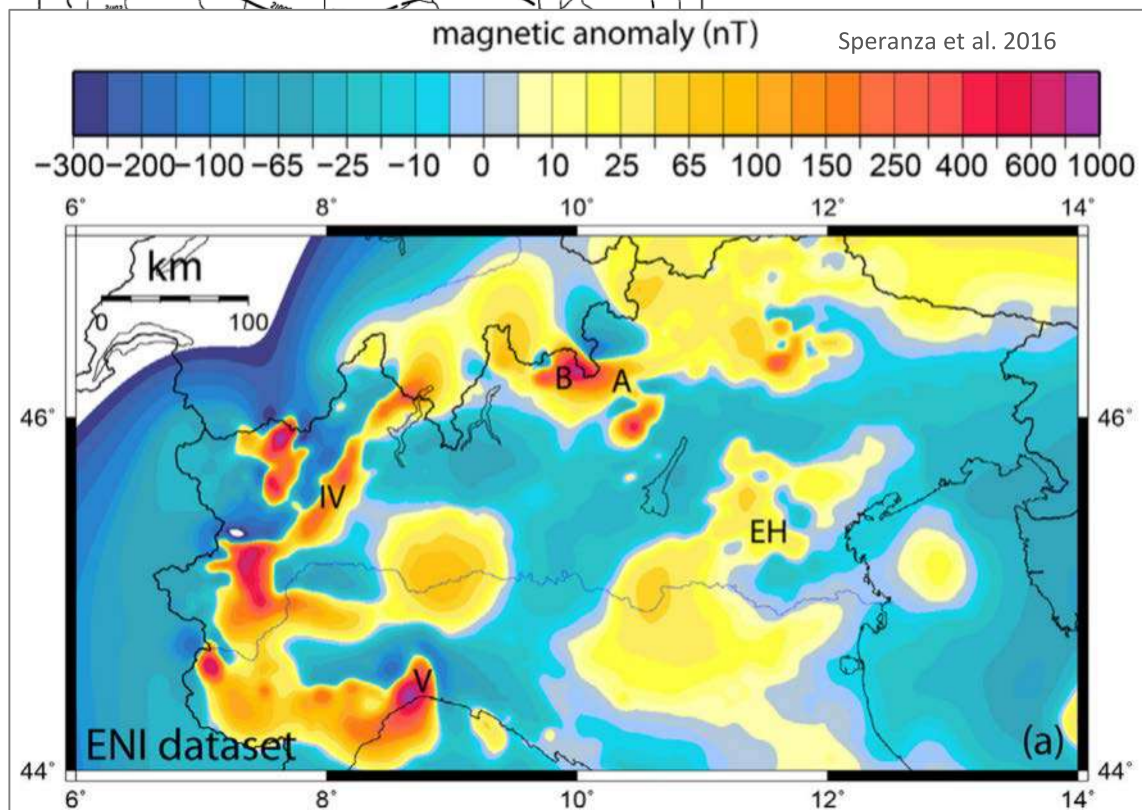
First observation: **V** and **H**

- anomalous body continues under the sediments





Weber 1949



Speranza et al. 2016

Magnetics

Several 2D models Froidevaux & Guillaume 1979, Albert 1979, Lanza 1982, Belluso et al. 1990, Mouge & Galdeano 1991

First 3D model Wagner et al. 1984

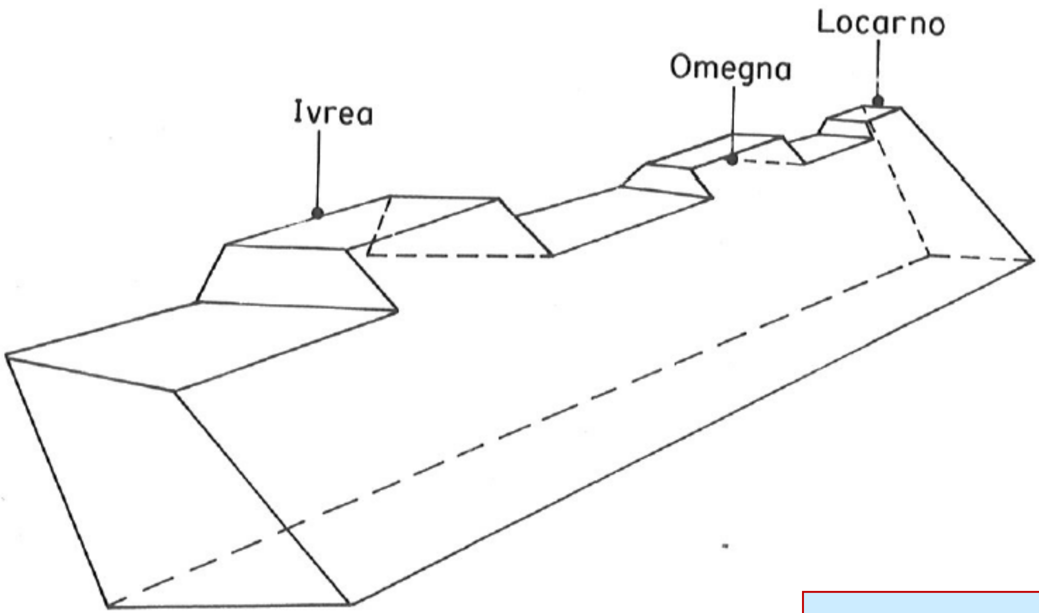
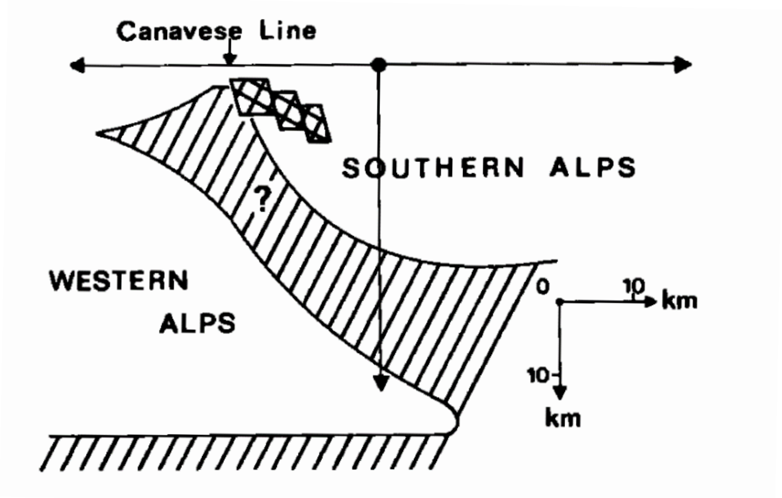


Figure 9: Sketch of the magnetic Ivrea body.

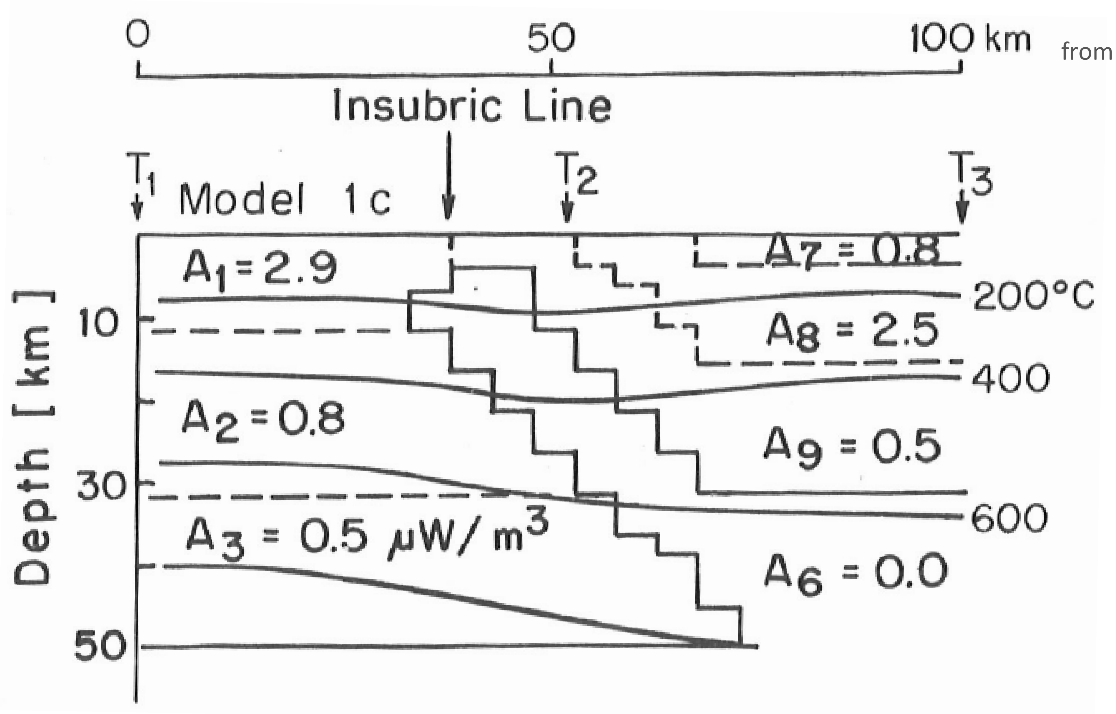


Magnetics – summary:

- IVZ top: 11 km with highs at 2.5-3 km
- in the S (Cuneo) 7-8 to 15 km
- does not (always) coincide with gravity
- no clear trend of magnetic susceptibility with rock type

Geothermics

- eighteen 2-metre probes in IVZ to obtain heat flow Haenel 1974
- rock heat production data Höhndorf 1975
- stationary thermal model Höhndorf et al. 1975



from Wagner 1984

- from Curie temperature depth estimates: steady-state thermal model is questioned

Speranza et al. 2016

Seismology

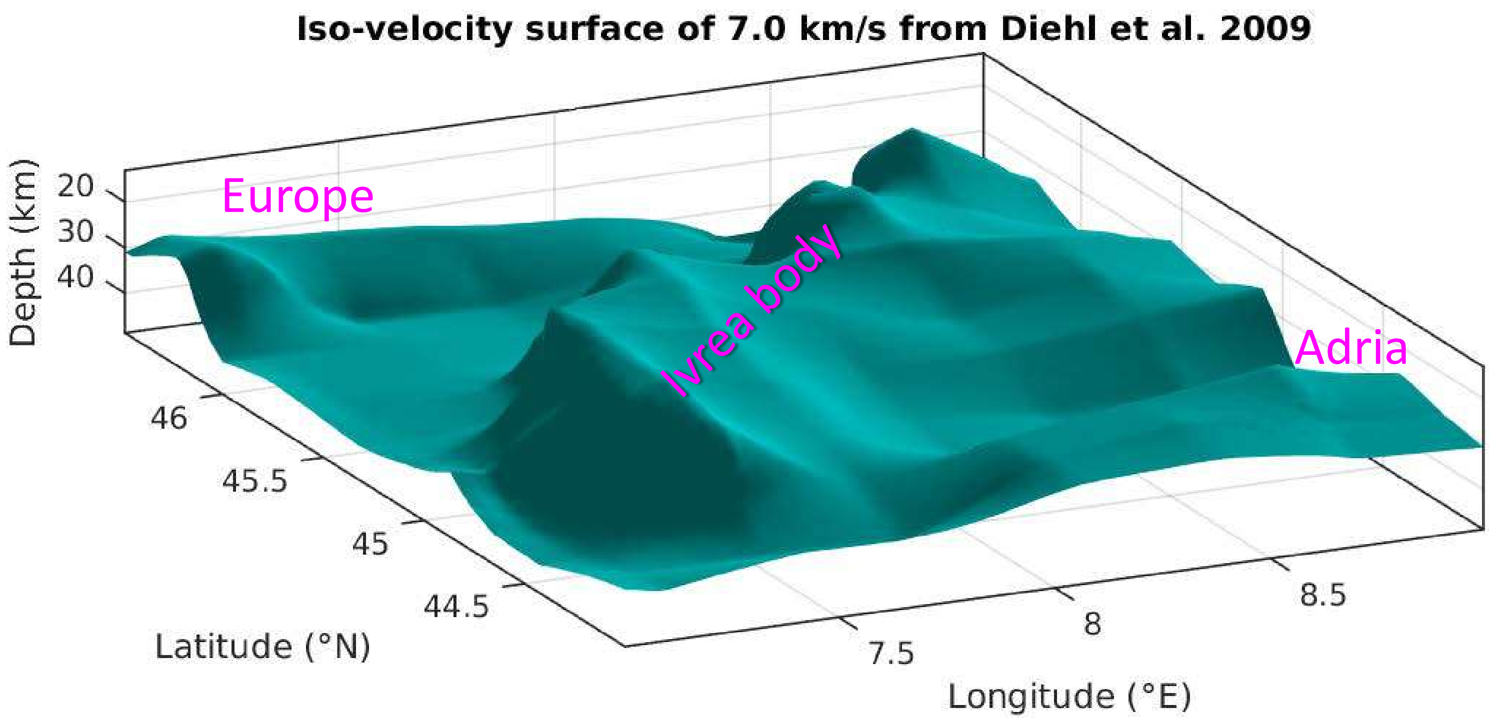
Active seismics:

- difficult to get signal (energy scatters), WA fan refr.+inline refl. is best so far
- VP = 7.2-7.83 km/s reached at 3-14 km

Ansorge 1968, Berckhemer 1968, Giese 1968, Giese et al. 1973, Kissling 1984, ECORS-CROP DSS Group 1989, Hirn et al. 1989, Eva et al. 2015

Local Earthquake Tomography:

Diehl et al. 2009 VP = 7.0 km/s at 13 km, VP = 7.5 km/s at 27 km



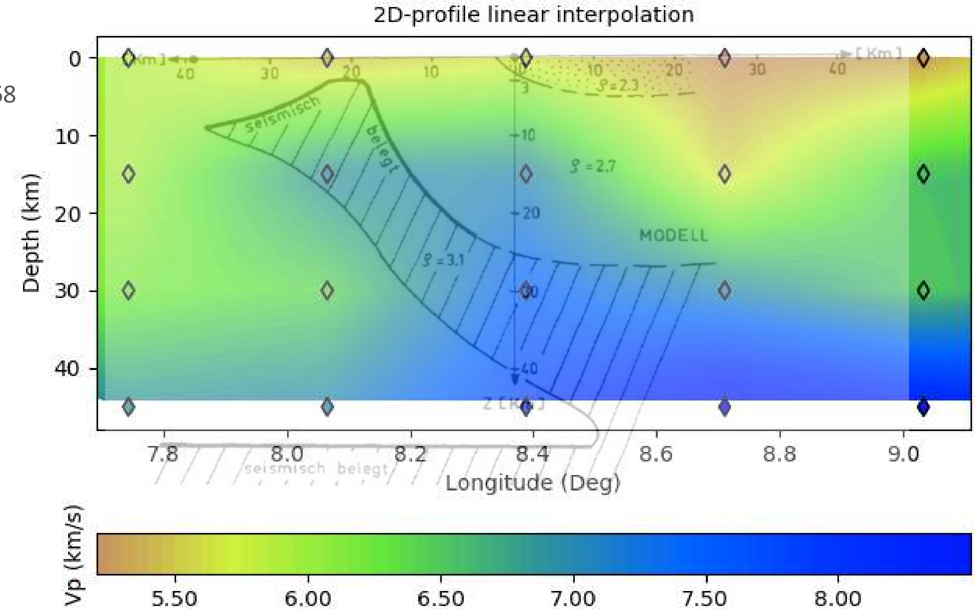
Seismology

Local Earthquake Tomography:

- Potin 2016 PhD thesis VP = 7.0 km/s at 13 km, VP = 7.5 km/s at 18 km
- depth to "high velocity" in earlier works:
  - IVZ: 5+ km De Franco et al. 1997
  - South: 7-10 km Solarino et al. 1997, Paul et al. 2001, Béthoux et al. 2007
- passive and active seismics comparison: gap in scales

Berckhemer 1968

Diehl et al. 2009



Summary of past surveys

Method	Z to anomaly (km)	Anomaly
Gravity	0 <5 ~10	3000 kg/m^3 3100 kg/m^3 3300 kg/m^3
Magnetics	IVZ highs 2.5-3 IVZ elsewhere 11 (South 7-8-15)	no clear trend with lithology
Active seismics	3-14	7.2-7.83 km/s
Passive seismology	13 local highs: 5-7-10	7.0 km/s “high velocity”
Geothermics	5	(model)

All passive geophysical data/models point to top-of-anomaly at

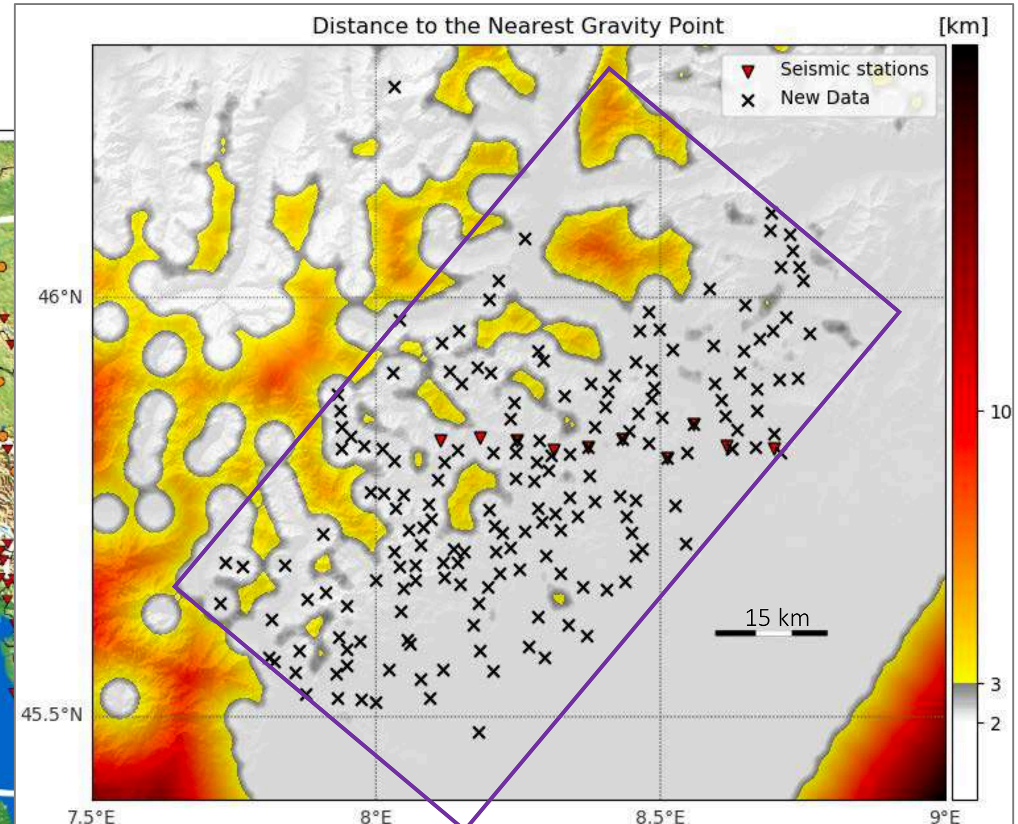
3-10 km,

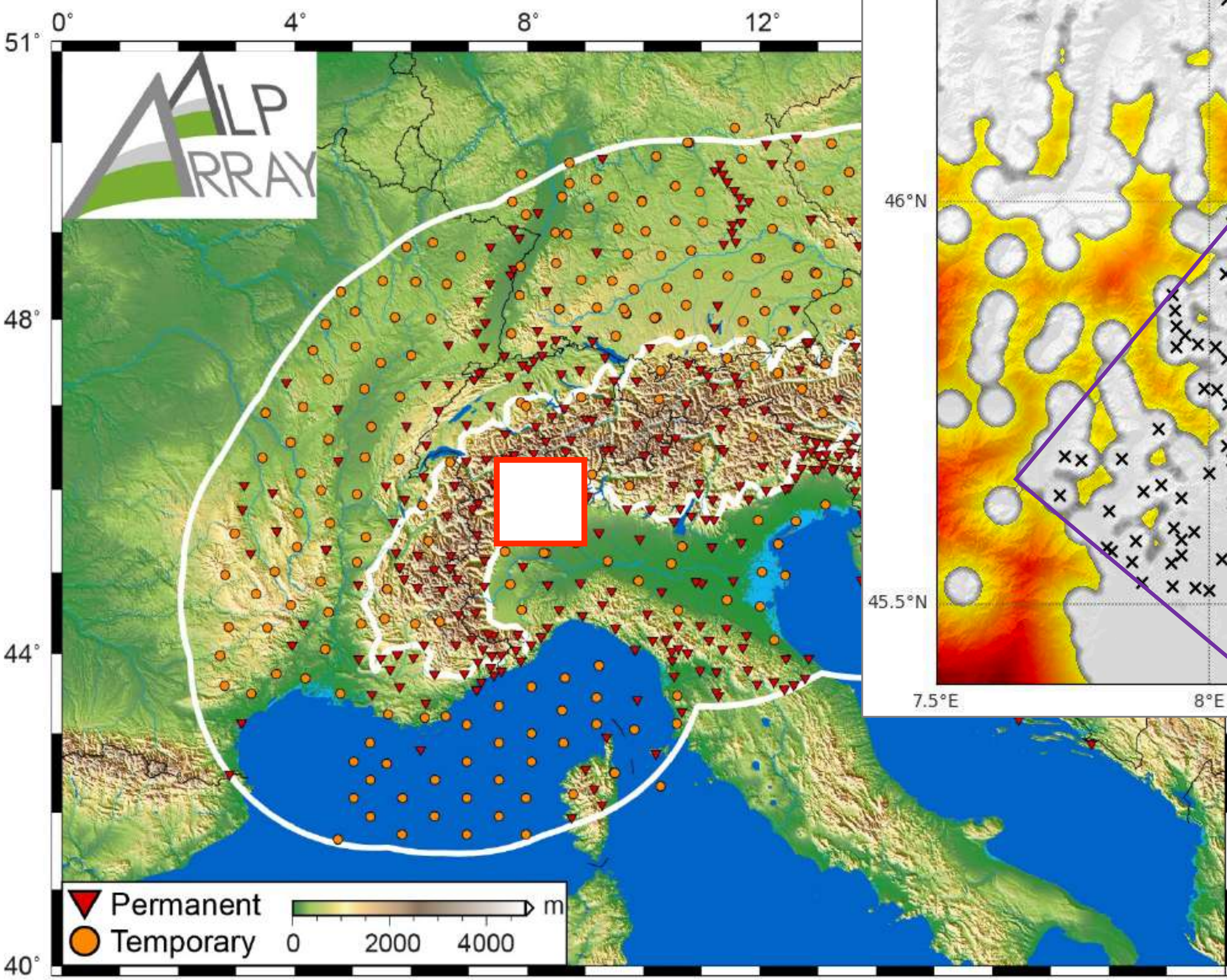
depending on location and model assumptions.

Recent campaigns

- AlpArray → too broad scale
- IvreaArray: 10 stations @5-km spacing, 207 new gravity points

Scarponi et al. in prep.





Hetényi et al. 2018 Surv Geoph

www.alparray.ethz.ch

~~Conclusions~~

A few pending questions…

- Is there a pattern in lower crustal earthquakes?
- How thick is the Moho transition in active orogens?

- What is below the Bird’s Head?
- Which rocks constitute the IGB?

DIVE
DRILLING THE IVREA-VERBANO ZONE

- How could geologists and geophysicist cooperate (even) better?
- How could we better bridge across temporal and spatial scales?