Absolute Tectonic Plate Motion Optimization

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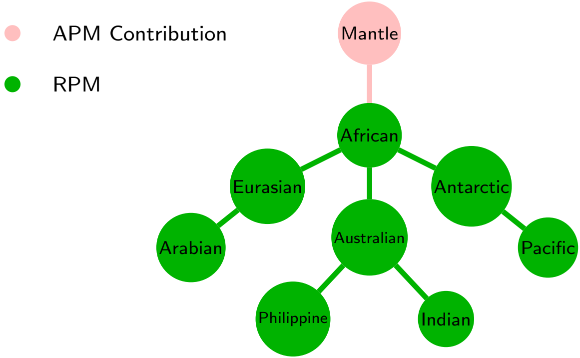
Plate Tectonics and Continental Drift

- Continental drift theory first developed in 1915, now widely accepted
- Earth's crust is partitioned into tectonic plates
- Supercontinents such as Pangea and Gondwana
  - Occur every 300-500 million years (Myr)
  - Separated by 90 degrees of latitude

Plate Reconstructions

- Plate motion models reconstruct the movement of plates millions of years ago



- **Relative Plate Motion Models** (RPMs)
  - Tree structure
  - Plates represented by nodes, with edges relating two plates
- **Absolute Plate Motion Models** (APMs)
  - Determine the relative motion between a "root" plate and the mantle

optAPM

- Code written in 2018 to optimize an absolute plate motion model (APM)
- Models are not continuous: absolute motion optimized **only at 5-million-year (5Myr) intervals**
  - Optimizing from 0-80Myr ago, the code adds 16 lines to the relative plate motion model (RPM)
  - Each line contains an Euler rotation at some reconstruction time

Plate	*Time*	*Lat*	*Long*	*Angle*	*Ref. Plate*
African	5.0	−26.805	−93.7412	8.8682	Mantle
African	10.0	−47.1273	−141.4427	−8.0848	Mantle
African	15.0	−33.0815	−102.3182	21.3154	Mantle
African	20.0	−54.4163	−144.6204	−8.4758	Mantle
...	...	...	...	...	...

Table: A simplified version of what would be appended to a rotation file in the optimized APM.

Data Constraints and Cost Functions

- 3 different constraints
- **Net Lithospheric Rotation** (crust's rotation relative to mantle)

$$\omega_{net} = 3/(8\pi r^4) \sum_i \int (\omega_i \times R) \times R dS_i$$

- **Trench Migration** (absolute plate boundary motion)

$$TM_k = \frac{\sum |V_T|}{T_n} + TM_{gT\sigma}$$

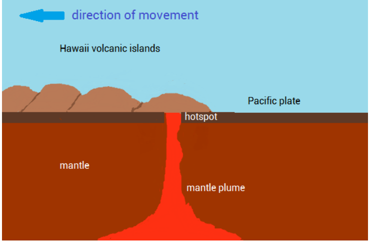
- **Hotspot Trail Misfit** (focal point of research)

$$HS_m = \sum_{i=0}^{n} (d_{1i} - d2i)^{-1} + HS_{gm}\sigma$$

- Objective function to minimize:

$$J = \frac{HS_m}{\sigma_1} + \frac{TM_k}{\sigma_2} + \frac{\omega_{net}}{\sigma_3}$$

Hotspot Motion



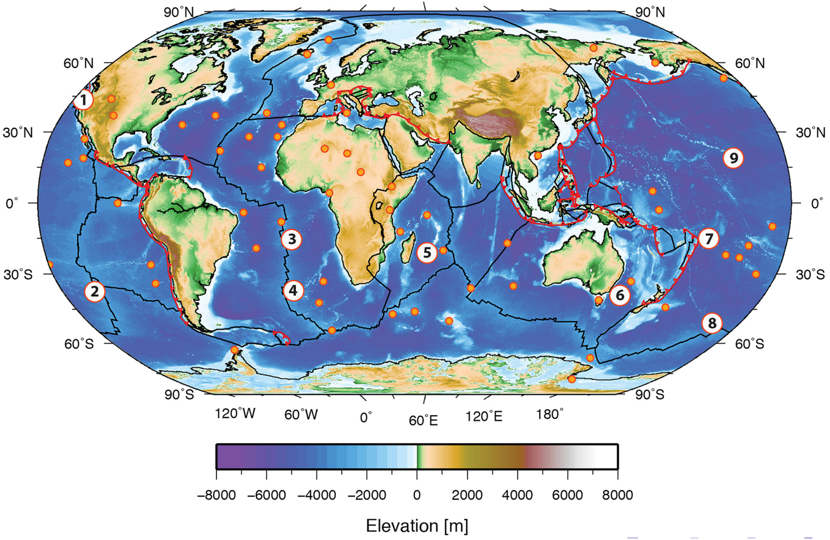
Definition

Hotspots: Area of Earth over a mantle plume.

- **Hotspot trails** form when a plate slides over a hotspot
- Hotspots are essentially stationary relative to the mantle
  - Reconstructing present-day hotspot locations according to model should reflect hotspot trail data
- Hotspot trail data is discrete
  - Data is considered robust for past 80Myr

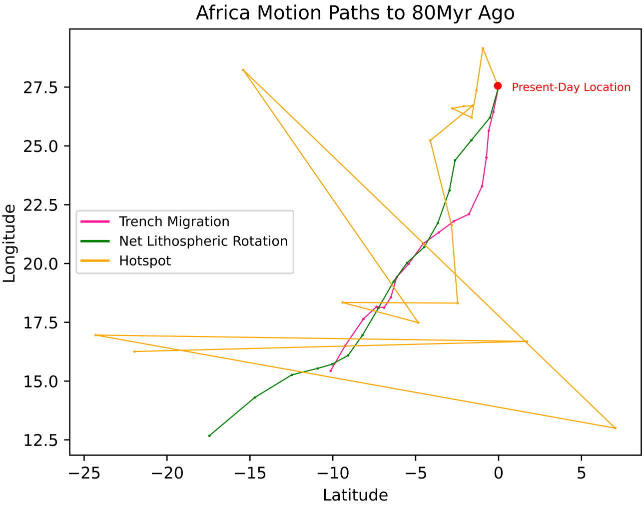
Hotspot Motion

- optAPM uses 9 well-studied hotspot trails



Isolating Constraints

What happens when we run the code with only **one of the three constraints?**

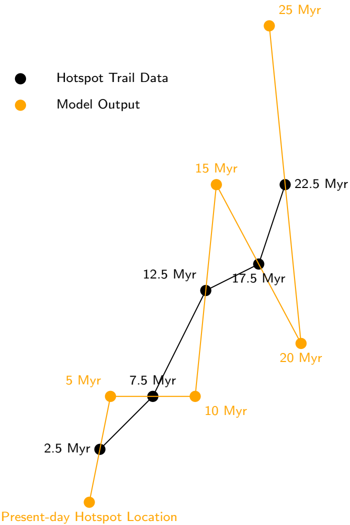


Hotspot Cost Function

Code "guesses" absolute motion at reconstruction time (e.g. 20Myr ago)

Original Cost Function:

1. Interpolates model output at hotspot data times (e.g. 17.5 Myr ago)
2. Minimize distances between
   - Model output (interpolated)
   - Hotspot data



Hotspot Cost Function

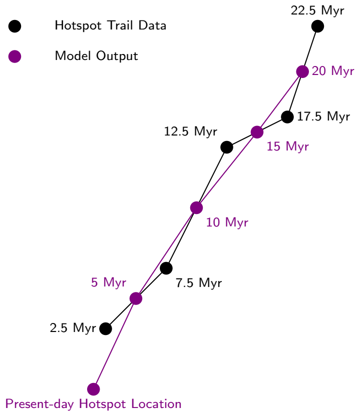
Code "guesses" absolute motion at reconstruction time (e.g. 20Myr ago)

Original Cost Function:

1. Interpolates model output at hotspot data times (e.g. 17.5 Myr ago)
2. Minimize distances between
   - Model output (interpolated)
   - Hotspot data

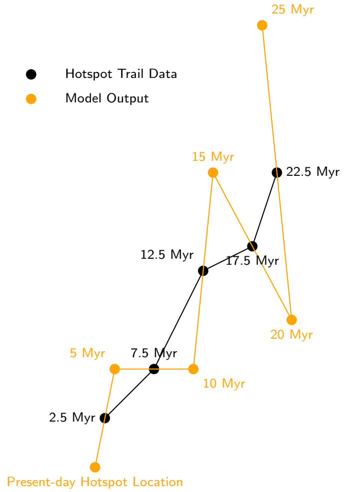
New Cost Function:

1. Interpolates hotspot data at reconstruction times (e.g. 20Myr ago)
2. Minimize distances between
   - Model output
   - Hotspot data (interpolated)

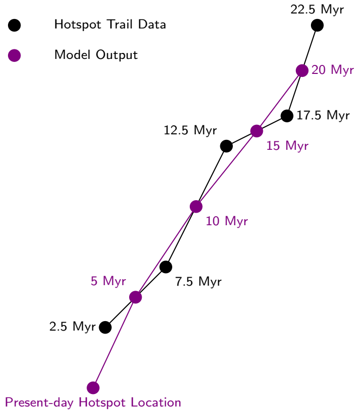


Hotspot Cost Function

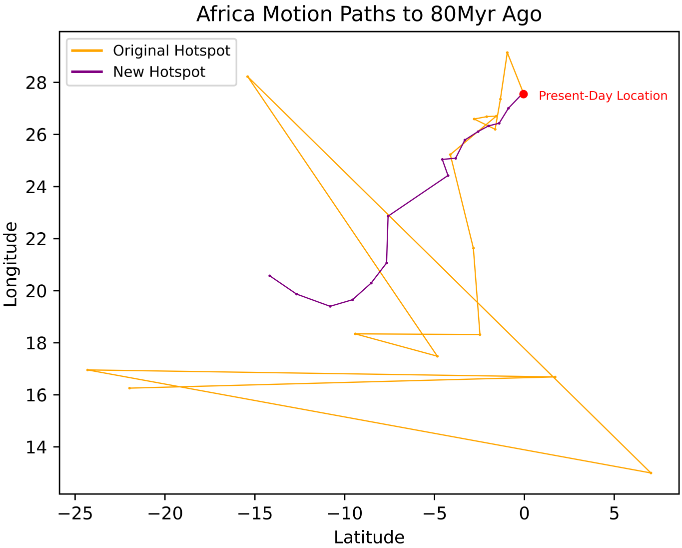
Before



After

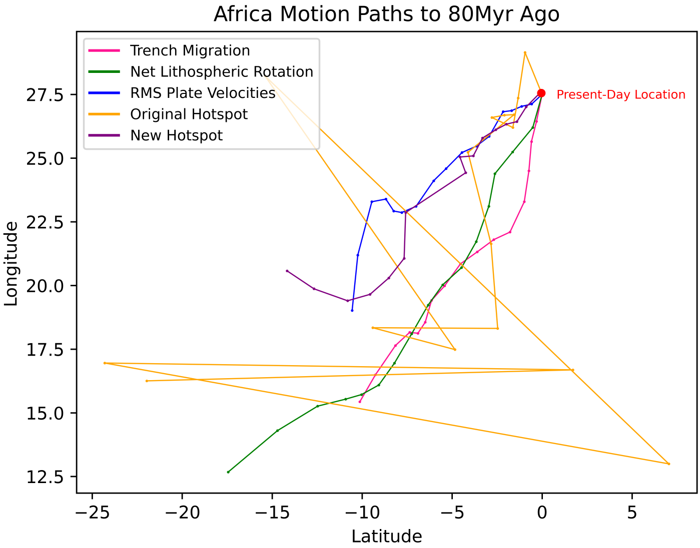


Results



Africa Motion Paths to 80Myr Ago
Original Hotspot
New Hotspot
Present-Day Location
28
26
24
22
20
18
16
14
Longitude
−25
−20
−15
−10
−5
0
5
Latitude

Results


Africa Motion Paths to 80Myr Ago
Trench Migration
Net Lithospheric Rotation
RMS Plate Velocities
Original Hotspot
New Hotspot
Present-Day Location
Longitude
27.5
25.0
22.5
20.0
17.5
15.0
12.5
−25
−20
−15
−10
−5
0
5
Latitude

Summary/Work in Progress

- Plate motion models are helpful for understanding Earth's long-term tectonic development
- Modeling has improved a lot, but many aspects still have significant room for growth
  - Weightings for 3 different constraints in the objective function

$$J = \frac{HS_m}{\sigma_1} + \frac{TM_k}{\sigma_2} + \frac{\omega_{net}}{\sigma_3}$$

  - Chi-square weighting using standard errors?

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- Thank you for listening!

References

[Mer17] Merdith, A. S., Collins, A. S., Williams, S. E., Pisarevsky, S., Foden, J. D., Archibald, D. B., Blades, M. L., Alessio, B. L., Armistead, S., Plavsa, D., Clark, C., & Müller, R. D. (2017). A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research*, 50, 84– 134.

[Mül22] Müller, R. D., Flament, N., Cannon, J., Tetley, M. G., Williams, S. E., Cao, X., Bodur, Ö. F., Zahirovic, S., and Merdith, A. (2022). A tectonic-rules-based mantle reference frame since 1 billion years ago — implications for supercontinent cycles and plate–mantle system evolution, Solid Earth, 13, 1127–1159.

[Tet19] Tetley, M. G., Williams, S. E., Gurnis, M., Flament, N., & Müller, R. D. (2019). Constraining absolute plate motions since the Triassic. *Journal of Geophysical Research: Solid Earth*, 124(7), 7231-7258.