8: SPREADING CENTERS

Understand kinematics & dynamics of boundary processes

Oceanic systems simpler than continental

Thermal evolution of oceanic lithosphere provides major plate driving force and hence plays major role in both oceanic and continental deformation

Major role in thermal, mechanical, chemical evolution of the earth

Smith & Cann, 2004
One-dimensional heat flow equation:

\( \frac{\partial T(z, t)}{\partial t} = \frac{k}{\rho C_p} \frac{\partial^2 T(z, t)}{\partial z^2} = \kappa \frac{\partial^2 T(z, t)}{\partial z^2} \)

\( \kappa = \) thermal diffusivity, \( k = \) thermal conductivity, \( \rho = \) density, \( C_p = \) specific heat at constant pressure

Its solution has the form

\[ T(z, t) = T_s + (T_m - T_s) \text{erf} \left( \frac{z}{2\sqrt{\kappa t}} \right) \]

with \( T_s = \) surface temperature, \( T_m = \) mantle temperature, and

\[ \text{erf}(s) = \frac{2}{\sqrt{\pi}} \int_{0}^{s} e^{-\sigma^2} d\sigma \]
COOLING OF HALFSPACE DESCRIBED BY 1-D CONDUCTIVE HEAT FLOW EQUATION

Cooling starts at surface and deepens with time

\[ T = 0 \quad t = 0 \quad T = T_m \]

\[ t = 1 \quad t = 5 \quad t = 10 \quad t = 40 \]

Cooling with time

\[ \text{erf } s = \frac{2}{\sqrt{\pi}} \int_{0}^{s} e^{-\sigma^2} d\sigma \]
If $T_s = 0^\circ C$, then

$$T(z, t) = T_m \text{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right)$$

or, as a function of distance from the ridge:

$$T(x, z) = T_m \text{erf}\left(\frac{z}{2\sqrt{\kappa x/v}}\right)$$

Isotherms are defined by

$$\frac{z_c}{2\sqrt{\kappa t}} = c \quad \text{or} \quad z_c = 2c\sqrt{\kappa t}$$

---> The depth to a given temperature increases as the square root of lithospheric age.

**LITHOSPHERE COOLS WITH TIME, SUCH THAT ISOTHERMS DEEPEN WITH THE SQUARE ROOT OF AGE**

**Consequences:**

By isostasy, ocean depth increases as square root of age (ridge is shallow)

Seafloor heat flow decreases as square root of age (highest at ridge)
SIMPLE MODEL WORKS WELL, WITH INTERESTING MISFITS

Depth seems to "flatten" at ~70 Myr: use variant called plate model in which lithosphere evolves toward finite thermal thickness.

For ages <~ 50 Ma, observed heat flow is lower than predictions, because water flow in the crust transports some of the heat.
Ocean depth, heat flow, and other observables measures reflect temperature in the cooling lithosphere.

Because observables depend on different combinations of parameters, can be used together to constrain model parameters that best fit data.

<table>
<thead>
<tr>
<th>OBSERVABLE</th>
<th>PROPORTIONAL TO</th>
<th>REFLECTS</th>
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<tbody>
<tr>
<td>Young Ocean Depth</td>
<td>$\int T(z, t) , dz$</td>
<td>$\alpha T_m$</td>
</tr>
<tr>
<td>Old Ocean Depth</td>
<td>$\int T(z, t) , dz$</td>
<td>$\alpha T_m a$</td>
</tr>
<tr>
<td>Old Ocean Heat Flow</td>
<td>$\frac{\partial T(z, t)}{\partial z} \big</td>
<td>_{z=0}$</td>
</tr>
<tr>
<td>Geoid Slope</td>
<td>$\frac{d}{dt} \int z T(z, t) , dz$</td>
<td>$\alpha T_m \exp(-t / \alpha^2)$</td>
</tr>
</tbody>
</table>

Plate thickness ($a$), basal temperature ($T_m$), coefficient of thermal expansion ($\alpha$)

Halfspace model corresponds to $a \to \infty$
Cooling of oceanic lithosphere also increases rock strength and seismic velocity. Thus

elastic thickness of the lithosphere inferred from the deflection caused by loads such as seamounts,

maximum depth of intraplate earthquakes within the oceanic lithosphere,

& depth to the low velocity zone determined from surface wave dispersion

all increase with age.

Stein and Stein, 1992
Slow Mid-Atlantic Ridge has earthquakes on both active transform and ridge segments. Strike-slip faulting occurs on a plane parallel to the transform. On ridge segments, normal faulting occurs with nodal planes parallel to the ridge trend.
Fault plane inferred from large earthquake focal mechanisms, and locations of microearthquakes from study using ocean bottom seismometers, are consistent with normal faulting along the east side of the axial valley.

Toomey et al., 1988
SEISMICITY DIFFERENCE
SLOW VERSUS FAST
SPREADING CENTERS

Fast East Pacific Rise has only strike-slip earthquakes on the transforms, since there is no axial valley.

Macdonald, 2004

Stein & Wysession, 2003
Midocean ridge

Subduction zone

Increasing temperature

Increasing depth & pressure

Melting curve for dry mantle rock

Decompression melting as rock is moved towards surface

Solid

Liquid

Melting curve for wet mantle rock

Flux melting as water is added to rock

Solid

Liquid

https://opentextbc.ca/geology/chapter/3-2-magma-and-magma-formation/
Below a ridge, the mantle of the asthenosphere (orange) rises to fill the gap between two separating lithospheric plates (blue). As they rise, some rocks melt to form magmas. The buoyant magmas or melts then surge into a magma chamber (red). Material in the magma chamber further segregates into various layers of the oceanic crust (dark green). The crust is less dense than the mantle. In the mantle, density decreases with increasing temperature and with depth.
Geologic interpretation of multichannel seismic velocity study on the East Pacific rise. Low velocity region under the axis is interpreted as a hot region of melting, capped by a magma lens. Dashed lines are possible paths of water circulation.

Schematic cross section across East Pacific rise. The broad region of low velocities is interpreted as the primary melting region.
At a given distance from the ridge, faster spreading produces younger lithosphere and isotherms closer to the surface than slow spreading.

If region beneath the 1185°C isotherm and above Moho depth of 5 km is a magma chamber, a fast ridge has a larger magma chamber. Hence crust moving away from a fast-spreading ridge is more easily replaced than from a slow ridge.

Thus in contrast to the axial valley and normal faulting earthquakes on a slow ridge, a fast ridge has an axial high and an absence of earthquakes.
Depths and maximum seismic moments of ridge crest normal faulting earthquakes decrease with spreading rate.

Seismic moment is product of rigidity, slip in the earthquake & fault area.

Observations are consistent with fault area decreasing on faster spreading & hotter ridges because faulting requires rock be below a limiting temperature, above which it flows.
Gravity data reveals gravity lows beneath the spreading segments of the North Mid-Atlantic Ridge. This pattern may be caused by thicker crust or less dense mantle beneath the midpoints of the spreading segments.

**LOW GRAVITY BULLSEYE**

FIG. 6 The preferred model of MAR density structures that are consistent with the results of gravity analyses. We propose that the MAR spreading segments are fed from below by buoyancy-driven mantle flows. Thick solid lines with arrow heads represent mantle flows. Broken curves represent lines of equal density in the mantle. The average crustal density is $2.7 \times 10^6 \text{ g m}^{-3}$. The mantle density is $\rho = 3.3(1 - f(x, z)) \times 10^6 \text{ g m}^{-3}$, where $f(x, z)$ depends primarily on the mantle temperature, the amount of melt extraction and the amount of trapped basaltic melts. $x$ and $z$ are horizontal and vertical coordinates. Over regions of ascending mantle plumes, large temperature gradients and a high degree of decompression melting are expected. This could result in thicker crust and lower mantle densities beneath mid-portions of spreading segments. Both the changes in crustal thickness and variations in mantle density are likely to contribute significantly to the gravity field. A crustal model is shown in Fig. 4b, which assumes that the changes of crustal thickness are the sole source of the residual gravity anomalies.
In this model of magma diapirs beneath a ridge, the partially molten asthenosphere (red) is not stable under the cold lithosphere (green). The gravitational instability of this partial melting zone will induce regularly spaced diapirs of magmas. The magma diapirs then percolate toward the surface to form discrete spreading segments.
ALONG STRIKE VARIATIONS - FAST vs SLOW RIDGE

2D FLOW BELOW FAST RIDGE because melt can flow along strike in magma chamber

Less along-strike variation

3D FLOW BENEATH SLOW RIDGE because colder & more rigid crust suppresses along-strike flow

More along-strike variation

Fig. 6. A spreading-rate dependent model of crustal accretion and mantle upwelling that is consistent with the observed gravity and bathymetry. Solid arrows show mantle flow directions. Open arrows show plate motion vectors. Dashed lines in the mantle show isotherms. Gravity analyses indicate that the crustal density structure is relatively uniform at a fast-spreading ridge (left). At a slow-spreading ridge, however, the crustal thickness may vary continuously along a spreading segment, even if the segment is bounded by non-transform offsets (right). Such contrasting crustal accretion patterns may result from a dominantly plume-like upwelling and melting beneath a slow-spreading ridge and sheet-like mantle upwelling and melting beneath a fast-spreading ridge. Smaller amplitude 3-D upwellings may still occur at a fast-spreading ridge, but their effects on crustal thickness variations will be further reduced by along-axis melt flows along a persistent low-viscosity crustal magma chamber.
TRANSFORM EARTHQUAKES GIVE INSIGHT INTO THERMOMECHANICAL STRUCTURE & SLIP PROCESS
Temperatures along a transform fault should be essentially average the expected temperature on the two sides; coolest at midpoint and hottest at either end. As expected from the area available for faulting, the maximum seismic moment for transform earthquakes decreases with spreading rate, consistent with faulting limited by isotherms.

Engeln et al., 1986

Solomon and Burr, 1979
ASEISMIC PLATE MOTION?

An interesting question is how the seismic moments of transform earthquakes relate to the plate motion.

The average slip rate from earthquakes can be inferred from the total seismic moment released on a transform, assuming

\[
\text{Seismic slip rate} = \frac{\text{total seismic moment}}{(\text{fault area} \times \text{rigidity} \times \text{time window})}
\]

Using this relation requires inferring fault area, which depends on the transform length and the depth to which faulting occurs.

Assuming the area above the 600-700°C isotherms fails seismically, the seismic slip rate for major Atlantic transforms is generally less than predicted by the plate motion.

Thus, if the time period sampled is long enough to be representative—a major question—some of the plate motion occurs aseismically.

Issue for other plate boundaries.
FOCAL MECHANISM TYPE AS A FUNCTION OF LITHOSPHERIC AGE FOR OCEANIC INTRAPLATE EARTHQUAKES

Older lithosphere is in compression

Younger lithosphere has both extensional & compressional mechanisms

Constrains intraplate stress and plate driving forces

Wiens and Stein, 1984
“RIDGE PUSH” - PLATE DRIVING FORCE DUE TO COOLING LITHOSPHERE

Ridge Push: $F_R = F_1 - F_2 - F_3$

$F_R = \alpha \rho_m T_m g \kappa t$

For a plate model, this approaches a constant value for old lithosphere.

“Ridge push” is zero at the ridge and increases linearly with plate age. It results not from force at the ridge but from the total force due to the density anomaly within the cooling plate out to any given age.
The stress within the oceanic lithosphere is given as a function of plate age:

\[
\bar{\sigma}_{xx}(t) = \frac{\sigma_b \nu t - F_R(t)}{m(t)} + \sigma_r
\]

\(\nu\) = half spreading rate

\(\sigma_b\) = basal shear stress (= \(Cu\) where \(C\) is drag coefficient and \(u\) is the absolute velocity)

\(m(x)\) = lithosphere thickness

\(\sigma_r = \bar{\sigma}_{xx}(0)\) = strength of ridge
INTRAPLATE STRESS DUE TO BALANCE BETWEEN:

- ridge push
- drag at plate base
- strength of ridge

For 0 drag, ridge push gives compression at all ages.

If drag too high, get extension in old lithosphere, which is not observed.

Wiens and Stein, 1985
Age of transition from ridge-normal extension to compression increases with strength of the ridge.
Viscosity, the proportionality constant between shear stress and the strain rate (or velocity gradient), controls how mantle flows in response to applied stress, and is thus crucial for mantle convection.

If drag on base of a plate due to motion over the viscous mantle, compressive earthquake mechanisms in old lithosphere constrain viscosity.

Data require low viscosity layer decoupling plates from rest of asthenosphere.

Consistent with constraints from gravity and glacial isostasy.
FOR AGES $<\sim 50$ MA, OBSERVED HEAT FLOW IS LOWER THAN PREDICTIONS, BECAUSE WATER FLOW IN CRUST TRANSPORTS SOME OF THE HEAT

Integrate difference to infer global flux of hydrothermal water

Extends out to $\sim 50$ Ma, showing presence of low-temperature flow as well as spectacular high-temperature flow near ridges

Humphris, 2004
### Hydrothermal Fluid vs. Seawater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fluid</th>
<th>Seawater</th>
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<tbody>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>360–365</td>
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<tr>
<td><strong>Acidity at 25°C</strong></td>
<td>3.35</td>
<td>7.8</td>
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<tr>
<td><strong>Dissolved Oxygen</strong></td>
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<td>0.076</td>
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<tr>
<td><strong>Hydrogen Sulfide (mM)</strong></td>
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<tr>
<td><strong>Sodium (mM)</strong></td>
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<tr>
<td><strong>Potassium (mM)</strong></td>
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<tr>
<td><strong>Calcium (nM)</strong></td>
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<td><strong>Silica (mM)</strong></td>
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<td><strong>Chloride (mM)</strong></td>
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<td><strong>Sulfate (mM)</strong></td>
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<td><strong>Iron (µM)</strong></td>
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<tr>
<td><strong>Copper (µM)</strong></td>
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<tr>
<td><strong>Zinc (µM)</strong></td>
<td>47–53</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**SOURCE** - Element leached from the crust to the ocean

**SINK** - Element taken up by the crust from seawater

Humphris, 2004
Hotspots and Mid-Ocean Ridges

Lin (1998)
HOT TOPIC -
HOTSPOT/RIDGE INTERACTIONS

How is excess crust produced?
Does excess magma flow down ridge?

Iceland

Lin (1998)
Model 3: radius=100 km; ΔT=180°C; dehydration viscosity increase

Ito, Lin & Gable (1996)