Lithospheric Heat Flow and Dynamics

- **obvious signals**
  - heat flow, depth, and geoid height versus age
  - does hydrothermal circulation really transport 10 TW?

- **inferred signals**
  - lithospheric thickness and strength versus age
  - swell-push force and global stress from the geoid

- **mysterious signals**
  - details of 3-D plate shrinkage
  - are gravity lineaments and volcanic ridges due to lithospheric shrinkage?
  - are transform faults thermal contraction cracks?
global heat budget

\[ q_s \]

44 TW

\[ q_b \]

7.5 TW

conduction

lithosphere

7.5 TW

convection

mantle  25-15 TW

convection

core  3-13 TW
oceanic lithosphere dominates mantle convection

largest surface area
greatest temperature drop across TBL = largest density contrast
> 1/2 of heat escapes in young oceanic lithosphere
Mean mantle heat production rates due to the decay of the radioactive isotopes of U, Th, and K as functions of time measured back from the present.
thermal expansion

volumetric expansion

\[
\frac{\Delta V}{V} = \alpha \Delta T \quad \text{or} \quad \frac{\Delta \rho}{\rho} = -\alpha \Delta T
\]

\( \alpha \) - thermal expansion coefficient \( \sim 3 \times 10^{-5} \, ^\circ C^{-1} \)

linear expansion

\[
\frac{\Delta l}{l} = \alpha_i \Delta T
\]

\( \alpha_i \equiv \frac{\alpha}{3} \)
obvious signals

- depth versus age
- heat flow versus age
- geoid height versus age
depth vs age $\Rightarrow d(t) = \frac{-\alpha \rho_m}{\rho_m - \rho_w} \int_0^L Tdz \Rightarrow d(t) \equiv 2500 + 350 t^{1/2}$

Fig. 1. Plot of mean depth in the North Pacific versus the square root of age. Numbers at the bottom of the figure denote selected Cenozoic and Mesozoic magnetic anomalies [from Parsons and Sclater, 1977].
heat flow vs age  \[ \Rightarrow \quad q(t) = k \frac{\partial T}{\partial z} \quad \Rightarrow \quad q(t) \approx 480 t^{-1/2} \]
What is the global heat output of the Earth?

How do we interpret this discrepancy?

A) The other 10 TW is transferred by hydrothermal circulation [Lister, 1972; Williams et al., 1974; Sleep and Wolery, 1978, Anderson and Hobart, 1976; Stein, 1995]

B) The other 10 TW does not exist and the total heat output from the Earth is < 34 TW [Hofmeister and Criss, 2005].
conservation of energy
\[ \rho_m C_p \mathbf{v} \cdot \nabla T = \nabla \cdot \mathbf{q} \]

thermal isostasy
\[ d(t) = \frac{-\alpha \rho_m}{\rho_m - \rho_w} \int_0^L T dz \]

\[ (q_b - q_u) = \frac{(\rho_m - \rho_w) C_p}{\alpha} (\mathbf{v} \cdot \nabla d) \]

heat = constant \times scalar subsidence rate

Parsons and McKenzie: Convection Beneath the Oceanic Plates
heat flow related to subsidence rate

\[
(q_b - q_u) = \frac{(\rho_m - \rho_w) C_p \nabla A \cdot \nabla d}{\alpha \nabla A \cdot \nabla A}
\]
Mueller, personal communication 2006
Mueller, personal communication 2006
Fig. 2. Temporal variation of the globally integrated heat flow based on the estimates from the two plate tectonic reconstructions as shown in Fig. 1. For regions with half-space cooling-derived heat flow \( q = CA \tau^{-1/2} \), we performed an integration over seafloor age by summing over 1-Myr age integrals and multiplying each of these integrals by the area of seafloor within that age interval. Error bars for each heat flow estimate are computed by assuming progressively increasing uncertainty in these area estimates as described below. Filled square symbols (Hall) are for Xu et al.'s (6) reconstruction based on Hall (34), and open squares (GJ86) are based on Gordon and Jurdy (33). Solid and dashed lines are best-fit linear trends with rates, \( c_d \), of relative change in total oceanic heat flow specified in the key.

Fig. 3. Cenozoic and Mesozoic evolution of the Pacific basin as characterized by seafloor distance to the nearest mid-ocean ridge. Notice the progression from four relatively small plates to one large plate and compare with Fig. 1. Maps were created after Lithgow-Bertelloni and Richards (39).

obvious signals - summary

heat flow versus age

- surface temperature gradient
- noisy, observations << model

depth versus age

- integrated temperature
- observations = model

geoid height versus age

- first moment of temperature
- dominated by mantle geoid, observations ~ model

\[ q_s(t) = k \frac{\partial T}{\partial z} \]

\[ d(t) = \frac{-\rho_m}{\rho_m - \rho_w} \int_0^L \alpha T dz \]

\[ N(t) = \frac{-2\pi G \rho_m}{g} \int_0^L \alpha T z dz \]
Inferred signals

- lithospheric strength versus age (see Watts, 2001)

- swell-push force and global stress from the geoid
Hawaiian-Emperor seamount chain

Plate kinematics

Plate Mechanics (flexure)

Sandwell & Smith 1997 (offshore) + Woollard et al 1966 (onshore)
Gravity anomalies and crustal structure at Oahu/Molokai

Watts & ten Brink (1989)
Estimating $T_e$

$T_e$ can be estimated by comparing the amplitude and wavelength of the observed gravity anomaly to the predicted anomaly based on an elastic plate model. The minimum in the RMS difference between observed and calculated gravity anomaly indicate a best fit $T_e \sim 30$ km.

The diagram shows the free-air gravity anomaly for different values of $T_e$. The observed anomaly is compared to the predicted anomaly for different elastic thicknesses. The bathymetry map also provides information about the oceanic crust, with density values for load, initial, and mantle layers.
Topography seaward of the Kuril Trench

Distance to bulge ~ 120-140 km

$T_e \sim 30$ km
Relationship between oceanic $T_e$ and plate and load age

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