Thermal Isostasy on Continents:
Applications to North America

Masters Defense

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ISOSTASY

“[The] condition of the terrestrial surface which follows from the flotation of the crust upon a liquid or highly plastic substratum...”

-Dutton (1882)

Airy (1855)

constant density

Pratt (1855)

variable density
OUTLINE

INTRODUCTION
Oceanic thermal isostasy
Continental thermal isostasy

METHODS
Compositional correction to elevation
Wyoming Craton as an example

RESULTS FROM NORTH AMERICA

DISCUSSION OF TWO OUTLIERS

CONCLUSIONS
Oceanic Thermal Isostasy

Motivation

Method

Results

Discussion

Conclusion

Stein and Stein (1992)
Continental Thermal Isostasy

- Temperature vs. Depth
- Observed Elevation vs. Heat Flow

$q_0 = 40$
Elevation Correction

\[ \Delta \varepsilon = h_c^\prime \left(1 - \frac{\rho_c^\prime}{\rho_m}\right) - h_c \left(1 - \frac{\rho_c}{\rho_m}\right) \quad \text{if } \varepsilon \geq 0 \]

\[ \Delta \varepsilon_w = \Delta \varepsilon - \varepsilon \frac{\rho_c}{\rho_m} \quad \text{if } \varepsilon < 0 \]

Standard:

\[ \rho_c^\prime = 2.83 \text{ g/cm}^3 \]

\[ h_c^\prime = 40 \text{ km} \]
ELEVATION BIAS TEST

**Area** [×10^4 km^2] vs. **Elevation [km]**

**Seismic Observations** vs. **Elevation [km]**

**Heat Flow Observations** vs. **Elevation [km]**

**Elevation Summary**

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTOPO30</td>
<td>1120</td>
<td>1070</td>
<td>290</td>
</tr>
<tr>
<td>Heat Flow</td>
<td>1400</td>
<td>1440</td>
<td>290</td>
</tr>
<tr>
<td>Seismic</td>
<td>1080</td>
<td>1100</td>
<td>220</td>
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</table>
**Crustal Parameters Quality Check**

- **Method**
  - Velocity-Density Conversion
  - Linear Relationship
  - Based on lab measurements
  - P-T-dependent

- **Results**
  - **Median:** 2974
  - **Mean:** 2955
  - **SD:** 66

- **Median:** 50.5
- **Mean:** 49.5
- **SD:** 4.9

*Christensen and Mooney (1995)*
Adjusted Elevation of the Wyoming Craton

Heat Flow [mW/m²] vs. Elevation [km]

Wyoming Craton

Adjusted Elevation

Observed Elevation

708 m
NORTH AMERICAN DATASETS

SEISMIC
Chulick and Mooney (2002)

HEAT FLOW
Pollack et al. (1993)
North American Elevation Adjustments

- pC craton/shields
- Pz orogens
- Mz-Cz orogens
- Cz rifts
- Cz volcanics

Crustal Density [kg/m³]

Crustal Thickness [km]
Sensitivity to Thermal Parameters

Thermal Expansion

\[ \alpha_V = 4.0 \times 10^{-5} \text{ K}^{-1} \]

\[ \Delta \varepsilon = \alpha_V \int_0^{z_{\text{max}}} [T_q(z) - T_{40}(z)] \, dz \]

Partition Coefficient

\[ p = 0.4, 0.5, 0.6, 0.7, 0.8 \]

\[ q_0 = q_A + q_b \]

\[ q_b \approx P q_0 \]
Thermal Isostatic Model of North America

$q_{ref} = 42.7 \text{ mW/m}^2$
$P = 0.61$
$\text{RMS} = 1.32$
The Sierra Nevada

Elevation Summary

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTOPO30</td>
<td>1541</td>
<td>1471</td>
<td>900</td>
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<tr>
<td>Heat Flow</td>
<td>40</td>
<td>1332</td>
<td>565</td>
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<tr>
<td>Seismic</td>
<td>11</td>
<td>1248</td>
<td>917</td>
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</table>

Correlations with Heat Flow:
- Elevation      \( r^2 = 0.10 \)
- Thermal Conductivity \( r^2 = 0.00 \)
- Thermal Gradient \( r^2 = 0.73 \)

Model Summary

<table>
<thead>
<tr>
<th>Dataset</th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Heat Flow</td>
<td>40</td>
<td>56</td>
<td>57</td>
<td>40</td>
<td>mW/m²</td>
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<tr>
<td>Thickness</td>
<td>11</td>
<td>38.0</td>
<td>39.8</td>
<td>0.8</td>
<td>km</td>
</tr>
<tr>
<td>Density</td>
<td>11</td>
<td>2866</td>
<td>2869</td>
<td>5</td>
<td>kg/m³</td>
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</table>
**Sierra Nevada**

**Elevation Anomaly:** +0.7 km  
**Heat Flow Anomaly:** -15 mW/m²

**Process or Property**
- Erosion
- Mantle Root Drop
- Shallow Subduction
THE WOPMAY OROGEN

Elevation Summary

<table>
<thead>
<tr>
<th></th>
<th>Mean [m]</th>
<th>Median [m]</th>
<th>SD [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTOPO30</td>
<td>376</td>
<td>311</td>
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<td>Heat Flow</td>
<td>445</td>
<td>381</td>
<td>267</td>
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<tr>
<td>Seismic</td>
<td>601</td>
<td>708</td>
<td>351</td>
</tr>
</tbody>
</table>

Correlations with Heat Flow:
Elevation \( r^2 = 0.25 \)
Thermal Conductivity N.D.
Thermal Gradient N.D.

Model Summary

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flow</td>
<td>18</td>
<td>75</td>
<td>75</td>
<td>14 mW/m²</td>
</tr>
<tr>
<td>Thickness</td>
<td>11</td>
<td>37.0</td>
<td>37.0</td>
<td>1.8 km</td>
</tr>
<tr>
<td>Density</td>
<td>11</td>
<td>2808</td>
<td>2816</td>
<td>16 kg/m³</td>
</tr>
</tbody>
</table>
Wopmay Orogen

Elevation Anomaly: -1.2 km
Heat Flow Anomaly: +20 mW/m²

Process or Property
- Glacial Retreat
- High Heat Production
- Eclogitic Mantle Root
General Conclusions

1. Observed continental elevation does not correlate with the theoretical thermal isostatic curve.

2. Elevation adjustments range from about -0.5 to 2.5 km, suggesting a 3 km compositional component to North American elevation.

3. Adjusted elevations correlate to the theoretical thermal isostatic curve and suggest a 3 km thermal component to continental elevation, similar to the oceans.

4. Best fitting thermal isostatic model has a zero-elevation heat flow of 43 mW/m² and a partition coefficient of 0.6.
Conclusions II

5. Partition coefficient of 0.6 supports the empirical model of *Pollack and Chapman* (1977).

6. This elevation and heat flow analysis may be used as a tool for tectonic analysis:
   - ex 1. Anomalous elevation of the Sierra Nevada is likely the combined effect of shallow slab subduction, mantle root drop and smaller competing effect of erosion.
   - ex 2. Heat flow of the Wopmay Orogen is likely high, resulting from upper crustal radioactivity. Additional elevation anomalies may result from a dense eclogitic root and lesser effect of prior glacial loading.
Future Work

Global thermal isostasy

Compositional evolution of continental mantle

Crustal heat production

Test province wide geodynamic models
Acknowledgements

I would like to thank my committee, lab mates and fellow grad students. I would also like to thank my parents and wife for their support. I would also like to thank the benefactors of the Cooper-Hansen and Mkulich fellowships, which supported me during my study.
If it could be demonstrated—as has been suggested several times—that large regions of the continental crust are elevated in a fashion that cannot be explained by crustal thickening alone, then we would have an important constraint on the behavior of continental lithosphere and its underlying mantle.

-England and Molnar (1990)
Compositional Parameters of North America

Median = 2858
SD = 55

Median = 38
SD = 6.8