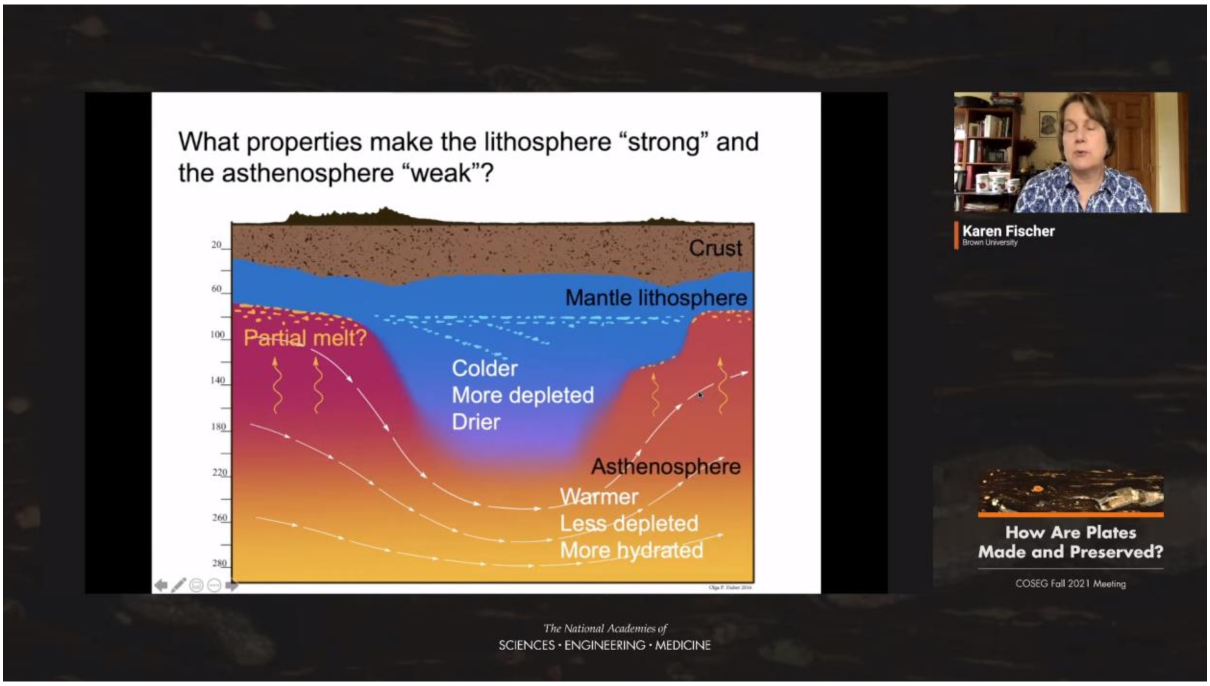

What properties make the lithosphere "strong" and the asthenosphere "weak"?

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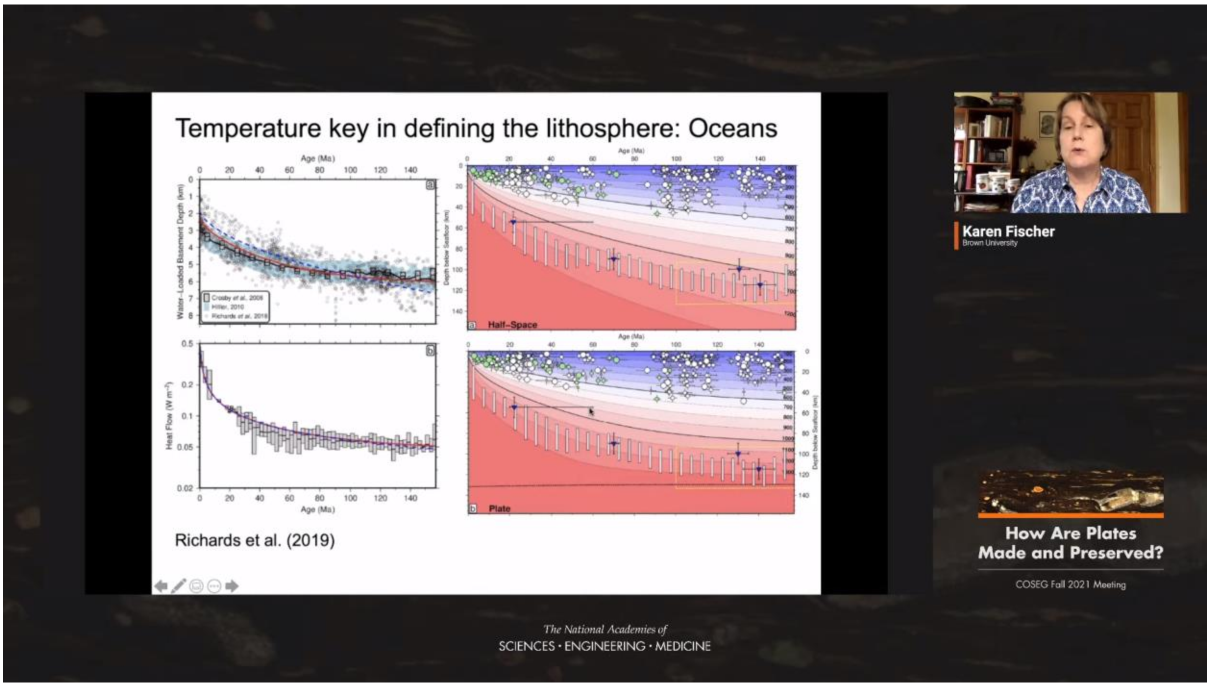

Temperature key in defining the lithosphere: Oceans

Richards et al. (2019)

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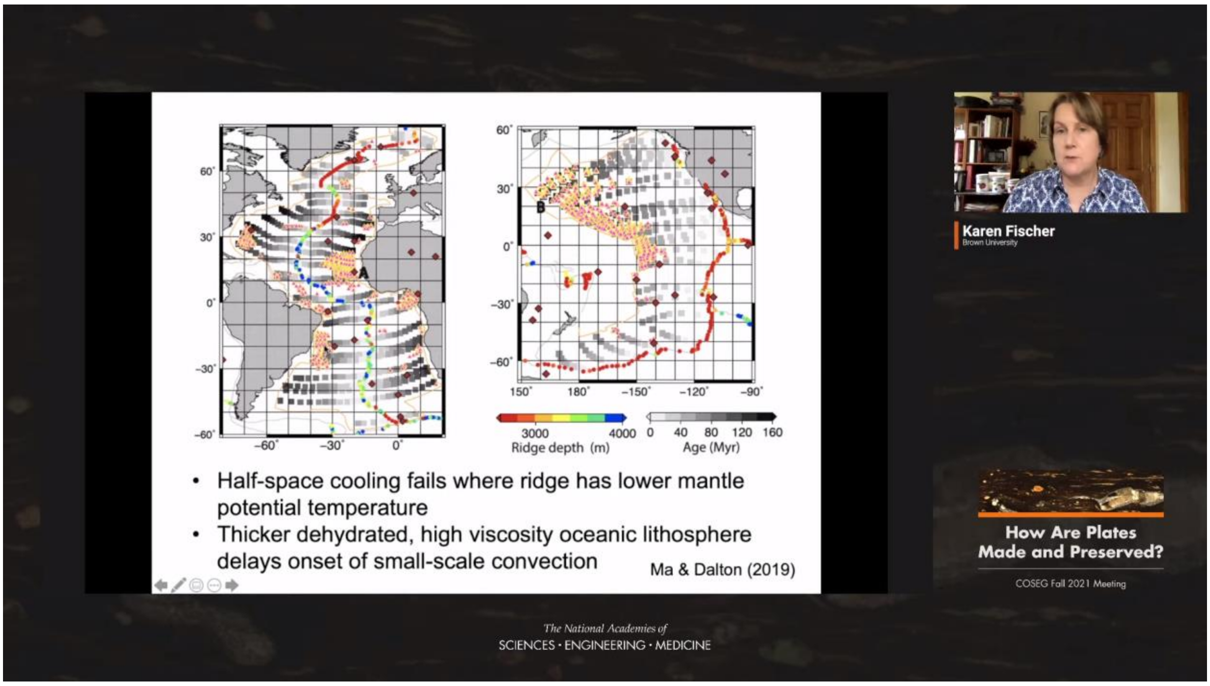
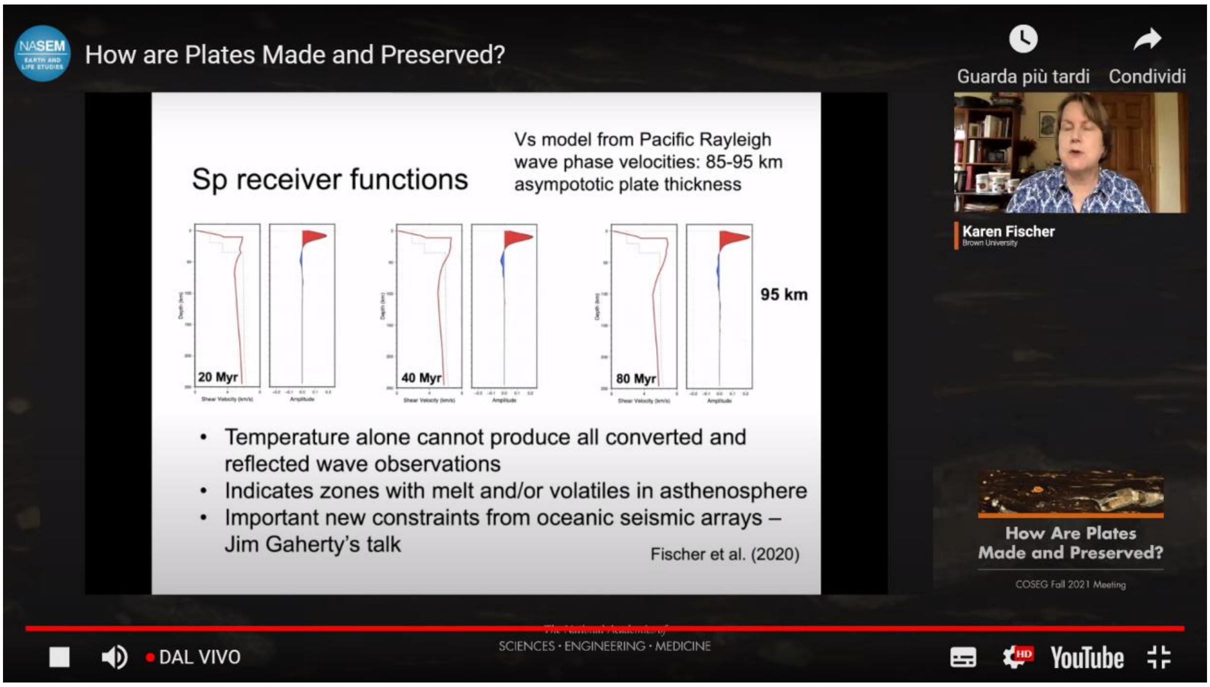


- Half-space cooling fails where ridge has lower mantle potential temperature
- Thicker dehydrated, high viscosity oceanic lithosphere delays onset of small-scale convection

Ma & Dalton (2019)

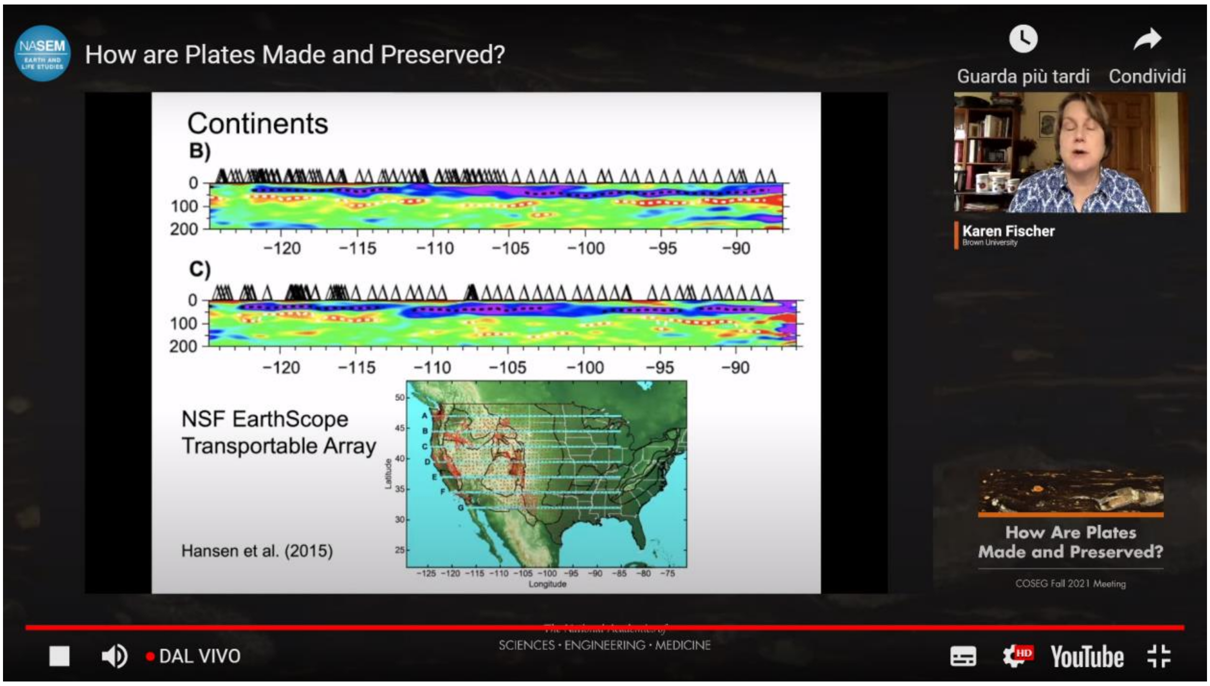


Sp receiver functions

Vs model from Pacific Rayleigh wave phase velocities: 85-95 km asympototic plate thickness

- Temperature alone cannot produce all converted and reflected wave observations
- Indicates zones with melt and/or volatiles in asthenosphere
- Important new constraints from oceanic seismic arrays – Jim Gaherty's talk

Fischer et al. (2020)



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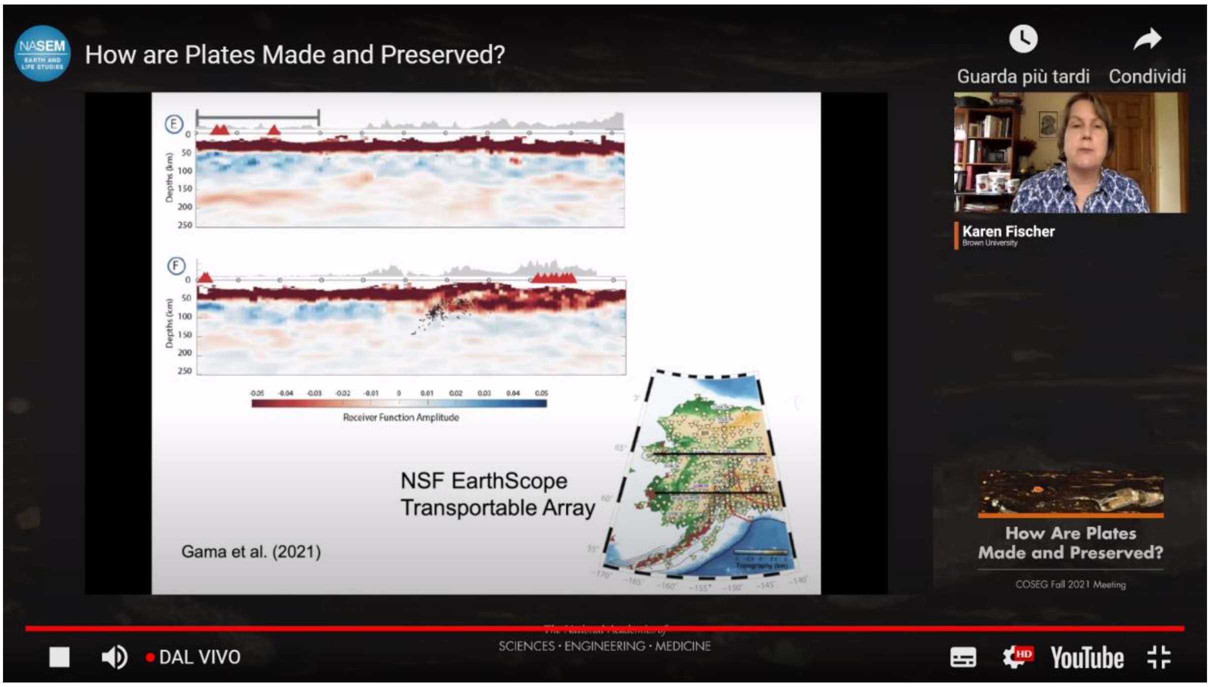
Continents

NSF EarthScope Transportable Array

Hansen et al. (2015)



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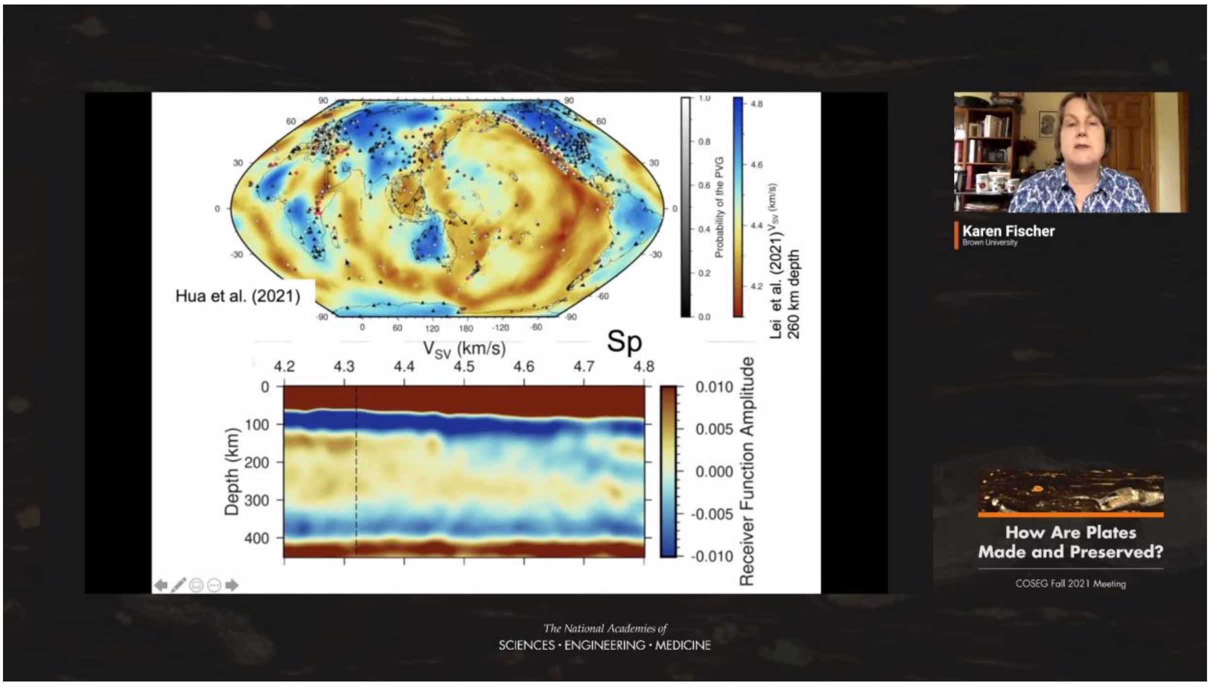
NSF EarthScope Transportable Array

Gama et al. (2021)



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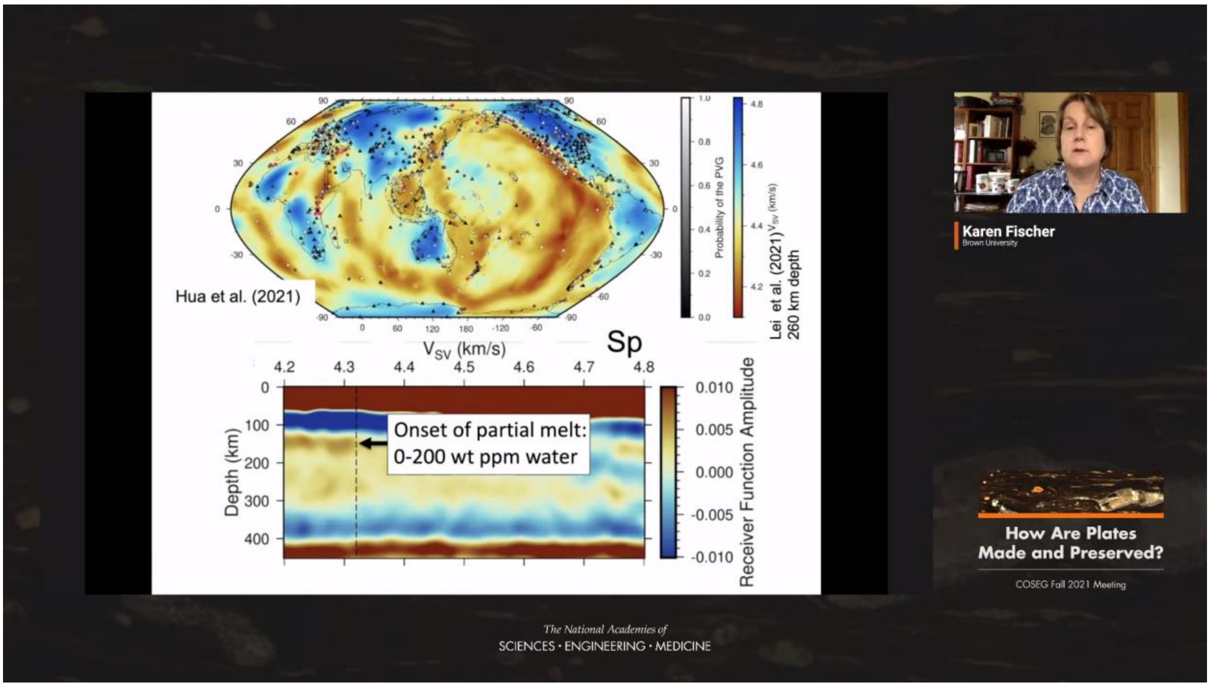

Onset of partial melt:
0-200 wt ppm water

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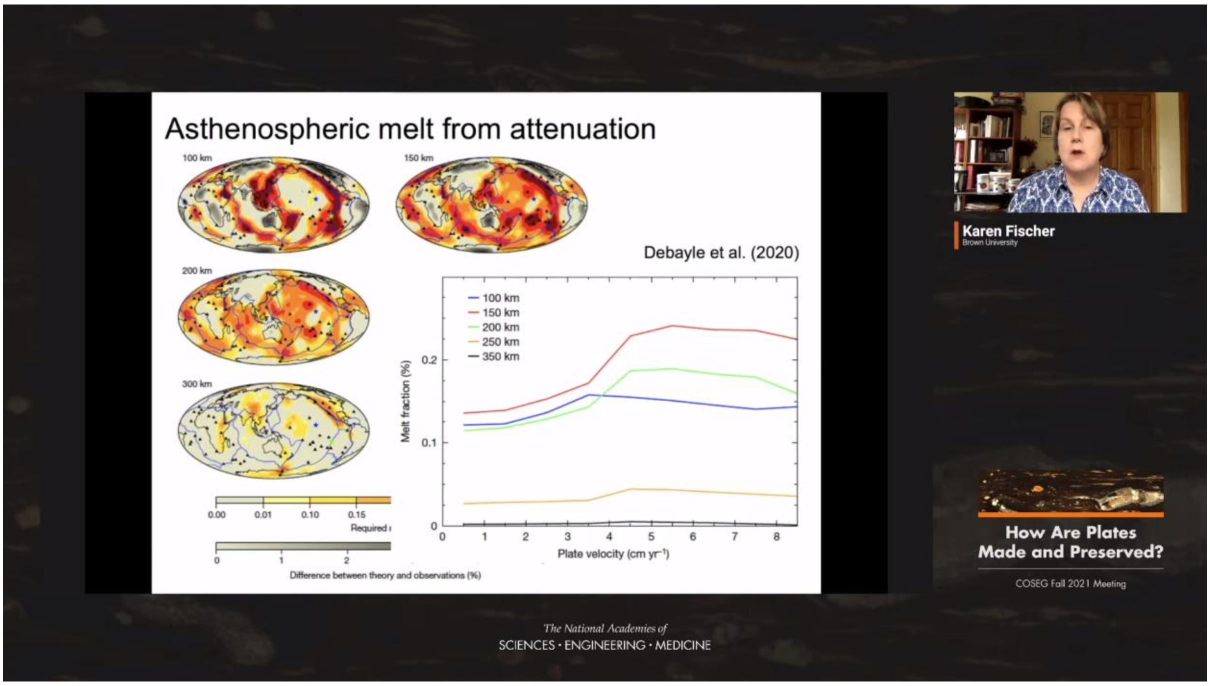

Asthenospheric melt from attenuation

Debayle et al. (2020)

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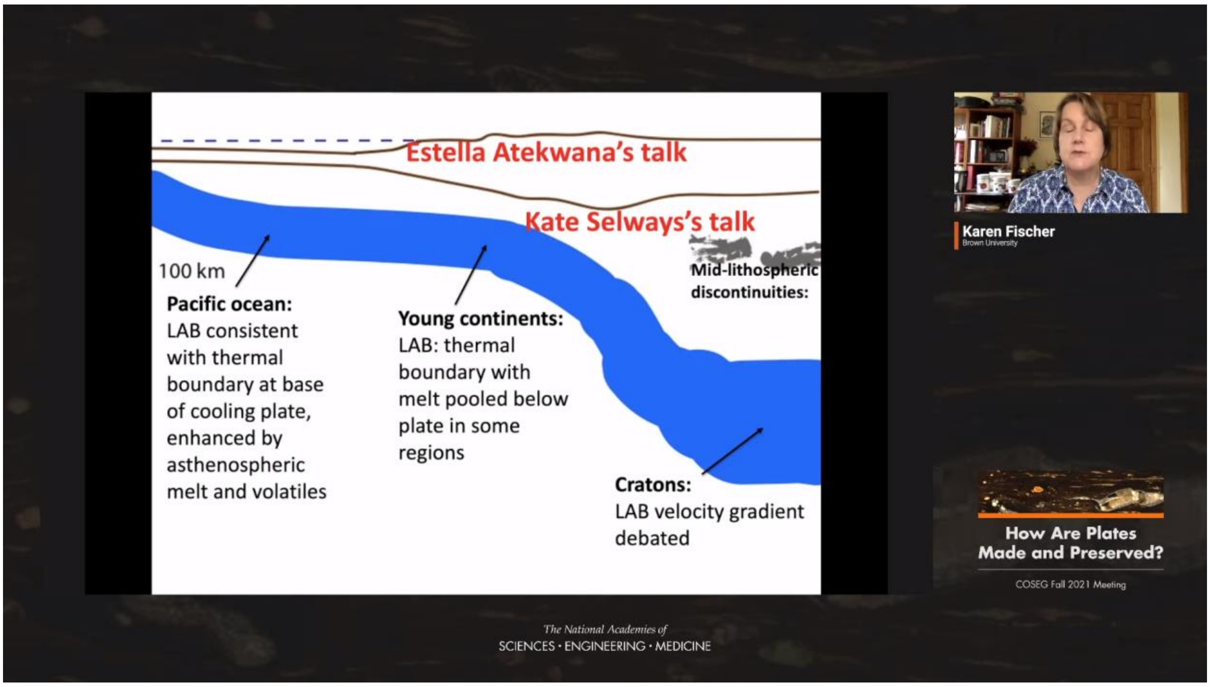

Estella Atekwana's talk

Kate Selways's talk

100 km

Pacific ocean: LAB consistent with thermal boundary at base of cooling plate, enhanced by asthenospheric melt and volatiles

Young continents: LAB: thermal boundary with melt pooled below plate in some regions

Mid-lithospheric discontinuities:

Cratons: LAB velocity gradient debated

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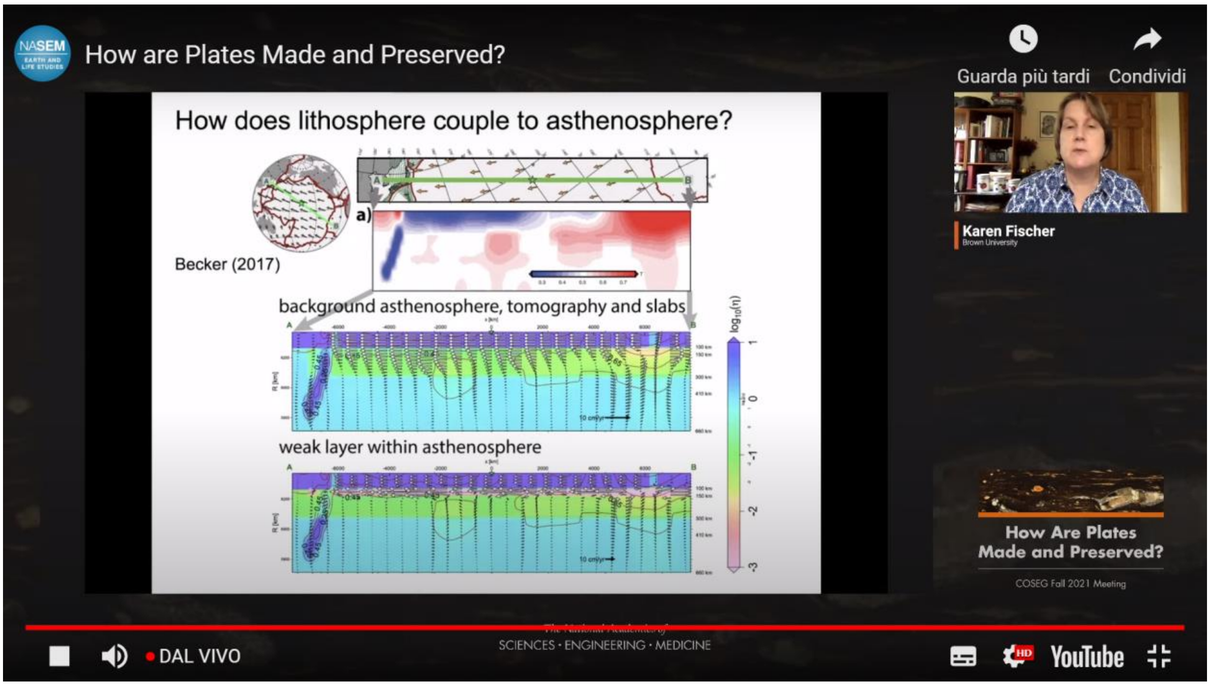
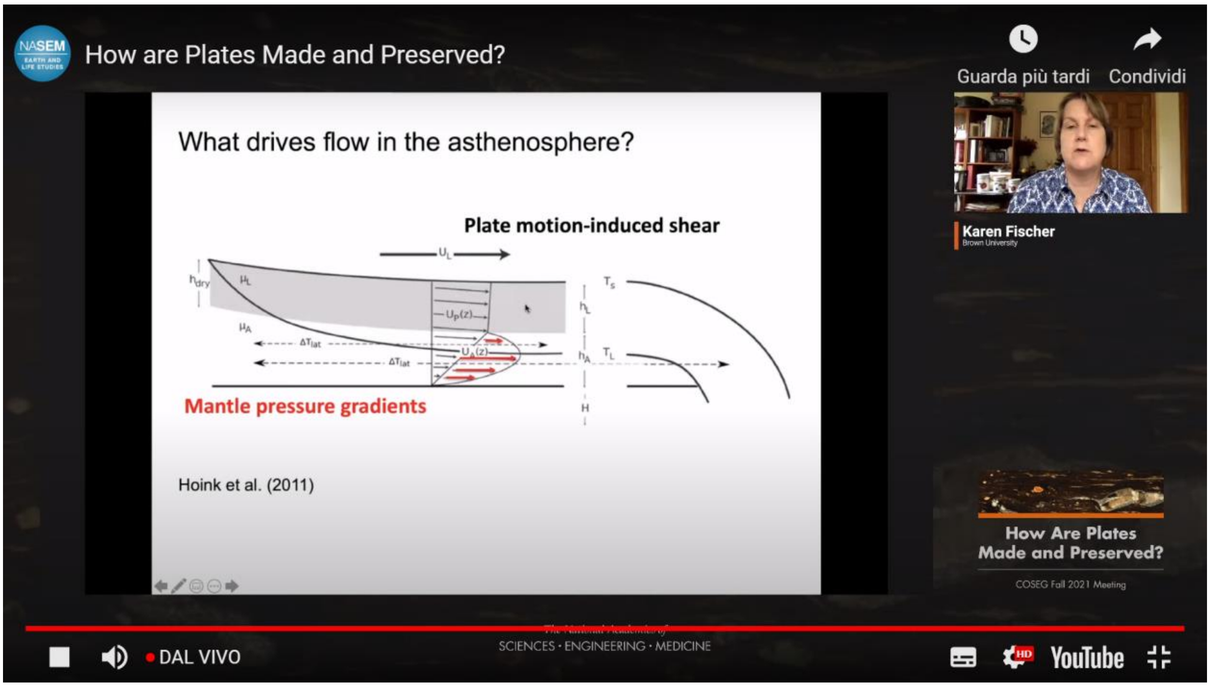


How does lithosphere couple to asthenosphere?

Becker (2017)

background asthenosphere, tomography and slabs

weak layer within asthenosphere

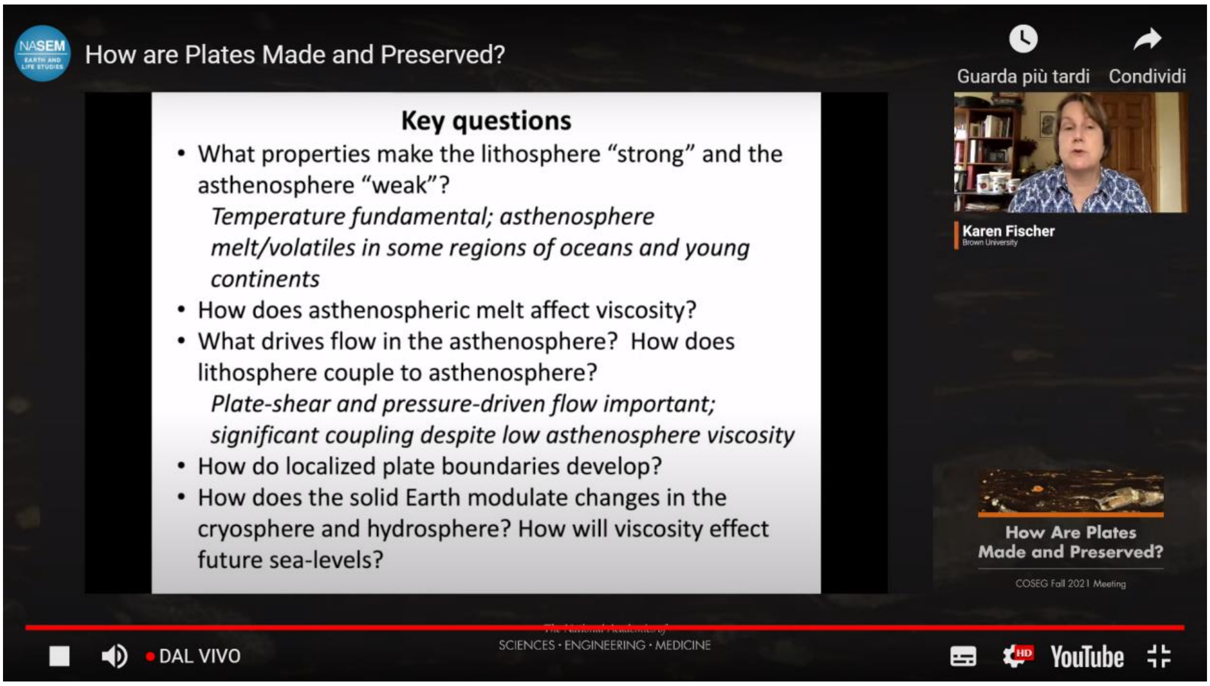


What drives flow in the asthenosphere?

Plate motion-induced shear

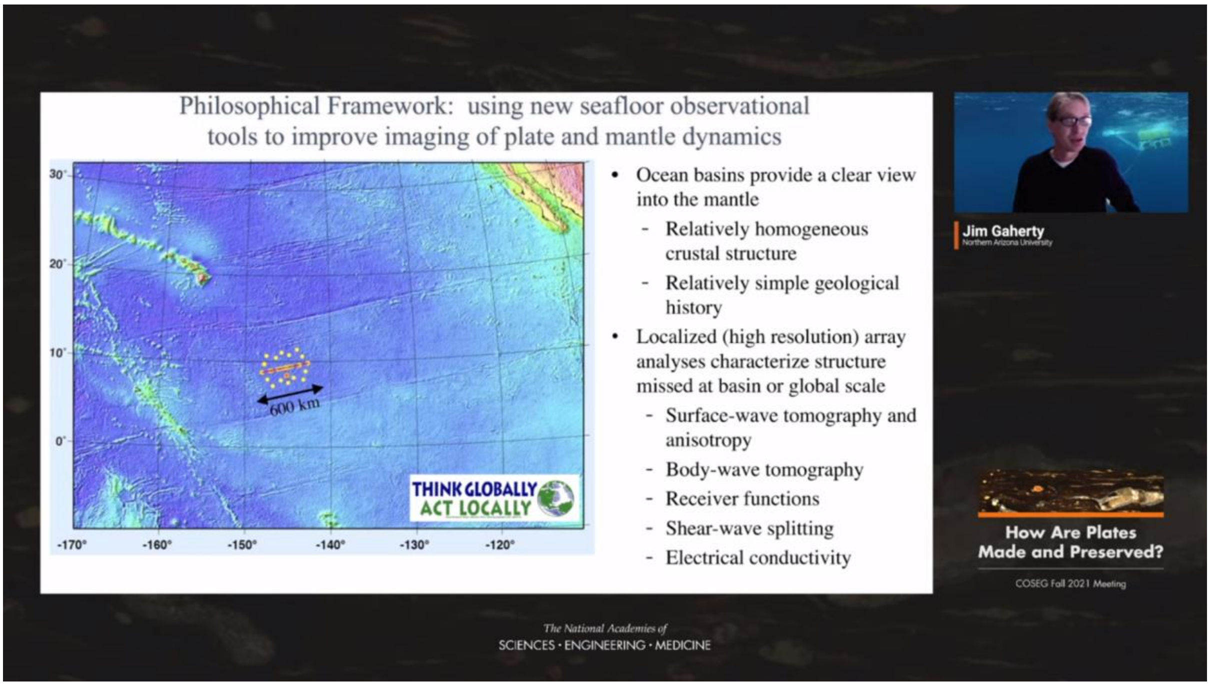
Mantle pressure gradients

Hoink et al. (2011)



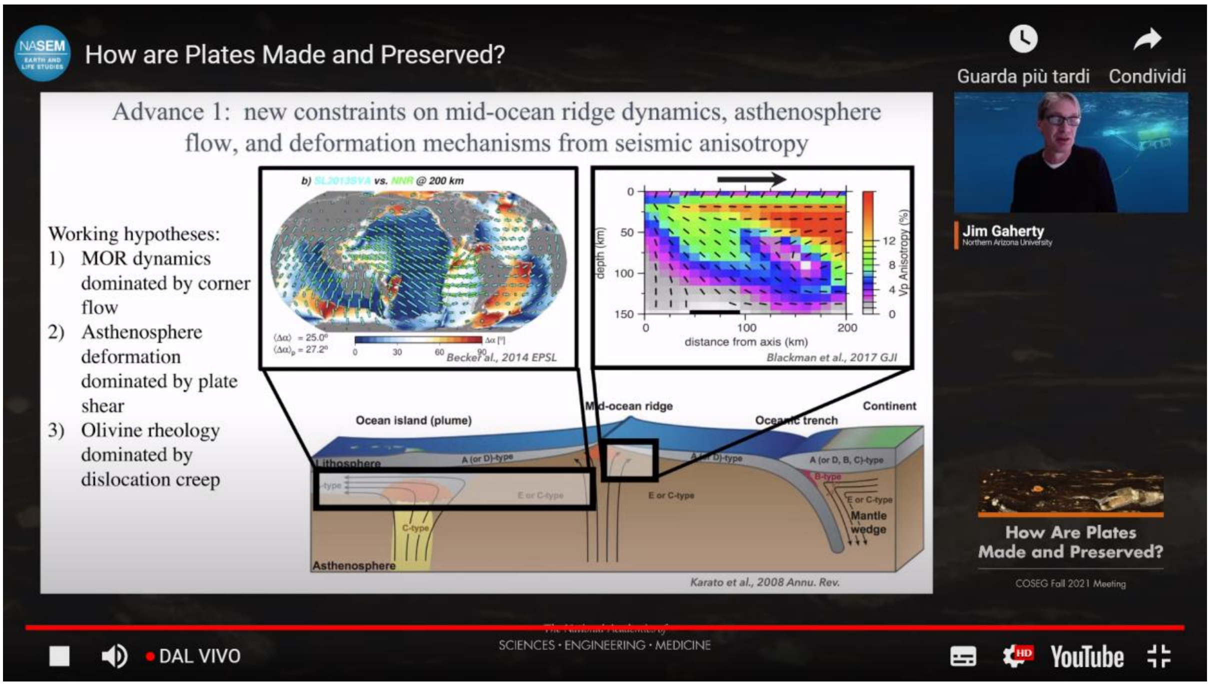
Key questions

- What properties make the lithosphere "strong" and the asthenosphere "weak"?
  Temperature fundamental; asthenosphere melt/volatiles in some regions of oceans and young continents
- How does asthenospheric melt affect viscosity?
- What drives flow in the asthenosphere? How does lithosphere couple to asthenosphere?
  Plate-shear and pressure-driven flow important; significant coupling despite low asthenosphere viscosity
- How do localized plate boundaries develop?
- How does the solid Earth modulate changes in the cryosphere and hydrosphere? How will viscosity effect future sea-levels?



Philosophical Framework: using new seafloor observational tools to improve imaging of plate and mantle dynamics

- Ocean basins provide a clear view into the mantle
  - Relatively homogeneous crustal structure
  - Relatively simple geological history
- Localized (high resolution) array analyses characterize structure missed at basin or global scale
  - Surface-wave tomography and anisotropy
  - Body-wave tomography
  - Receiver functions
  - Shear-wave splitting
  - Electrical conductivity



Advance 1: new constraints on mid-ocean ridge dynamics, asthenosphere flow, and deformation mechanisms from seismic anisotropy

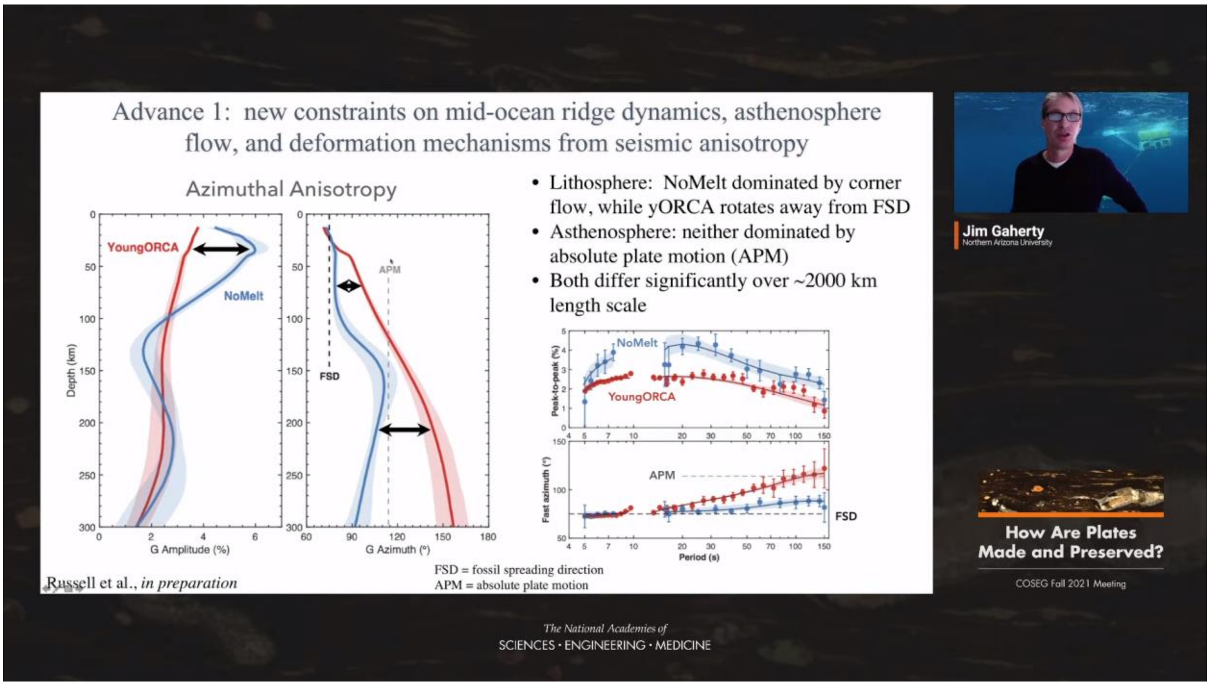
Working hypotheses:

1) MOR dynamics dominated by corner flow
2) Asthenosphere deformation dominated by plate shear
3) Olivine rheology dominated by dislocation creep

Becker et al., 2014 EPSL

Blackman et al., 2017 GJI

Karato et al., 2008 Annu. Rev.



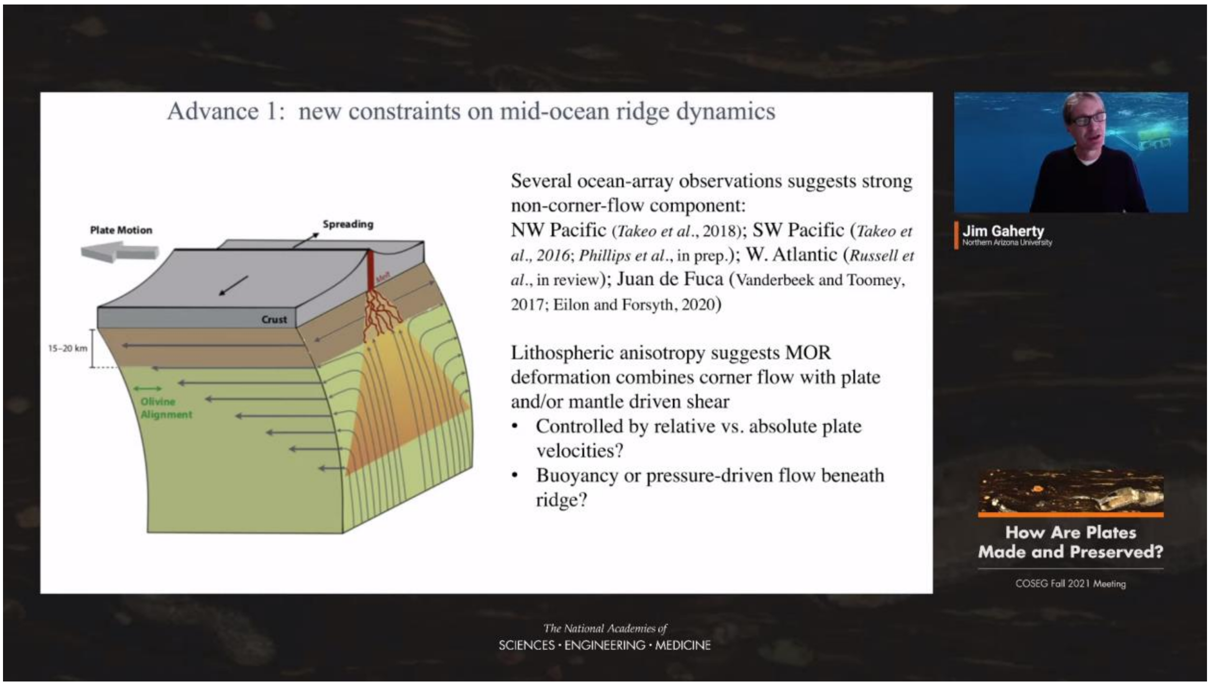
Advance 1: new constraints on mid-ocean ridge dynamics, asthenosphere flow, and deformation mechanisms from seismic anisotropy

Azimuthal Anisotropy

- Lithosphere: NoMelt dominated by corner flow, while yORCA rotates away from FSD
- Asthenosphere: neither dominated by absolute plate motion (APM)
- Both differ significantly over ~2000 km length scale

Russell et al., *in preparation*

FSD = fossil spreading direction
APM = absolute plate motion



Advance 1: new constraints on mid-ocean ridge dynamics

Several ocean-array observations suggests strong non-corner-flow component: NW Pacific (*Takeo et al*., 2018); SW Pacific (*Takeo et al., 2016*; *Phillips et al*., in prep.); W. Atlantic (*Russell et al*., in review); Juan de Fuca (Vanderbeek and Toomey, 2017; Eilon and Forsyth, 2020)

Lithospheric anisotropy suggests MOR deformation combines corner flow with plate and/or mantle driven shear

- Controlled by relative vs. absolute plate velocities?
- Buoyancy or pressure-driven flow beneath ridge?

Jim Gaherty
Northern Arizona University

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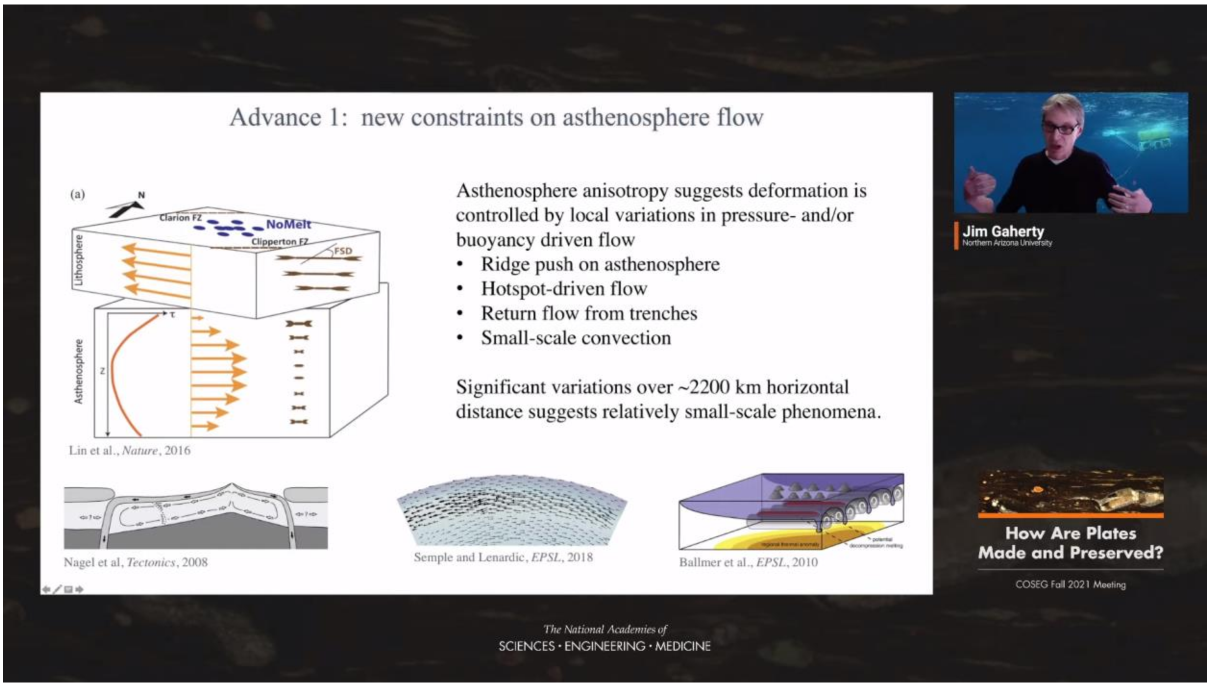

Advance 1: new constraints on asthenosphere flow

Asthenosphere anisotropy suggests deformation is controlled by local variations in pressure- and/or buoyancy driven flow

- Ridge push on asthenosphere
- Hotspot-driven flow
- Return flow from trenches
- Small-scale convection

Significant variations over ~2200 km horizontal distance suggests relatively small-scale phenomena.

Lin et al., *Nature*, 2016

Nagel et al, *Tectonics*, 2008

Semple and Lenardic, *EPSL*, 2018

Ballmer et al., *EPSL*, 2010

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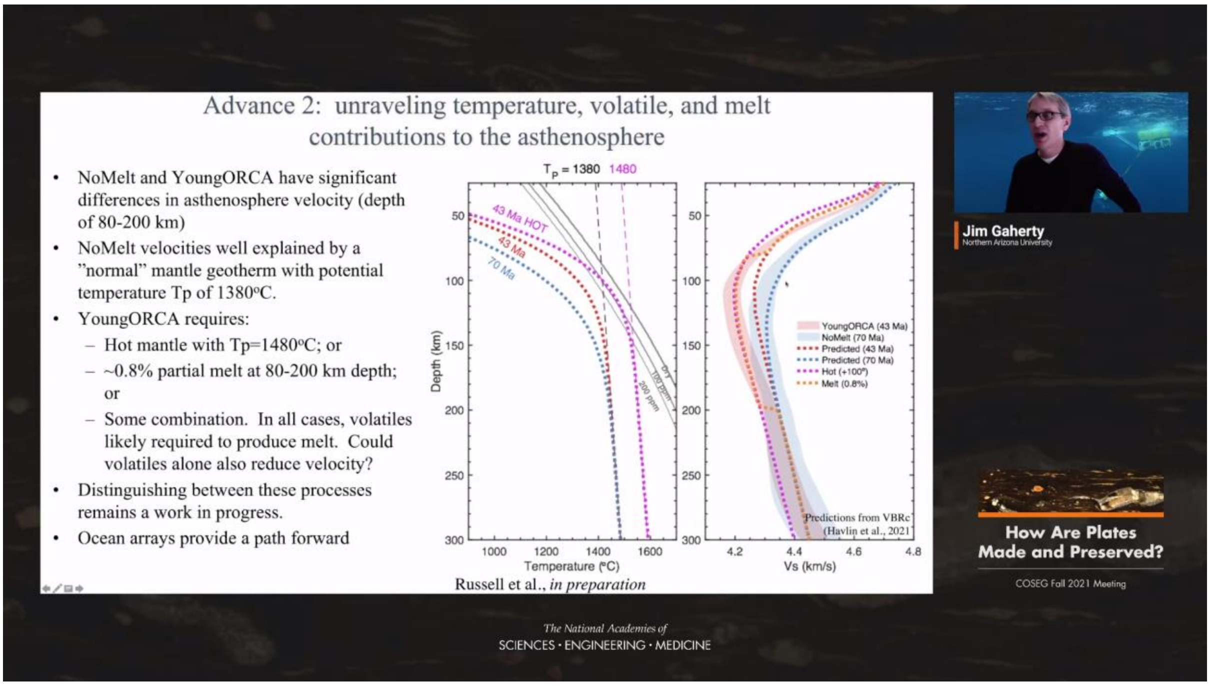
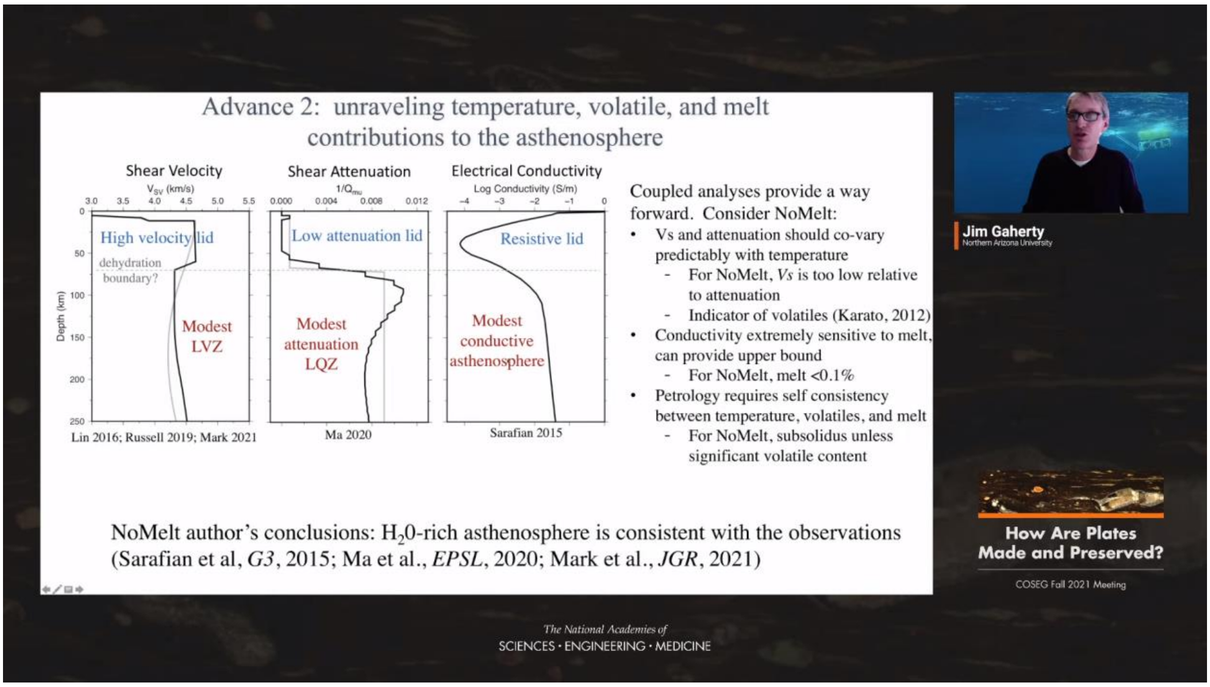


Advance 2: unraveling temperature, volatile, and melt contributions to the asthenosphere

- NoMelt and YoungORCA have significant differences in asthenosphere velocity (depth of 80-200 km)
- NoMelt velocities well explained by a "normal" mantle geotherm with potential temperature Tp of 1380°C.
- YoungORCA requires:
  - Hot mantle with Tp=1480°C; or
  - ~0.8% partial melt at 80-200 km depth; or
  - Some combination. In all cases, volatiles likely required to produce melt. Could volatiles alone also reduce velocity?
- Distinguishing between these processes remains a work in progress.
- Ocean arrays provide a path forward

Russell et al., *in preparation*



Advance 2: unraveling temperature, volatile, and melt contributions to the asthenosphere

Lin 2016; Russell 2019; Mark 2021

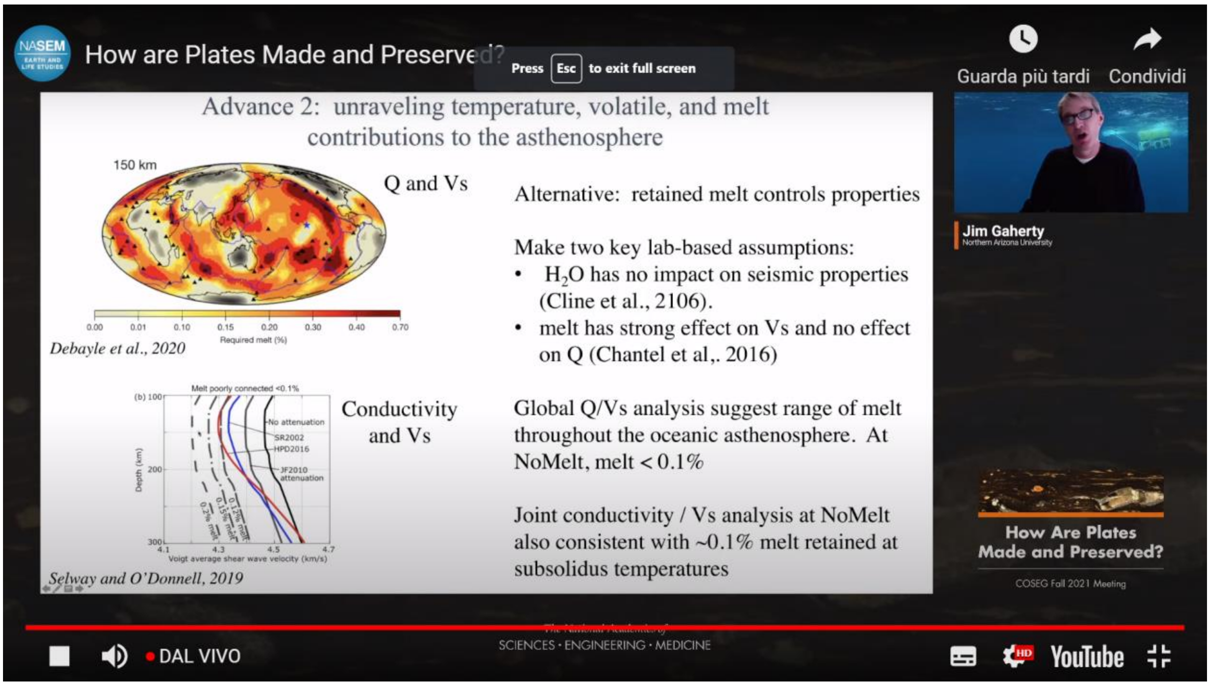
Ma 2020

Sarafian 2015

Coupled analyses provide a way forward. Consider NoMelt:

- Vs and attenuation should co-vary predictably with temperature
  - For NoMelt, *Vs* is too low relative to attenuation
  - Indicator of volatiles (Karato, 2012)
- Conductivity extremely sensitive to melt, can provide upper bound
  - For NoMelt, melt <0.1%
- Petrology requires self consistency between temperature, volatiles, and melt
  - For NoMelt, subsolidus unless significant volatile content

NoMelt author's conclusions: H_20-rich asthenosphere is consistent with the observations (Sarafian et al, *G3*, 2015; Ma et al., *EPSL*, 2020; Mark et al., *JGR*, 2021)



Advance 2: unraveling temperature, volatile, and melt contributions to the asthenosphere

Debayle et al., 2020

Selway and O'Donnell, 2019

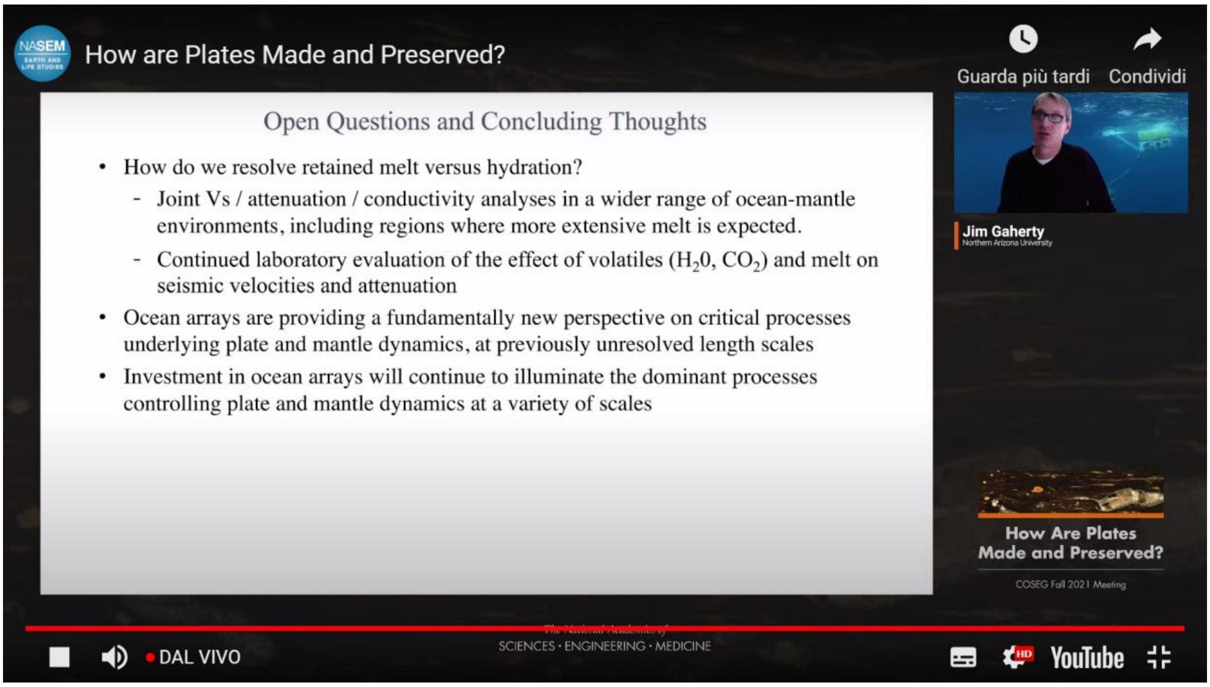
Alternative: retained melt controls properties

Make two key lab-based assumptions:

- H_2O has no impact on seismic properties (Cline et al., 2106).
- melt has strong effect on Vs and no effect on Q (Chantel et al,. 2016)

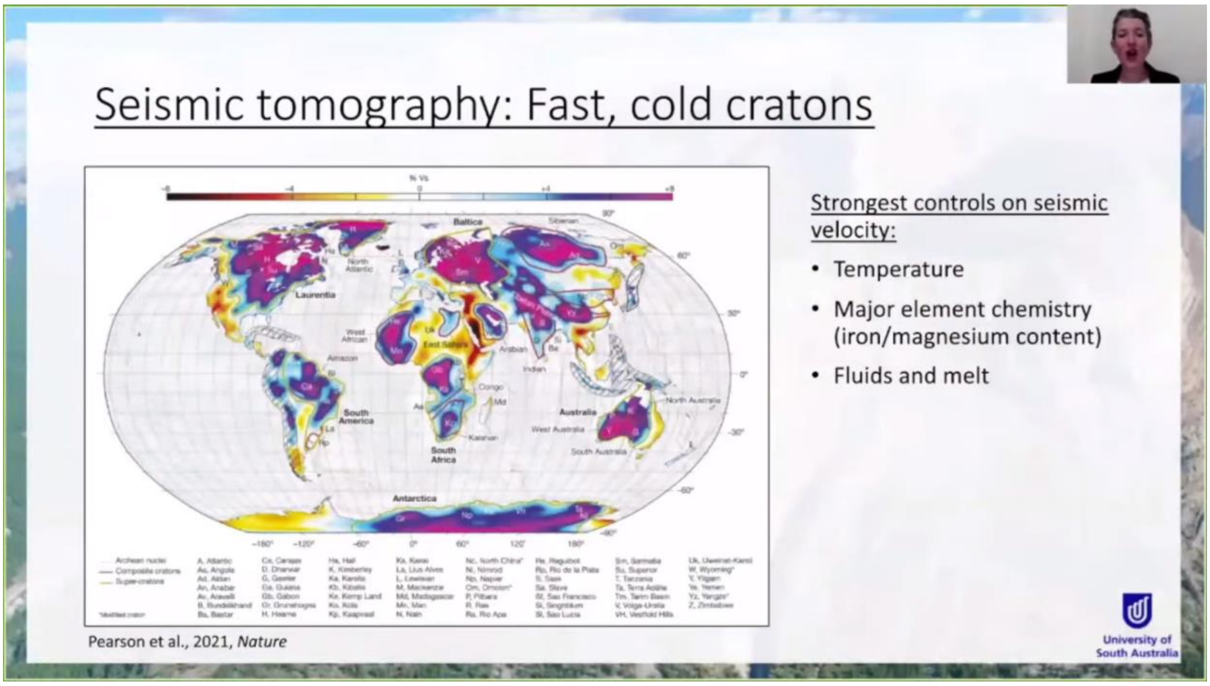
Global Q/Vs analysis suggest range of melt throughout the oceanic asthenosphere. At NoMelt, melt < 0.1%

Joint conductivity / Vs analysis at NoMelt also consistent with ~0.1% melt retained at subsolidus temperatures



Open Questions and Concluding Thoughts

- How do we resolve retained melt versus hydration?
  - Joint Vs / attenuation / conductivity analyses in a wider range of ocean-mantle environments, including regions where more extensive melt is expected.
  - Continued laboratory evaluation of the effect of volatiles (H_20, CO_2) and melt on seismic velocities and attenuation
- Ocean arrays are providing a fundamentally new perspective on critical processes underlying plate and mantle dynamics, at previously unresolved length scales
- Investment in ocean arrays will continue to illuminate the dominant processes controlling plate and mantle dynamics at a variety of scales

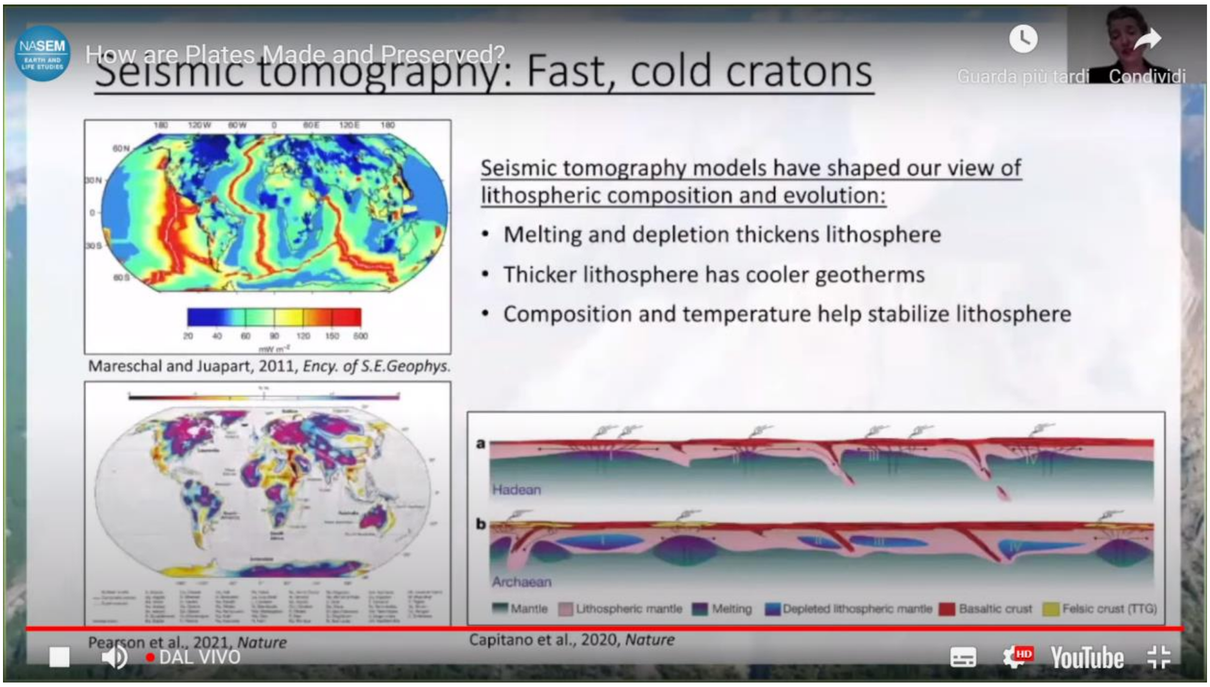


Seismic tomography: Fast, cold cratons

Pearson et al., 2021, *Nature*

Strongest controls on seismic velocity:

- Temperature
- Major element chemistry (iron/magnesium content)
- Fluids and melt



Seismic tomography: Fast, cold cratons

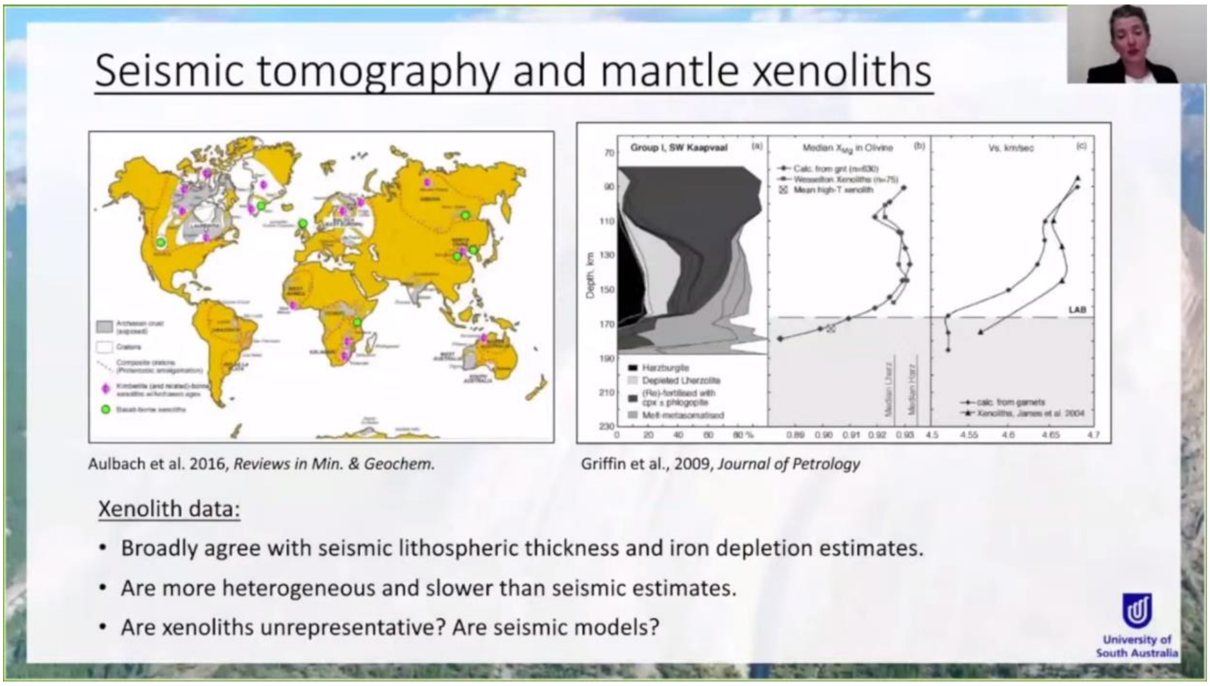
Mareschal and Juapart, 2011, *Ency. of S.E.Geophys.*

Pearson et al., 2021, *Nature*

Seismic tomography models have shaped our view of lithospheric composition and evolution:

- Melting and depletion thickens lithosphere
- Thicker lithosphere has cooler geotherms
- Composition and temperature help stabilize lithosphere

Capitano et al., 2020, *Nature*



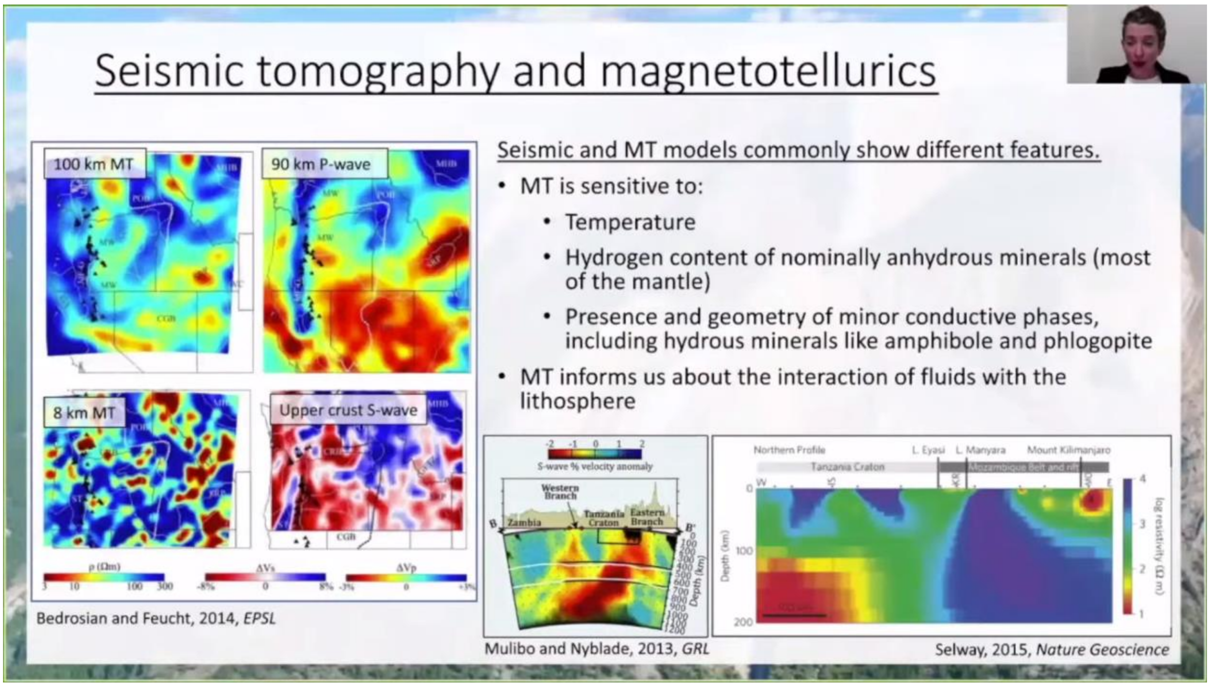
Seismic tomography and mantle xenoliths

Aulbach et al. 2016, *Reviews in Min. & Geochem.*

Griffin et al., 2009, *Journal of Petrology*

Xenolith data:

- Broadly agree with seismic lithospheric thickness and iron depletion estimates.
- Are more heterogeneous and slower than seismic estimates.
- Are xenoliths unrepresentative? Are seismic models?



Seismic tomography and magnetotellurics

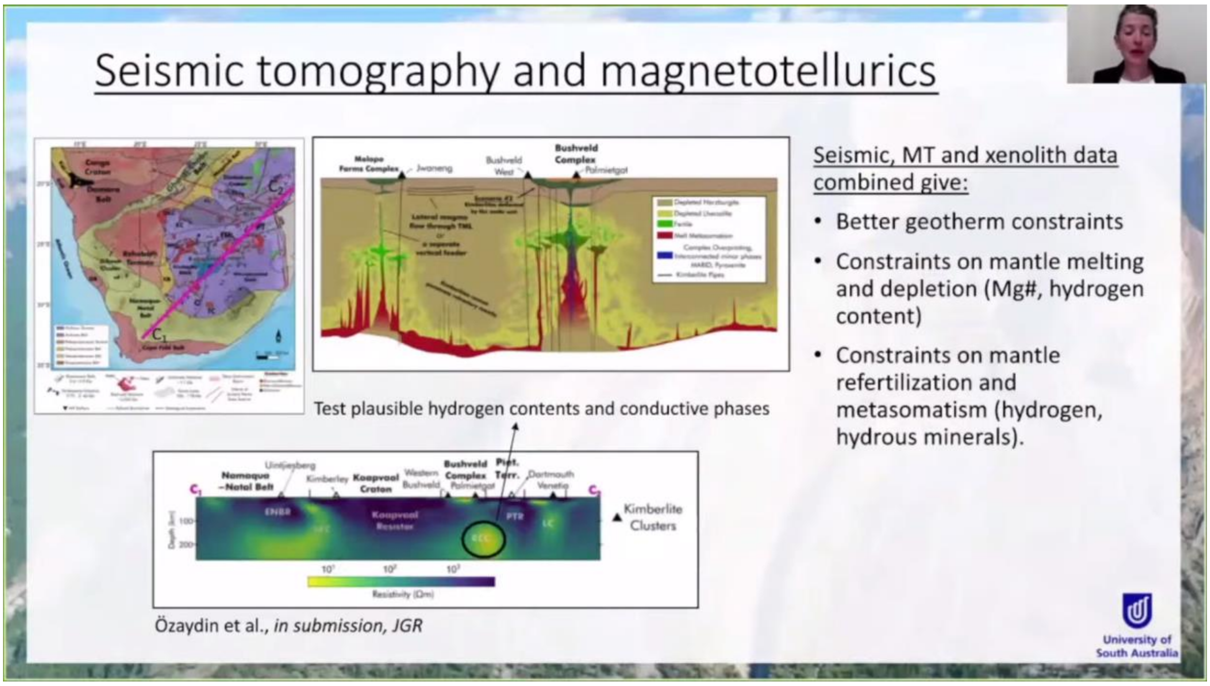
Seismic and MT models commonly show different features.

- MT is sensitive to:
  - Temperature
  - Hydrogen content of nominally anhydrous minerals (most of the mantle)
  - Presence and geometry of minor conductive phases, including hydrous minerals like amphibole and phlogopite
- MT informs us about the interaction of fluids with the lithosphere

Bedrosian and Feucht, 2014, *EPSL*

Mulibo and Nyblade, 2013, *GRL*

Selway, 2015, *Nature Geoscience*



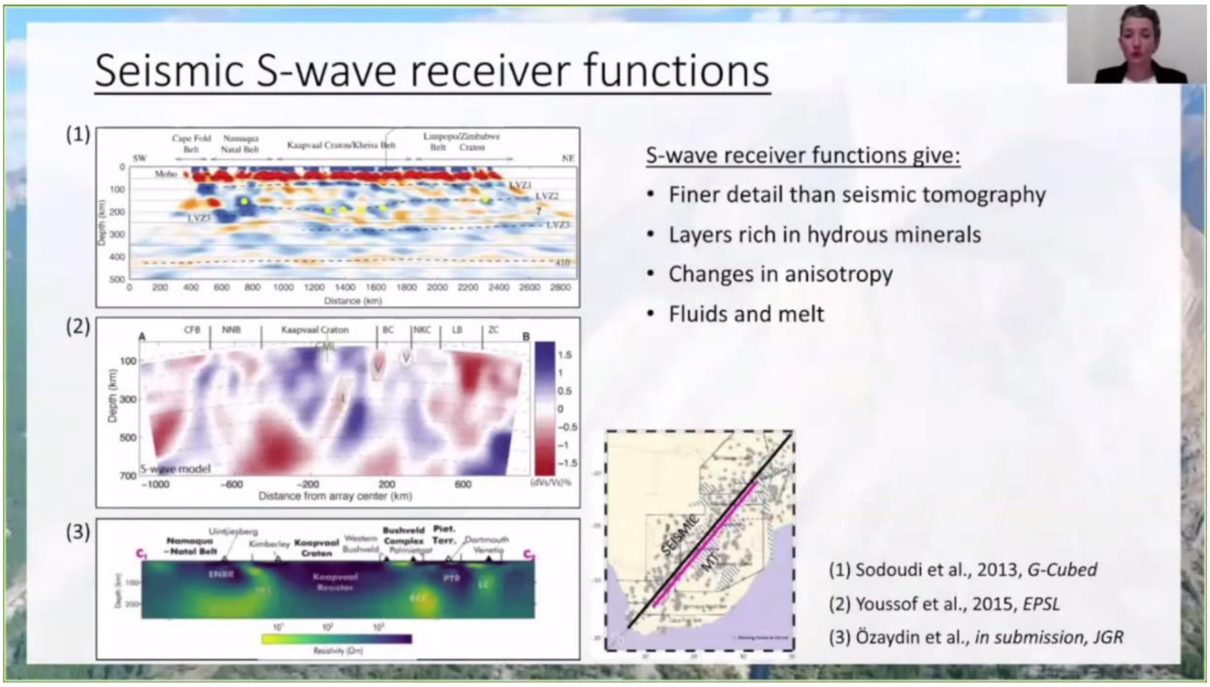
Seismic tomography and magnetotellurics

Test plausible hydrogen contents and conductive phases

Özaydin et al., *in submission, JGR*

Seismic, MT and xenolith data combined give:

- Better geotherm constraints
- Constraints on mantle melting and depletion (Mg#, hydrogen content)
- Constraints on mantle refertilization and metasomatism (hydrogen, hydrous minerals).



Seismic S-wave receiver functions

(1)

(2)

(3)

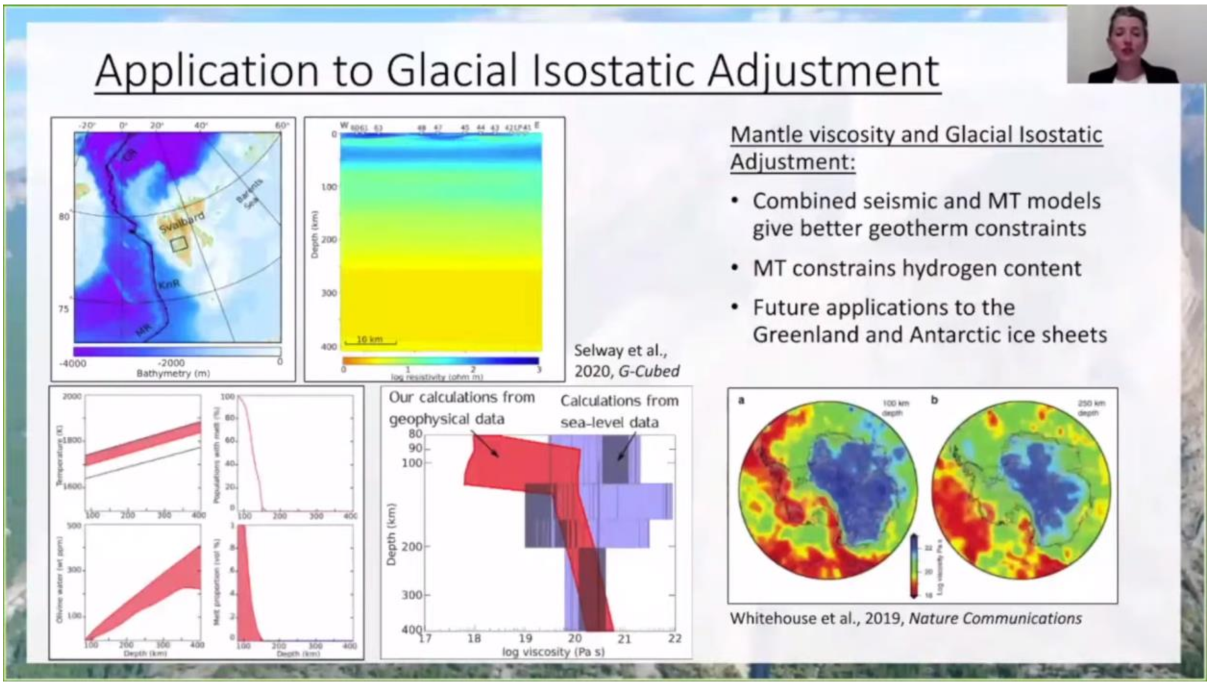
S-wave receiver functions give:

- Finer detail than seismic tomography
- Layers rich in hydrous minerals
- Changes in anisotropy
- Fluids and melt

(1) Sodoudi et al., 2013, *G-Cubed*

(2) Youssof et al., 2015, *EPSL*

(3) Özaydin et al., *in submission, JGR*



Application to Glacial Isostatic Adjustment

Selway et al., 2020, *G-Cubed*

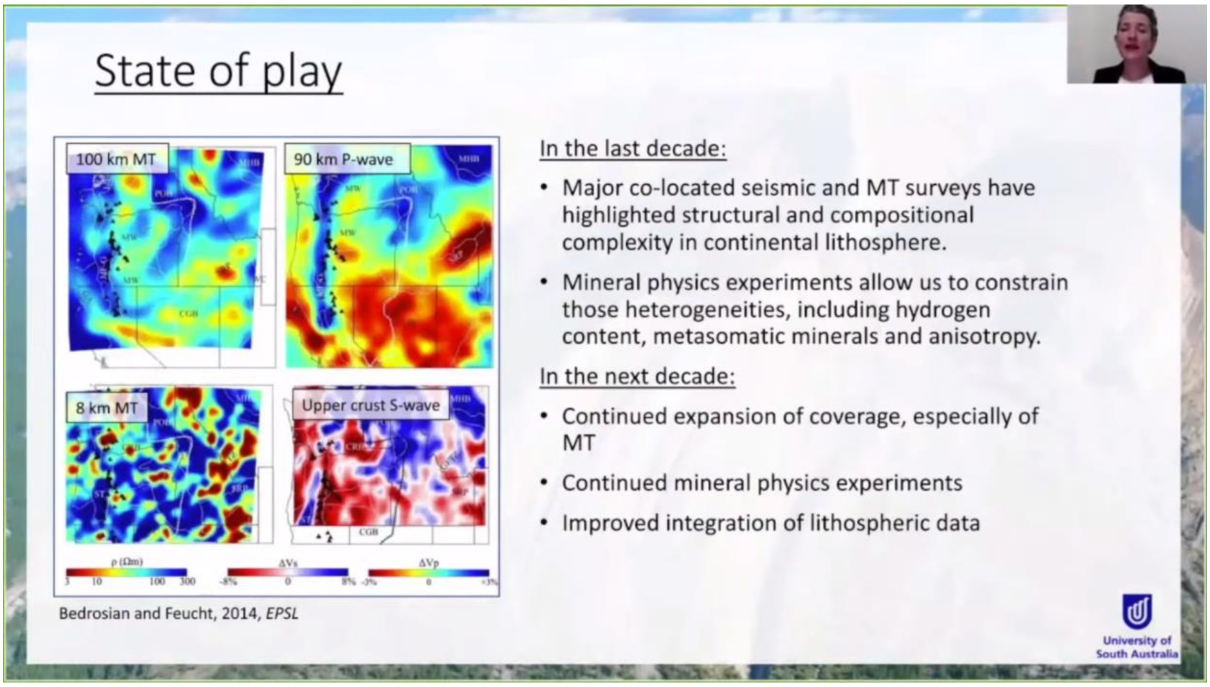
Our calculations from geophysical data

Calculations from sea-level data

Whitehouse et al., 2019, *Nature Communications*

Mantle viscosity and Glacial Isostatic Adjustment:

- Combined seismic and MT models give better geotherm constraints
- MT constrains hydrogen content
- Future applications to the Greenland and Antarctic ice sheets



State of play

Bedrosian and Feucht, 2014, *EPSL*

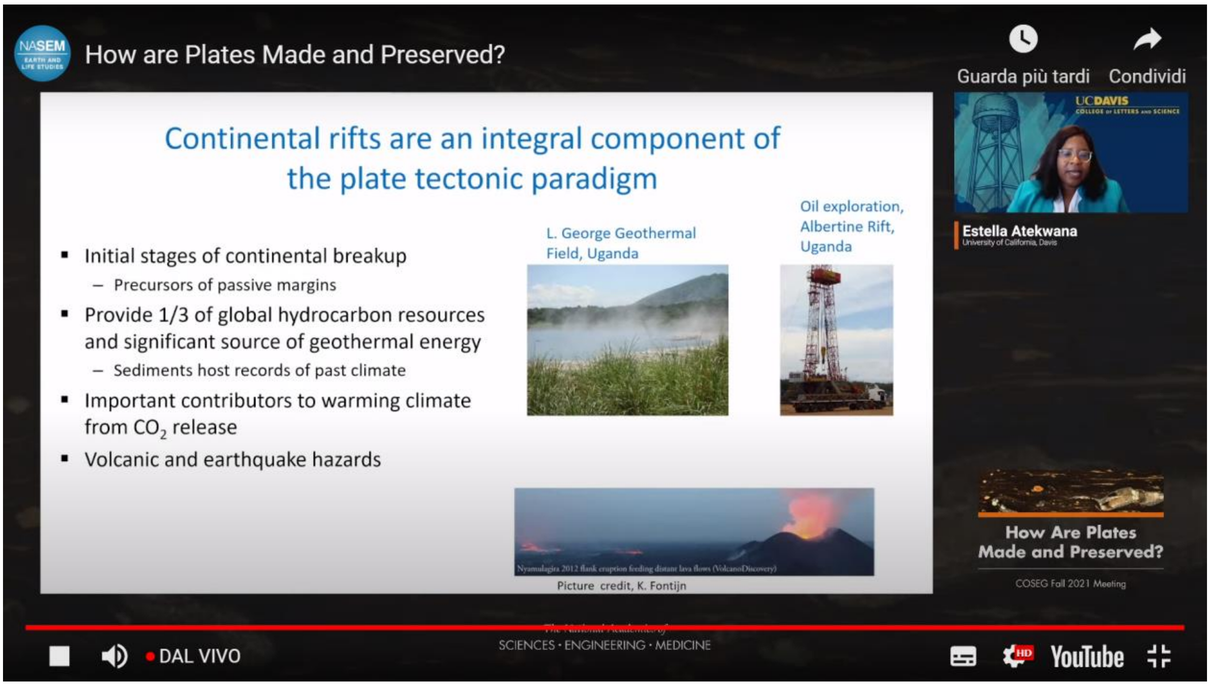
In the last decade:

- Major co-located seismic and MT surveys have highlighted structural and compositional complexity in continental lithosphere.
- Mineral physics experiments allow us to constrain those heterogeneities, including hydrogen content, metasomatic minerals and anisotropy.

In the next decade:

- Continued expansion of coverage, especially of MT
- Continued mineral physics experiments
- Improved integration of lithospheric data

University of South Australia



Continental rifts are an integral component of the plate tectonic paradigm

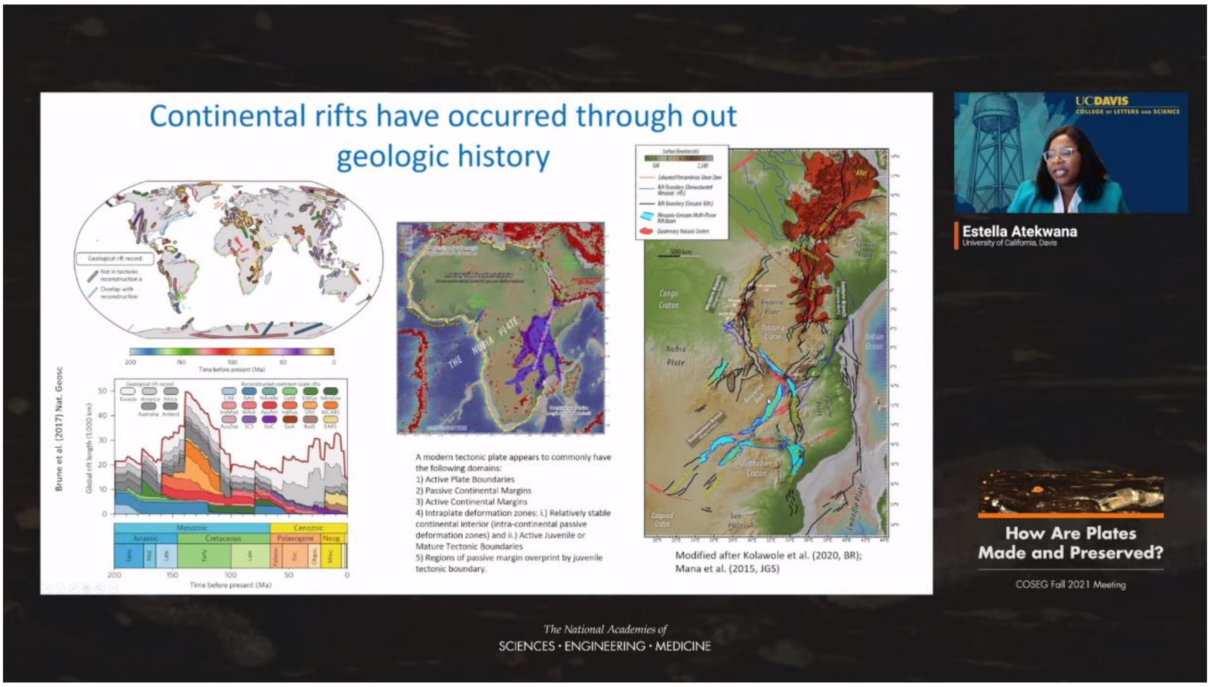
- Initial stages of continental breakup
  - Precursors of passive margins
- Provide 1/3 of global hydrocarbon resources and significant source of geothermal energy
  - Sediments host records of past climate
- Important contributors to warming climate from CO_2 release
- Volcanic and earthquake hazards

L. George Geothermal Field, Uganda

Oil exploration, Albertine Rift, Uganda

Nyamulagira 2012 flank eruption feeding distant lava flows (VolcanoDiscovery)

Picture credit, K. Fontijn

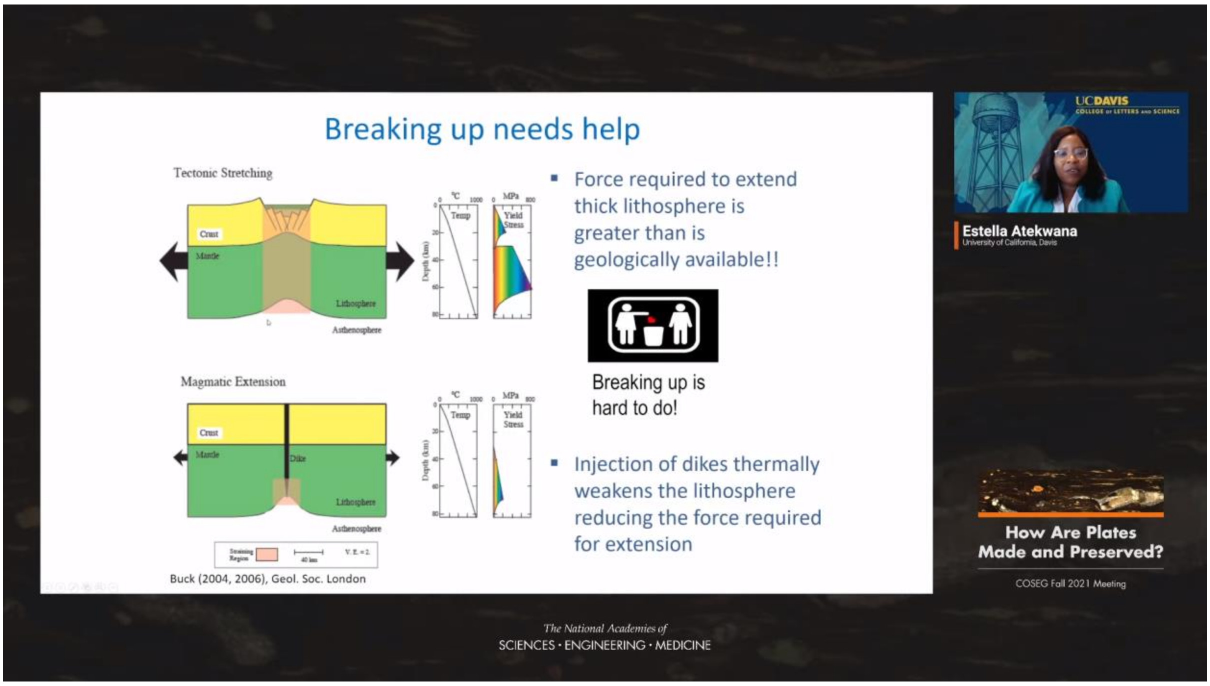


Continental rifts have occurred through out geologic history

Brune et al. (2017) Nat. Geosc

A modern tectonic plate appears to commonly have the following domains:
1) Active Plate Boundaries
2) Passive Continental Margins
3) Active Continental Margins
4) Intraplate deformation zones: i.) Relatively stable continental interior (intra-continental passive deformation zones) and ii.) Active Juvenile or Mature Tectonic Boundaries
5) Regions of passive margin overprint by juvenile tectonic boundary.

Modified after Kolawole et al. (2020, BR); Mana et al. (2015, JGS)



Breaking up needs help

Buck (2004, 2006), Geol. Soc. London

- Force required to extend thick lithosphere is greater than is geologically available!!

Breaking up is hard to do!

- Injection of dikes thermally weakens the lithosphere reducing the force required for extension

Estella Atekwana
University of California, Davis

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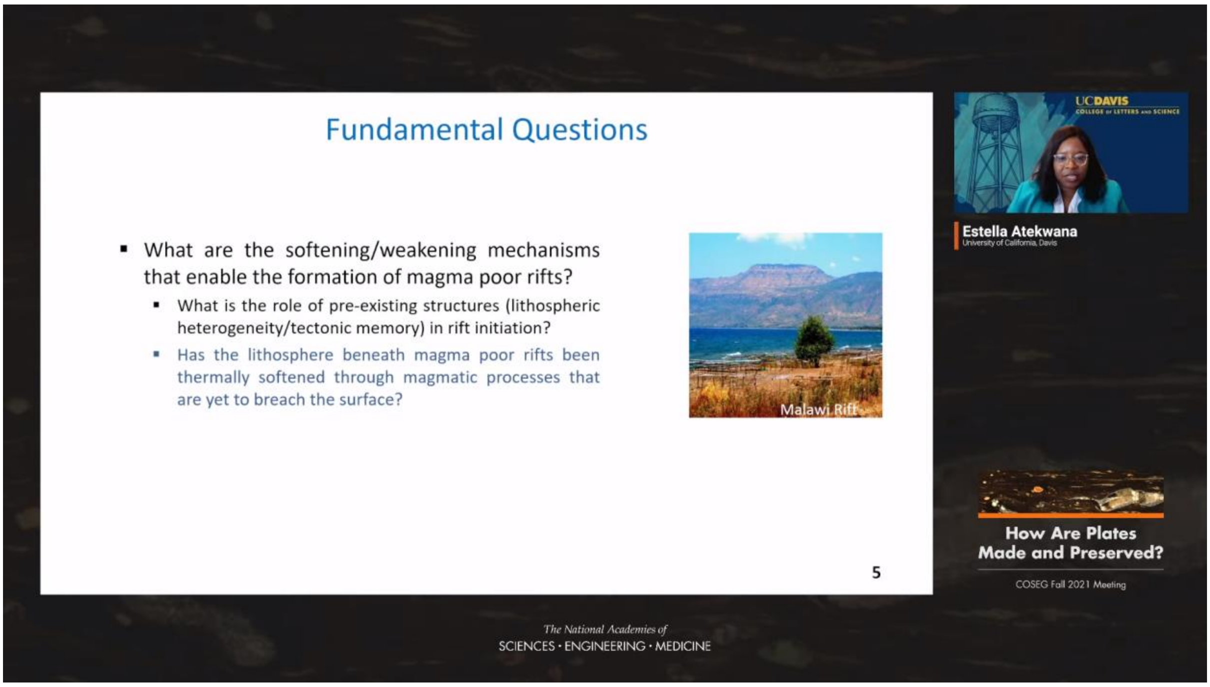

Fundamental Questions

- What are the softening/weakening mechanisms that enable the formation of magma poor rifts?
  - What is the role of pre-existing structures (lithospheric heterogeneity/tectonic memory) in rift initiation?
  - Has the lithosphere beneath magma poor rifts been thermally softened through magmatic processes that are yet to breach the surface?

Malawi Rift

Estella Atekwana
University of California, Davis

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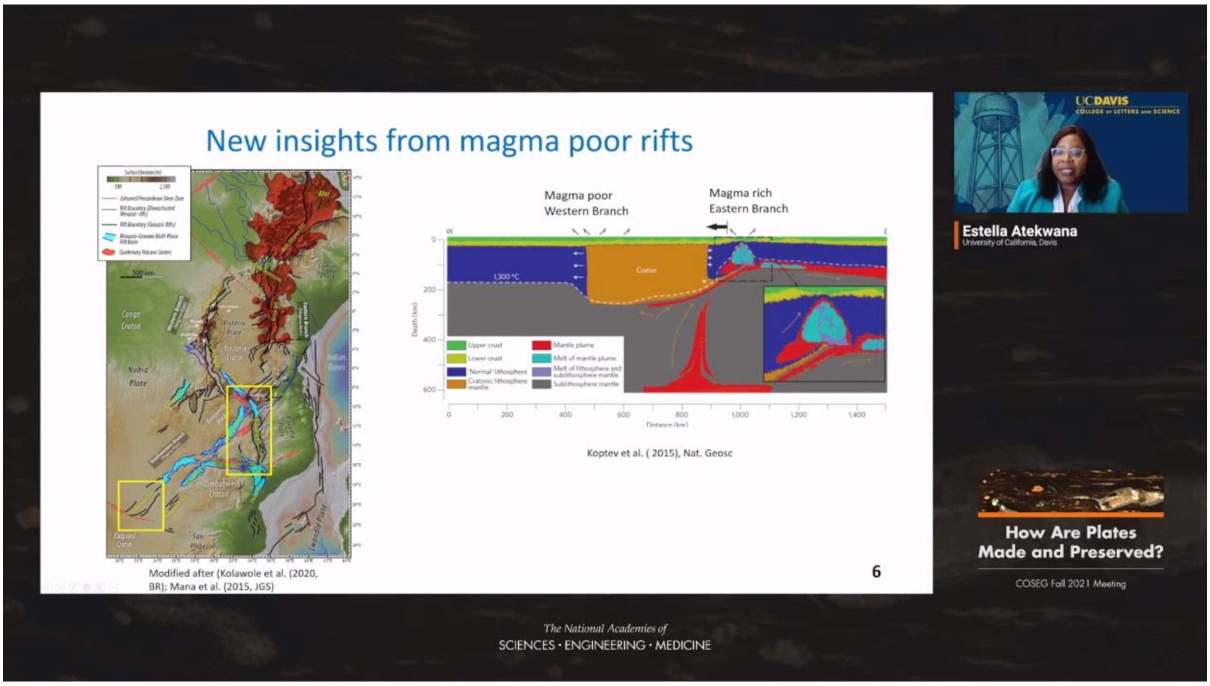
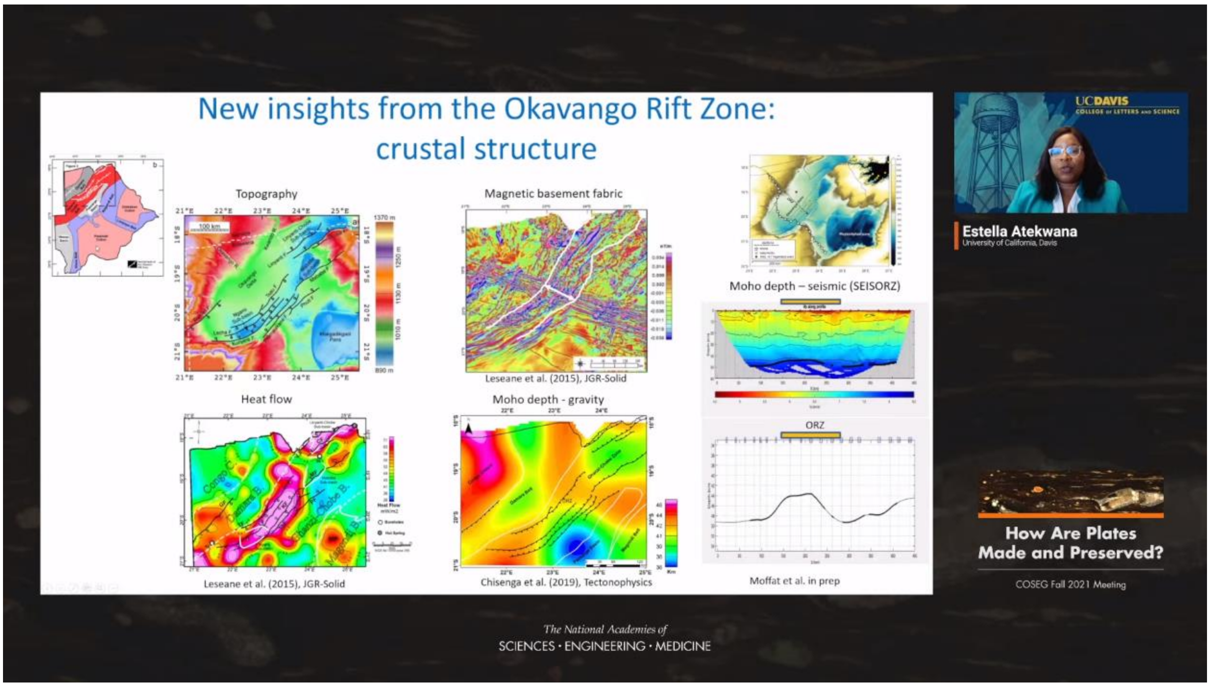


New insights from magma poor rifts

Modified after (Kolawole et al. (2020, BR); Mana et al. (2015, JGS)

Koptev et al. (2015), Nat. Geosc



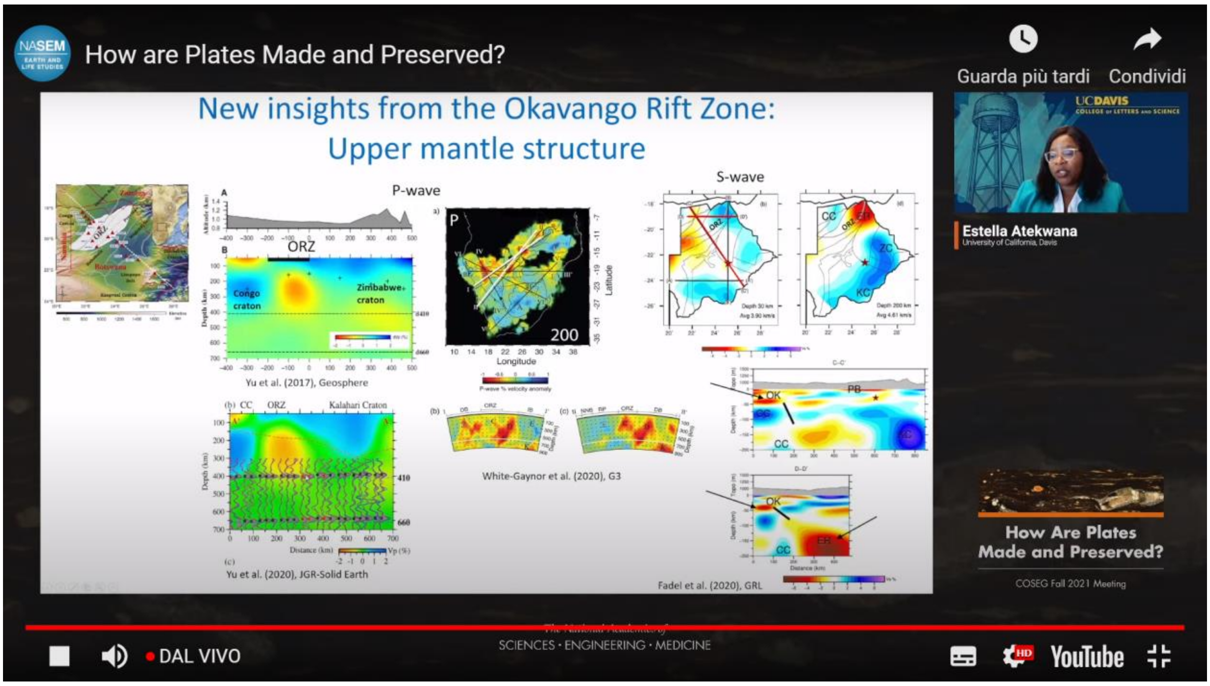
New insights from the Okavango Rift Zone: crustal structure

Leseane et al. (2015), JGR-Solid

Leseane et al. (2015), JGR-Solid

Chisenga et al. (2019), Tectonophysics

Moffat et al. in prep



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New insights from the Okavango Rift Zone: Upper mantle structure

Yu et al. (2017), Geosphere

White-Gaynor et al. (2020), G3

Yu et al. (2020), JGR-Solid Earth

Fadel et al. (2020), GRL

Estella Atekwana
University of California, Davis

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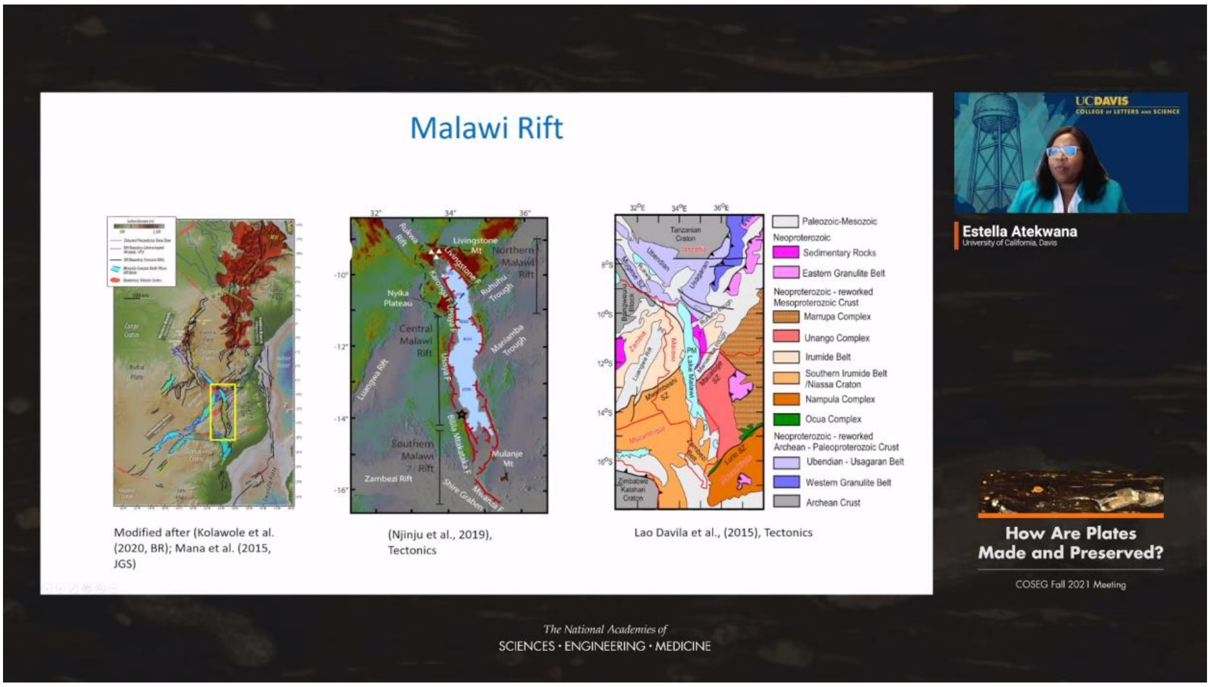

Malawi Rift

Modified after (Kolawole et al. (2020, BR); Mana et al. (2015, JGS)

(Njinju et al., 2019), Tectonics

Lao Davila et al., (2015), Tectonics

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University of California, Davis

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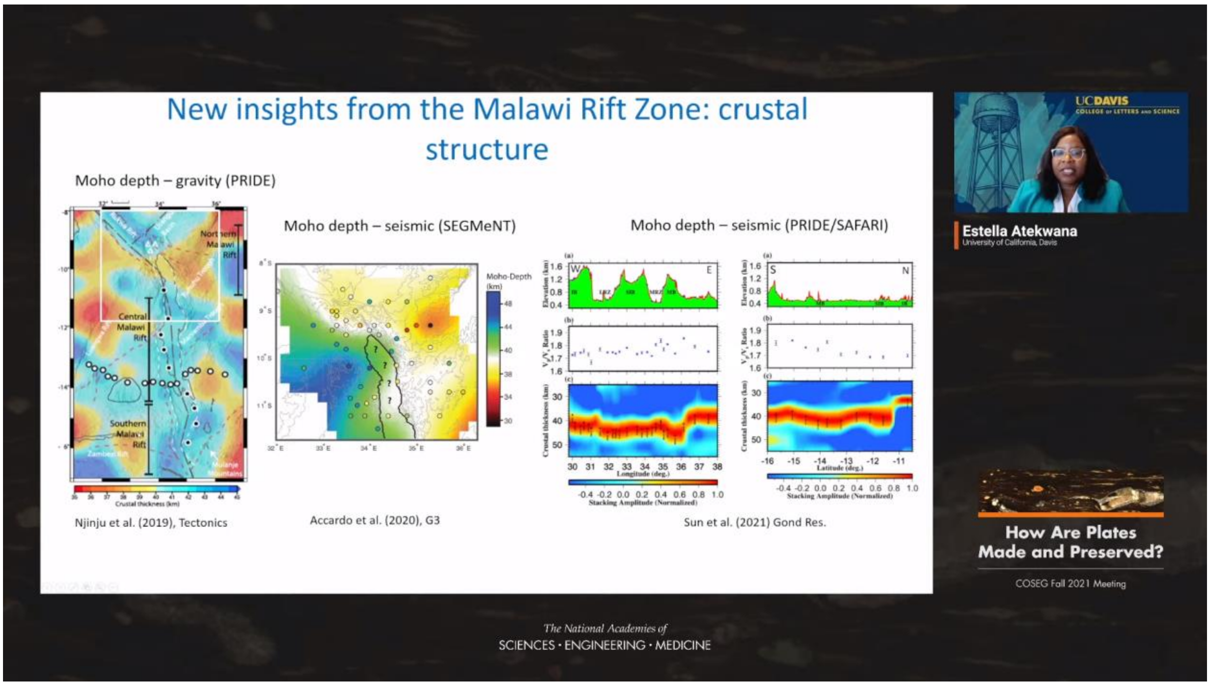

New insights from the Malawi Rift Zone: crustal structure

Moho depth – gravity (PRIDE)

Moho depth – seismic (SEGMeNT)

Moho depth – seismic (PRIDE/SAFARI)

Njinju et al. (2019), Tectonics

Accardo et al. (2020), G3

Sun et al. (2021) Gond Res.

Estella Atekwana
University of California, Davis

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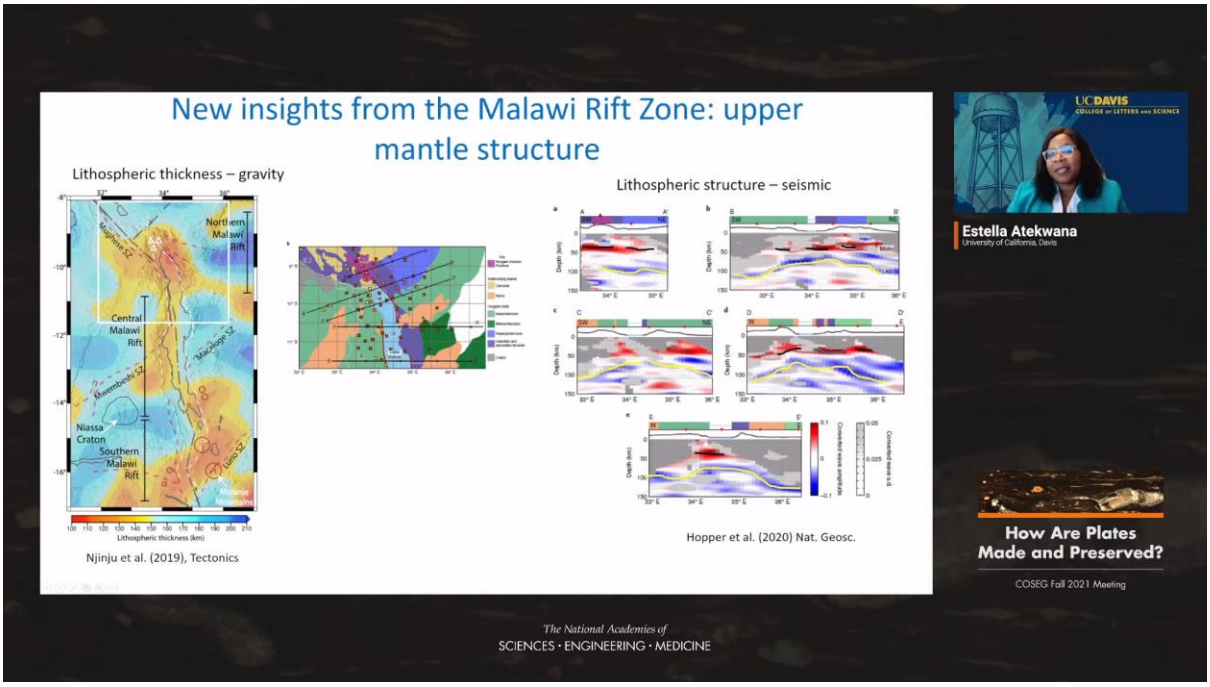

New insights from the Malawi Rift Zone: upper mantle structure

Lithospheric thickness – gravity

Lithospheric structure – seismic

Njinju et al. (2019), Tectonics

Hopper et al. (2020) Nat. Geosc.

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University of California, Davis

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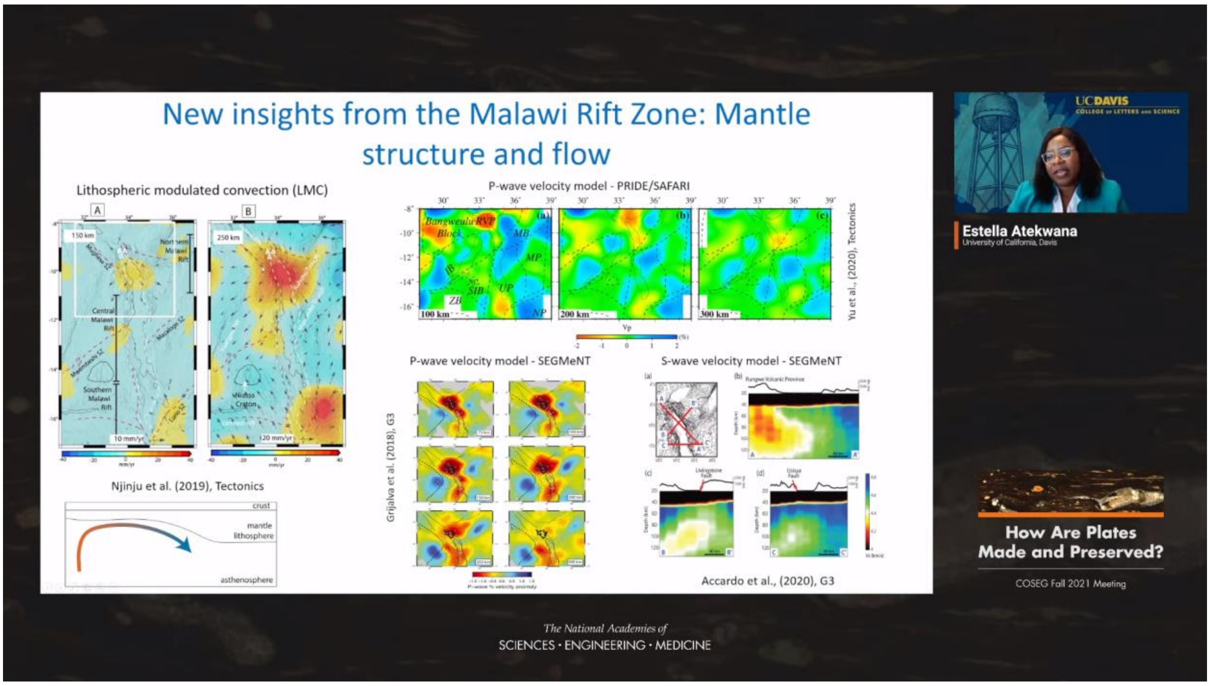


New insights from the Malawi Rift Zone: Mantle structure and flow

Lithospheric modulated convection (LMC)

Njinju et al. (2019), Tectonics

P-wave velocity model - PRIDE/SAFARI

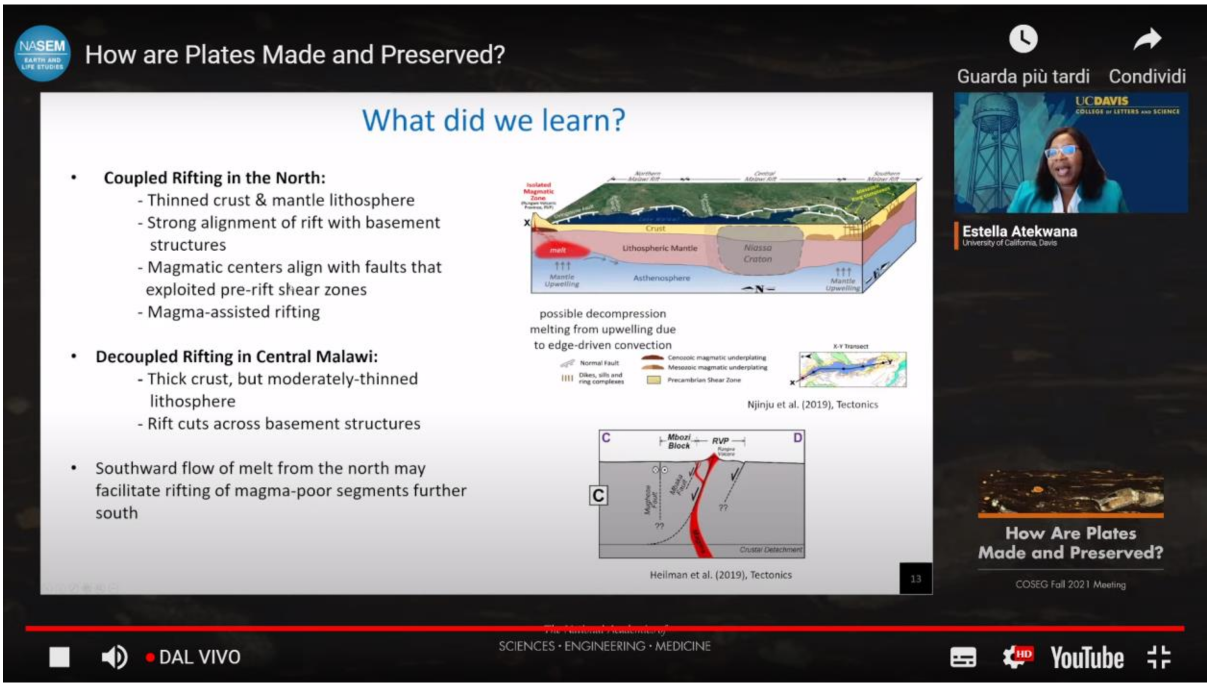
Yu et al., (2020), Tectonics

P-wave velocity model - SEGMeNT

Grijalva et al. (2018), G3

S-wave velocity model - SEGMeNT

Accardo et al., (2020), G3



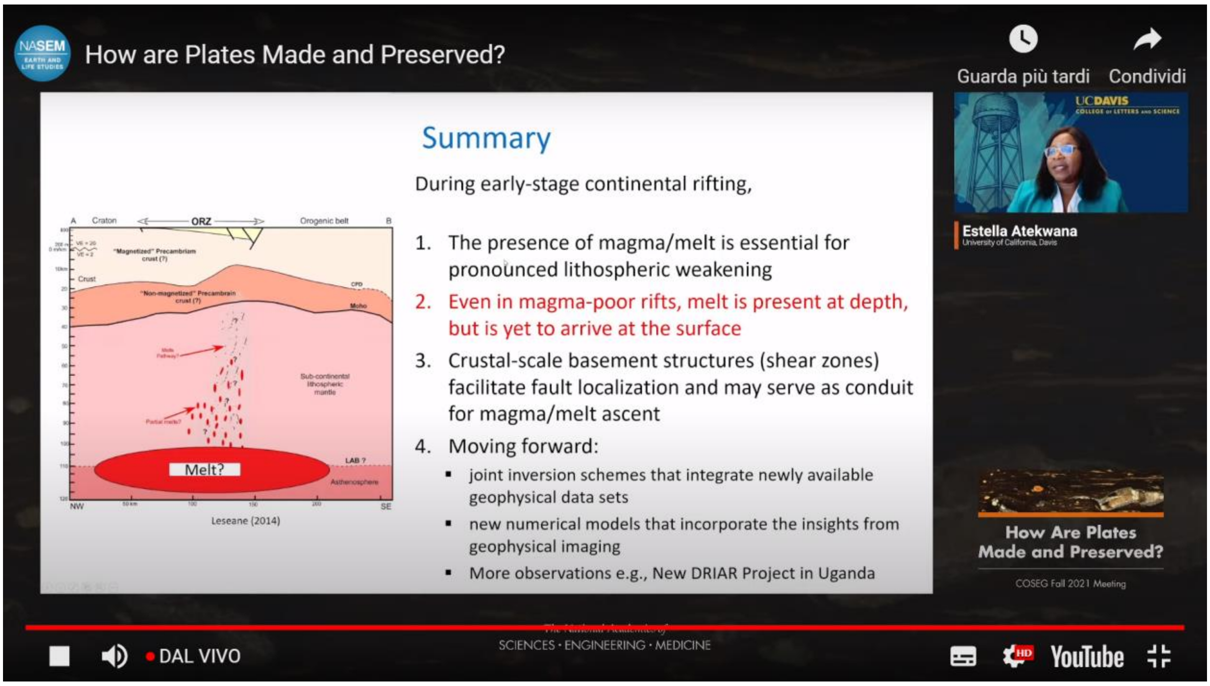
What did we learn?

- **Coupled Rifting in the North:**
  - Thinned crust & mantle lithosphere
  - Strong alignment of rift with basement structures
  - Magmatic centers align with faults that exploited pre-rift shear zones
  - Magma-assisted rifting
- **Decoupled Rifting in Central Malawi:**
  - Thick crust, but moderately-thinned lithosphere
  - Rift cuts across basement structures
- Southward flow of melt from the north may facilitate rifting of magma-poor segments further south

possible decompression melting from upwelling due to edge-driven convection

Njinju et al. (2019), Tectonics

Heilman et al. (2019), Tectonics

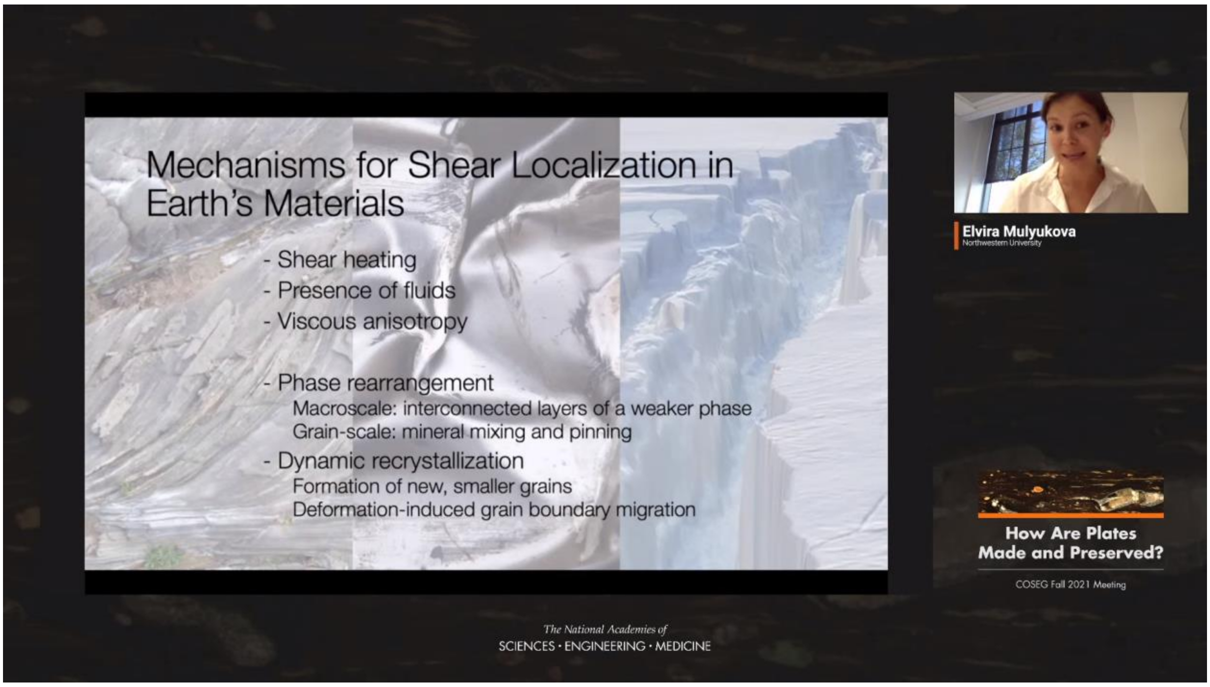


Summary

Leseane (2014)

During early-stage continental rifting,

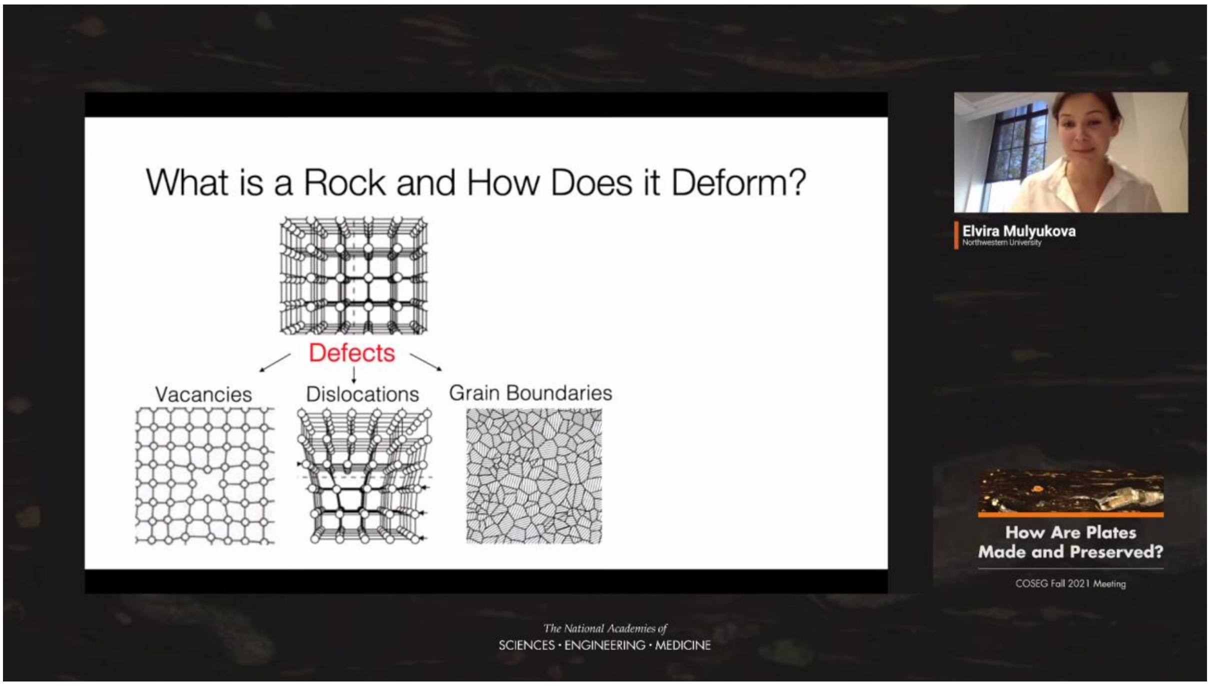
1. The presence of magma/melt is essential for pronounced lithospheric weakening
2. Even in magma-poor rifts, melt is present at depth, but is yet to arrive at the surface
3. Crustal-scale basement structures (shear zones) facilitate fault localization and may serve as conduit for magma/melt ascent
4. Moving forward:
   - joint inversion schemes that integrate newly available geophysical data sets
   - new numerical models that incorporate the insights from geophysical imaging
   - More observations e.g., New DRIAR Project in Uganda



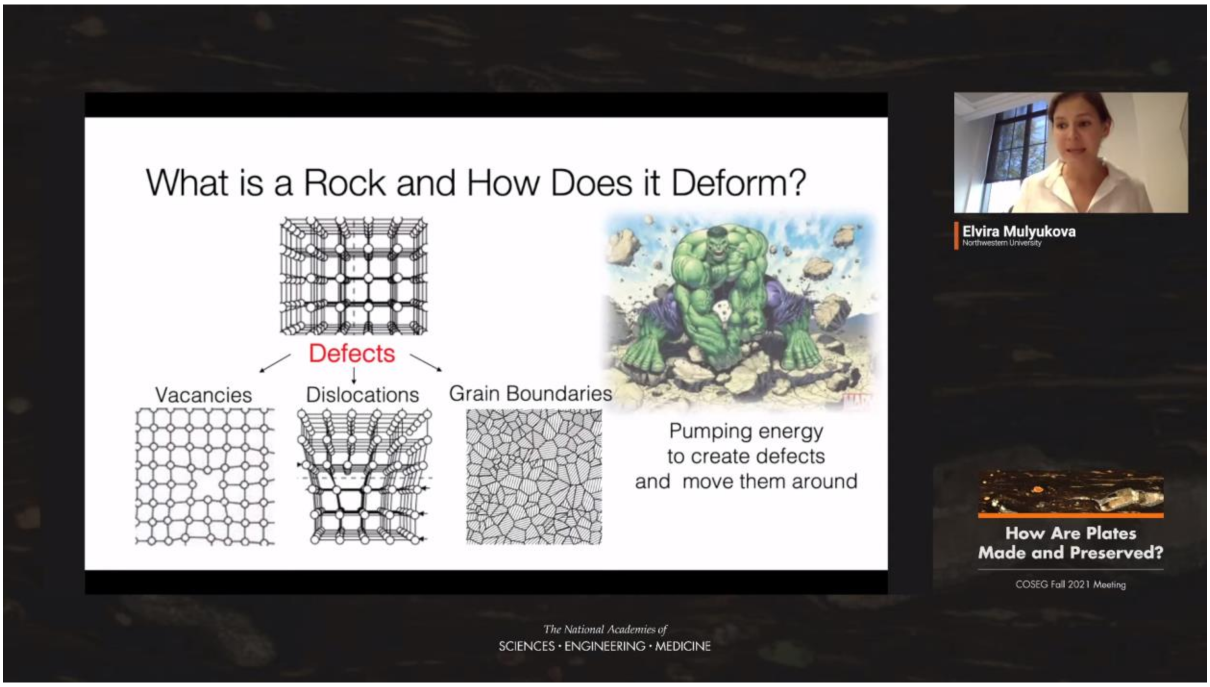
Mechanisms for Shear Localization in Earth's Materials

- Shear heating
- Presence of fluids
- Viscous anisotropy

- Phase rearrangement
  - Macroscale: interconnected layers of a weaker phase
  - Grain-scale: mineral mixing and pinning
- Dynamic recrystallization
  - Formation of new, smaller grains
  - Deformation-induced grain boundary migration

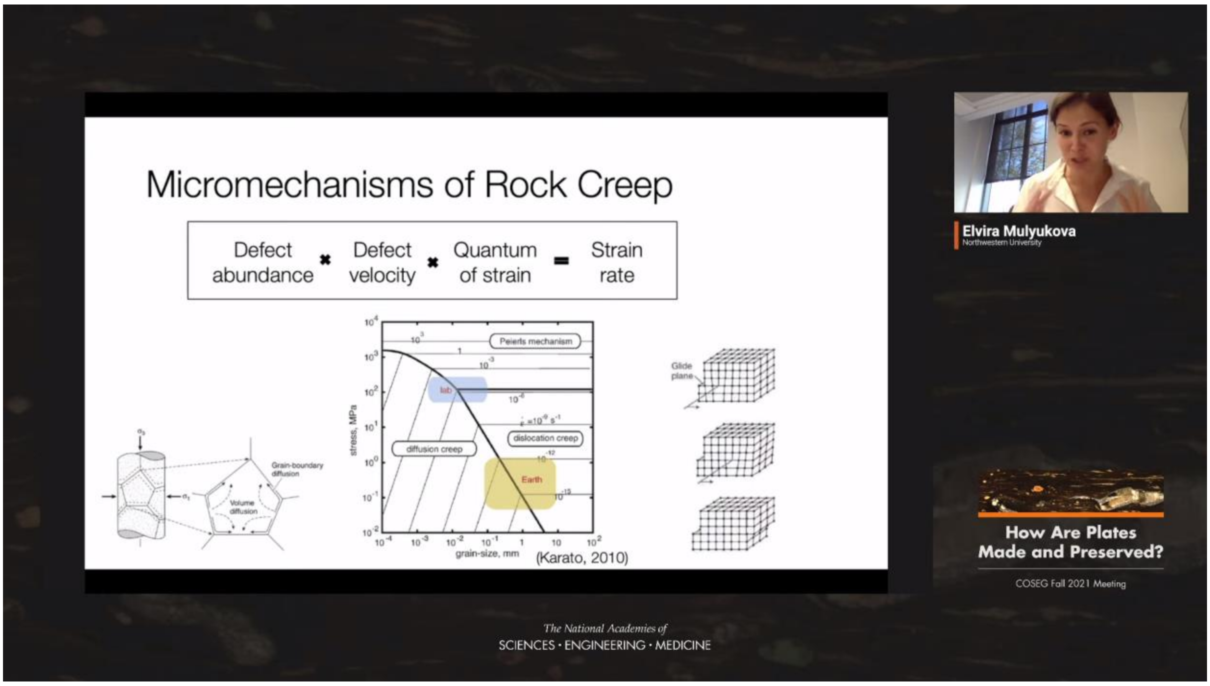


What is a Rock and How Does it Deform?



What is a Rock and How Does it Deform?

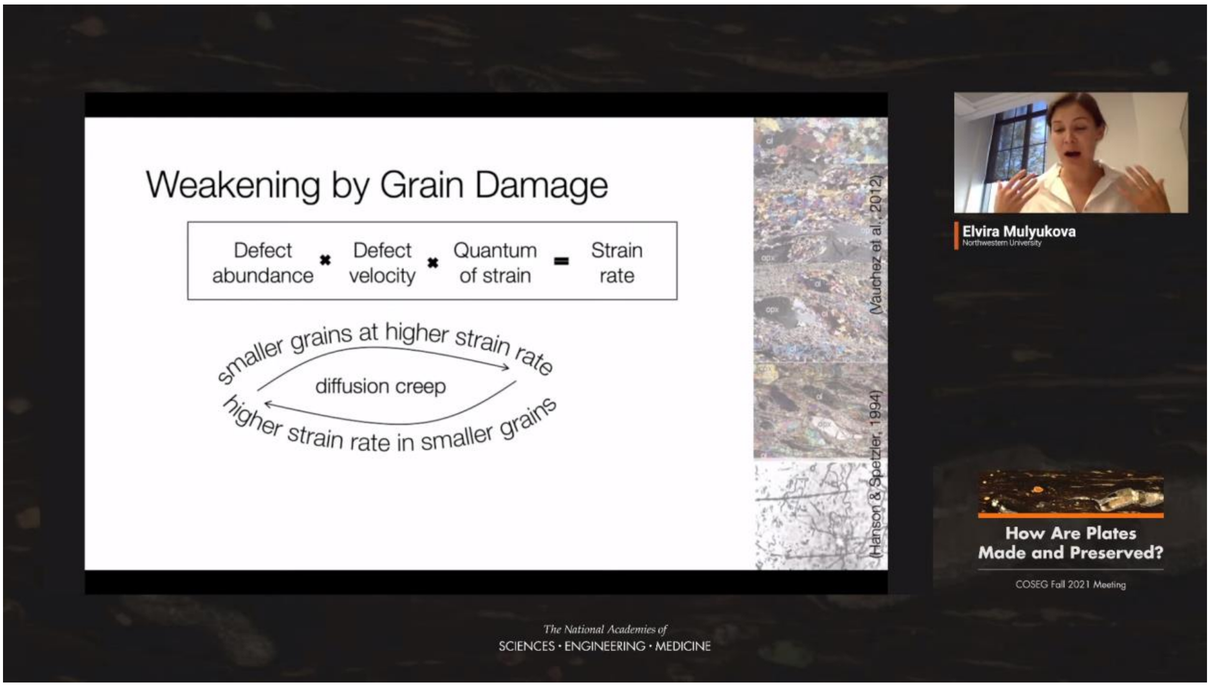
Pumping energy to create defects and move them around



Micromechanisms of Rock Creep

Defect abundance ✖ Defect velocity ✖ Quantum of strain = Strain rate

(Karato, 2010)



Weakening by Grain Damage

Defect abundance ✖ Defect velocity ✖ Quantum of strain = Strain rate

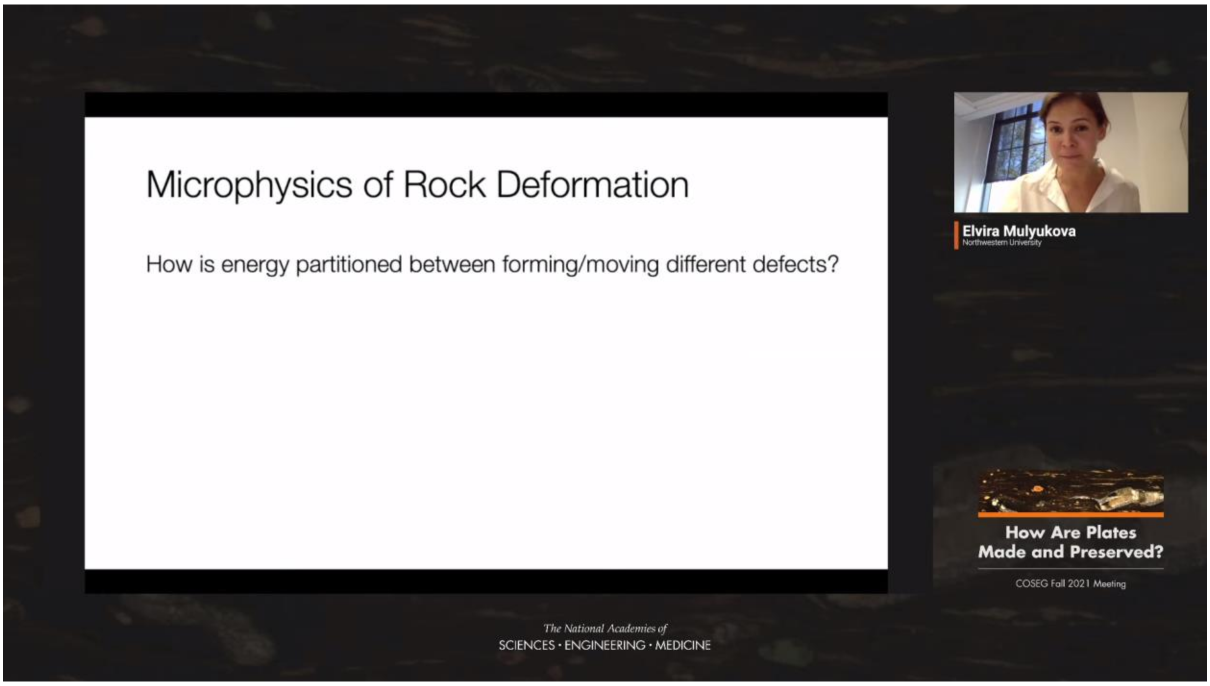
smaller grains at higher strain rate

diffusion creep

higher strain rate in smaller grains

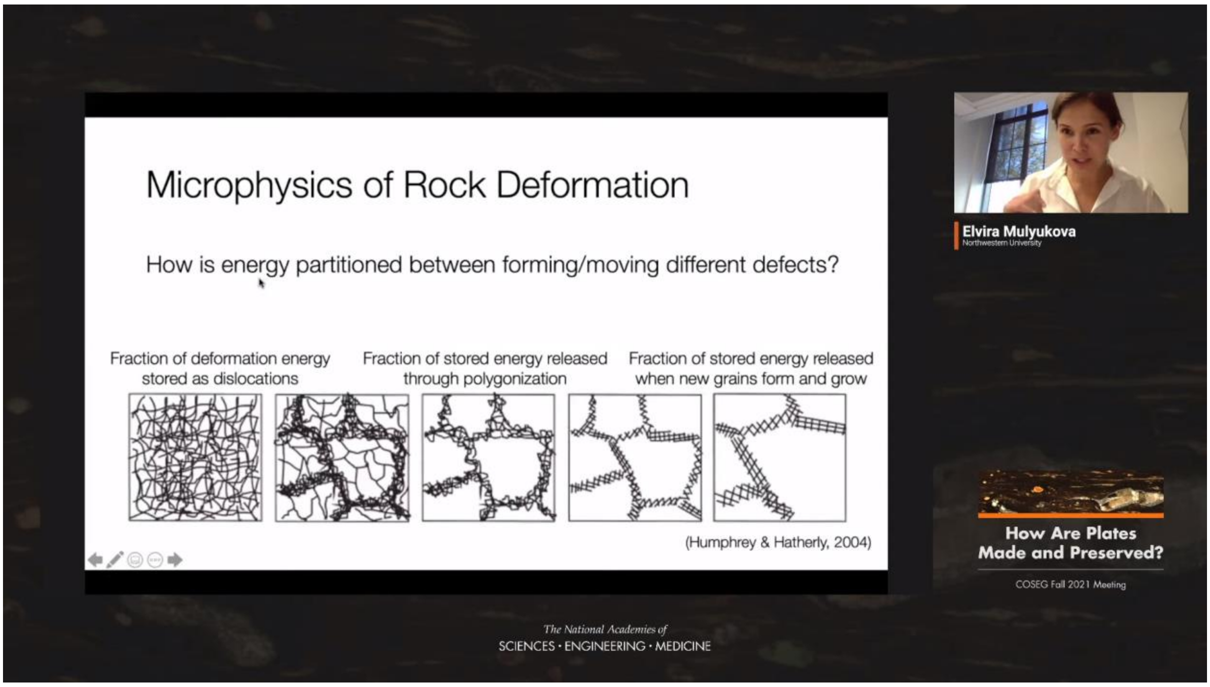
(Vauchez et al., 2012)

(Hanson & Spetzler, 1994)



Microphysics of Rock Deformation

How is energy partitioned between forming/moving different defects?



Microphysics of Rock Deformation

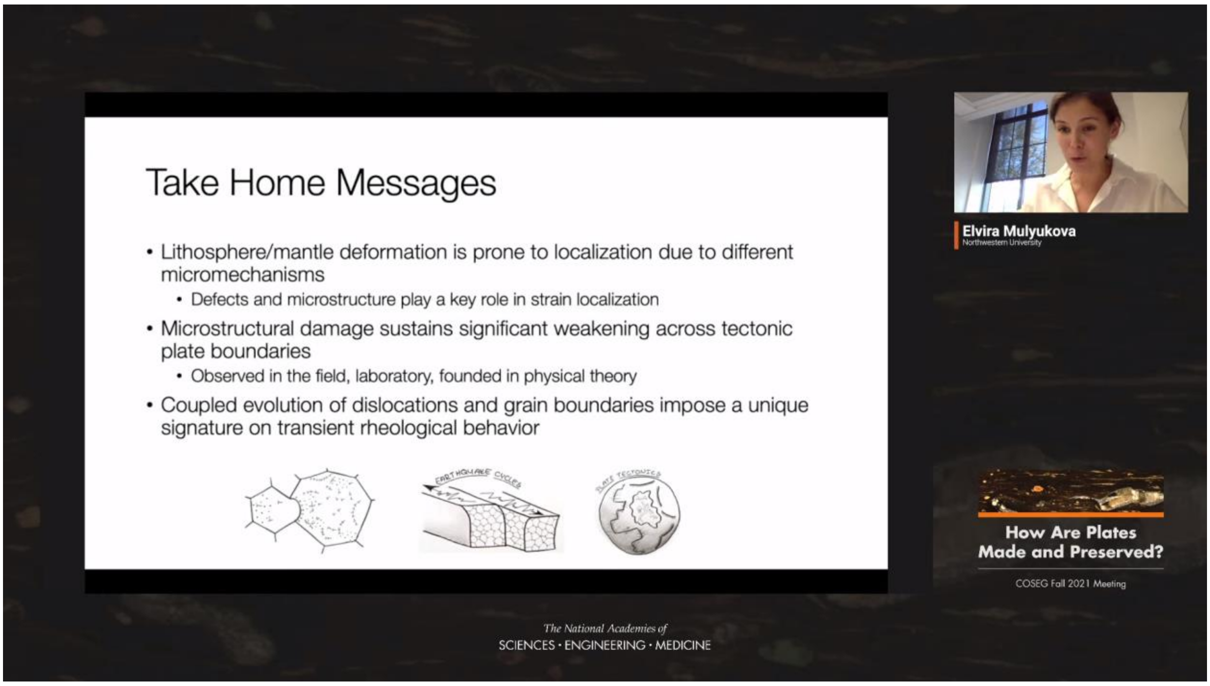
How is energy partitioned between forming/moving different defects?

Fraction of deformation energy stored as dislocations

Fraction of stored energy released through polygonization

Fraction of stored energy released when new grains form and grow

(Humphrey & Hatherly, 2004)



Take Home Messages

- Lithosphere/mantle deformation is prone to localization due to different micromechanisms
  - Defects and microstructure play a key role in strain localization
- Microstructural damage sustains significant weakening across tectonic plate boundaries
  - Observed in the field, laboratory, founded in physical theory
- Coupled evolution of dislocations and grain boundaries impose a unique signature on transient rheological behavior

Elvira Mulyukova
Northwestern University

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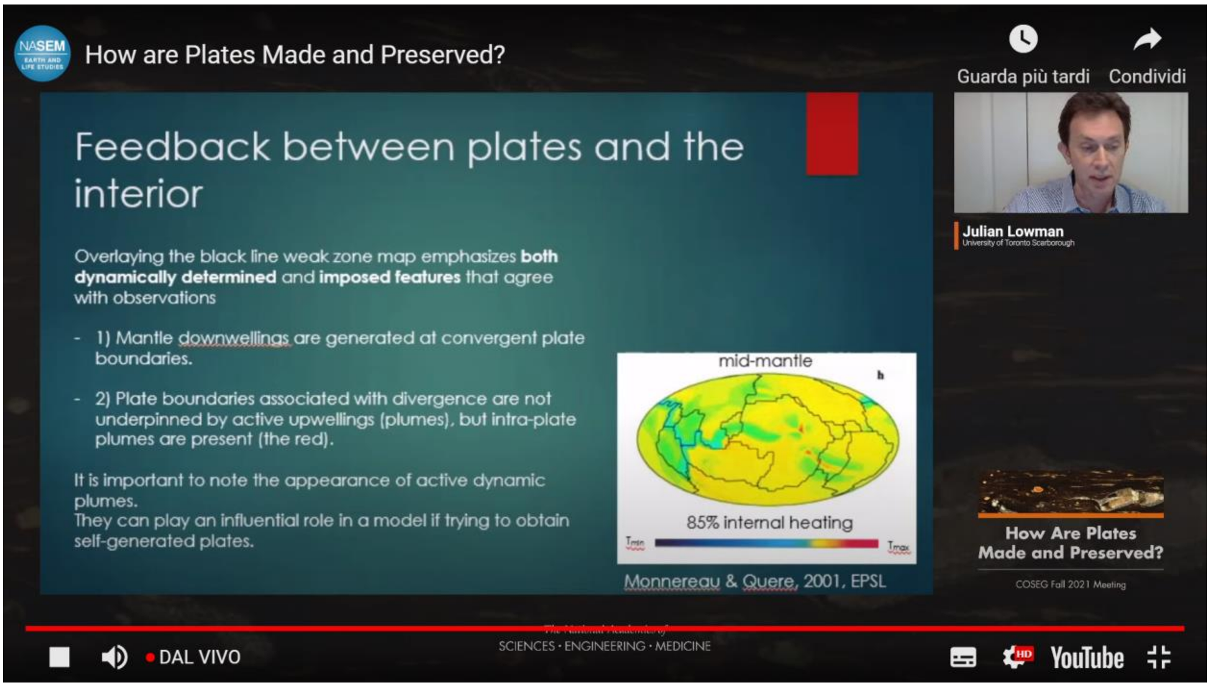

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Feedback between plates and the interior

Overlaying the black line weak zone map emphasizes **both dynamically determined** and **imposed features** that agree with observations

- 1) Mantle downwellings are generated at convergent plate boundaries.
- 2) Plate boundaries associated with divergence are not underpinned by active upwellings (plumes), but intra-plate plumes are present (the red).

It is important to note the appearance of active dynamic plumes.
They can play an influential role in a model if trying to obtain self-generated plates.

Monnereau & Quere, 2001, EPSL

Julian Lowman
University of Toronto Scarborough

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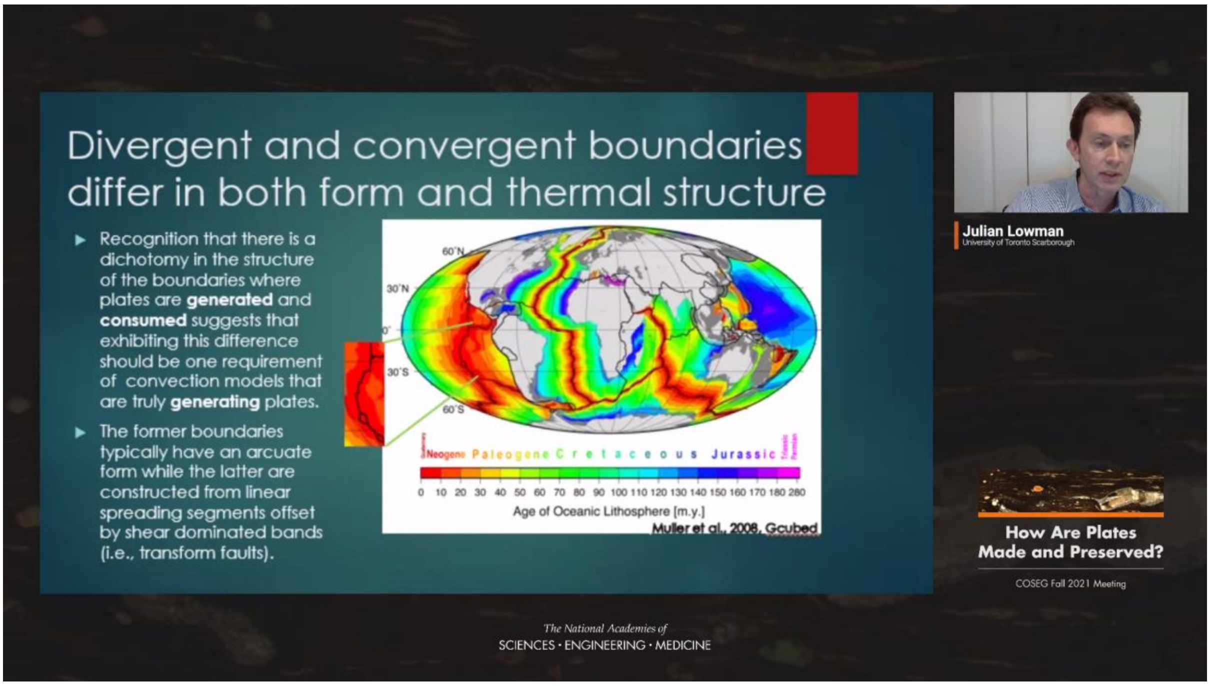

Divergent and convergent boundaries differ in both form and thermal structure

- Recognition that there is a dichotomy in the structure of the boundaries where plates are **generated** and **consumed** suggests that exhibiting this difference should be one requirement of convection models that are truly **generating** plates.
- The former boundaries typically have an arcuate form while the latter are constructed from linear spreading segments offset by shear dominated bands (i.e., transform faults).

Muller et al., 2008, Gcubed

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University of Toronto Scarborough

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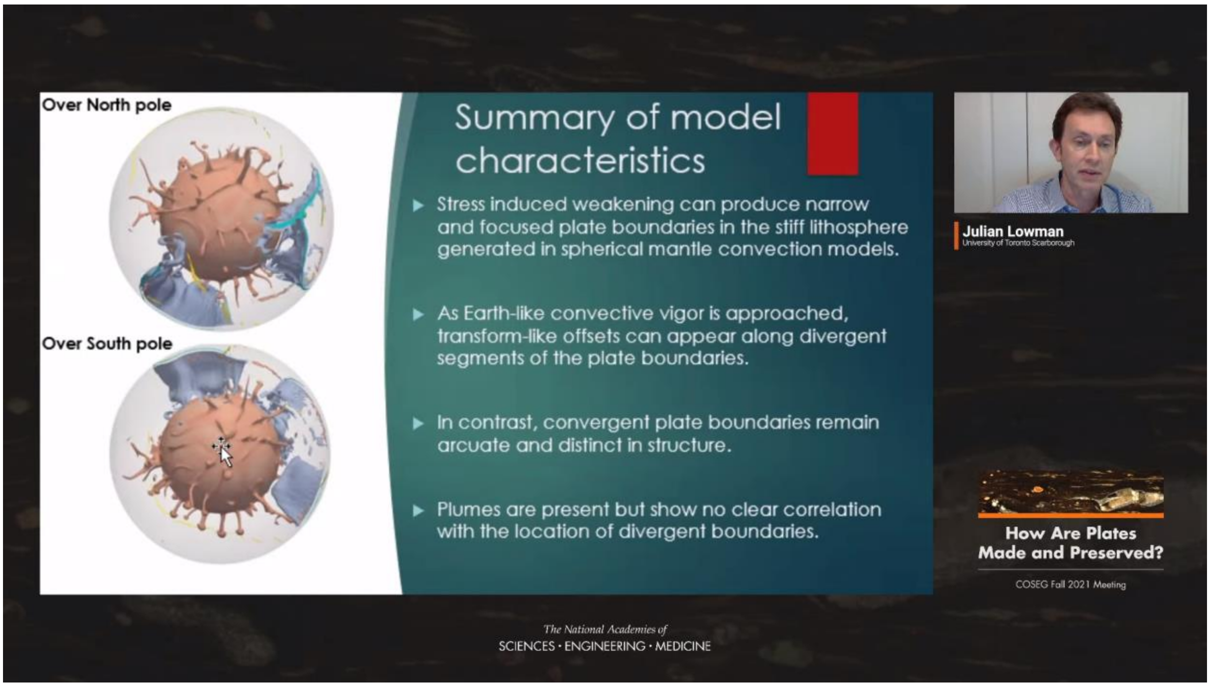

Summary of model characteristics

- Stress induced weakening can produce narrow and focused plate boundaries in the stiff lithosphere generated in spherical mantle convection models.
- As Earth-like convective vigor is approached, transform-like offsets can appear along divergent segments of the plate boundaries.
- In contrast, convergent plate boundaries remain arcuate and distinct in structure.
- Plumes are present but show no clear correlation with the location of divergent boundaries.

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University of Toronto Scarborough

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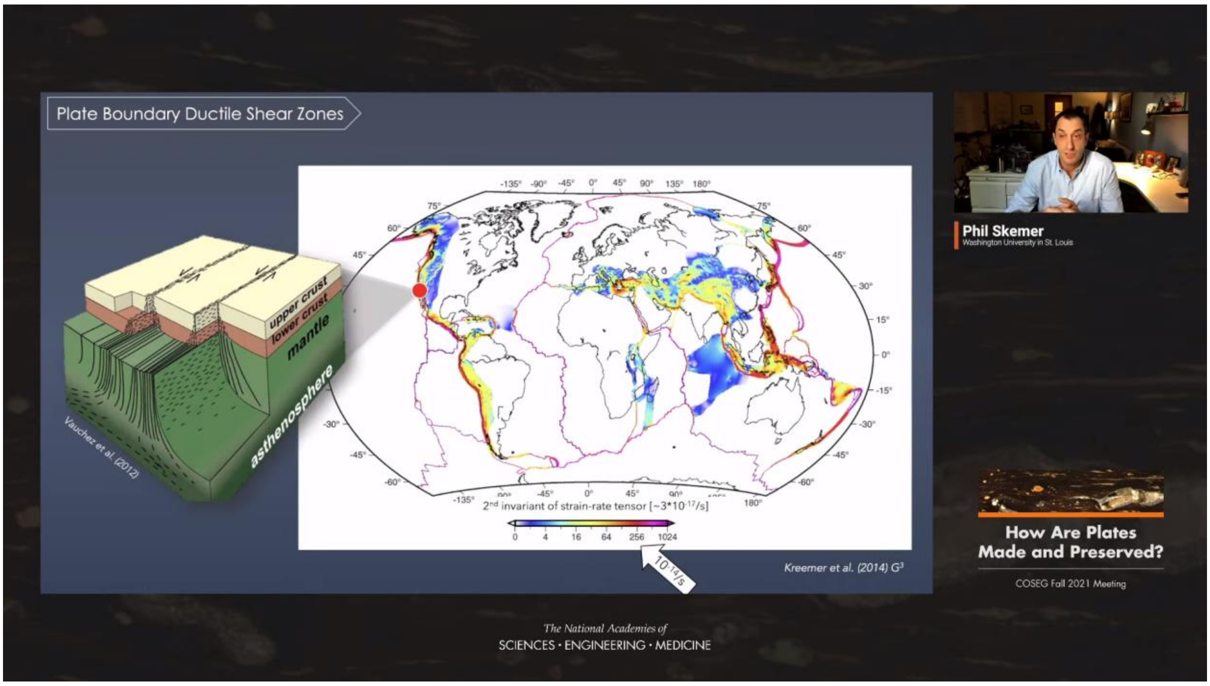

Plate Boundary Ductile Shear Zones

Kreemer et al. (2014) G³

Phil Skemer
Washington University in St. Louis

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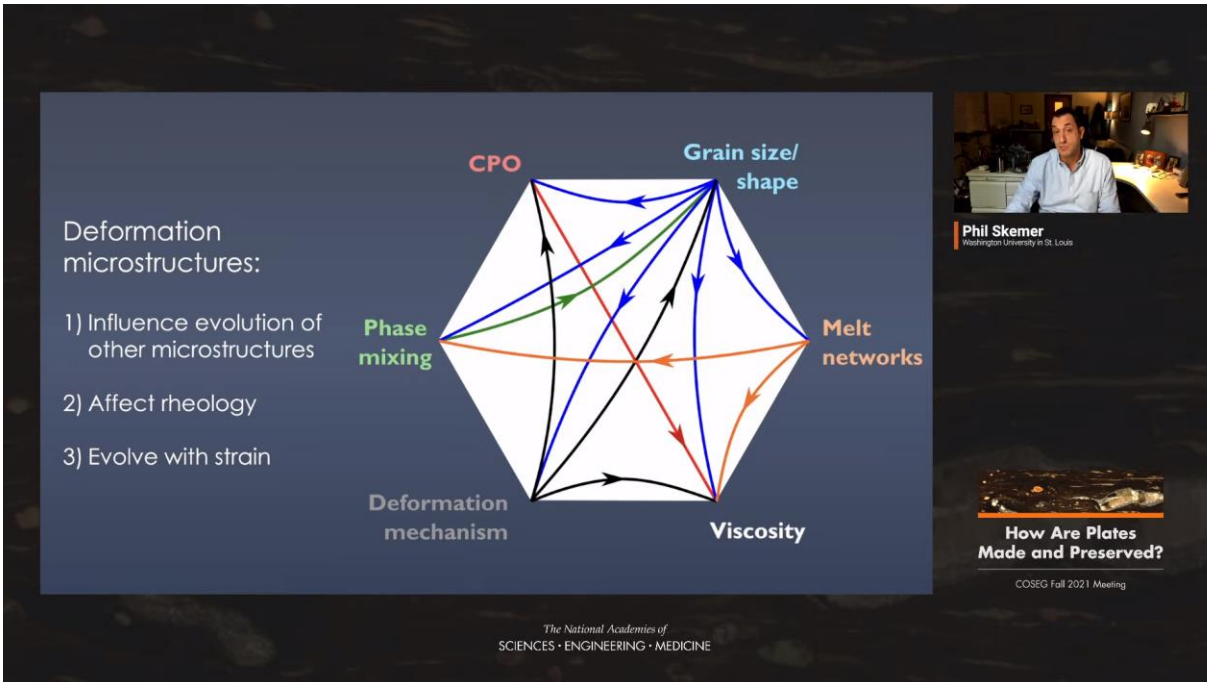

Deformation microstructures:

1) Influence evolution of other microstructures

2) Affect rheology

3) Evolve with strain

Phil Skemer
Washington University in St. Louis

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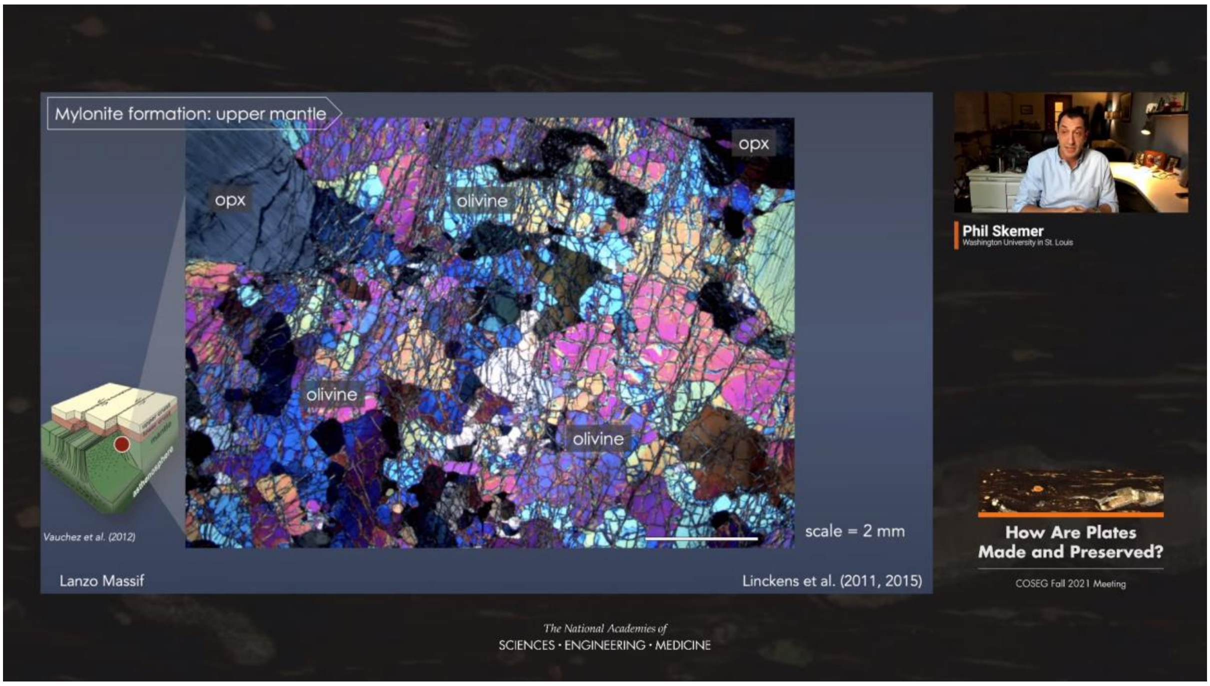

Mylonite formation: upper mantle

Lanzo Massif

Linckens et al. (2011, 2015)

Phil Skemer
Washington University in St. Louis

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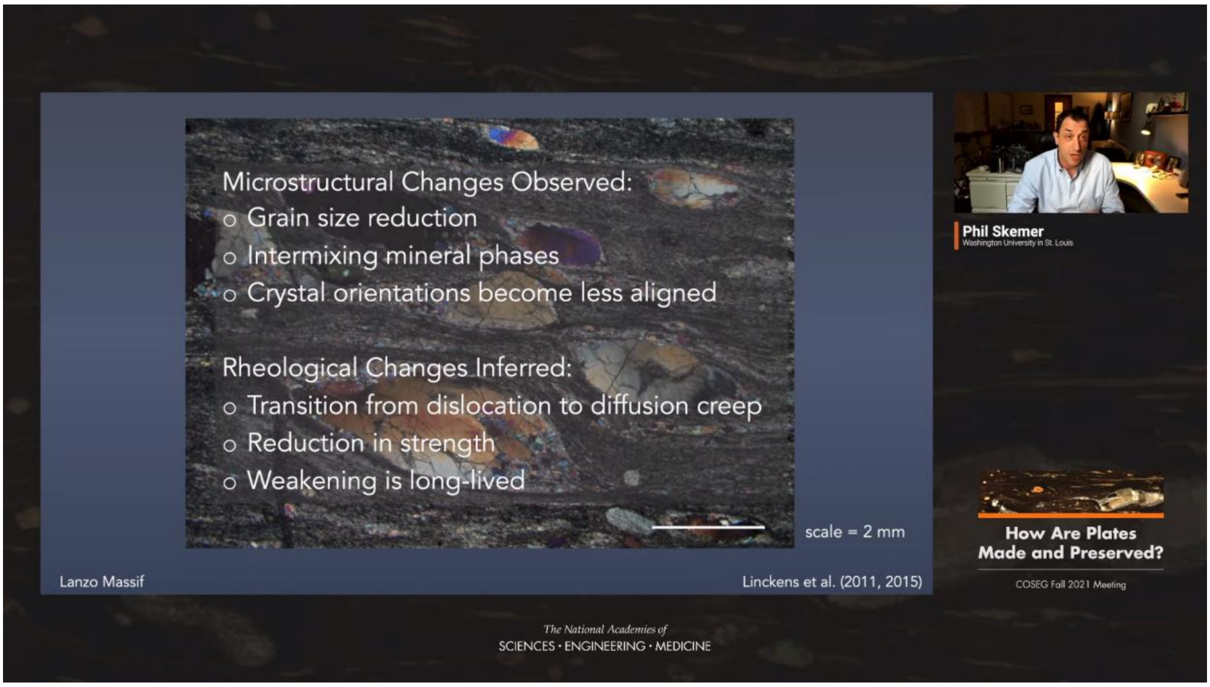

Microstructural Changes Observed:
- Grain size reduction
- Intermixing mineral phases
- Crystal orientations become less aligned

Rheological Changes Inferred:
- Transition from dislocation to diffusion creep
- Reduction in strength
- Weakening is long-lived

Lanzo Massif

Linckens et al. (2011, 2015)

Phil Skemer
Washington University in St. Louis

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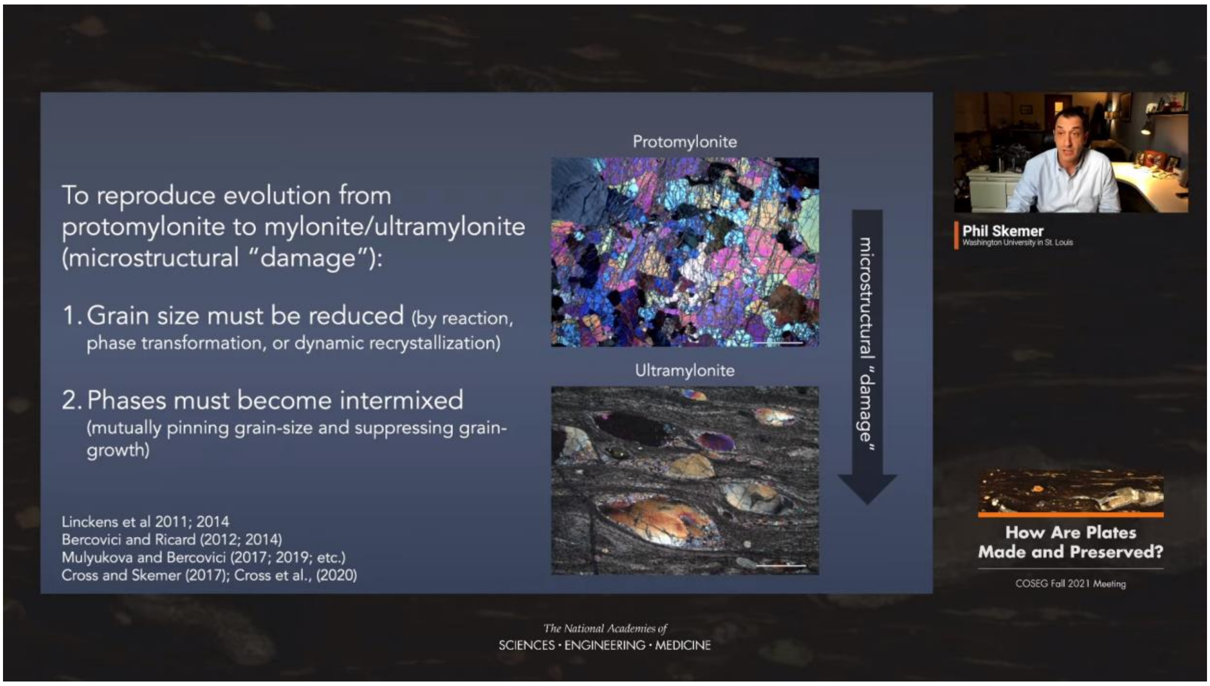


To reproduce evolution from protomylonite to mylonite/ultramylonite (microstructural "damage"):

1. Grain size must be reduced (by reaction, phase transformation, or dynamic recrystallization)
2. Phases must become intermixed (mutually pinning grain-size and suppressing grain-growth)

Linckens et al 2011; 2014
Bercovici and Ricard (2012; 2014)
Mulyukova and Bercovici (2017; 2019; etc.)
Cross and Skemer (2017); Cross et al., (2020)

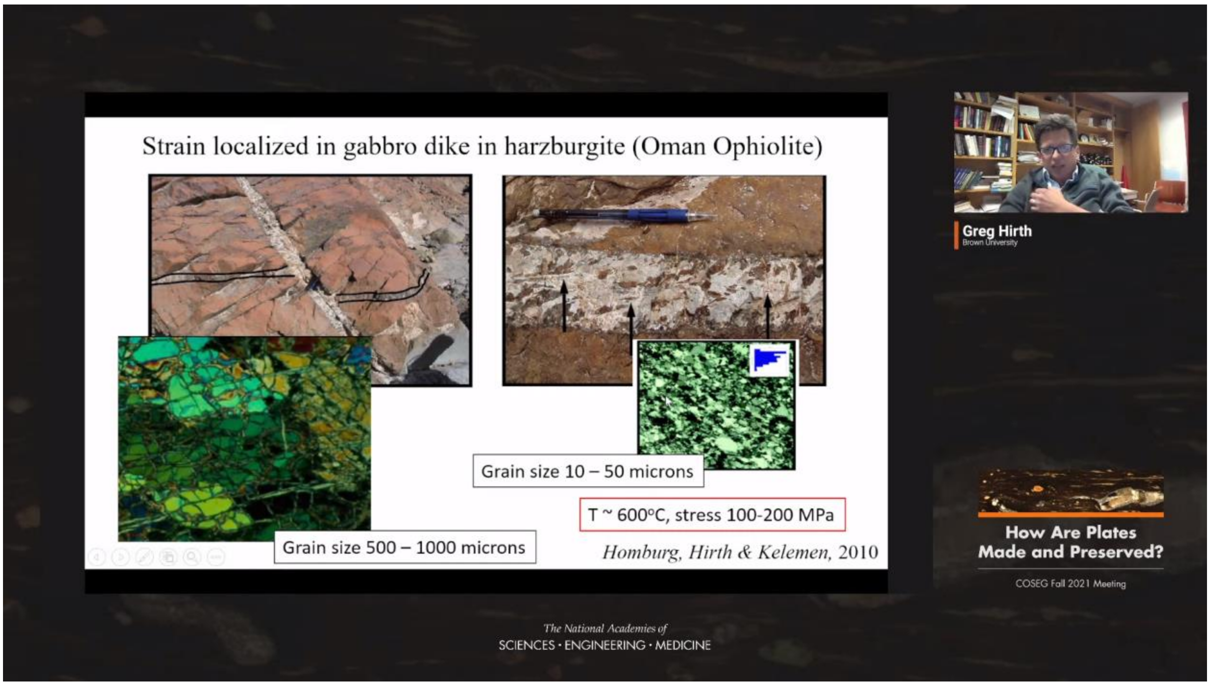
How are Plates Made and Preserved?

Conclusions:

The formation of mylonites and the associated rheological weakening requires the protracted evolution of deformation microstructures.

Plate boundary shear zones evolve slowly towards steady state, and exhibit transient rheologies over long geologic intervals.

The weakening required for Earth-like plate tectonics likely requires more than one set of physical processes – one to initiate and one to maintain.



Strain localized in gabbro dike in harzburgite (Oman Ophiolite)

Grain size 10 – 50 microns

T ~ 600°C, stress 100-200 MPa

Grain size 500 – 1000 microns

Homburg, Hirth & Kelemen, 2010

Greg Hirth
Brown University

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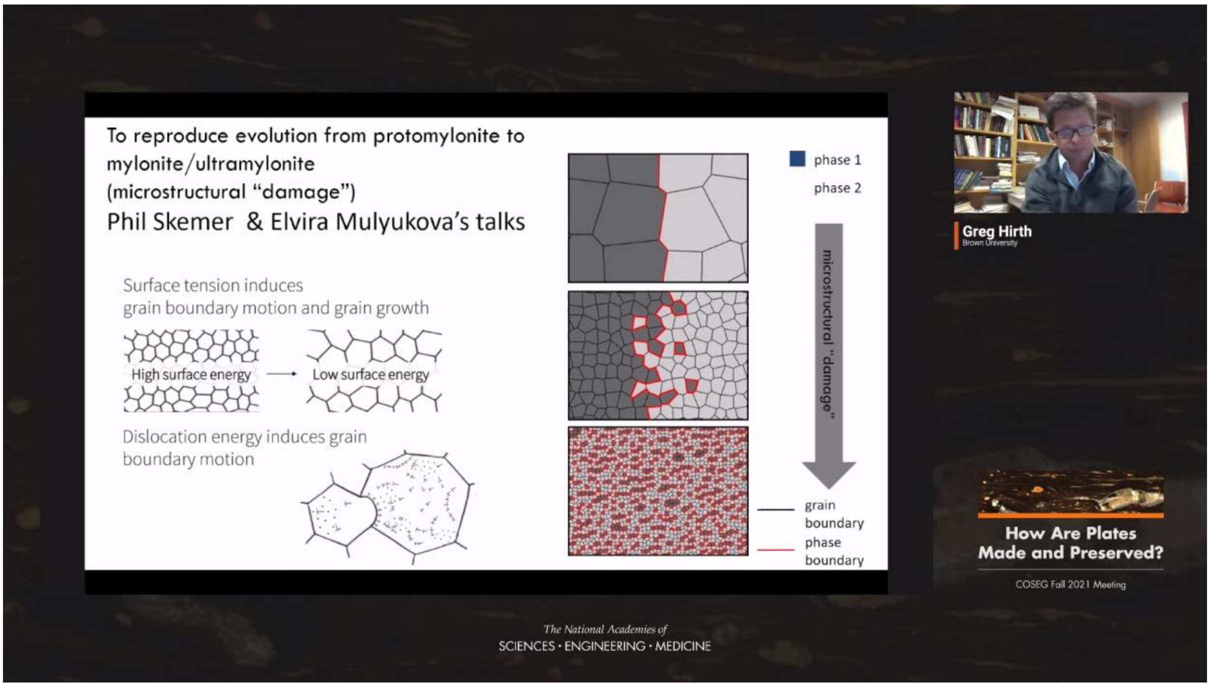

To reproduce evolution from protomylonite to mylonite/ultramylonite (microstructural “damage”)

Phil Skemer & Elvira Mulyukova’s talks

Surface tension induces grain boundary motion and grain growth

Dislocation energy induces grain boundary motion

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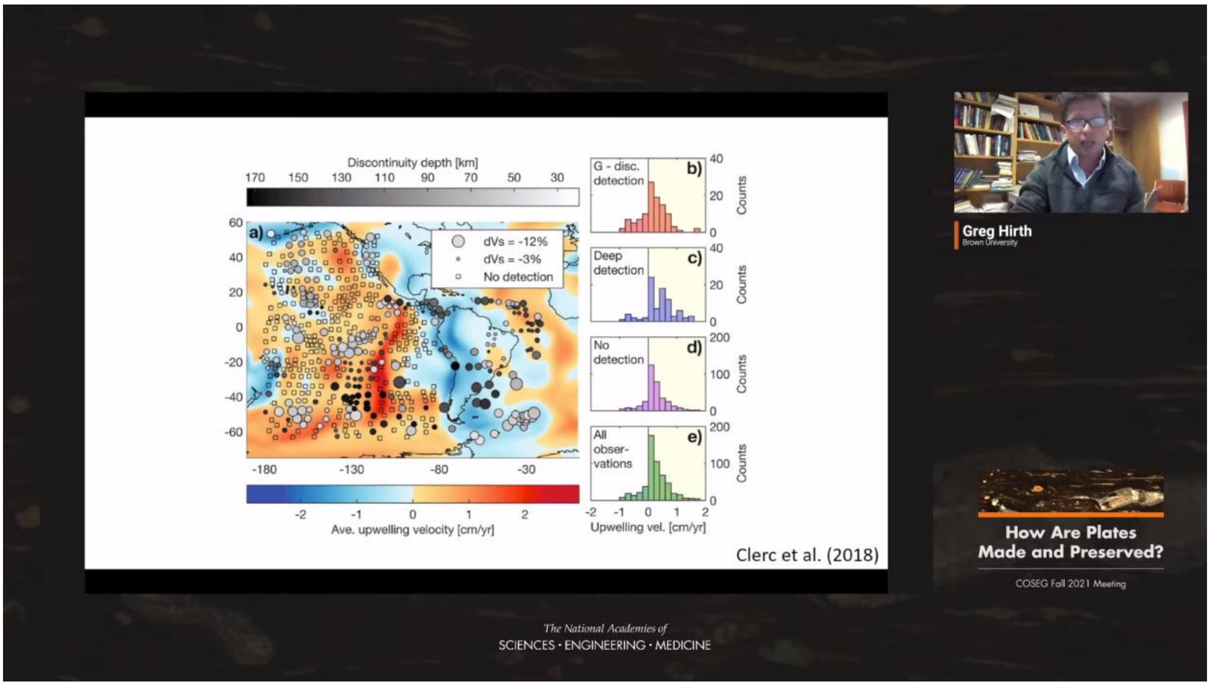
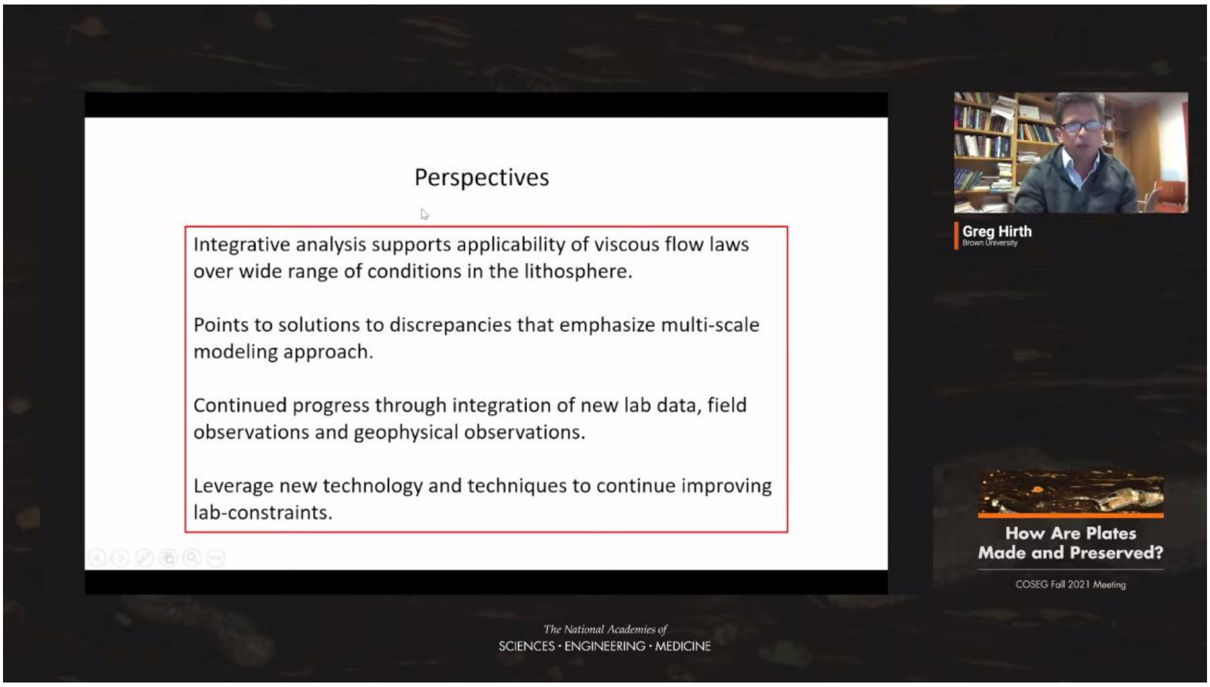


Clerc et al. (2018)



Perspectives

Integrative analysis supports applicability of viscous flow laws over wide range of conditions in the lithosphere.

Points to solutions to discrepancies that emphasize multi-scale modeling approach.

Continued progress through integration of new lab data, field observations and geophysical observations.

Leverage new technology and techniques to continue improving lab-constraints.