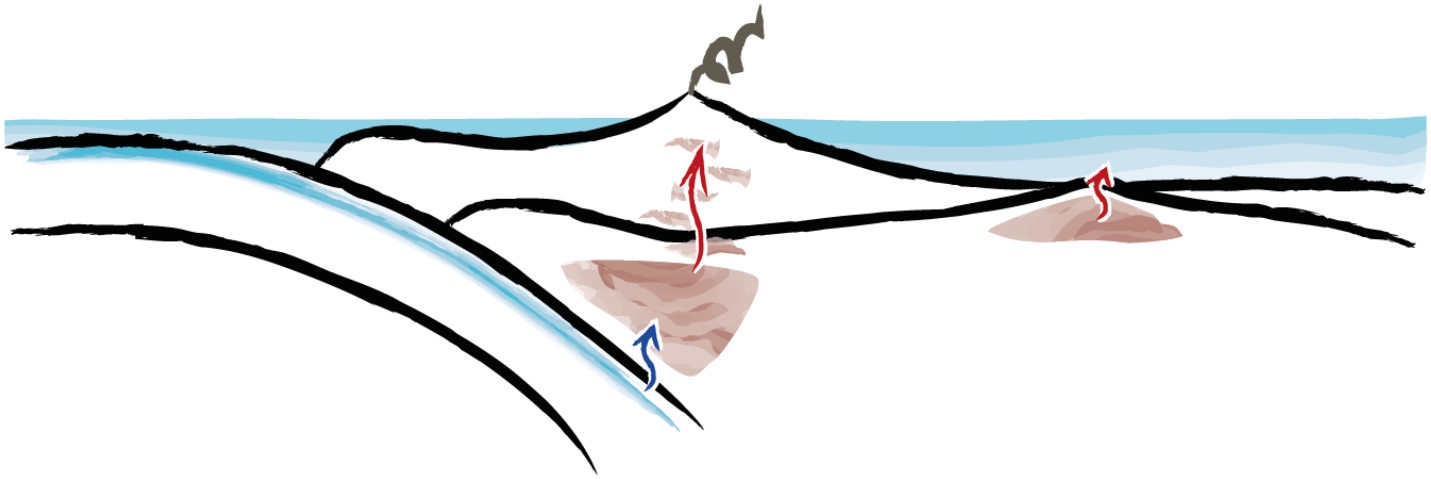
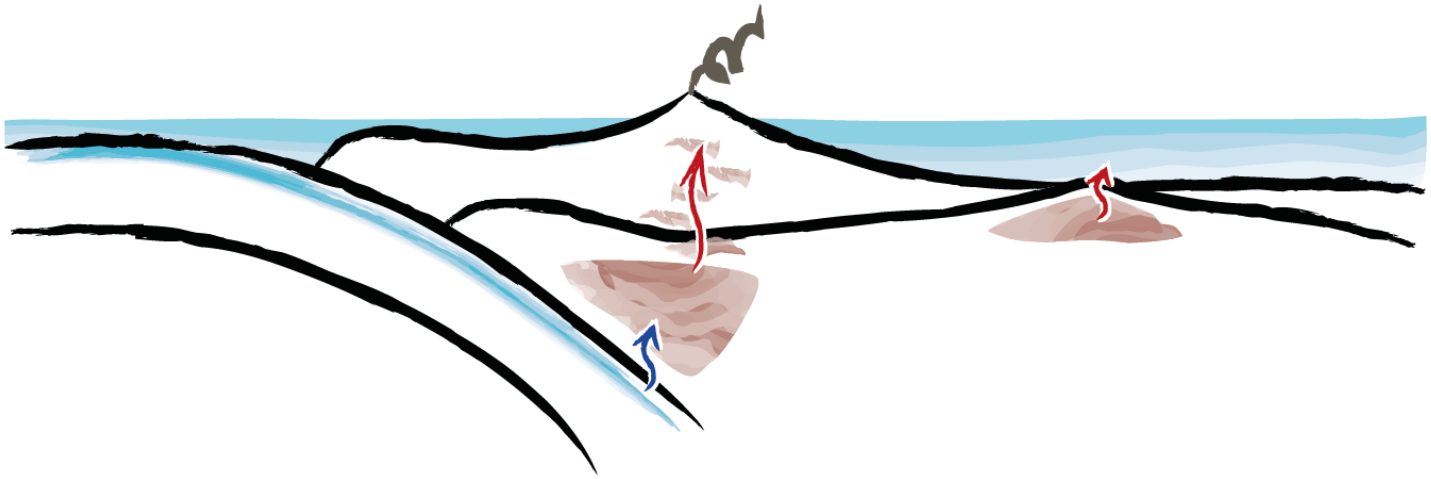
The link between mantle flow and magmatism in subduction zones

Valentina Magni



CEED
The Centre for Earth Evolution and Dynamics
UiO : Universitetet i Oslo

Monks judging our slides



CEED
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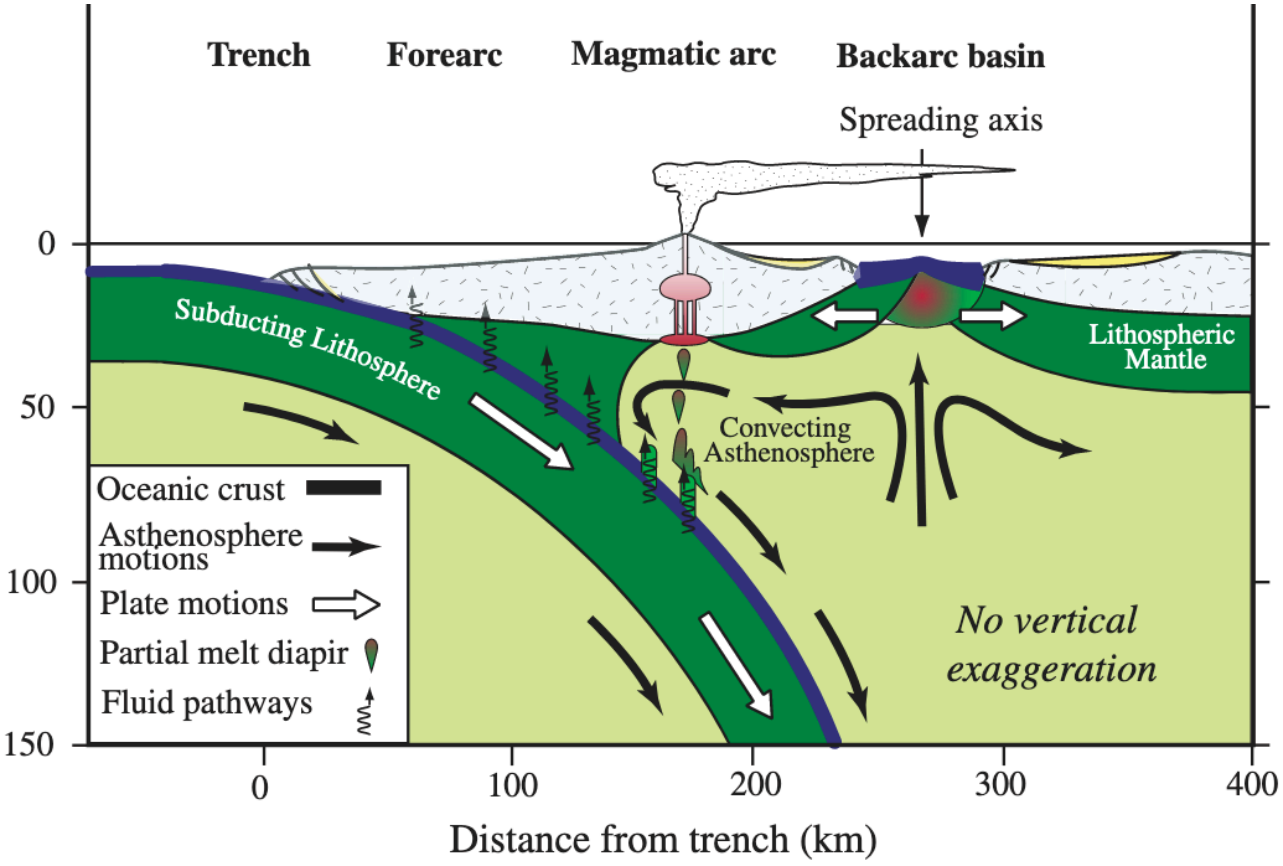
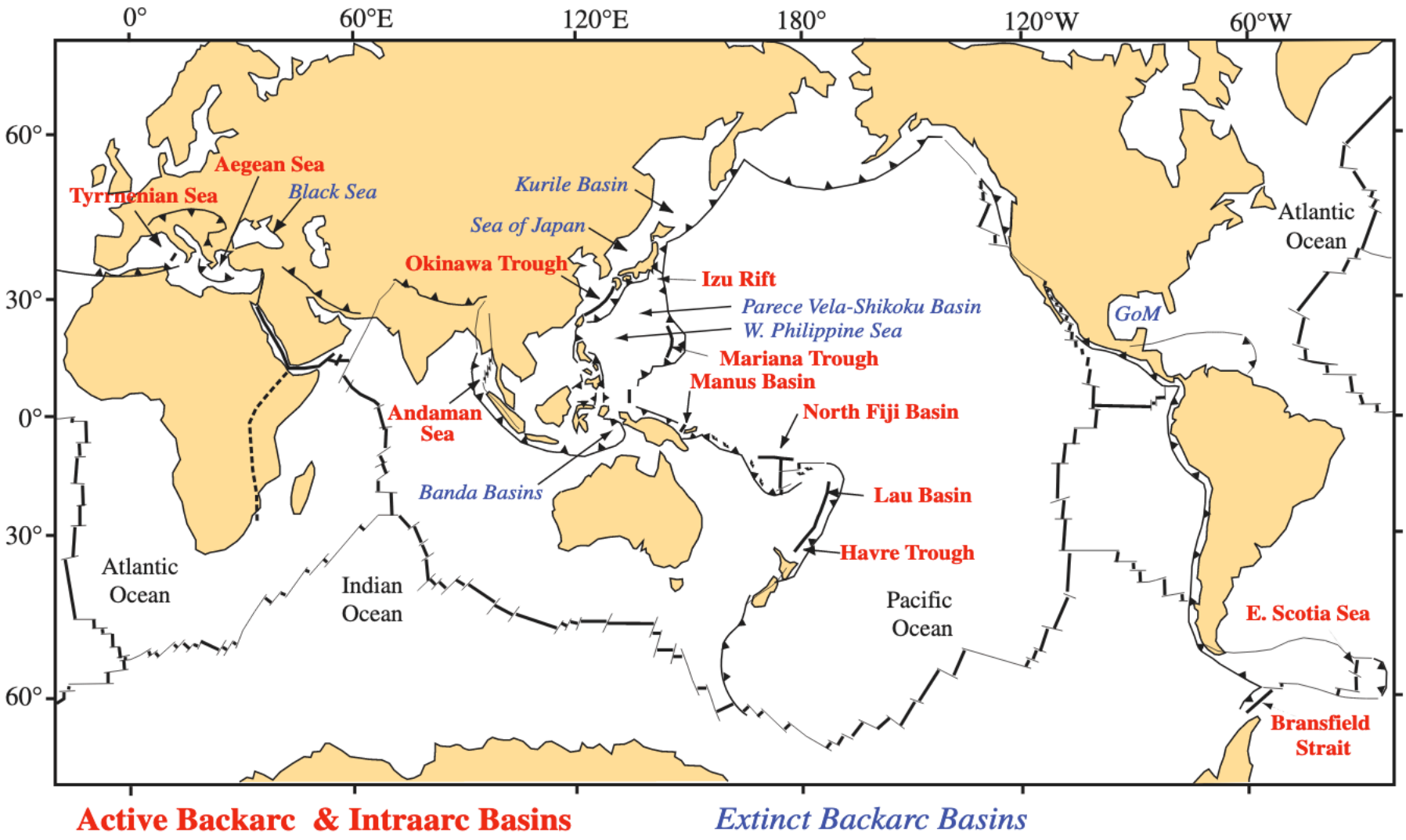
Arc magmatism

Stern and Dickinson, 2010



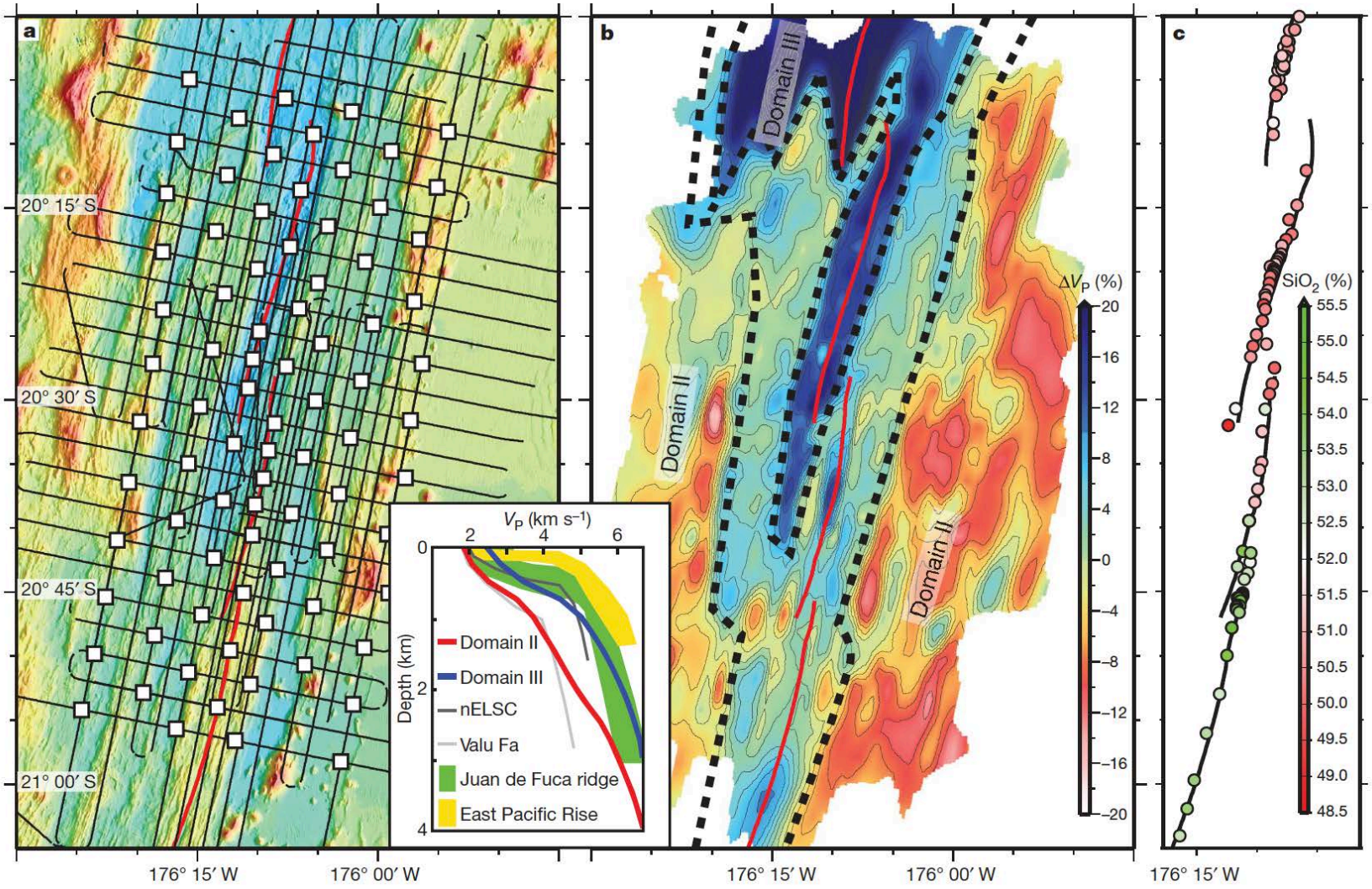
- Composition of the subducting plate
- Slab dehydration pattern
- Thermal structure of the subduction zone
- Mantle wedge dynamics
- Mantle source
- Melt migration
- Thickness and composition of the overriding plate
- Overriding plate stress regime
- Fractional crystallization processes
- ...

Back-arc basins



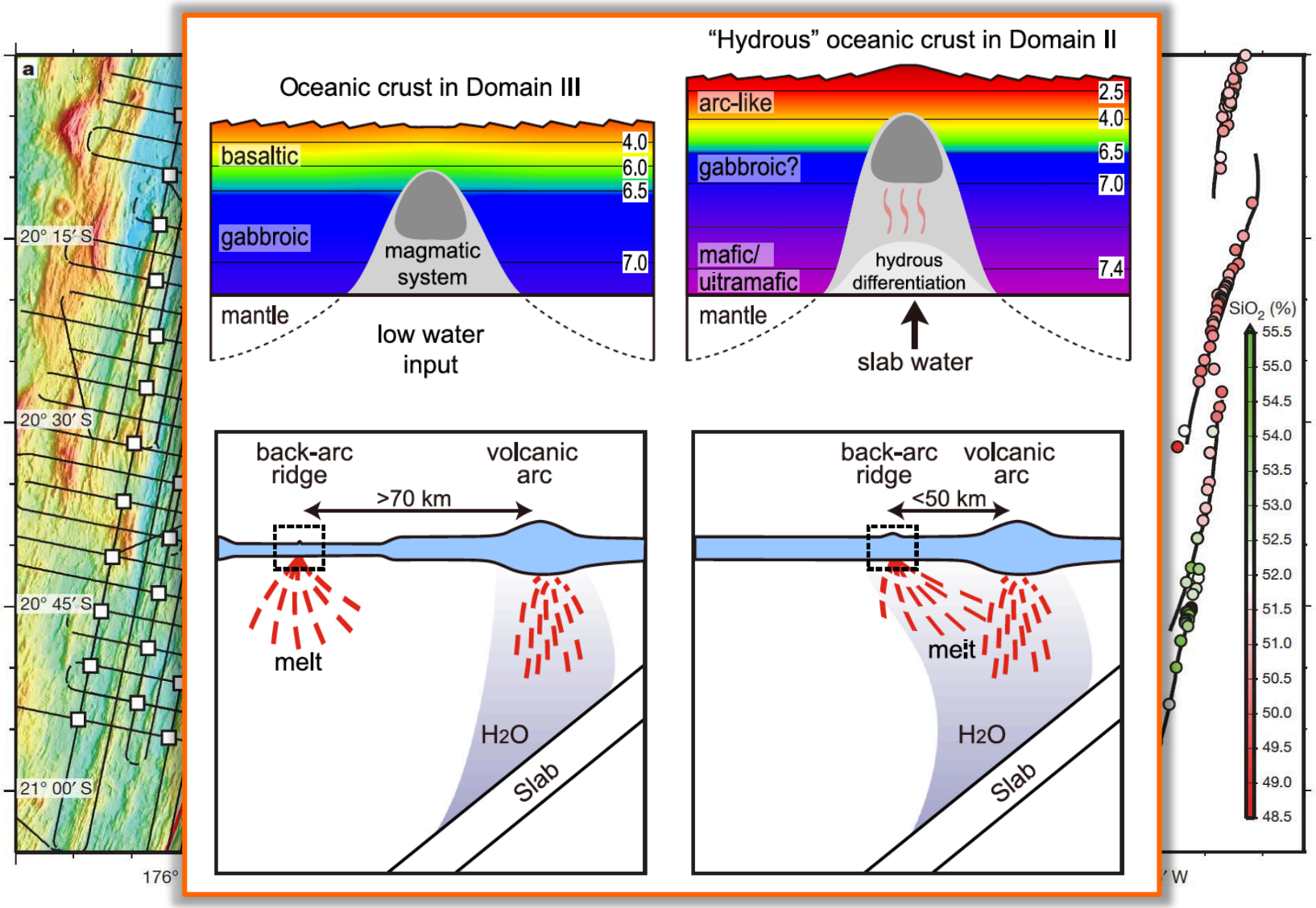
Stern and Dickinson, 2010

Back-arc magmatism



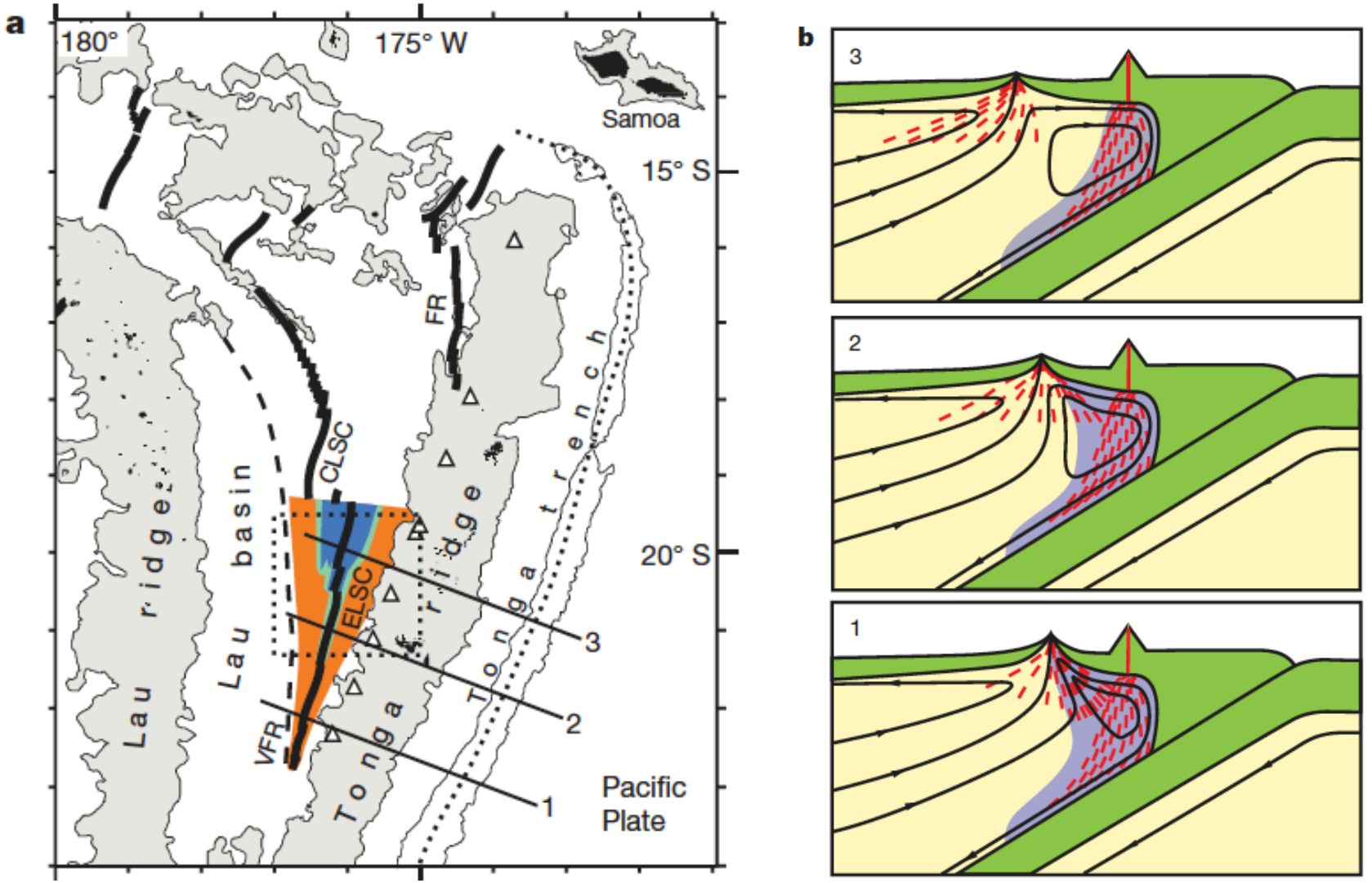
Arai and Dunn, EPSL, 2014

Back-arc magmatism



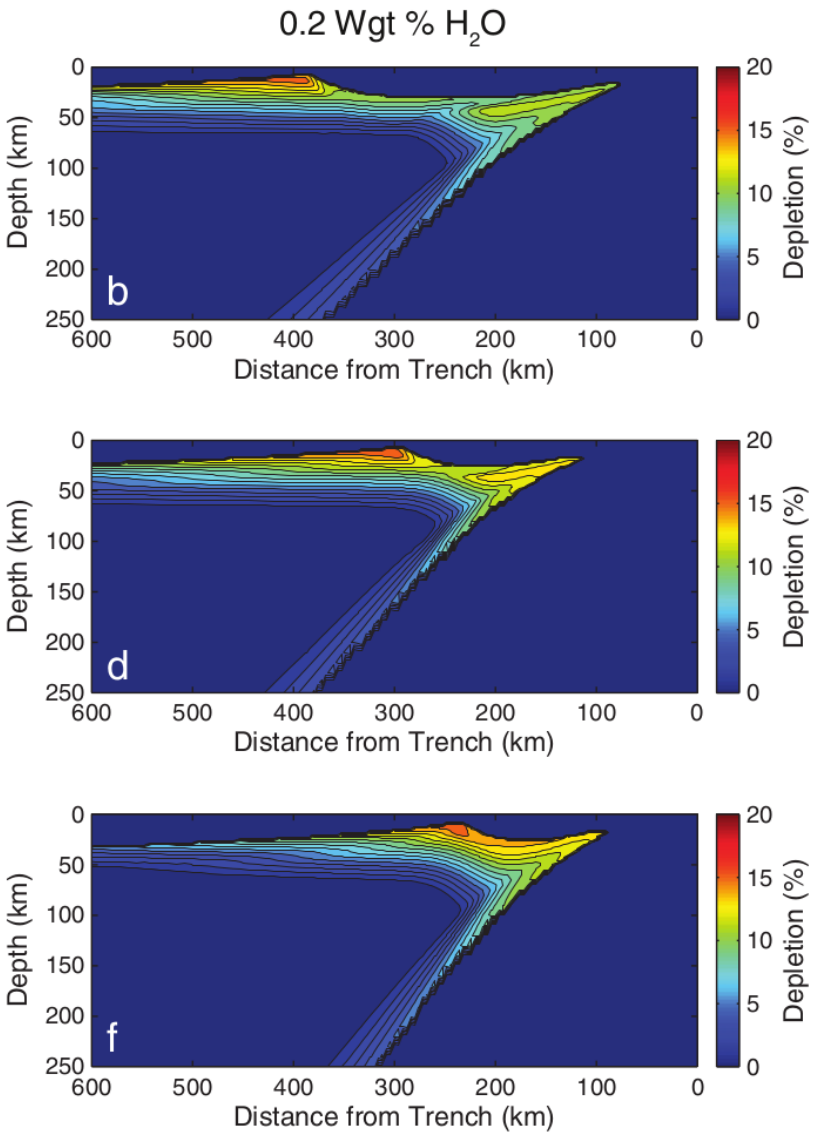
Arai and Dunn, EPSL, 2014

Back-arc magmatism

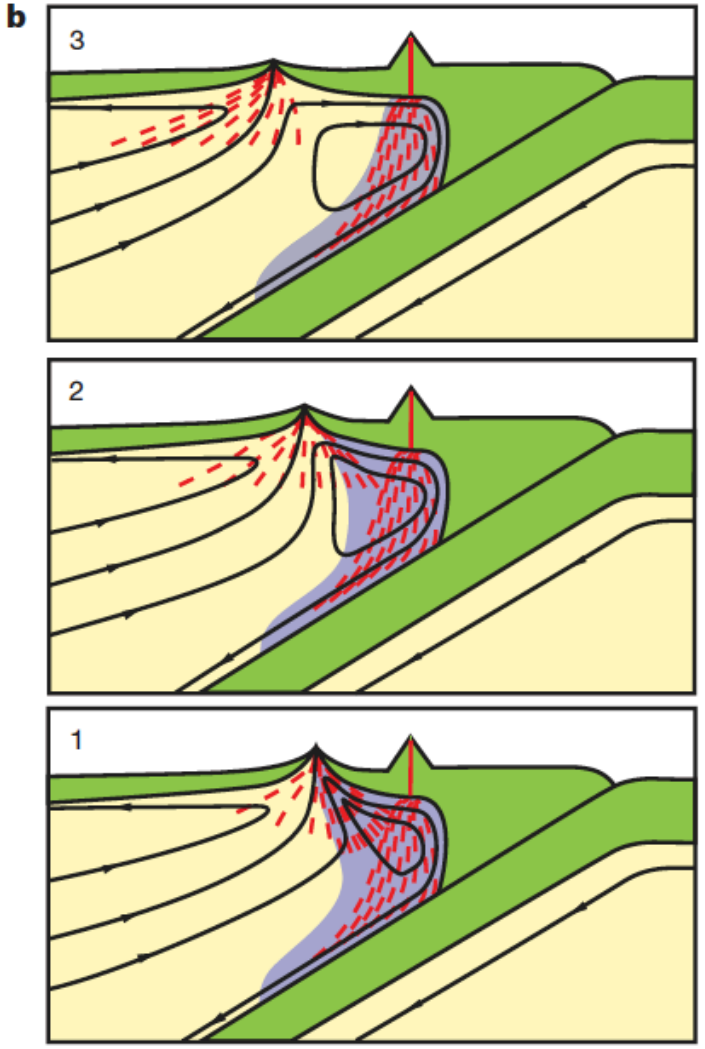


Dunn and Martinez, Nature, 2011

Back-arc magmatism

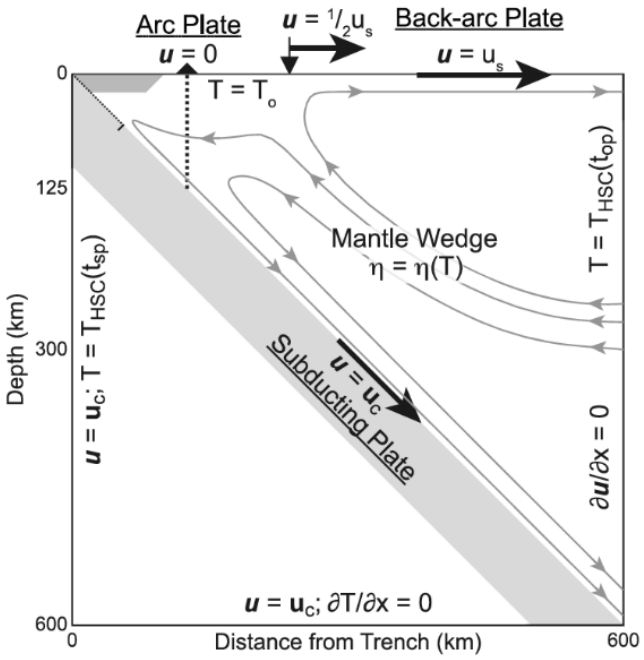


Harmon and Blackman, EPSL, 2010

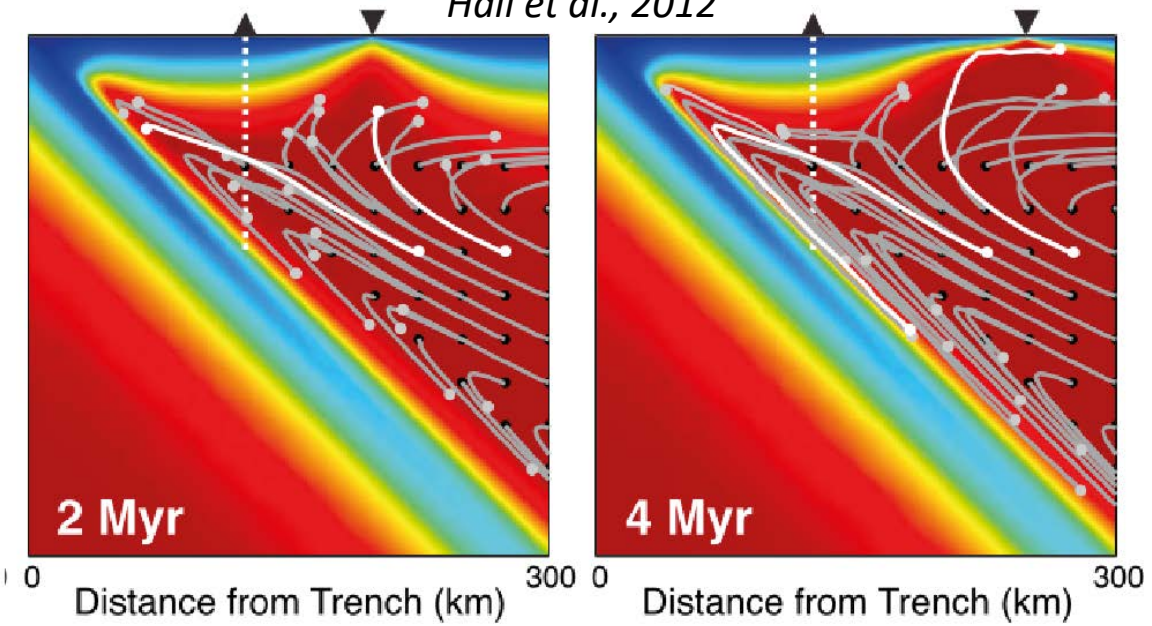


Dunn and Martinez, Nature, 2011

Back-arc - Arc magmatism

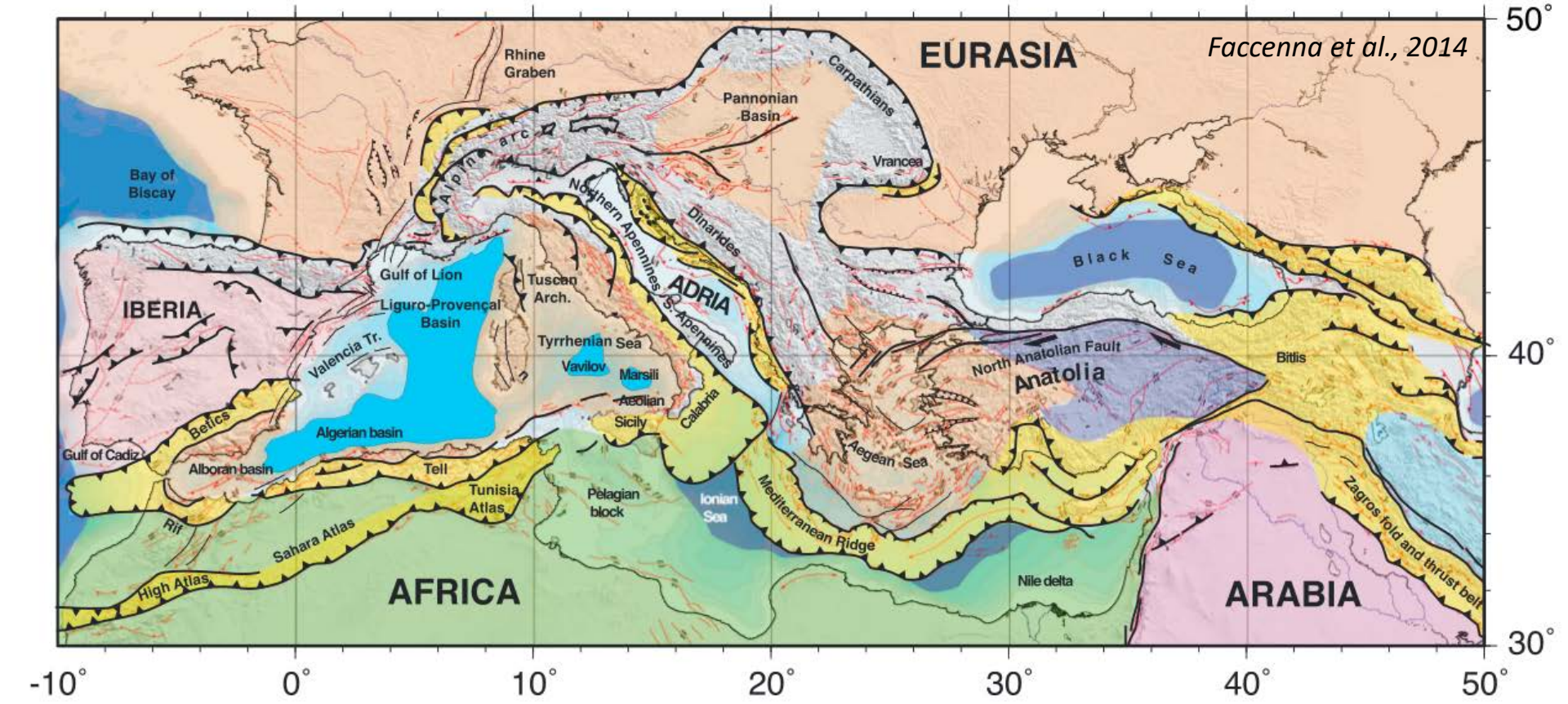


Hall et al., 2012

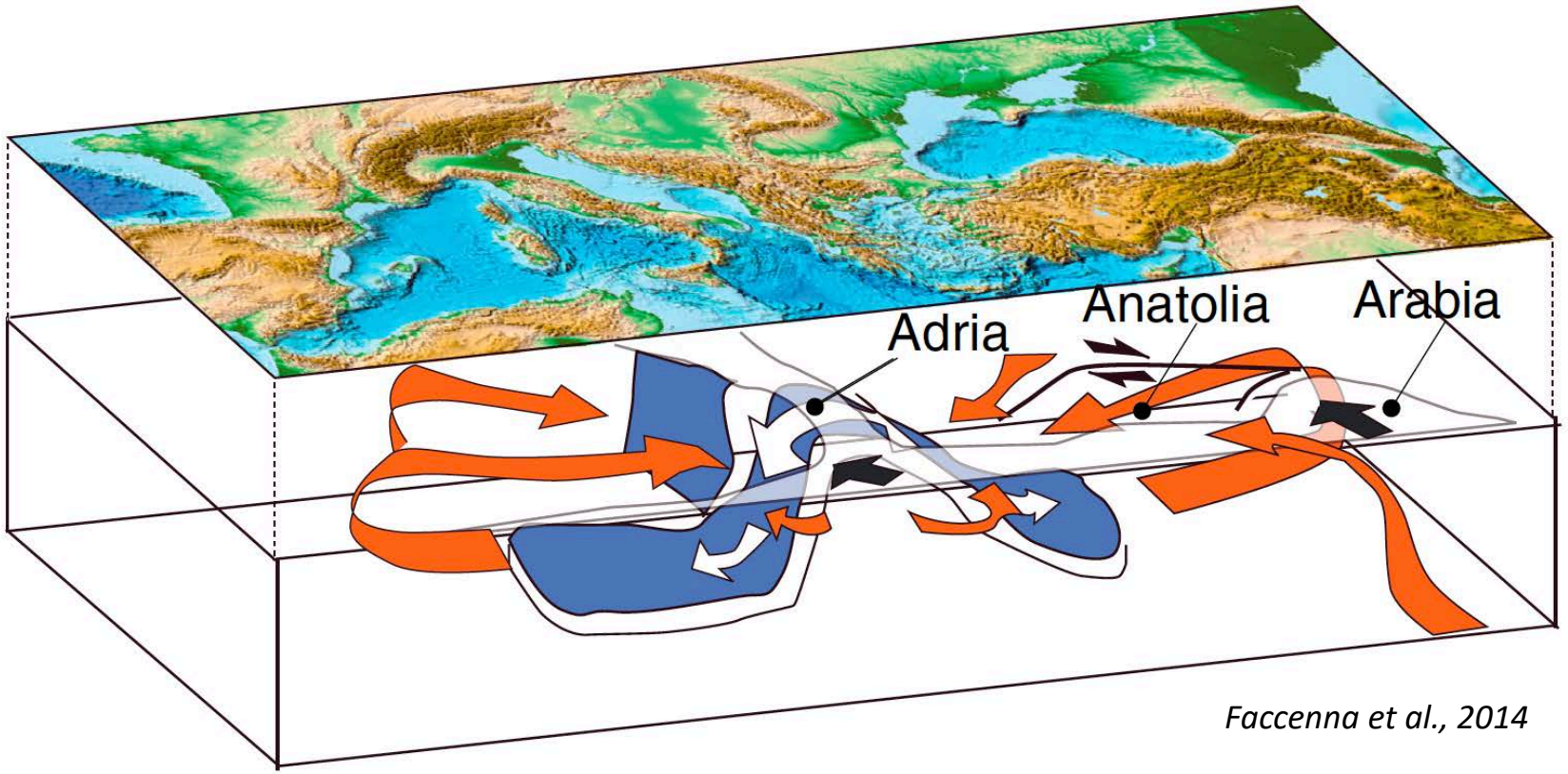


- Temperature increase in the mantle wedge due to onset of back-arc spreading
- Sub-arc mantle becomes increasingly more depleted with time following the onset of spreading, as mantle that has experienced decompression melting and melt extraction beneath the BA flows into the mantle wedge above the slab

Subduction zones geometry

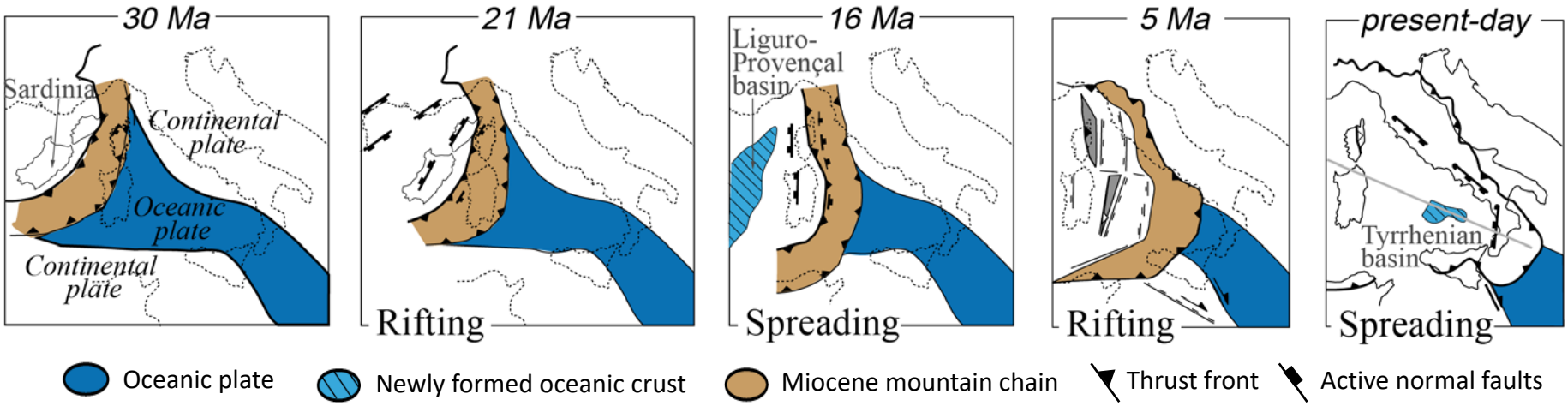


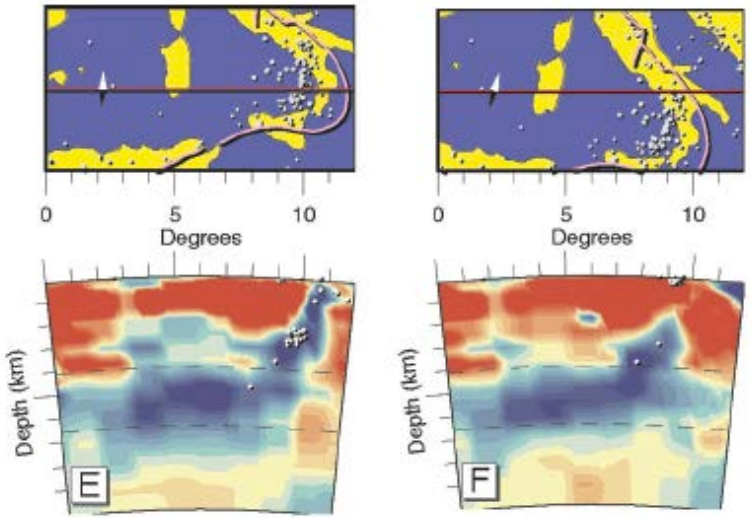
Subduction zones mantle flow



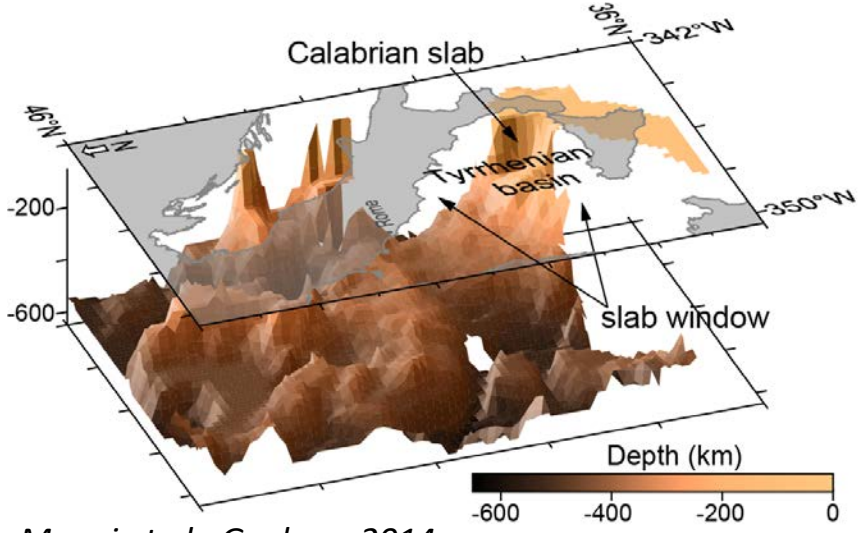
Faccenna et al., 2014

The Central Mediterranean



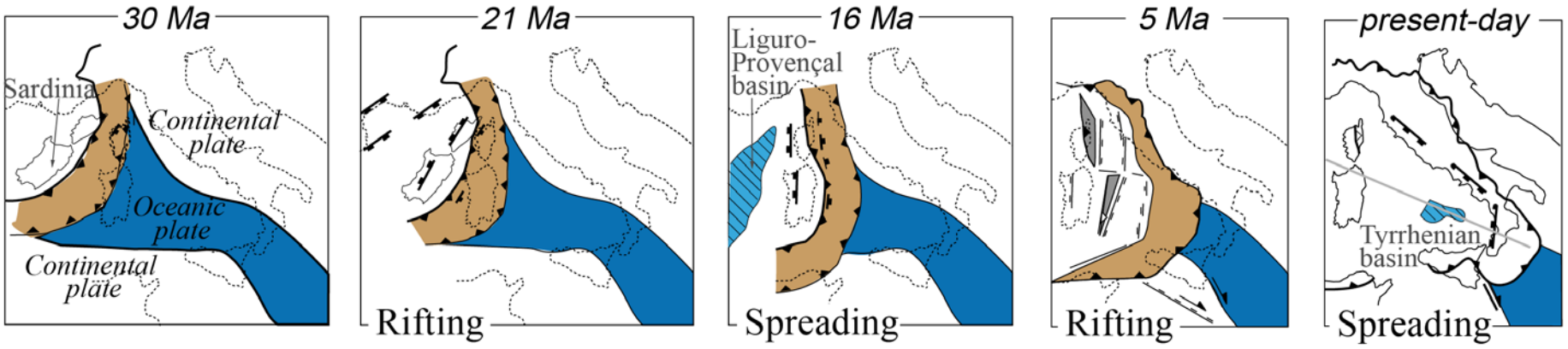


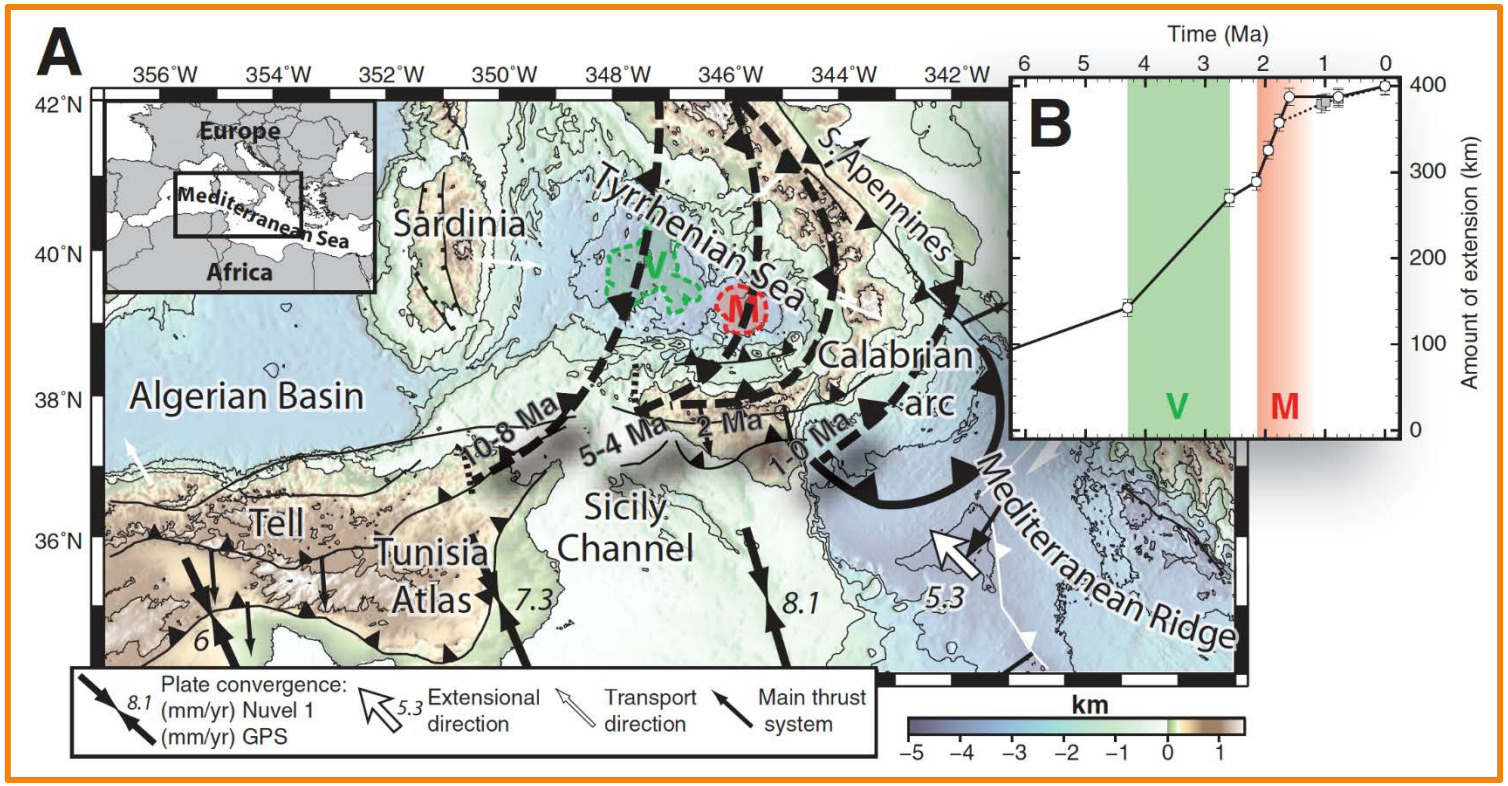
Wortel and Spakman, Science, 2000



Magni et al., Geology, 2014
(tomographic data from: Piromallo and Morelli, JGR, 2003)

The Central Mediterranean

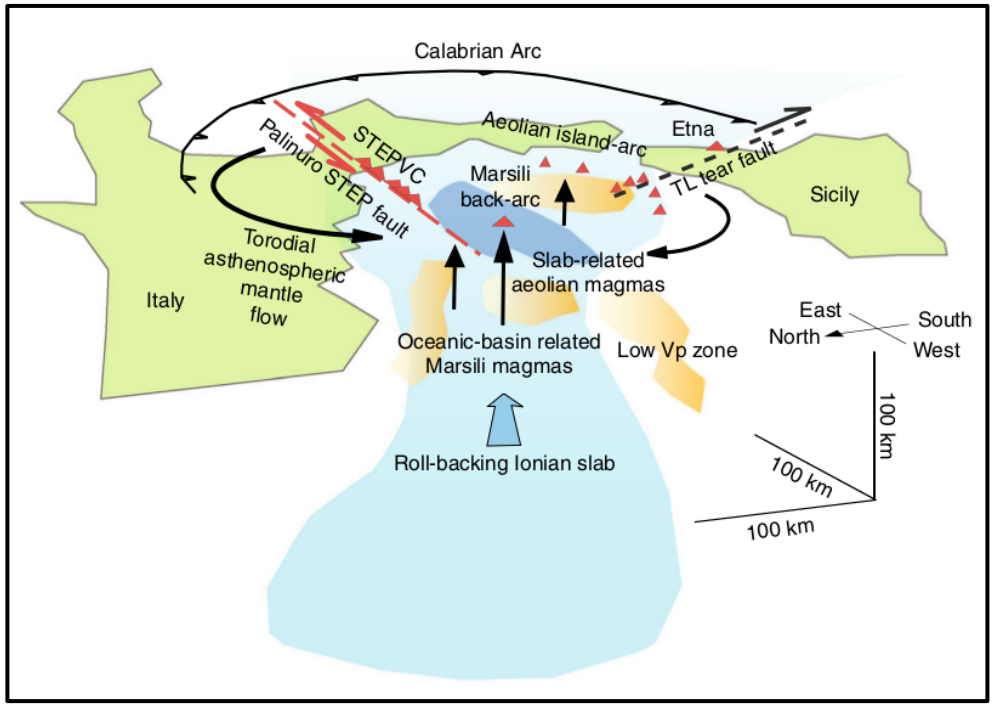




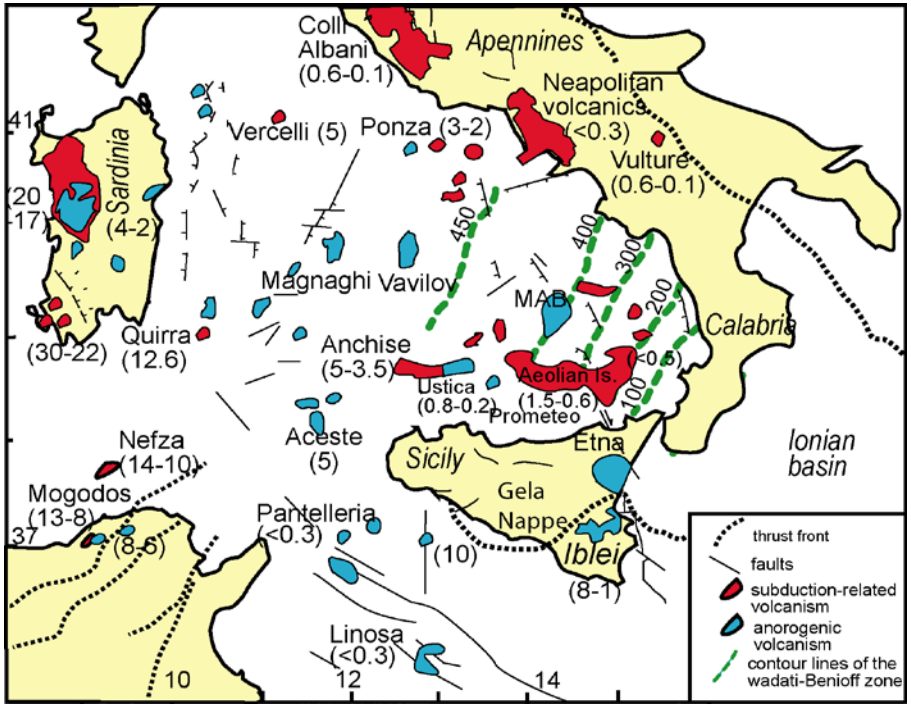
Guillaume et al., 2010

The Central Mediterranean

Cocchi et al., 2017



Faccenna et al., 2005

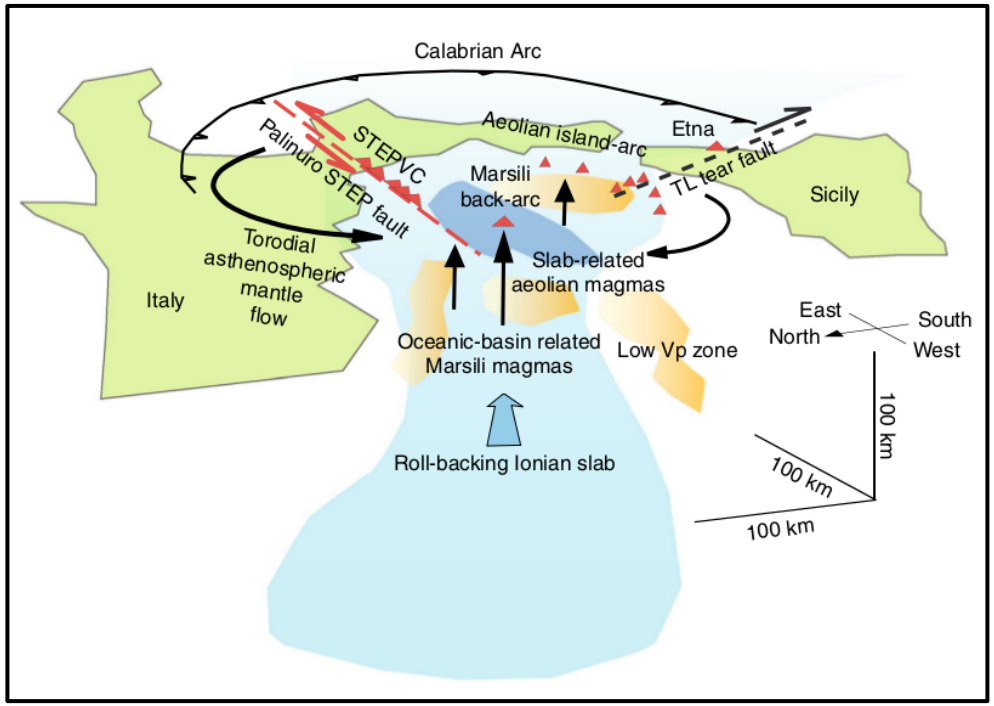


Subduction-related volcanism

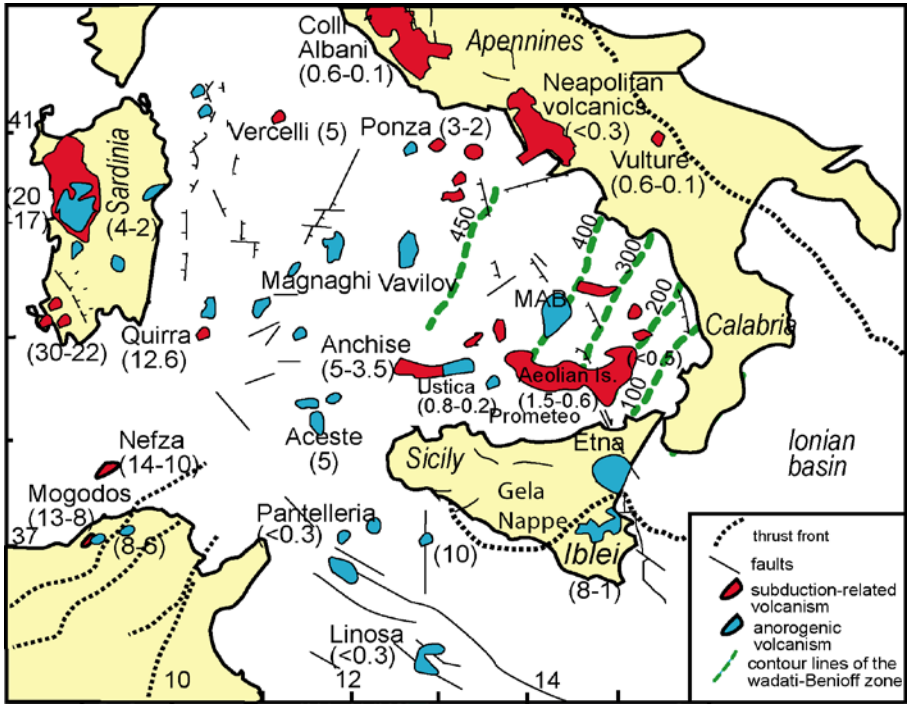
- Arc: slab dehydration and mantle wedge melting
- Back-arc spreading: adiabatic decompression melting due to extension at the back-arc
- STEP faults volcanoes: mantle upwelling through transform faults focusing volcanism

The Central Mediterranean

Cocchi et al., 2017



Faccenna et al., 2005



How do these different types of volcanism interact with each other?

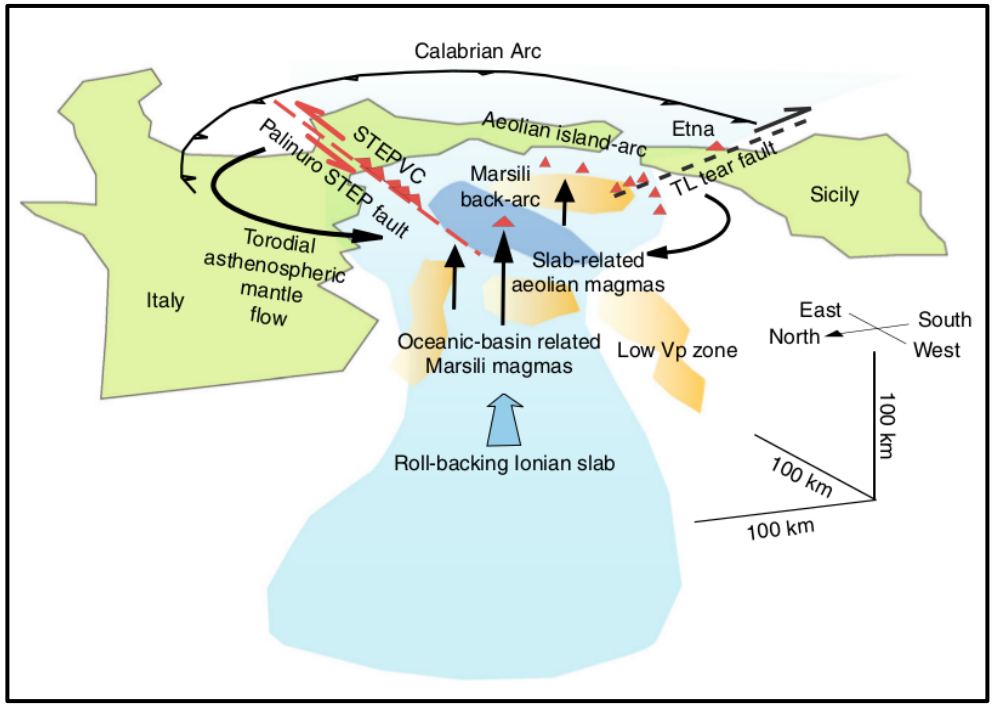
How do they evolve through time?

What is the source of melting?

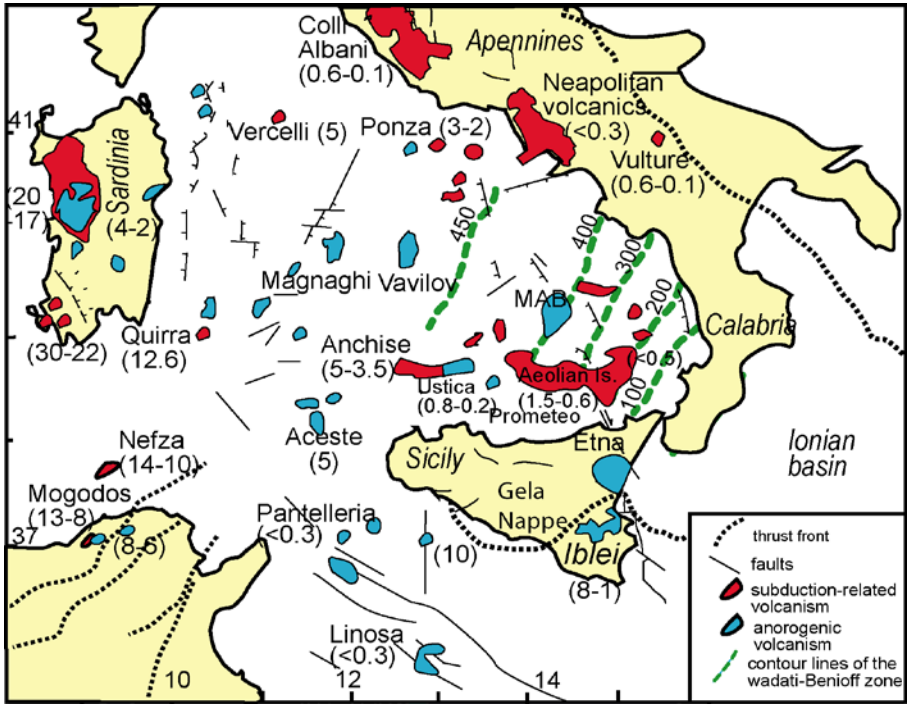
Where does the mantle that melts at the arc and back-arc come from?

The Central Mediterranean

Cocchi et al., 2017



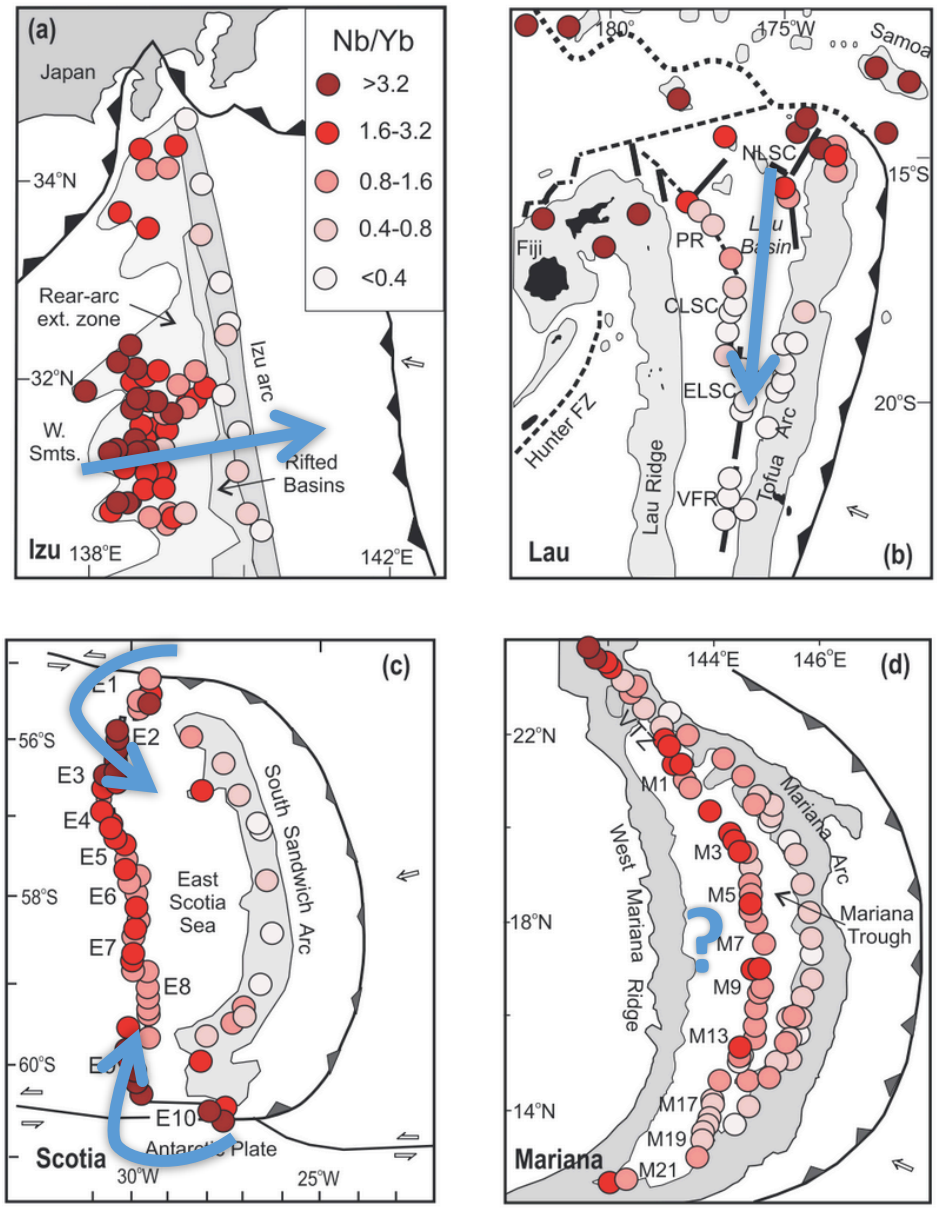
Faccenna et al., 2005



How does mantle flow affect the source of magmatism in the different regions of a subduction zone?

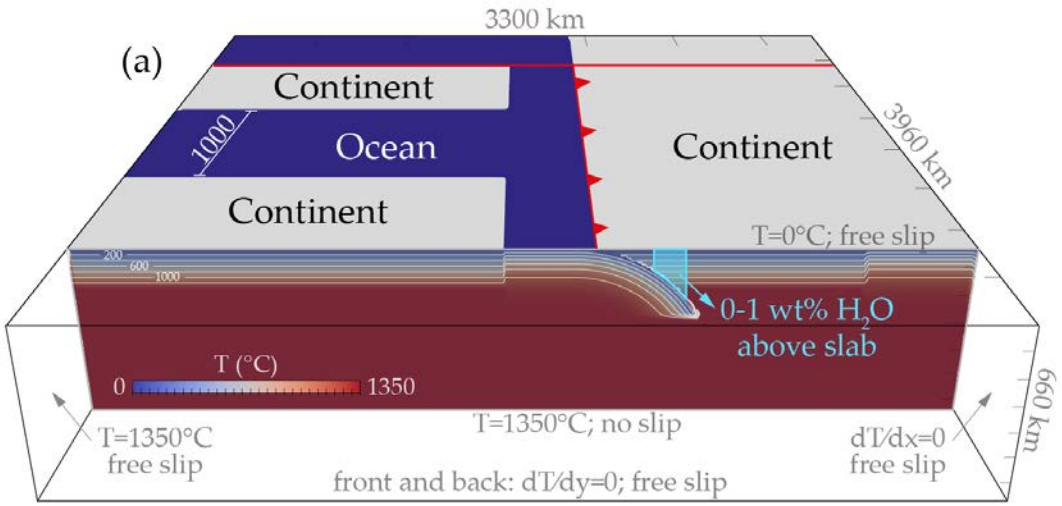
Mantle flow from geochemistry

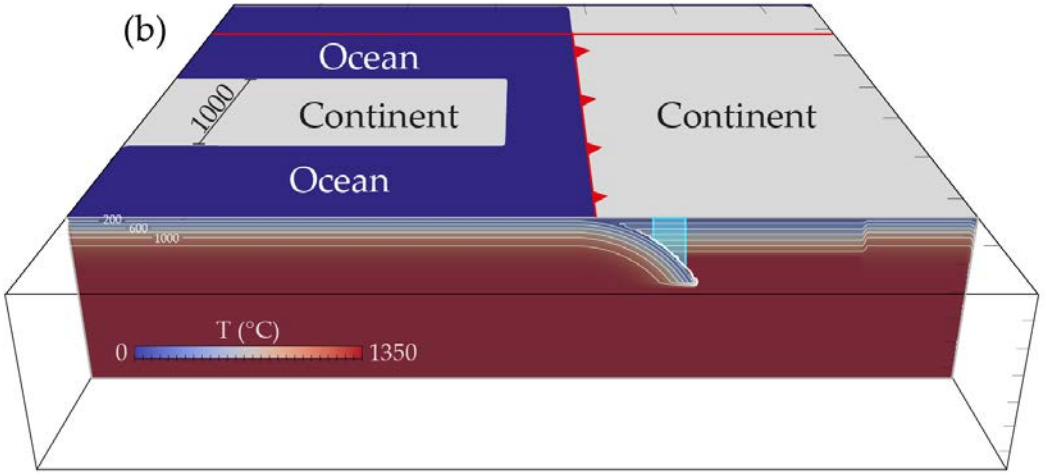
Nb/Yb: proxy for mantle fertility



Pearce and Stern, 2006

3D model setup



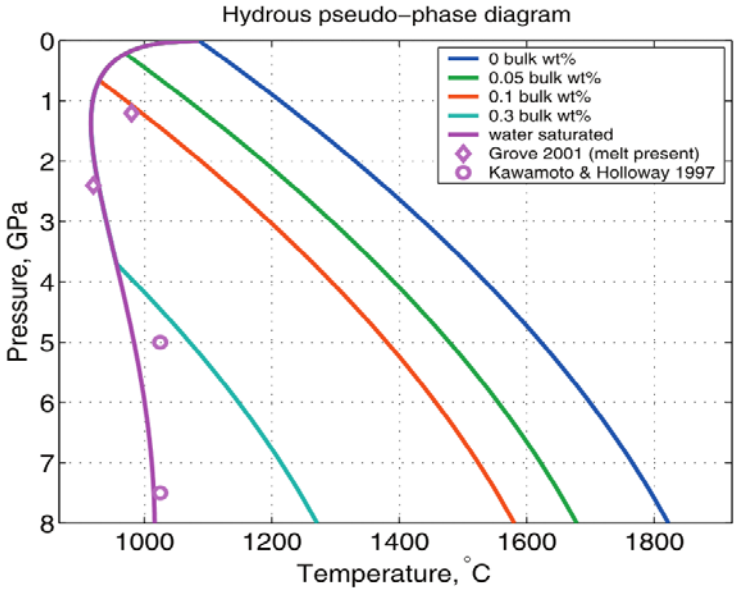


- Finite element code CITCOM *(Moresi and Gurnis, 1996)*
- Temperature and stress dependent rheology

$$\eta = A\dot{\varepsilon}_{II}^{\frac{1-n}{n}} exp\left(\frac{E^*}{nRT_{abs}}\right)$$

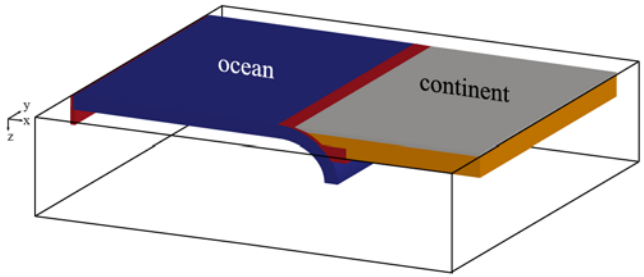
$$\eta_{by} = \frac{\tau_y}{\dot{\varepsilon}} \quad \eta_{eff} = \min(\eta, \eta_{by})$$

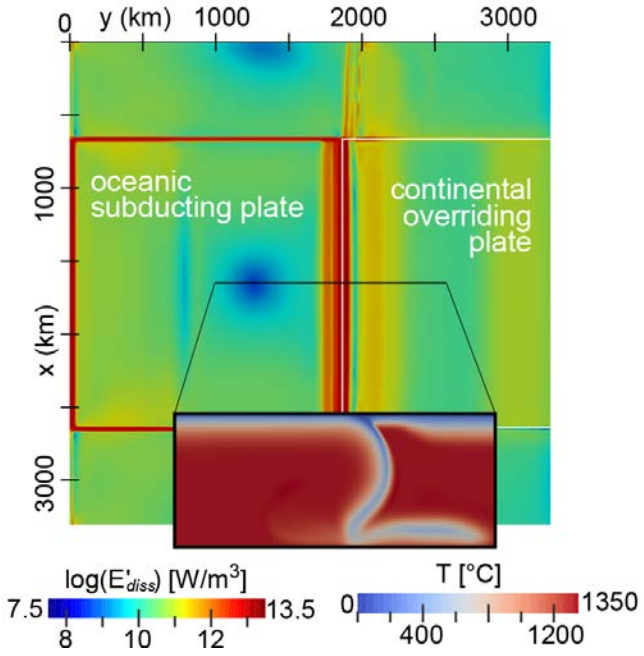
- Melting computed with the parameterization of *Katz et al. (2003)*



Back-arc basin formation

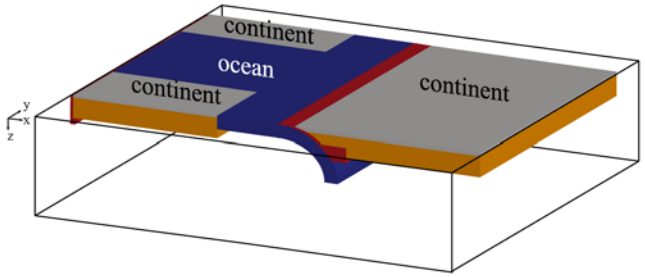
Only oceanic subduction

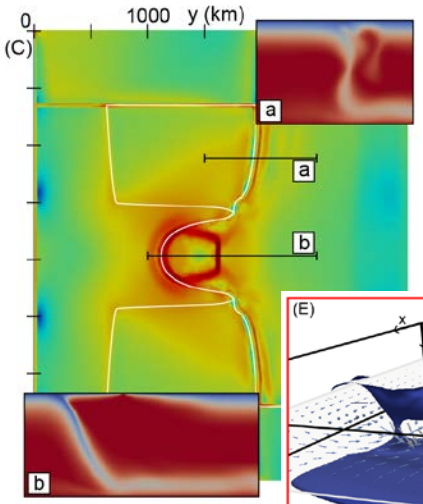




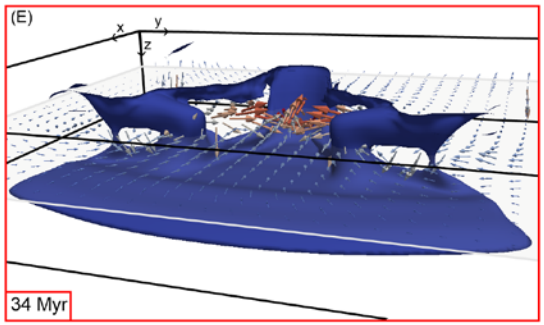
- **No backarc basin formation**
- **No episodes of fast retreat**

Along trench variations



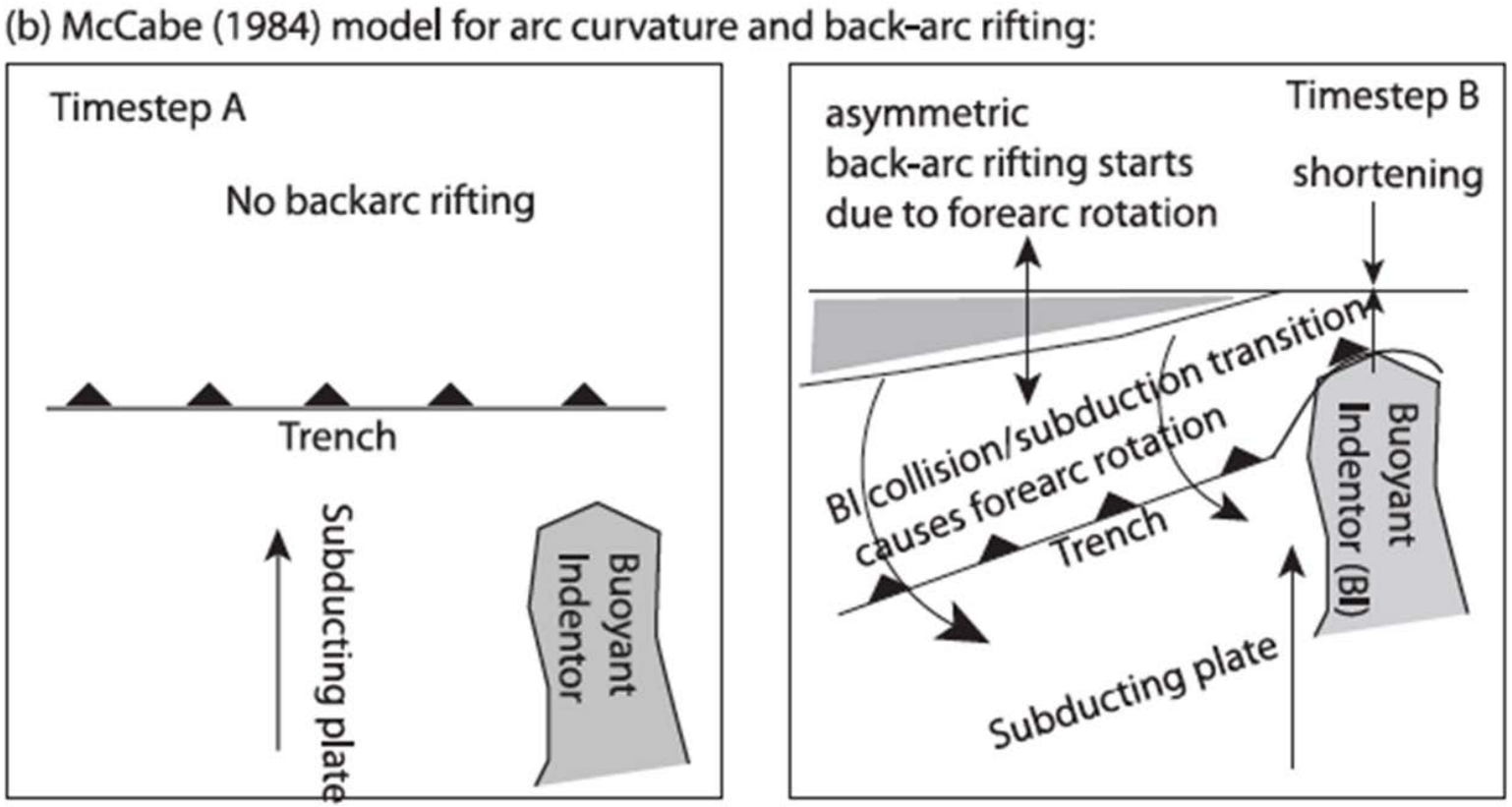


Magni et al., 2014

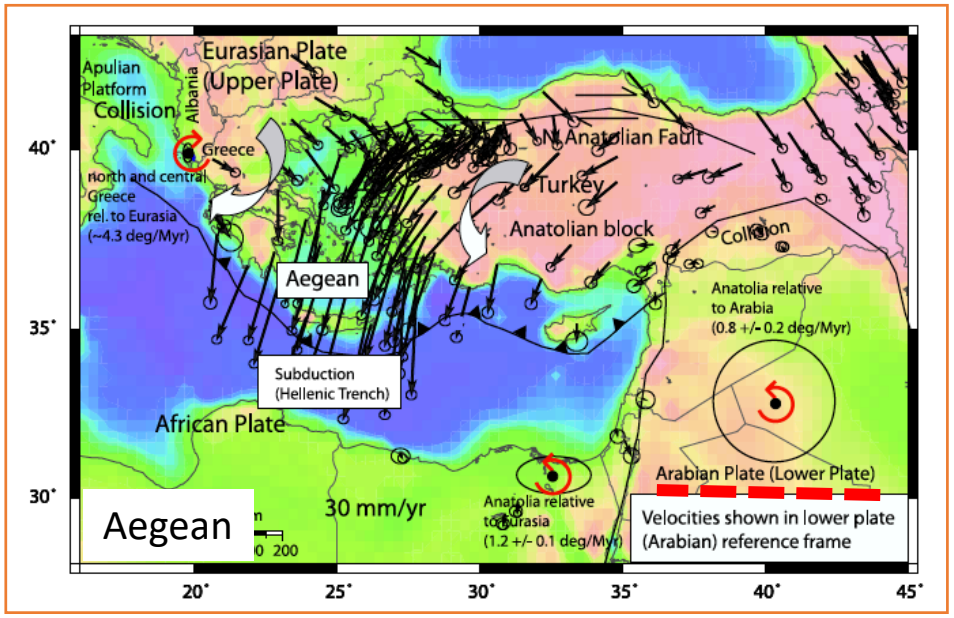


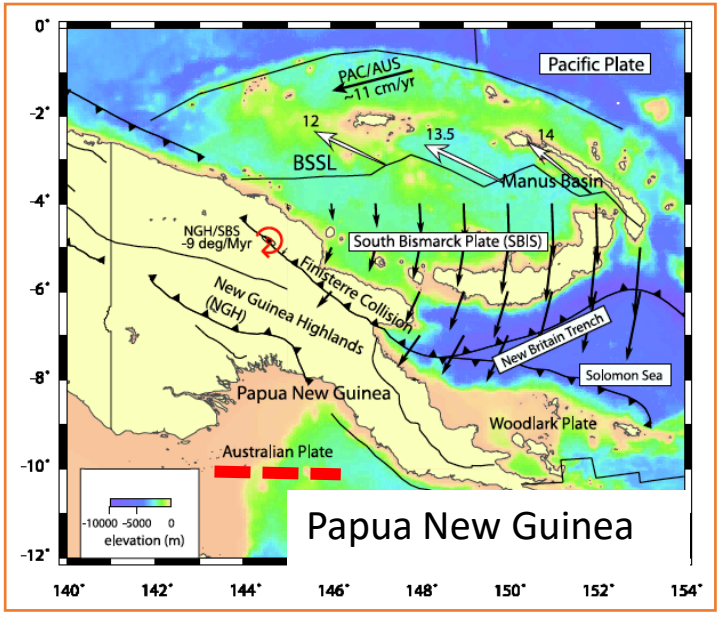
- **Backarc basin formation** ✓ **YES**
- **Slab windows formation** ✓ **YES**
- **Two episodes of fast retreat**

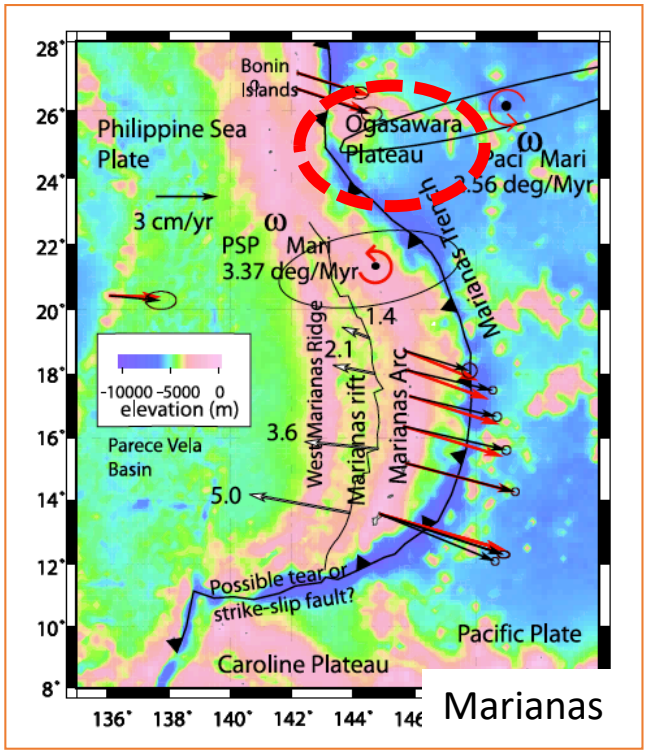
The occurrence of continental collision nearby oceanic subduction is important to trigger the formation of a back-arc basin

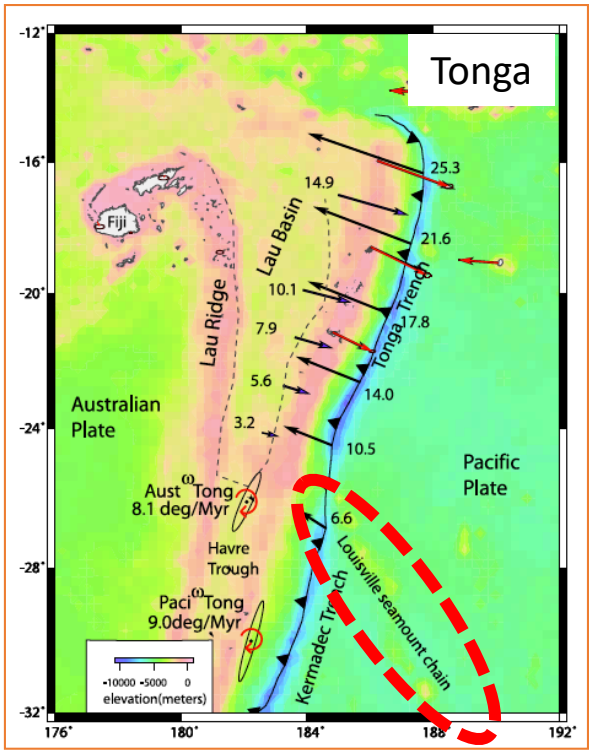


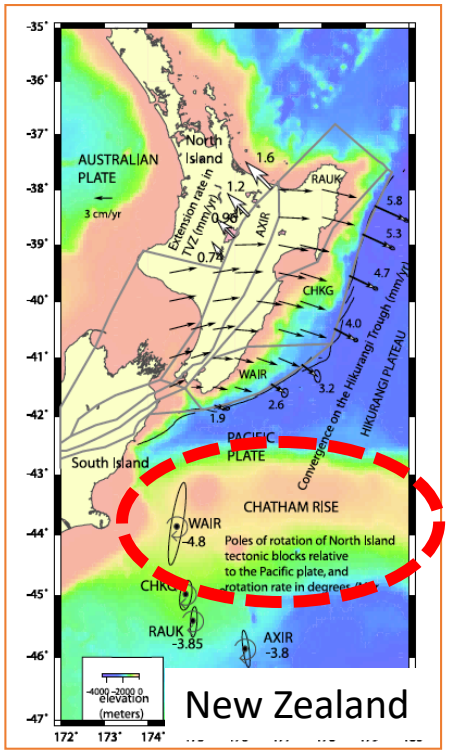
Wallace et al., 2009



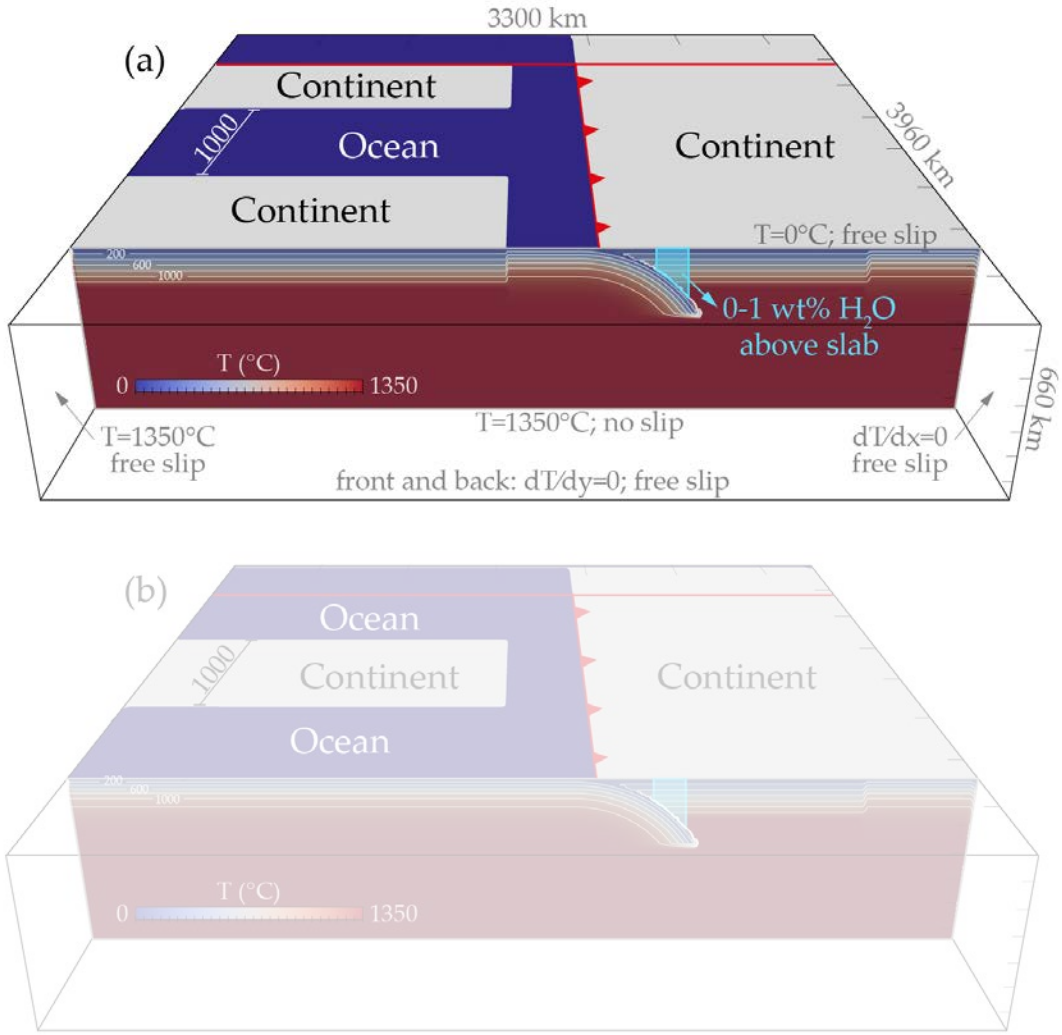




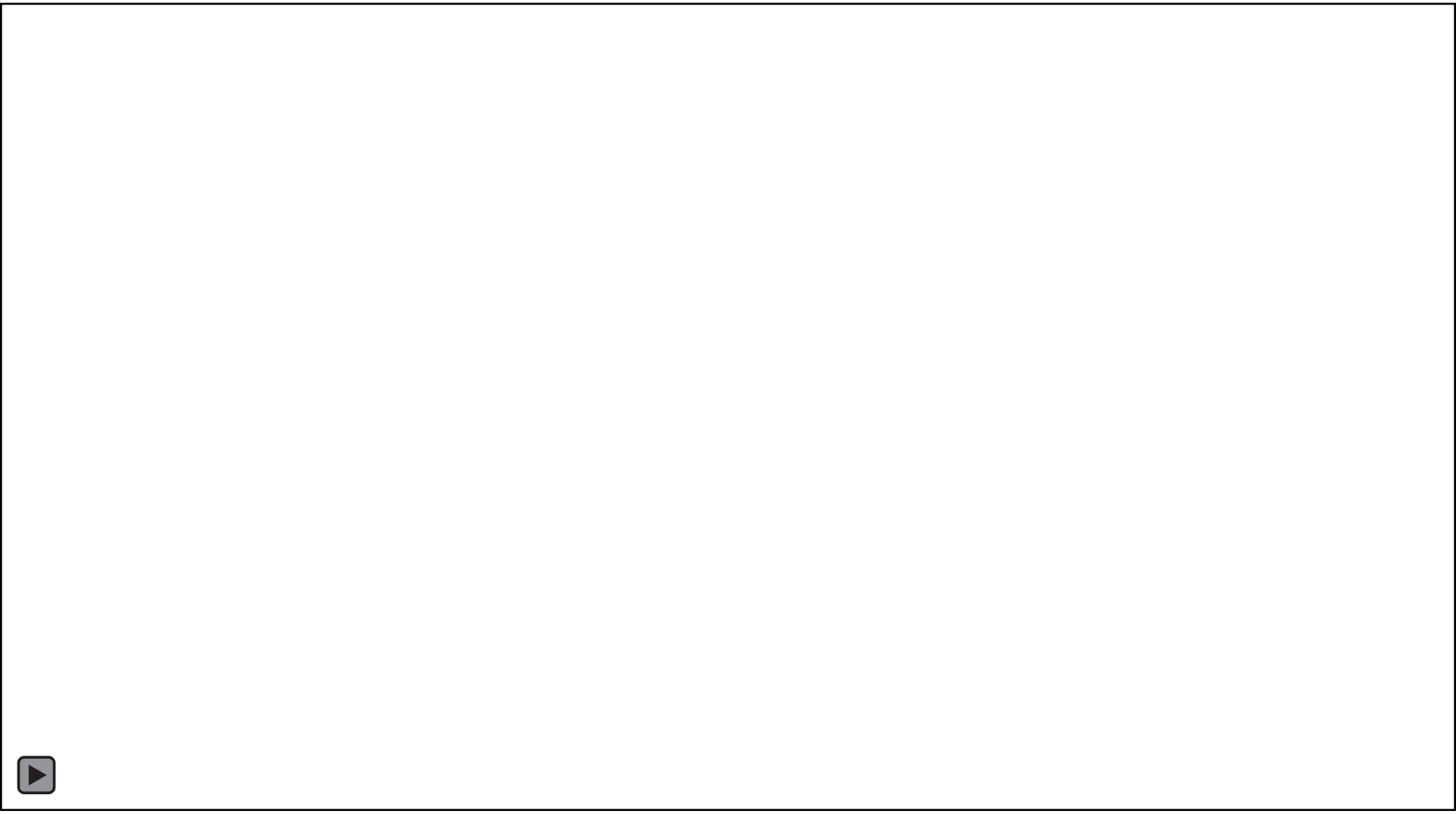




Wallace et al., 2009

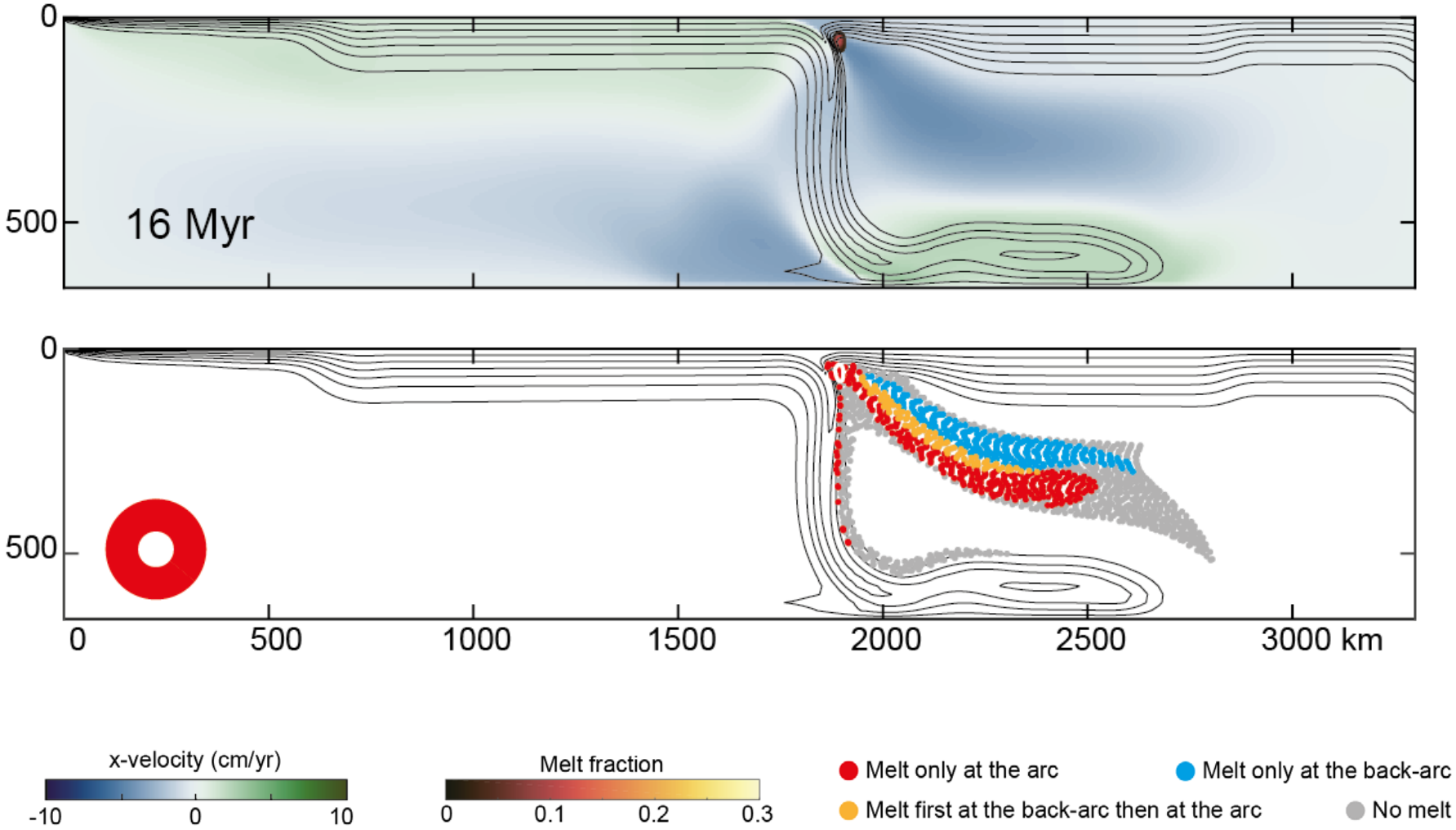

(a)
3300 km
Continent
Ocean
Continent
1000
Continent
3960 km
T=0°C; free slip
200
600
1000
0-1 wt% H2O
above slab
T (°C)
0
1350
660 km
T=1350°C
free slip
T=1350°C; no slip
dT/dx=0
free slip
front and back: dT/dy=0; free slip
(b)
Ocean
Continent
Continent
1000
Ocean
200
600
1000
T (°C)
0
1350

Melt production



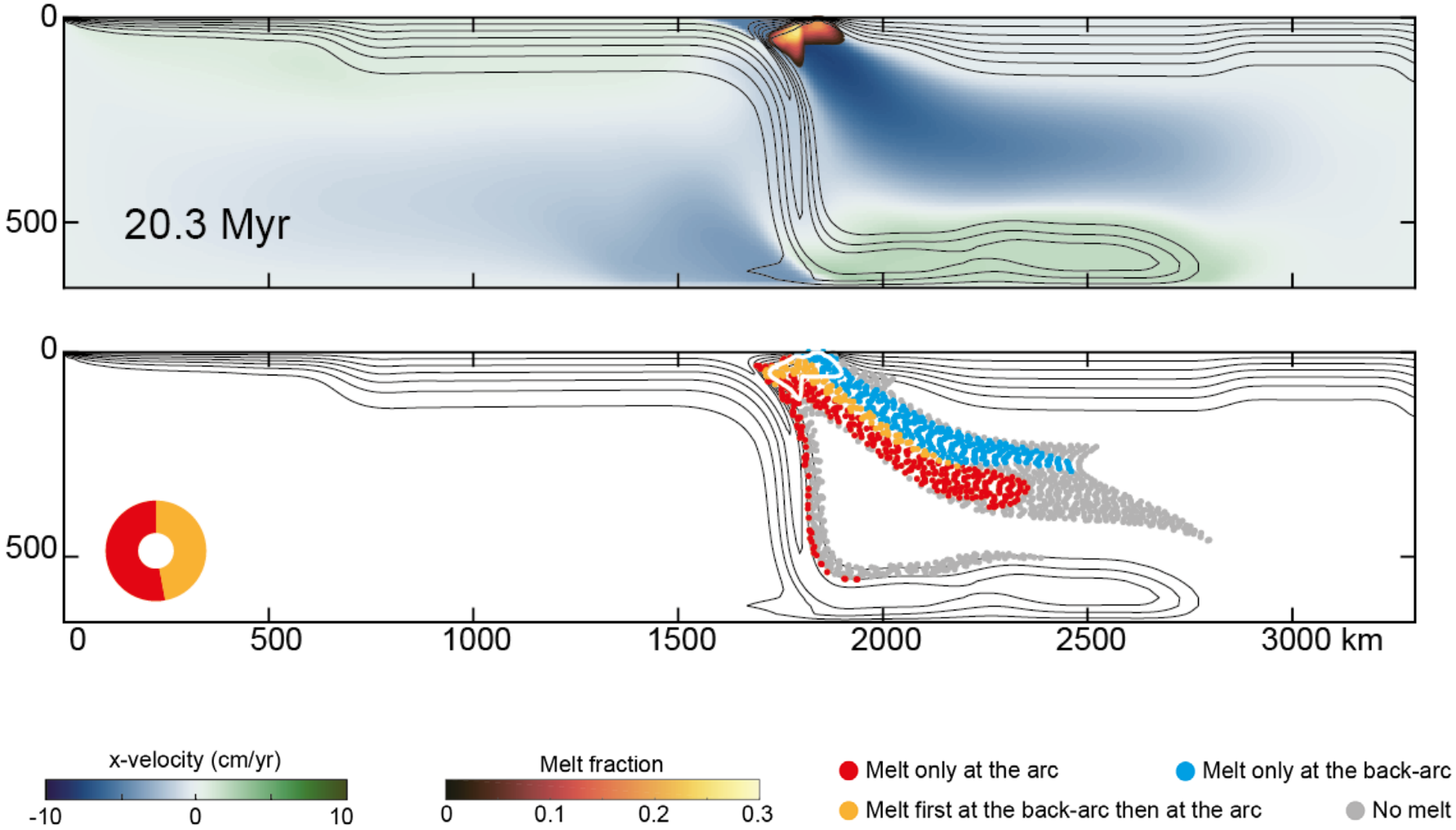
Link to video:
https://www.sciencedirect.com/science/article/pii/S0012821X19302766#ec0020

Source of mantle melting



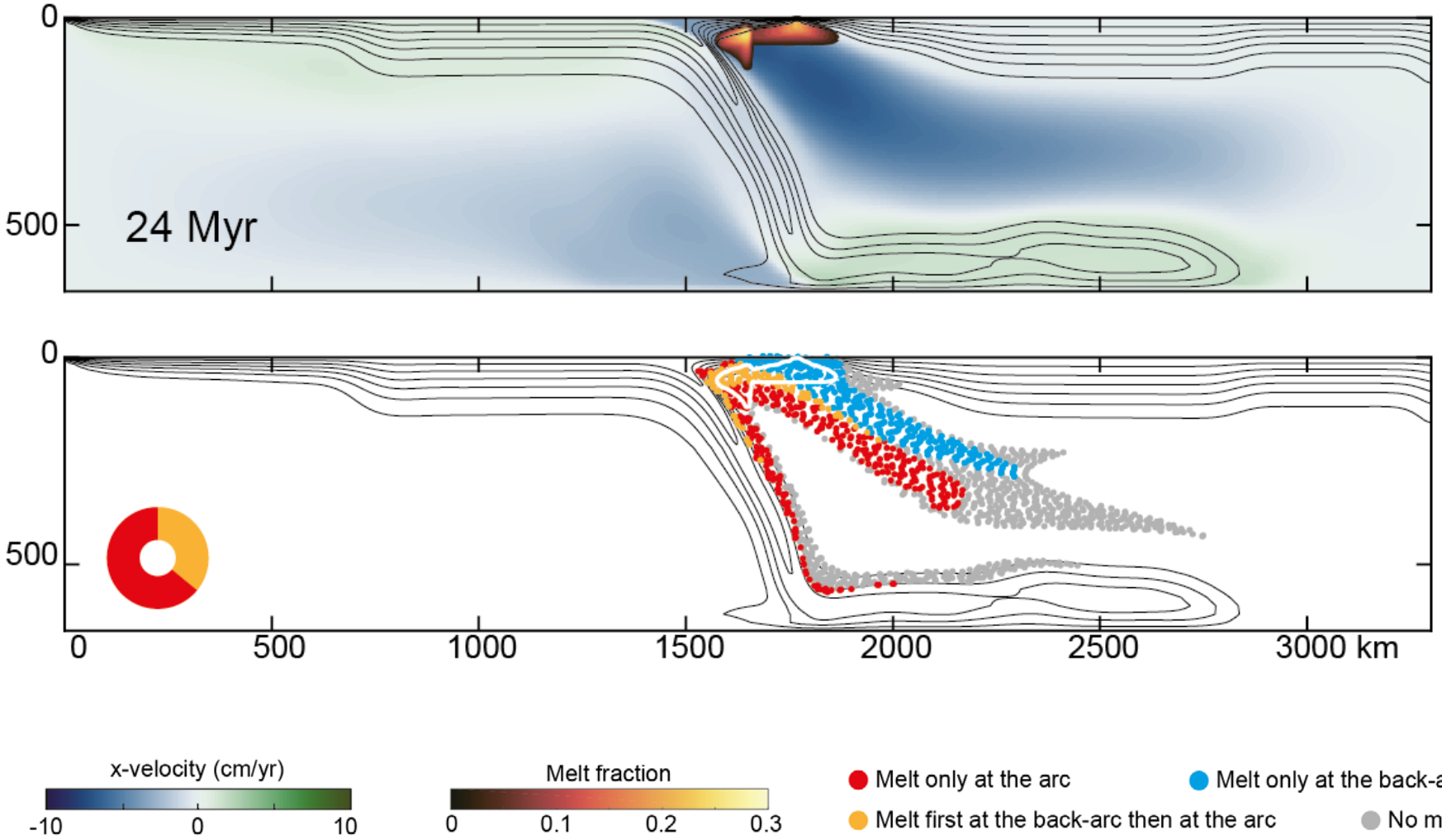
Magni, EPSL, 2019

Source of mantle melting



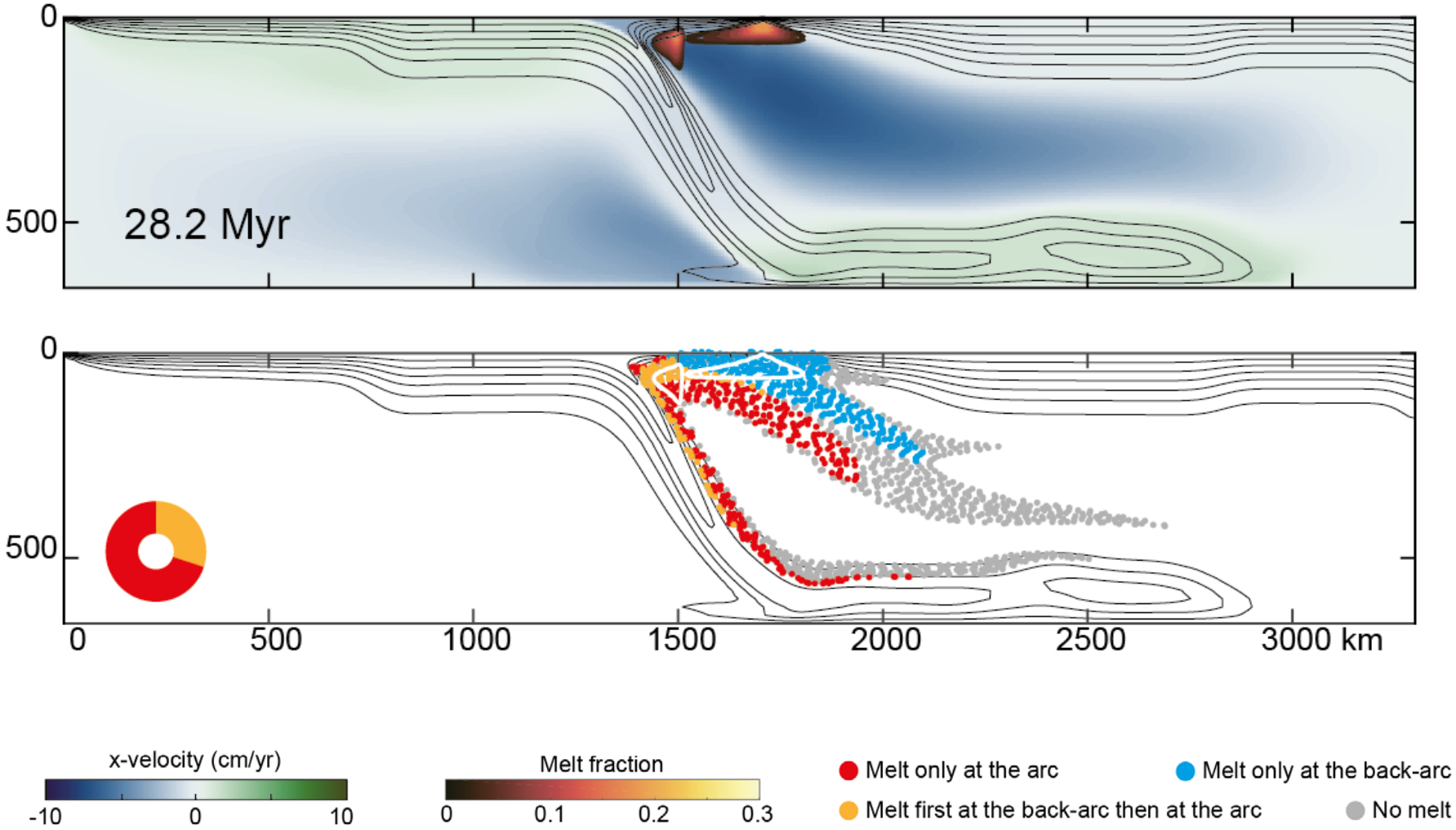
Magni, EPSL, 2019

Source of mantle melting



Magni, EPSL, 2019

Source of mantle melting



Magni, EPSL, 2019

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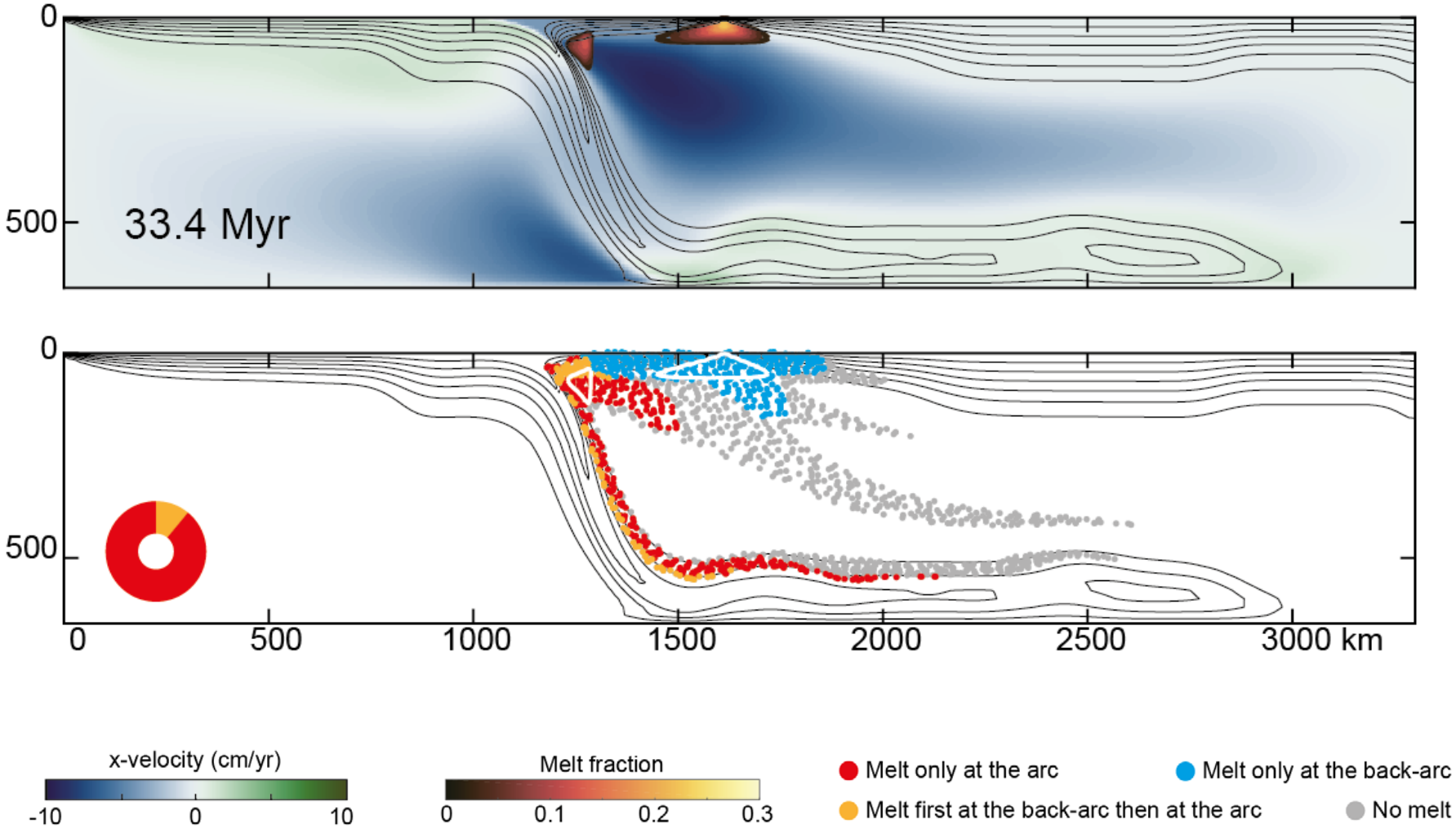

Magni, EPSL, 2019

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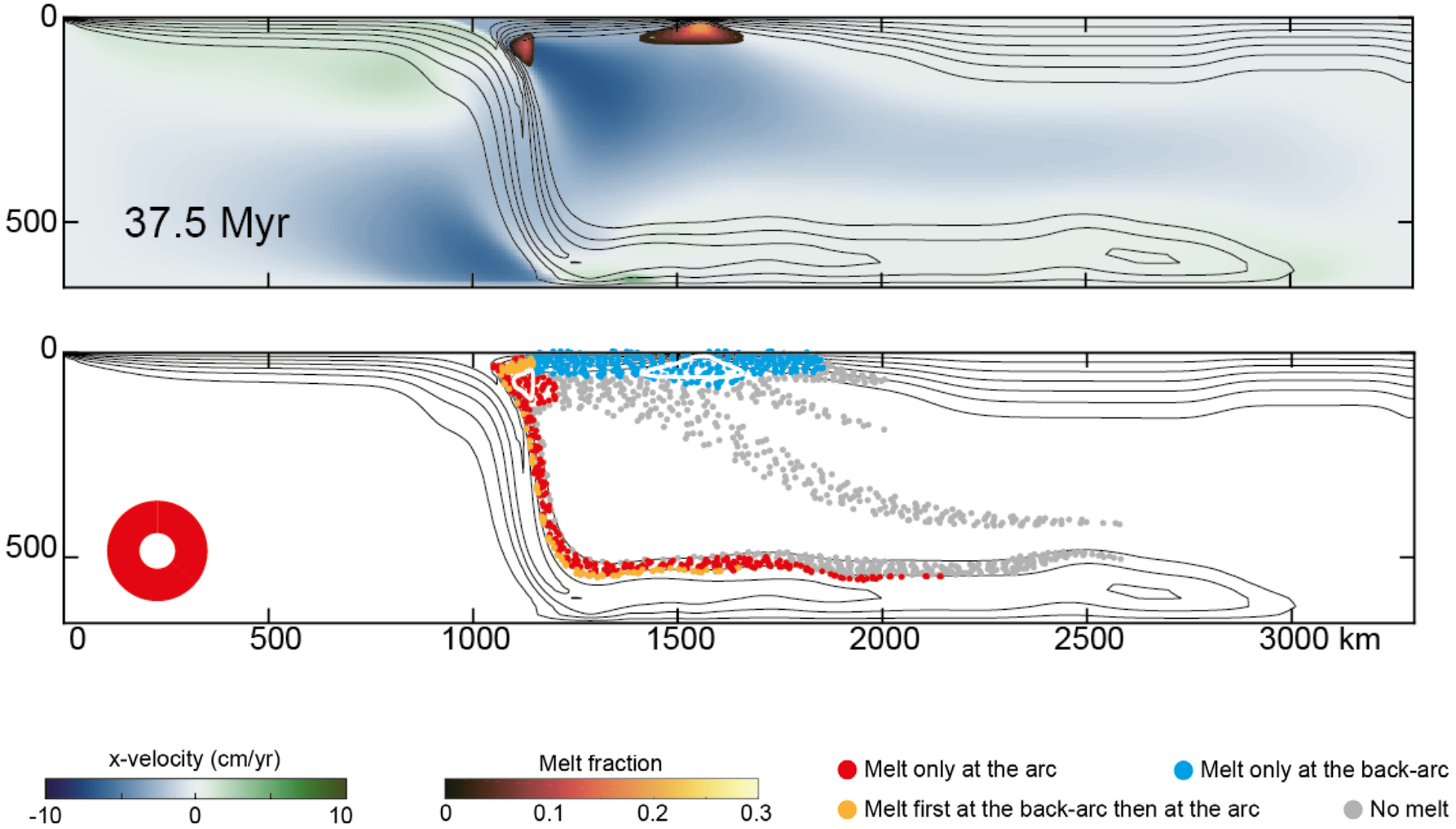

Magni, EPSL, 2019

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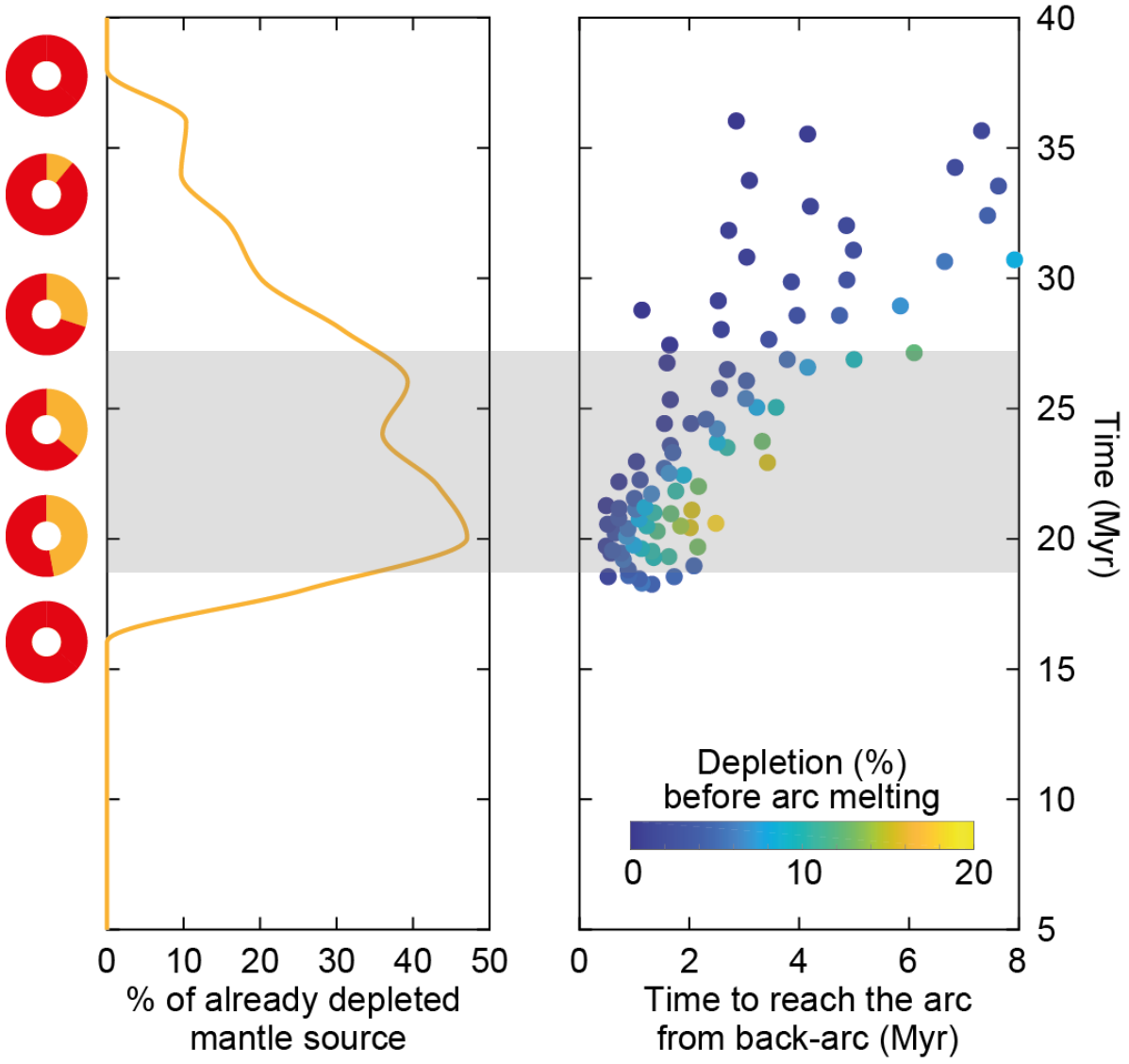
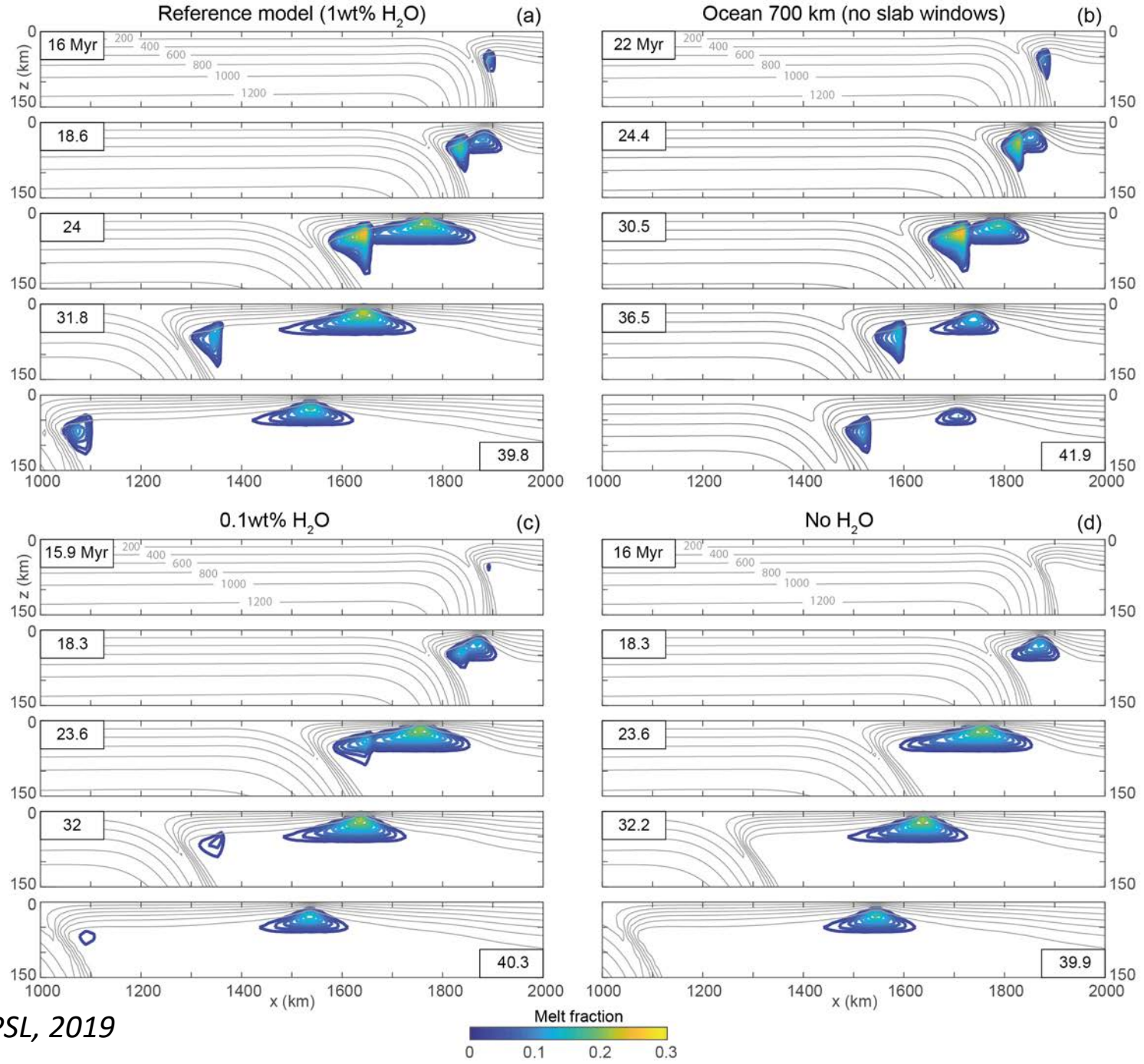


Magni, EPSL, 2019



Magni, EPSL, 2019

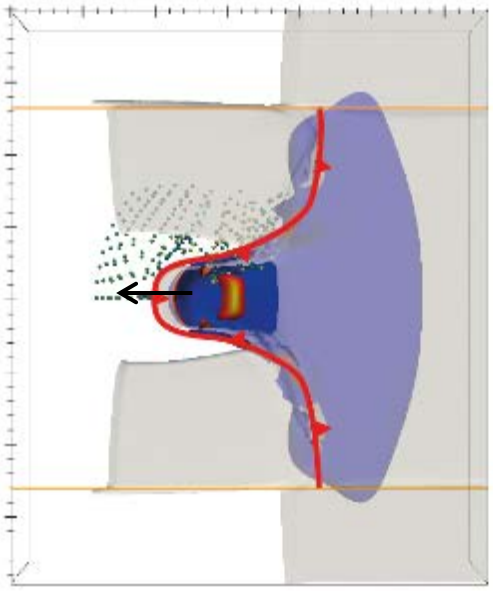
3D mantle flow

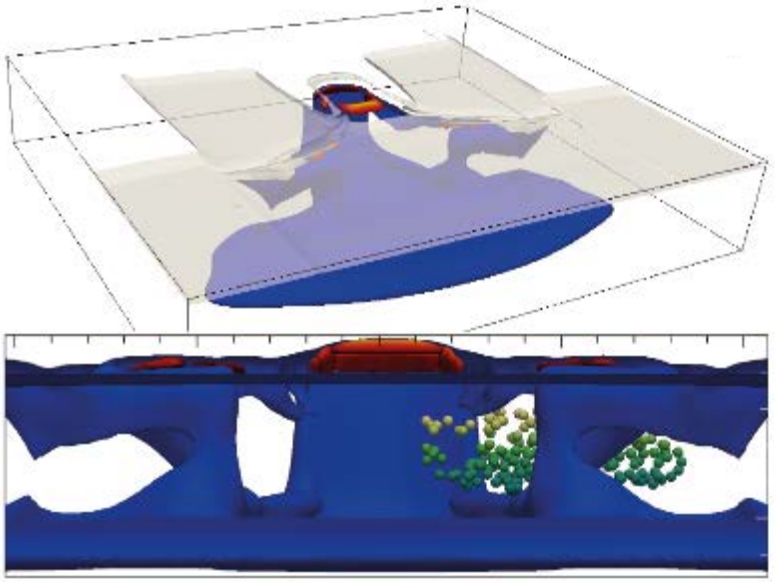
Link to video:
https://www.sciencedirect.com/science/article/pii/S0012821X19302766#ec0020

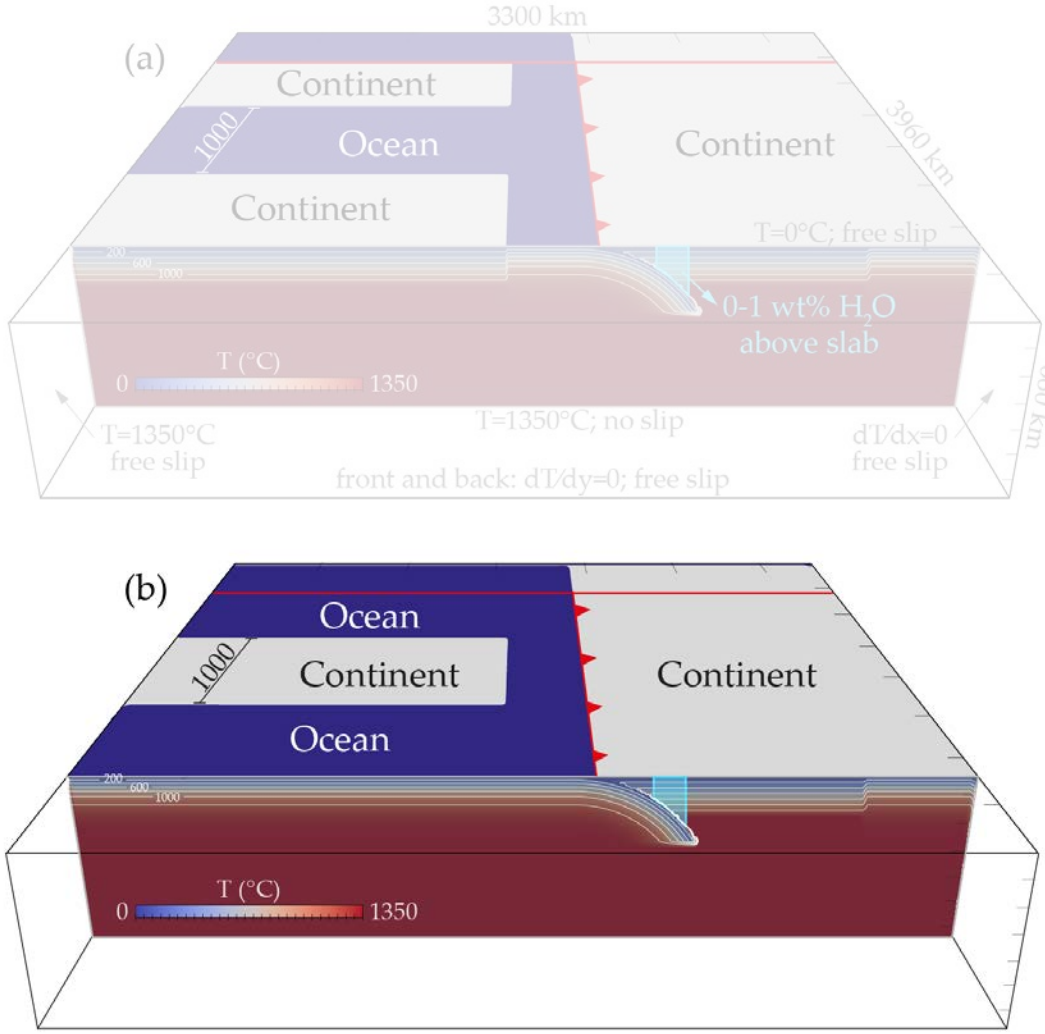
3D mantle flow

Slab window

Sub-horizontal mantle flow through slab window






(a)
3300 km
Continent
Ocean
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1000
Continent
3960 km
T=0°C; free slip
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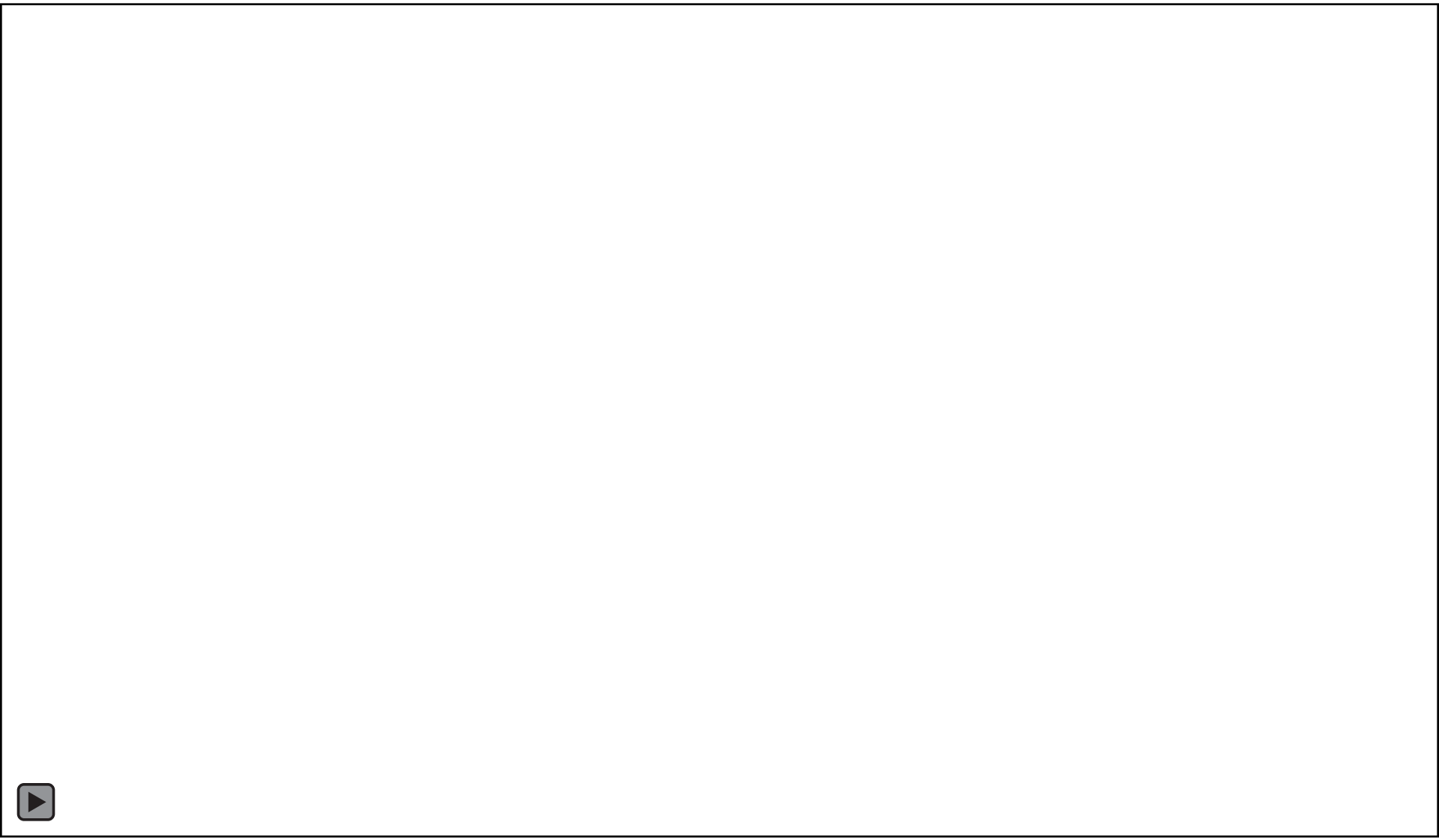
600
1000
0-1 wt% H2O
above slab
T (°C)
0
1350
660 km
T=1350°C
free slip
T=1350°C; no slip
dT/dx=0
free slip
front and back: dT/dy=0; free slip
(b)
Ocean
Continent
Continent
1000
Ocean
200
600
1000
T (°C)
0
1350

3D mantle flow

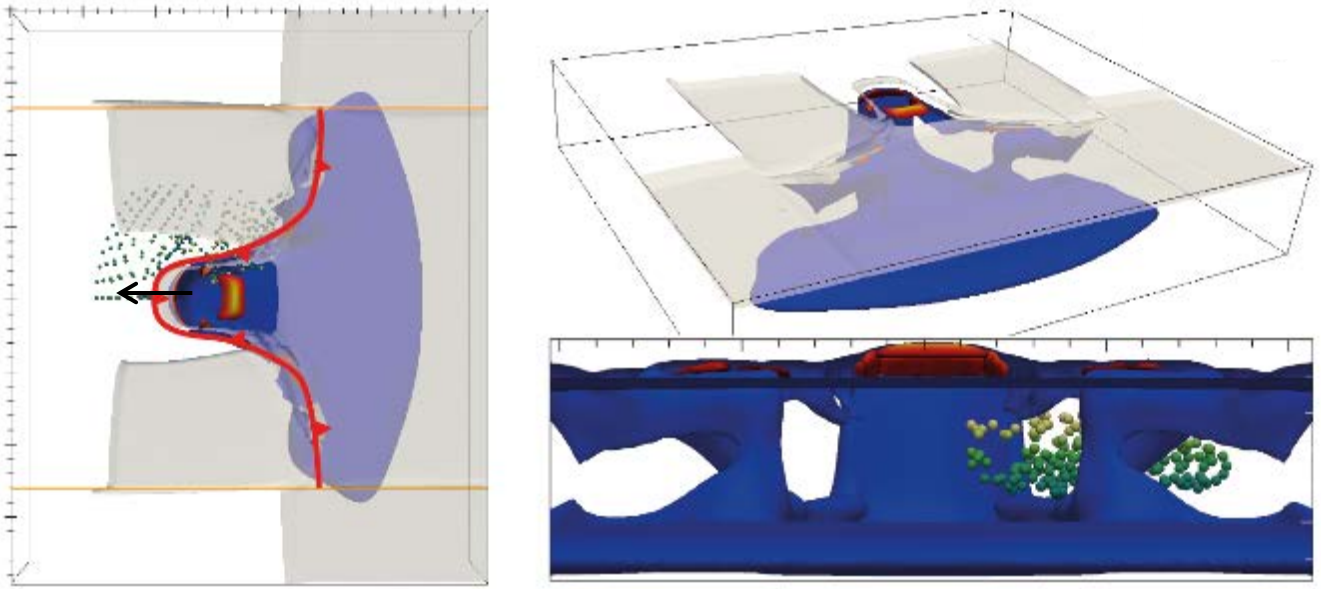


Link to video:
https://www.sciencedirect.com/science/article/pii/S0012821X19302766#ec0040

3D mantle flow

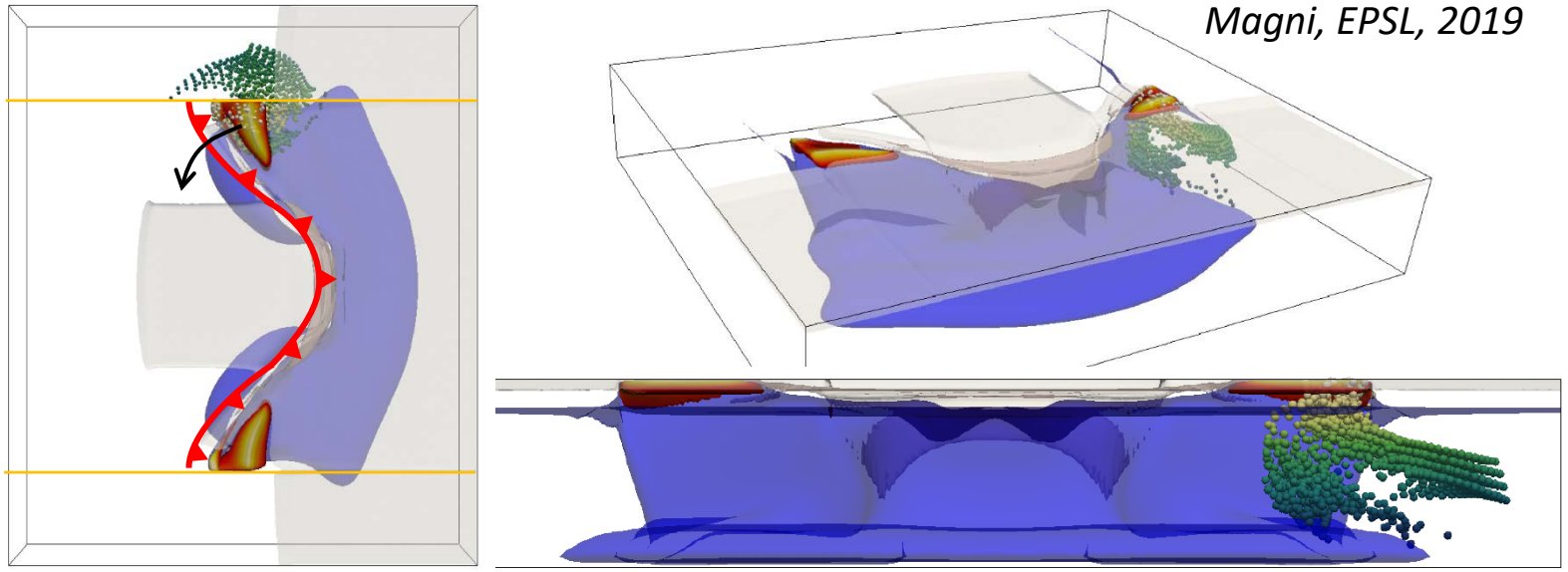
Slab window

Sub-horizontal mantle flow through slab window



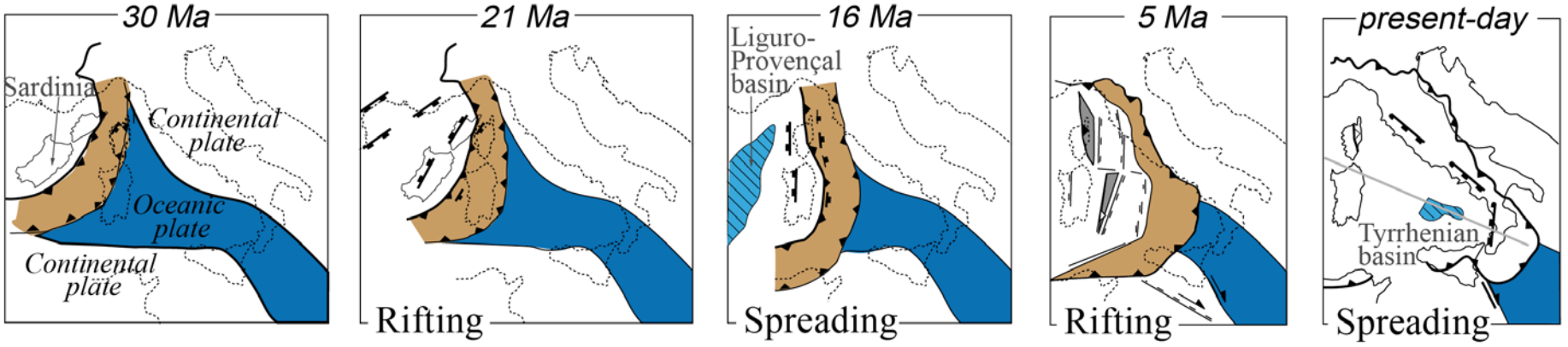
Slab edge

Toroidal flow + strong upwelling component around slab edge

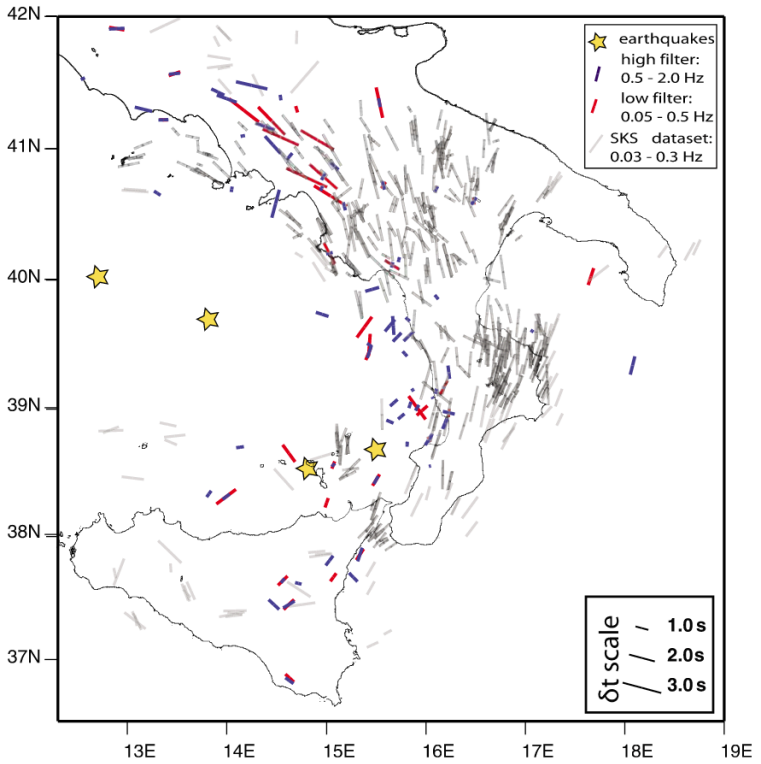


Magni, EPSL, 2019

Toroidal flow *(some thoughts out loud)*

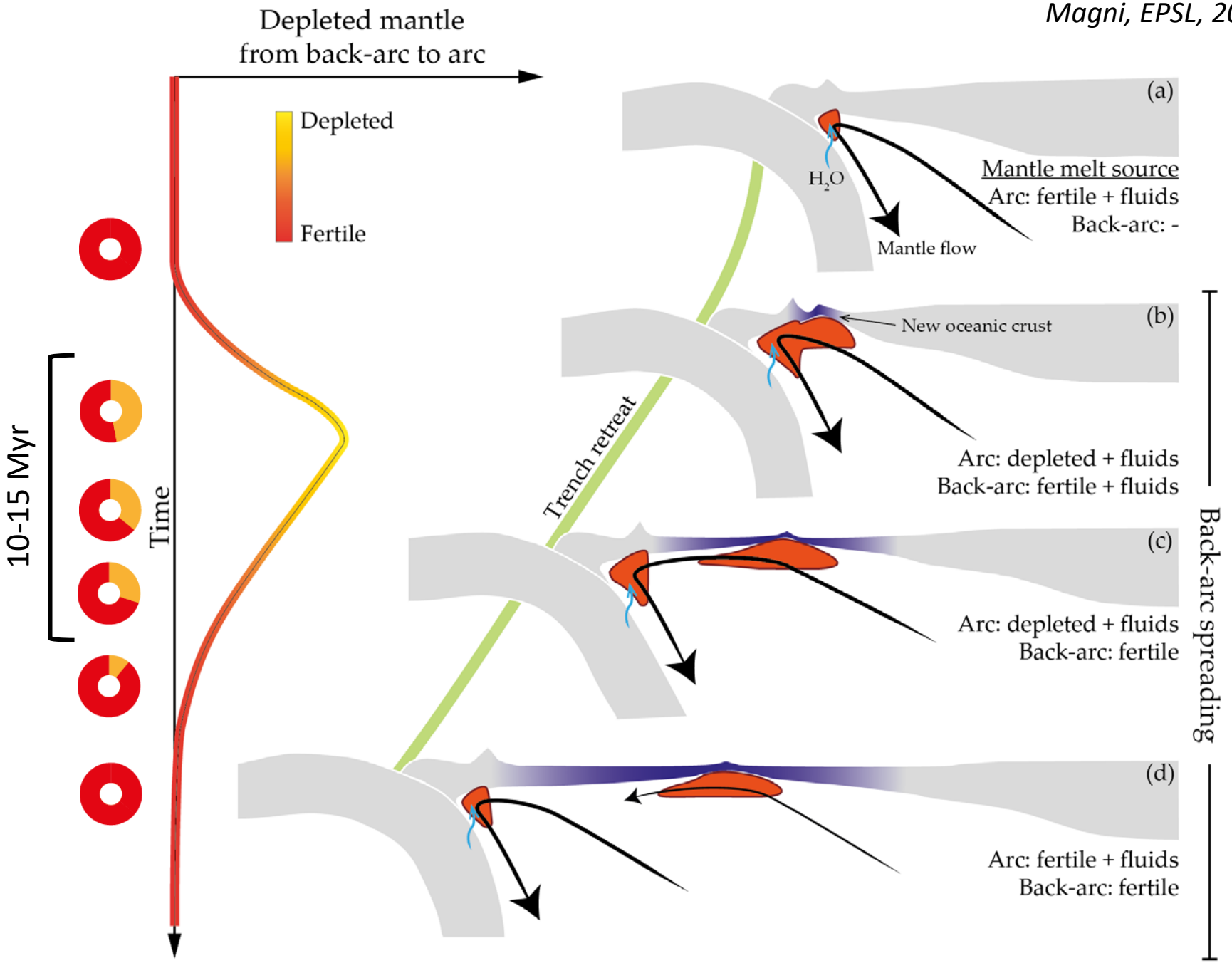


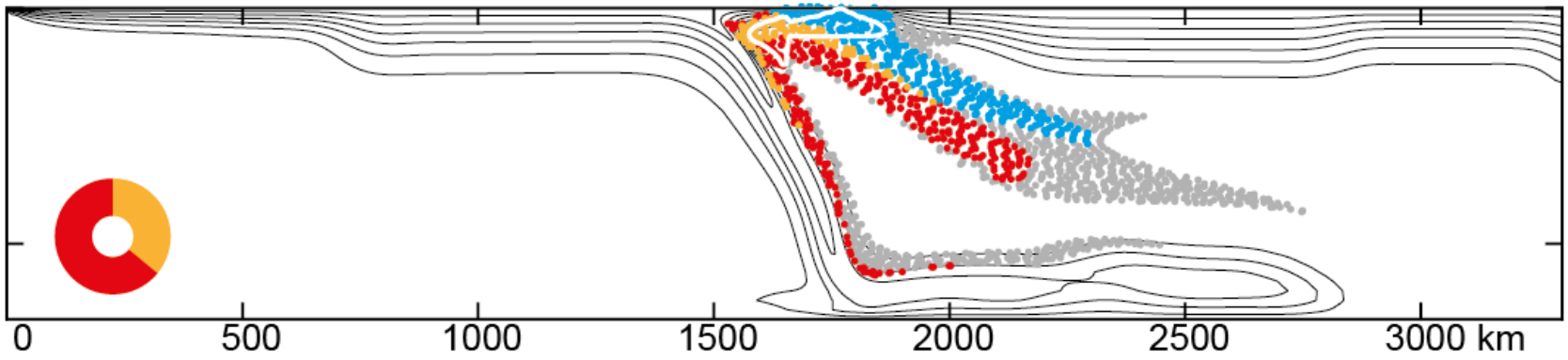
- Toroidal mantle flow is suggested to occur around the Calabrian slab, on both sides.
- The upwelling component of the flow can be different at the African margin and the Apennines.
- Toroidal flow does not necessarily bring fertile mantle to the arc and back-arc melting regions



Baccheschi et al., 2011

Magni, EPSL, 2019





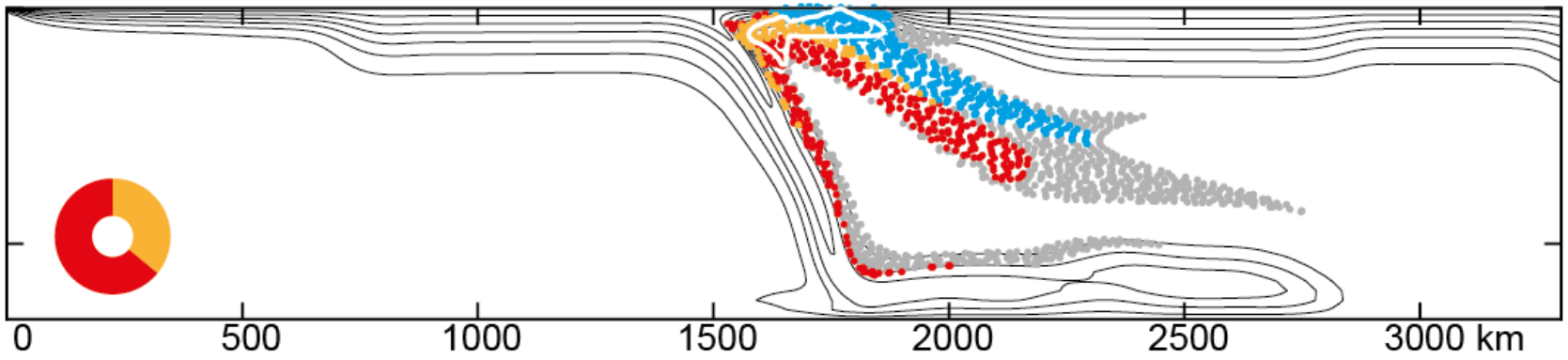
Large amount of highly depleted mantle flows in the mantle wedge

⇩

Much harder to produce melt beneath the arc

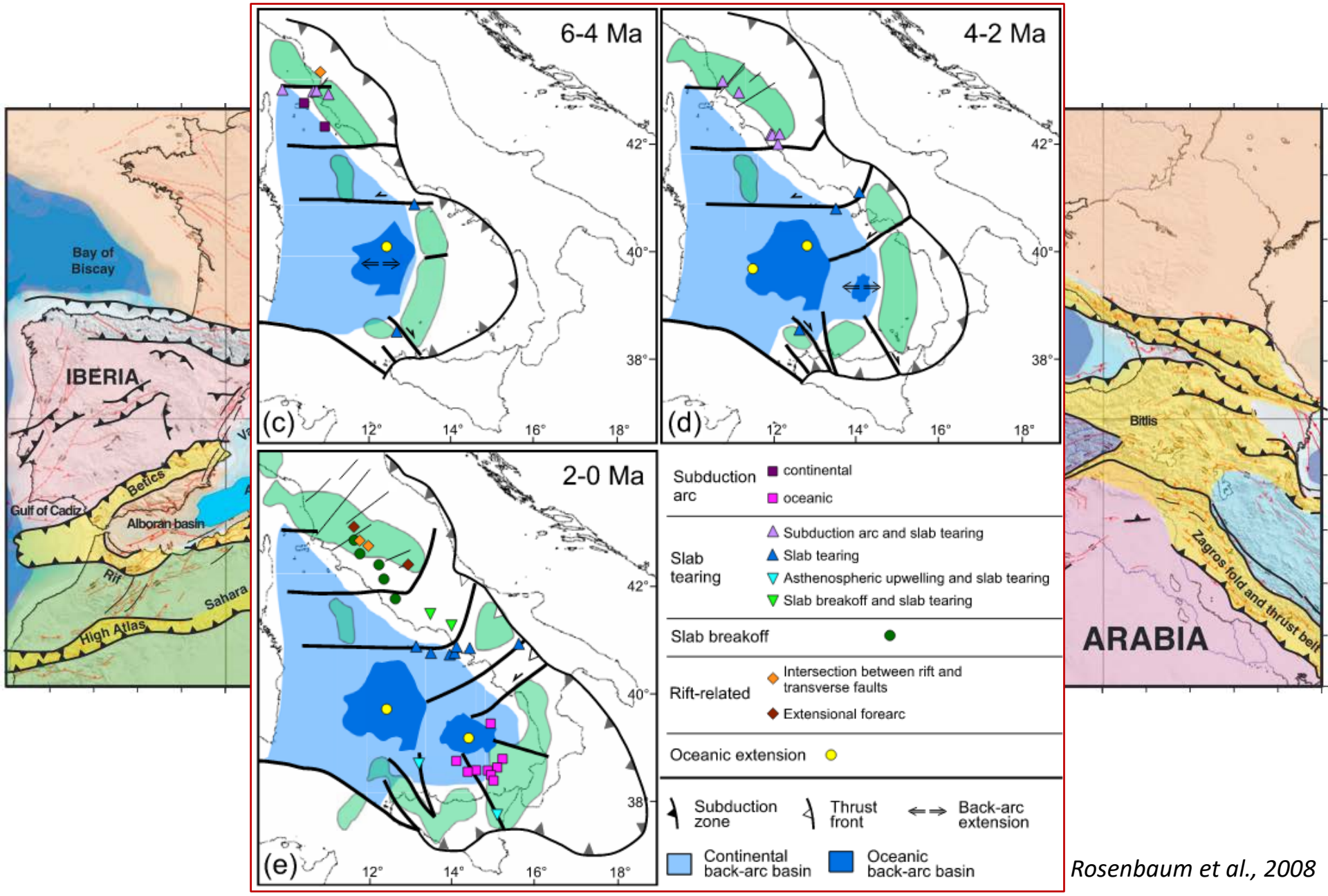
⇩

Decrease/stop or compositional change of magmatic activity at the arc



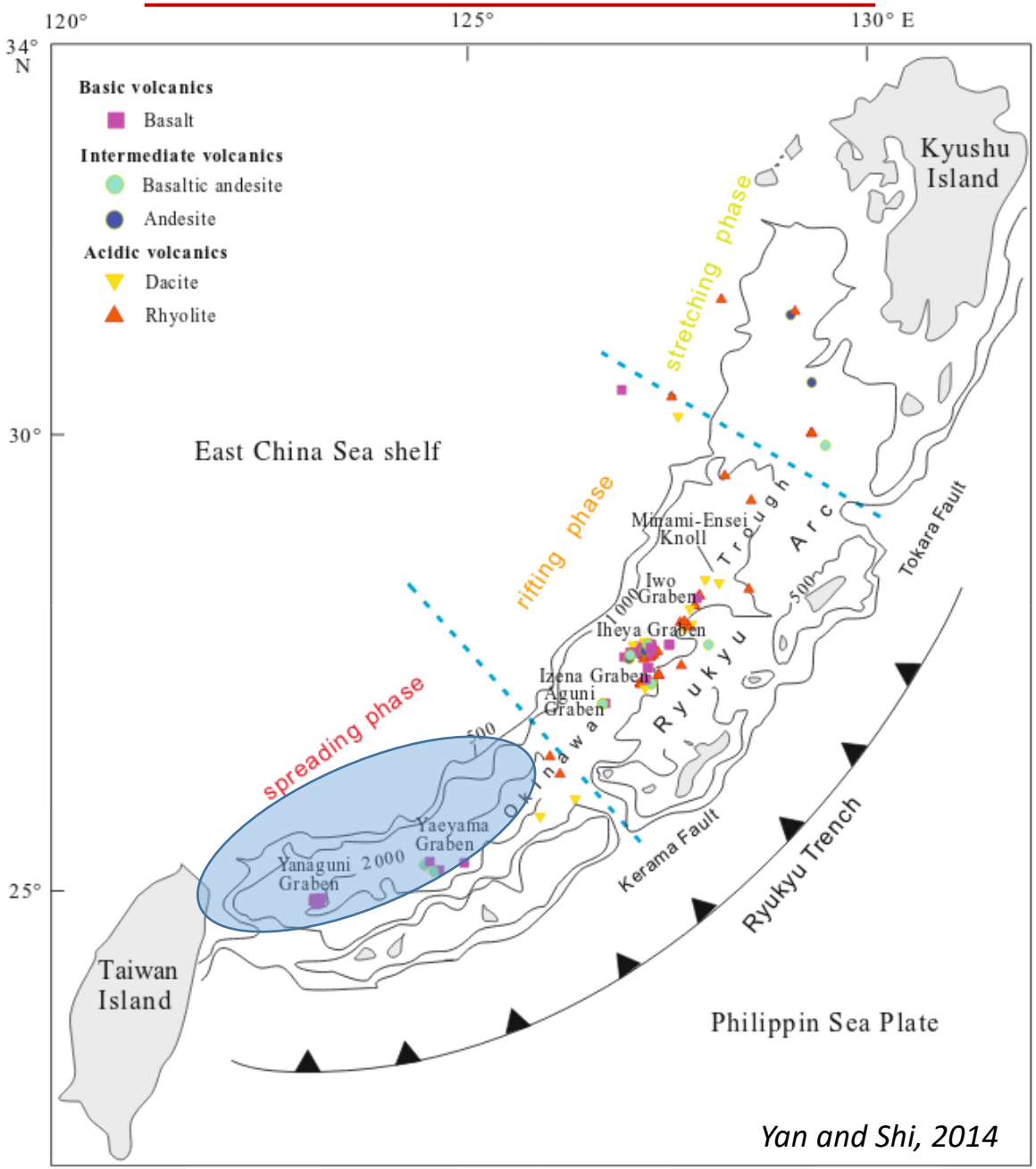
Do we see this in volcanic arcs today?

Tyrrhenian basin



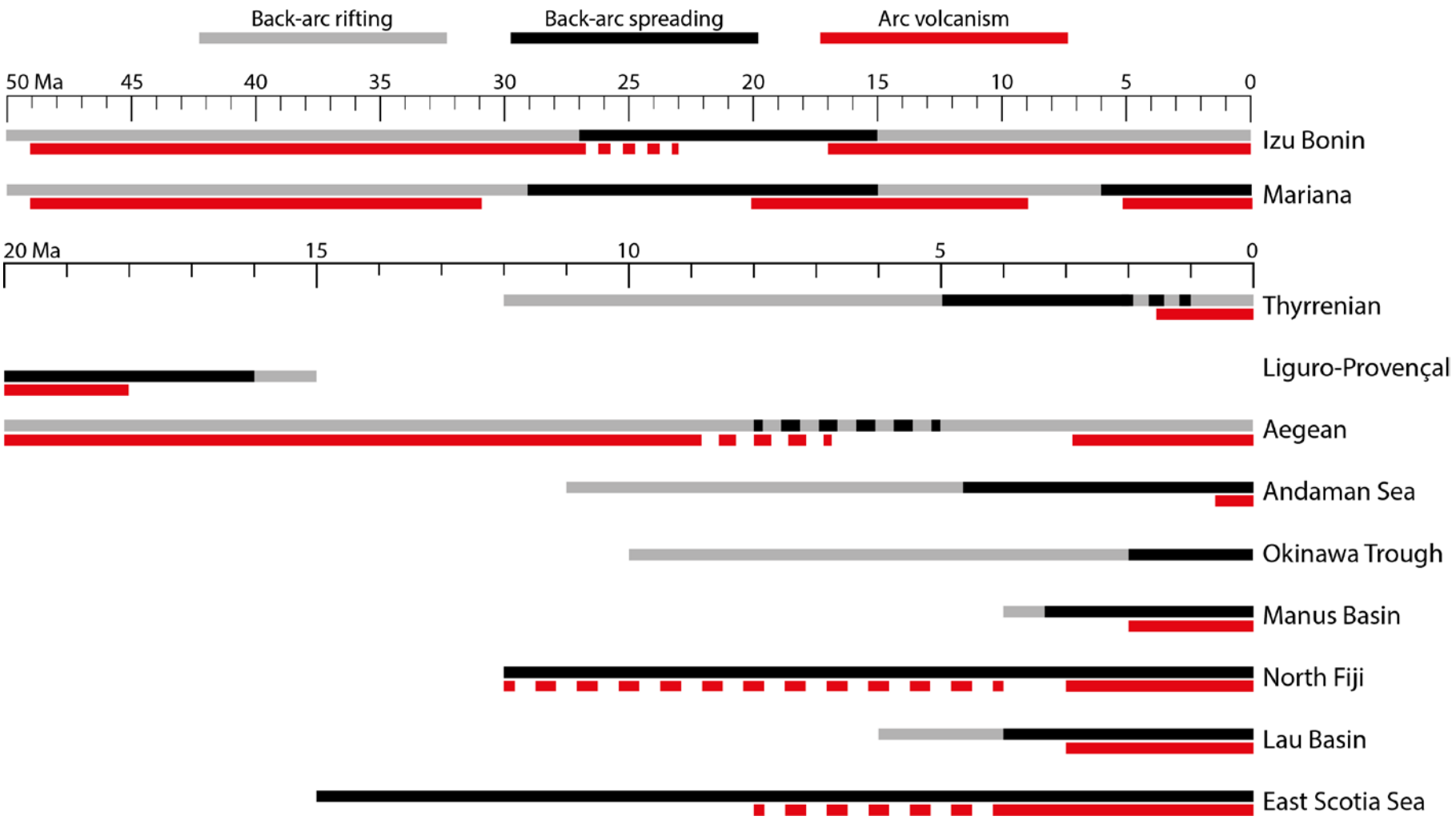
Rosenbaum et al., 2008

Okinawa Trough

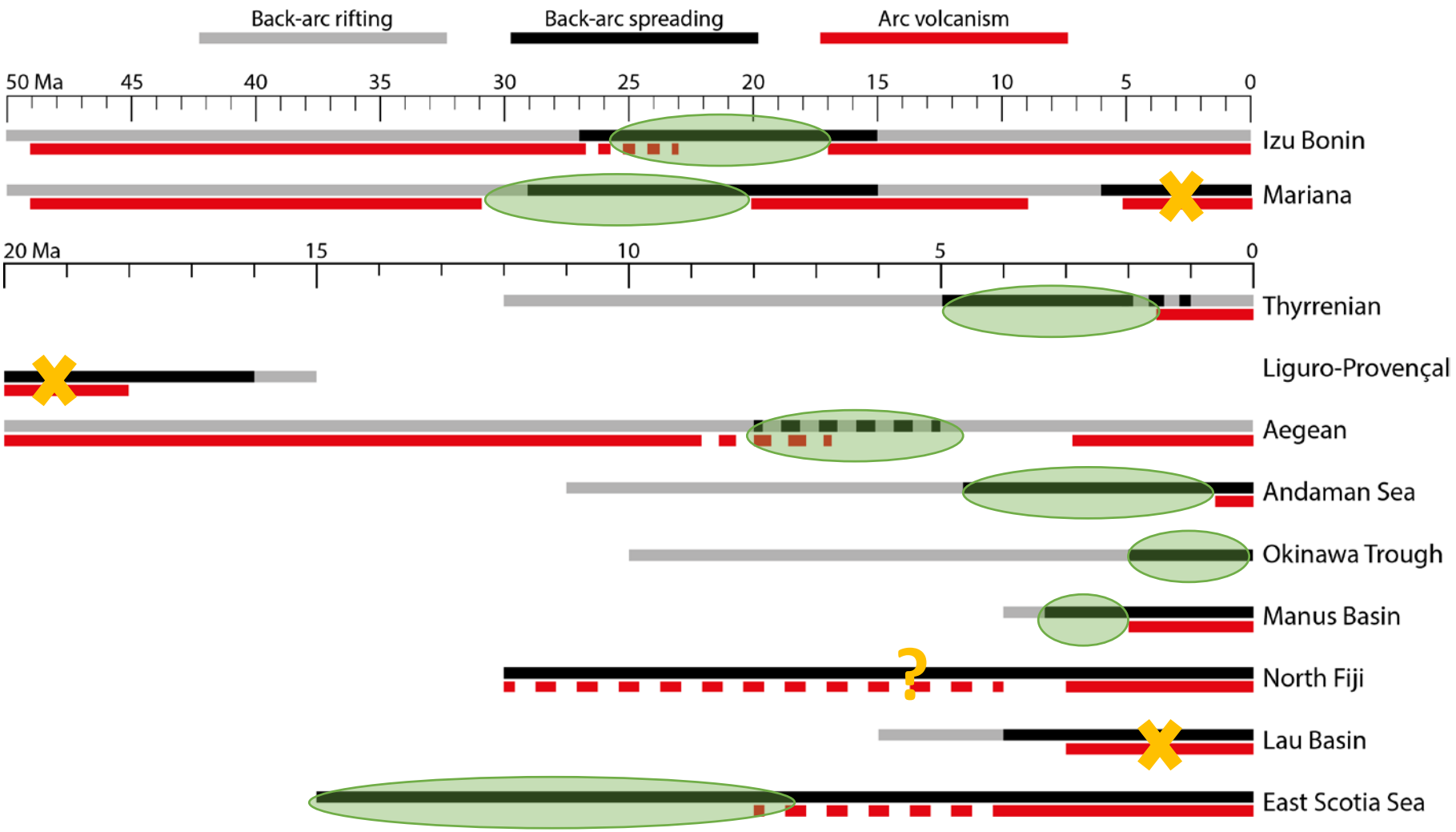


Yan and Shi, 2014

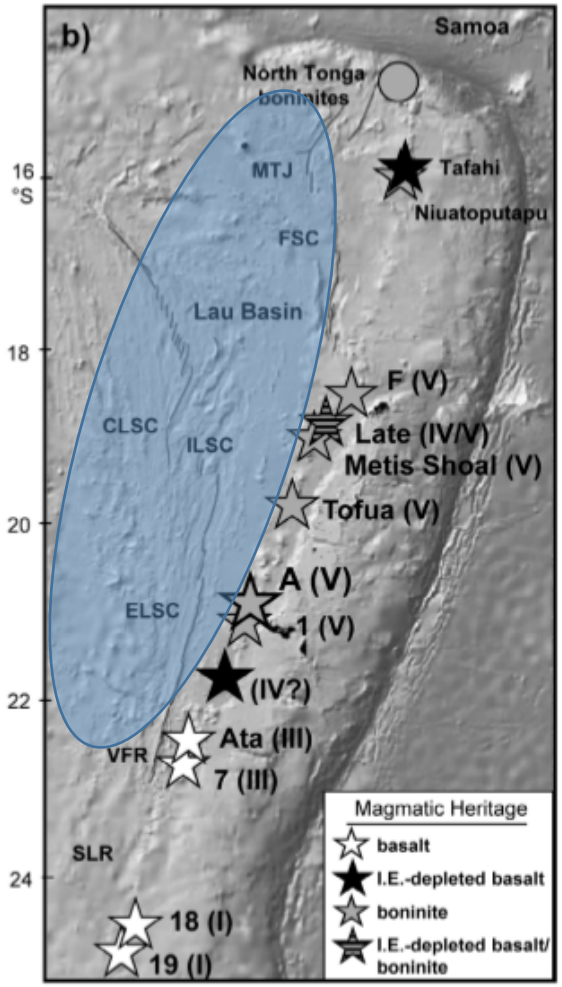
Timing of arc and back-arc magmatic activity



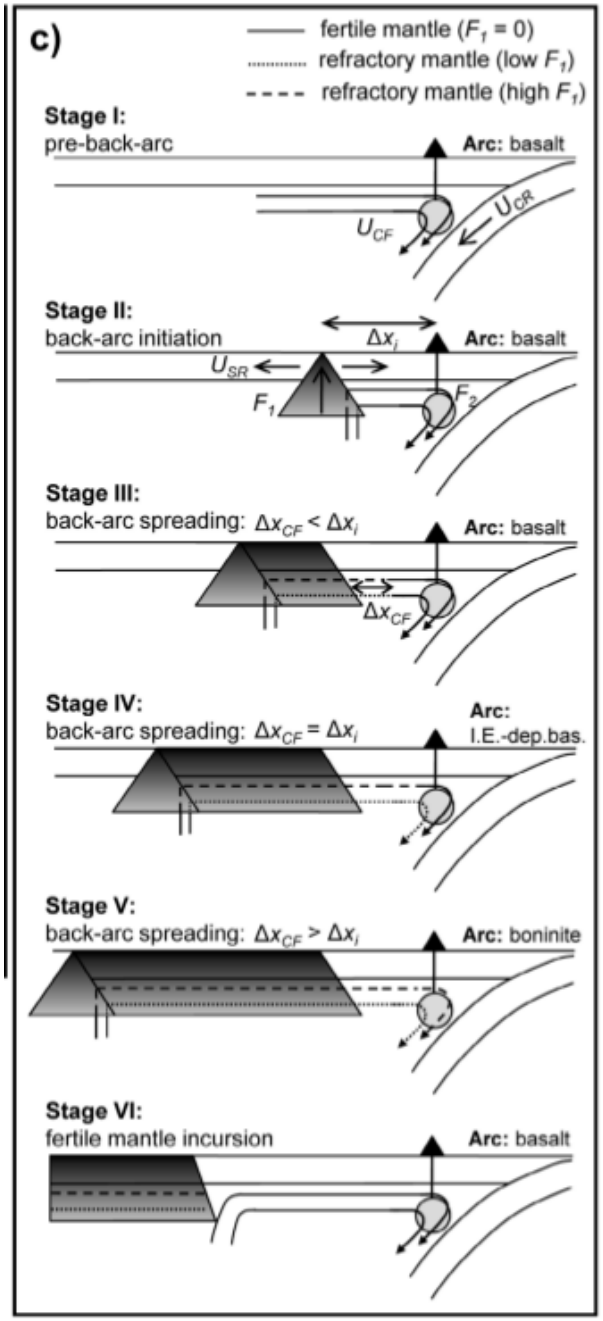
Timing of arc and back-arc magmatic activity



Lau basin



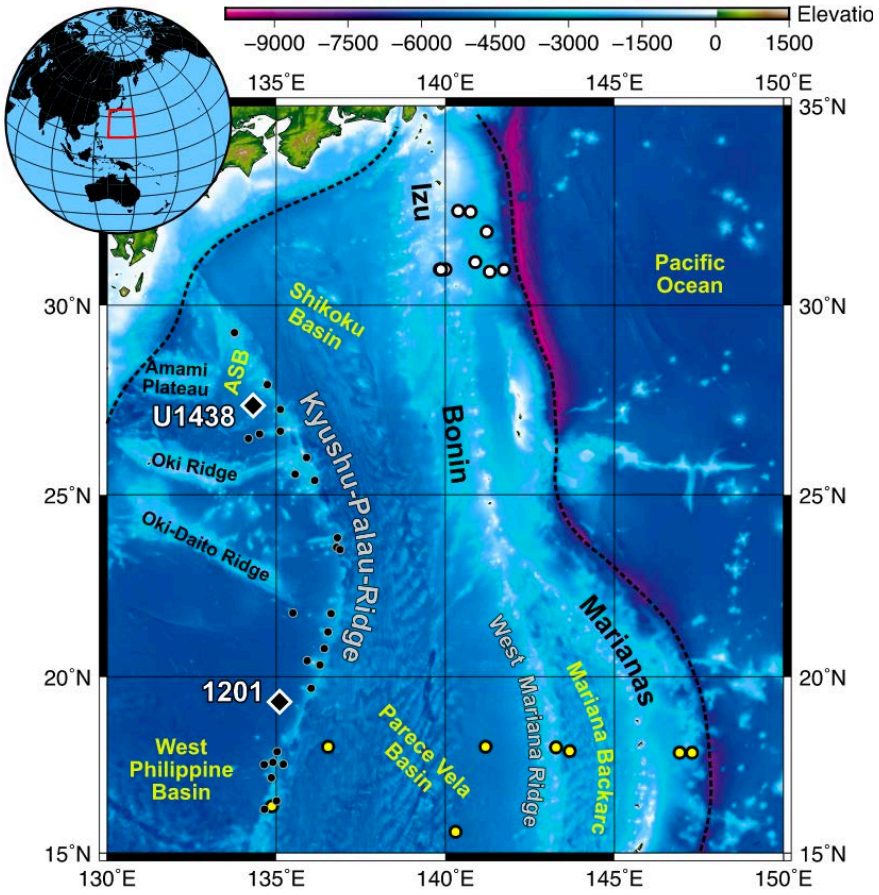
Cooper et al., 2010



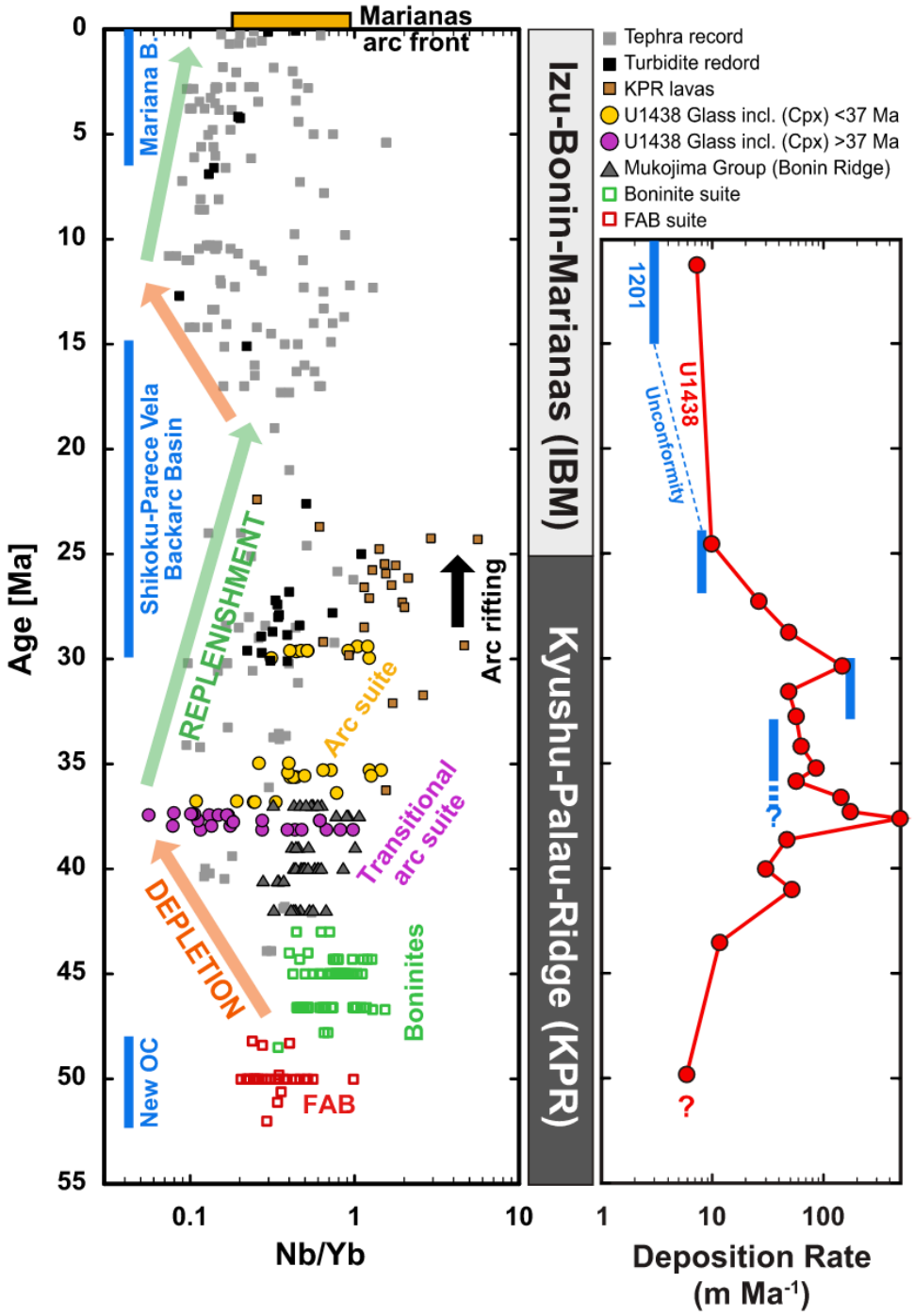
- High-Ca boninites presence in Tonga arc explained with residual peridotite brought by mantle flow to the mantle wedge from the back-arc *(Cooper et al., 2010)*

- Mantle wedge was depleted in incompatible elements during multi-stage back-arc basalt extraction (*Turner and Hawkesworth, 1997)*

Izu-Bonin-Marianas

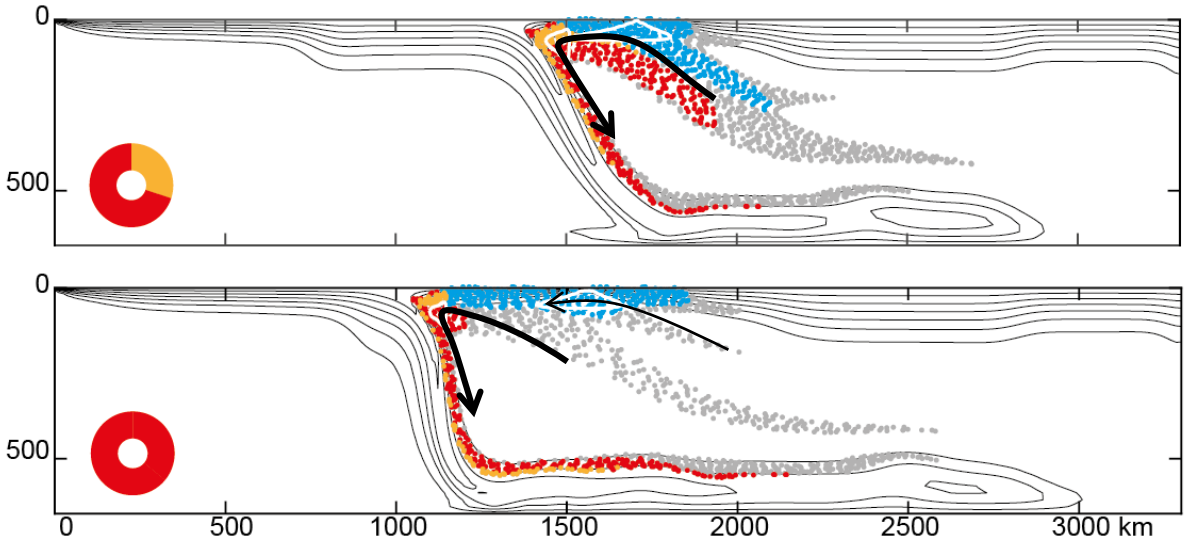


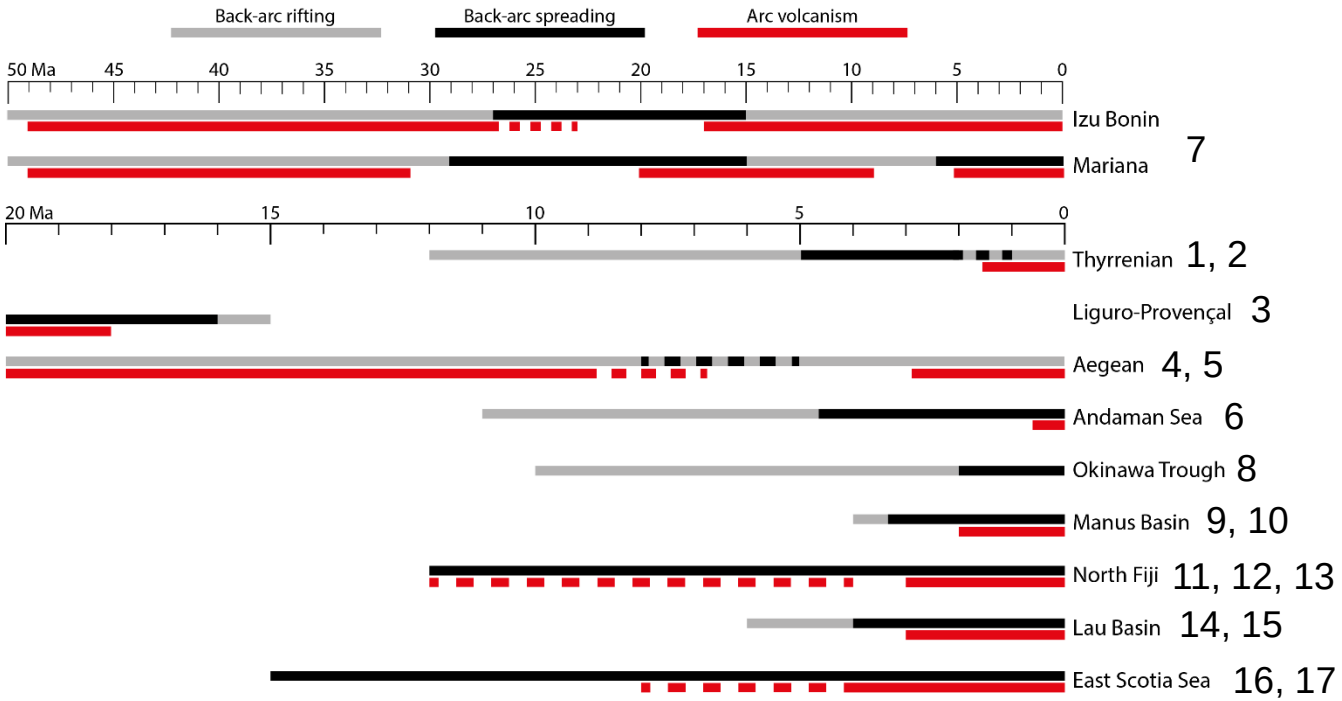
Brandl et al., EPSL, 2017



Conclusions

- Mantle flow can influence the amount and composition of arc magmatism.
- During back-arc spreading, for about 10 Myr, highly depleted mantle flows into the mantle wedge, beneath the arc.
- During trench retreat, back-arc spreading can correspond to minimum or no activity of the volcanic arc. Alternatively, it can temporary change the composition of arc lavas.
- Toroidal mantle flow pattern is associated with a much stronger upwelling component at slab edges than at slab windows.





1. Guillaume et al., 2010
2. Faccenna et al., 2005
3. Malusa' et al., 2016
4. Jolivet et al., 2012 (Fig. 11) (also Jolivet and Brun, 2010)
5. Jolivet and Faccenna, 2000
6. Chakraborty and Khan, 2009
7. Lallemand 2016
8. Letouzey and Kimura, 1986
9. Beier et al., 2010
10. Woodhead et al., 1998
11. Greene et al., 1994
12. Lagabrielle et al., 1997
13. Meffre and Crawford, 2001
14. Turner and Hawkesworth, 1997
15. Ewart and Hawkesworth, 1986
16. Leat et al., 2003, 2004
17. Larter at a., 2003