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WATER-LOADED DEPTH AND HEAT FLOW PATTERN OF THE EASTERN MEDITERRANEAN SEA

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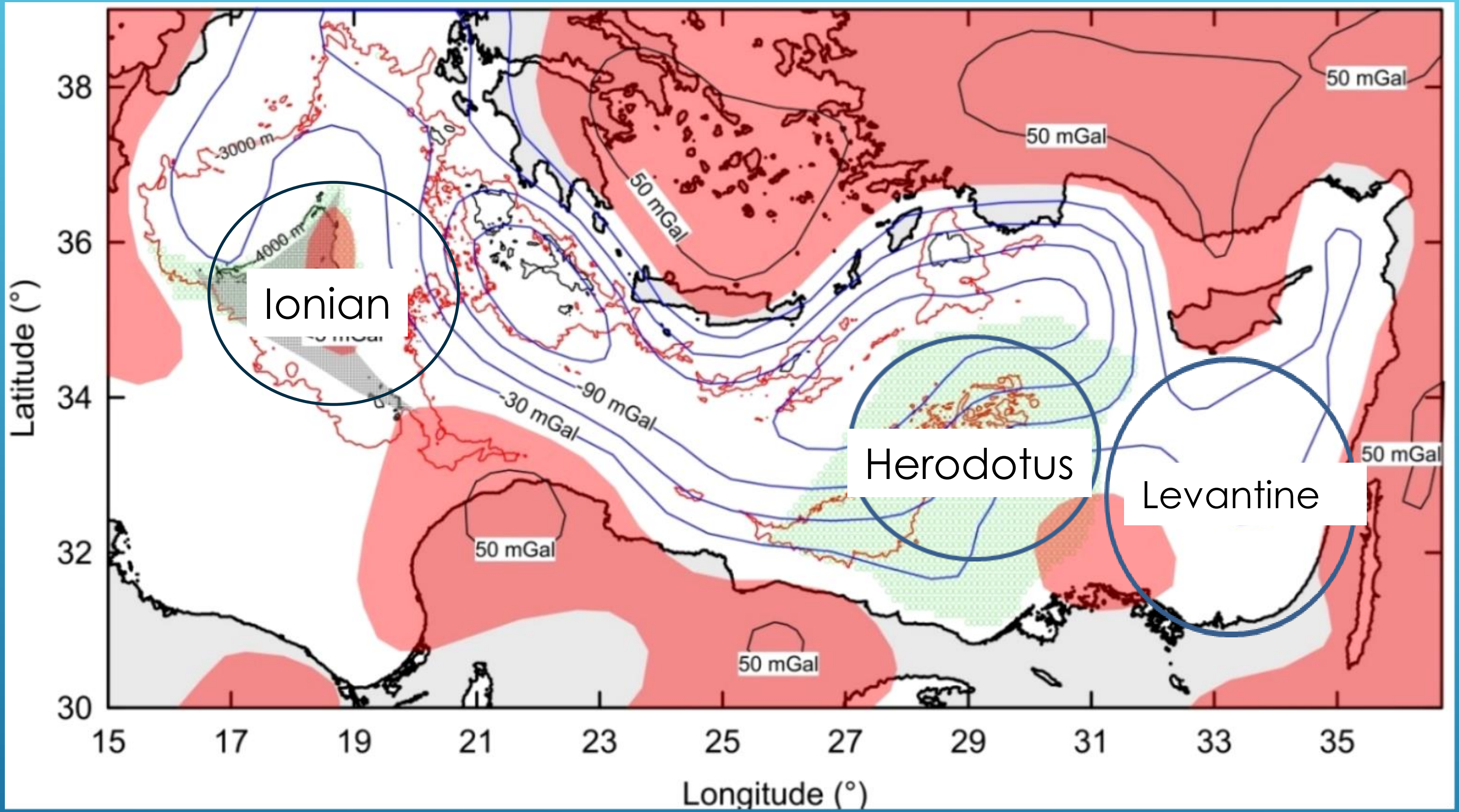
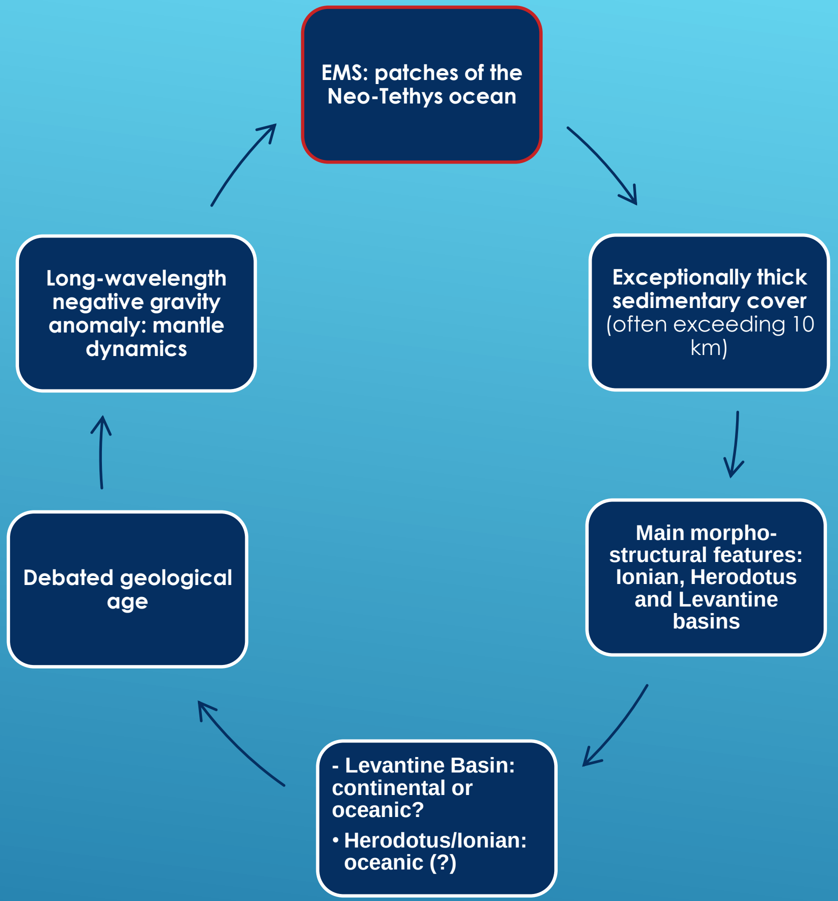
GEOPHYSICAL AND STRUCTURAL FEATURES OF EMS

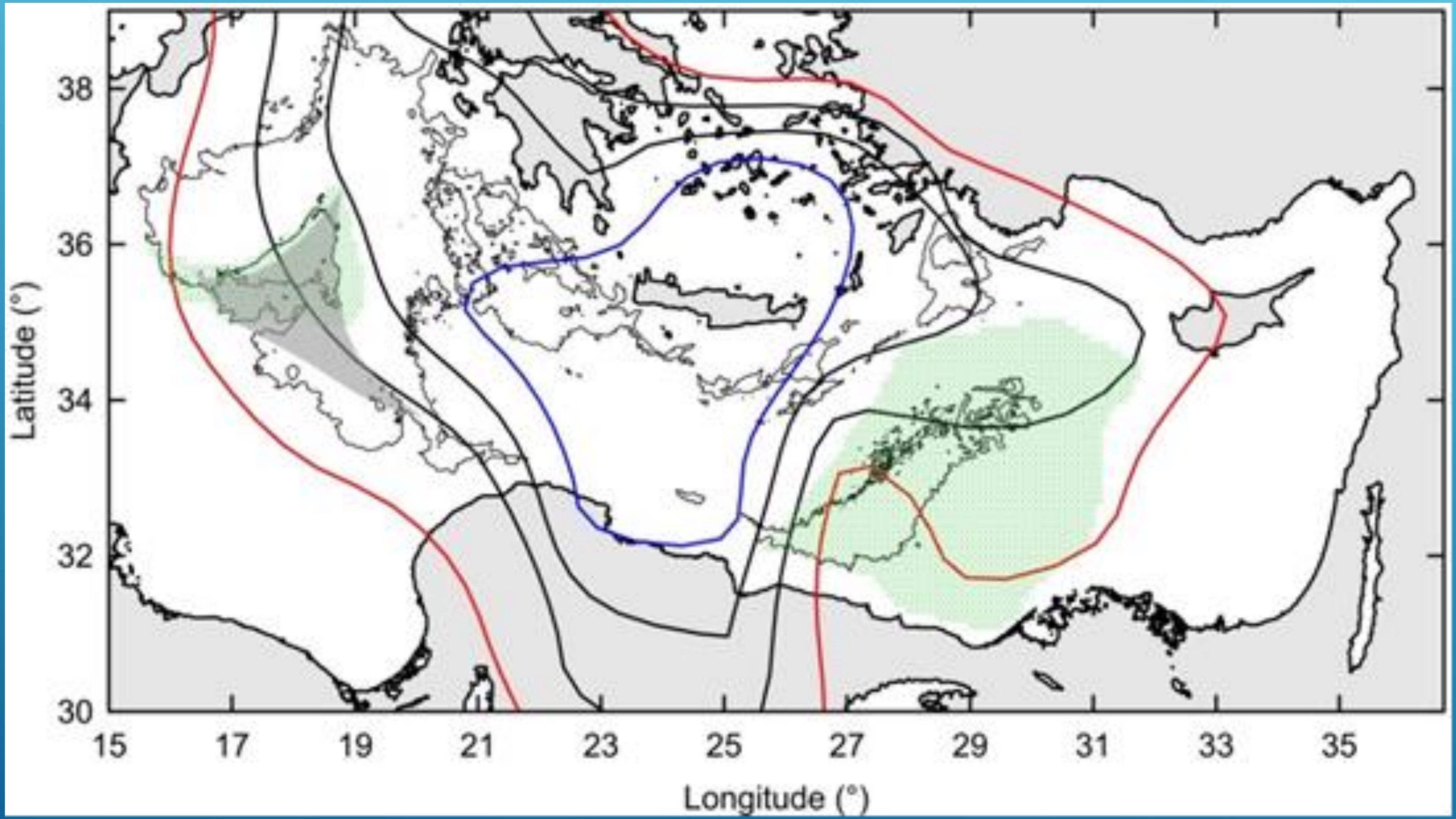


Gravity anomalies from GOCE with wavelengths larger than 300 km (after, McKenzie, 2020). Areas with a positive anomaly in red; blue contours indicate negative values plotted every -30 mGal (~-1 km of dynamic topography). Bathymetry (in m) is derived from the global seafloor database V18.1 (Smith and Sandwell, 1997), from satellite altimetry and ship depth soundings (http://topex. ucsd.edu/cgi-bin/get_data.cgi). The limits of the oceanic lithosphere (light green hatch) by Seton et al. (2020). Grey area, oceanic lithosphere below the seafloor in the Ionian Basin (undeformed portion) as determined by seismic studies (Dannowski et al., 2019).



LITHOSPHERIC AGE and THICKNESS

	Age (Ma)	Lithosphere thickness (km)
Ionian Basin	220-230*	100-140
Herodotus Basin	315-365**	100-140
Levantine Basin	95-125***	< 100



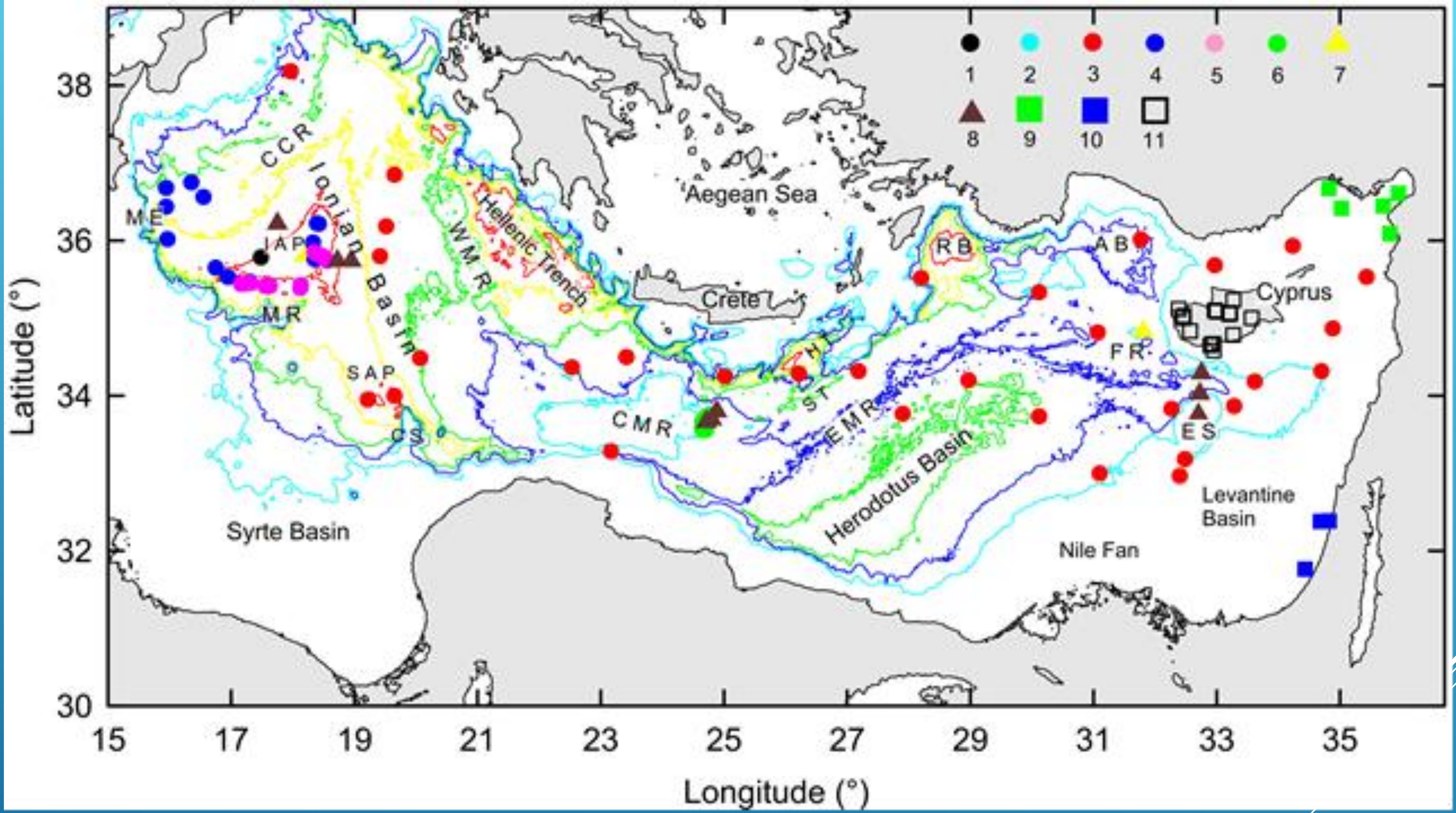
Contour lines: red - 100 km; blue - 160 km (after McKenzie, 2020).

* Speranza et al. (2012);
** Granot (2016);
*** Segev et al. (2018).

APPROACH

- Investigating the nature of the Eastern Mediterranean lithosphere → Calculation of sediment load-corrected basement depth (WLD) → Geothermal flow: an insight into the lithosphere thermal state
- Data processing → Bathymetry and heat-flow data: removing effects of sediment → Calculation of WLD and the estimation of the corrected HF (sedimentation, paleoclimate, radiogenic heat)
- Comparison of WLD and corrected HF with predictions of reference models of continental stretching ocean lithosphere and cooling → Discriminating between oceanic and continental realms of the Eastern Mediterranean lithosphere

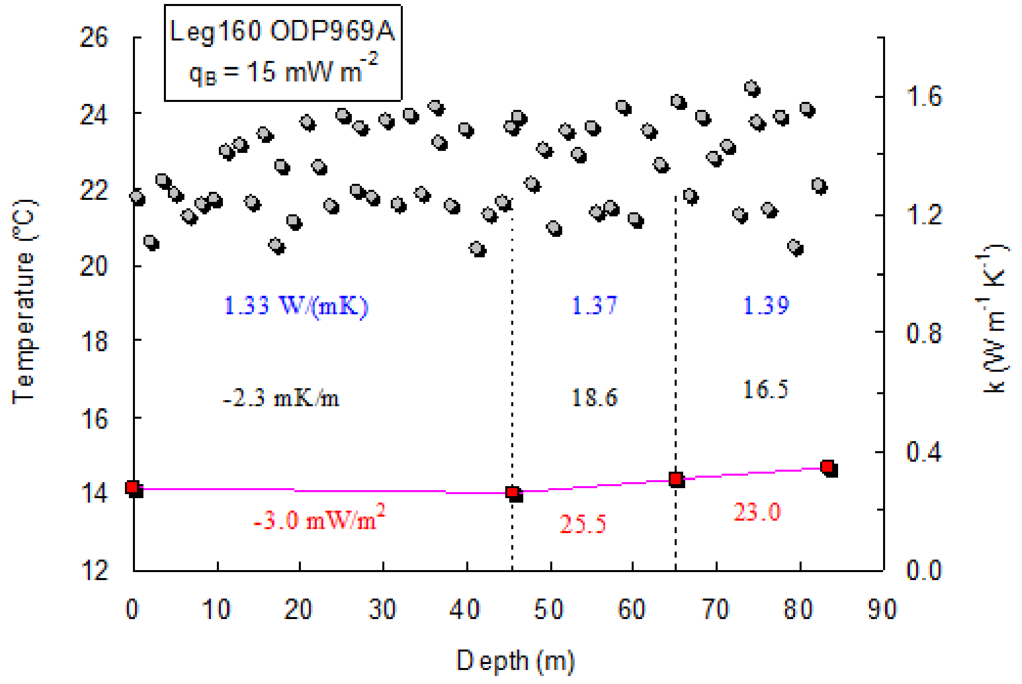
OBSERVED HEAT FLOW

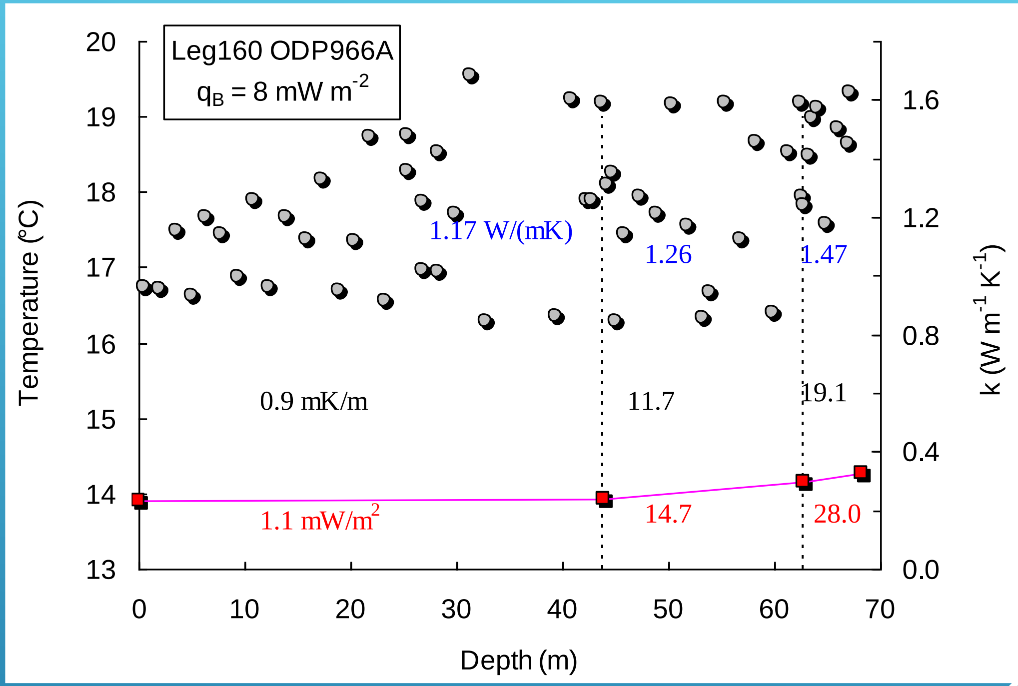


Location of heat-flow data in the EMS and bathymetries from the global seafloor database V18.1 by Smith and Sandwell (1997), derived from satellite altimetry and ship depth soundings (http://topex.ucsd.edu/cgi-bin/get_data.cgi): - 2000 m (cyan line), -2500 m (blue line), -3000 m (green line), -3500 m (yellow line) and -4000 m (red line). Full circle = data obtained with the Ewing probe (1 – Birch and Halunen, 1966; 2 – Haenel, 1972; 3 – Erickson, 1970; 4 – Della Vedova and Pellis, 1986; 5 – Della Vedova and Pellis, 1992; 6 – Camerlenghi et al., 1995). Full triangle = data from temperature logging in deep-sea boreholes (7 - Erickson and Von Herzen, 1978; 8 – Pribnow et al., 2000). Full square = data from bottom hole temperatures (BHTs) recorded in oil wells (9 - Tezcan and Turgay, 1991; 10 - Shalev et al., 2013). Empty square = data from shallow boreholes for water and mineral exploration (11 - Morgan, 1979). CCR = Calabria continental rise; ME = Malta Escarpment; IAP = Ionian abyssal plain; SAP = Syrte abyssal plain; MR = Medina Ridge; WMR = Western Mediterranean Ridge; EMR = Eastern Mediterranean Ridge; CMR = Central Mediterranean Ridge; CS = Cyrene Seamount; HT = Hellenic Trench; ST = Strabo Trench; RB = Rhodes Basin; AB = Antalya Basin; FR = Florence Rise; ES = Eratosthenes seamount.

HF DATA QUALITY ASSESSMENT

Rejecting data unrepresentative of the lithosphere thermal state



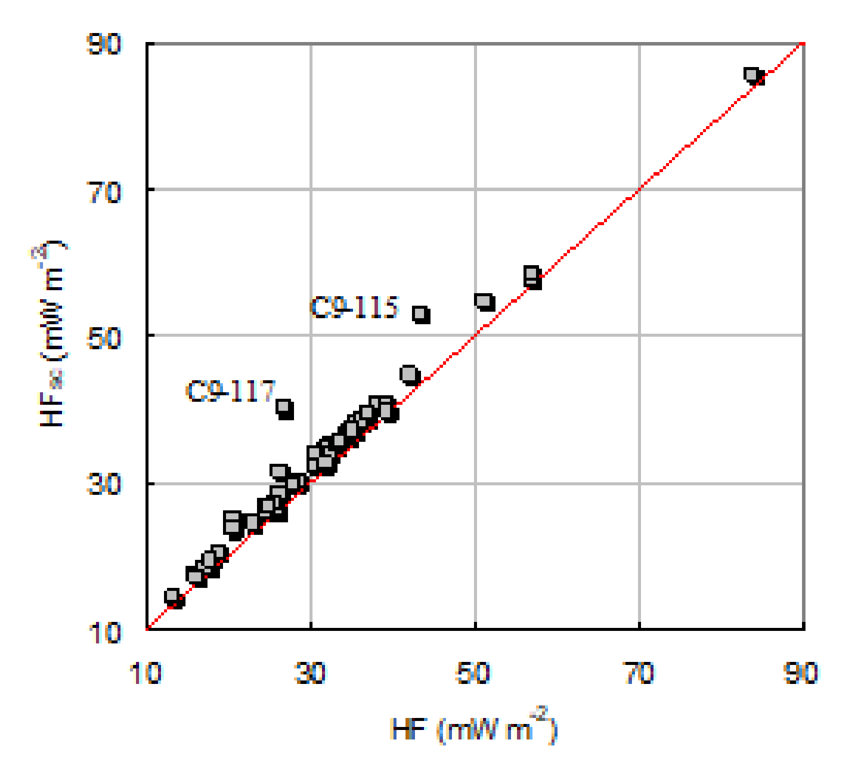


Example of two low-quality HF data (ODP)

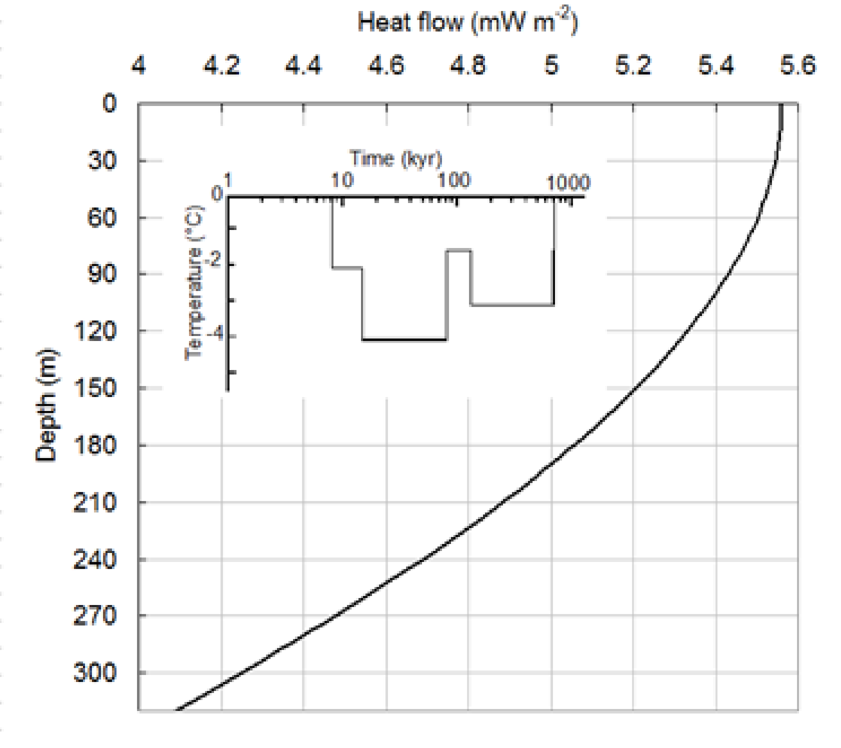
Thermal gradient and, consequently, the heat flow are extremely low or even negative

Are they affected by local disturbances (fluid flow?)

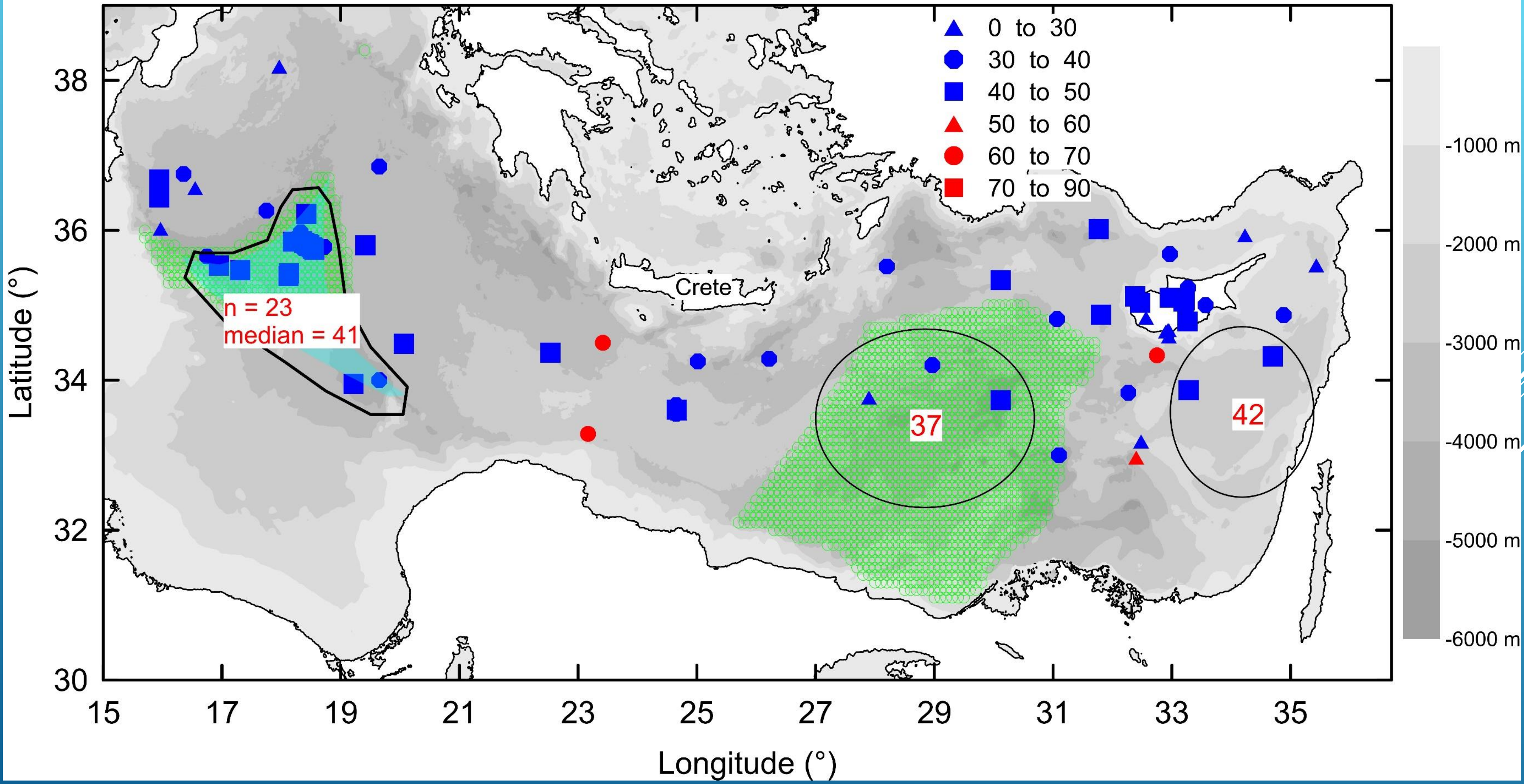
HF CORRECTIONS



Sedimentation (2 mW m^{-2})
Paleoclimate (4 — 6 mW m^{-2})



CORRECTED HEAT FLOW



WATER LOADED SEAFLOOR DEPTH (WLD)

- WLD: assuming Airy isostasy; adding the **correction for sediment loading, c_s**, to the seafloor depth (**bathymetry**)

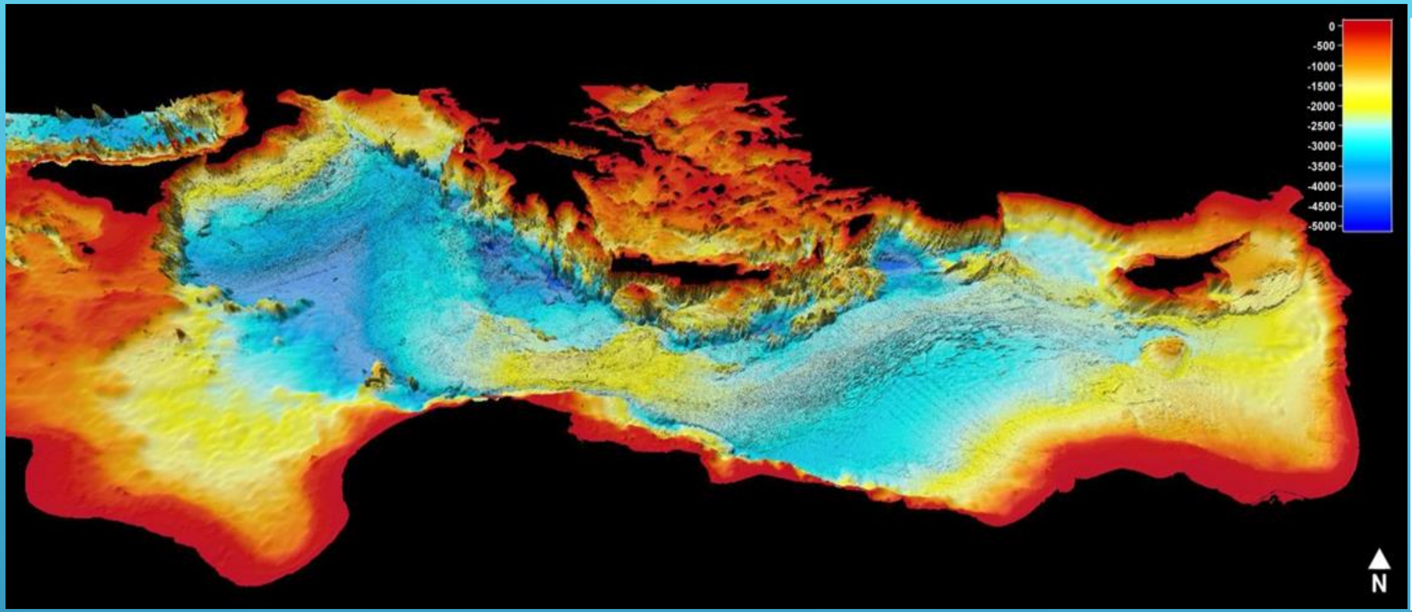
$$c_s = \frac{\rho_a - \rho_s}{\rho_a - \rho_w} h_s$$

- where $\rho_a = \rho_m (1 - \alpha T_a)$ is the asthenosphere density
- ρ_m is lithospheric mantle density at room temperature
- T_a the asthenosphere temperature
- α the thermal expansion coefficient, ρ_w the seawater density
- ρ_s the **mean bulk density** of the sedimentary column
- h_s is the **sedimentary column thickness**

ρ_s varies with depth**, z**, according to

$$\rho_s = \rho_{sg} + \frac{\phi_o \lambda}{z} (\rho_w - \rho_{sg}) \left(1 - e^{\frac{-z}{\lambda}} \right)$$

where ρ_{sg} is the solid grain density, ϕ_o the porosity of sediment at depth z=0, and λ the compaction decay length scale for oceanic sediments



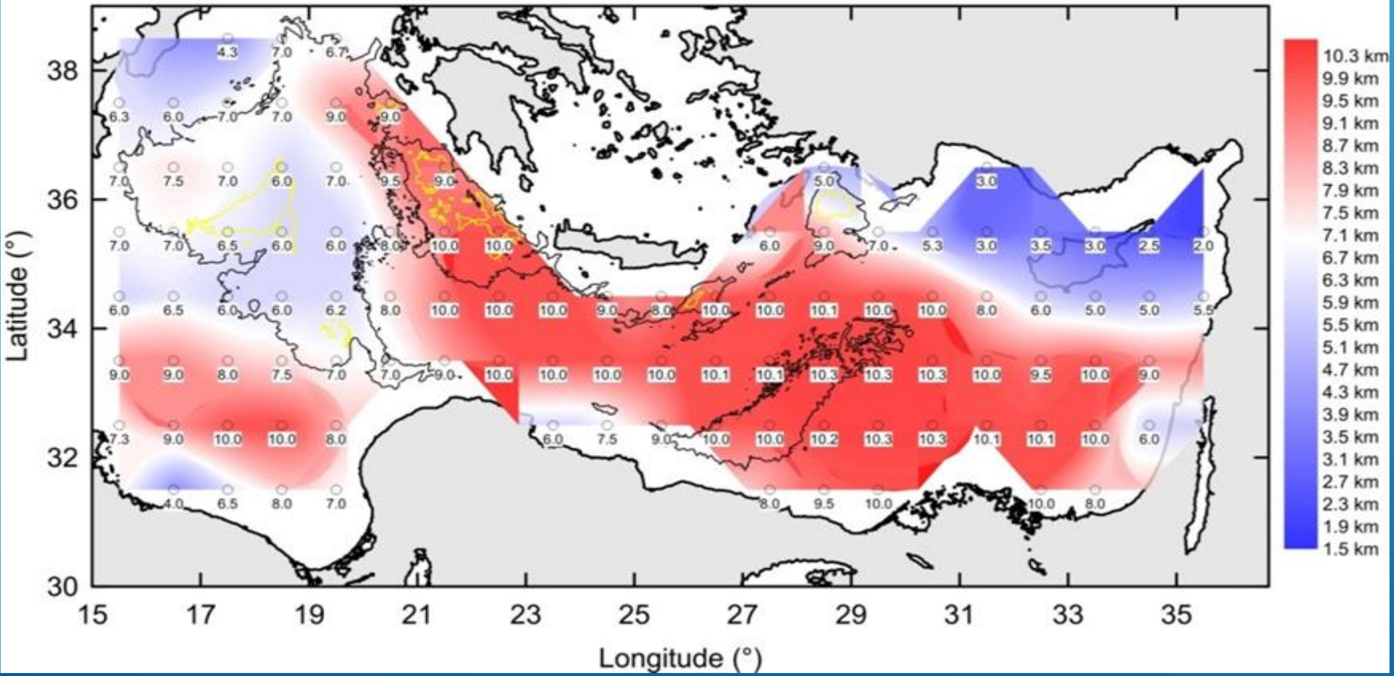
Bathymetry data

EMODnet – NOAA - ETOPO 1 – TOPEX **GEBCO**

Mean difference in bathymetric data from global datasets: 30-100 m

Easy detection of local tectonic features: **Seamounts, Flexural moats** (may be filled with sediments)

EMS Bathymetry and Sediment thickness



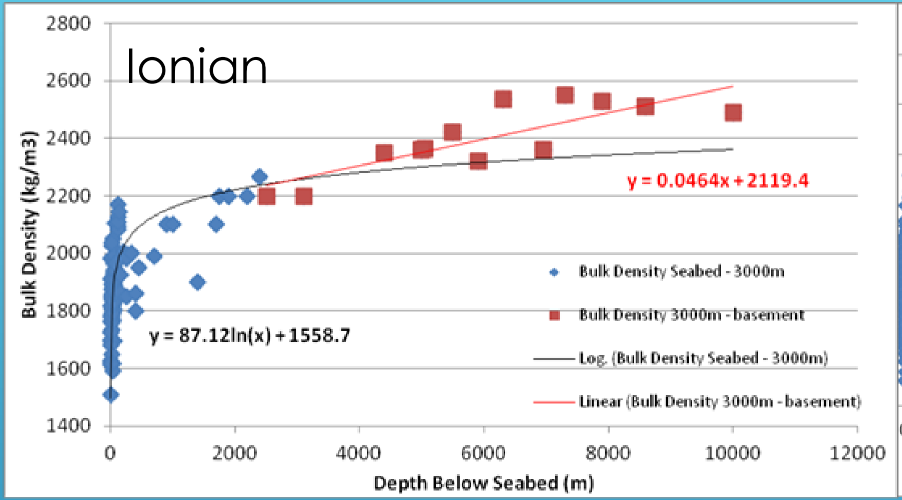
Sediment Thickness (*hs*)

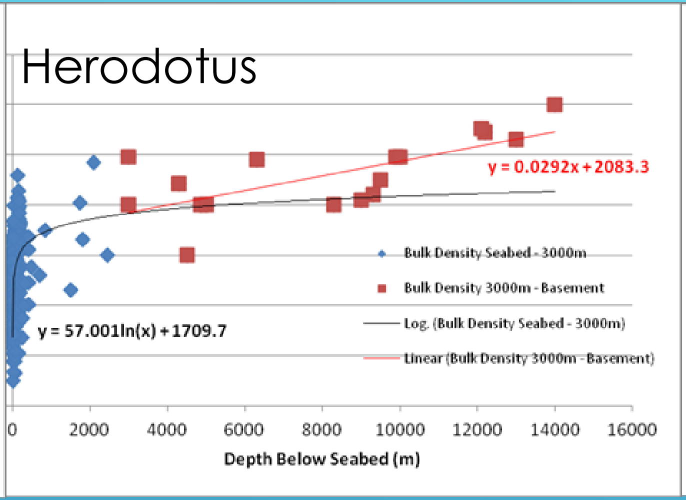
Dataset: **Crust 1.0 model** / seismic data

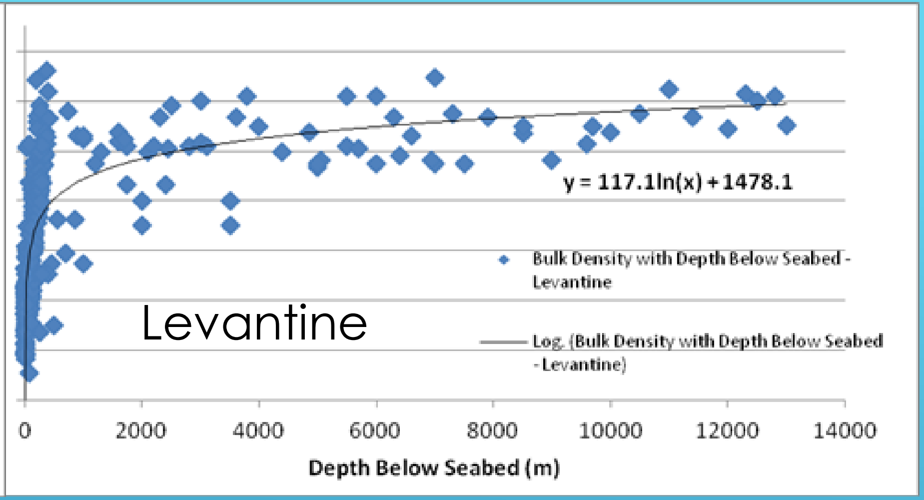
Spatial resolution: 1°x1°

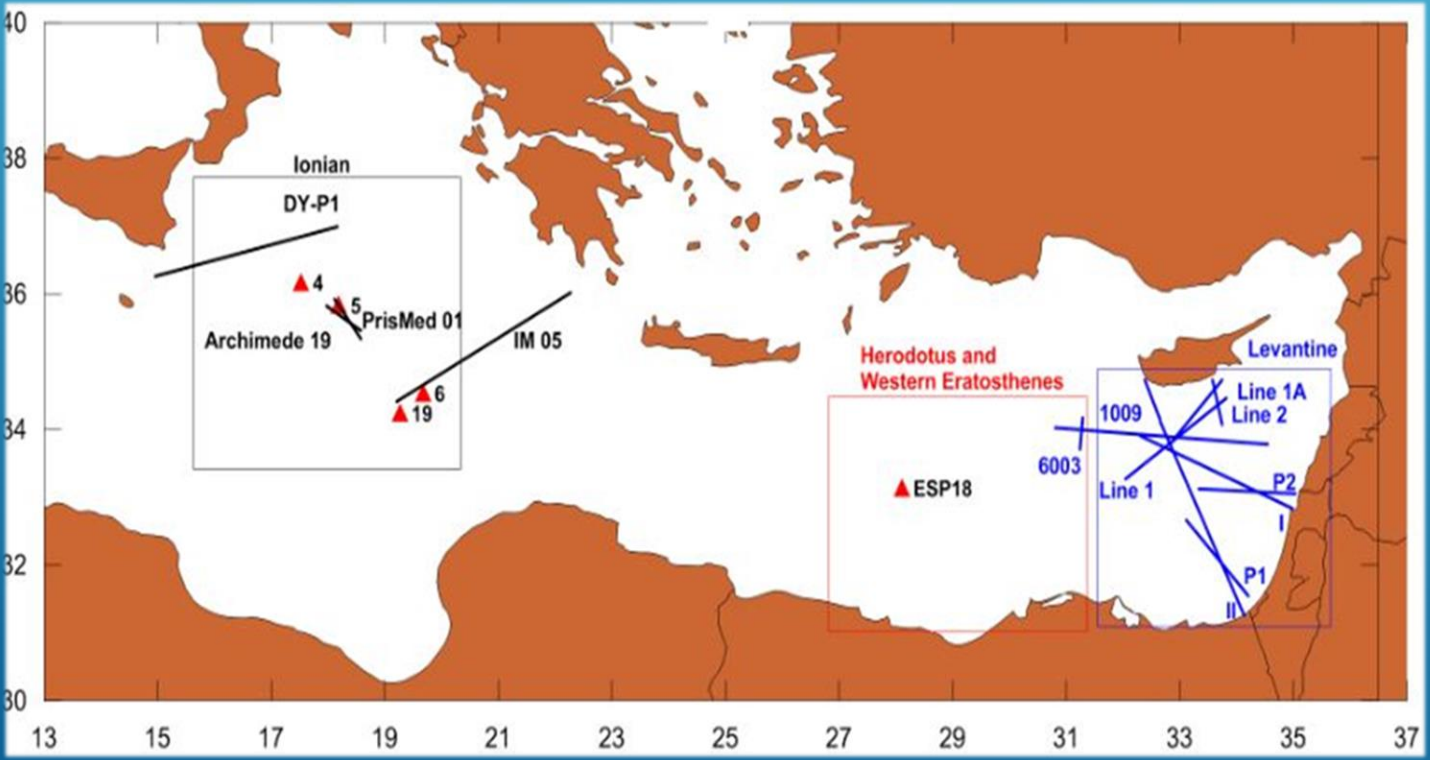
Calculated sediment correction and WLDs for 1°x1° bins

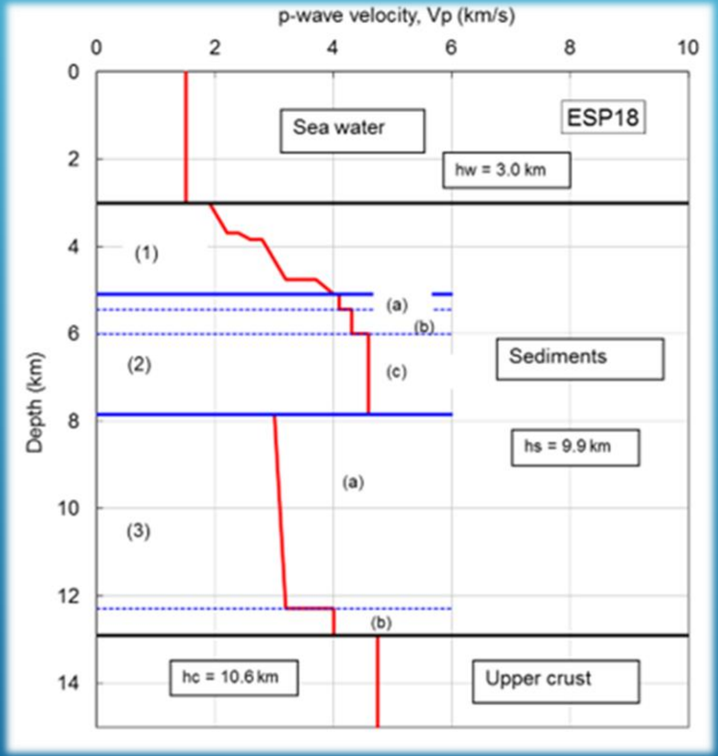
ESTIMATION OF BULK DENSITY



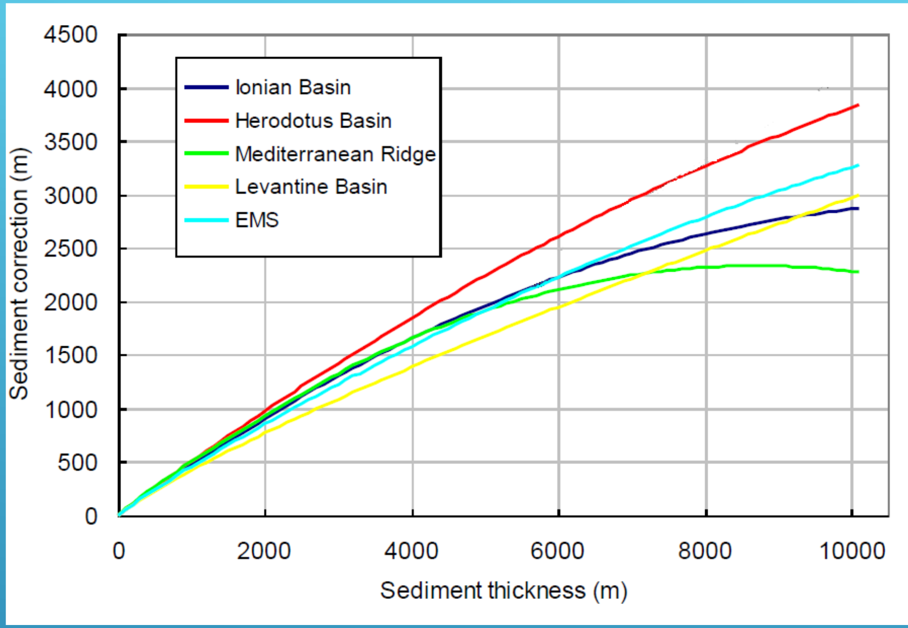




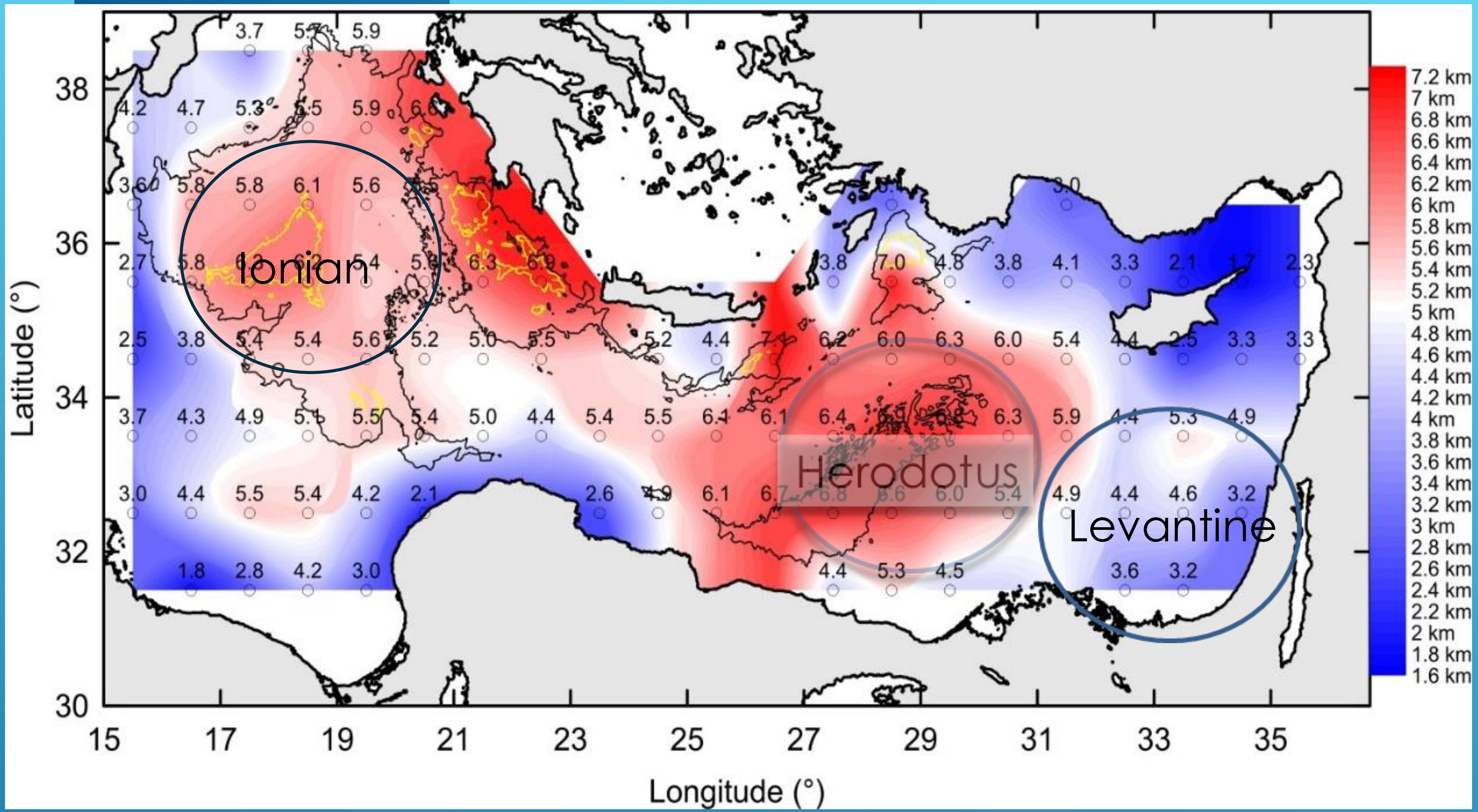




WLD

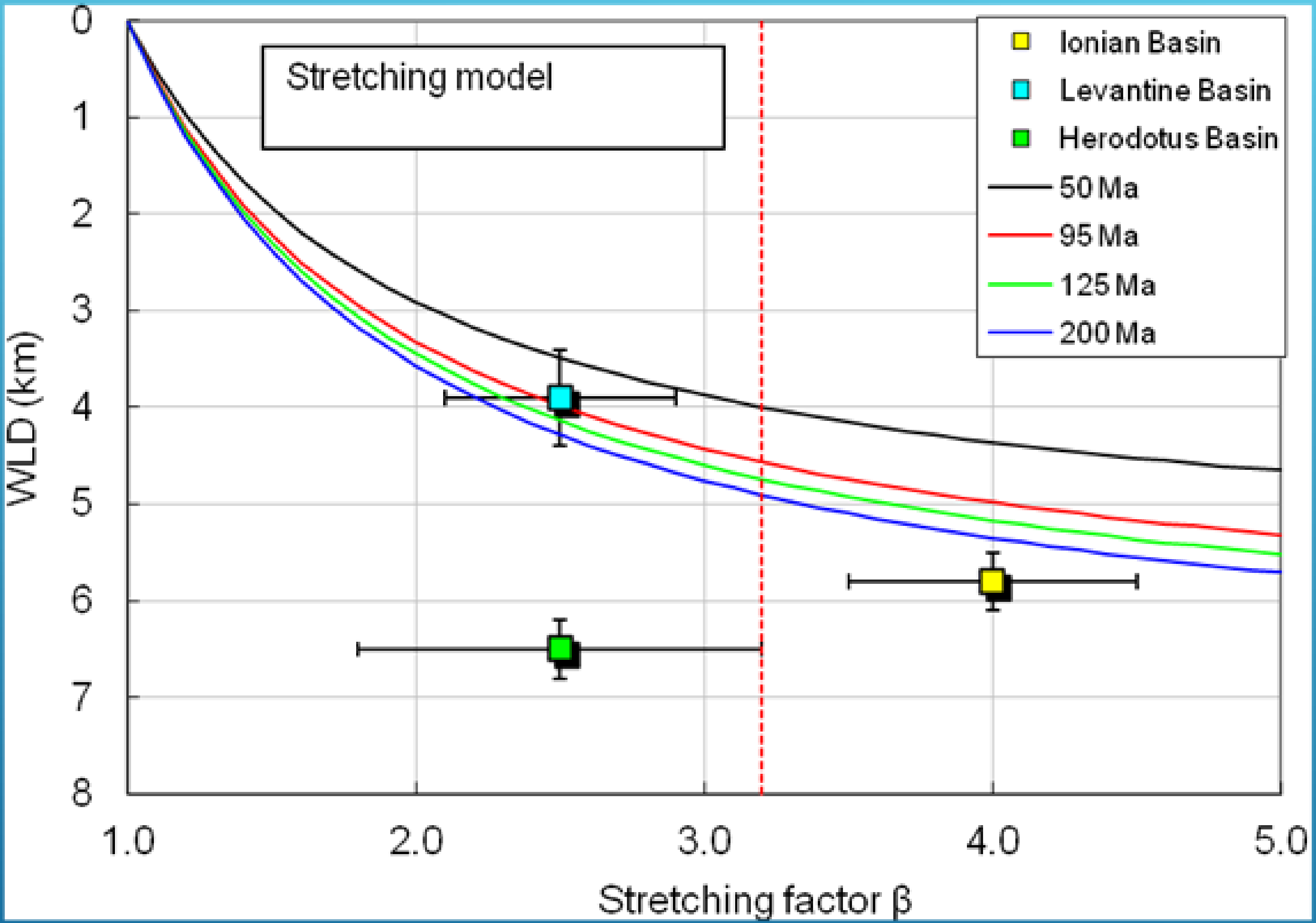


Sediment correction c_s as a function of sediment thickness



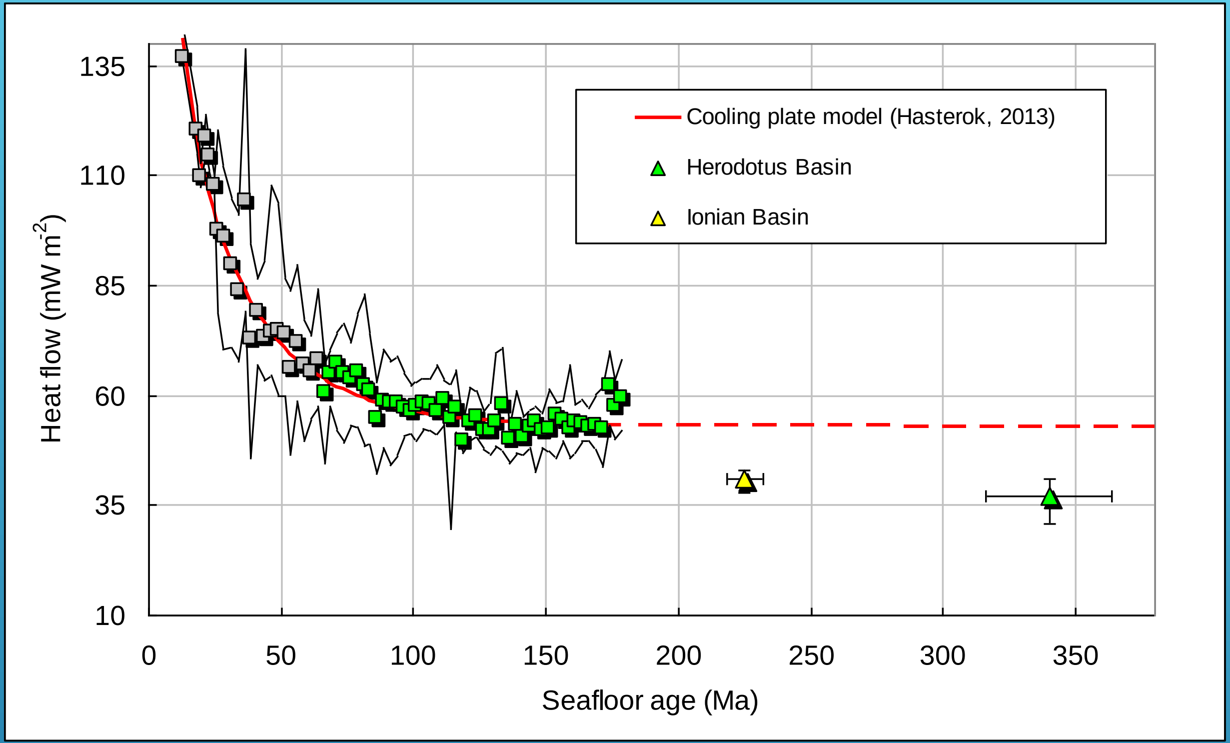
Basin	Sites/Datasets	WLD_s (km)
Ionian	2 ESP, 5 global datasets and 3 seismic profiles	5.8 (0.3)
Herodotus	1 ESP, 15 global datasets and 1 seismic profile	6.5 (0.3)
Levantine	4 global datasets and 5 seismic profiles	3.9 (0.5)

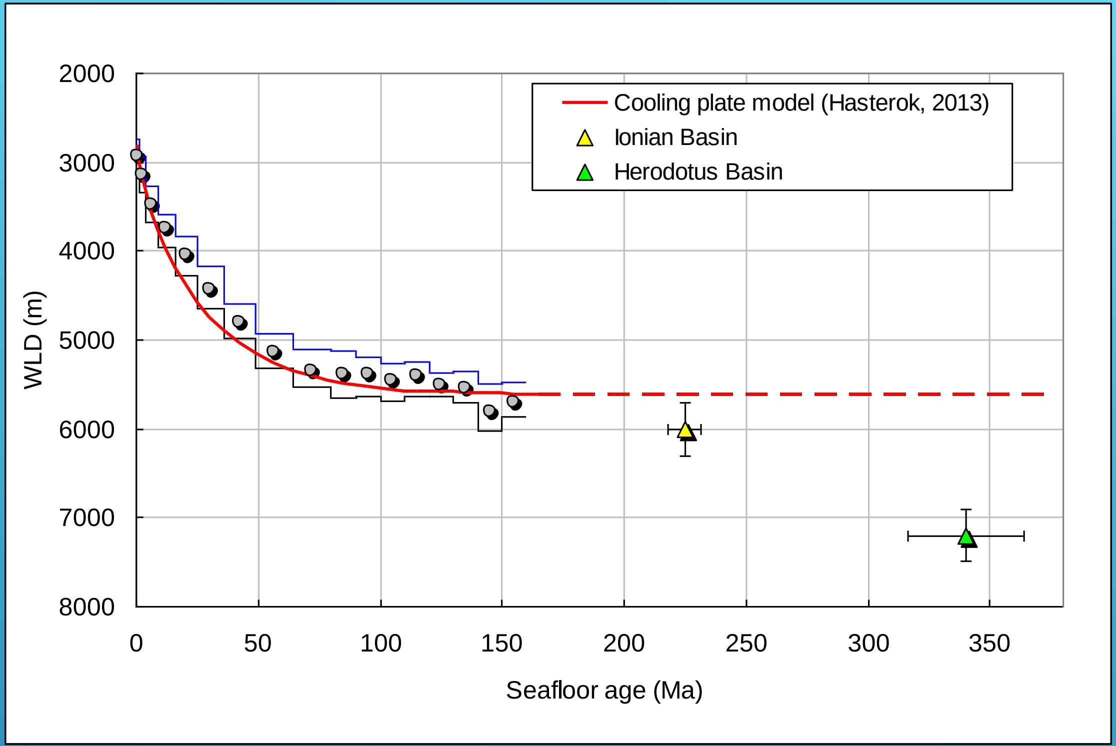
COMPARISON OF WLD AND CORRECTED HF WITH PREDICTIONS OF REFERENCE MODELS (I) LITHOSPHERE PURE STRETCHING (CONTINENTAL BASIN)



BASIN	WLD
LEVANTINE	• **Estimated age of age** of **95-125 Ma (Early Cretaceous)** • Likely reached **thermal equilibrium** (no more enhanced HF) • **Agree with the predicted value** for 2.1<β**<** 2.9 • **Estimated β** in agreement with previous studies (2.3 – 3.0)
HERODOTUS	**WLD excess of 2.2 km than the predicted** value (Probably of Oceanic nature)
IONIAN	**WLD excess of 2.2 0.5 km > than the predicted** value (Probably of Oceanic nature)

(II) OCEANIC LITHOSPHERE: PLATE MODEL (PM)





Lithosphere age

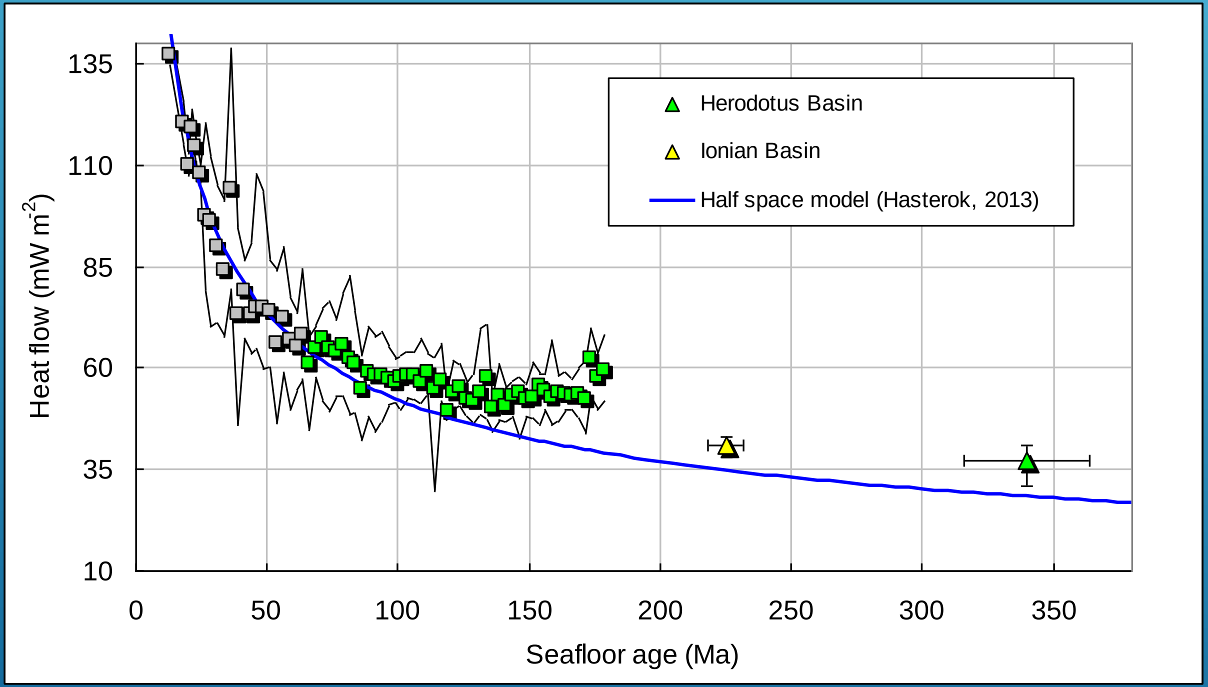
Ionian Basin
225 Ma

Herodotus Basin
340 Ma

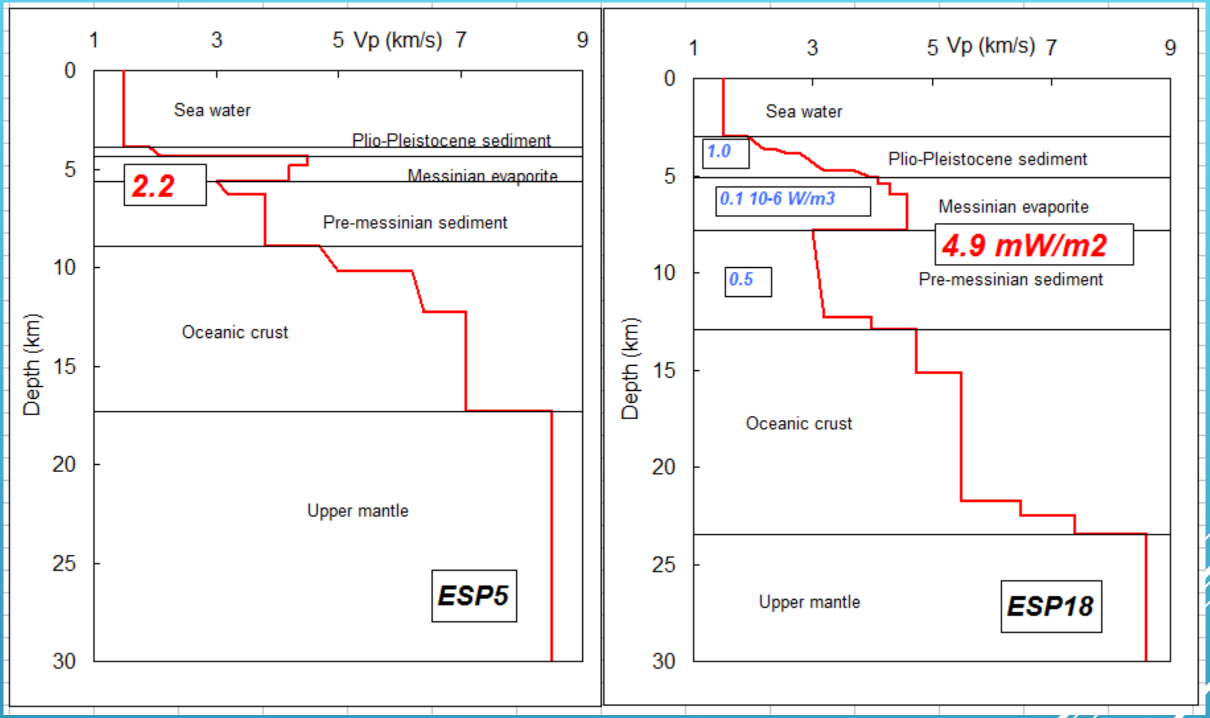
- HF and WLD in the Ionian and Herodotus oceanic areas do not fit the reference PM
- HF is 12 and 16 mW/m2 < reference value (53 mW/m^2) in the Ionian and Herodotus basins, respectively.
- WLD exceeds the expected value of 0.4 km in the Ionian Basin and 1.6 km in the Herodotus Basin. However consistent with the free-air gravity anomaly pattern (dynamic topography)
- The reference PM (Hasterok, 2013) assumes the lithosphere to have a thickness of 90 km which is lower than that observed in EMS by McKenzie (2020)

(III) OCEANIC LITHOSPHERE: HALF-SPACE (HS)

- The HF of the Ionian and Herodotus basins exhibits similarities to that of the Gulf of Mexico (Nagihara et al., 1996).
- Small scale convection might be inapplicable to a narrow basin surrounded by continental lithosphere like the EMS.
- In this context a semi-infinite half-space cooling law may apply up to much larger ages.



HF is 6 and 9 mW/m2 > reference value in the Ionian and Herodotus basins, respectively.

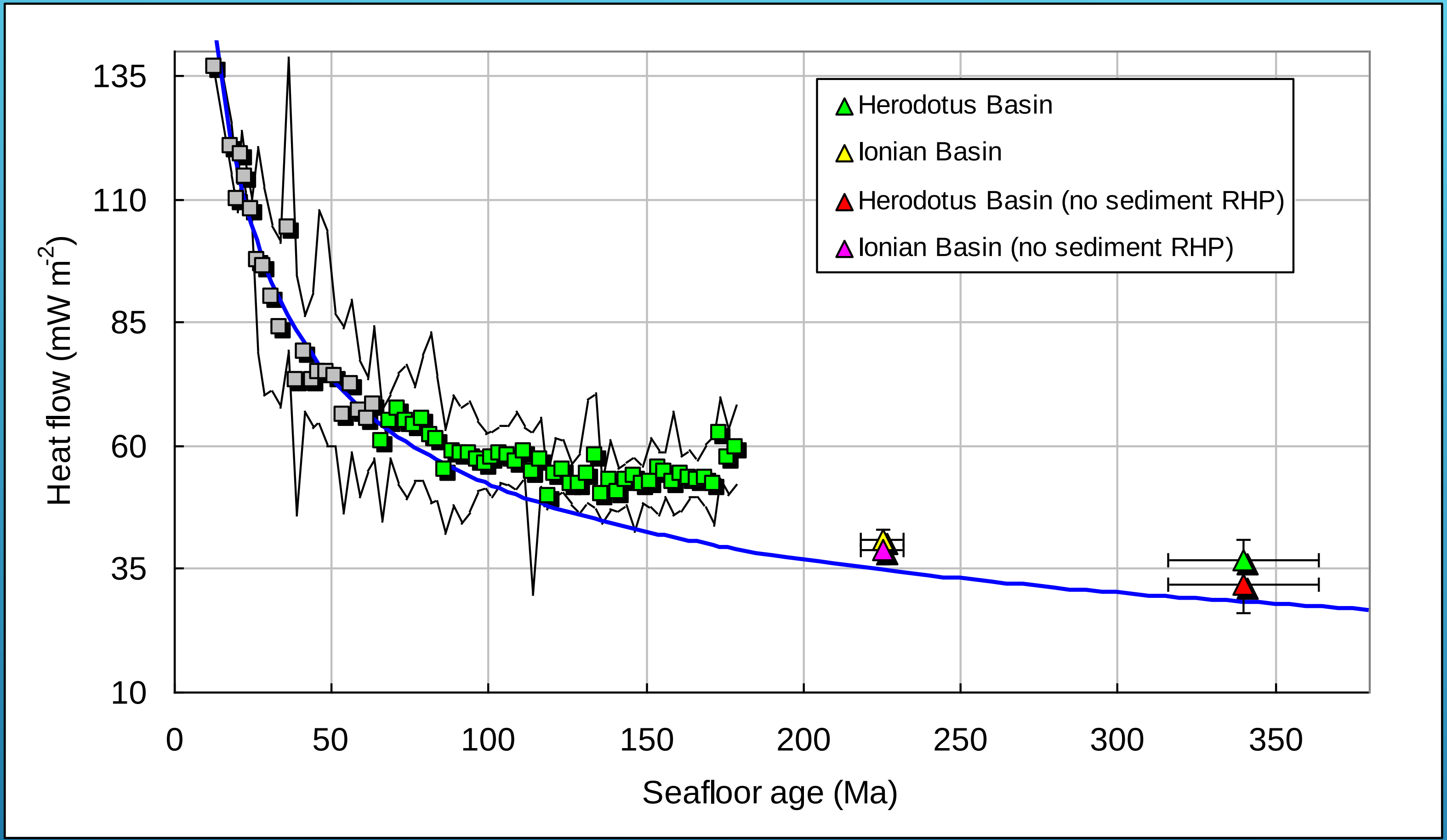


Heat flow has been reduced for the contribution by radioactive decay within the sediments.

An estimated contribution of 2 mW/m2 for the Ionian and 5 mW/m2 for Herodotus

This reduces the median HF to 39 and 32 mW/m2 in the Ionian and Herodotus, respectively.

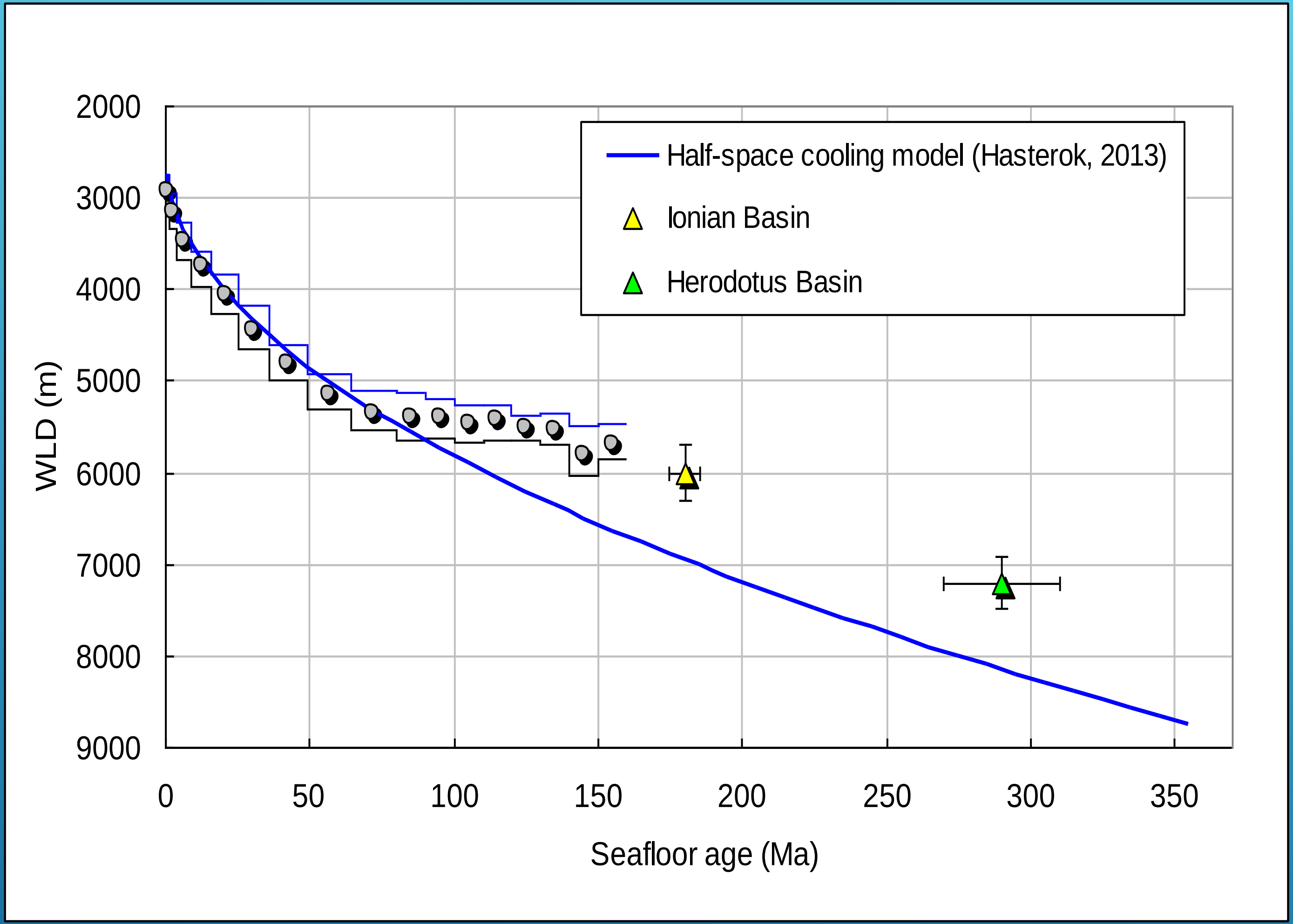
(III) OCEANIC LITHOSPHERE: HALF-SPACE (HF after reduction for radiogenic contribution)



The HF values better match those predicted by the HS model (differences are of 4 mW/m2 in both basins)

- A perfect match would be obtained for ages of about **180 Ma** for the Ionian Basin and **290 Ma** for the Herodotus Basin.

(III) OCEANIC LITHOSPHERE: HALF-SPACE (WLD)



WLD does not agree with the HS model

Reference models assume isostatic equilibrium and ignore the effects of the flexural rigidity of the lithosphere

Failure to account for flexural rigidity will result in over-or underestimates of dynamic topography amplitude, and underestimates of the size of topographic load that can be supported by the plate without flexure (Kirby, 2018).

The heat flow predicted by the HS model HF, rather than WLD, seems thus more effective in defining the age of the oceanic lithosphere in such old oceanic basins

CONCLUDING REMARKS

Continental lithosphere in the Levantine Basin. Since stretching likely occurred about 90 Ma ago, this basin could have reached thermal equilibrium, and thus the surface heat flow does show no enhancement caused by extension.

The large WLD and low heat flow in the Herodotus and Ionian basins argue for an oceanic lithosphere.

Both the adopted reference models for the oceanic lithosphere (the plate model and the half-space cooling) are not satisfactory in accounting for calculated WLD

This means that EMS escapes from classical schemes of ocean lithosphere cooling and subsidence: similarities with the Gulf of Mexico

The WLD excess estimated with the plate model is consistent with free-air gravity data, whereas the heat flow data seem in better agreement with the half-space model

The WLD excess, the negative long-wavelength gravity anomaly and the low heat flow argue for:

- the presence of a colder and thick lithosphere in the Ionian and Herodotus basins and the lack of small-scale boundary layer convection
- the downwelling of mantle material as a result of a negatively buoyant, thick lithosphere.