Plate Tectonics: Knowns and Unknowns
David Sandwell - SOEST, October 2, 2008

- Knowns: ridges, transforms, subduction zones, propagators, microplates, ...
- Unknowns: hotspot connection to plumes and origin of Haxby gravity lineations

How many hotspots are caused by mantle plumes (0 - 49)?

Do Haxby gravity lineations originate in the lithosphere or asthenosphere?
What were they smoking in the 60’s?

bumps on the surface of the ocean

confirmations and discoveries from satellite altimetry

- confirming/refining plate tectonics
- microplates and propagating ridges
- seafloor roughness versus spreading rate
- global seafloor age
- global bathymetry grids
- seamounts > 2 km tall
- Haxby gravity lineations
ridges and transforms

fracture zones
subduction zones

triple junction
back-arc spreading

It is not always this perfect.
confirmations and discoveries from satellite altimetry

• confirming/refining plate tectonics

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microplates and overlapping spreading ridges
propagating rifts

confirmations and discoveries from satellite altimetry

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fast vs. slow spreading

East Pacific Rise

Mid-Atlantic Ridge

Small and Sandwell, Geology, 1994

fast spreading vs. slow spreading
confirmations and discoveries from satellite altimetry

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fracture zones = spreading direction
confirmations and discoveries from satellite altimetry

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USS San Francisco crashed into 2-km tall uncharted guyot

- Los Angeles class nuclear submarine ran aground in route from Guam to Brisbane, Australia - 8 January, 2005
- One sailor killed, 115 injured
- Crash depth ~160 m, speed 33 kn, Sonar measured a depth of 2000 m 4 minutes before crash
- 30-hour trip back to Guam, crew managed to keep the sub from sinking
confirmations and discoveries from satellite altimetry

- confirming/refining plate tectonics
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gravity lineations and linear volcanic ridges: asthenosphere or lithosphere?

What processes form linear volcanic chains?
- mantle plumes (upper and lower mantle)
- cracks in the plate (lithosphere)
- small scale convection (asthenosphere)

How to crossgrain gravity lineaments form?
- small scale convection or mantle return flow (asthenosphere)
- thermal bending or boudinage (lithosphere)
linear volcanic chains

possible processes:

A) mantle plumes

B) plate boundary forces and thermal stress crack the plate allowing magma to escape

C) small-scale convection
Attributes of Mantle Plumes

(Courtillot, Davaille, Besse and Stock, EPSL, v205, 2003.)

1. linear volcanic chain with monotonous age progression
2. flood basalt at origin of track
3. large buoyancy flux
4. consistently high ratios of 3 of 4 isotopes of helium
5. significant low shear wave velocity in underlying mantle.
6. geoid/topography ratio > 2.5 m/km

possible deep mantle plumes

(Courtillot, Davaille, Besse and Stock, EPSL, v. 205, 2003.)

9 hotspots have > 3 attributes

1. Afar
2. Caroline
3. Easter
4. Hawaii
5. Iceland
6. Louisville
7. Reunion
8. Samoa
9. Tristan

Table 1
Scores for 49 hotspots with respect to five criteria used to diagnose a potentially deep mantle (see text).

<table>
<thead>
<tr>
<th>Hotspot</th>
<th>Lat (%)</th>
<th>Track</th>
<th>Floodplains</th>
<th>Age (Map)</th>
<th>Basalt</th>
<th>Refrlec</th>
<th>3He/4He</th>
<th>Teno*Hz</th>
<th>Teno (*Hz)</th>
<th>Count</th>
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<tbody>
<tr>
<td>Australia E</td>
<td>35S 143 yes no / 0.9 fair na 0 1+?</td>
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<tr>
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<td>35N 302 yes no / 1.1 fair high? 0 1+?</td>
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<td>Bejo/Chad</td>
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<td>67R 163 no no / na na na 0 1+?</td>
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<td>Belewa</td>
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<td>Cameroon</td>
<td>4H 9 yes no / 0.5 poor high 0 1+?</td>
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<tr>
<td>Cannee</td>
<td>25N 220 no no / 1 fair low slow 2</td>
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<td>Cape Verde</td>
<td>14N 240 no no / 1.6 poor low slow 2</td>
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<td>Cenozoic</td>
<td>12S 40 no no / na na na 0 1+?</td>
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<td>Dade</td>
<td>12N 24 yes no / na poor na 0 1+?</td>
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<td>Discovery</td>
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</tbody>
</table>

9 hotspots have > 3 attributes

1. Afar
2. Caroline
3. Easter
4. Hawaii
5. Iceland
6. Louisville
7. Reunion
8. Samoa
9. Tristan
low GTR = Airy-compensated plateaus

high GTR = thermally-compensated swells
separating swells from plateaus
(Sandwell and MacKenzie, JGR, v. 94, 1989)

- thermal swells

Hawaii
- linear volcanic chain with monotonous age progression

Iceland
- flood basalt at origin of track

Reunion
- large buoyancy flux
- consistently high ratios of 3 of 4 isotopes of helium
- significant low shear wave velocity in underlying mantle.
- geoid/topography ratio > 2.5 m/km
Many intraplate features have few plume attributes.

Are these features related to asthenospheric or lithospheric processes?
What produced these features??

Plate Boundary Forces

Proposed processes:

A) mantle plumes (~3 hotspots have all the attributes)

B) plate boundary forces and thermal stress crack the plate allowing magma to escape

C) small-scale convection
Plate Driving Forces on Earth

$F_S$ - swell push

$F_D$ - drag

$F_T$ - trench pull

$trench \, pull \approx 3 \times ridge \, push$

On the origin of the Cocos-Nazca spreading center

Rinus Wortel, Sierd Cloetingh

(Geology, v.9, 1981)
Rifting of old oceanic lithosphere is caused by slab pull.

Is the Easter/Salas y Gomez Chain a rift?
changes in plate boundary configuration in the past

Lithospheric Stresses, Great Fissures, and Volcanism at Seamounts and Plateaus
James H. Natland, and Edward L. Winterer, GSA Penrose Volume, in press, 2005

“We propose that changes in the distribution of large seamounts and ocean islands in the Pacific are closely linked to this history and to the shifting patterns of lithospheric stress imposed on the plate from its boundaries since the Mesozoic. The stresses produce great fissures and systems of fissures through the plate that root in zones of mantle where partial melting occurs and magma accumulates. The fissures thus provide avenues for escape of buoyant magma, thence formation of seamounts, islands, and volcanic ridges. Today, many fissures propagate, not always at the same rate, in directions immediately opposed to the direction of plate motion, and this gives rise to the linear volcanic chains of the Pacific.”

Haxby gravity lineations

- gravity lineations are common on the Pacific and Nazca plates
- they cross the grain of the seafloor spreading fabric
- they are not apparent at the ridge and form in 3-5 Ma
- volcanic ridges are in troughs of gravity lineations
gravity lineations

Haxby and Weissel, JGR, v. 91, 1986

development of gravity lineations
10% extension not observed in FZ spacing
(Goodwillie and Parsons, 1992; Gans et al., 2003)
ridges are in troughs of lineations

(Haxby and Wessel, 1986) (Sandwell et al., 1995) (Gans et al., 2003) (Weerarante et al., 2003)

volcanic ridges occur in the troughs of the gravity lineations

(a) SMALL SCALE CONVECTION
(b) EXTENSION
(c) THERMAL CONTRACTION
(d) ASTHENOSPHERIC CHANNELS

(Gans et al., 2003) (Sandwell et al., 1995)
small scale convection

(Ballmer et al., GRL 2007)

Figure 3. Amount of volcanism vs. age of the underlying seafloor for different model runs (varying the parameters $T_m$ and $\eta_m$), Vertical axis is the total volumetric rate of melt production in vertical ($y-z$) cross-section of our model divided by the number of SSC cells. It represents the average volume of melt produced by a single SSC cell per unit time and per kilometer in the direction of plate motion. Curves are shaded according to $\eta_m$ as indicated in the scale above. Colors indicate different reference temperatures. Numbers indicate heights (in km) of volcanic edifices with a slope of $10^6$ that could be created if all of the melt extracted above a SSC upwelling accretes as continuous volcanic ridges or, in parentheses, as chains of circular volcanoes spaced 100 km apart. Viscosity predominantly controls volcano height, whereas $T_m$ controls both the age of seafloor during magmatism and volcano height.

(Ballmer et al., GRL 2007)
small scale convection cannot explain formation on lithosphere < 25 Ma.

thermoelastic model can predict both the amplitude and wavelength of the gravity lineations
modeling gravity lineations

- calculate thermoelastic bending moment (Parmentier and Haxby, 1986; Wessel, 1992)

- introduce cracks in the plate and calculate topography and gravity lineations (Turcotte, 1974; Gans et al., 2003)

- find maximum in thermoelastic energy released versus crack spacing (Sandwell and Fialko, 2004)
seagoing proposal – (4th try)

![Map Image]

seagoing proposal – (4th try)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>gravity lineaments</th>
<th>volcanic ridges in troughs</th>
<th>distance between fracture zones</th>
<th>topography correlated with gravity (not flat)</th>
<th>conductivity variations in asthenosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>small-scale convection</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y or N</td>
<td>Y - high conductivity = high gravity</td>
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<td>extension</td>
<td>Y</td>
<td>Y</td>
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<td>Y</td>
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<td>Y - high conductivity = low gravity</td>
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<td>published studies</td>
<td>this proposal</td>
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</table>
Conclusions

- Plate tectonics explains ridges, transforms, subduction zones, propagators, microplates, . . .
- Plate tectonics makes predictions about the present, past, and future of the Earth.
- How many hotspots were formed by mantle plumes (0 - 49)?
- What causes Haxby gravity lineations and associated linear volcanic ridges?