THE ROLE OF ANISOTROPY IN OCEANIC LITHOSPHERE FROM 'CRADLE TO GRAVE'

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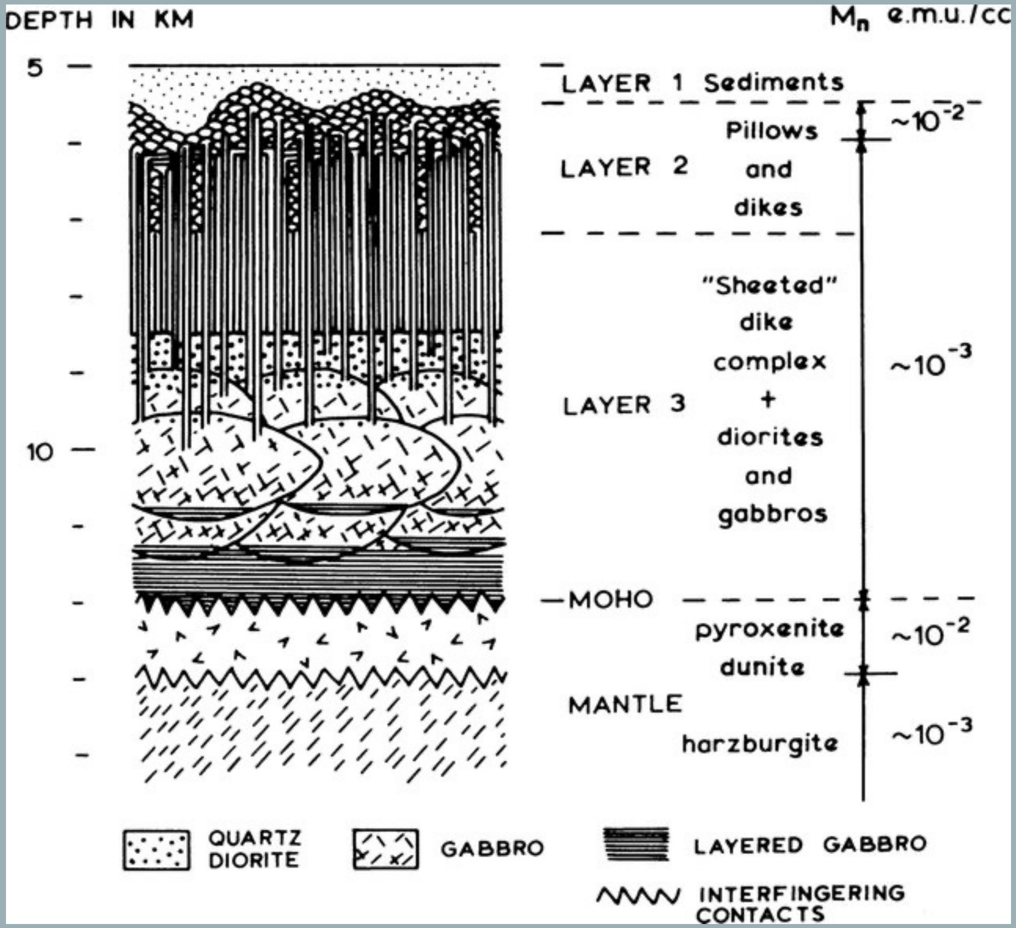
With thanks to Benjamin Cohen, Neil Mitchell, Jordan Phethean, Wen Shi, and many others

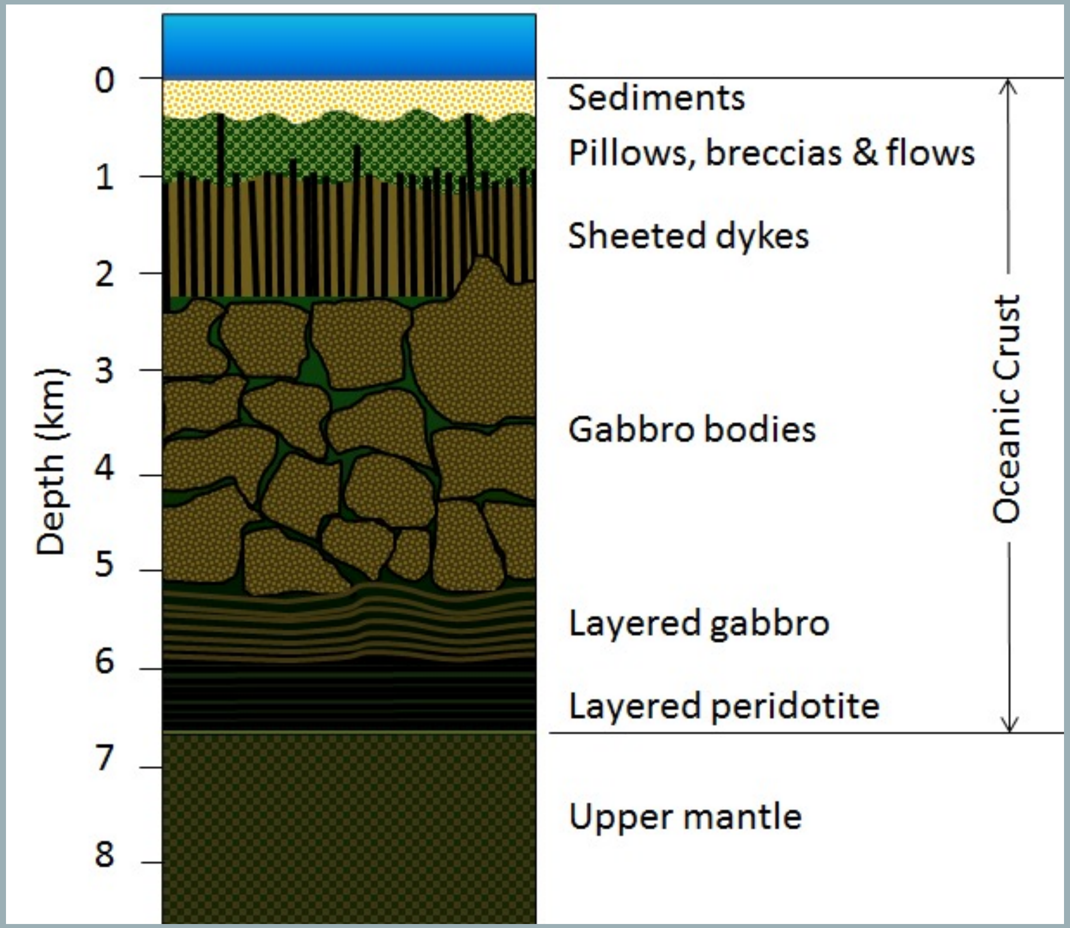
Most of the time, our models for oceanic lithosphere are simple:

1972 model of structure of oceanic lithosphere



Vine & Matthews, 1972

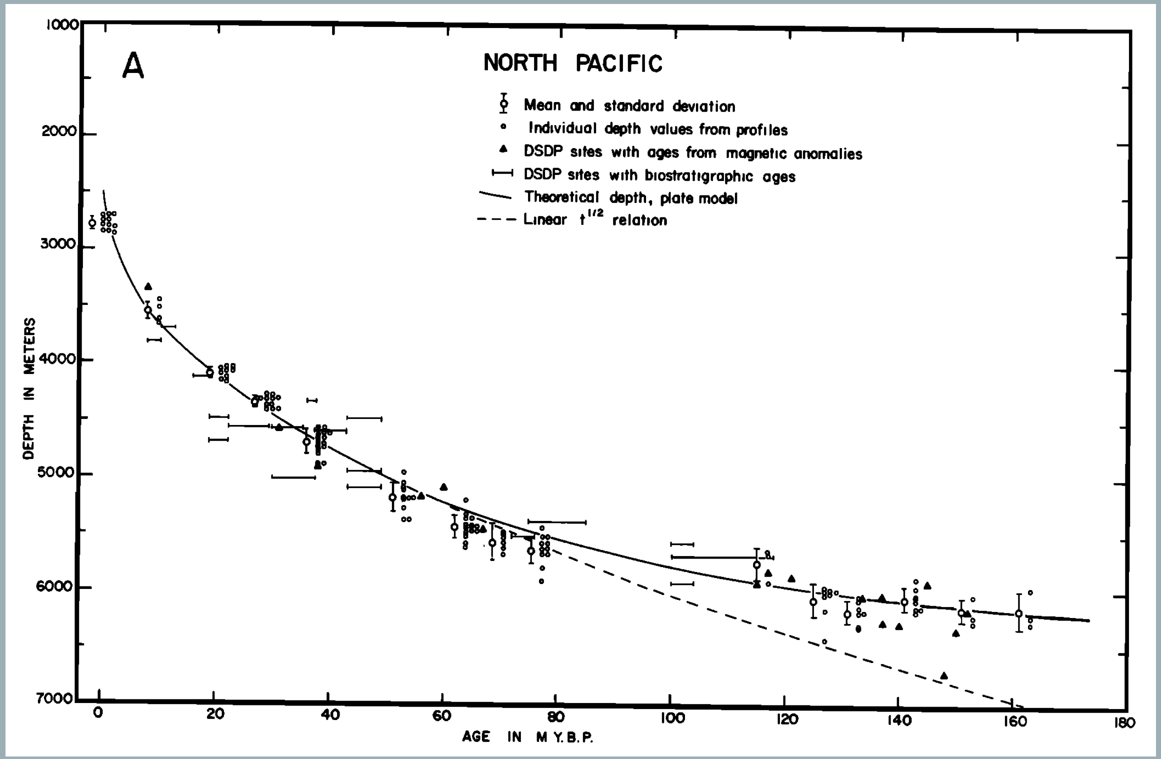
2019 textbook model



Stevens, Physical Geology, 2019

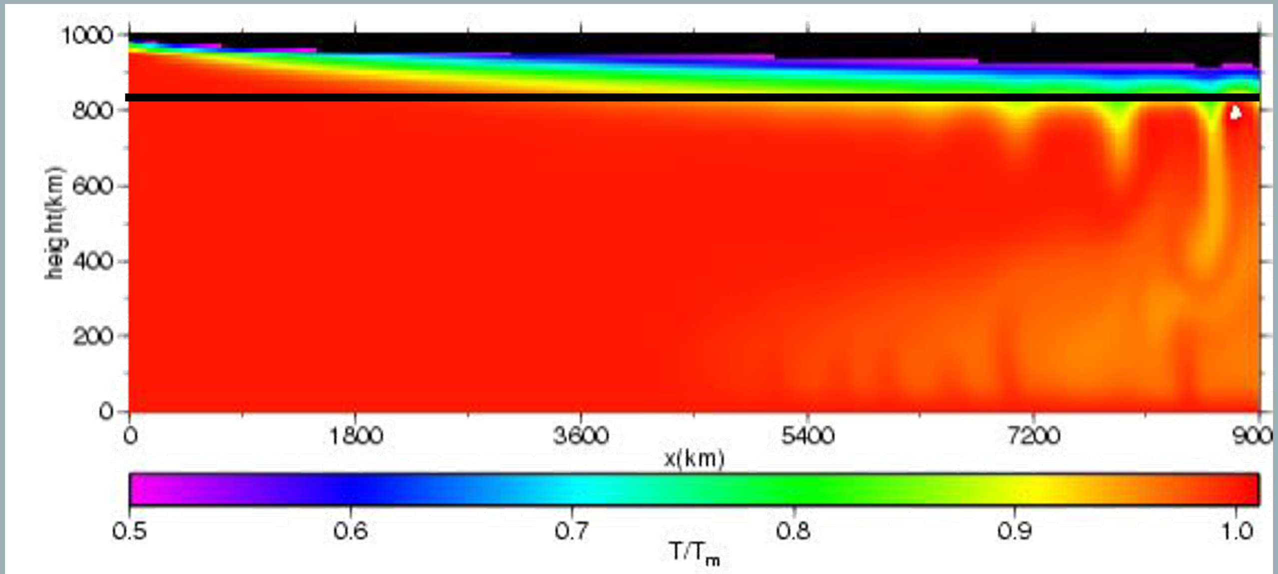
Most of the time, our models for oceanic lithosphere are simple:

1977 cooling plate model, thickness empirically determined to match depth and heat flow data



Parsons & Sclater, 1977

~2010 view of the plate model, with lithospheric instability and dripping controlling the plate thickness

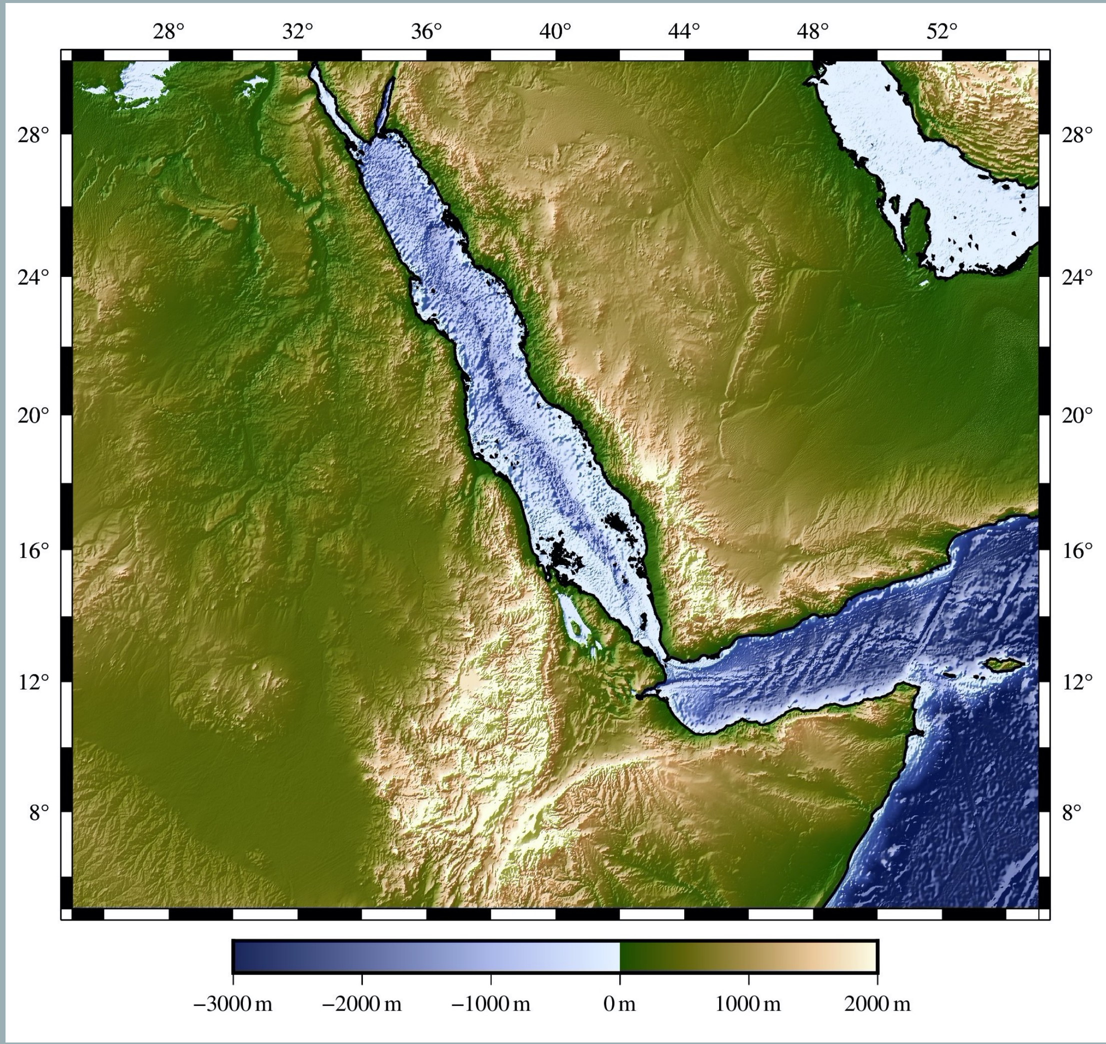


J. van Hunen

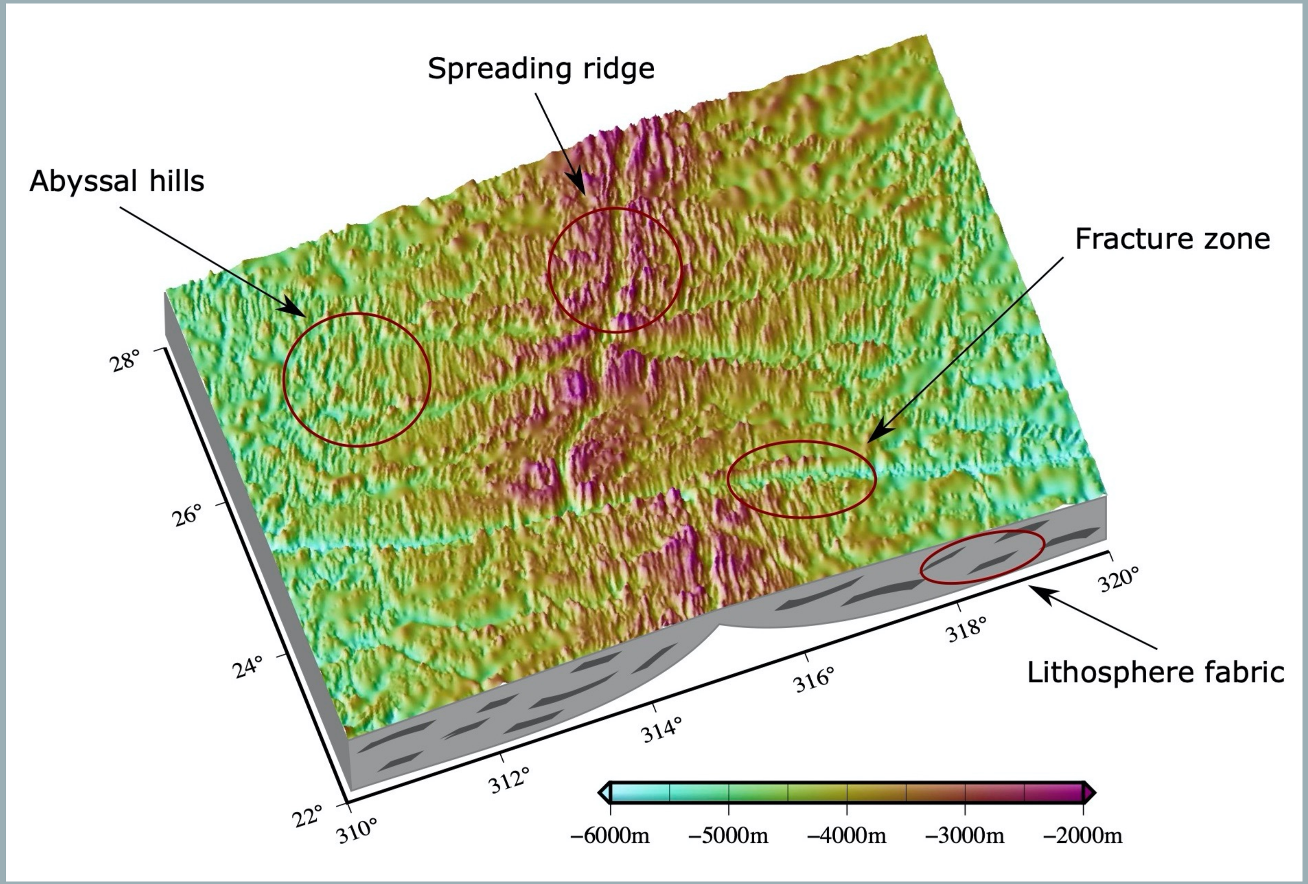
- These are very useful models, but they are just the beginning
- In particular, they are simply functions of time: there is no sense of directionality or anisotropy

Anisotropy in the formation and growth of oceanic lithosphere:

Rifting: highly anisotropic 'birth' of oceans, often approximately linear



Mature MORs: strong directionality from spreading ridge and abyssal hills; contrasting directionality from fracture zones



Thickening: as the plate moves, additional lithosphere forms from the shearing mechanical boundary layer

The processes behind the formation and development of oceanic lithosphere are extremely anisotropic:

Anisotropy should be a fundamental part of our thinking about oceanic lithosphere's structure and behaviour

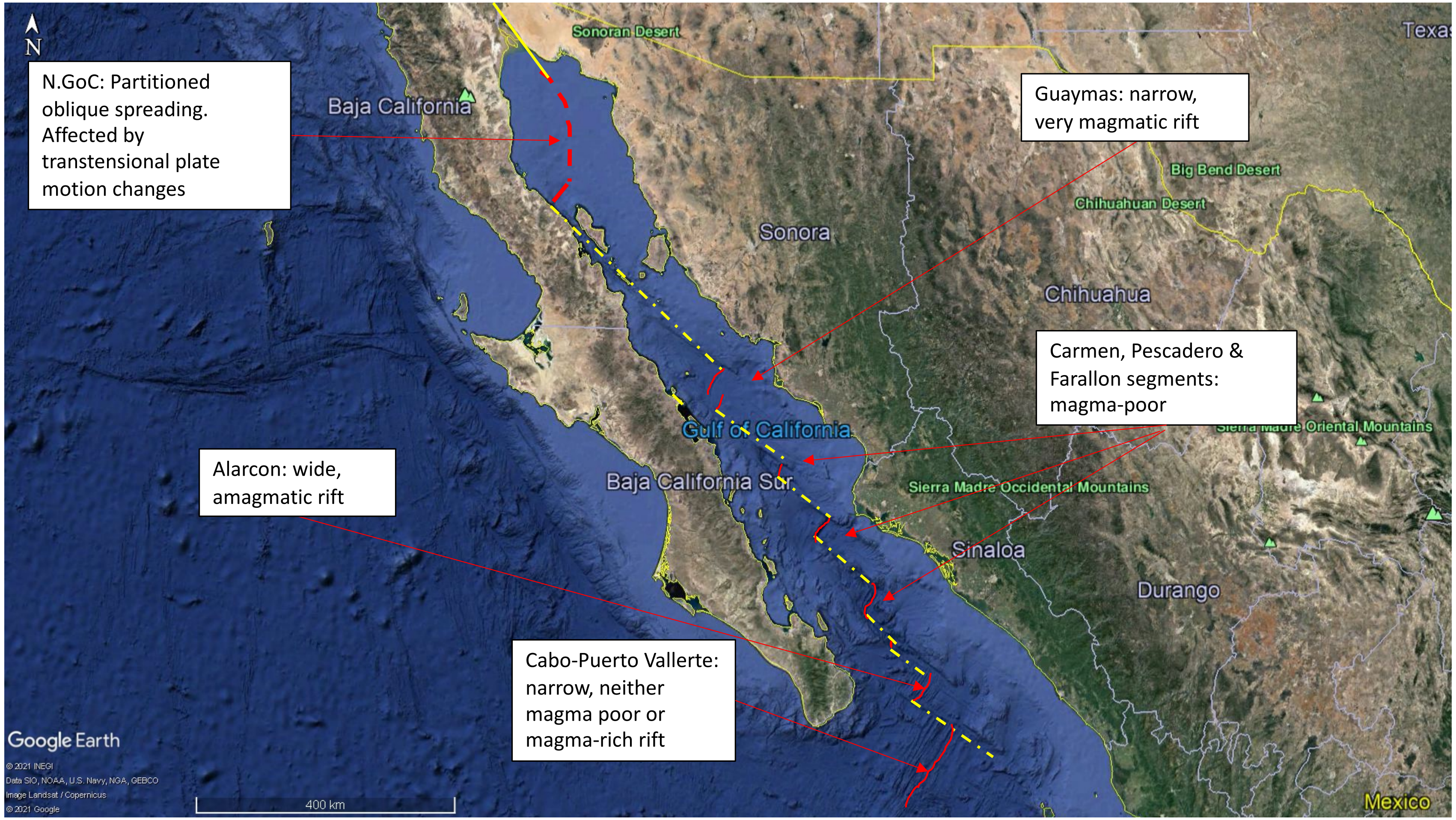
Formation, part 1: Rifting

Even at its simplest – orthogonal rifting in a uniform material – rifting is highly anisotropic. In addition, there may be:

- Tectonic inheritance in the rifting continental lithosphere
- Asymmetry between margin pairs, with one wide and one narrow margin
- Variations between magma-rich and magma-poor segments
- Oblique rifting
- Changes in relative plate motion as the system establishes or regional tectonics adapt

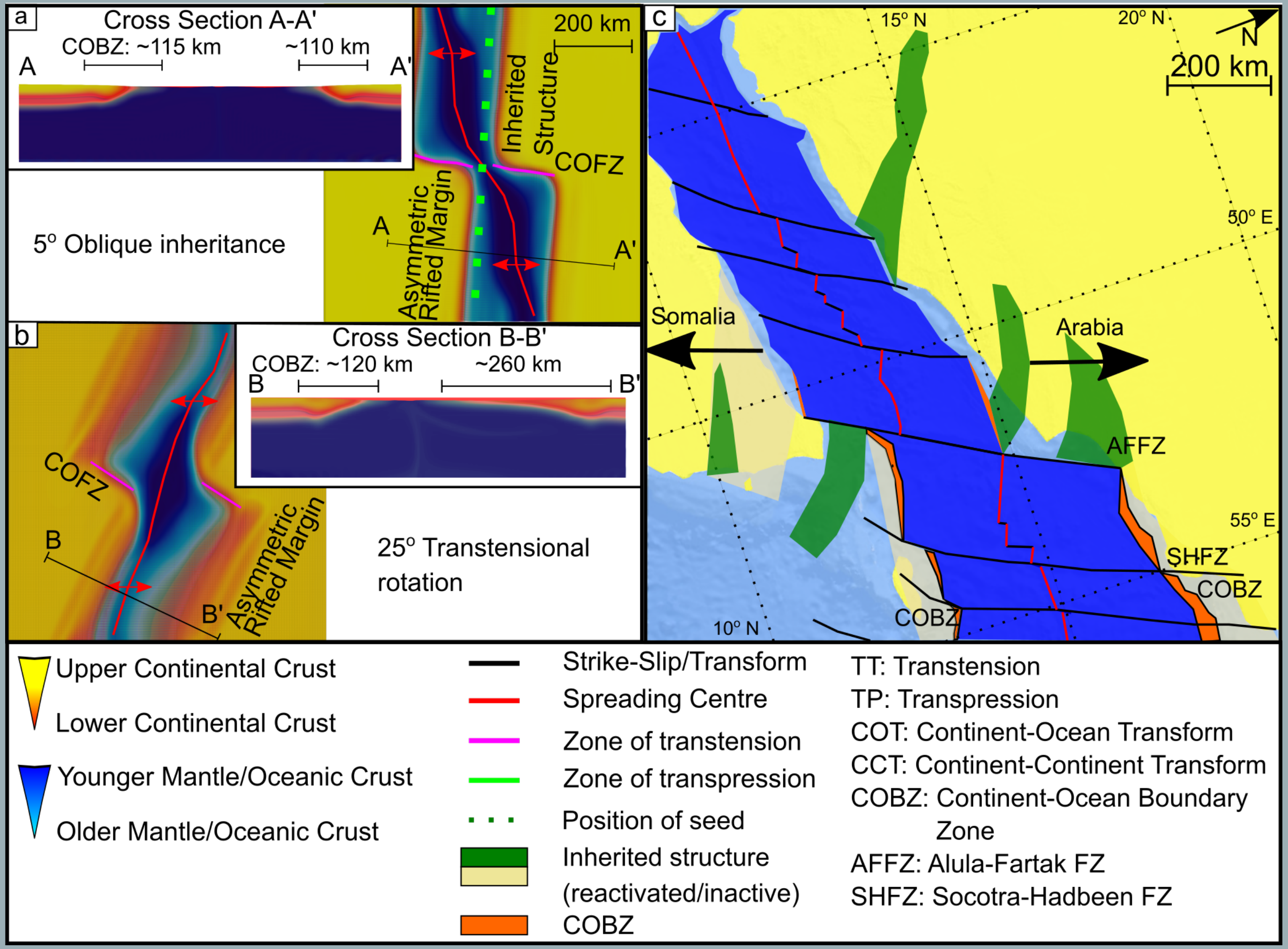
Rifting: Gulf of California

- Transitioning from rifting to spreading
- Nature of rift segments is highly varied
  - Thick sediment in the north may delay rupture and/or increase magmatism
- Transtensional plate motion changes associated with jump in deformation loci
  - Abandoned faults add additional anisotropy
- The Red Sea shows similar segmented variation, but with clear progression from rifted blocks in the north to established seafloor spreading in the south



Rifting: Gulf of Aden

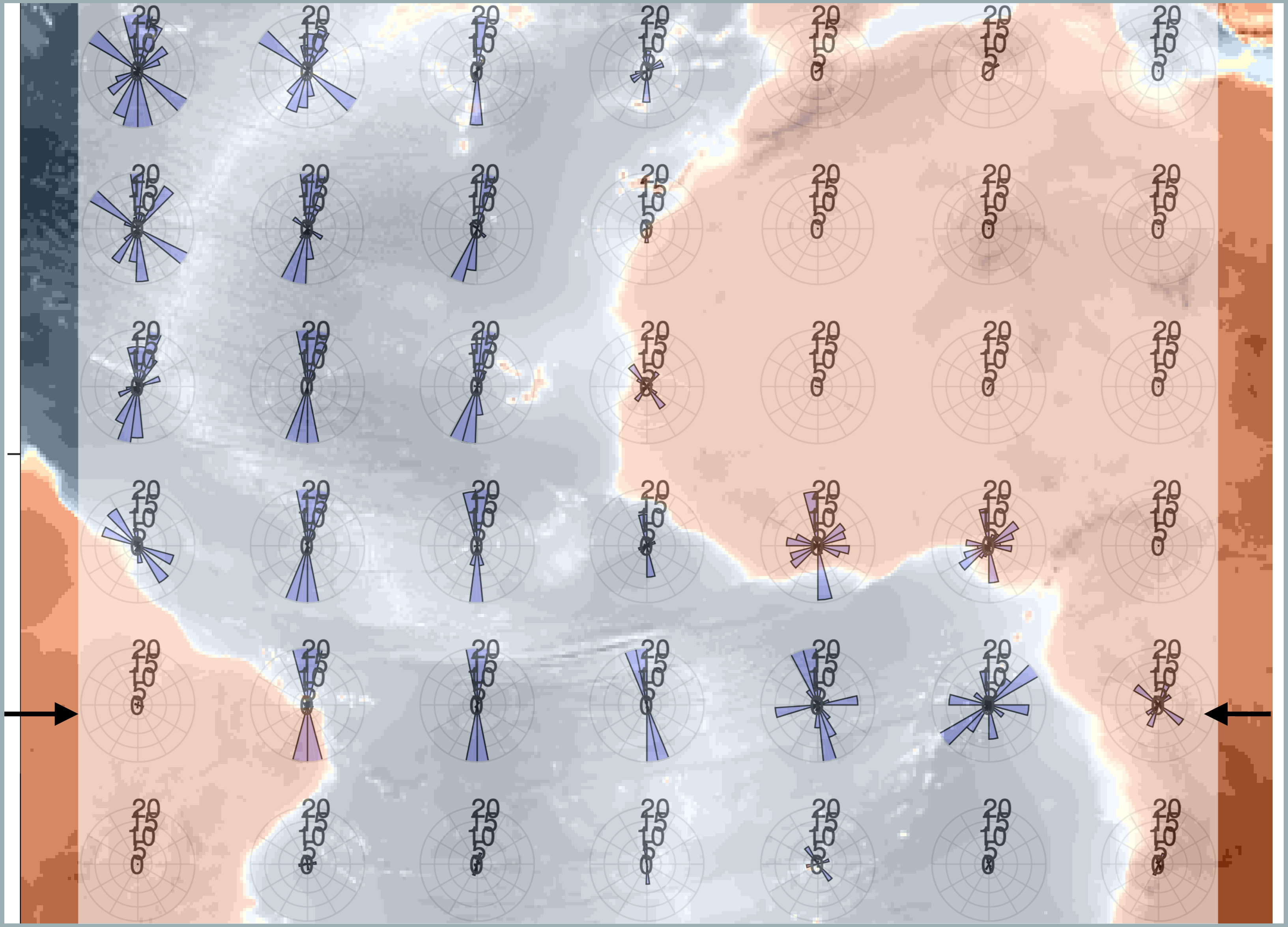
- Multiple factors at play:
  - Tectonic inheritance (green bands in [c])
  - Oblique rifting
  - Asymmetric margin (orange bands in southern part of [c])
  - Change in relative plate motion of ~ 26° at ~20 Ma
- Numerical modelling shows that inherited structure can influence the path of the rift [a], but the width of the margin is much better explained by the change in relative plate motion
  - A transtensional rotation of 25° in the model reproduces the observed pattern of a broad margin at outside corners and a narrow one at inside corners.



Modified from Farangitakis et al., 2020

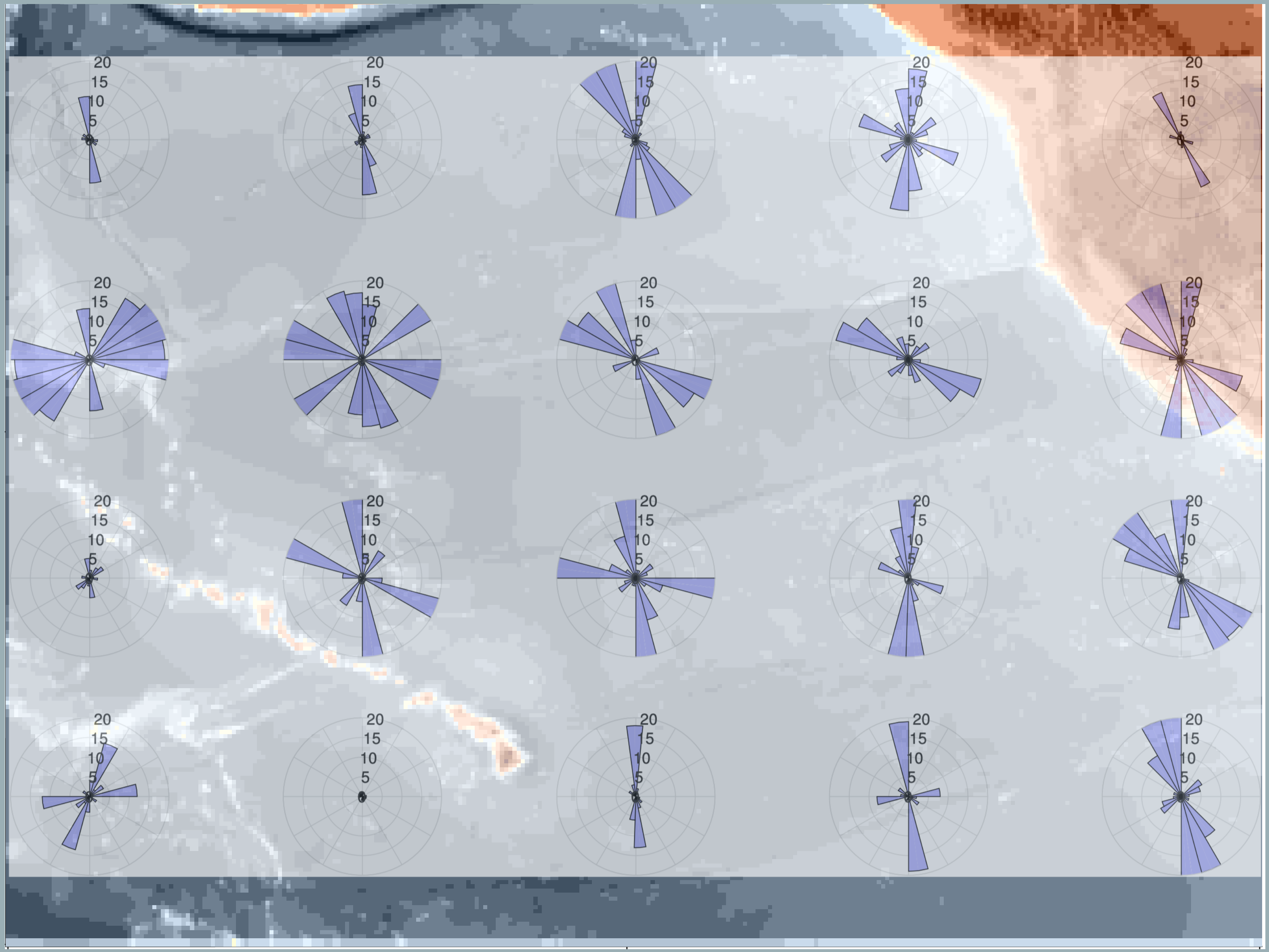
Formation, part 2: Seafloor spreading

- Structure of oceanic crust and uppermost lithosphere is formed at the highly-anisotropic spreading ridge. Does this create a persistent pattern of directional strength?
- Map shows rose diagrams of mechanically strong dimensions (measured from coherence between bathymetry and gravity) in 1000 km x 1000 km boxes (100 measurements each box)
  - Except near margins, strong directions are generally ridge-parallel
  - In some cases, e.g., the row marked with arrows, they clearly track the subtle small circle pattern of the fracture zones.



Formation & Maturation: Seafloor spreading

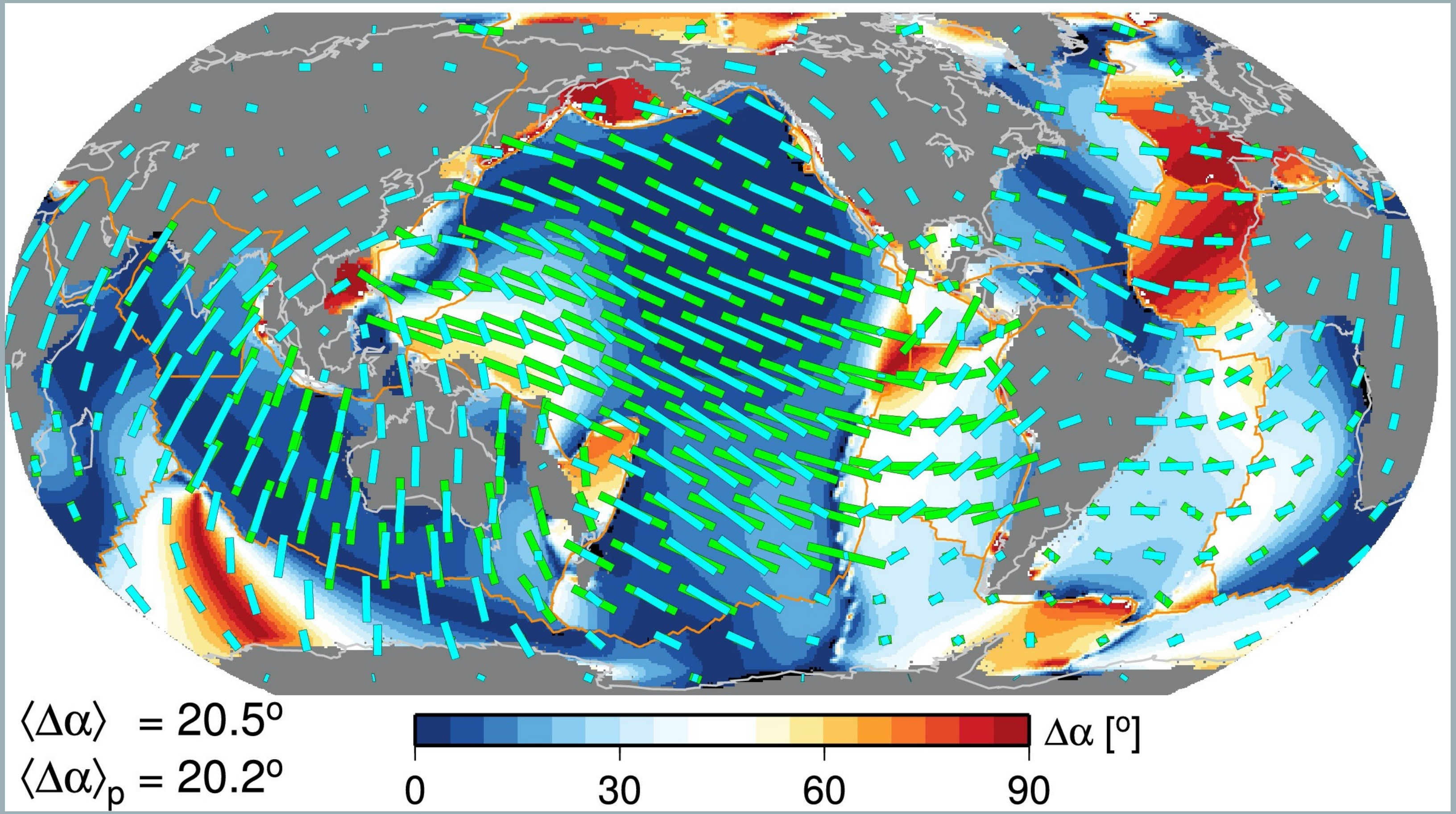
- Same analysis for part of the Pacific
- General pattern holds, but less clearly. Many diagrams show 2 or 3 strong directions.
  - Effect of faster spreading rate, faulting at the ridge less important?
  - Effect of later changes in plate motion? The Pacific has a more complex spreading history than the Atlantic, and a number of regions show strong directions parallel to the Hawaiian-Emperor Seamounts.
- There is also a lack of robust strong directions in some regions near Hawaii; this is also observed around Cape Verde and the Canary Islands in the Atlantic, but their smaller scale makes it less obvious when directions are binned at this scale.



Maturation

- Seismic anisotropy with fast directions aligned with plate motion commonly found in lower lithosphere and uppermost asthenosphere (100-200 km depth), attributed to crystal alignment
  - Will often align with structure inherited from the ridge, but, as in the Pacific, may not due to plate motion changes
  - Becker et al. (2014) find stronger agreement between seismic anisotropy and plate motion at rates > 5 cm/yr, consistent with this second signal detected in the Pacific
- Anisotropy in resistivity shows a similar change from low direction ridge-parallel in the crust (fault-controlled) to ridge-perpendicular (crystal controlled) in the mantle (Chesley et al., 2019)

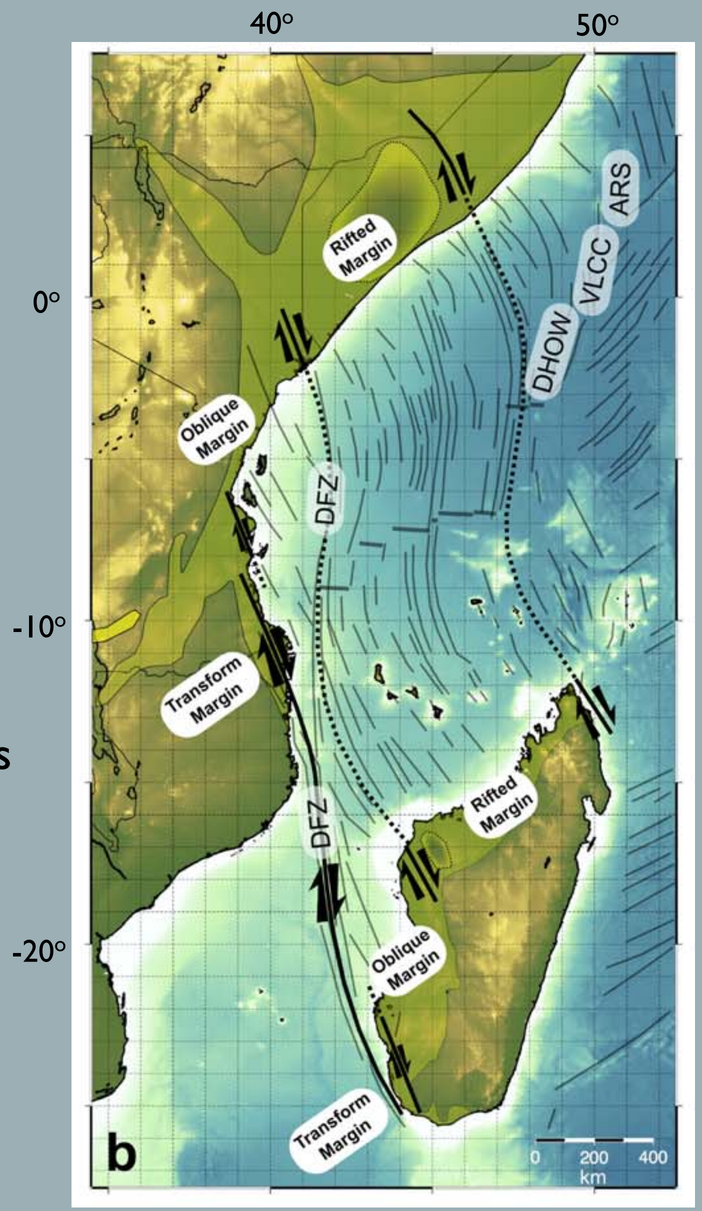
Seismic anisotropy (cyan) and absolute plate motion in a ridge-no-rotation reference frame (green), both at 200 km depth



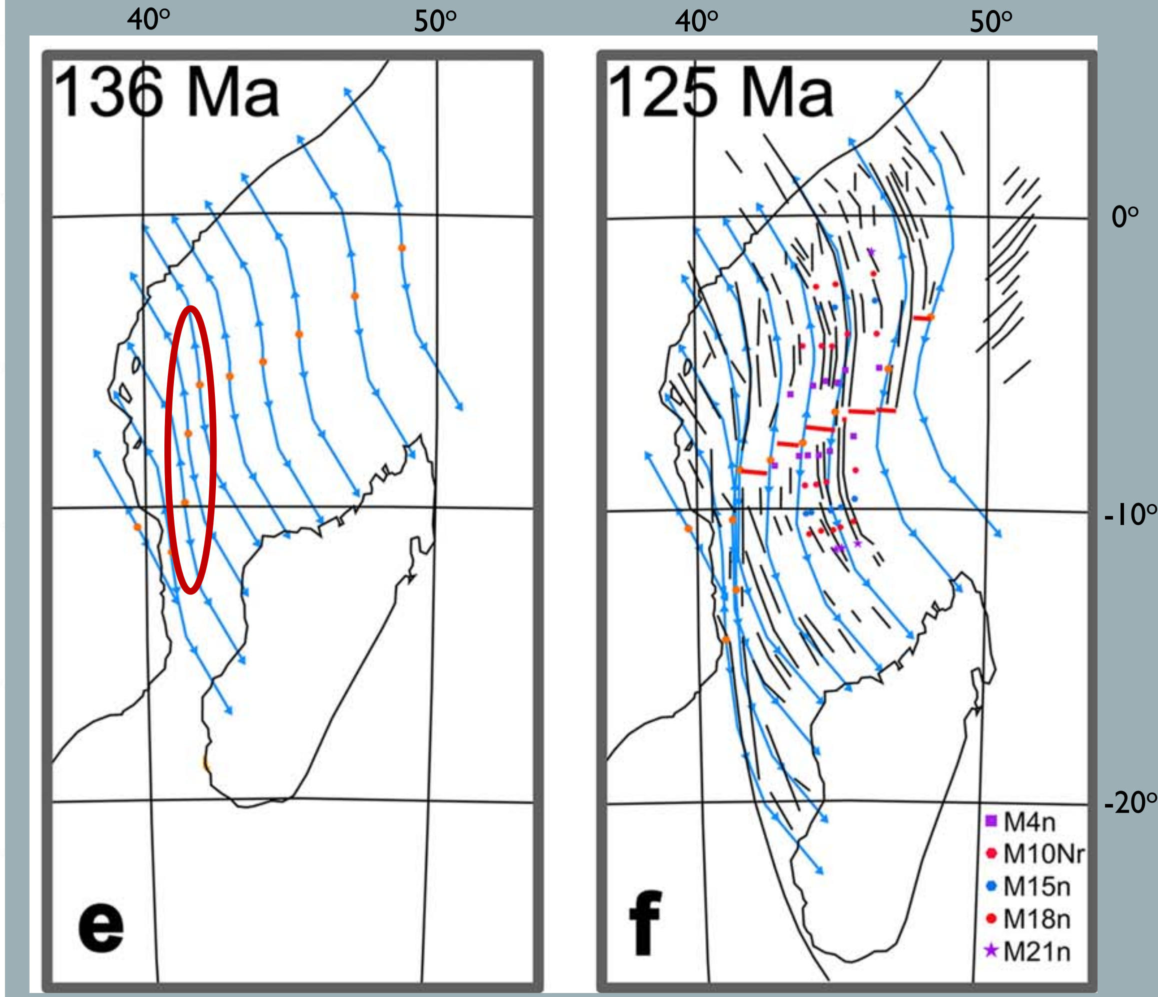
Becker et al. (2014)

Modification: Plate Motion Changes

- Somali Basin characterised by one very dominant fracture zone, the Davie Fracture Zone (DFZ)
  - Once thought to be the continent-ocean boundary because of its prominence
- Analysis of directional gravity gradients and tectonic reconstruction show that a plate motion change created an alignment of fracture zones (red oval)
- The DFZ broke through this natural zone of weakness
- Later compression was also accommodated by this zone



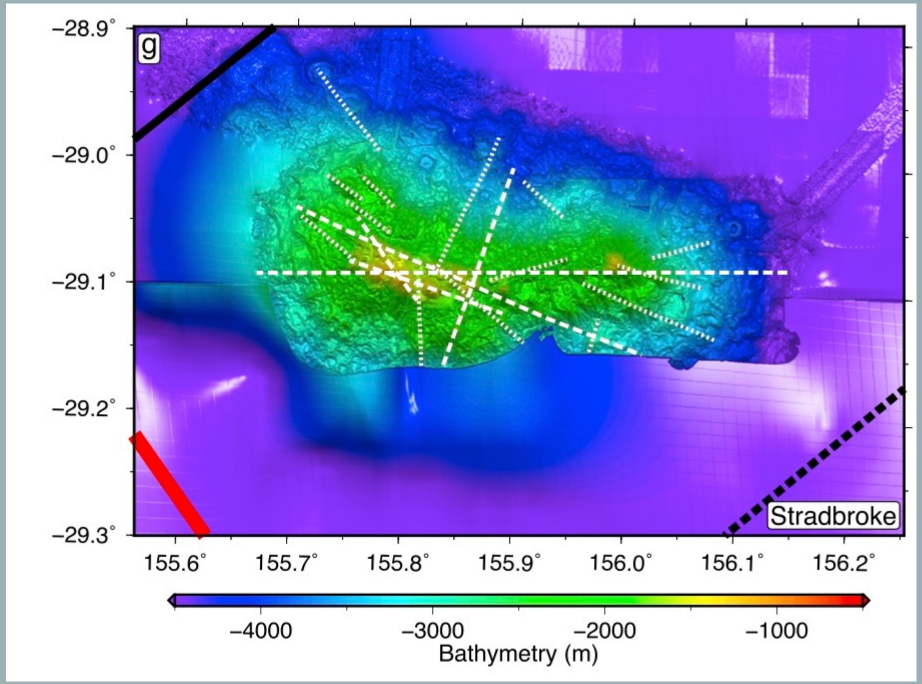
Kalnins et al., EGU 2021

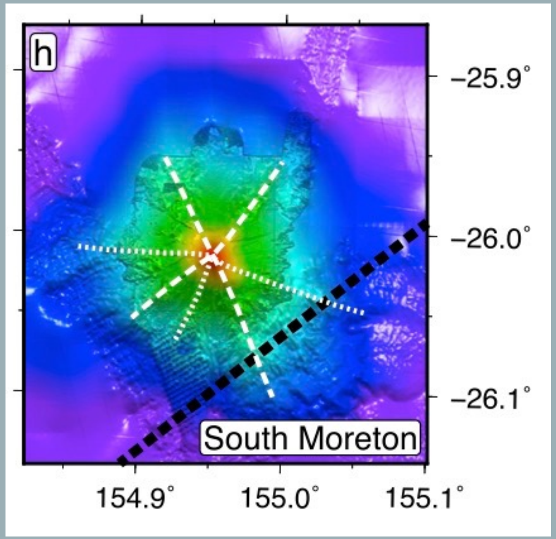


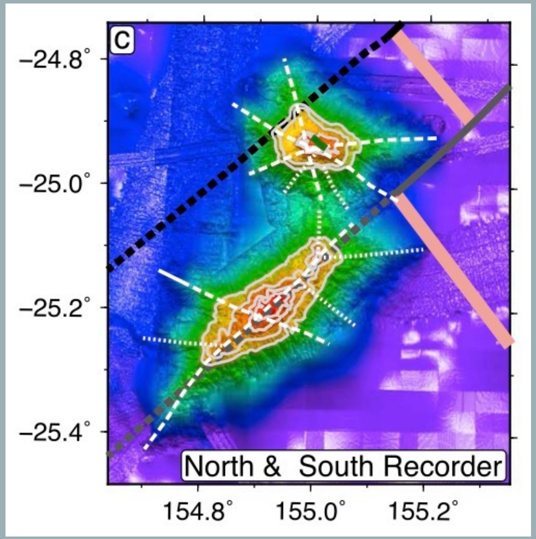
Phethean et al., 2016

Modification: Volcanism

- Tasmantid Seamounts off eastern Australia criss-cross extinct Tasman Sea spreading centre, but postdate it by 10s of millions of years
- Position of volcanoes appears unaffected, but size, shape, and overall morphology all correlate with position relative to the spreading ridge (on an inside corner, outside corner, fracture zone or mid-segment)
  - For example, large, elongate volcanoes typically occur along fracture zones and rough, irregularly shaped ones on outside corners or across multiple short segments
  - Influence of shallow ridge structure despite >20 Ma of 'normal' lithospheric thickening beneath it
- Effective elastic thickness analysis of the mechanical strength of the lithosphere suggests the lithosphere remained very weak, lacking the typical correlation between age of the lithosphere at seamount emplacement and strength
  - Potentially due to increased amagmatic strain and faulting as spreading ceased







Richards et al., 2018

Destruction: Subduction

Future Work:

- How do the strong directions in the downgoing plate align with trench orientation and convergence direction, both at subduction initiation and throughout the subduction zone's life?
  - For ocean-ocean subduction zones, how does this compare with the strong directions in the overriding plate?
- Does the alignment influence the pattern of faulting on the outer rise?
- Does it influence the decrease in mechanical strength observed as the plate bends into the trench, e.g., Hunter & Watts, 2016

Conclusions

- Oceanic lithosphere forms through processes that are highly anisotropic. It acquires an anisotropic signature during:
  - Rifting
  - Seafloor spreading
  - Thickening as it matures
- This anisotropy affects how later plate motion changes are accommodated, and both affects and is affected by later volcanism, with the potential to affect subduction patterns as well
- **Anisotropy should thus be a fundamental part of our thinking about oceanic lithosphere's structure and behaviour**