Lithospheric-scale Three-dimensional Modelling

(Application to the EARS and Plateau)

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Aims

- Homogenise existing gravity surveys;
- Compile constraining data and information;
- Investigate isostasy and isostatic state;
- Investigate the effect of dynamic topography;
- Carry out 3-D density modelling;
- Study the rigidity of the lithosphere.

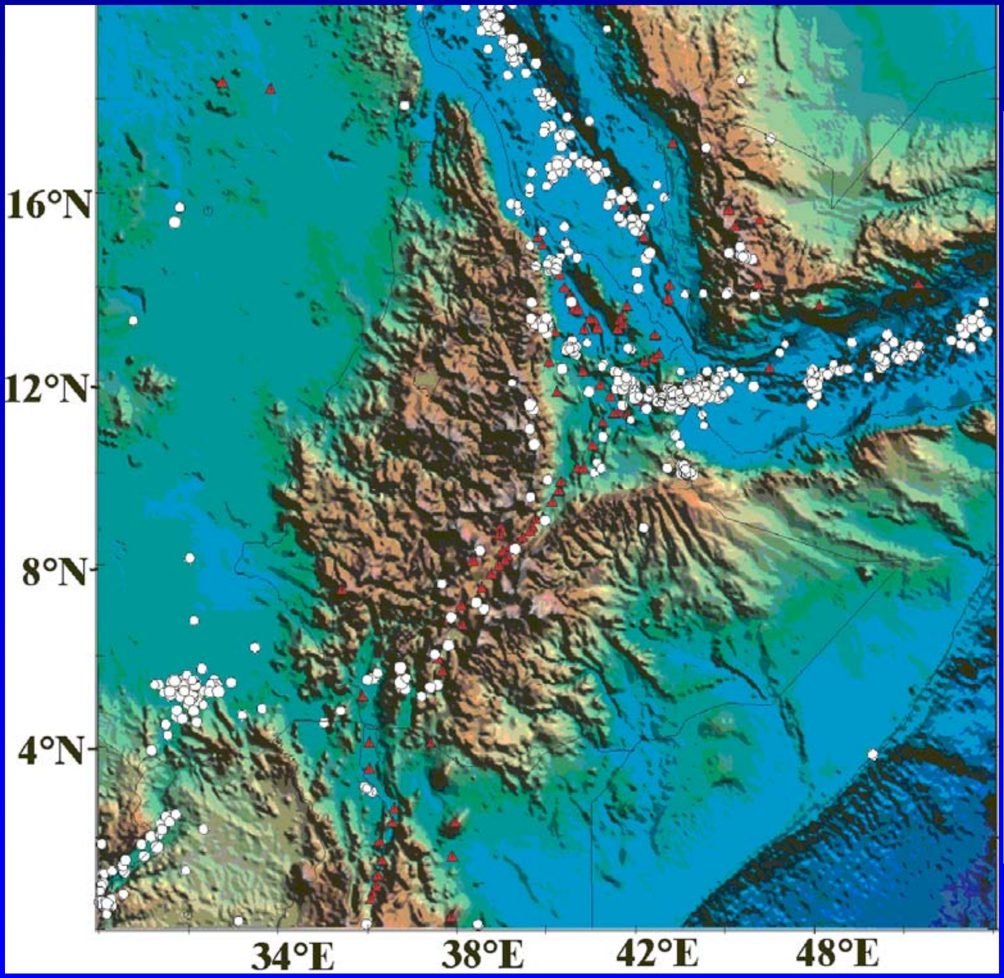
Regional setting

Contents

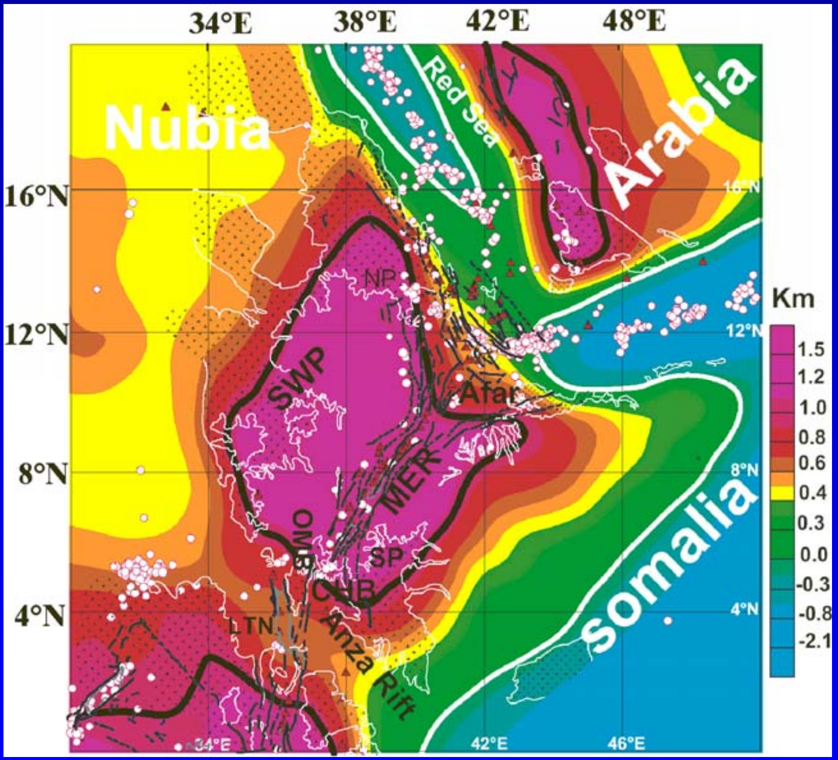
Topography, tectonics, geology

- Database
- Methodology
- Isostasy
- Examples from the 3D modelling
- Key results of the 3D modelling
- Summary

Topography and tectonic setting



Merged topography and bathymetry, data source: GTOPO30, Smith and Sandwell (1997)

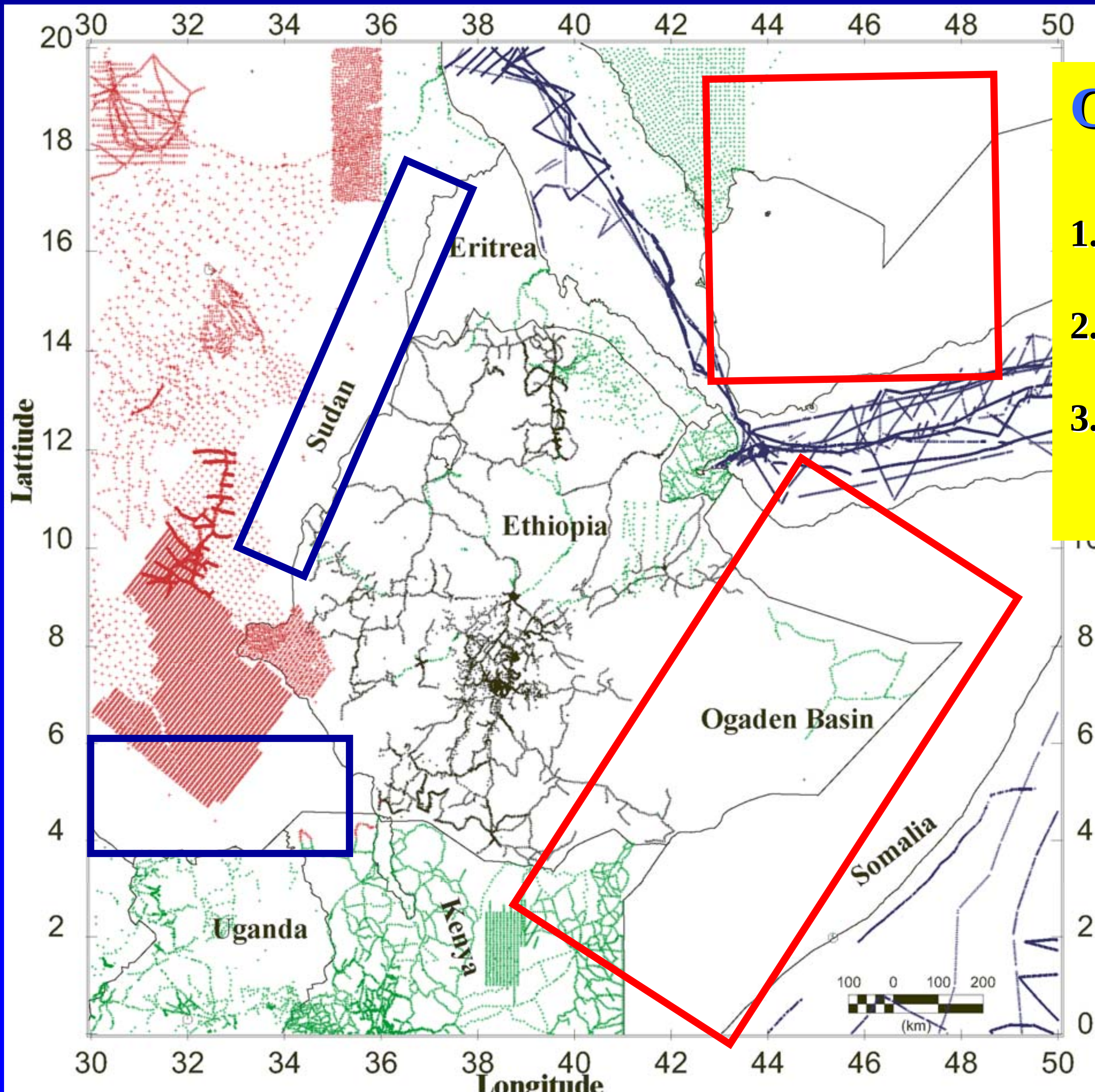


● = Earthquakes

▲ = Volcanoes

Database

Gravity database



Gravity stations:
(~ 45000)

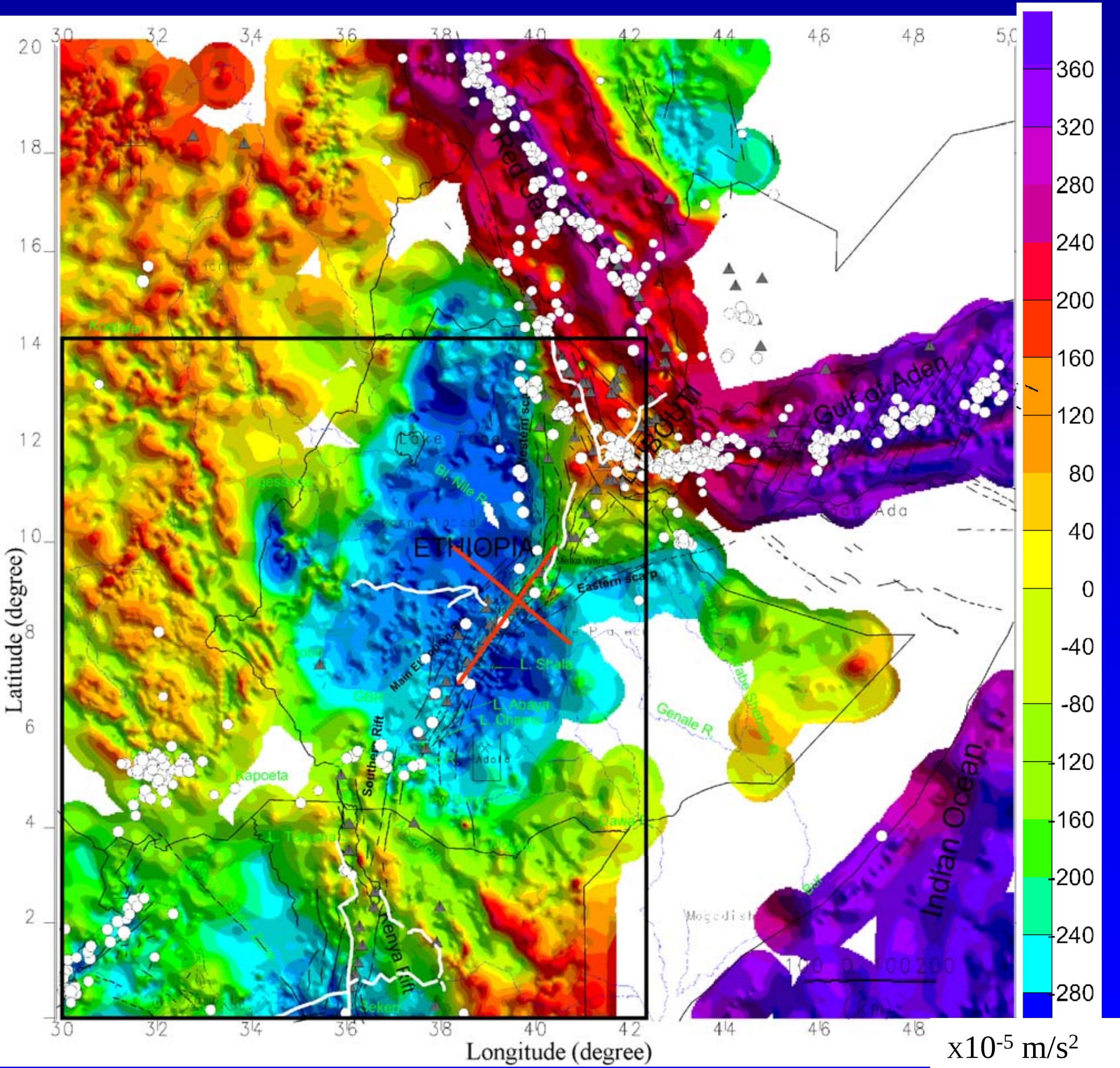
1. **Geological Survey of Ethiopia (GSE) (black)**
2. **Bureau Gravimetrique Internat. (BGI) (Land: green, Sea: blue)**
3. **GETECH and Sudan Geological Authority (red)**

Important data gaps

Blue box	unsurveyed
Red box	confidential/or not accessible

Estimated Error:
$1.5\text{-}4.5 \times 10^{-5}\ m/s^2$

Bouguer anomaly map



Positive Bouguer anomalies:

along fracture systems of Gulf of Aden, Indian Ocean and Red Sea axial zone.

Relative positive anomalies:

Afar, Anza cross rift, Eastern Sudan.

Negative anomalies

MER, KR, Western Rift, Plateaus of Ethiopia, Kenya and Saudi Arabia.

Seismic experiments

Berckhemer et al. 1970 (Ethiopia) and KRISP in Kenya

EAGLE (2001-2004)

3-D modelling area

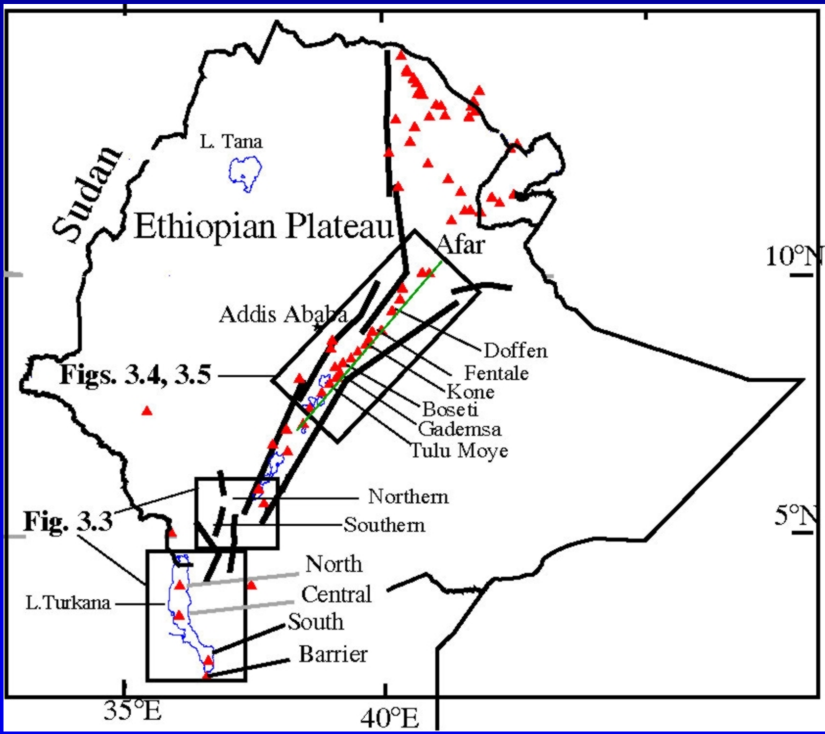
Geometry and density information

- Topography and geography
- Geology, tectonics
- Crustal densities

  Density measurements in Ethiopia (~ 800)

  Density information from eastern Sudan

  Density from chemical composition data



- Constraints from seismic

  Afar experiment (1970); KRISP (1990) & EAGLE (2001-2004)

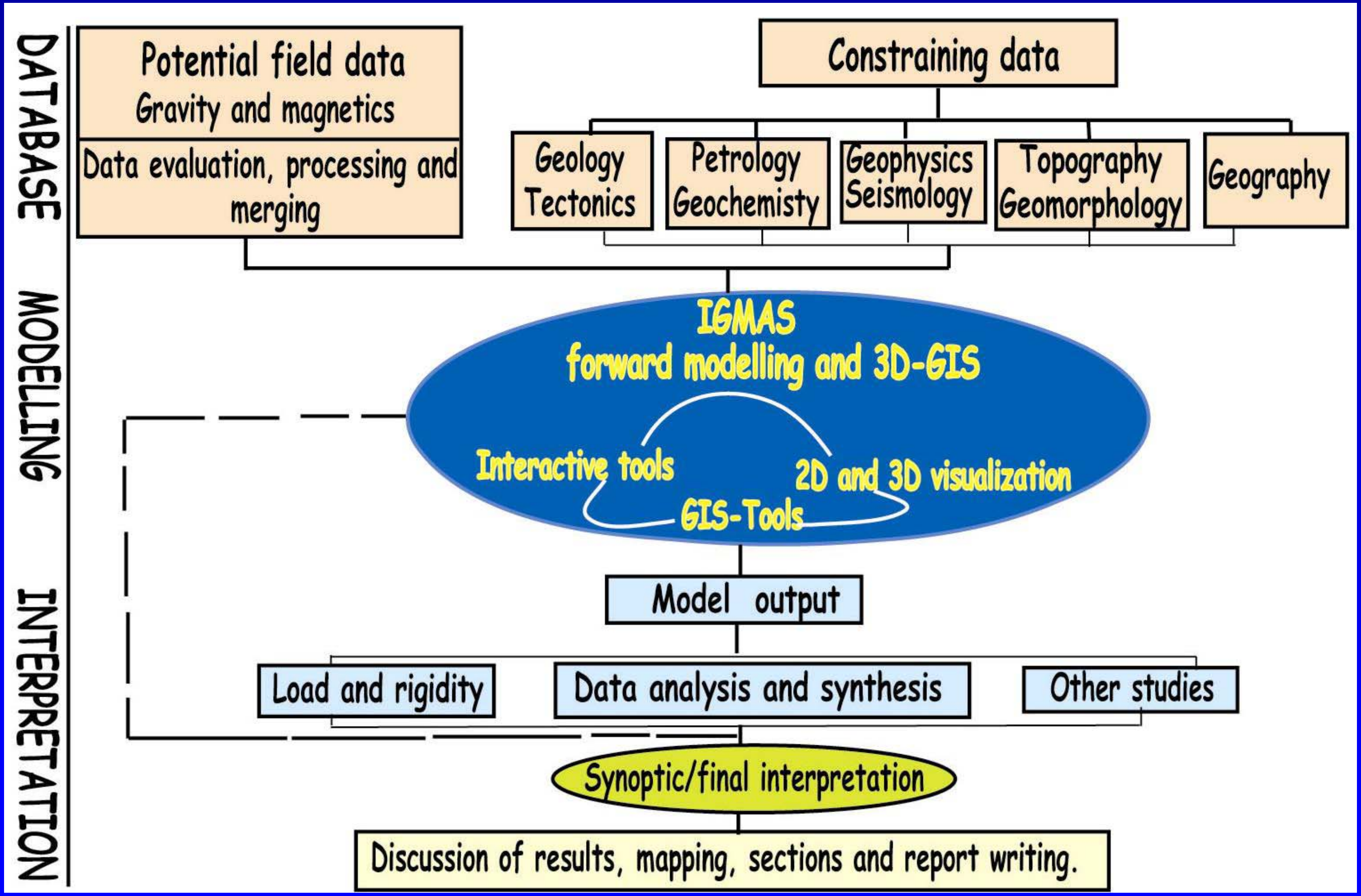
  Axial thinning: Turkana (KRISP, 1900);
  NMER (Keller et al. 2004 and EAGLE).

  Low velocity: (7.4-7.8 km/s) in Afar (Berckhemer, 1975).

  Velocity-density conversions: Sobolev & Babeyko (1994)

Methodology

3-D density modelling: process



Isostasy

Why is it necessary to investigate isostasy ?

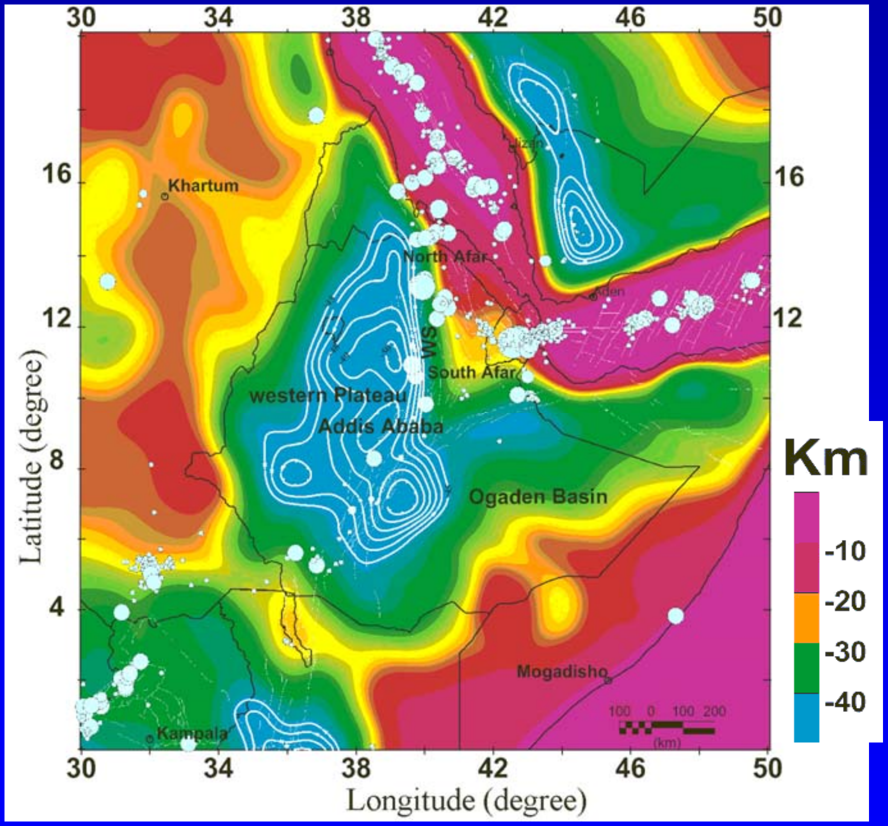
For more constraints (e.g. isostatic Moho)
For geological correlation

- **Isostatic models**
- **Interpretation**
- **Study the effect of dynamic topography**

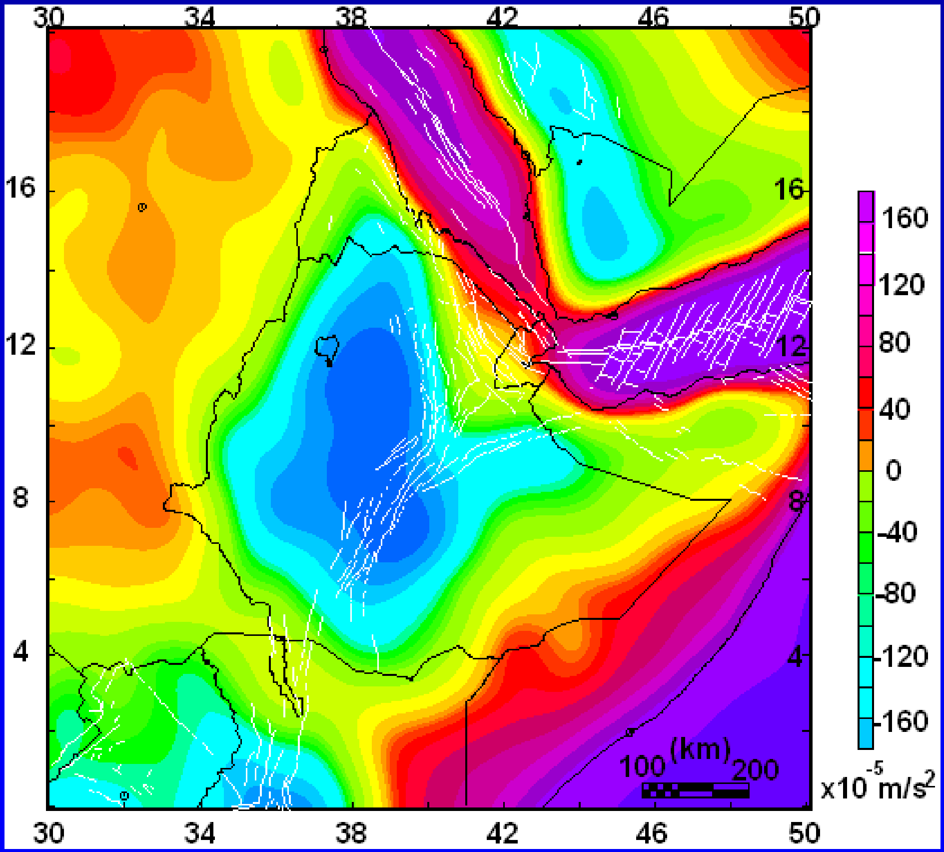
Isostatic models

Vening-Meinesz (VM) modelled Moho

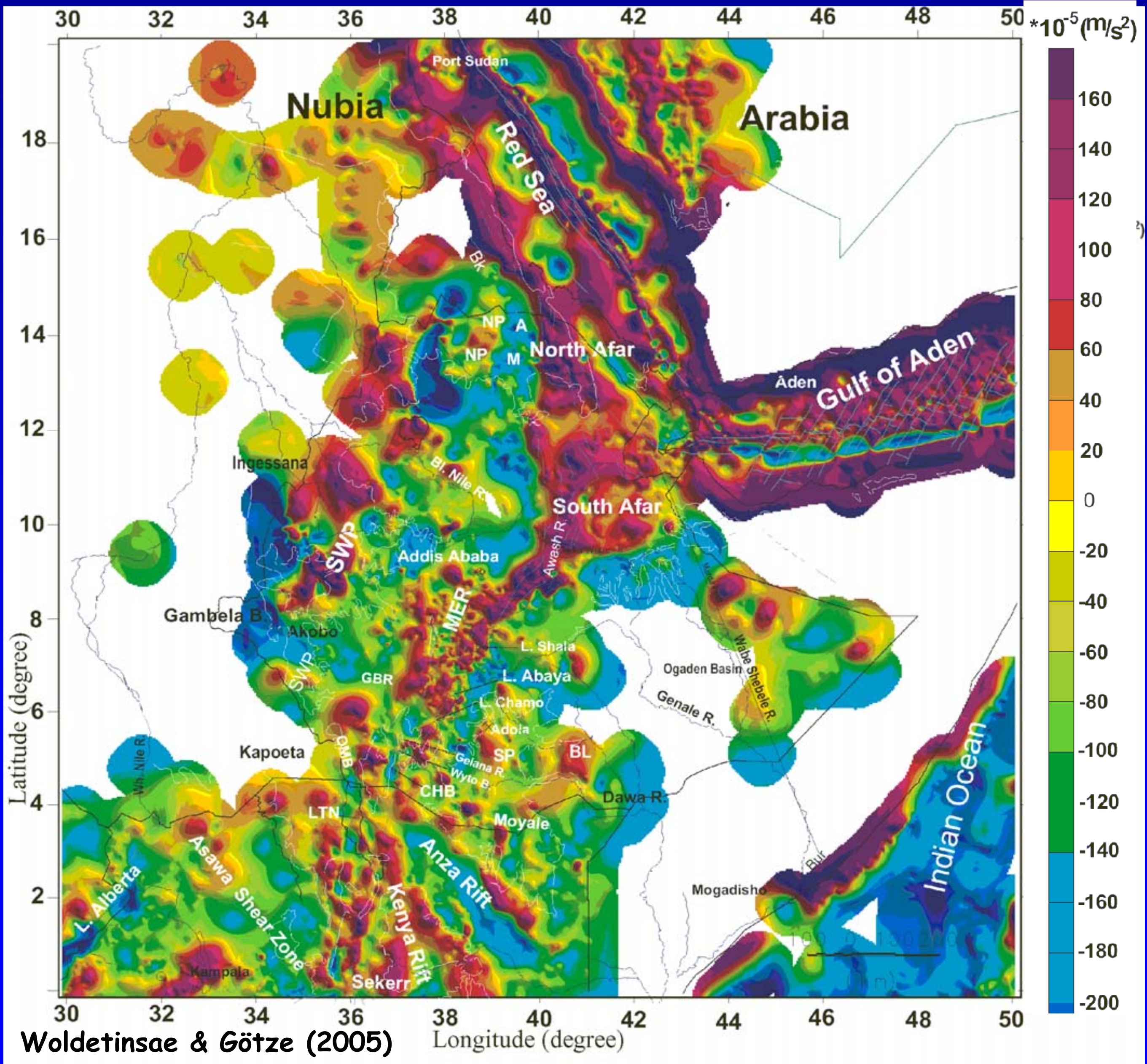
(D= 10^{22} Nm, Te= 10 km),



Isostatic regional gravity



Isostatic residual field

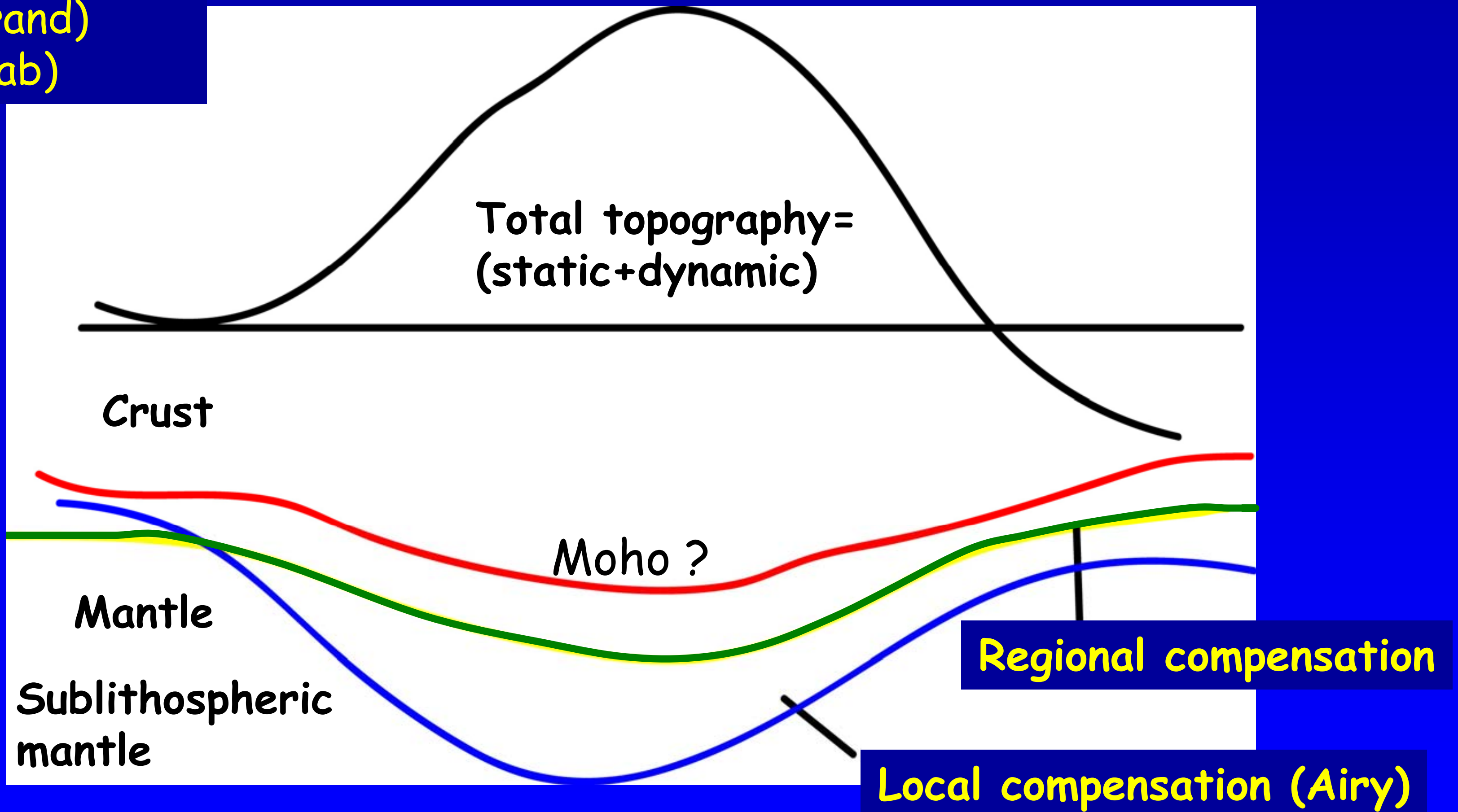


Woldetinsae & Götze (2005)

Dynamic topography

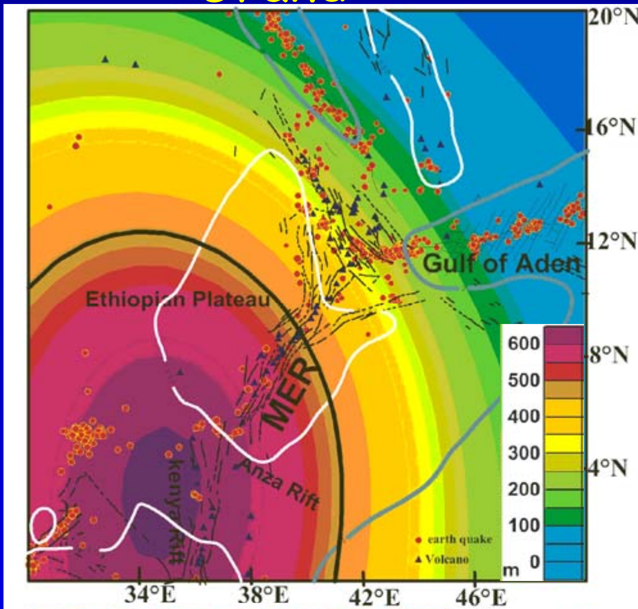
Dynamic topography is generated
by flow within the mantle

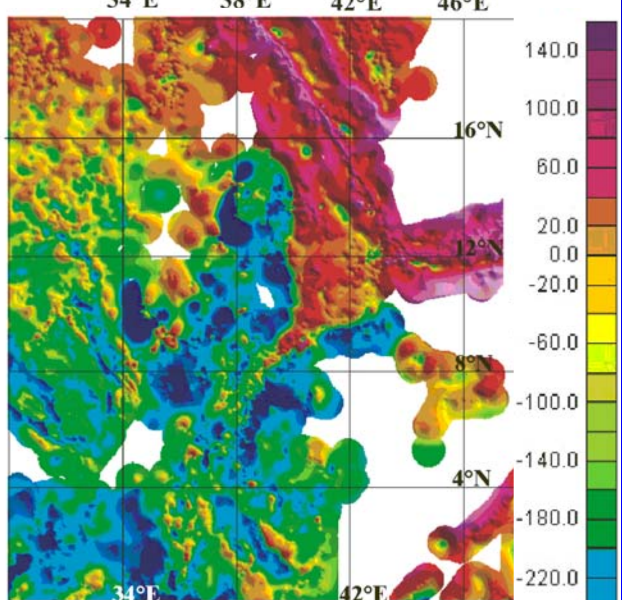
Dynamic topography
~600m (Grand)
~400m (Slab)



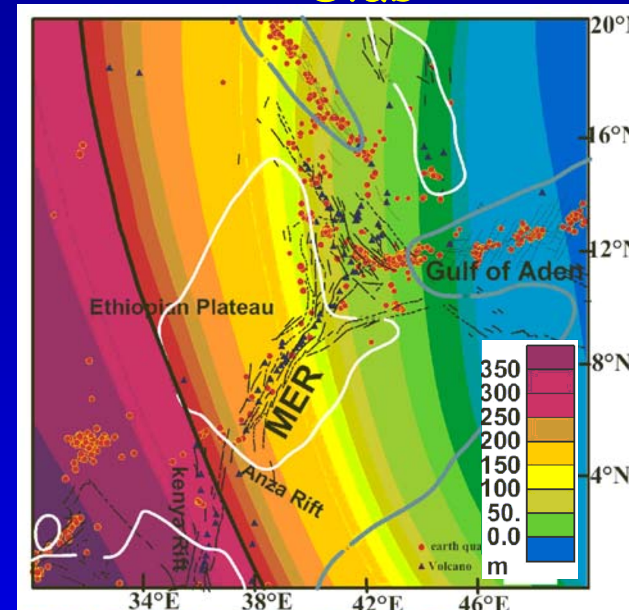
Dynamic topography & isostatic residual field

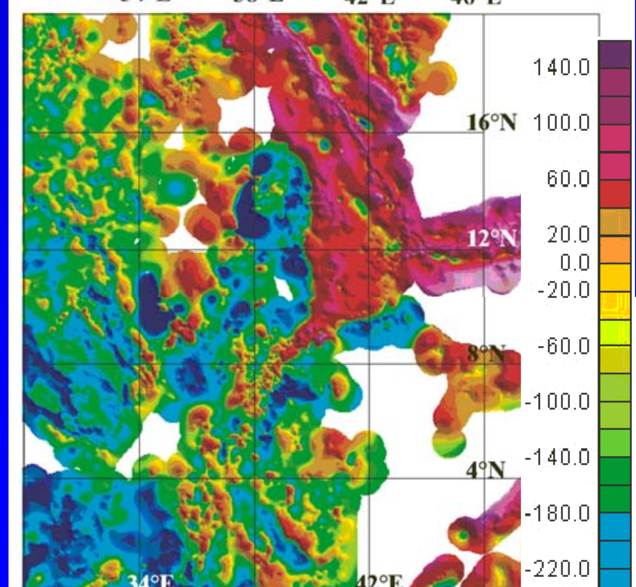
Grand





Slab





Dynamic topographic models

Data source:
Lithgow-Bertelloni, pers. comm.

Residual fields
($\times 10^{-5}$ m/s^2)

Modelling

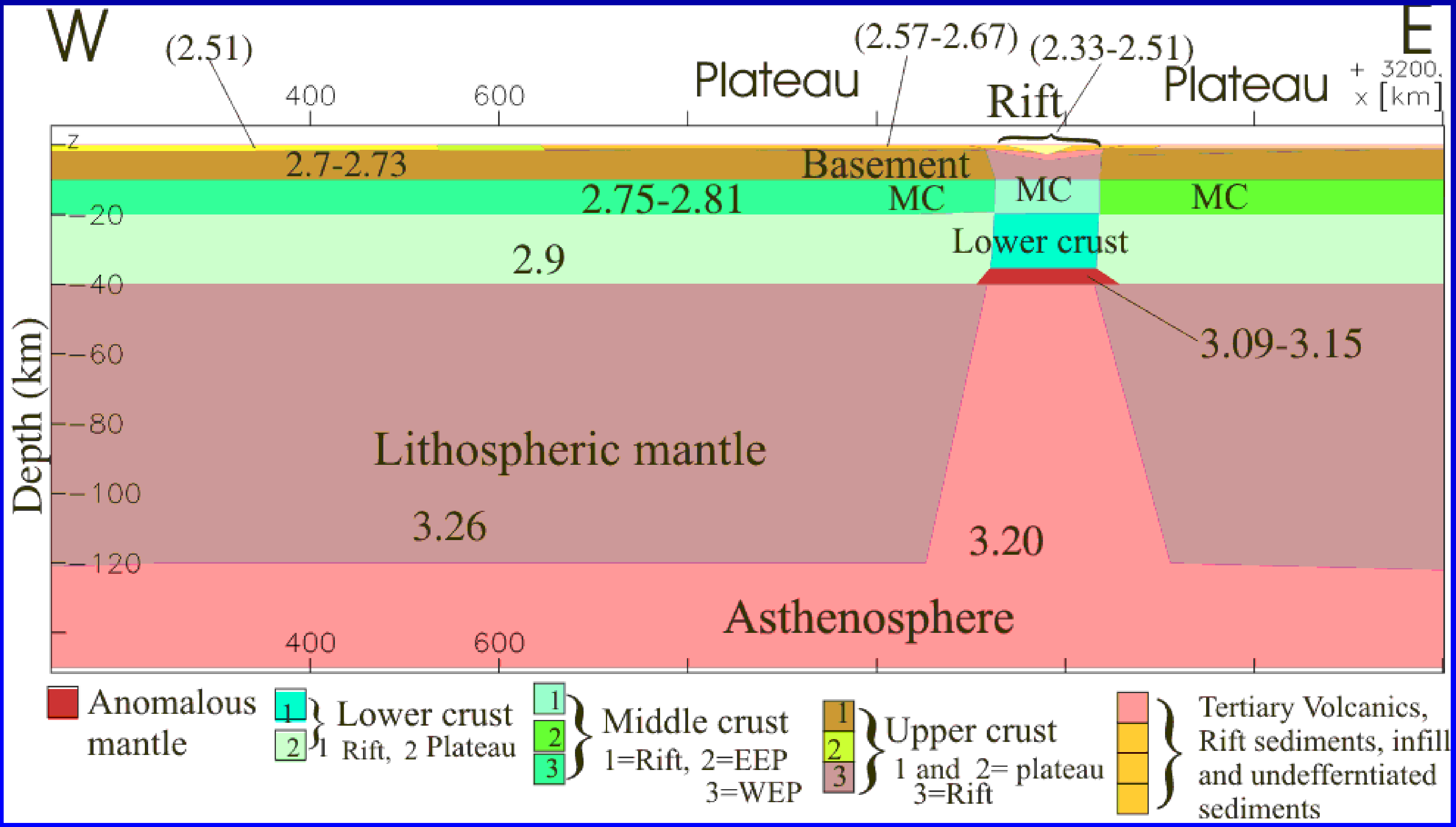
IGMAS features

- Geometry input
- Automatically triangulated geometry
- Graphical integration of constraining data
- Interactive modification
- ASCII output, postscript

Calculation of:

- Gravity, gravity gradients, potential, geoid undulation, remanent & induced magnetic field.

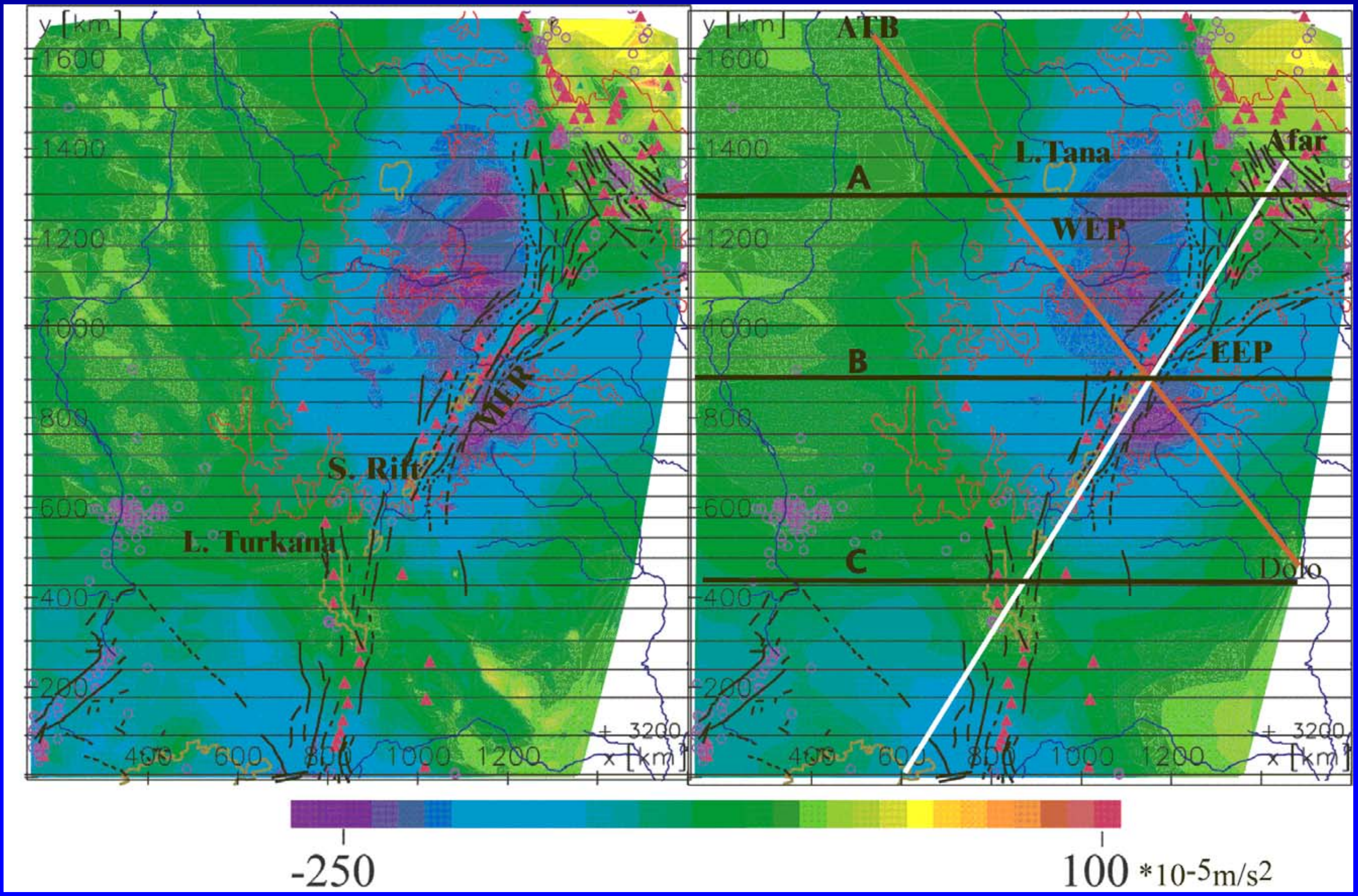
General structure of the model



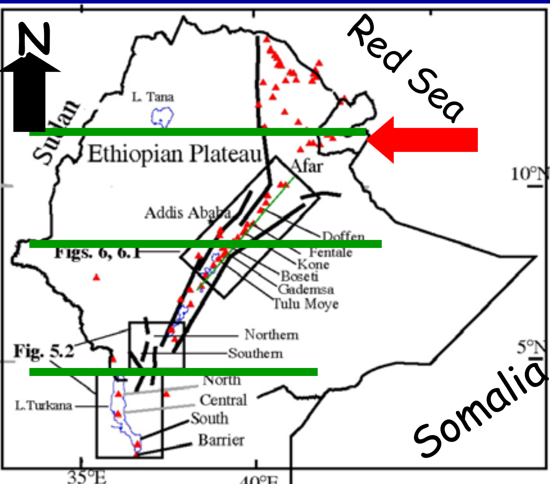
Densities: Mg/m^3

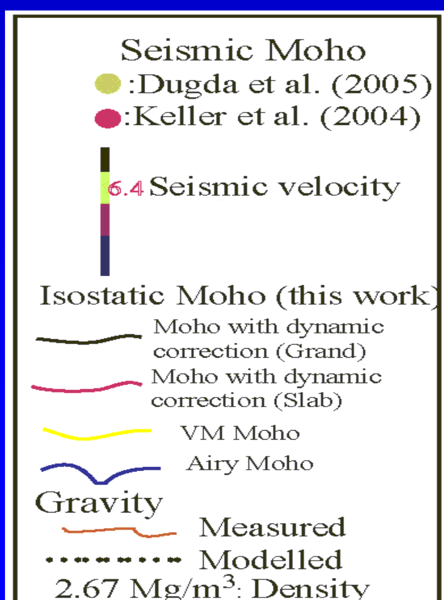
Modelling results and interpretation

Measured gravity | Modelled gravity

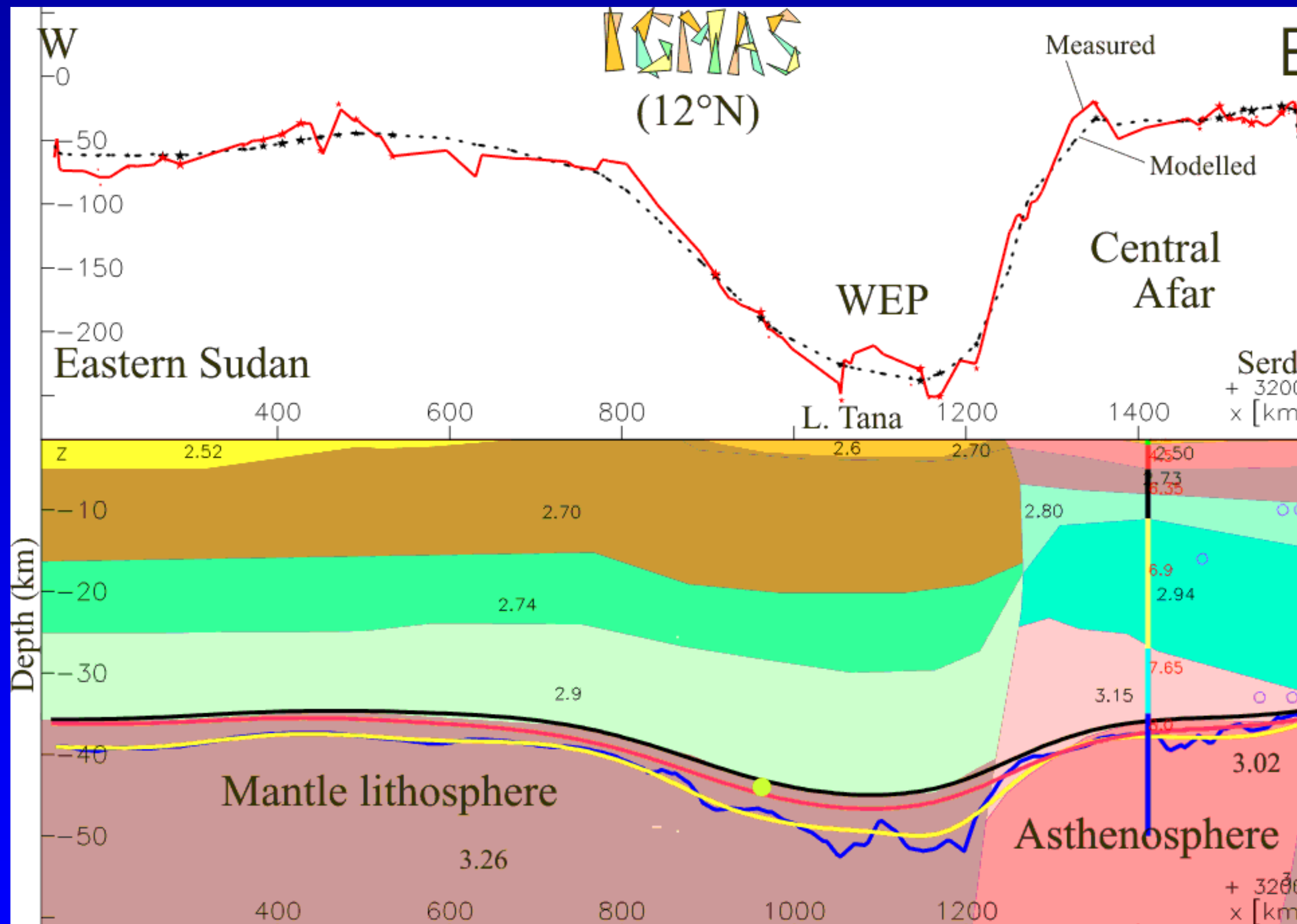


Crustal models



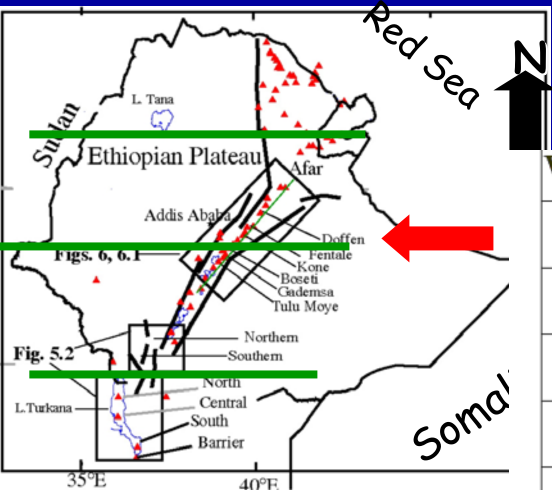


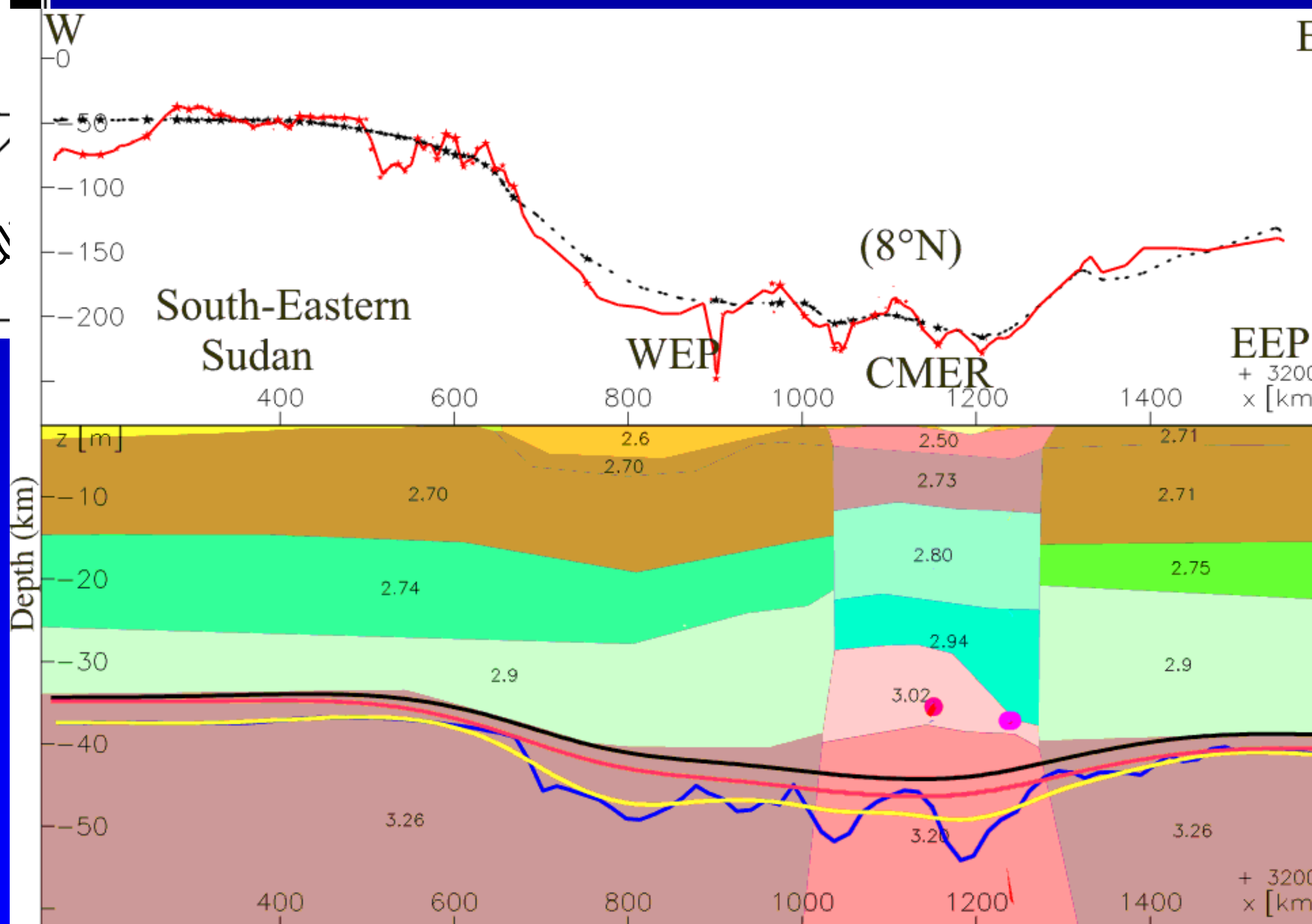
(A)

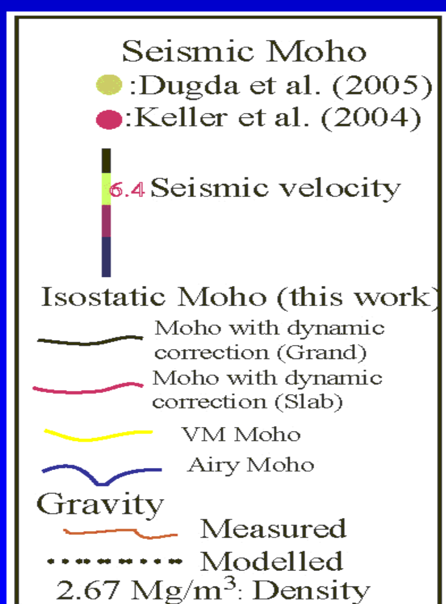


Crustal models

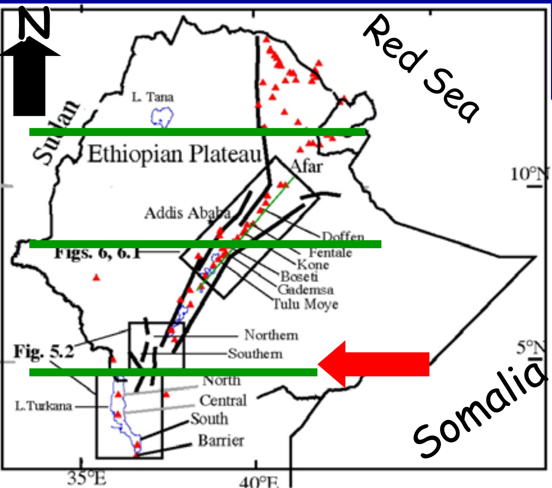
(B)

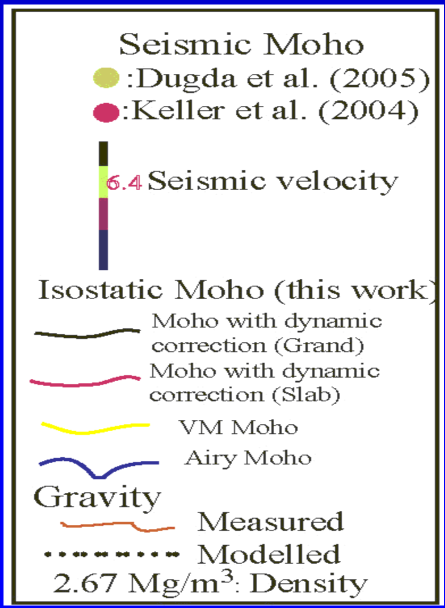




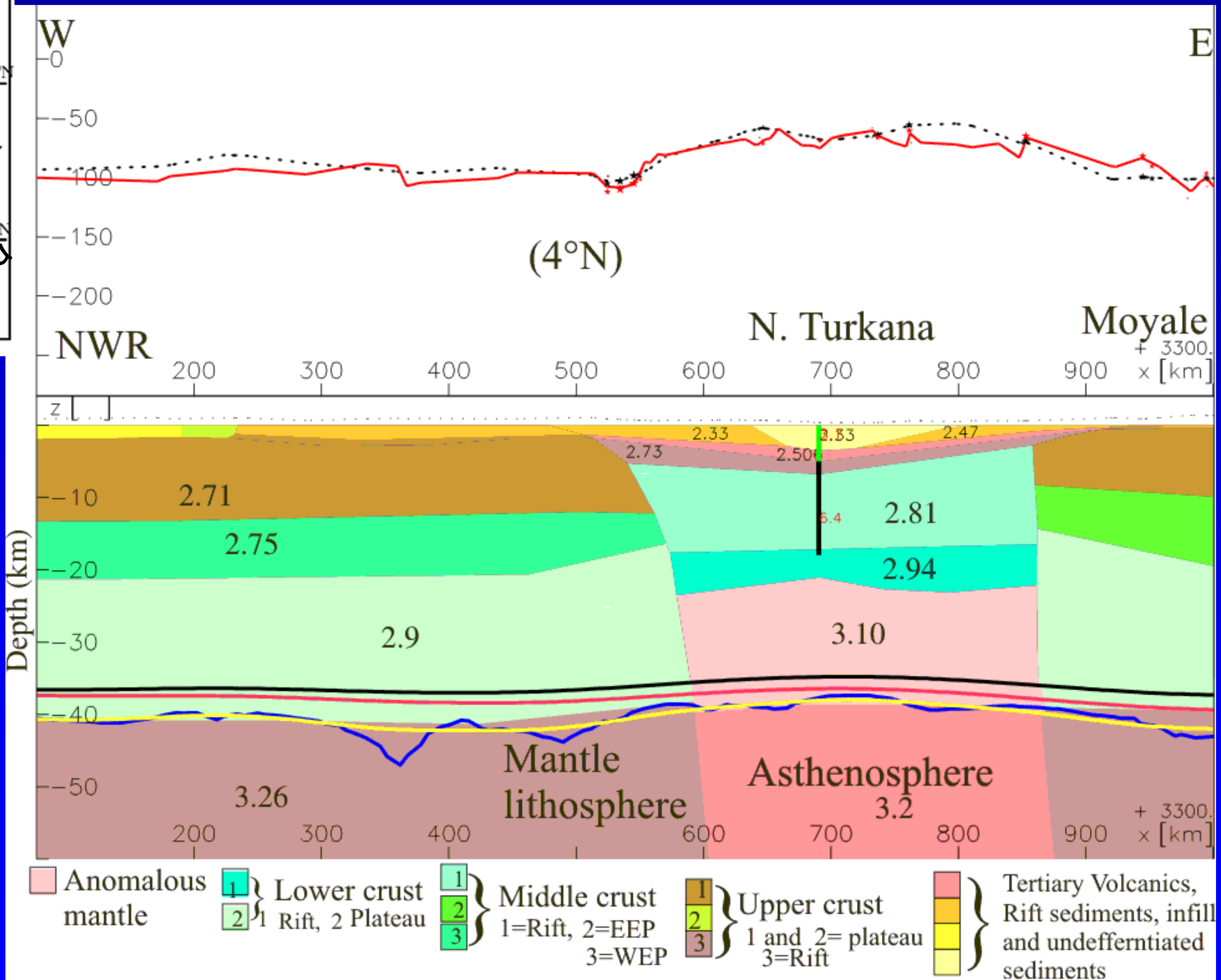


Crustal models

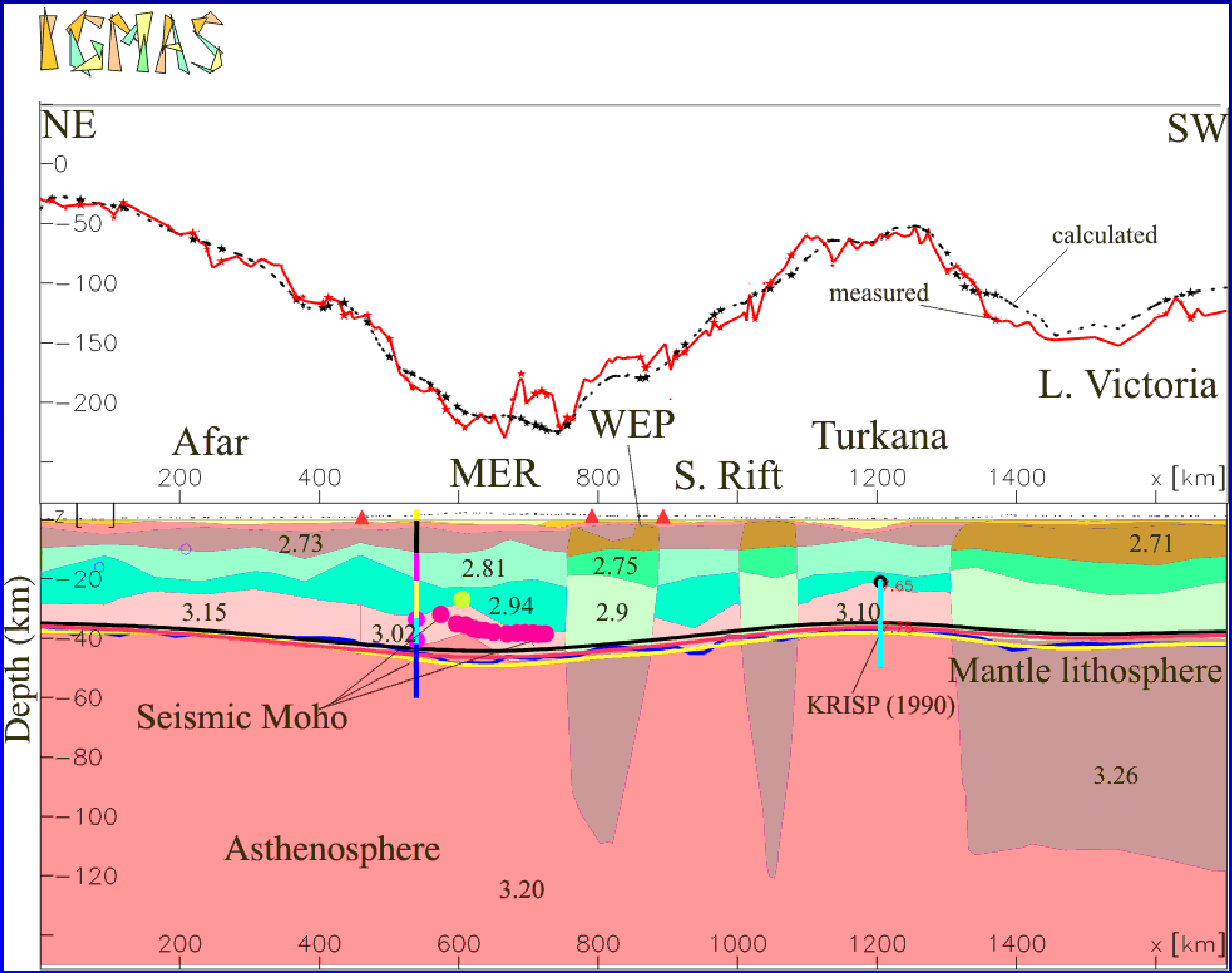




(C)

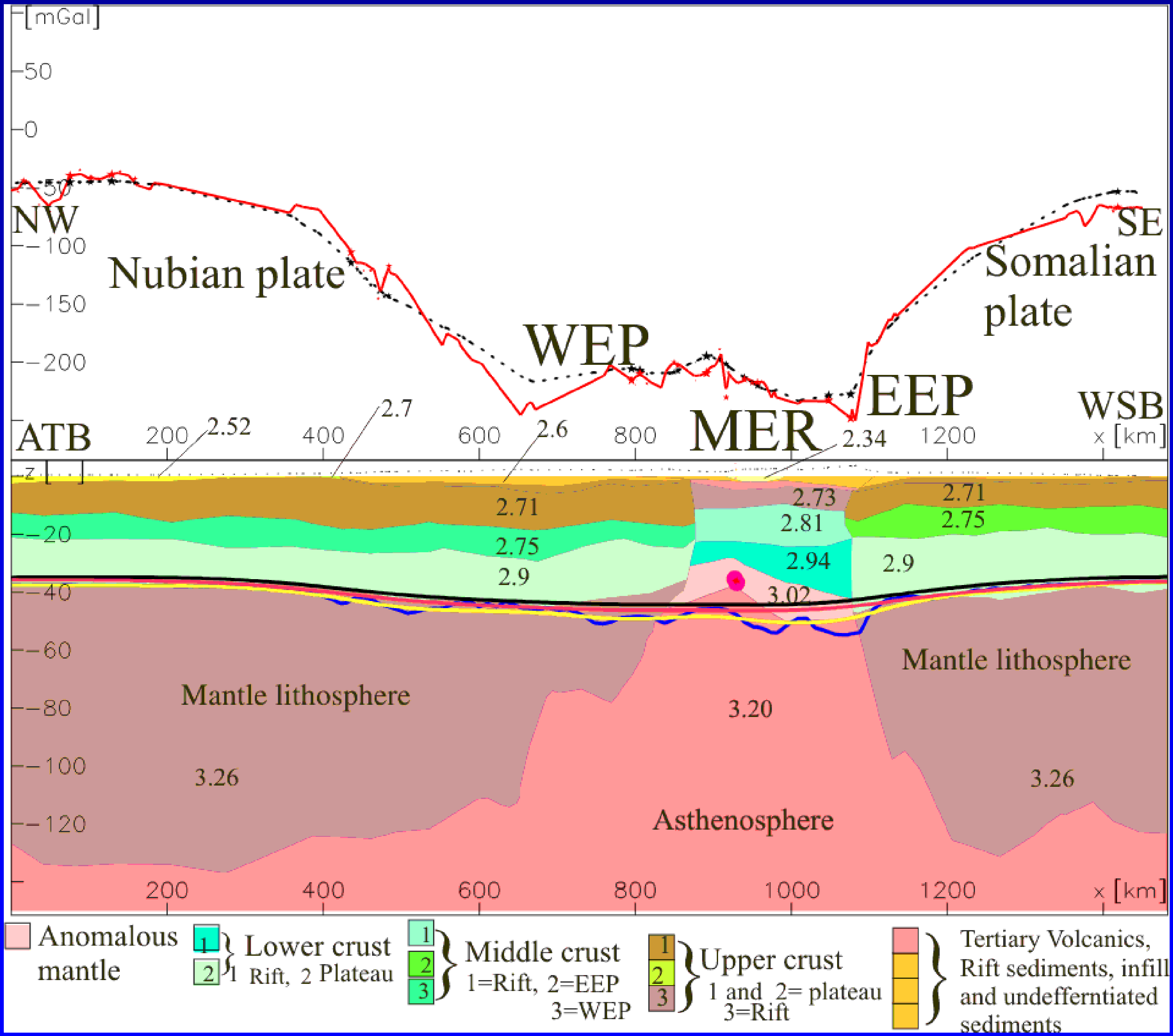


Rift axial

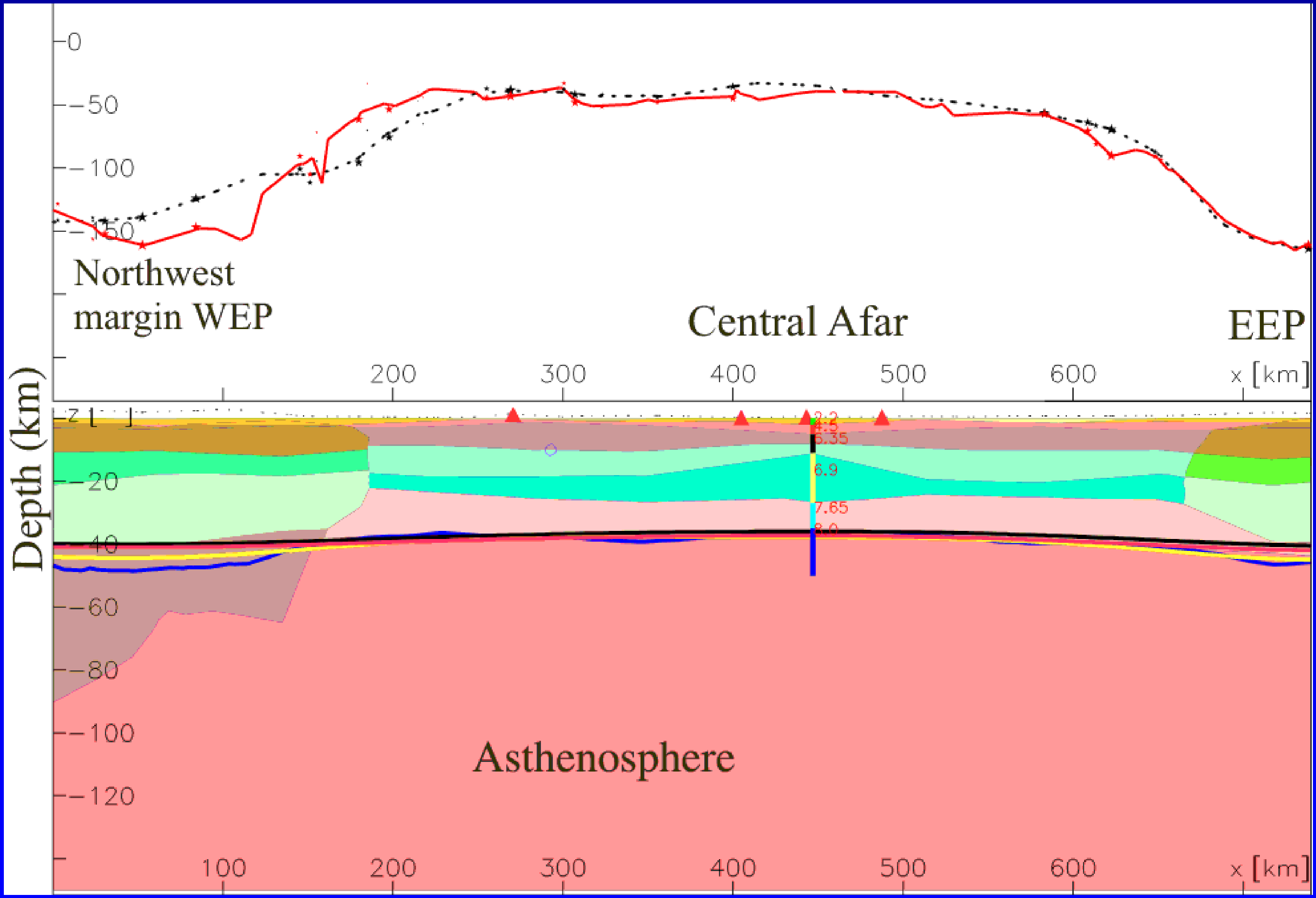


IGMAS
NE
SW
0
-50
-100
-150
-200
calculated
measured
L. Victoria
Afar
WEP
Turkana
MER
S. Rift
200
400
800
1200
1400
x [km]
Depth (km)
-20
-40
-60
-80
-100
-120
2.73
2.81
2.75
2.71
3.15
2.94
2.9
3.10
3.02
Seismic Moho
KRISP (1990)
Mantle lithosphere
3.26
Asthenosphere
3.20
200
400
600
800
1000
1200
1400
x [km]

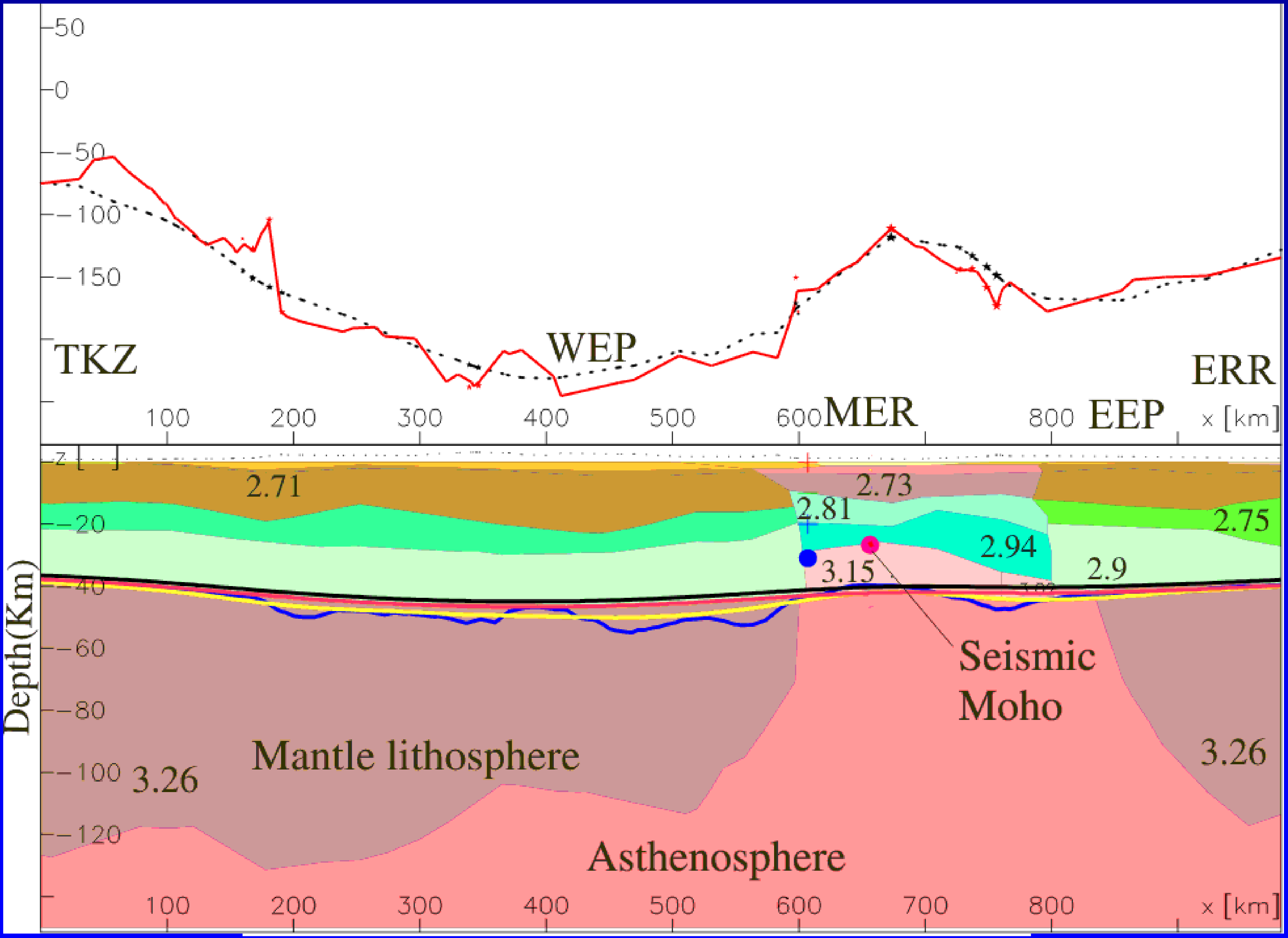
Rift perpendicular



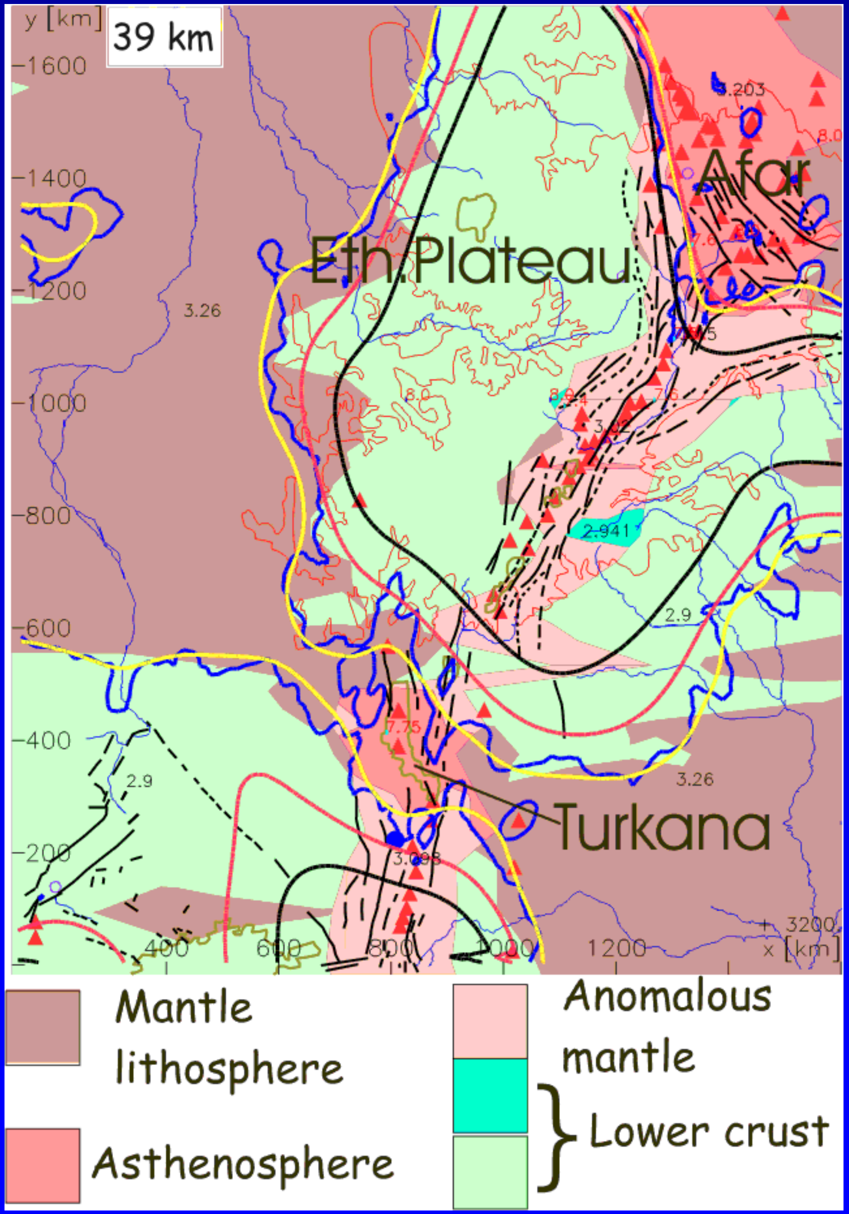
Wide to narrow rift



Wide to narrow rift

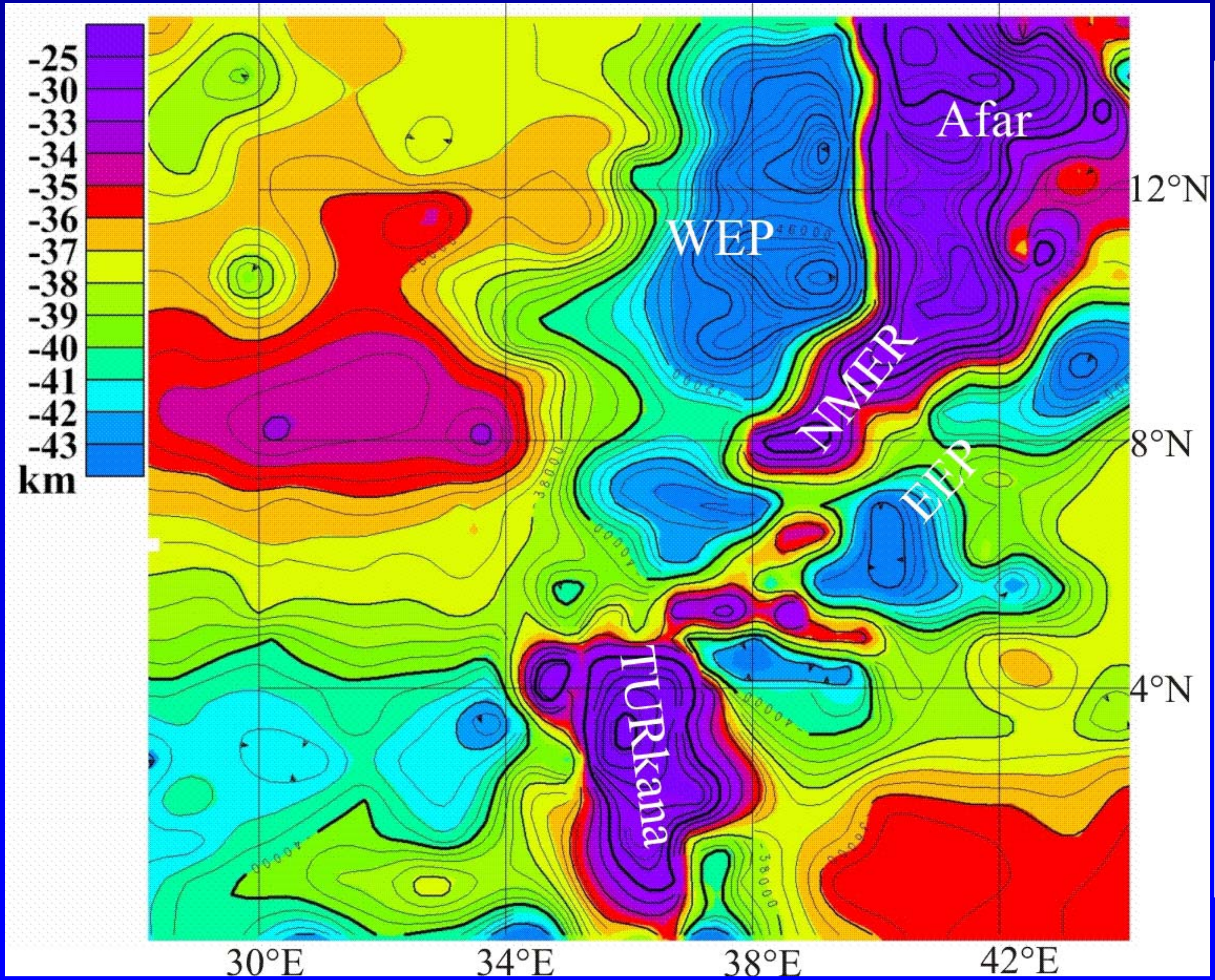


Horizontal cross-sections



Moho and basement

Moho from 3D model



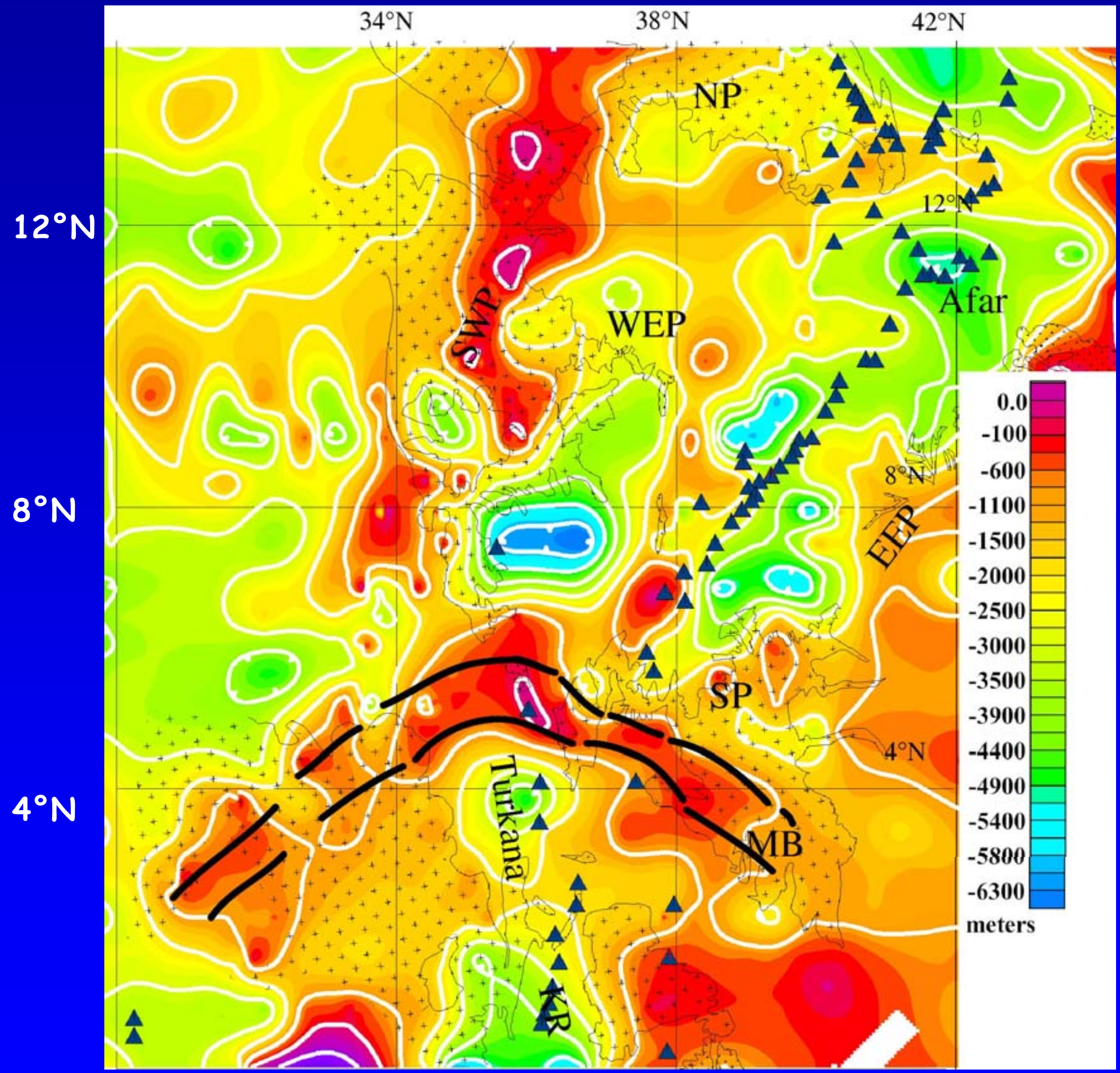
Shallowest Moho in Afar: ~16 km.

Deepest Moho in WEP: 48km.

Mean Moho: ~30km.

The maximum load in WEP: ~8×10^{18}kg/m^2 and induces a downward flexure of the Moho from average 35km to about 45km.

Basement topography



- Basement topography varies from few 100 m to 7 km.
- Deep basement exists in the rift, south west Ethiopia, Afar, Turkana and Eastern Sudan related to sedimentary structures.
- Shallow basement corresponds to the Precambrian structures.

Rigidity

Effective elastic thickness/rigidity

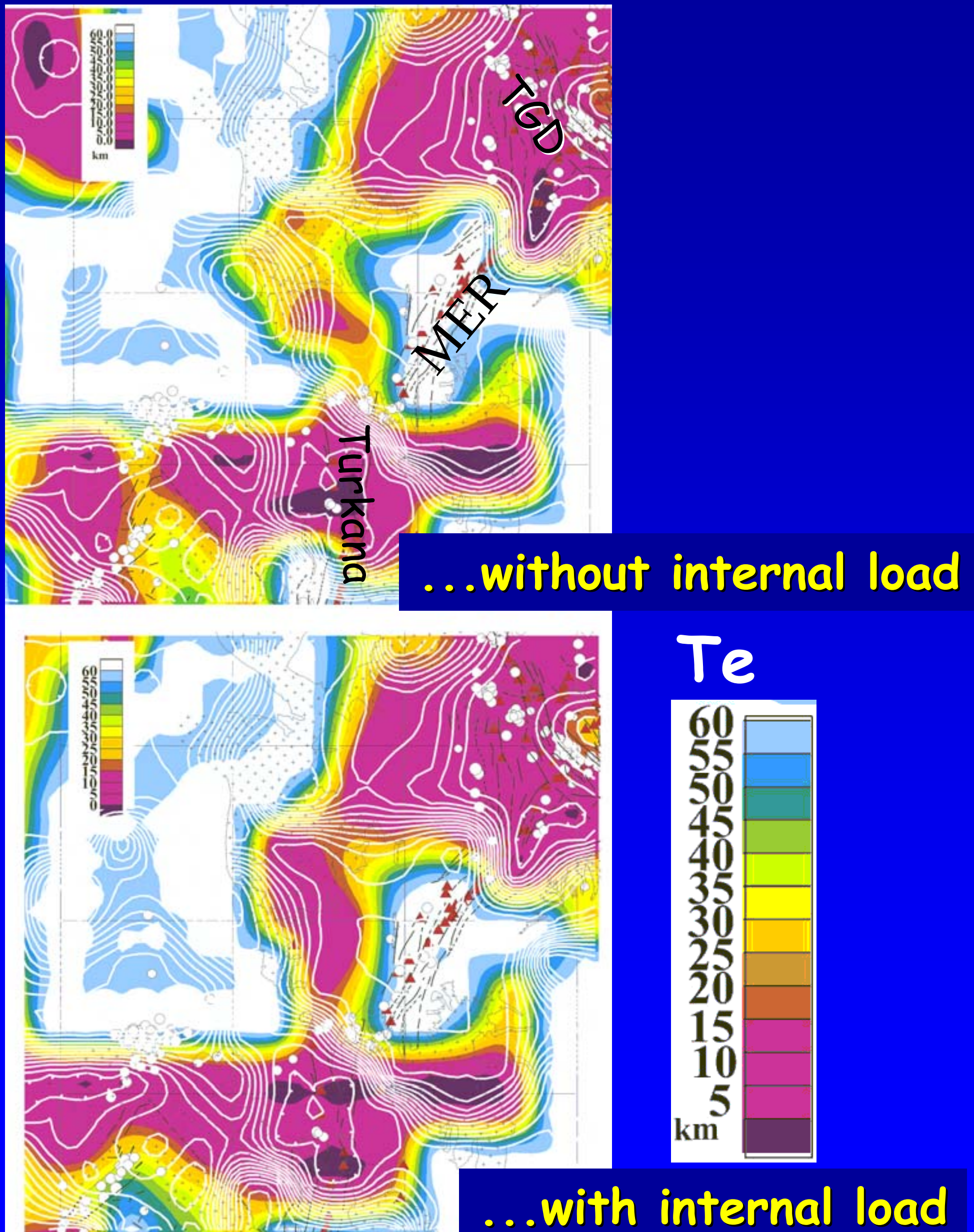
Coherence/admittance

- Require large areas
- Difficult to include internal loads
- Methods and results are in many cases controversial

(Convolution method, e.g. Braitenberg et al. 2002)

- Possible to include both external and internal loads
- No need to calculate admittance
- Higher resolution is possible
- Input: Moho geometry and total load from a 3D model

Rigidity



Summary results

- Rigidity estimates from this work and previous work are different in MER.
- All the models show low rigidity in highly tectonized zones of Afar and Turkana.
- Precambrian areas have medium to high rigidity.
- In Afar, the TGD is marked by change of lithospheric strength in all models.

Summary

- A new consistent regional gravity database;
- Bouguer gravity and isostatic residual maps;
- Isostatic models;
- A new regional 3-D density model using old and recent constraints;
- Moho and basement topography maps constrained where possible;

- The 3D model offers quantitative estimates of sedimentary thicknesses;
- The controls on rift architecture are: sediment loading, asthenospheric upwelling (40 km depth and 300 km wide) and lower-crustal modifications;
- Elastic thickness estimates:

Te Afar and Turkana: 5-20 km;

Te Plateau (WEP, EEP), MER: 40-60 km;

Te Western rift, eastern Sudan basin: 20-30 km;

Te Sudan craton: 50-60 km.

Acknowledgement

Gysers in Dallol-Afar (Ethiopia)

http://www.dankalia.com/index.htm

I thank

The Geological Survey of Ethiopia (GSE) for permission to use most of the data sets and information.

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Katholischer Akademischer Ausländer-Dienst • KAAD

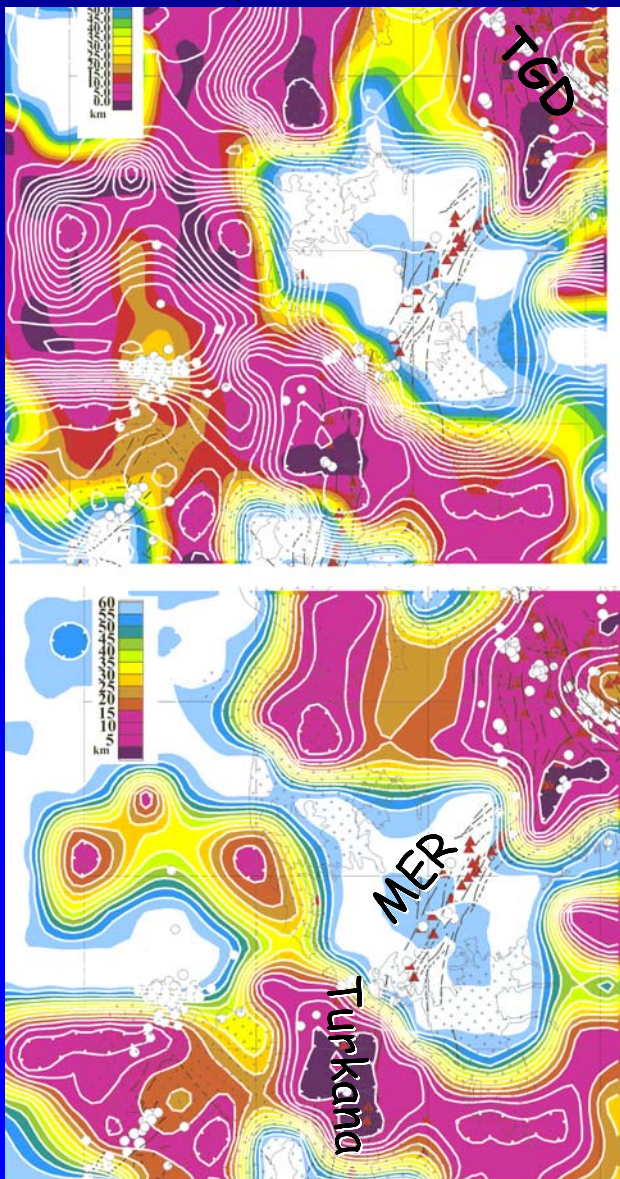
All members at the Institute of Geosciences of CAU and FU Berlin for useful discussions and friendship.

veritas iustitia libertas

C | A | U

Rigidity

Without dynamic topography

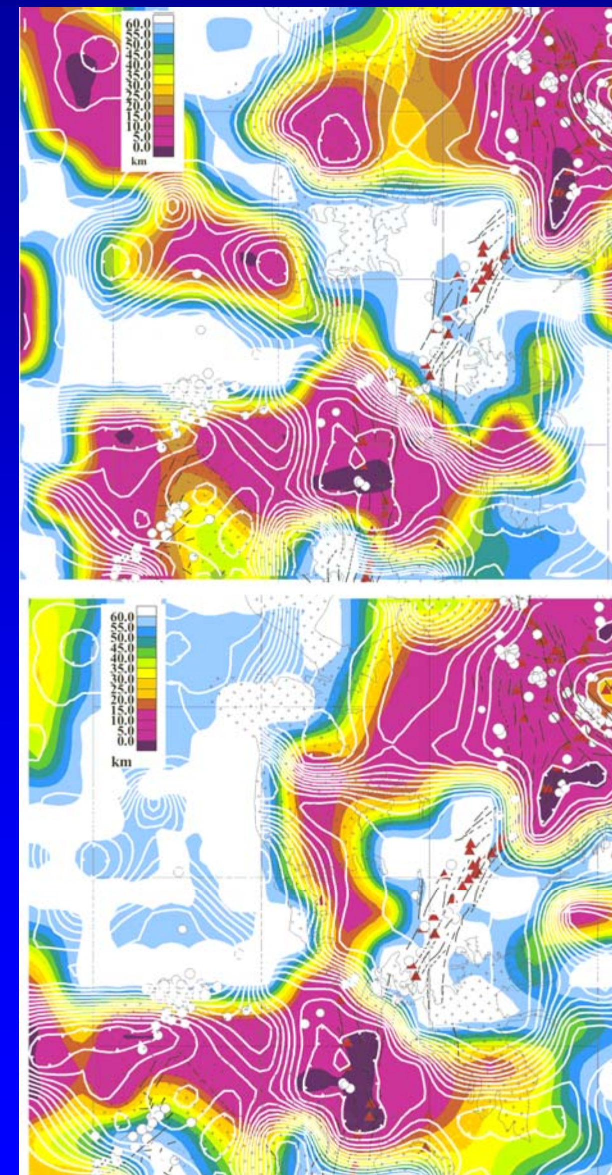


...Without internal load

Te

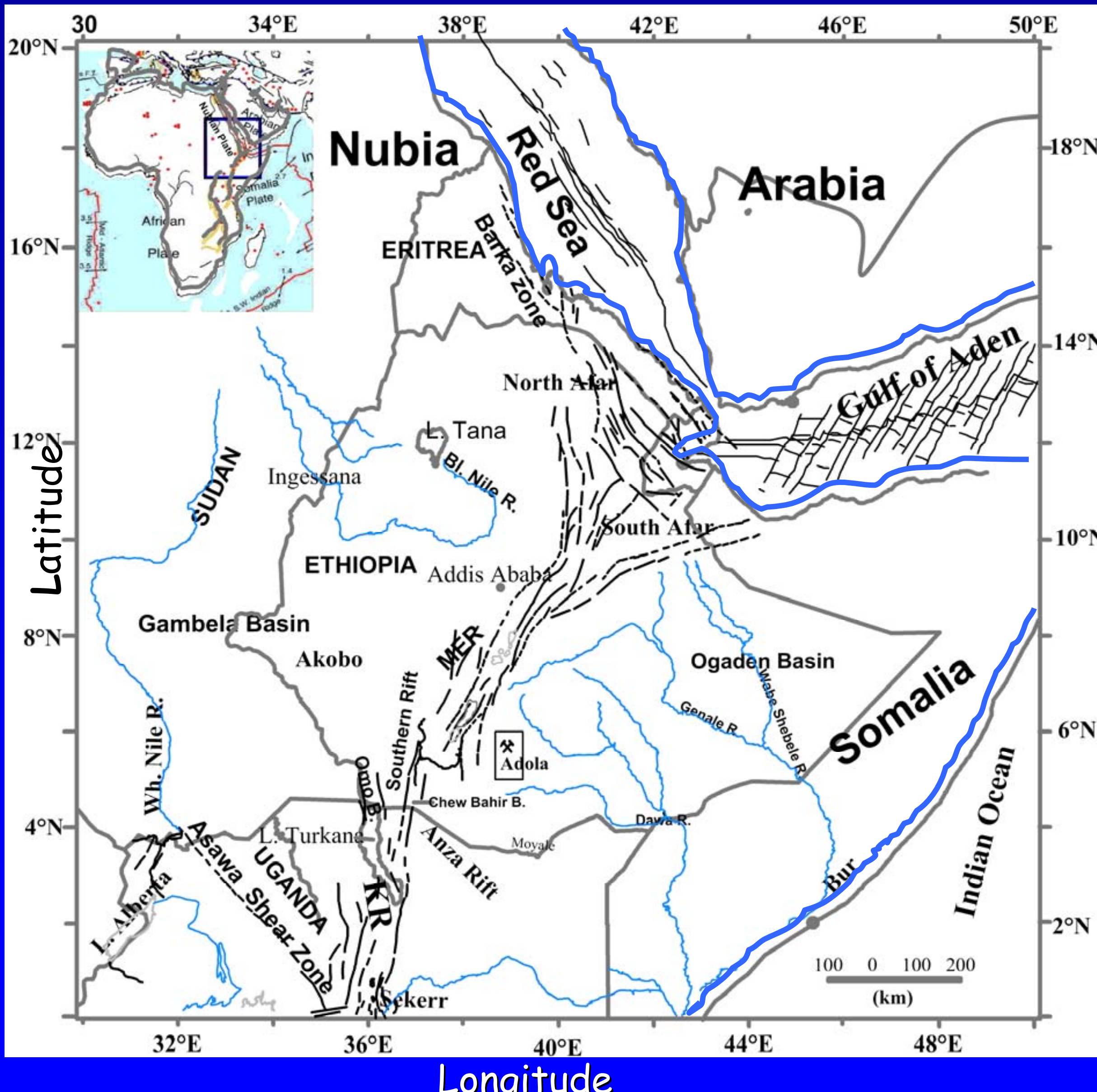
...With internal load

Slab dynamic topography



TGD= Tendaho-Goba'ad discontinuity

Fault systems



Major rivers

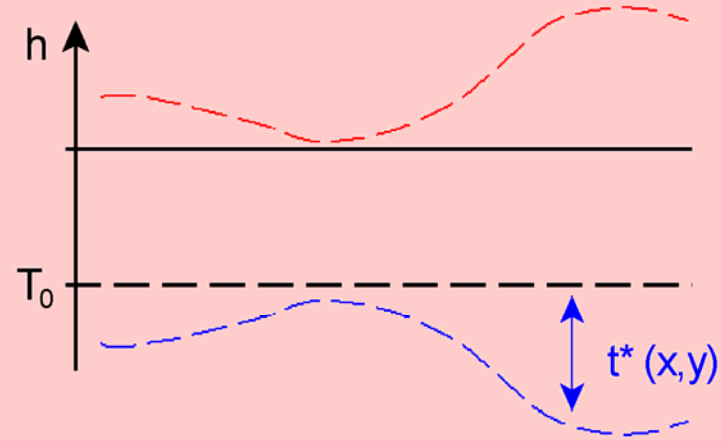
fault systems (CGMW, 1968)

Coast line

Isostasy

AIRY - model:

$$t_i = (x,y) = -T_0 - \underbrace{\frac{\rho_K}{\rho_M - \rho_K} h(x,y)}_{t_i^*(x,y)}$$



VENING - MEINESZ - model (elastic plate, Banks, 1975):

$$T_i^*(k_x,k_y) = \underbrace{\frac{\rho_K}{\rho_M - \rho_K}\left[1 + \frac{16\Pi^4 \cdot |(k_x,k_y)|^4 \cdot D}{(\rho_M - \rho_K)g}\right]^{-1}}_{low\ pass\ filter:\ TP(|k_z,k_y|)} H(k_x,k_y)$$

$$t_i(x,y) = -T_0 - t_i^*(x,y)$$

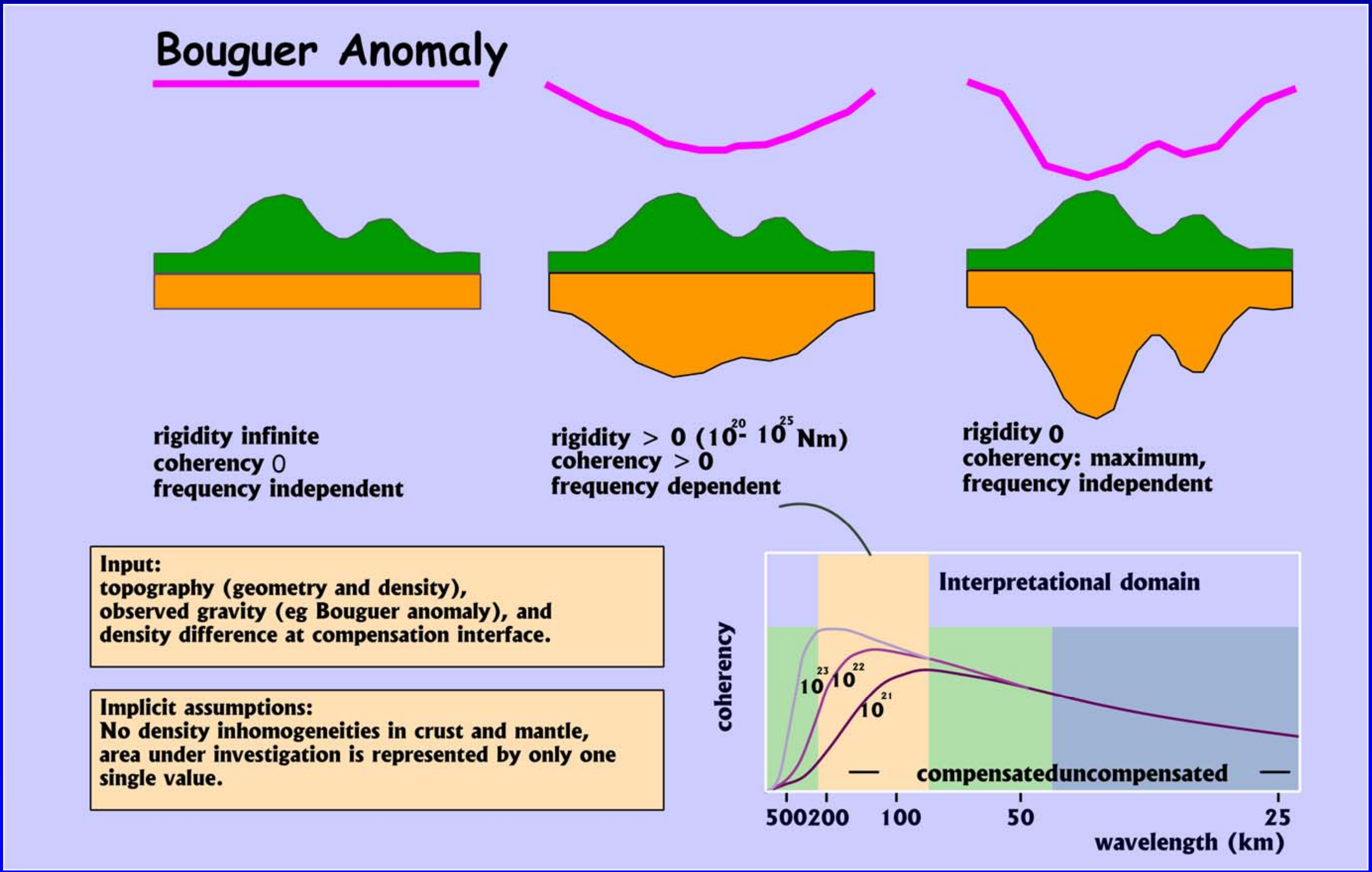
Flexural rigidity D:

$D = E\ (T_e)^3 / 12\ (1 - L^2)$

E, Young´s modulus
L, Poisson ratio

with: T_0 = normal crustal thickness at h = 0 km; ρ_M ρ_K = density mantle & crust
H = Fourier transform of topography; T* = Fourier transform of t * ; g = gravity

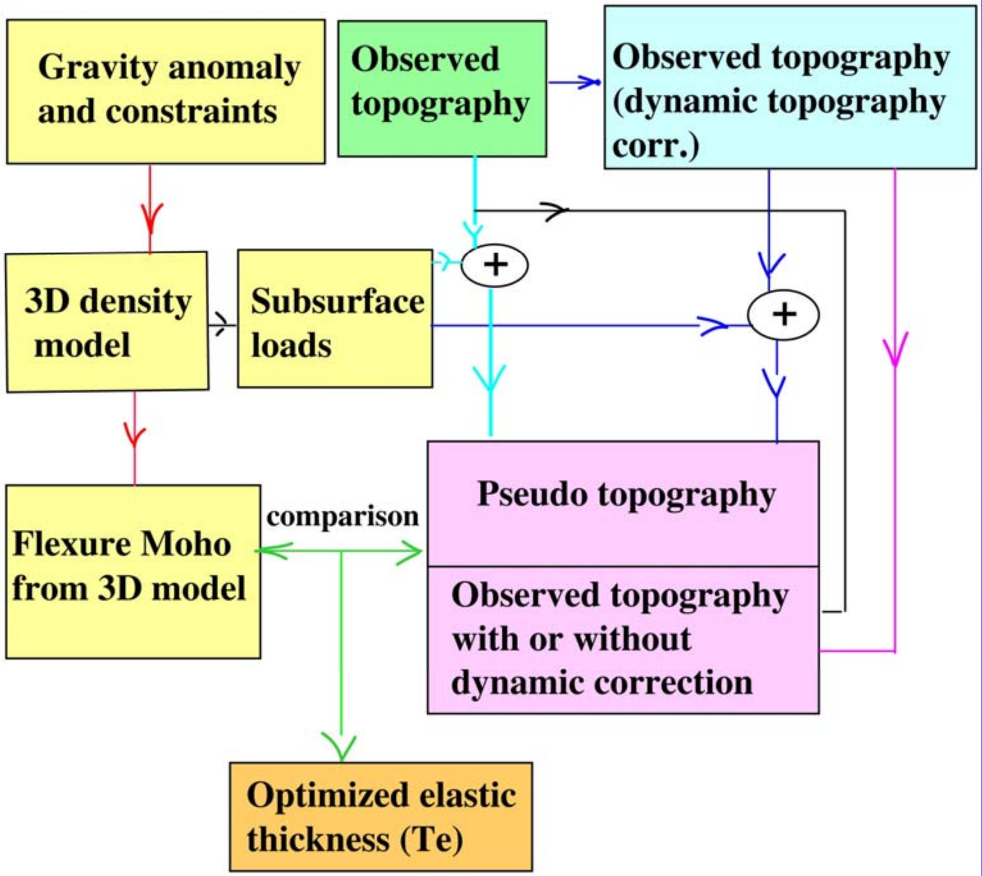
Rigidity



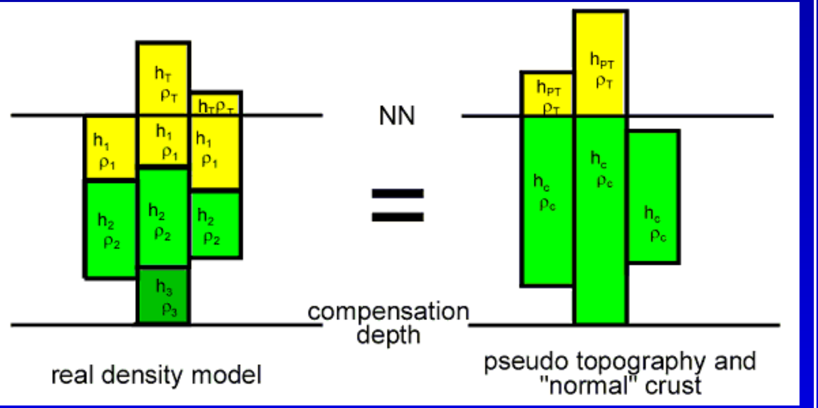
Bouguer Anomaly
rigidity infinite
coherency 0
frequency independent
rigidity > 0 (10^20 - 10^25 Nm)
coherency > 0
frequency dependent
rigidity 0
coherency: maximum,
frequency independent
Input:
topography (geometry and density),
observed gravity (eg Bouguer anomaly), and
density difference at compensation interface.
Implicit assumptions:
No density inhomogeneities in crust and mantle,
area under investigation is represented by only one
single value.
Interpretational domain
coherency
10^23
10^22
10^21
compensated
uncompensated
500
200
100
50
25
wavelength (km)

Rigidity estimation

Elastic thickness estimation using Braitenberg et al. 2002 modified from (Ebbing, 2002) with the addition of dynamic topographic correction.



Pseudo topography (P_{PT})



$$L = h_T \rho_T + \sum_{i=1}^{N} h_i (\rho_i - \rho_c)$$

$$h_{PT} = L / \rho_{PT}$$

Source:
http://userpage.fu-berlin.de/~hajo/Bratislava/Files/Isostat/Isostat.html