Crustal Thickness, Oceanic Lithosphere Distribution and OCT Structure for the Eastern Mediterranean from Gravity Inversion*

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Abstract

The distribution of oceanic and continental crust in the eastern Mediterranean region is not well understood but has major implications for the tectonic evolution of this region and its petroleum systems. Gravity inversion, incorporating a lithosphere thermal gravity anomaly correction, has been used to map Moho depth, crustal basement thickness, and continental lithosphere thinning for the eastern Mediterranean in order to determine ocean-continent transition (OCT) structure and the distribution of oceanic lithosphere. Knowledge and understanding of OCT structure and the distal extent of continental crust are of critical importance in evaluating petroleum systems in deepwater frontier oil and gas exploration at continental margins and in predicting heat flow.

The data used in the gravity inversion are public domain free-air gravity (Sandwell and Smith, 2009), bathymetry (Amante and Eakins, 2009) and sediment thickness (Laske and Masters, 1997). Gravity inversion results are dependent on the age of continental breakup and oceanic lithosphere because of the inclusion of the lithosphere thermal gravity correction; however, these ages are uncertain for the eastern Mediterranean. Gravity inversion sensitivities to break-up ages of 225 Ma (Late Triassic) and 100 Ma (Middle Cretaceous) have been examined.

Gravity inversion results show thin crust (5-8 km thickness) for the Ionian Sea and the Herodotus Basin, consistent with these basins being underlain by oceanic or highly thinned continental crust. The sharp increase in crustal thickness to the south of the very thin crust within the Herodotus Basin and eastern Ionian Sea suggests that the COB to the northwest of Egypt and eastern Libya is a transform margin. In contrast, the much broader transition from thick to thin crust in the Levantine Basin to the east of the Herodotus Basin most probably indicates that this is a rifted continental margin.

Continental lithosphere thinning and post-breakup residual thicknesses of continental crust determined from gravity inversion have been used to predict the preservation of continental crustal radiogenic heat productivity and the transient lithosphere heat-flow contribution within thermally equilibrating rifted continental margin and oceanic lithosphere. The resulting crustal radiogenic productivity and lithosphere transient heat flow components, together with base lithosphere background heat-flow, are used to produce regional maps of present-day top-basement heat-flow.

References Cited

Amante, C., and B.W. Eakins, 2009, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis: NOAA Technical Memorandum NESDIS NGDC-24, 19 p.

Chappel, A., and N. Kusznir, 2008, An Algorithm to calculate the gravity anomaly of sedimentary basins with exponential density-depth relationships: Geophysical Prospecting, v. 56/2, p. 249-258.

Cowie, L., and N. Kusznir, 2012, Mapping crustal thickness and oceanic lithosphere distribution in the eastern Mediterranean using gravity inversion, *in* A. Belopolsky, G. Tari, J. Craig, and J. Iliffe, (prefacers), New and emerging plays in the eastern Mediterranean: Petroleum Geoscience, v. 18/4, p. 373-380.

de Voodg, B., C. Truffert, N. Chamot-Rooke, P. Huchon, S. Lallemant, and X. Le Pichon, 1992, Two-ship deep seismic soundings in the basins of the eastern Mediterranean Sea (Pasiphae cruise): Geophysical Journal International, v. 109/3, p. 536-552.

Garfunkel, Z., 1998, Constrains on the origin and history of the eastern Mediterranean Basin, *in* A.H.F. Robertson, and M.C. Comas, (eds.), Collison related processes in the Mediterranean region: Tectonophics, v. 298/1-3, p. 5-35.

Greenhalgh, E.E., and N.J. Kusznir, 2007, Evidence for thin oceanic crust on the extinct Aegir Ridge, Norwegian Basin, NE Atlantic derived from satellite gravity inversion: Geophysical Research Letters, v. 34/6, p. LO6305.

Hallet, D., 2002, The Wieliczka salt mine: Geology Today, v. 18/5, p. 182-185.

Laske, G., and T.G. Masters, 1997, A global digital map of sediment thickness: EOS Transactions of American Geophysical Union, v. 78/46, p. 483.

Moulin, M., D. Aslanian, P. Unternehr, 2010, A new starting point for the South and Equatorial Atlantic Ocean: EarthScience Reviews, v. 98/1-2, p. 1-37.

Sandwell, D.T., and W.H.F. Smith, 2009, Global marine gravity from retracked Geosat and ERS-1 altimetry; ridge segmentation versus spreading rate: Journal of Geophysical Research, v. 114/B1, p. Citation BO1411.

Stampfli, G.M., C. Hochard, C. Wilhem, and J. von Raumer, 2008, Global Reconstruction and Database Project: AAPG Search and Discovery Article #30055. Website accessed 18 June 2013.
http://www.searchanddiscovery.com/documents/2008/08017stamfli/index.htm

Steinberg, B., and R. Holme, 2008, Mantle flow models with core-mantle boundary constraints and chemical heterogeneities in the lowermost mantle: Journal of Geophysical Research: Solid Earth, v. 113/B5, p. BO5403.

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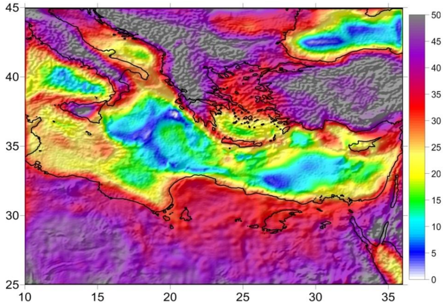
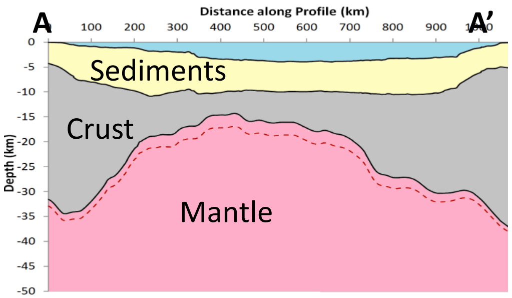
University of Liverpool

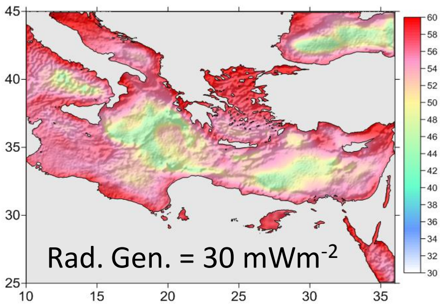
Aims:



- To determine crustal thickness and oceanic lithosphere distribution in the eastern Mediterranean

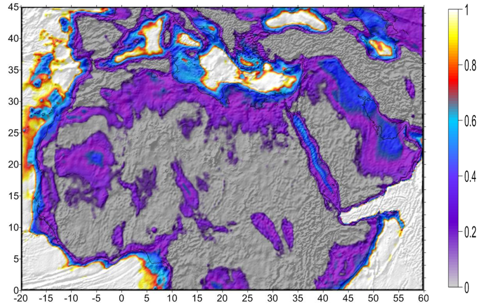
- To determine the ocean-continent transition (OCT) structure for the eastern Mediterranean





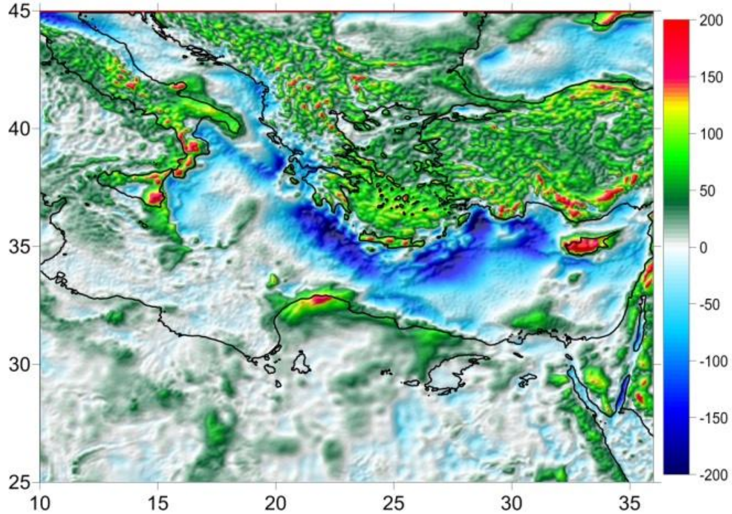
- To predict present day top basement heat flow in the eastern Mediterranean

- To examine the potential tectonic relationship between the Cretaceous West and Central African Rift System (WCARS) and the Sirte and Ionian basins of the eastern Mediterranean.



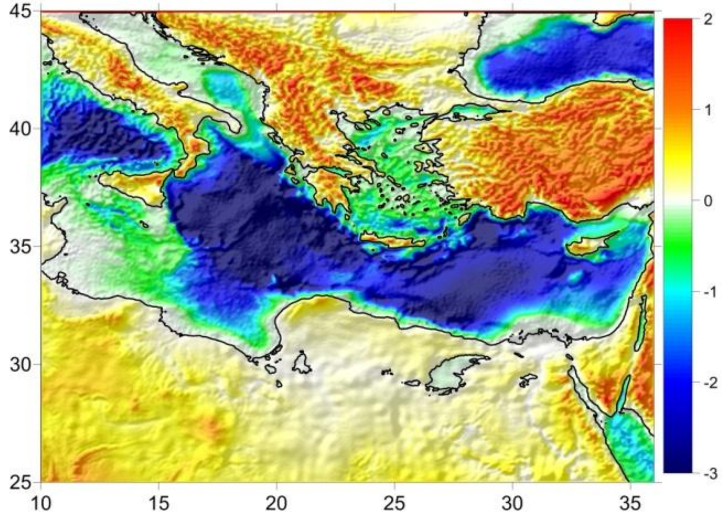
Public Domain Data:

Free Air Gravity (mgal)



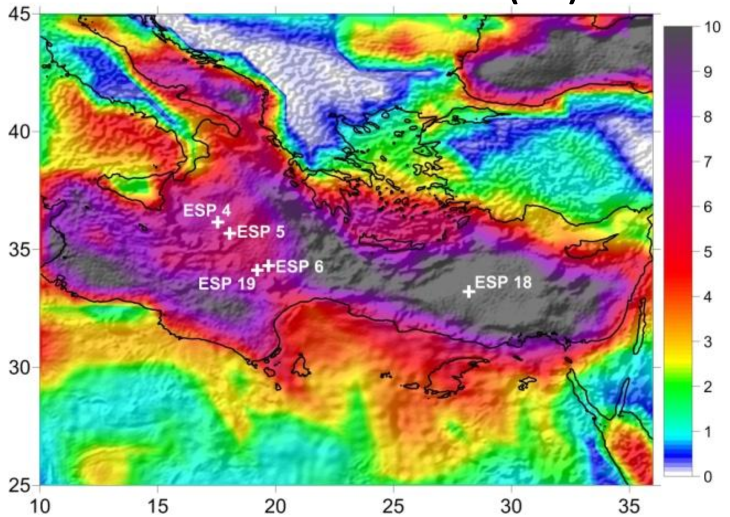
(Sandwell & Smith, 2009)

Bathymetry (km)



(Amante and Eakins, 2009)

Sediment Thickness (km)



(Laske & Masters, 1997)

Age of break-up (Ma)

100 Ma (mid Cretaceous)

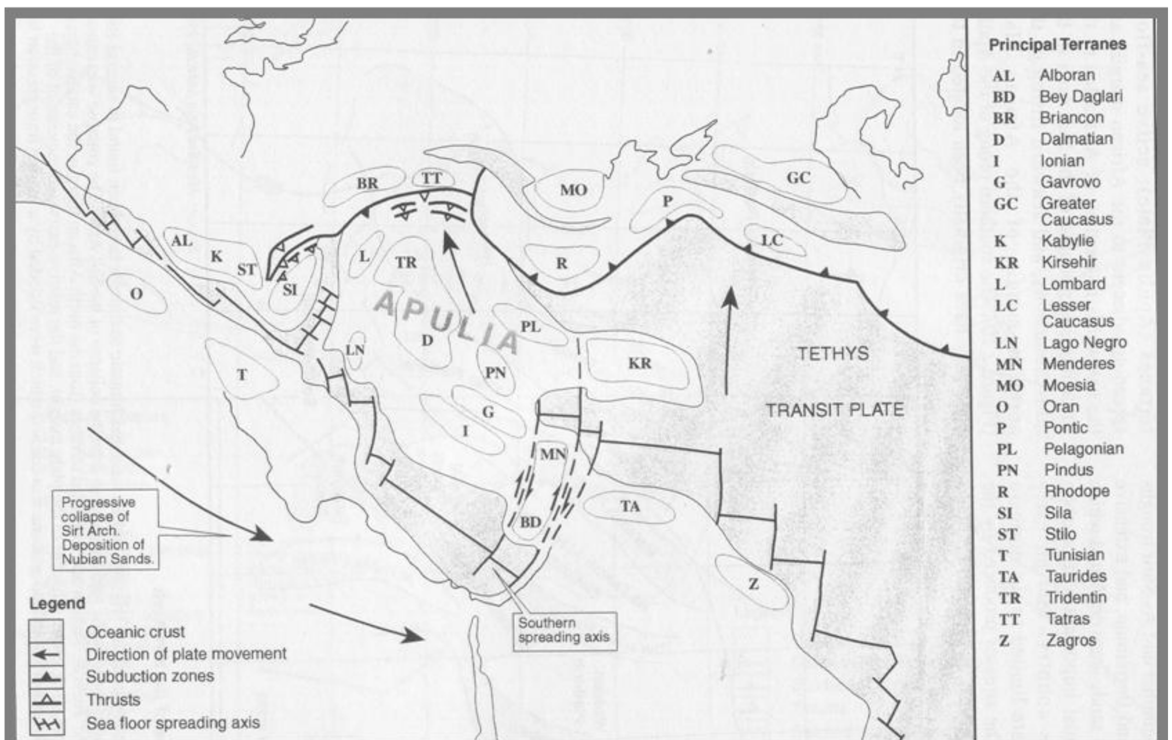
225 Ma (Late Triassic)

Break-up Age

- The age of formation of the eastern Mediterranean basins, in particular the Ionian and the Herodotus, is uncertain.

- Dercourt et al. (1993) propose that the eastern Mediterranean is Cretaceous in age (Aptian to Campanian) and is linked to the closure of the Tethys Ocean.

Early Aptian (120 Ma)



Decourt et al. 1993

Break-up Age

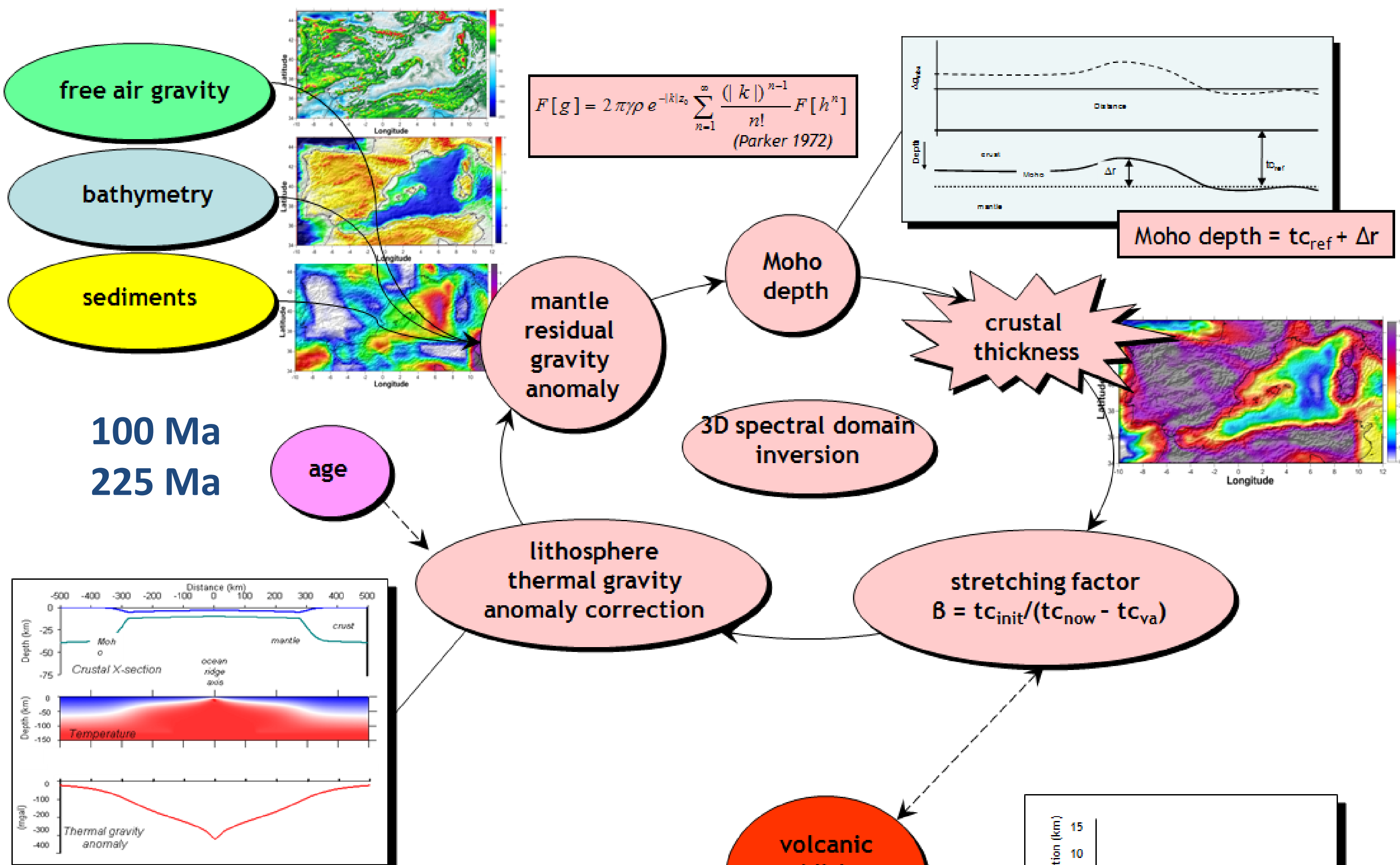
- Stampfli et al. (2008) and Hallett (2002) propose that the eastern Mediterranean is late Triassic in age and is linked to the breakup of Pangaea and the closure of the Neo-Tethys and Tethys oceans.

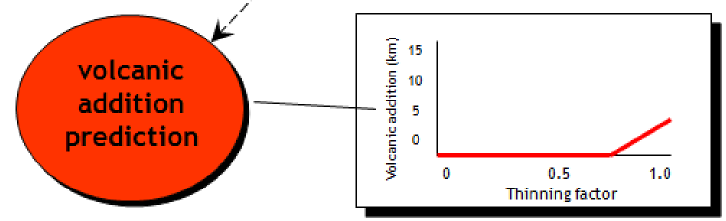
250 Ma - Permian-Triassic boundary

Stamfli et al., 2008

Gravity Inversion: Method

Rifted Margin Crustal Thickness & Thinning Factor from Gravity Inversion

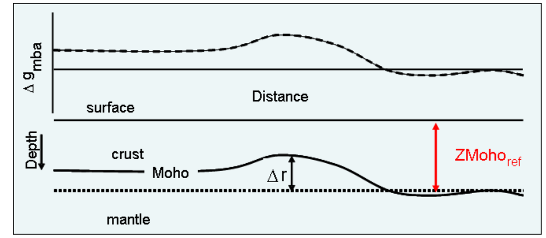




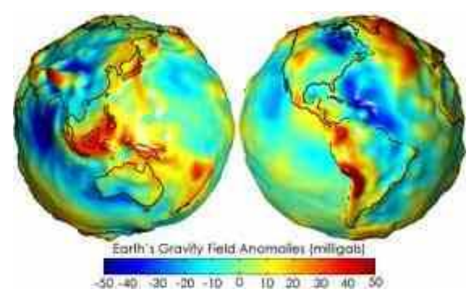
Greenhalgh & Kusznir (Geophys. Res. Lettr., 2007)
Chappell & Kusznir (Geophys. J. Int., 2008)
Cowie & Kusznir (Petroleum Geoscience, 2012)

Reference Moho Depth

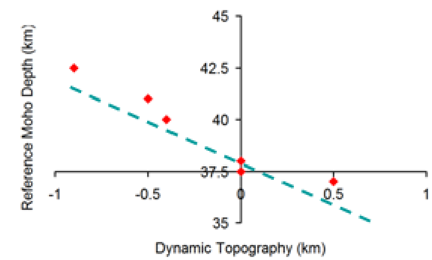
- Important parameter in gravity inversion crustal thickness mapping



- Lower orders of Earth's gravity field not controlled by lithosphere or crustal structure



- Reference Moho depth varies with mantle dynamic topography

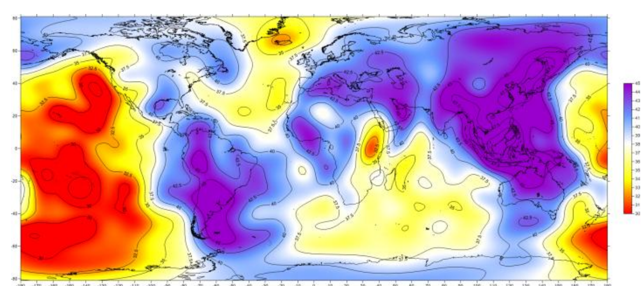


- Global average ~38km

- Best calibrated against seismic refraction Moho depth

- Can be predicted from mantle dynamic topography

- Can be used to measure mantle dynamic topography

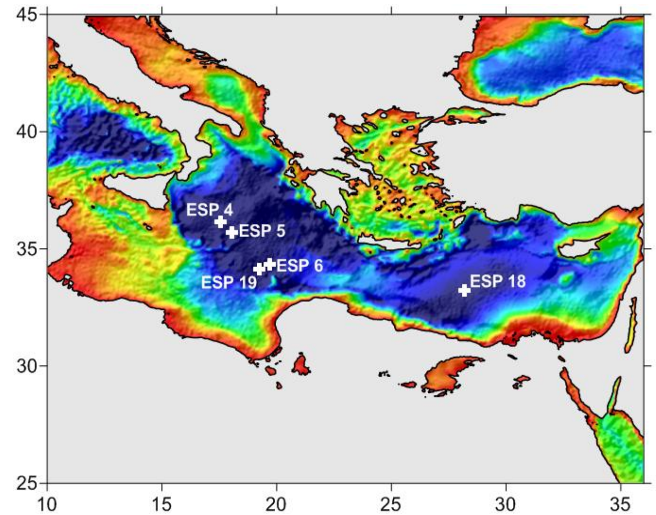


(predicted from Steinberger 2008)

Gravity Inversion: Calibration

- Use available seismic Moho depths to calibrate the reference Moho depth used in the gravity inversion

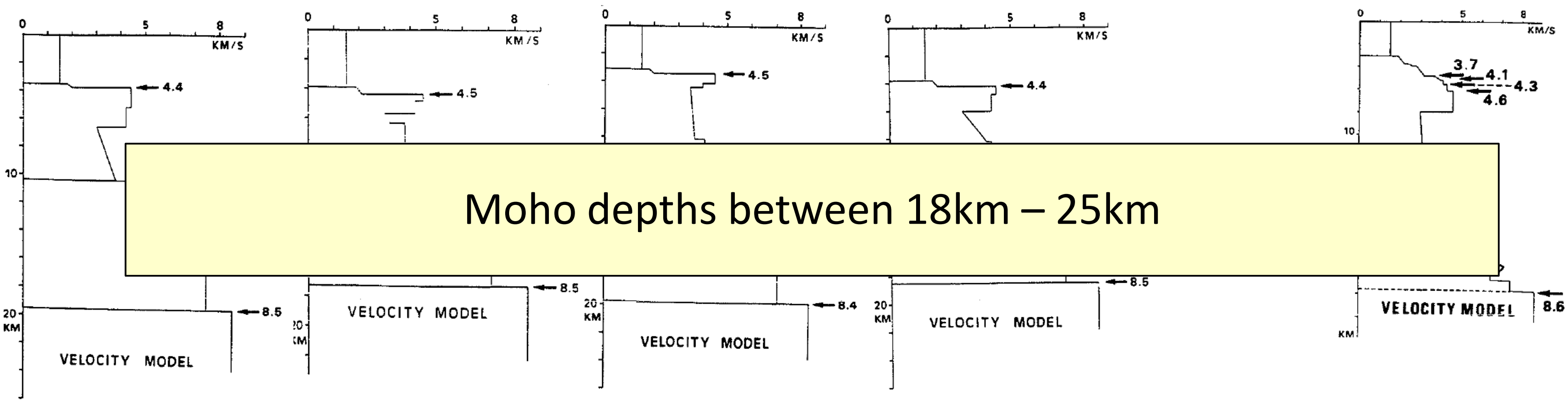
- Expanding Spread Profile (ESP) seismic observations (de Voogd et al. 1992) are used for calibration.



Ionian Sea

Herodotus Basin

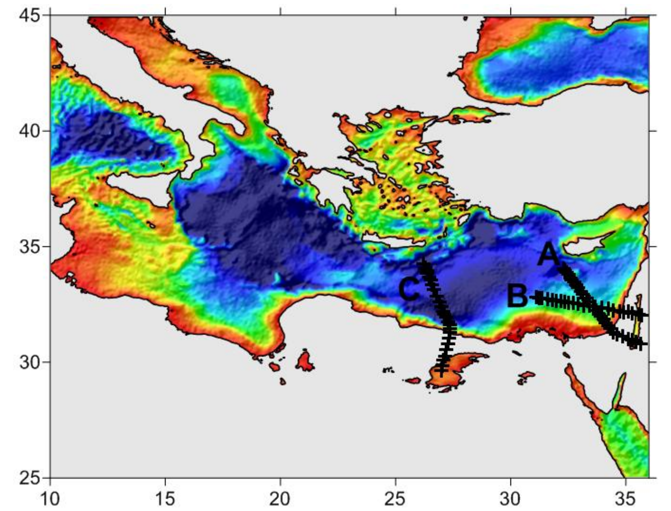
ESP 4 **ESP 5** **ESP 6** **ESP 19** **ESP 18**



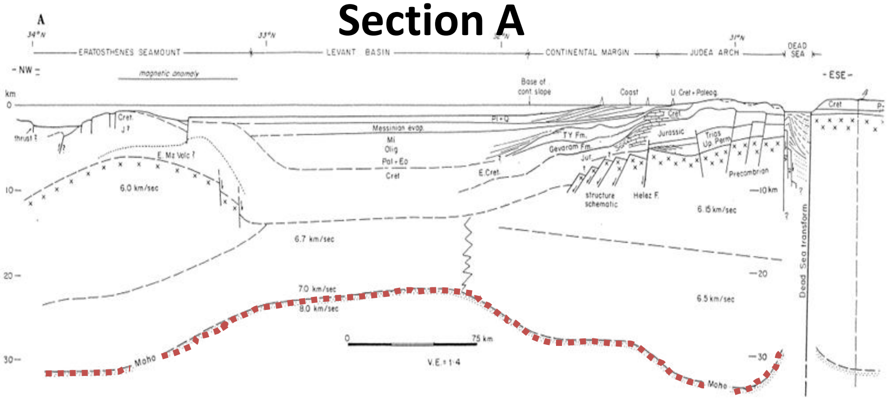
Moho depths between 18km – 25km

Gravity Inversion: Calibration

- Moho depths from Garfunkel (1998) for Herodotus Basin are consistent with ESP measurements (de Voogd et al. 1992).

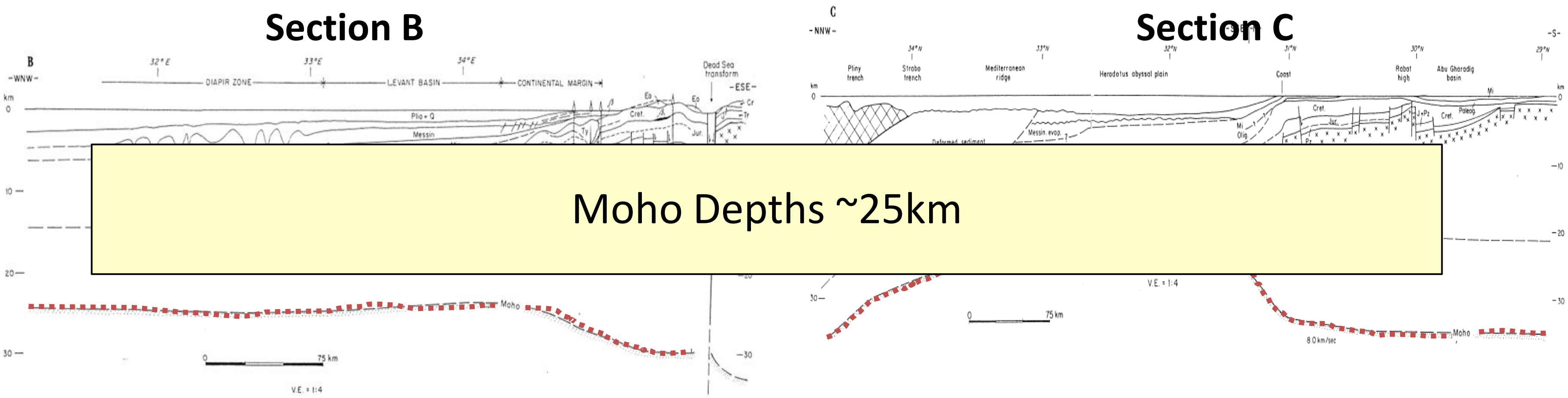


Section A



Section B

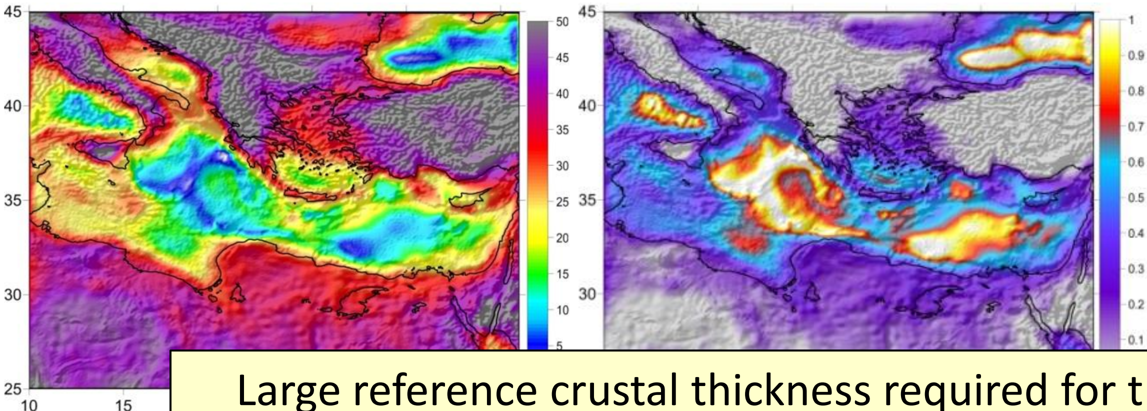
Section C



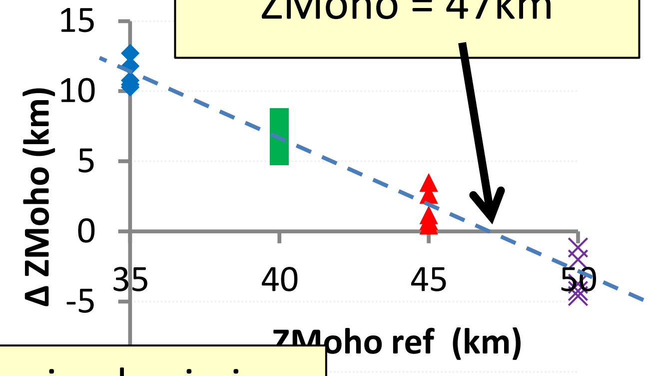
Moho Depths ~25km

Sensitivity to Break-up age

Break-up age of 100 Ma



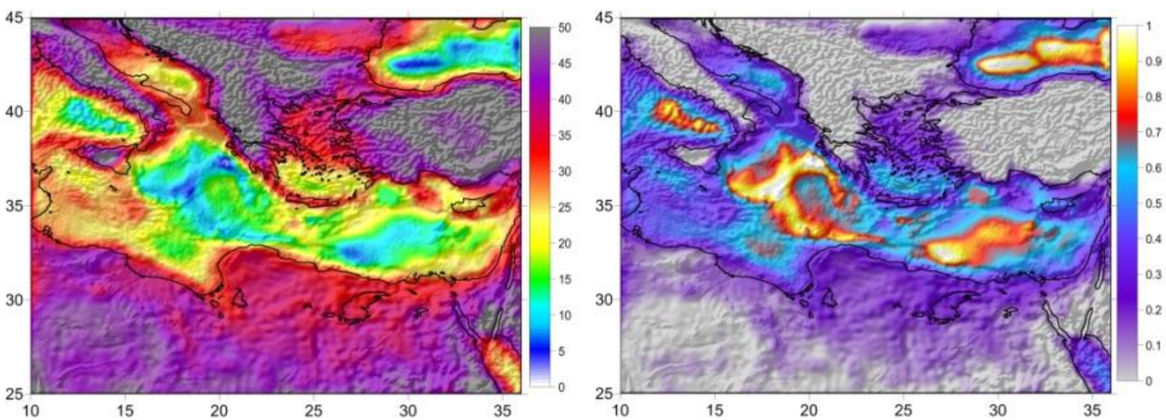
Crust



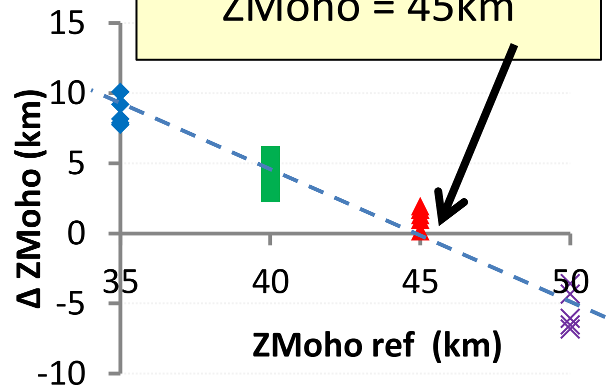
Calibrated reference
ZMoho = 47km

Large reference crustal thickness required for the Ionian basin is caused by the Hellenic Arc subduction dynamic subsidence

Break-up age of 225 Ma



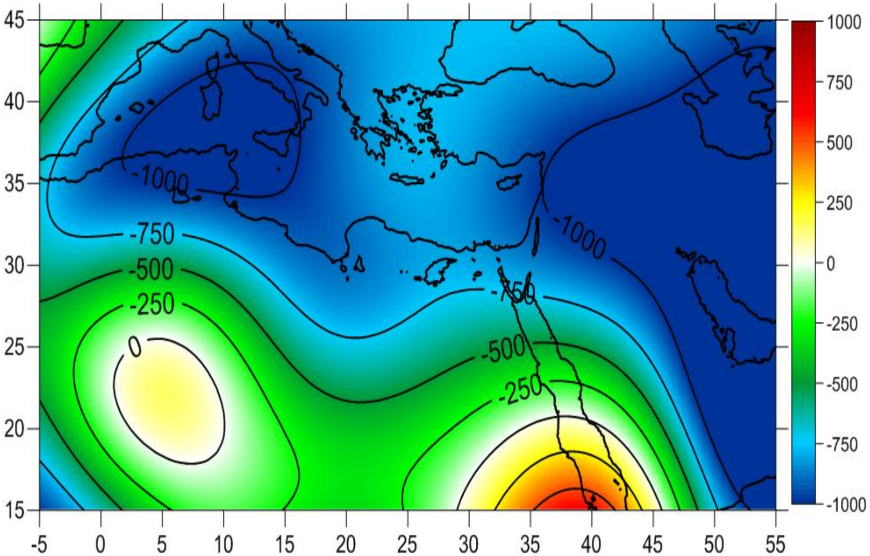
Crustal Thickness (km) Thinning Factor (1-1/β)



Calibrated reference
ZMoho = 45km

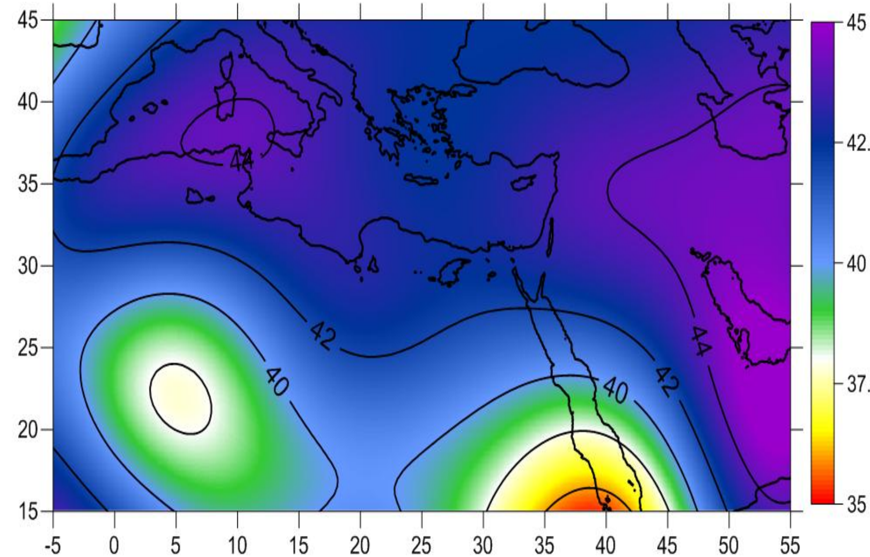
Dynamic Topography

Dynamic Topography (m)



Steinberger (2007)

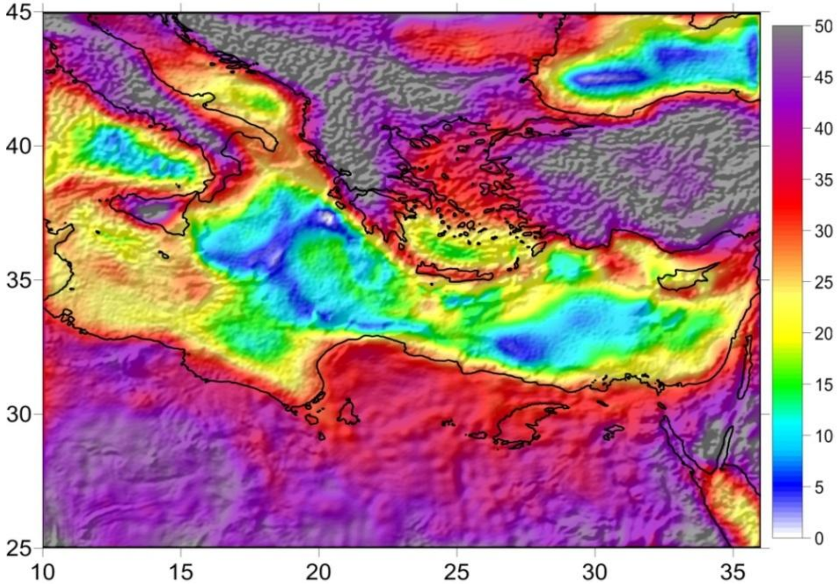
Reference Moho Depth (km)



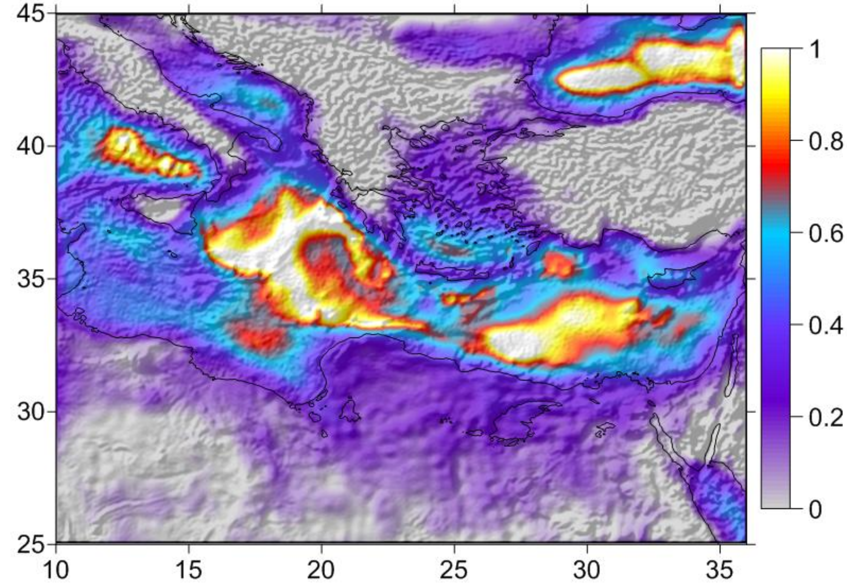
- Mantle dynamic topography shows negative values between -800 and -1000m in the eastern Mediterranean → mantle dynamic subsidence
- Calculated reference Moho depth from dynamic topography.
- Reference Moho depths predicted from dynamic topography are between 42km and 44km.

Crustal Thickness & Lithosphere Thinning

Crustal Thickness (km)



Continental Lithosphere Thinning (1-1/β)



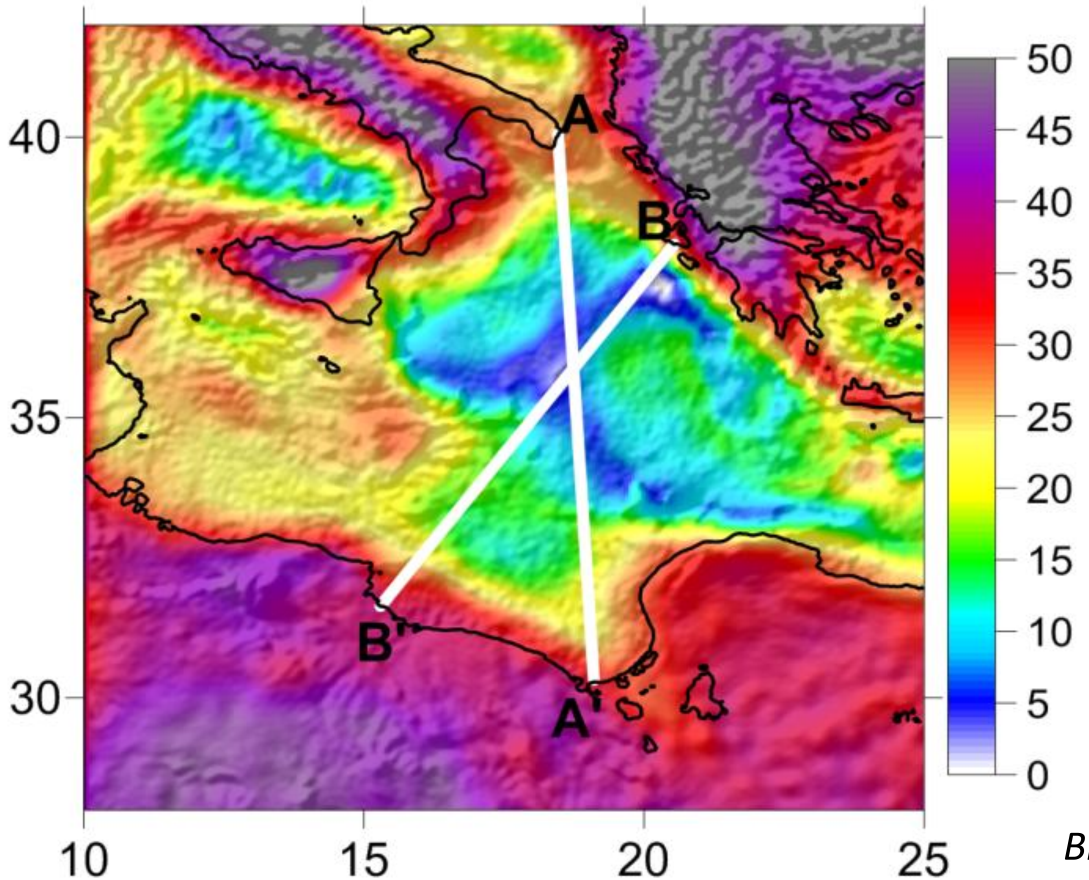
Break-up age of 225 Ma
ZMoho ref = 45km

- Ionian and Herodotus basins:
  - Thin crust and high continental lithosphere thinning factors
  - Predicted crustal thicknesses range from 5 - 8km
- Sirte Basin:
  - Predicted basement crustal thicknesses are between 15 and 20km
- North African Coast
  - Predicted basement crustal thickness are less than 30km

Results: Ionian Sea

- Locations of Cross sections A-A’ and B-B’ through the Ionian sea and Sirte basin determined from gravity inversion are shown.

- Moho depth sensitivities to break-up ages of 100Ma and 225Ma are considered.

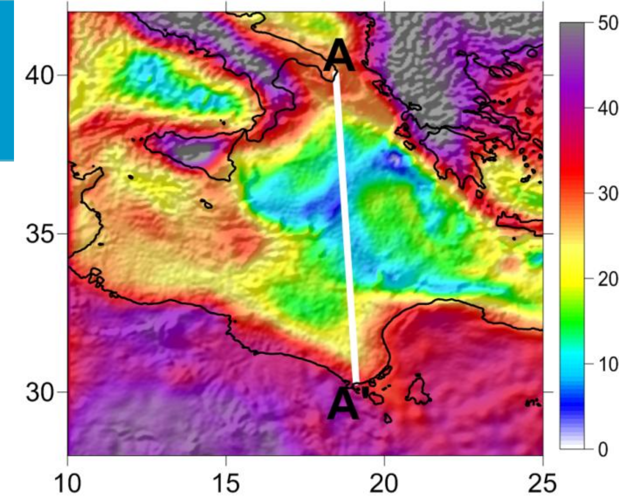


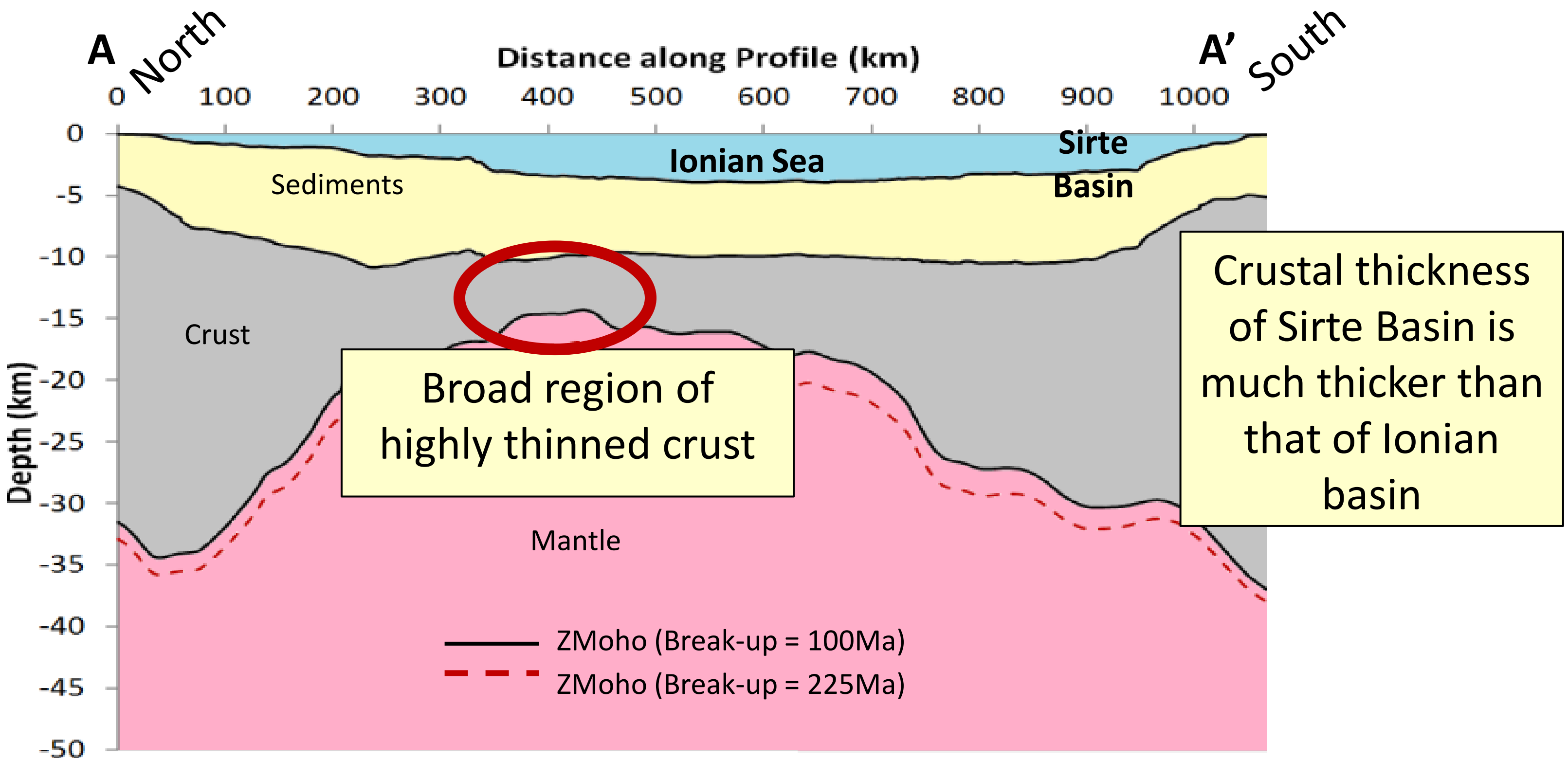
Break-up age of 225 Ma
ZMoho ref = 45km

Results: Ionian Sea

- Cross sections A-A' through the Ionian sea and Sirte basin show bathymetry, sediment thickness and Moho depth determined from gravity inversion

- Moho depth sensitivities to break-up ages of 100Ma and 225Ma are indicated.

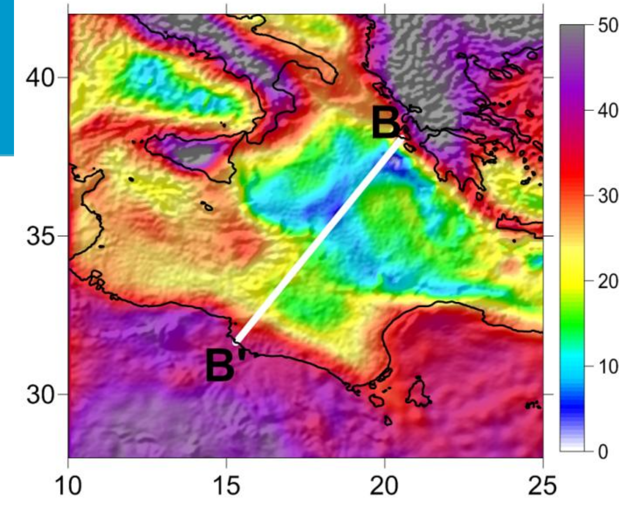


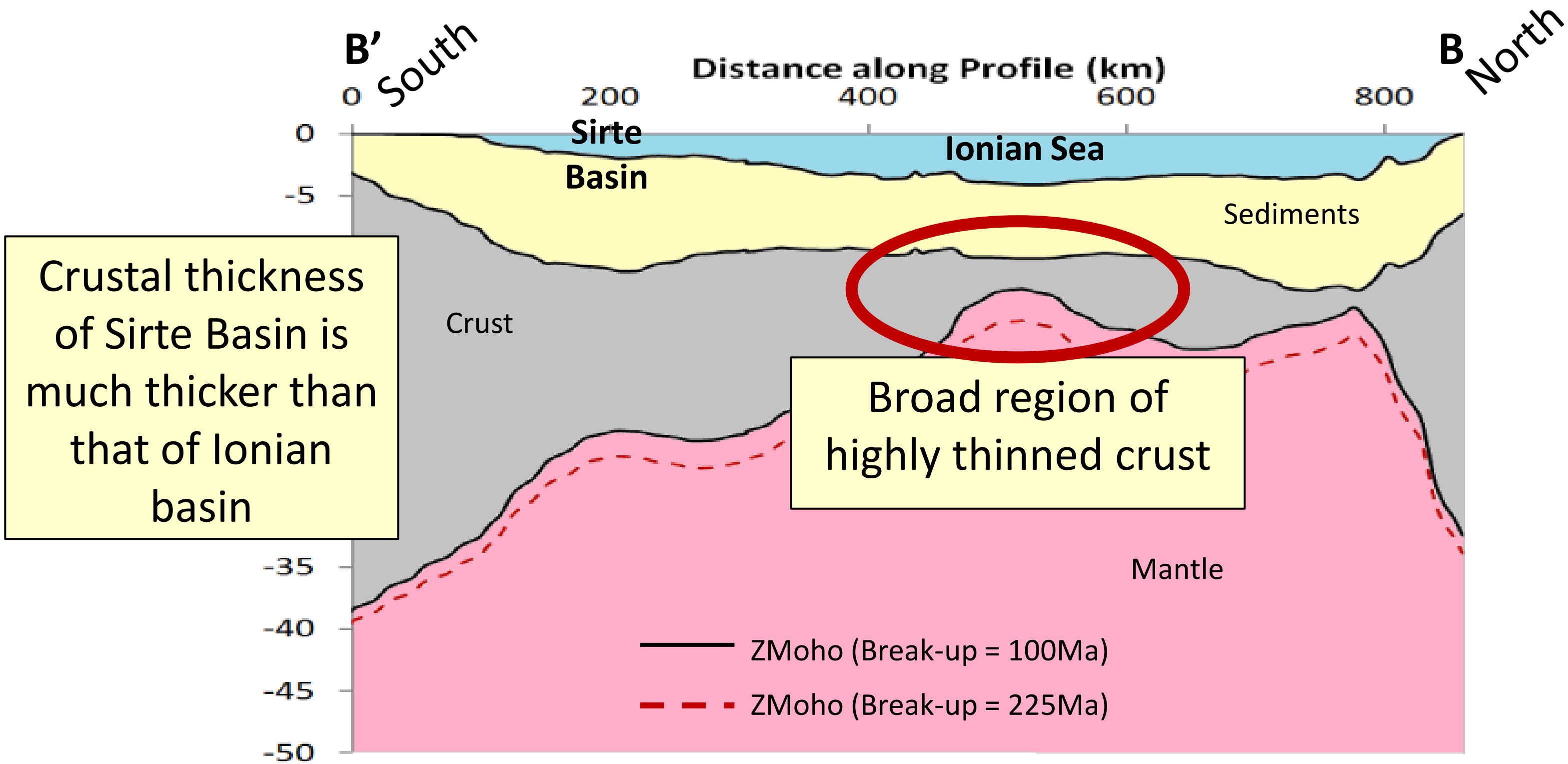


Results: Ionian Sea

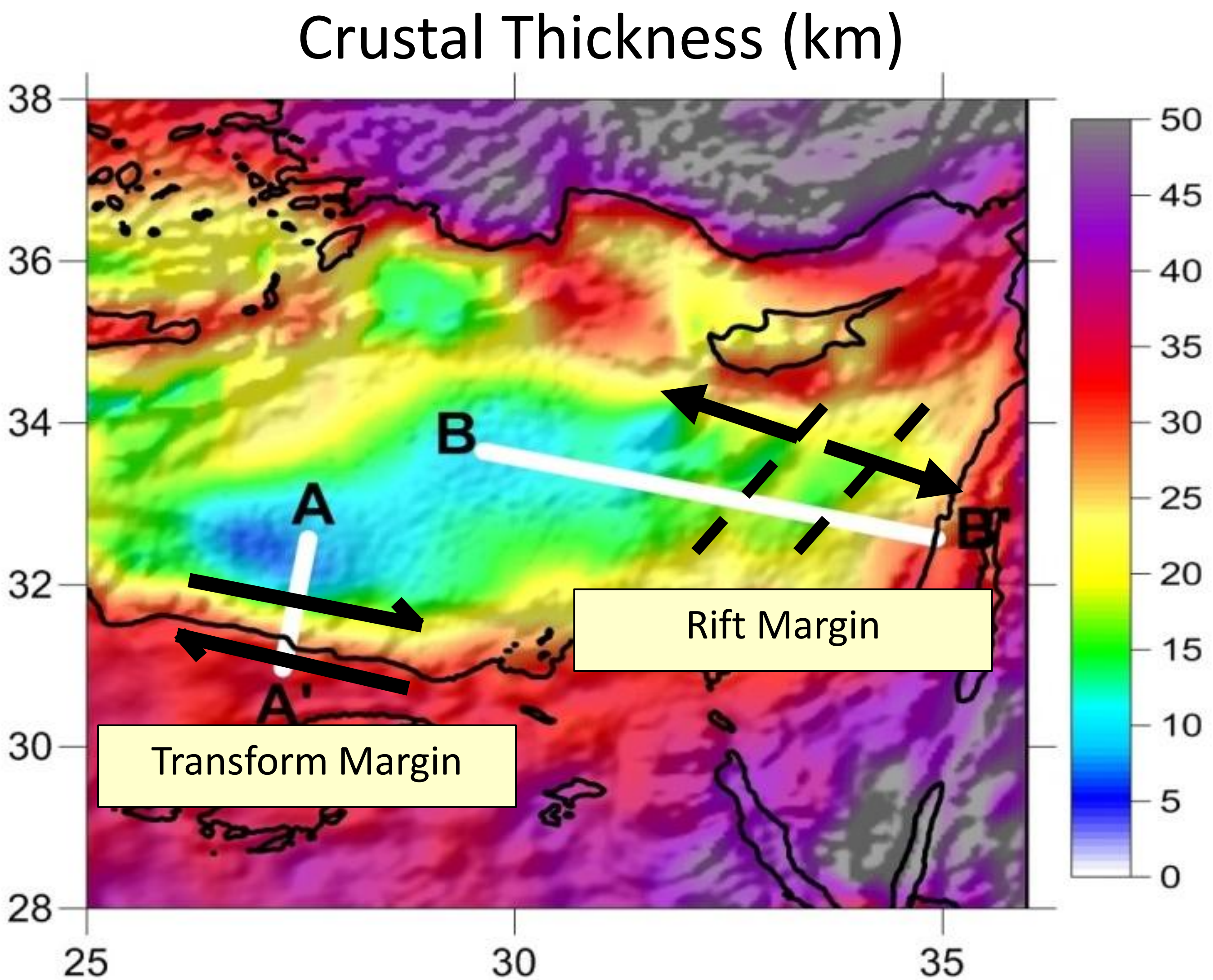
- Cross sections B-B' through the Ionian sea and Sirte basin show bathymetry, sediment thickness and Moho depth determined from gravity inversion

- Moho depth sensitivities to break-up ages of 100Ma and 225Ma are indicated.



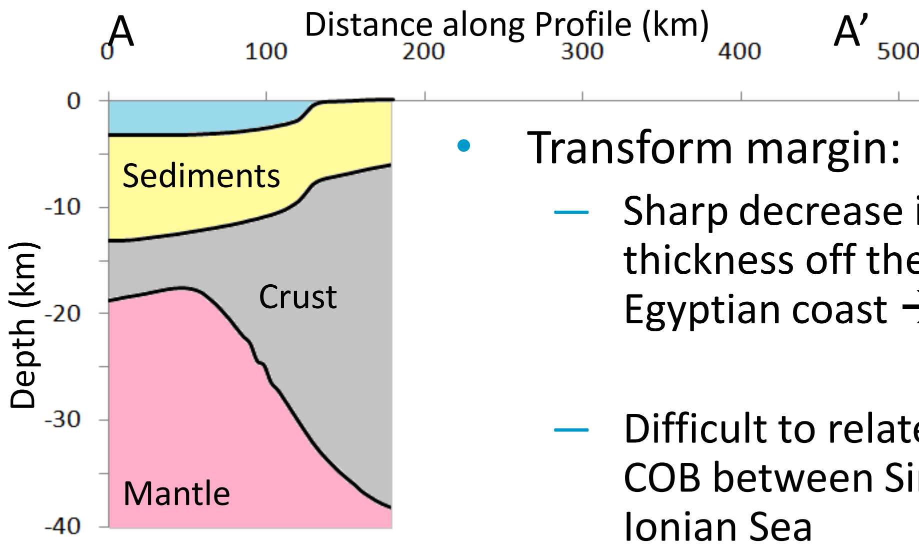


Results: Levant Basin

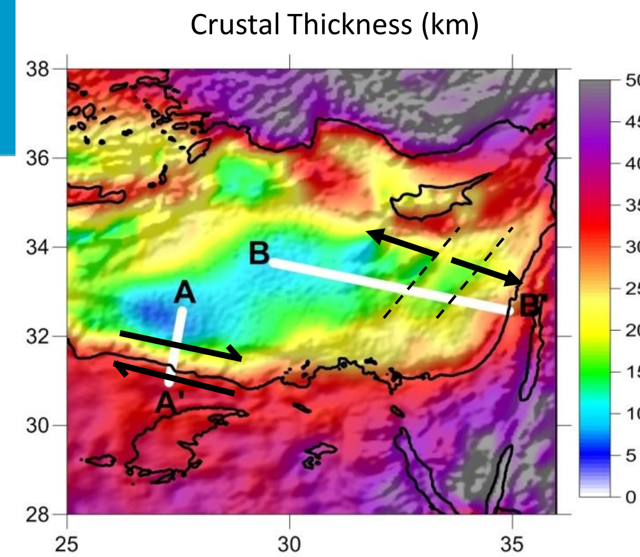


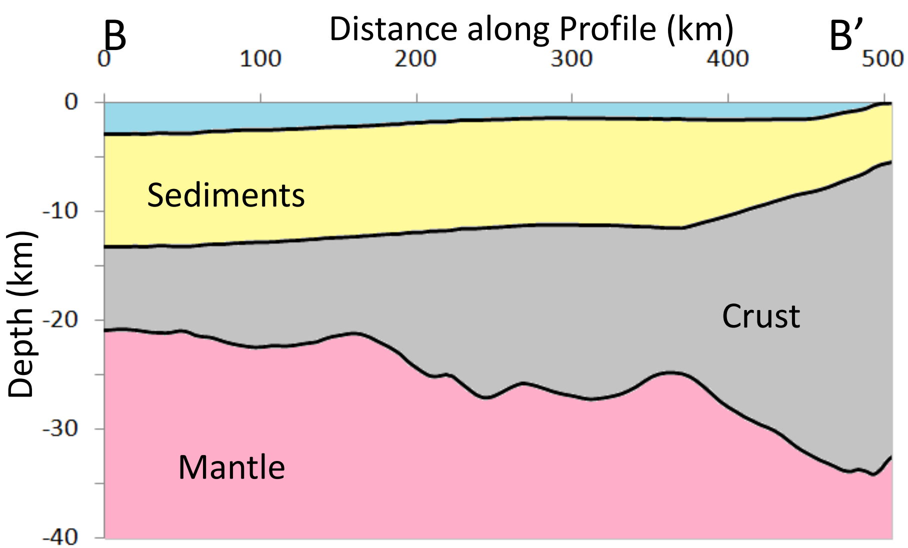
Break-up age of 225 Ma
ZMoho ref = 45km

Results: Levant Basin



- Transform margin:
  - Sharp decrease in crustal thickness off the Libyan and Egyptian coast → COB location
  - Difficult to relate to proposed COB between Sirte Basin and SW Ionian Sea
  - A transform margin north of Egypt is consistent with rifted Levantine basin

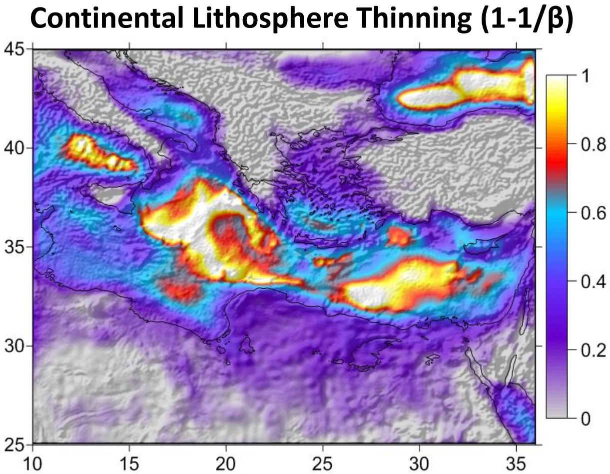


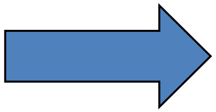


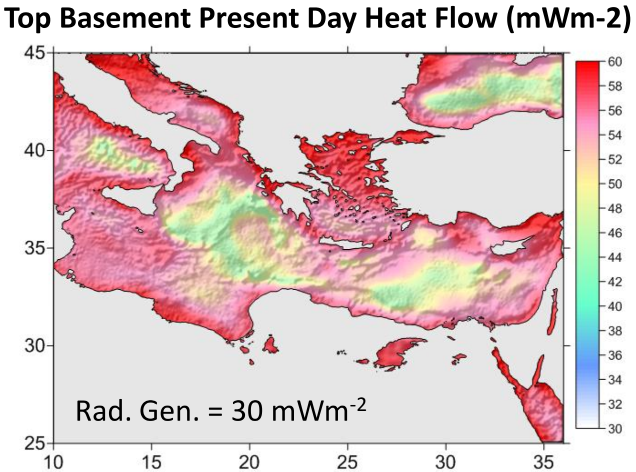
- Rift margin:
  - Rift basin axes are orientated NNE–SSW
  - separated by intervening structural highs with a similar orientation

Predicted Heat Flow: Methodology

Heat-flow prediction







Age of break-up (Ma)

100 Ma (mid Cretaceous)

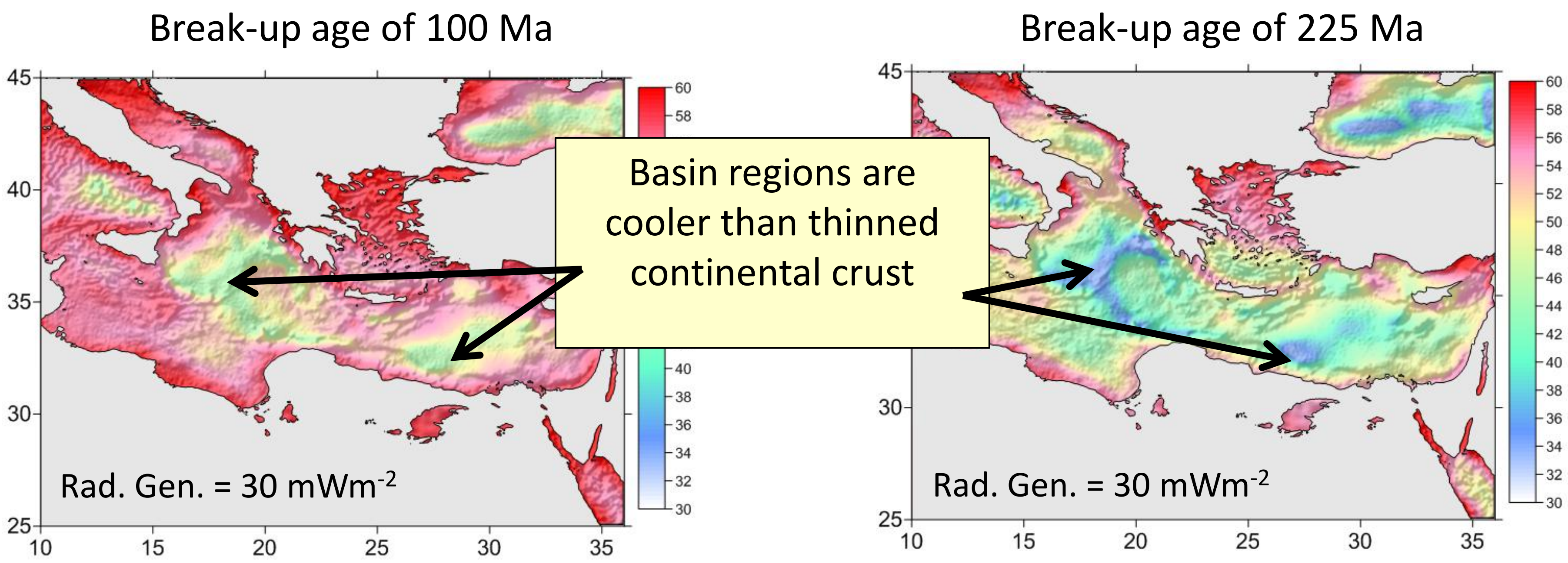
225 Ma (Late Triassic)

Heat Flow Components
(using McKenzie 1978 framework)

- Radiogenic heat productivity (in residual continental crust)
- Post lithosphere thinning transient
- Top asthenosphere convective heat flux

Predicted Heat Flow: Results

Present day top basement heat flow (mWm^{-2})



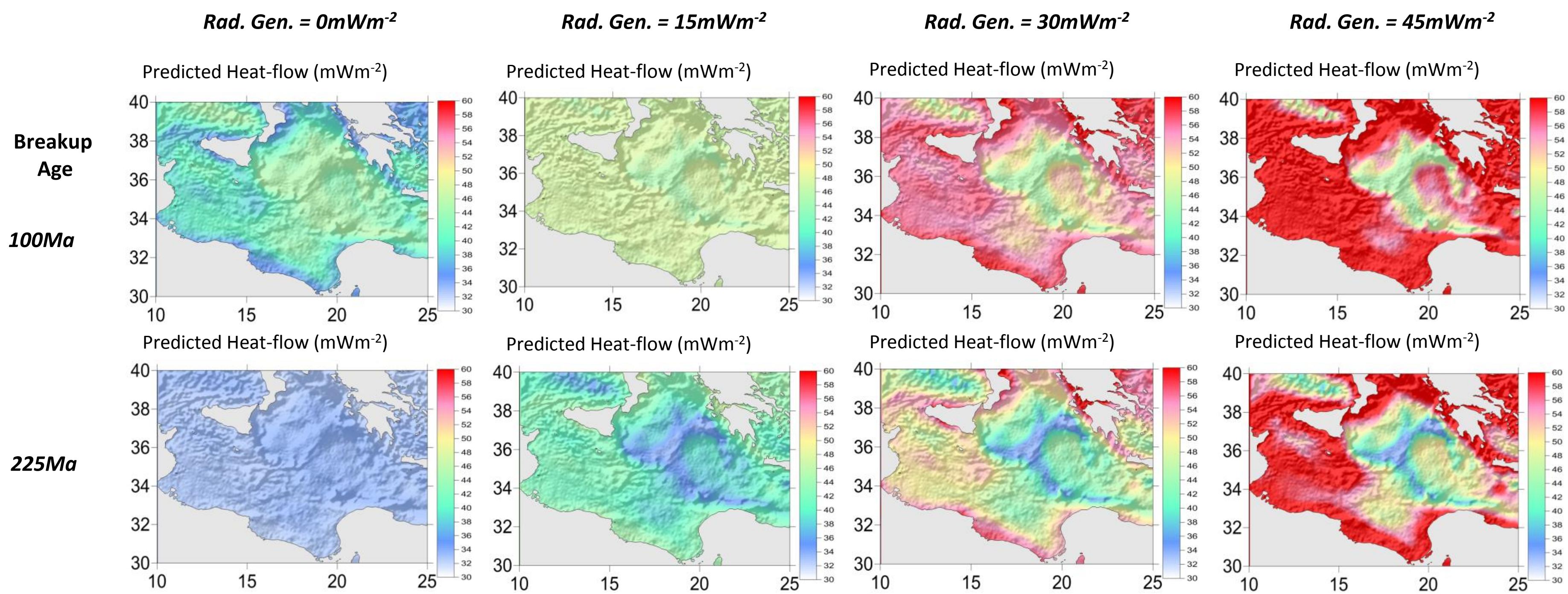
- A higher lithosphere thinning gives a lower preservation of continental radiogenic heat-productivity and a higher transient component.

- Resultant top basement heat-flow is a “trade-off” between these and depends on post-thinning thermal re-equilibration (cooling) time and initial radiogenic heat-productivity.

Predicted Heat Flow: Sensitivity

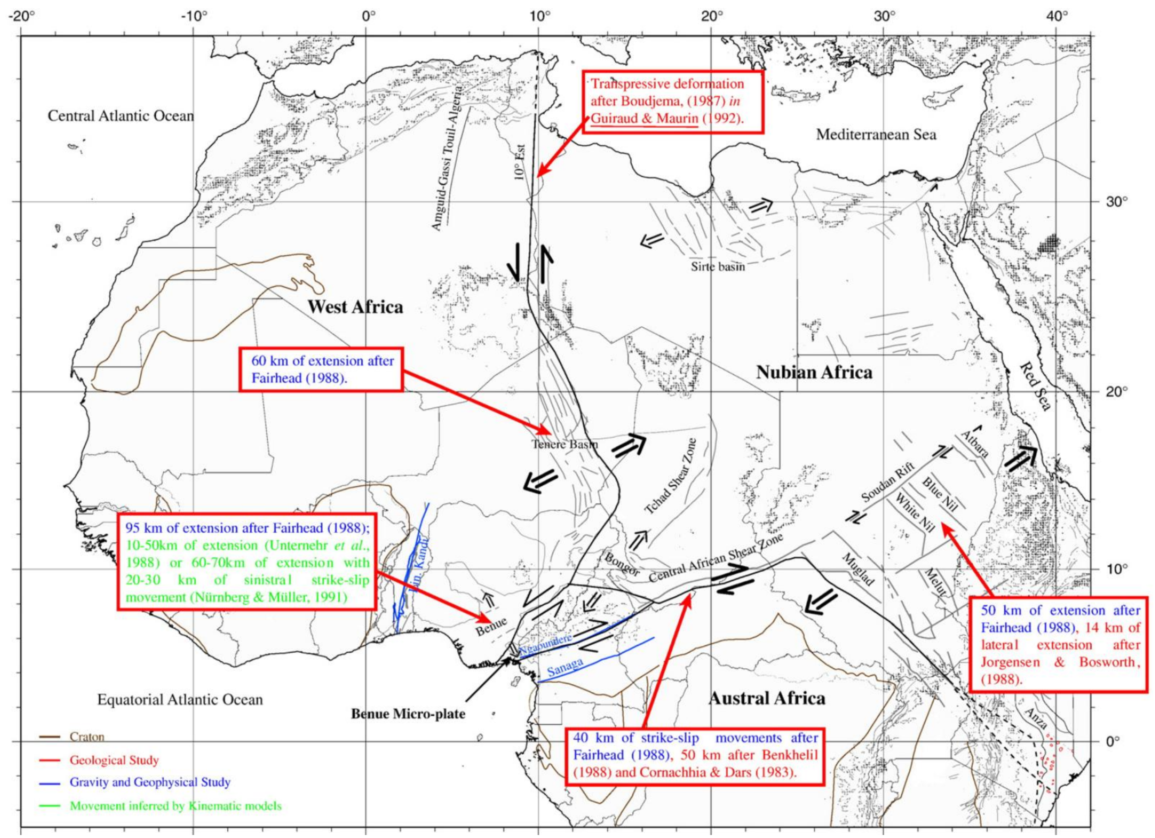
- Predicted heat flow is sensitive to
  - initial continental radiogenic heat-productivity
  - continental margin breakup age (lithosphere post-thinning thermal re-equilibration (cooling) time)
  - and initial radiogenic heat-productivity.

Sensitivity to radiogenic heat productivity (mWm^{-2})



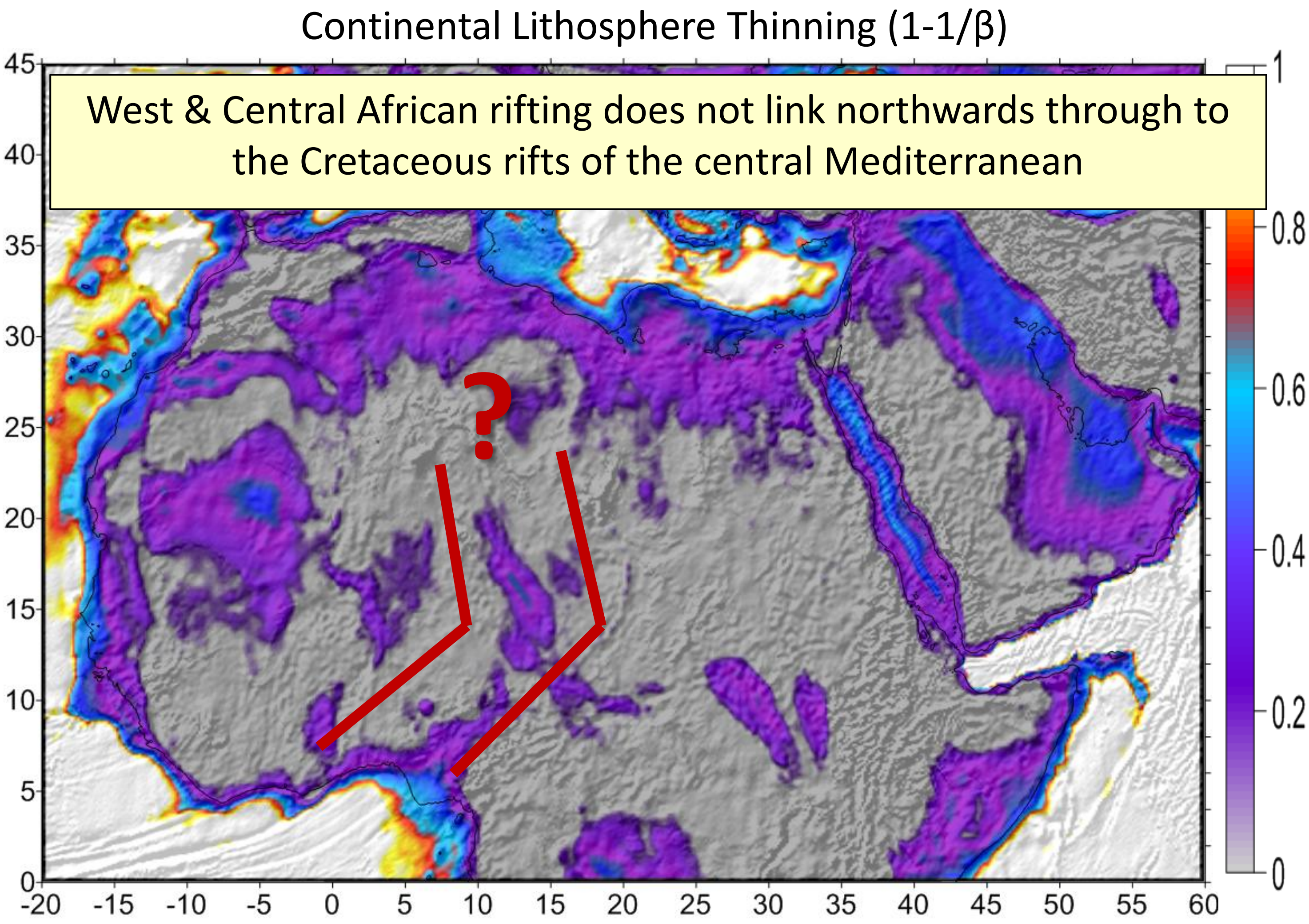
Cretaceous Rifting in North Africa

- Early Cretaceous rifts in West and central Africa are related to the opening of the south and equatorial Atlantic.
- It has been suggested that this rifting links northwards to the central Mediterranean.



Moulin et al., 2010

Lithosphere Thinning for North Africa



Break-up age= 100Ma
ZMoho ref= 37.5km

Summary:

- Gravity inversion has been used to map the distribution of oceanic and continental crust in the eastern Mediterranean, using public domain data.

- The Ionian and Herodotus Basin → underlain by oceanic/highly thinned continental crust

- Sirte and Levant Basin → underlain by highly thinned continental crust (<20km)

- West and central African rifting does not propagate far enough northwards to tectonically link with the cretaceous rifts of central Mediterranean.

- Not possible to further determine age of break-up of eastern Mediterranean.