Slab dragging, subduction evolution, and slab deformation

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Houston 2015 (review paper):

“**There appears to be a tendency for ruptures, particularly those of intermediate-depth earthquakes, to propagate along strike and near-horizontally** (Antolik et al., 1999; Kiser et al., 2011; Myhill and Warren, 2012; Tibi et al., 2002; Warren et al., 2007, 2008).”

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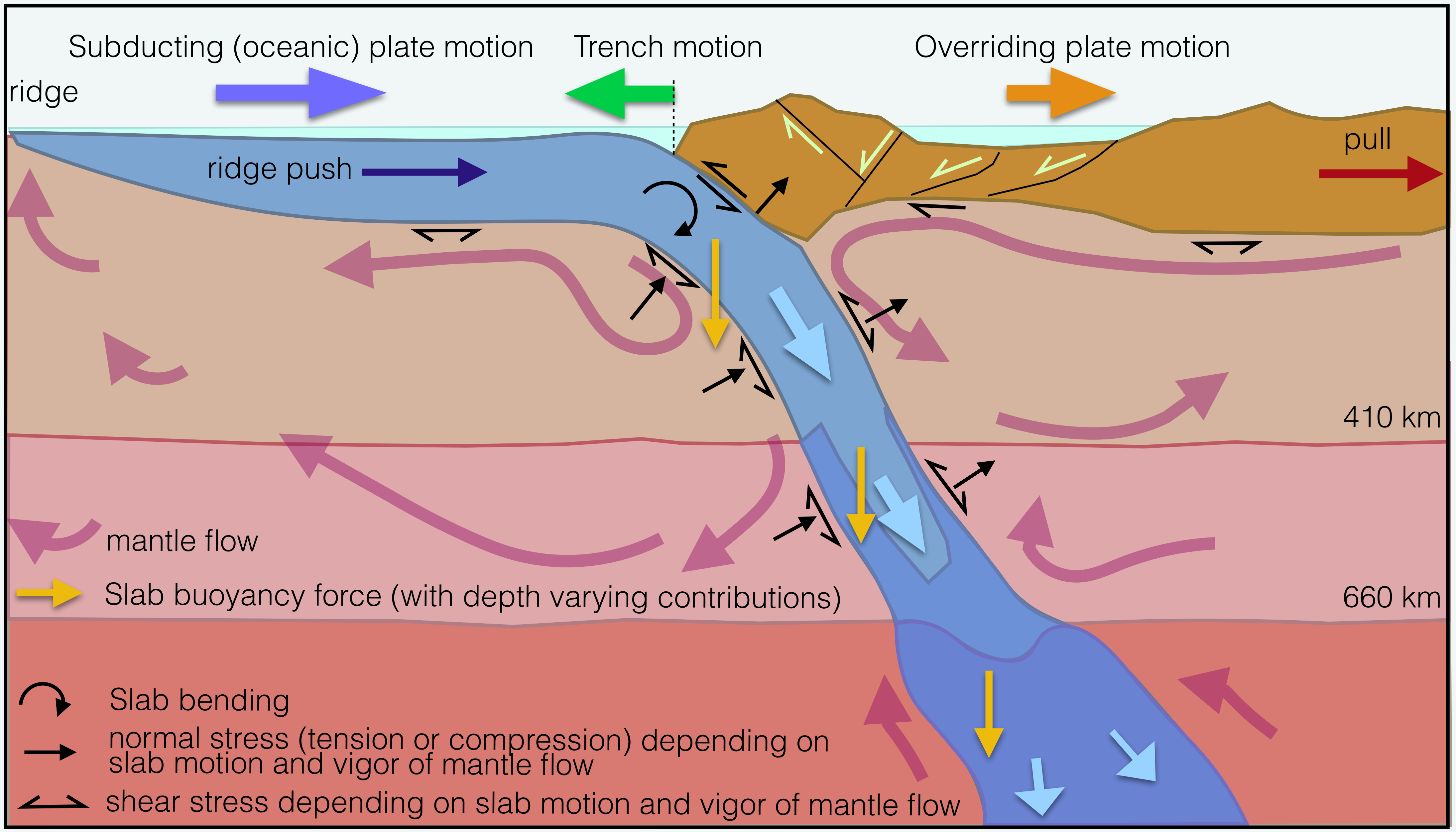
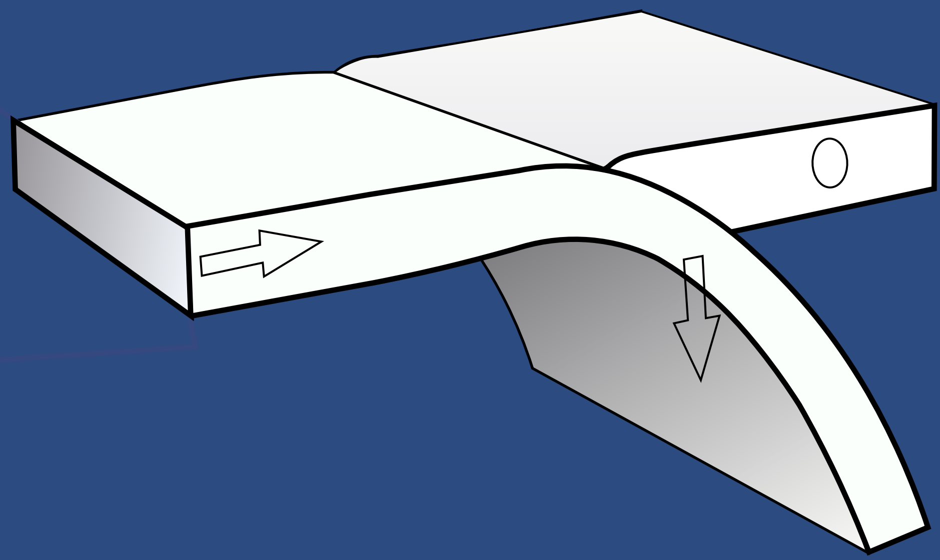
Next: Make a step to an aspect of subduction systems, which has been largely overlooked in past 5 decades.

This aspect, called slab dragging, may bring, among other, a slab-strike parallel forcing into play

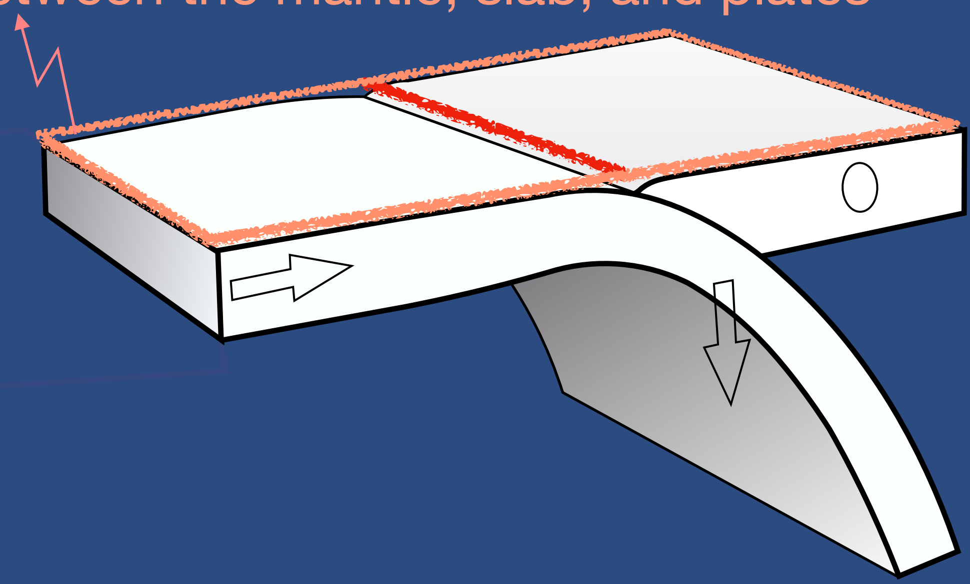
Lithosphere subduction:
The largely trench-perpendicular perspective



After: Billen, 2008



Frame fixed to the deep mantle:
crucial for proper physical incorporation of the viscous coupling between the mantle, slab, and plates



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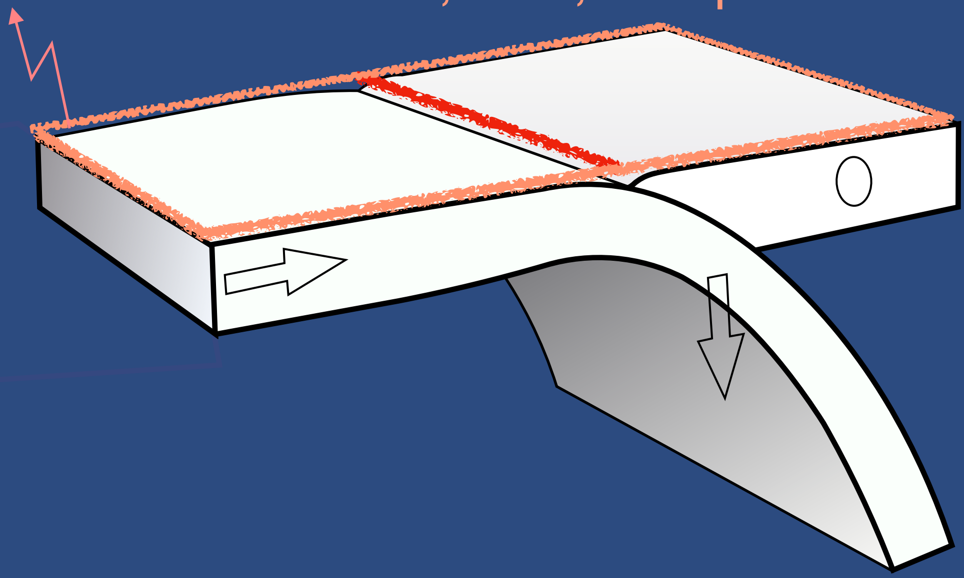

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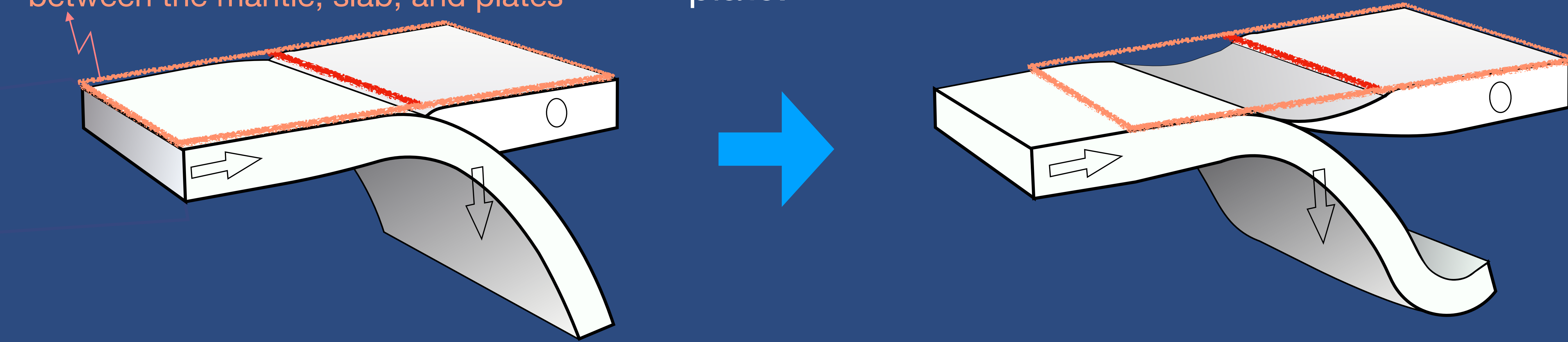

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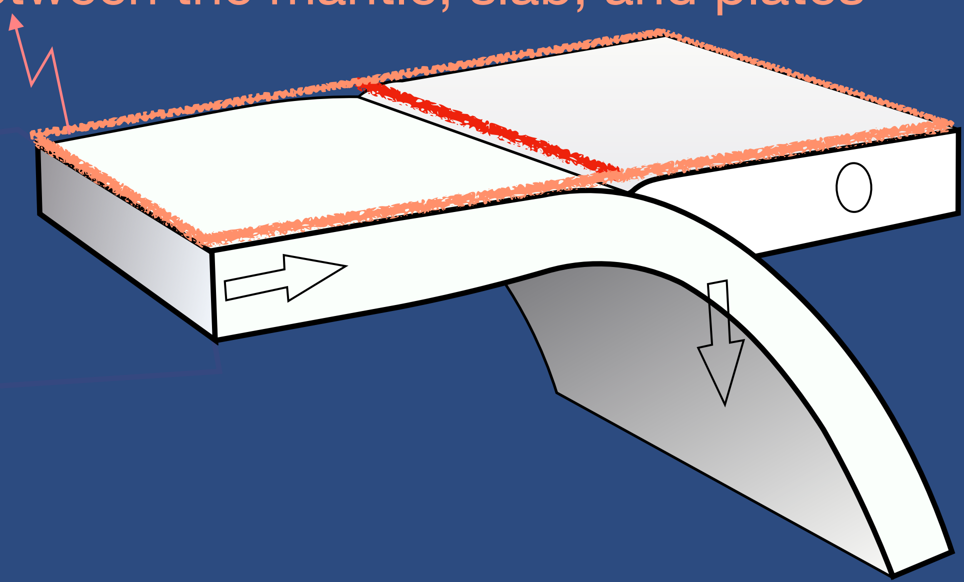

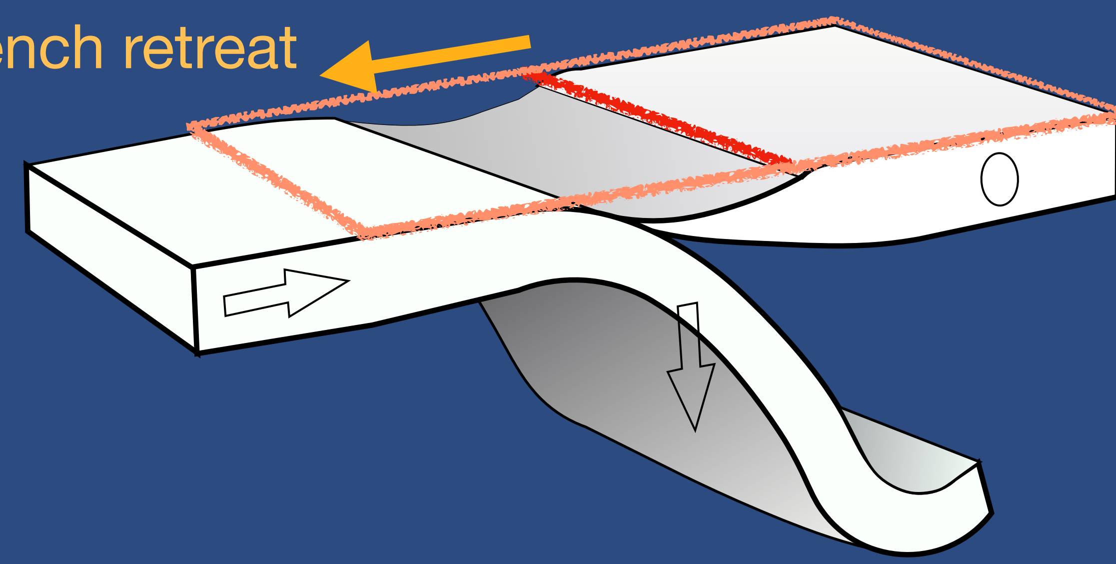

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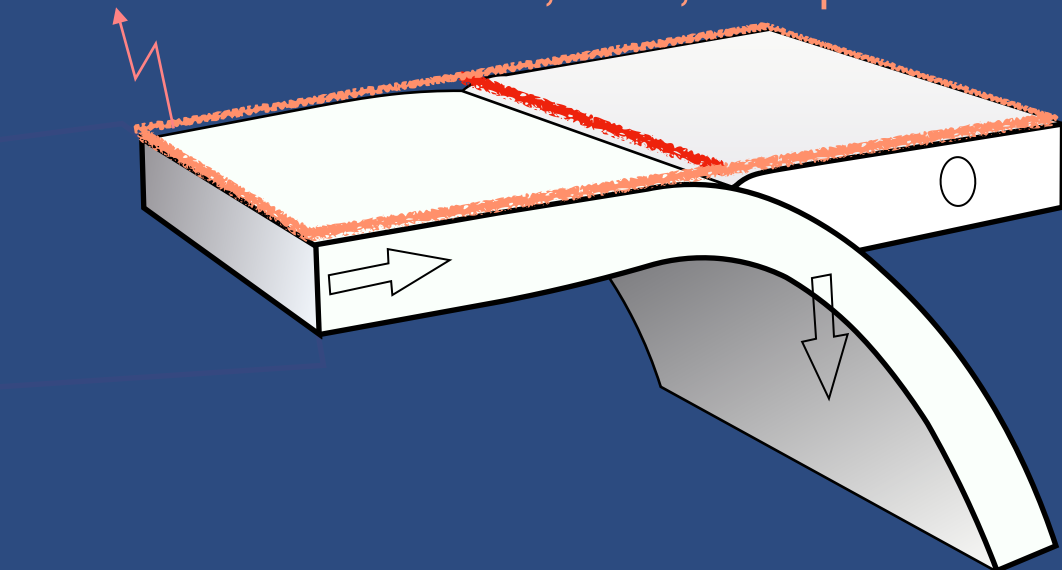

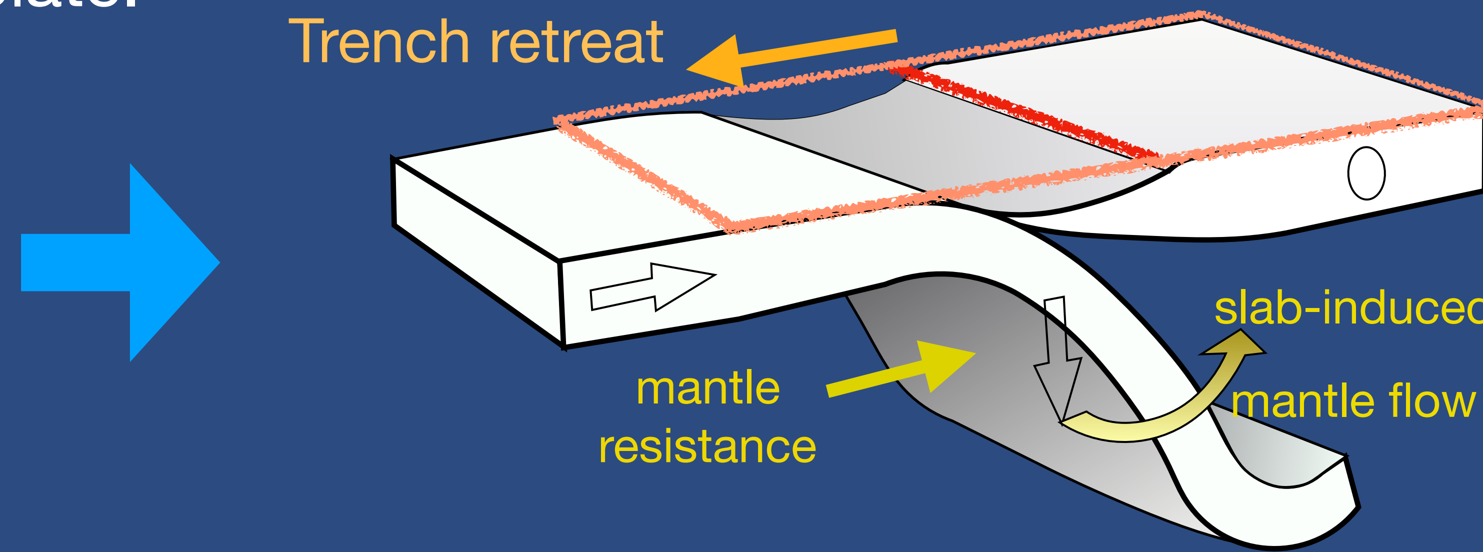

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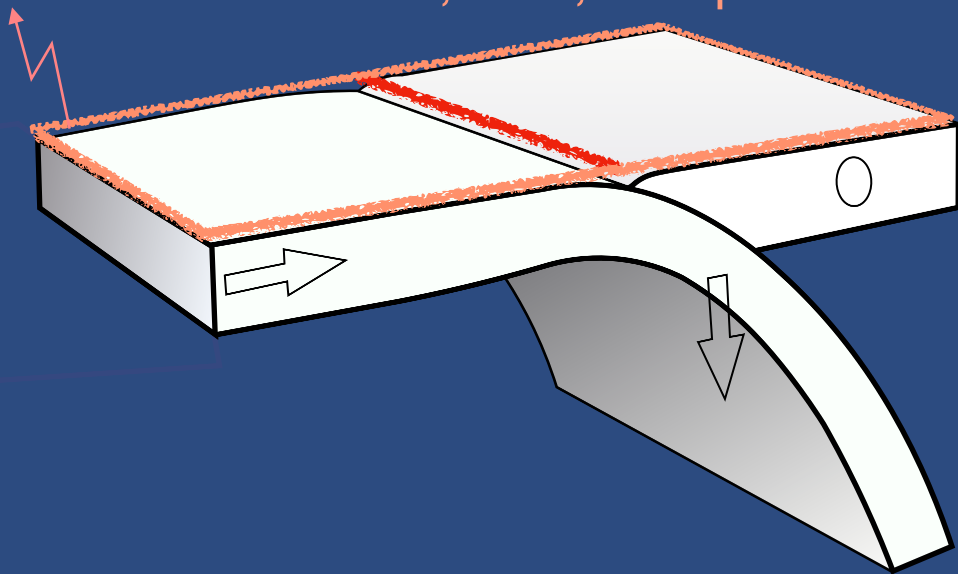

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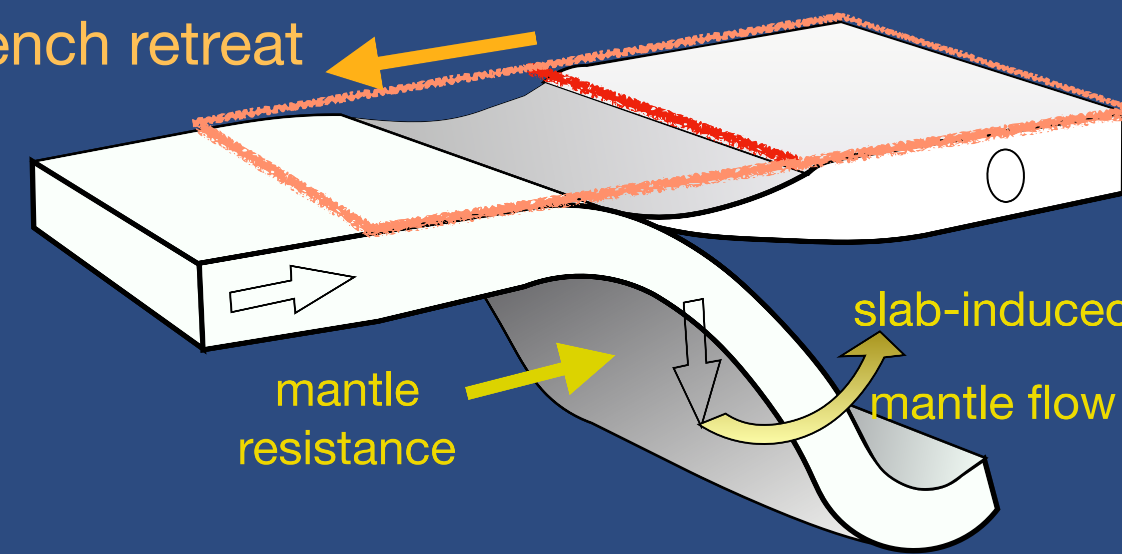

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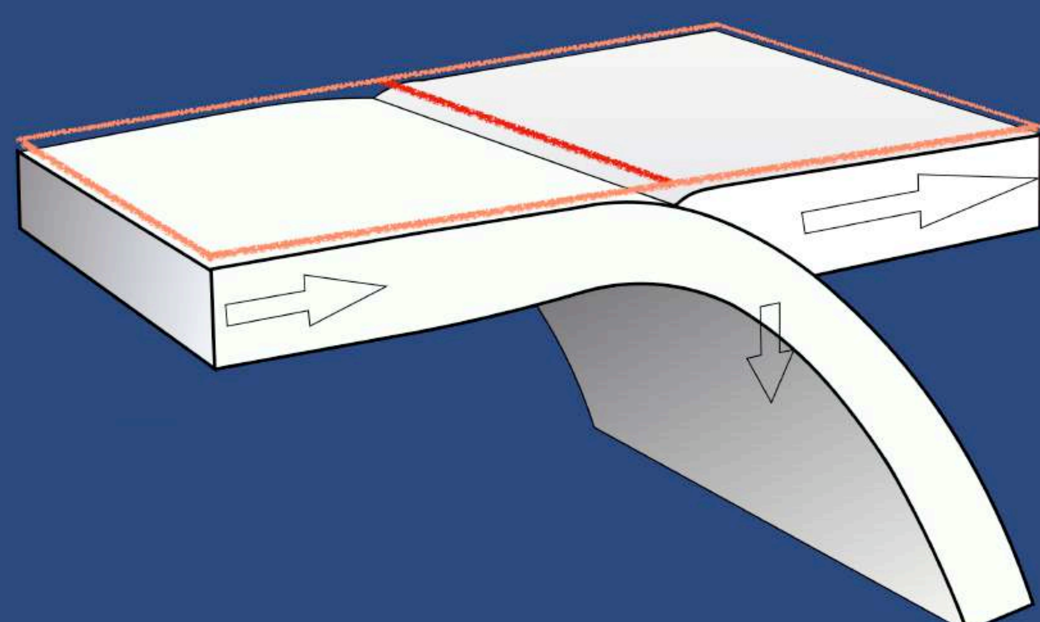

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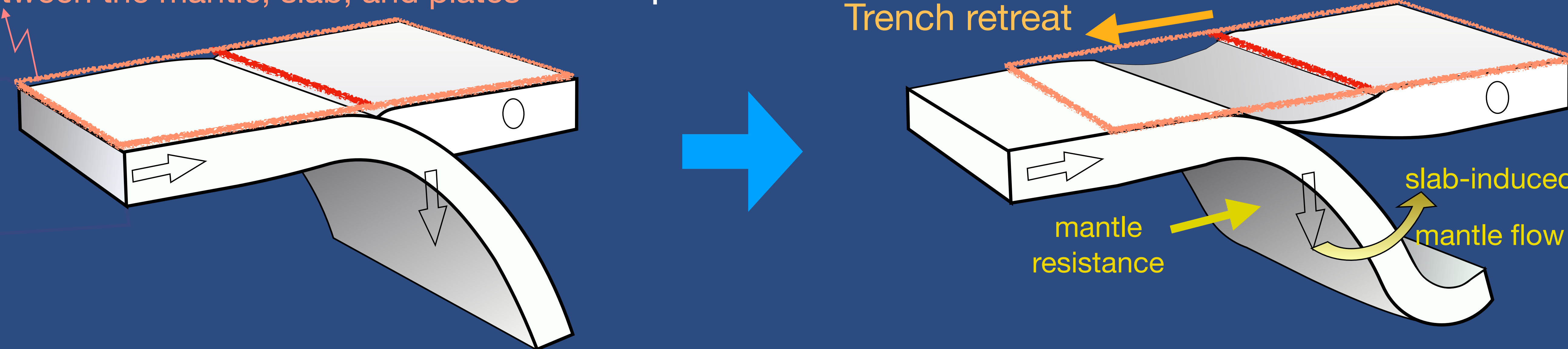

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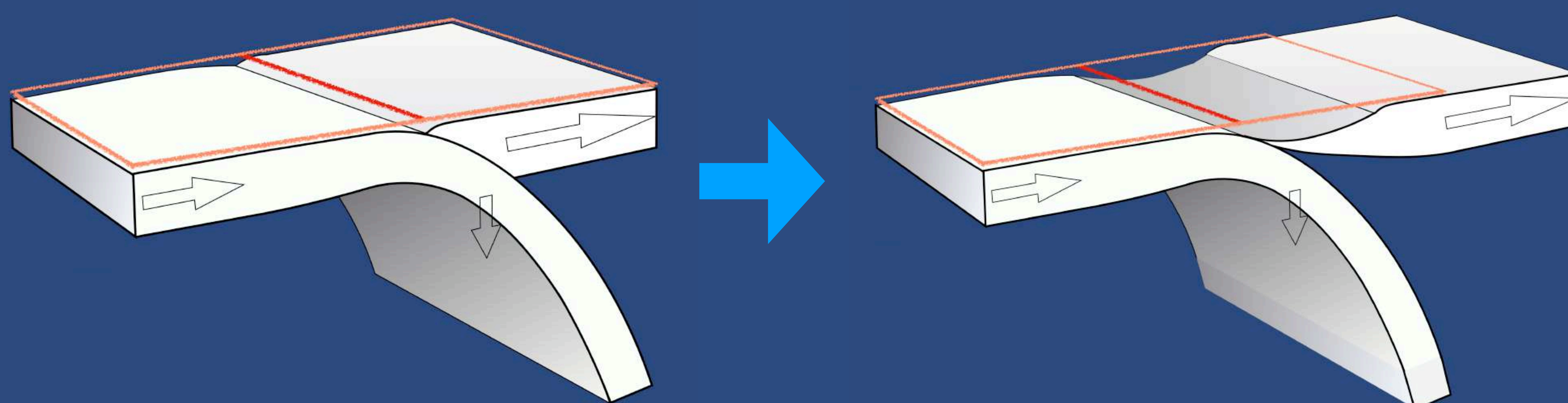

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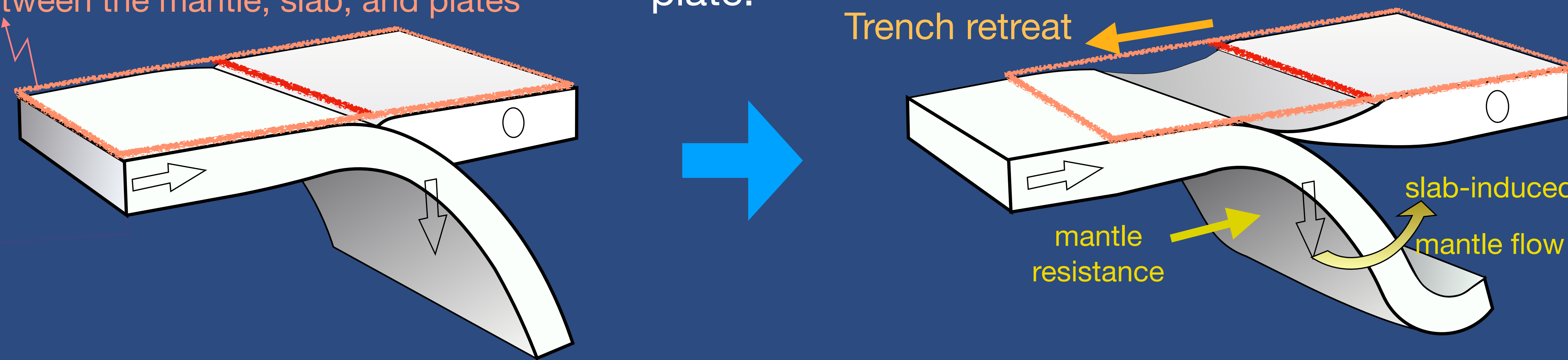

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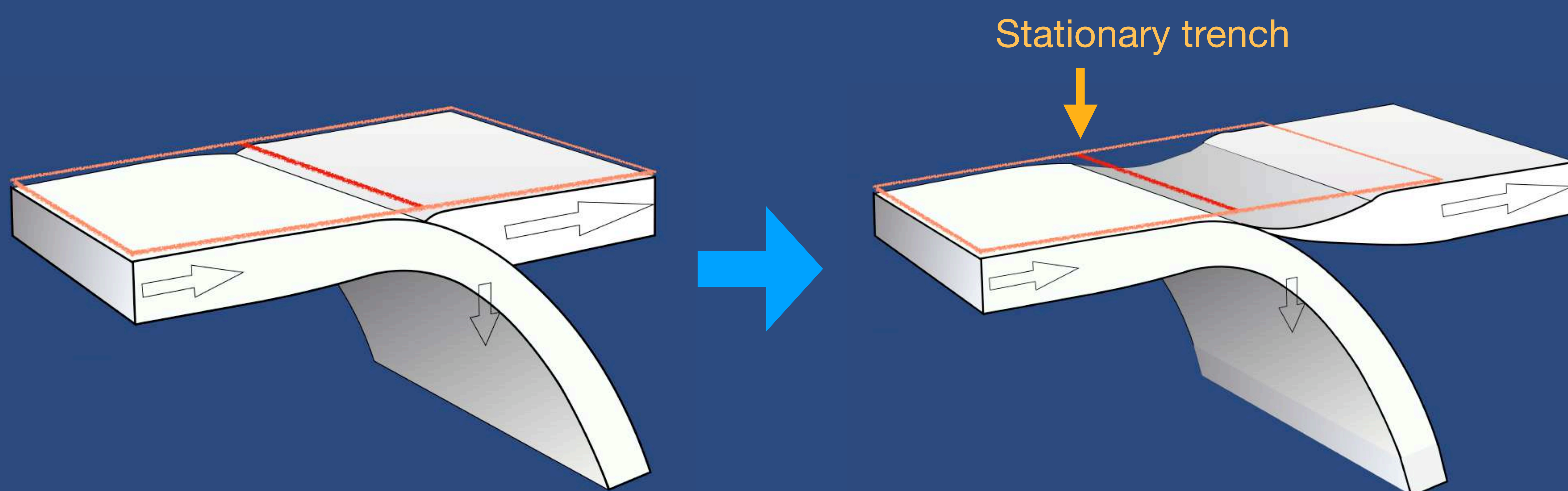

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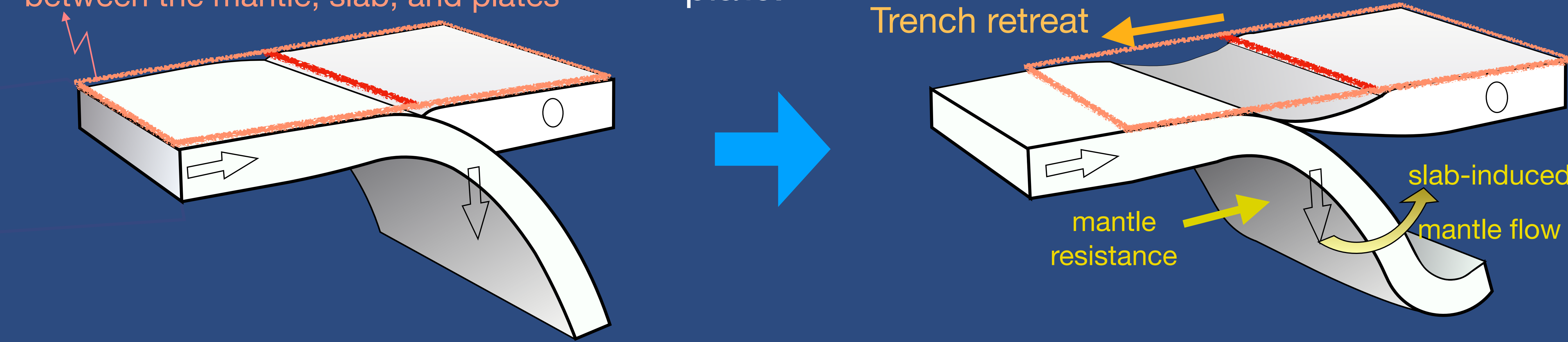

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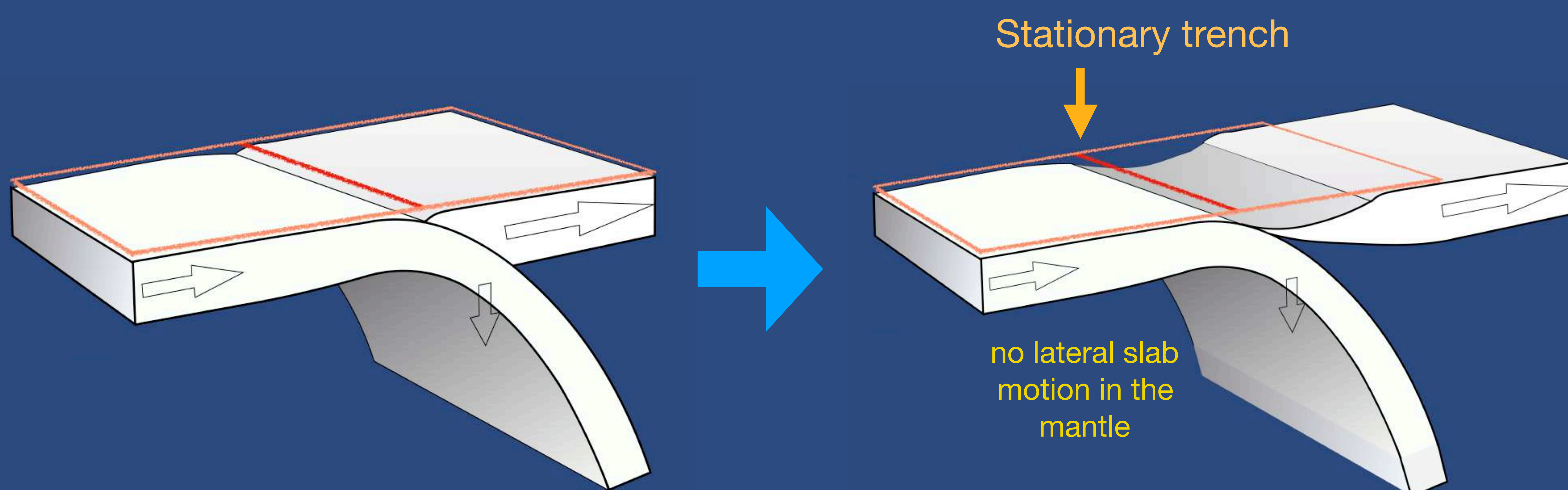

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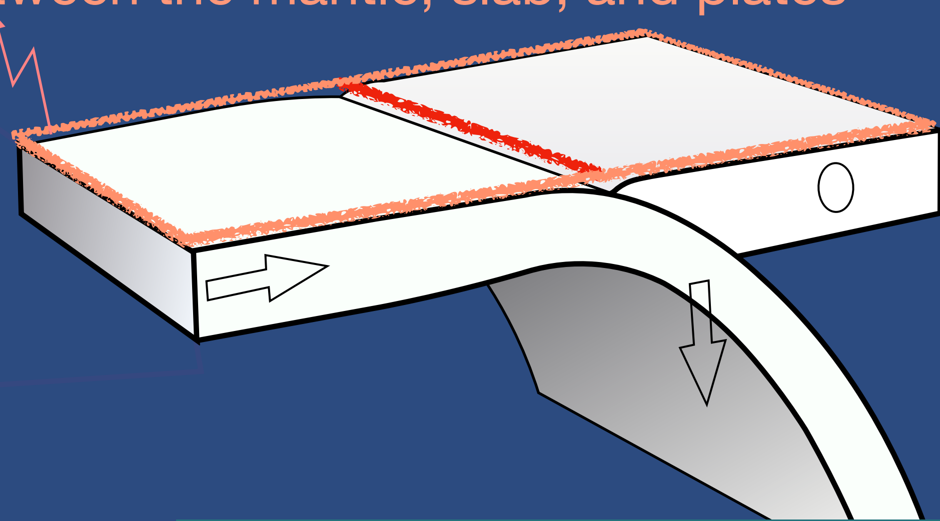
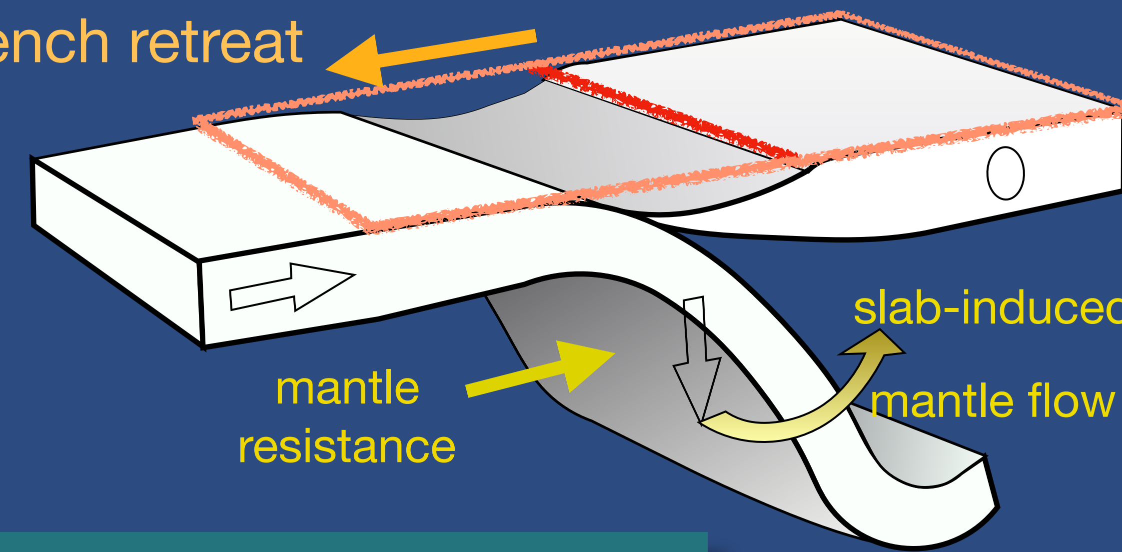
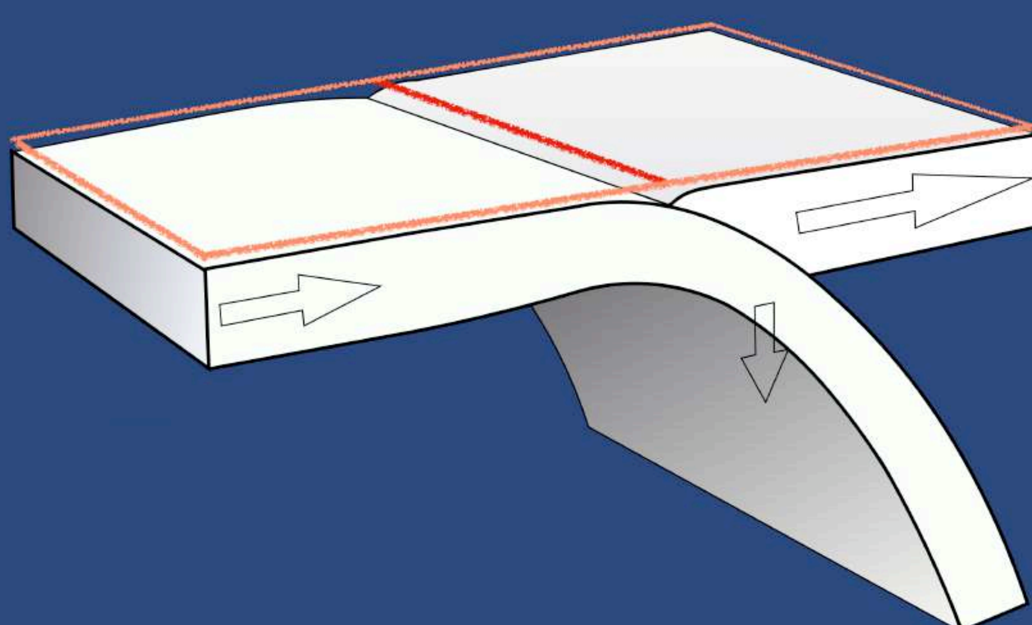


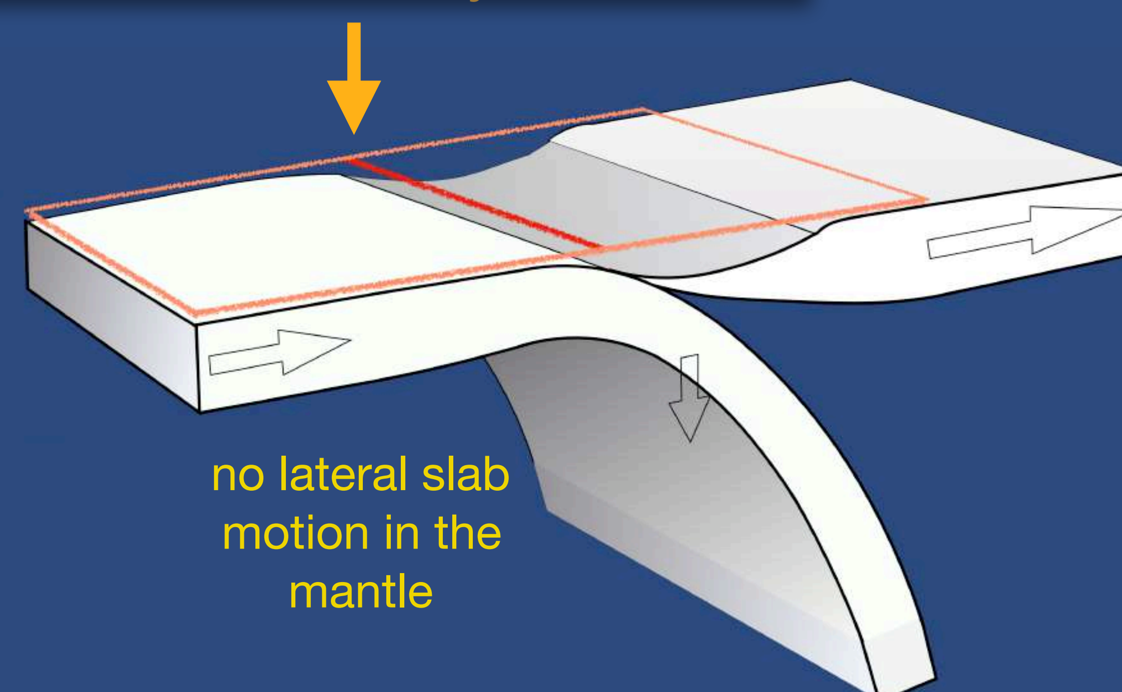


The fundamental difference between the two scenarios is the slab-mantle coupling.

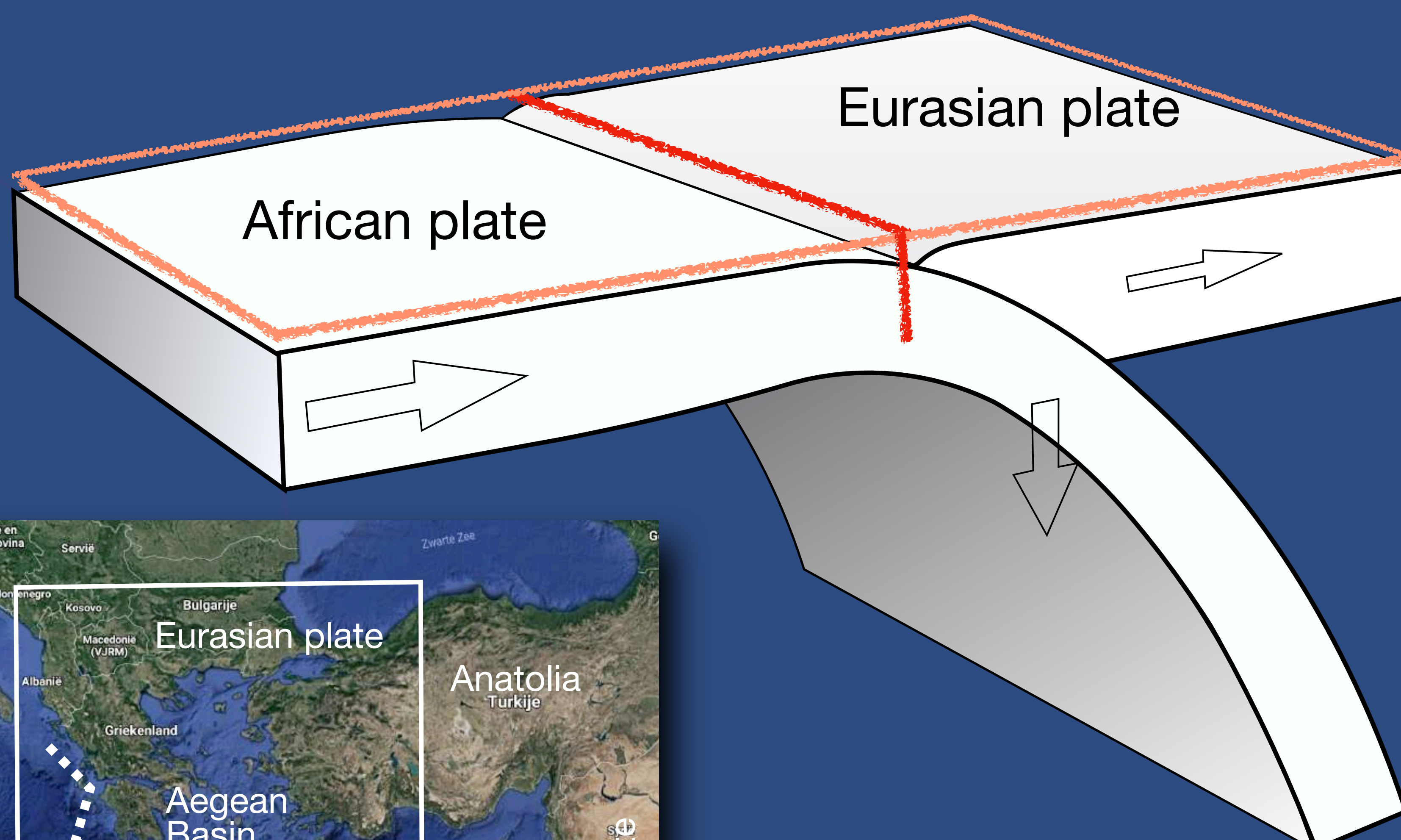
This will excite a different stress field in the slab that may be reflected in focal mechanisms (even if it is only subtle) and which may have impact on the tectonic evolution overhead

by overriding





Example: Trench retreat AND overriding plate escape: Africa-Eurasia convergence across the Hellenic trench



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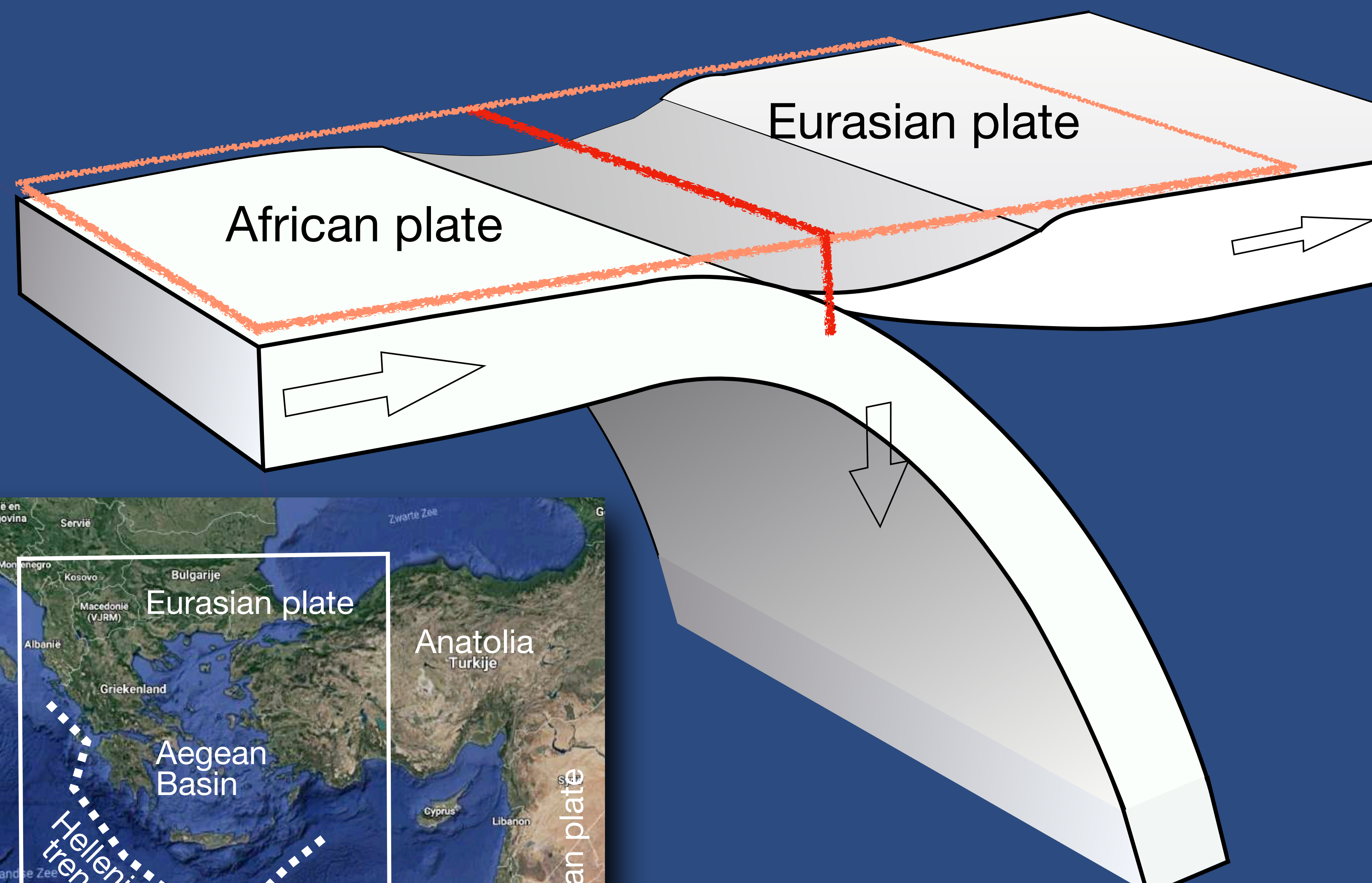

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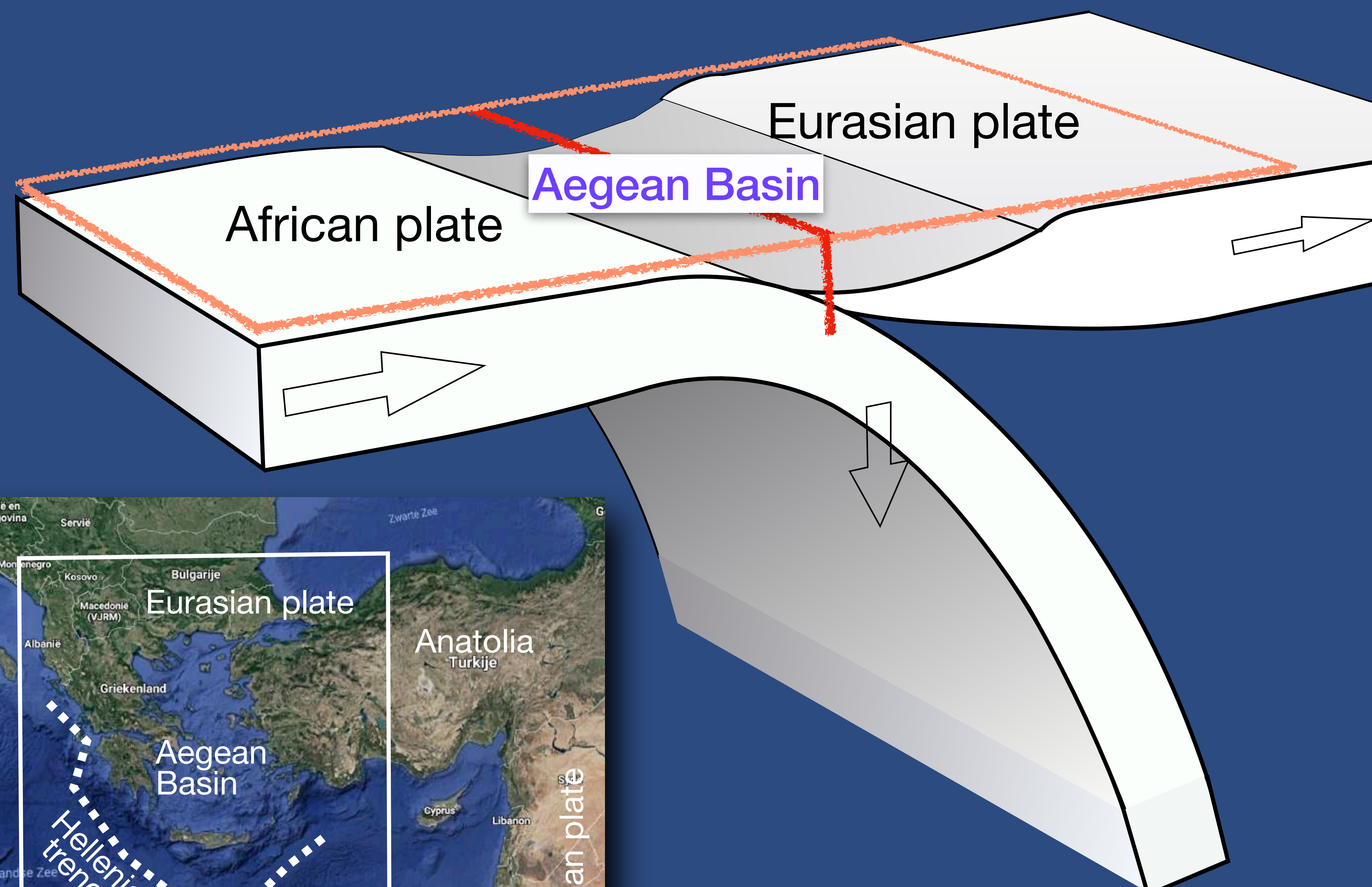

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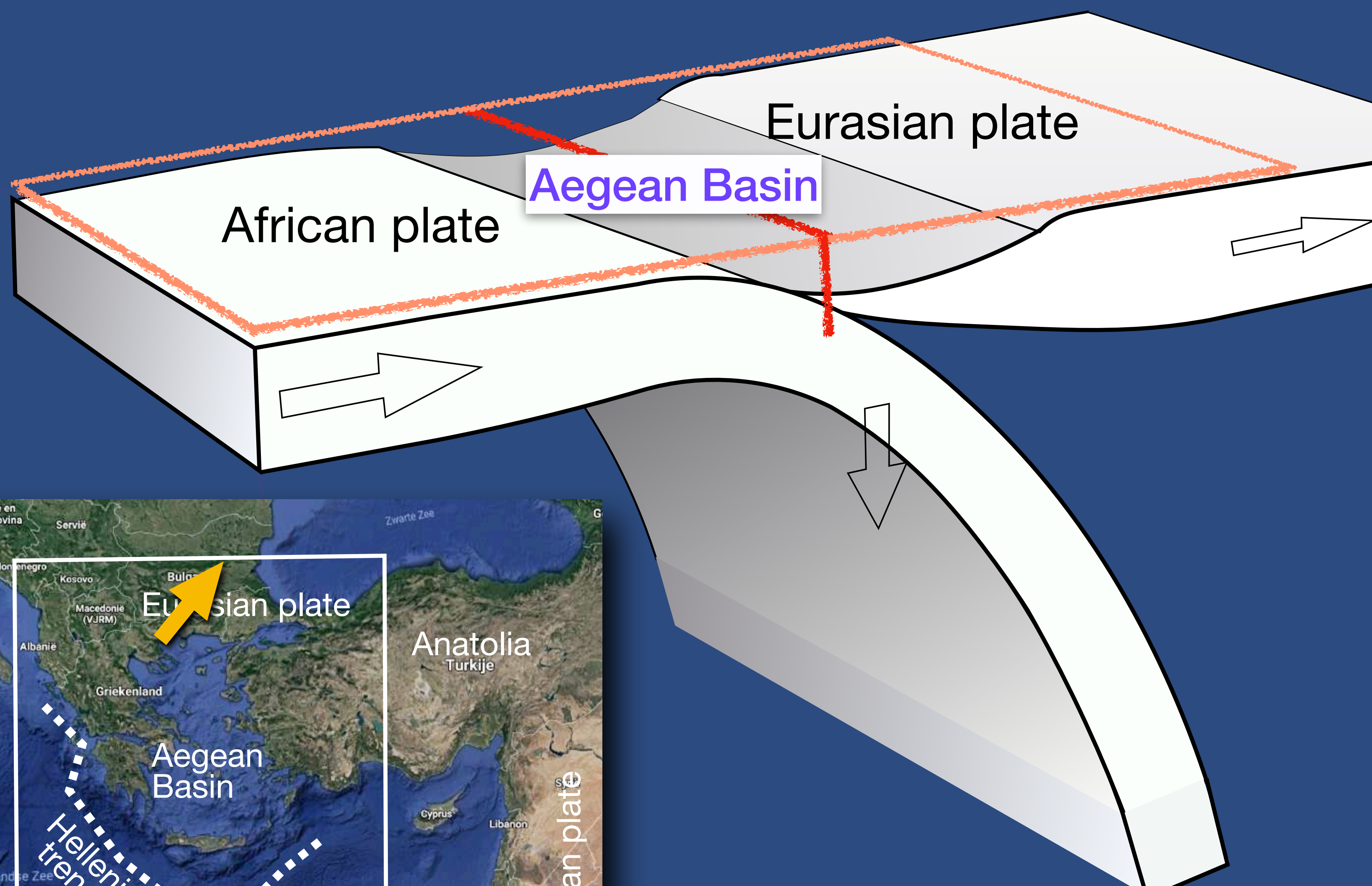

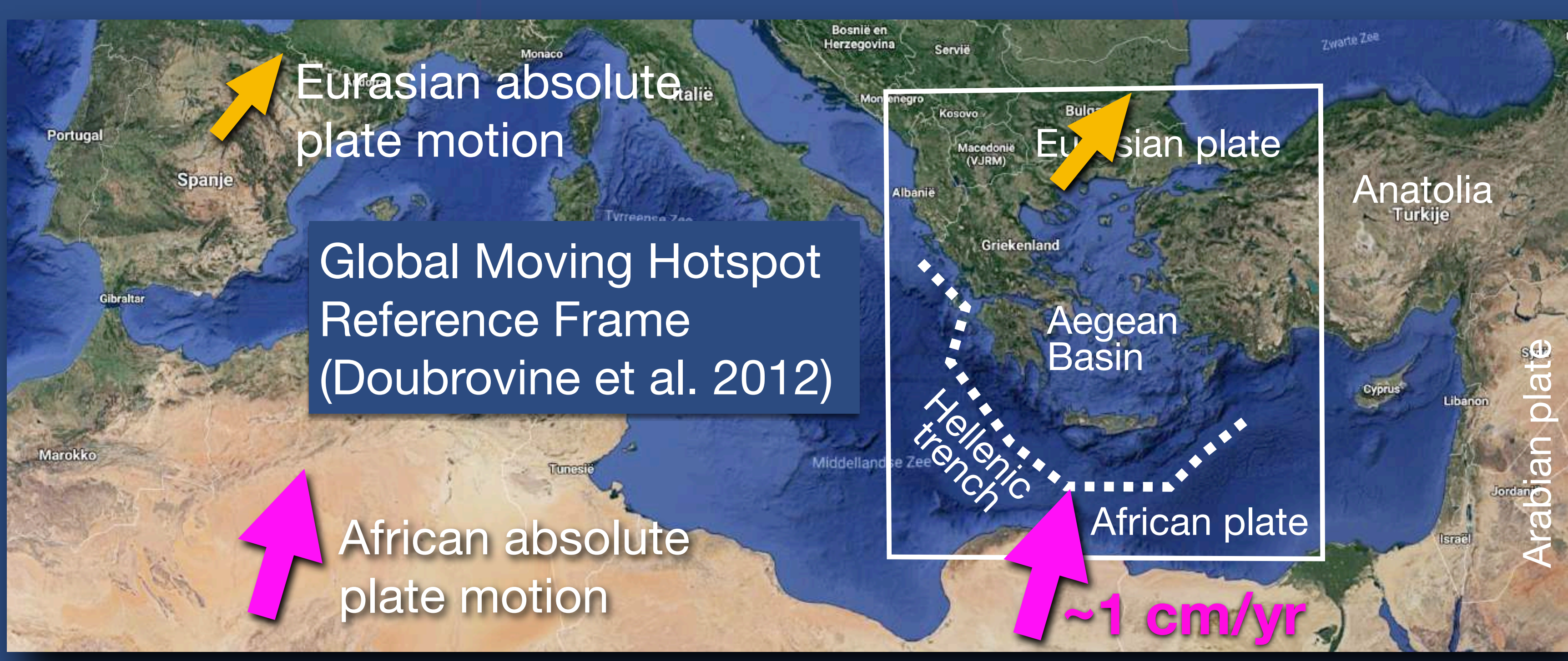

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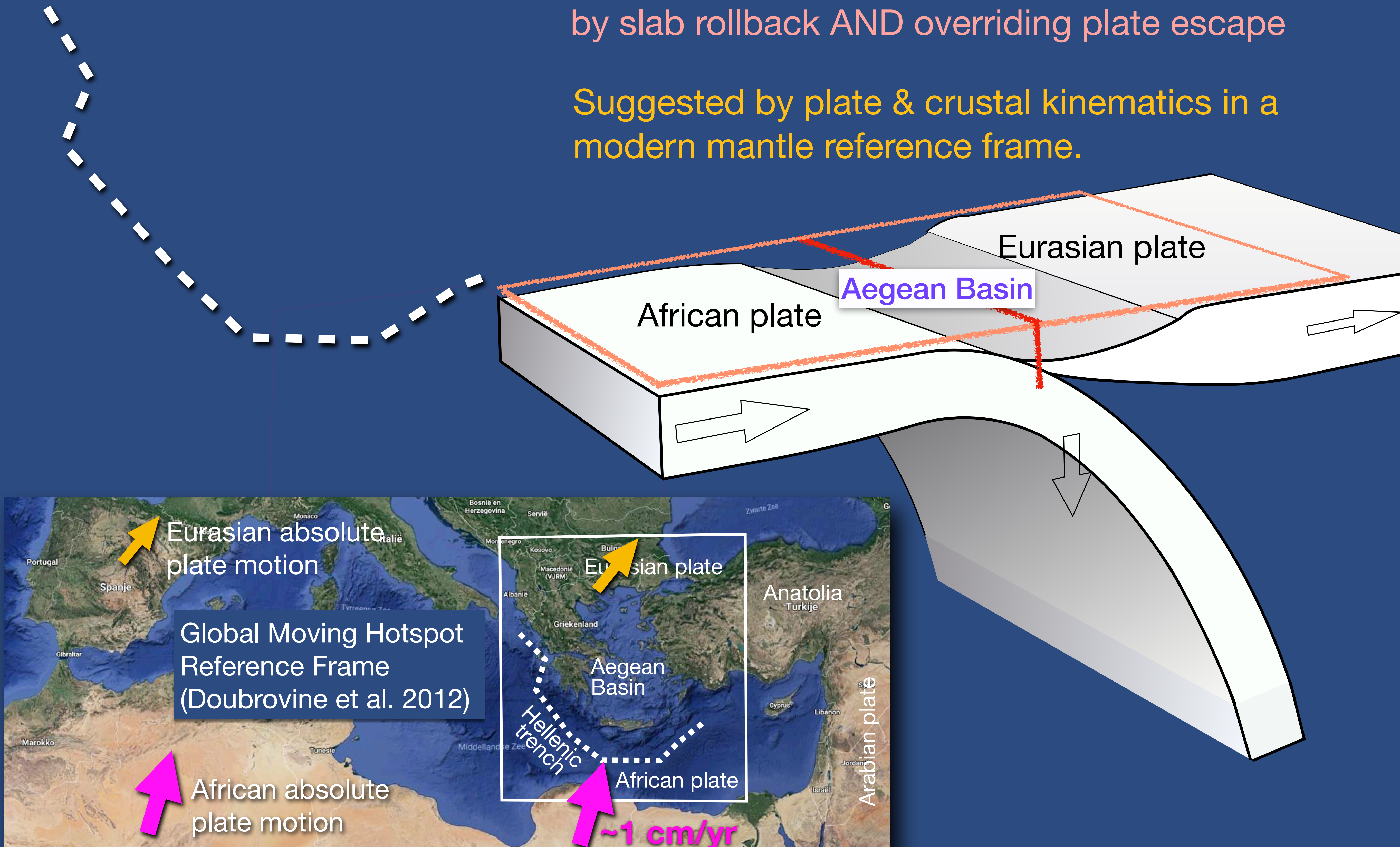

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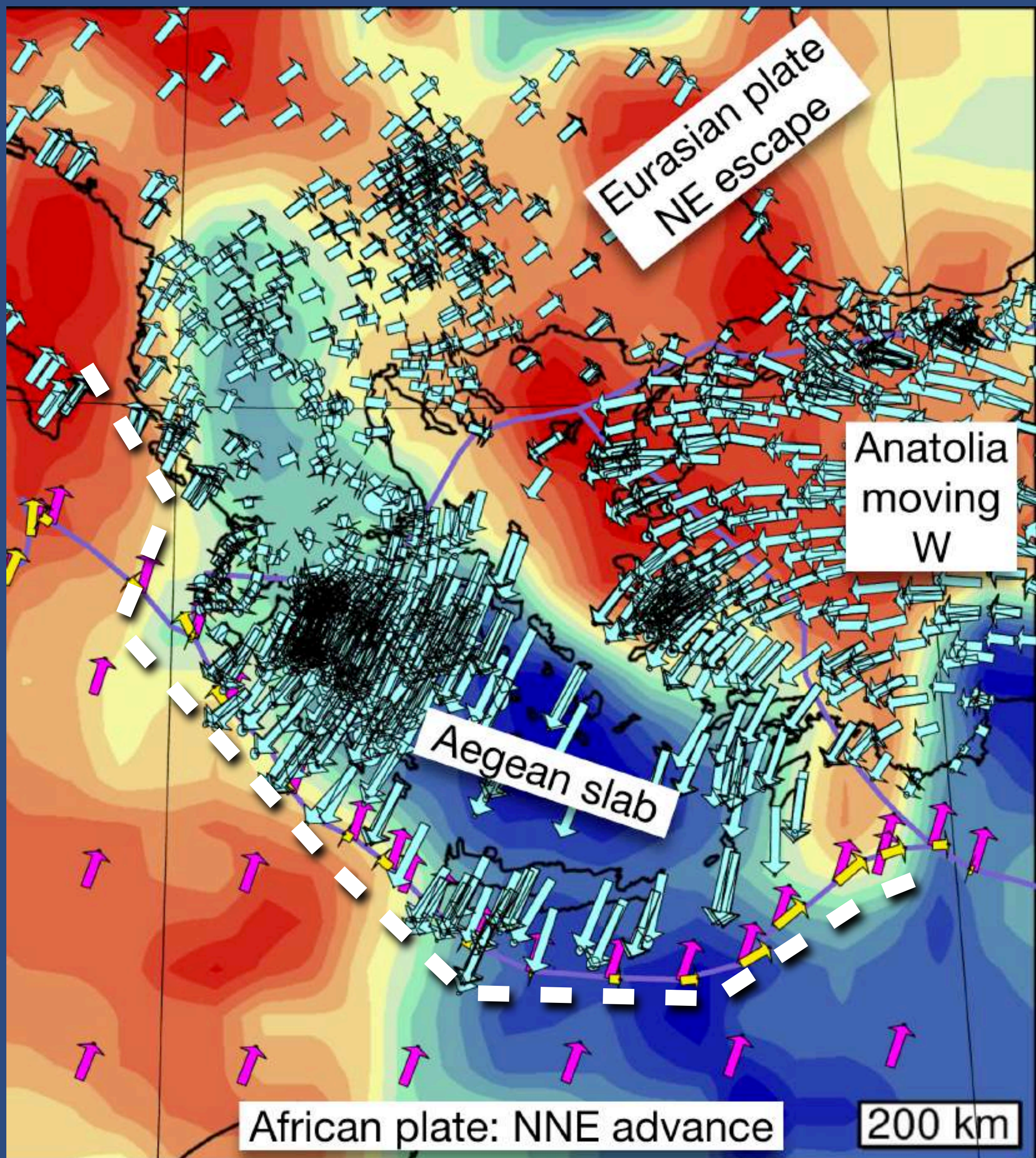

African plate motion (magenta) and GPS motions (blue) in the mantle frame of Doubrovine et al. 2012

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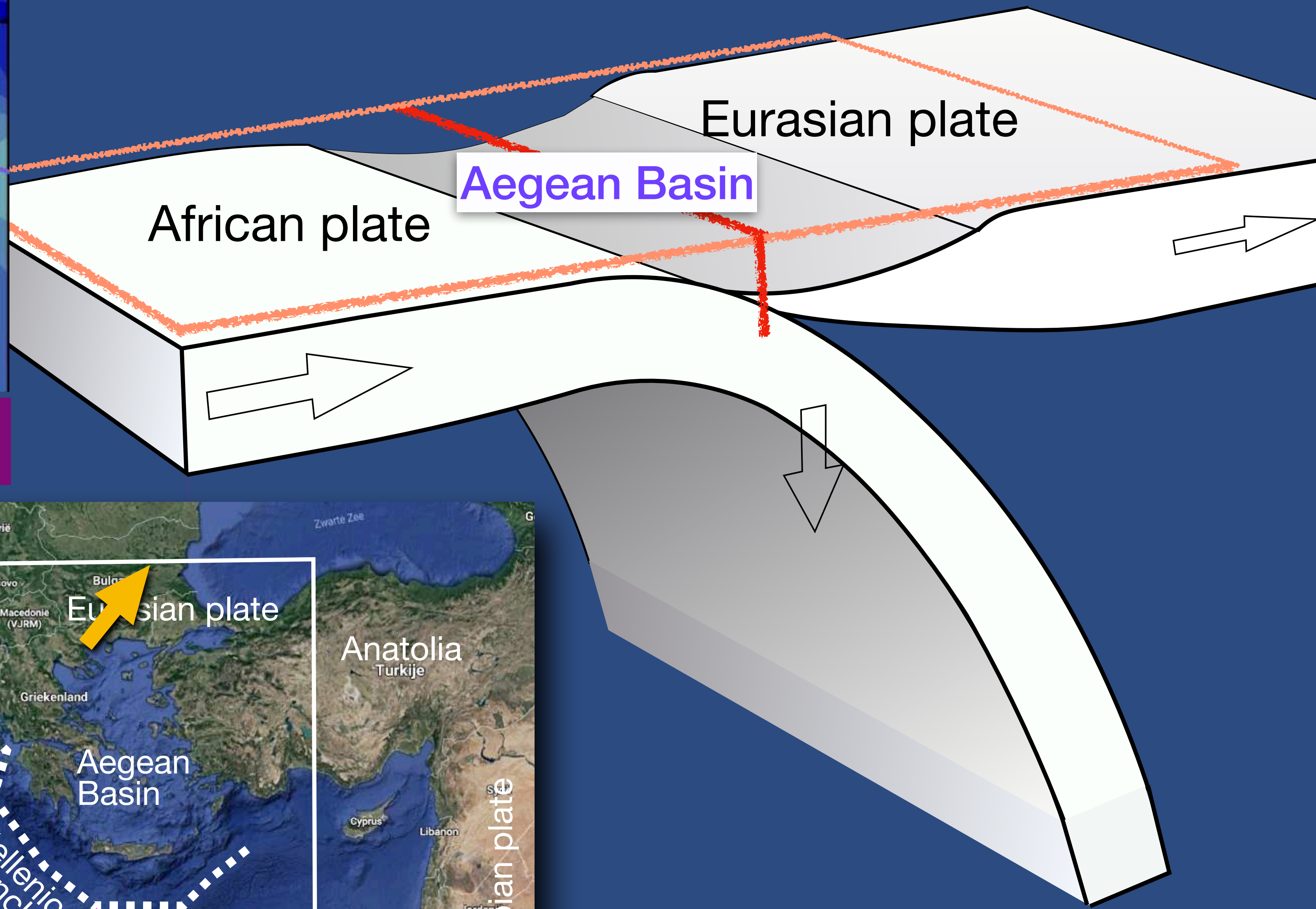

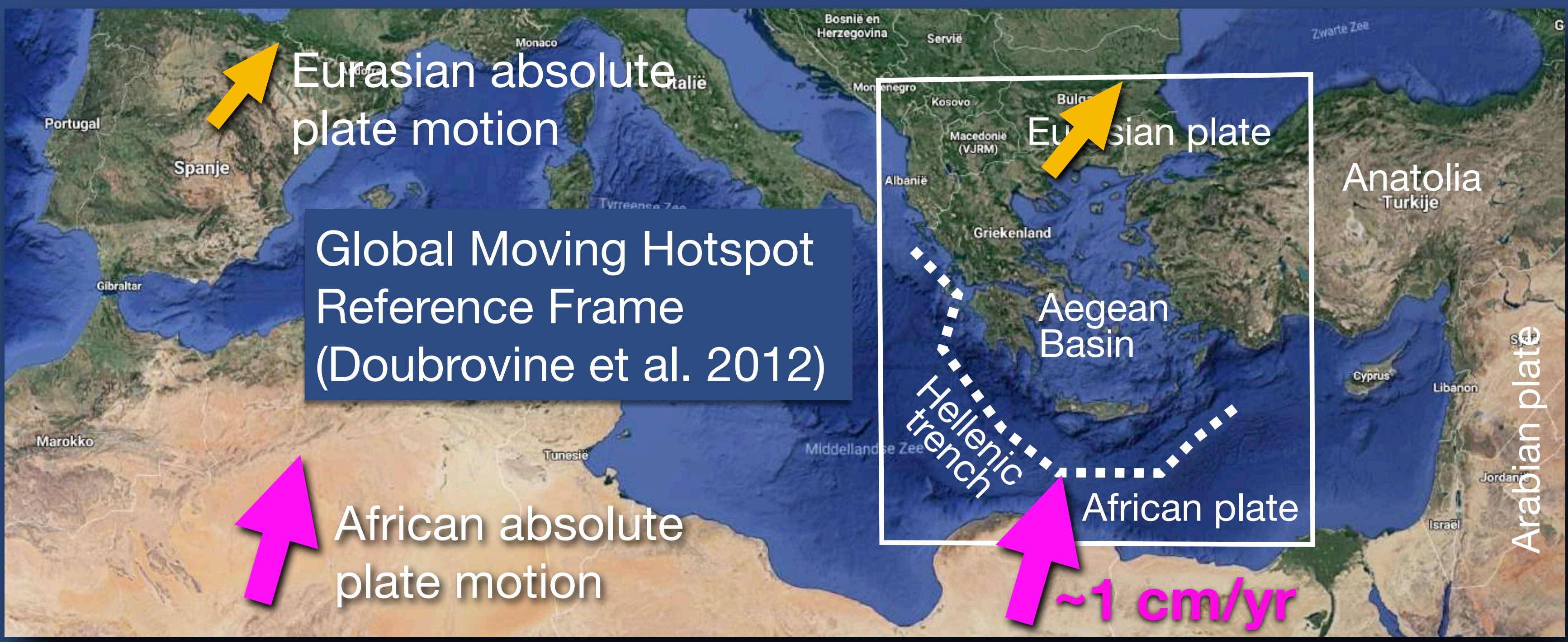

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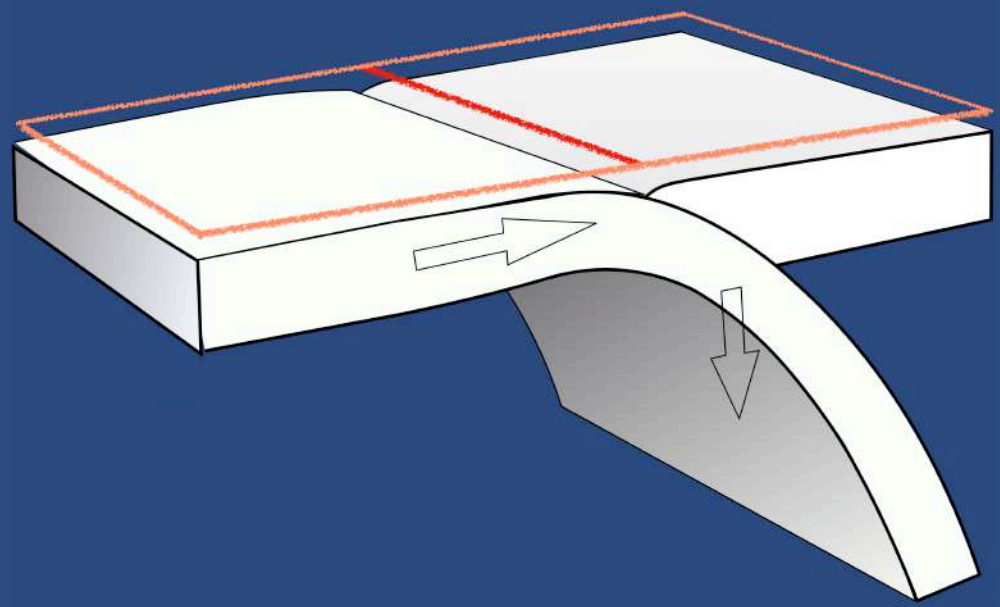

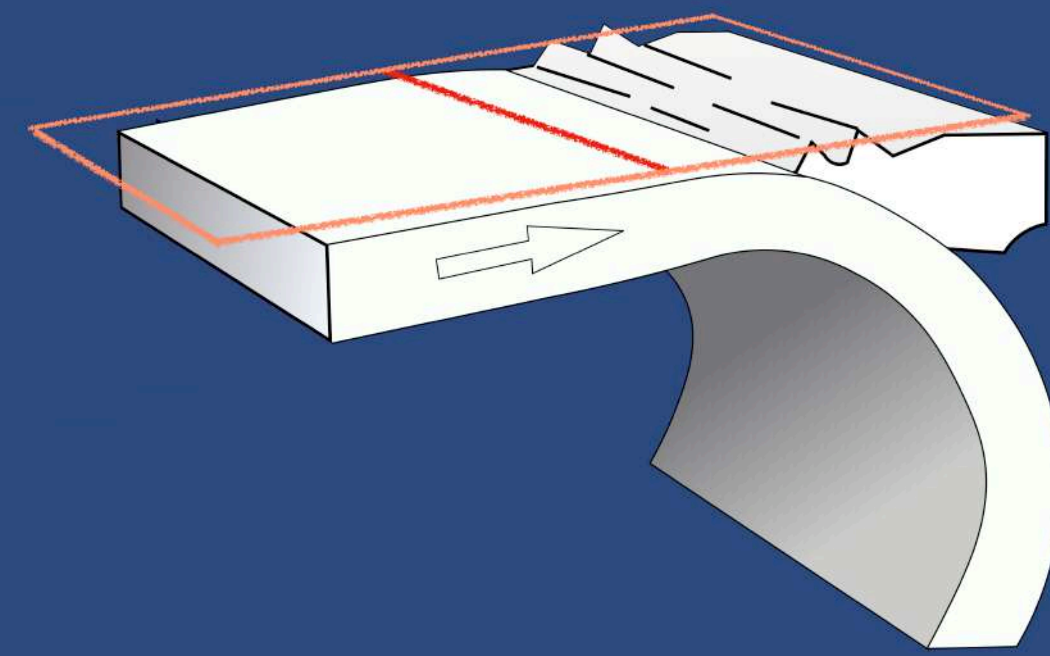

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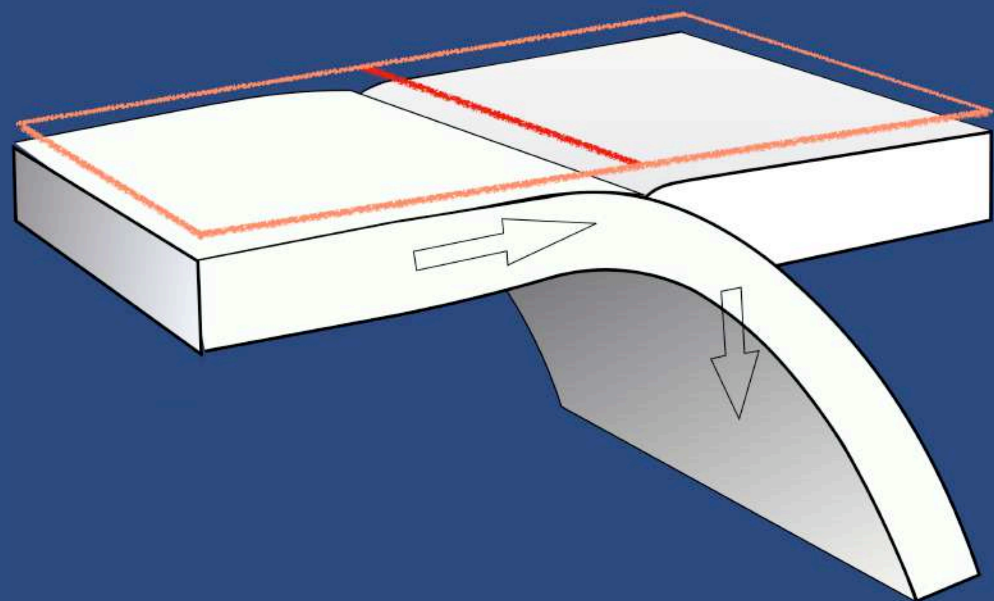

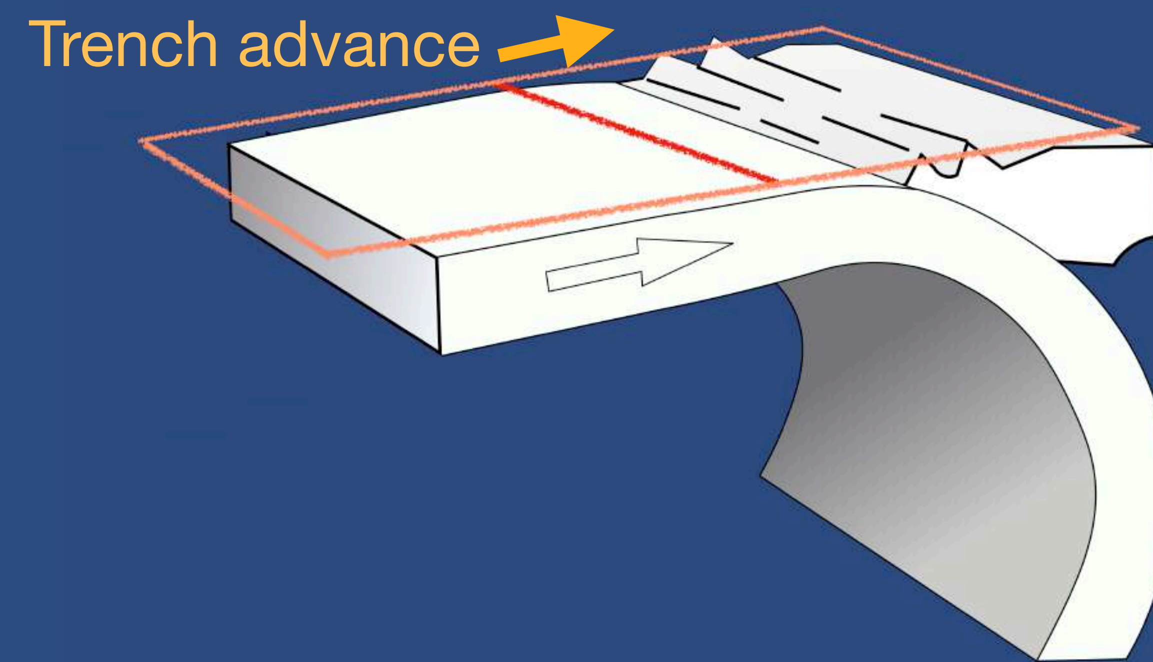

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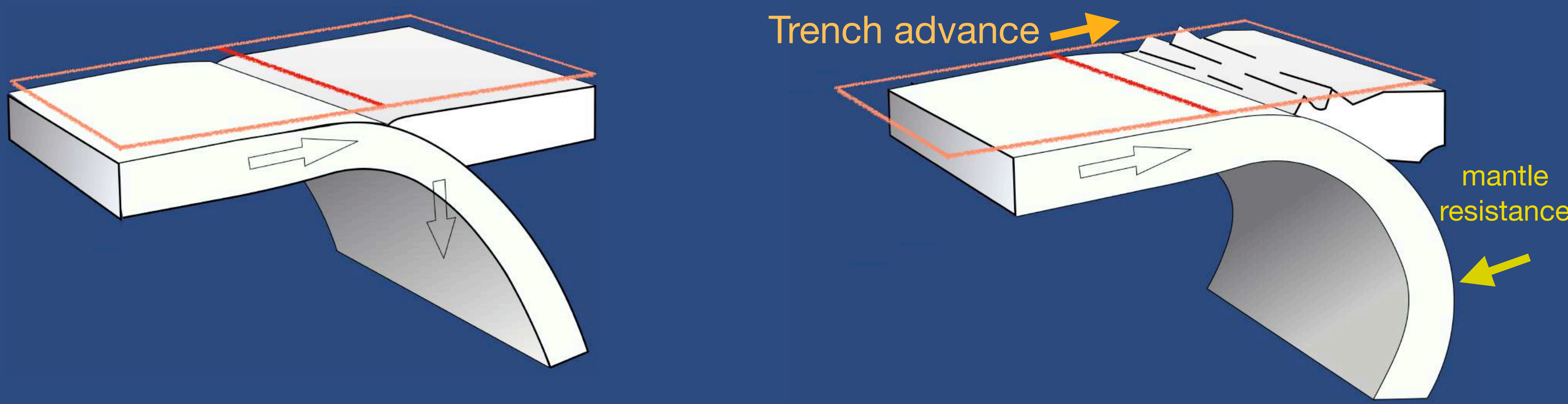

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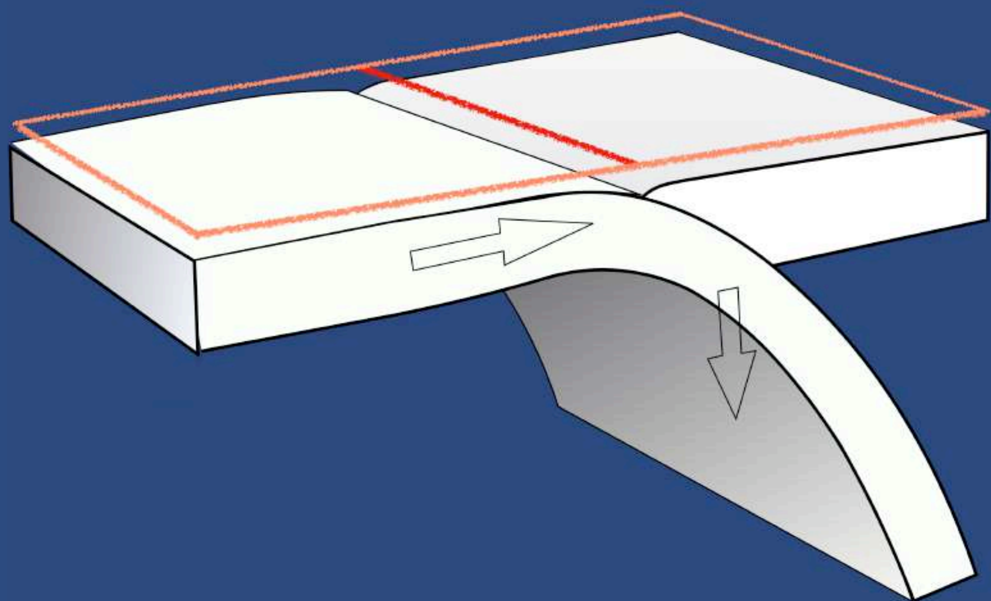

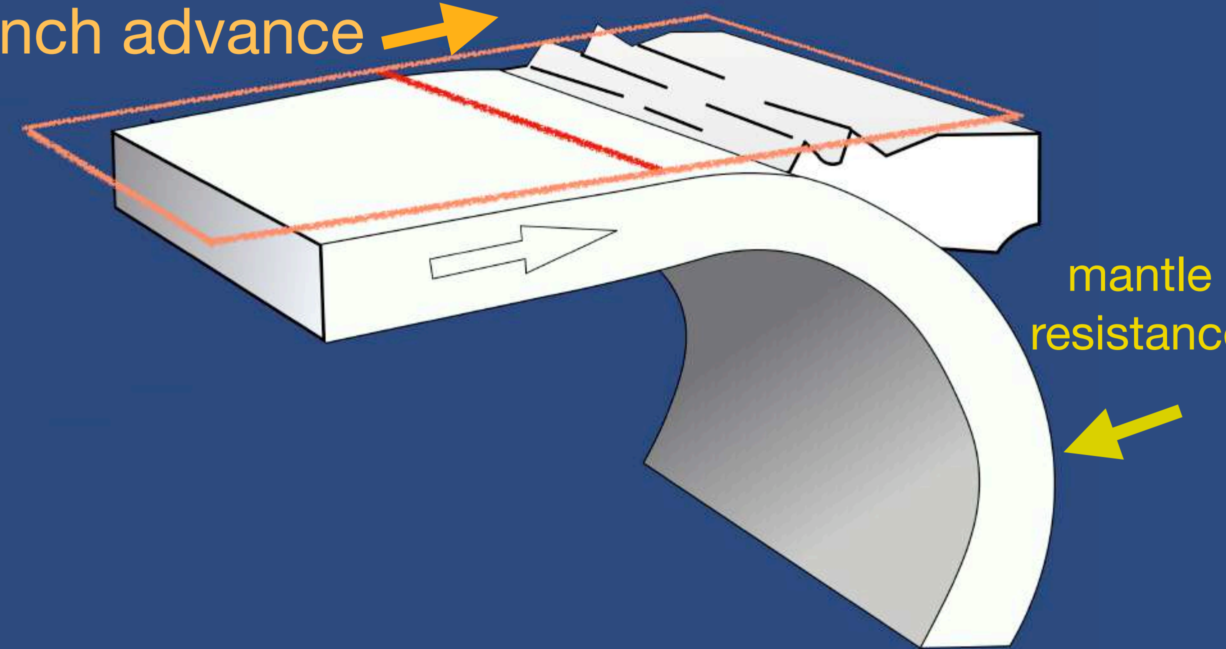

At present: Hindu-Kush

In the Past: during evolution of India-Eurasia collision (van Hinsbergen et al. 2018)

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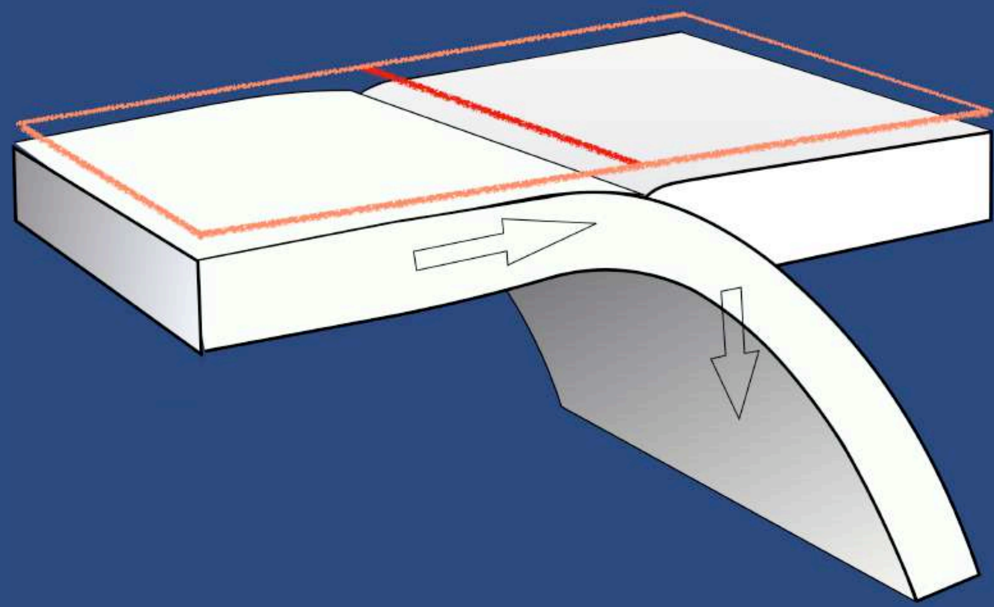

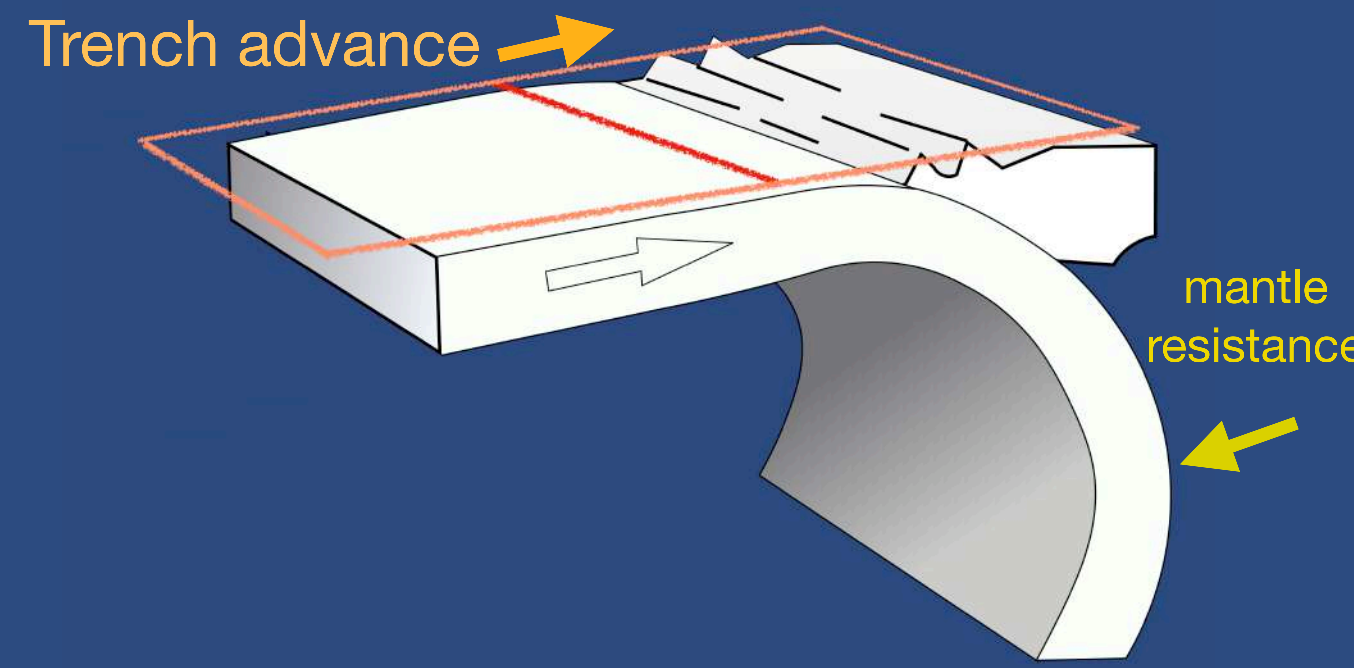

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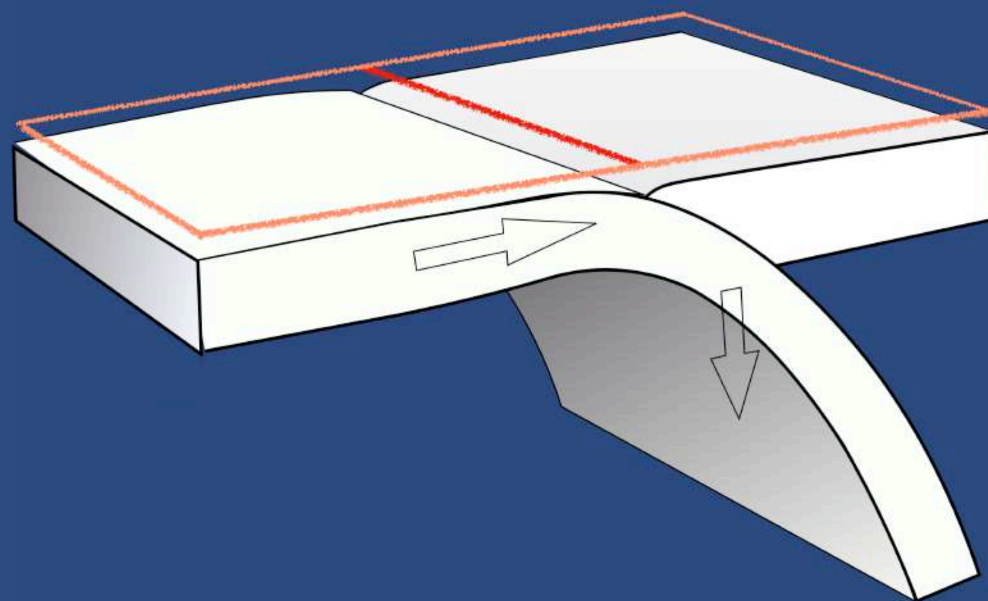

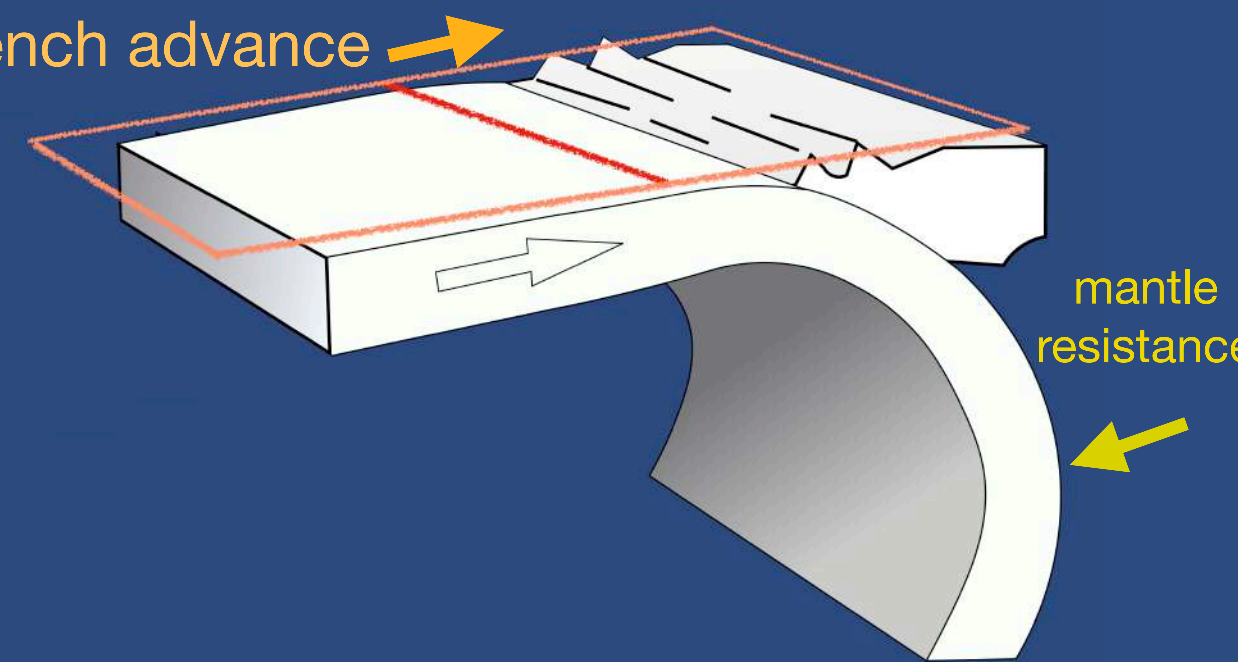

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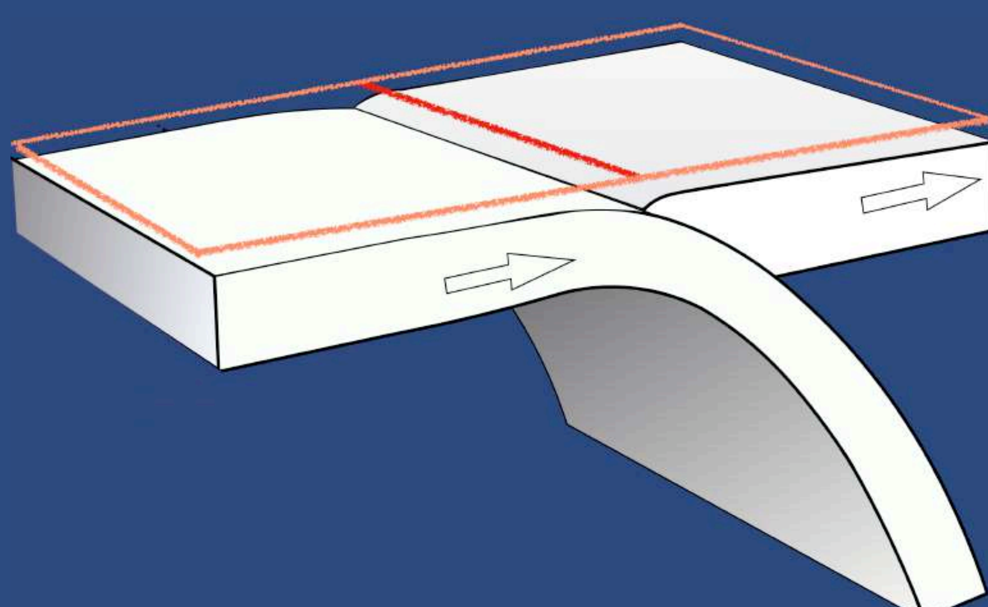

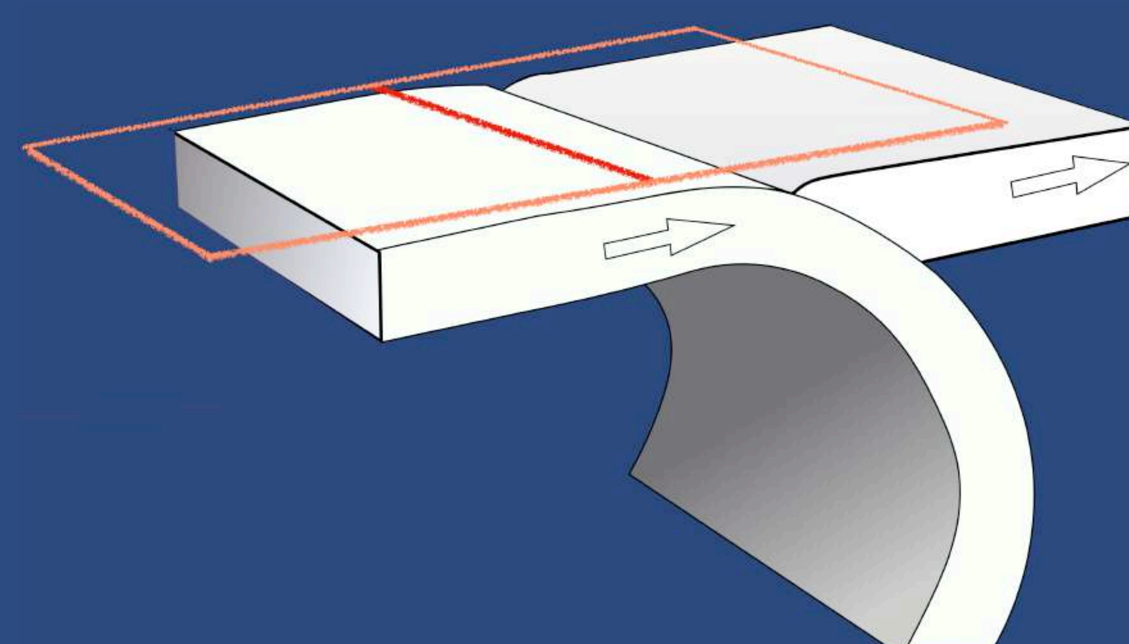

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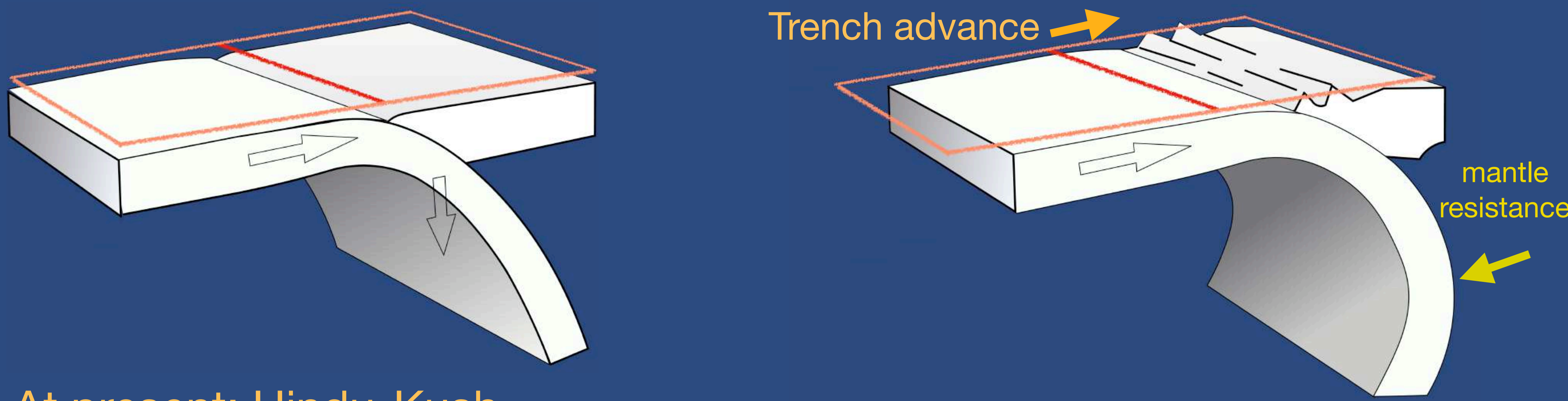

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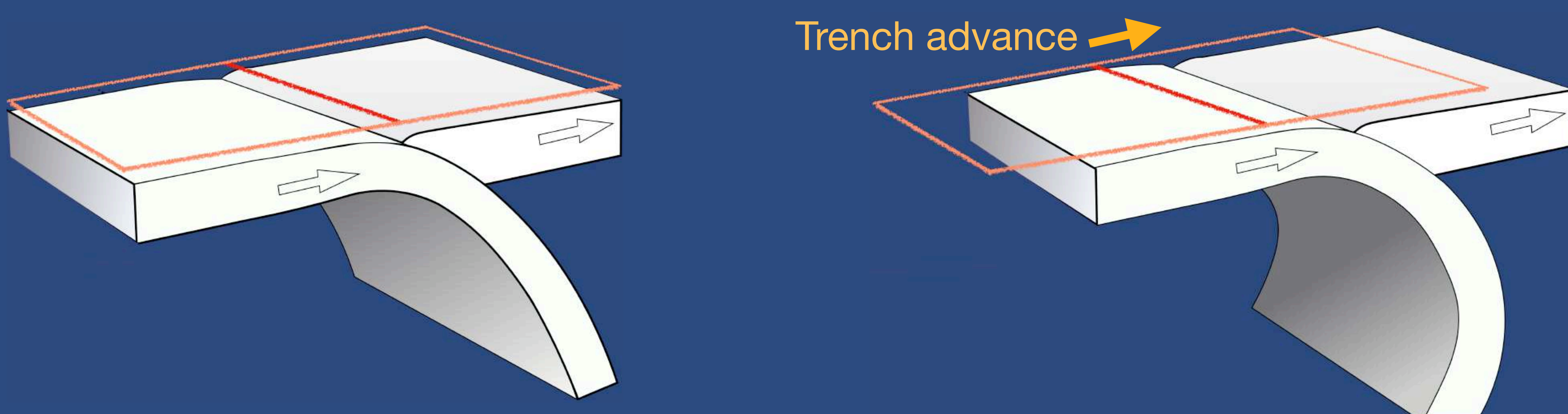

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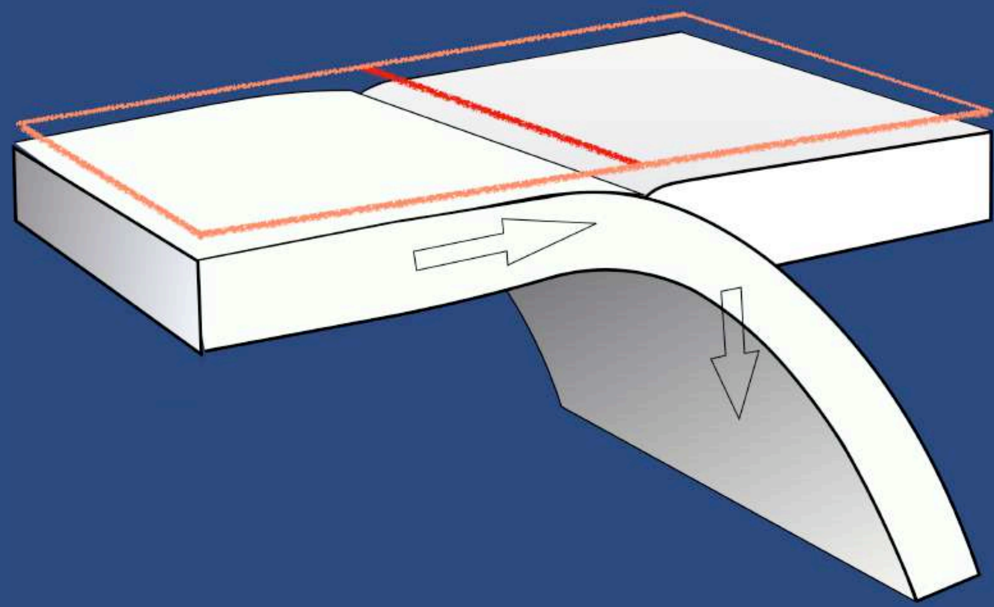

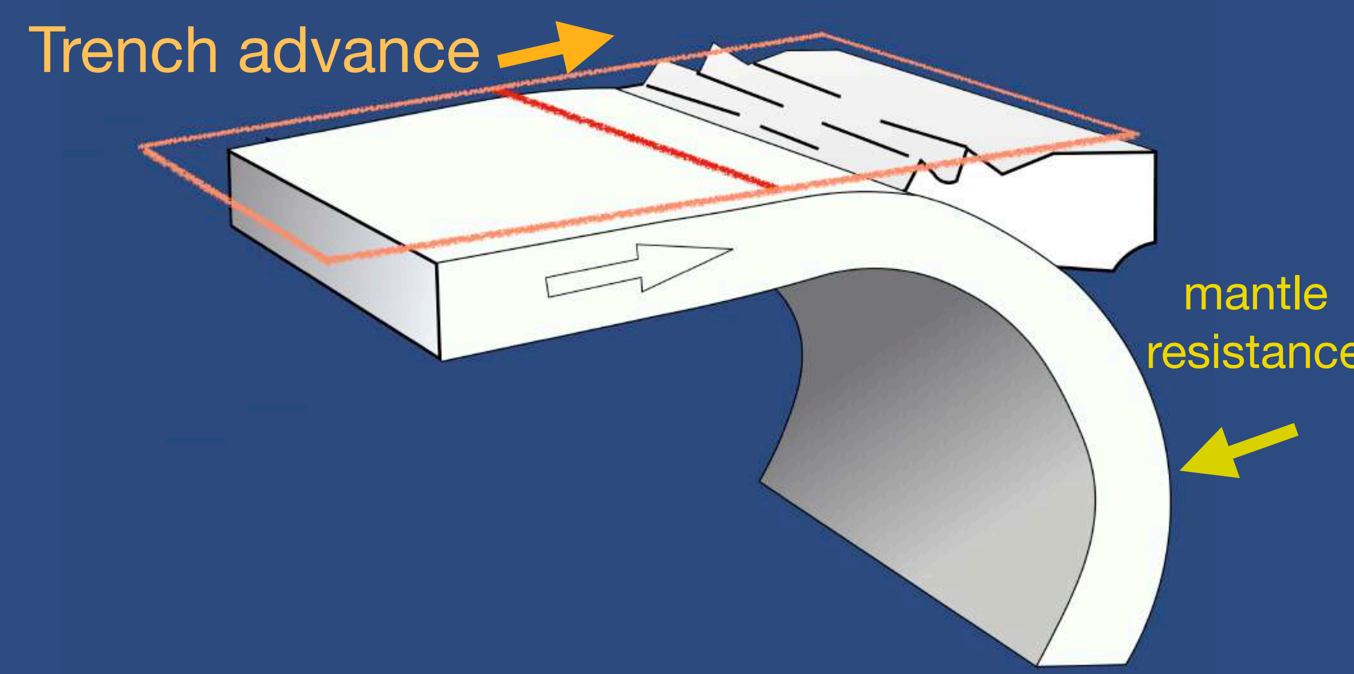

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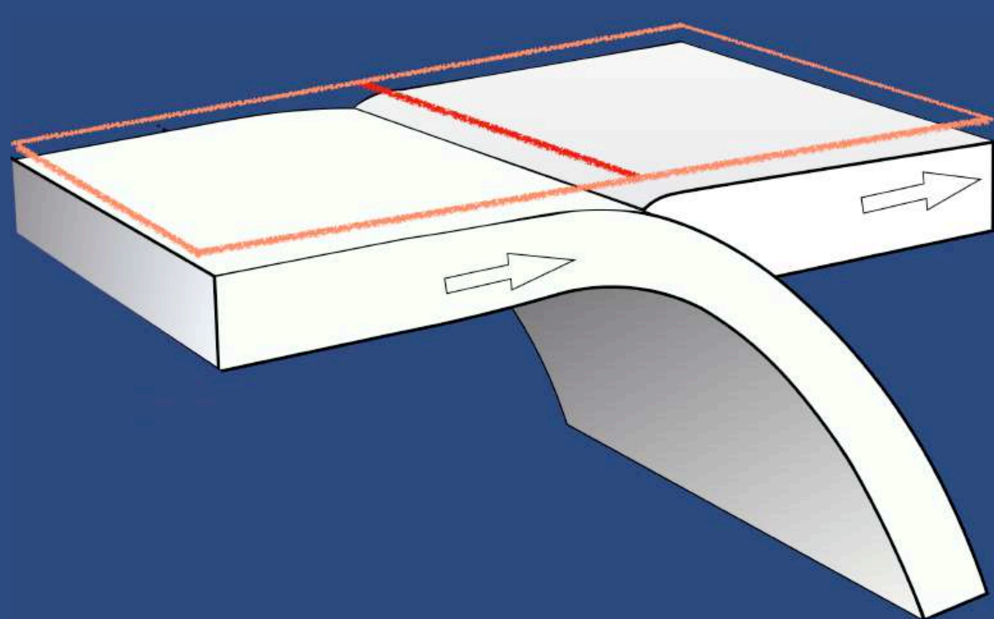

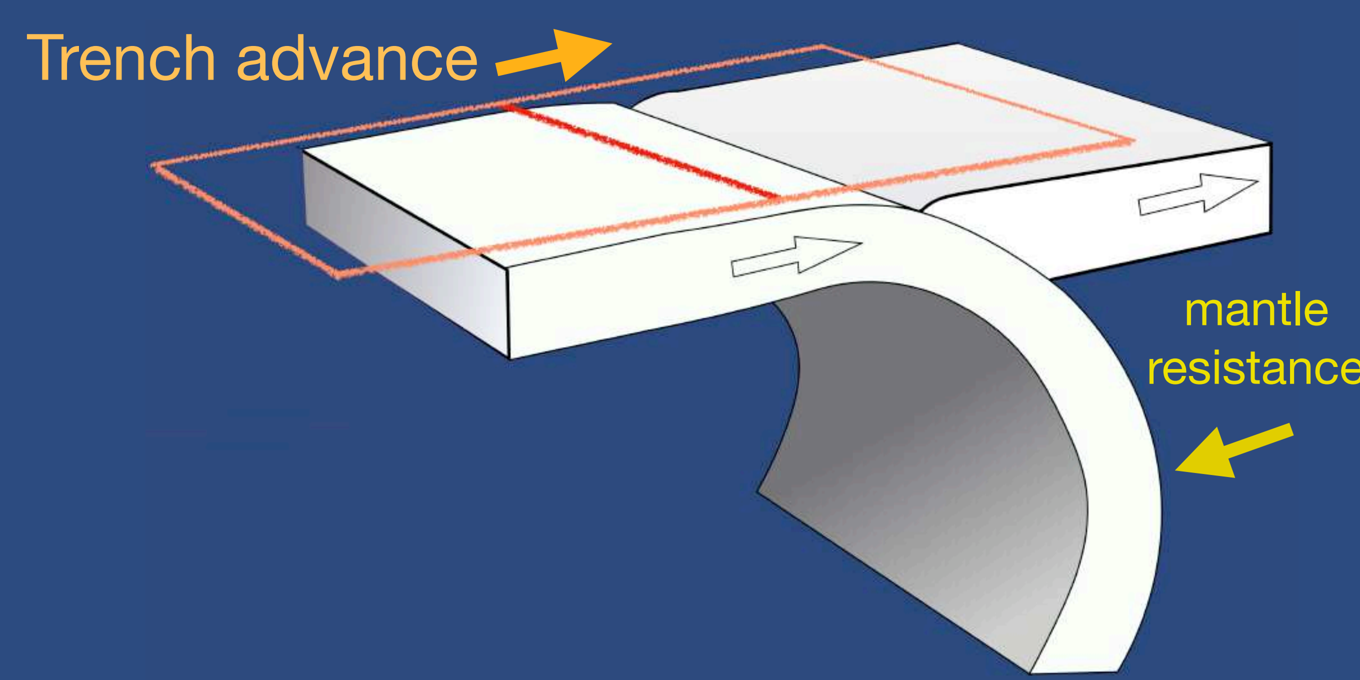

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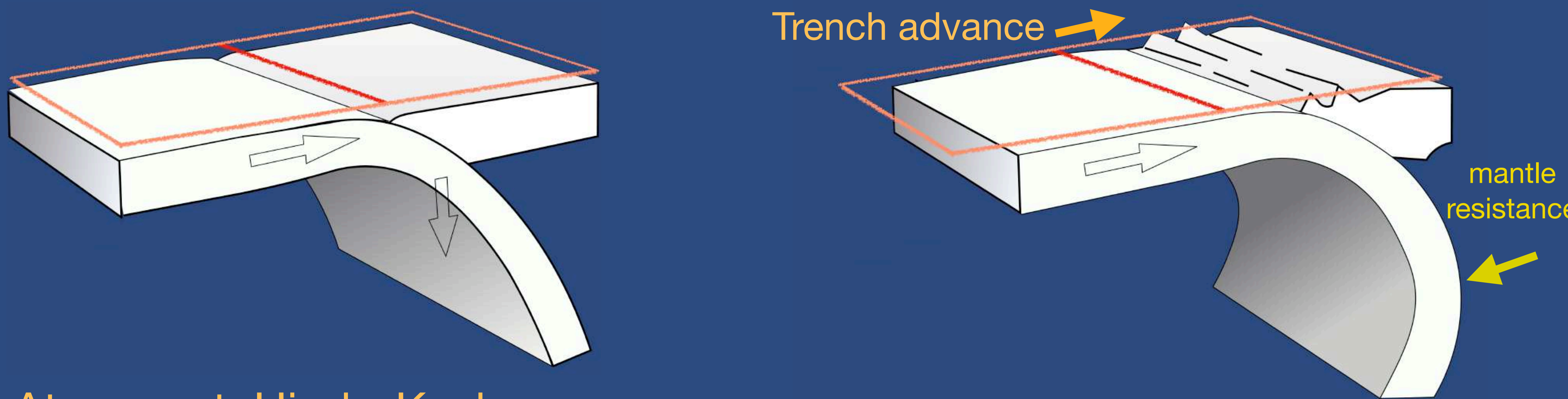

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At present:
Marianas-Philippines Sea plate
e.g. Cizkova and Bina 2015

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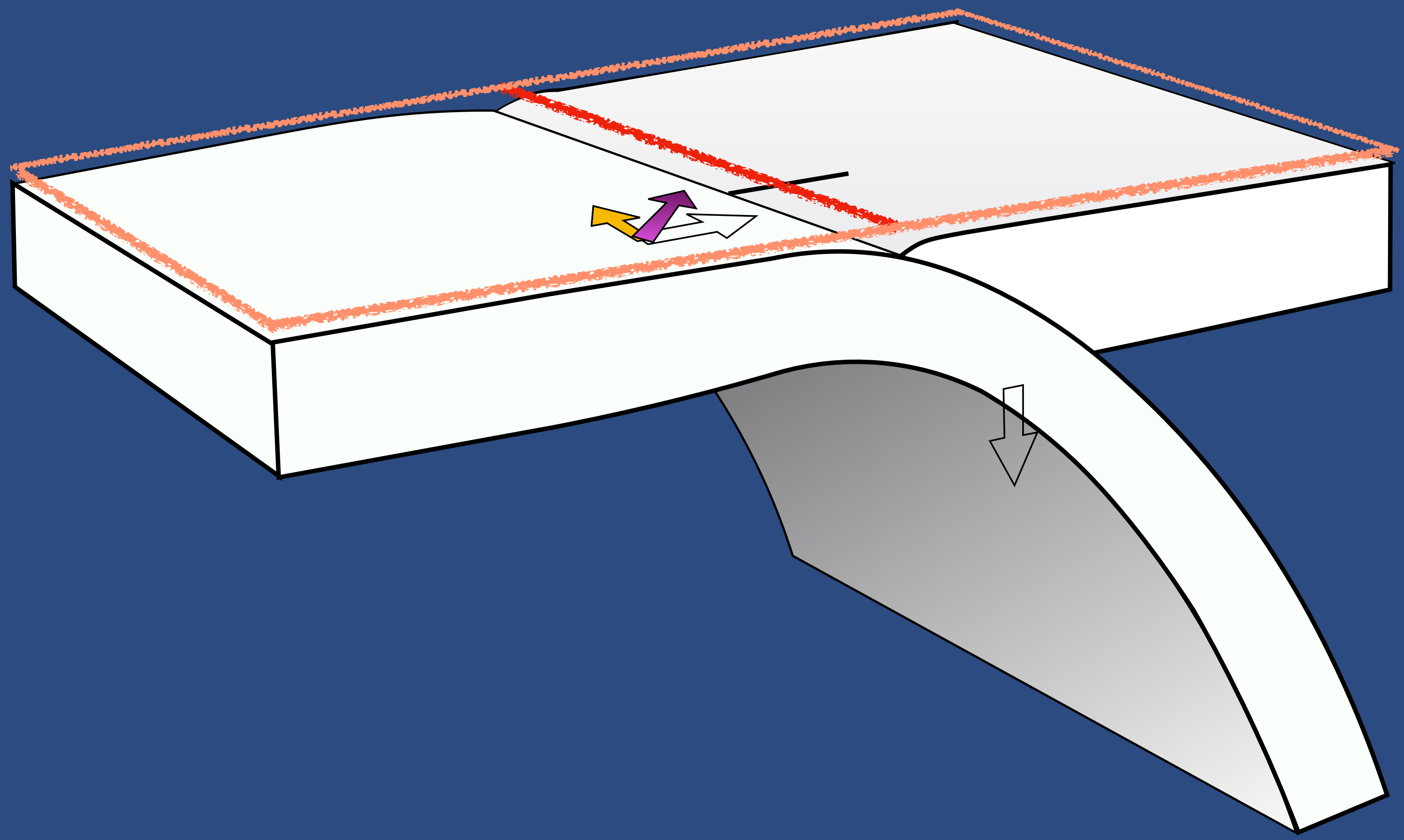
The forcing of trench and slab curvature is still not well understood although it is consistent with the trench-perpendicular nature of slab pull, modelling shows.

There is, however, more to be discovered. Invariably there has been a focus on the trench-perpendicular motions of plates, but plate convergence is generally trench-oblique.



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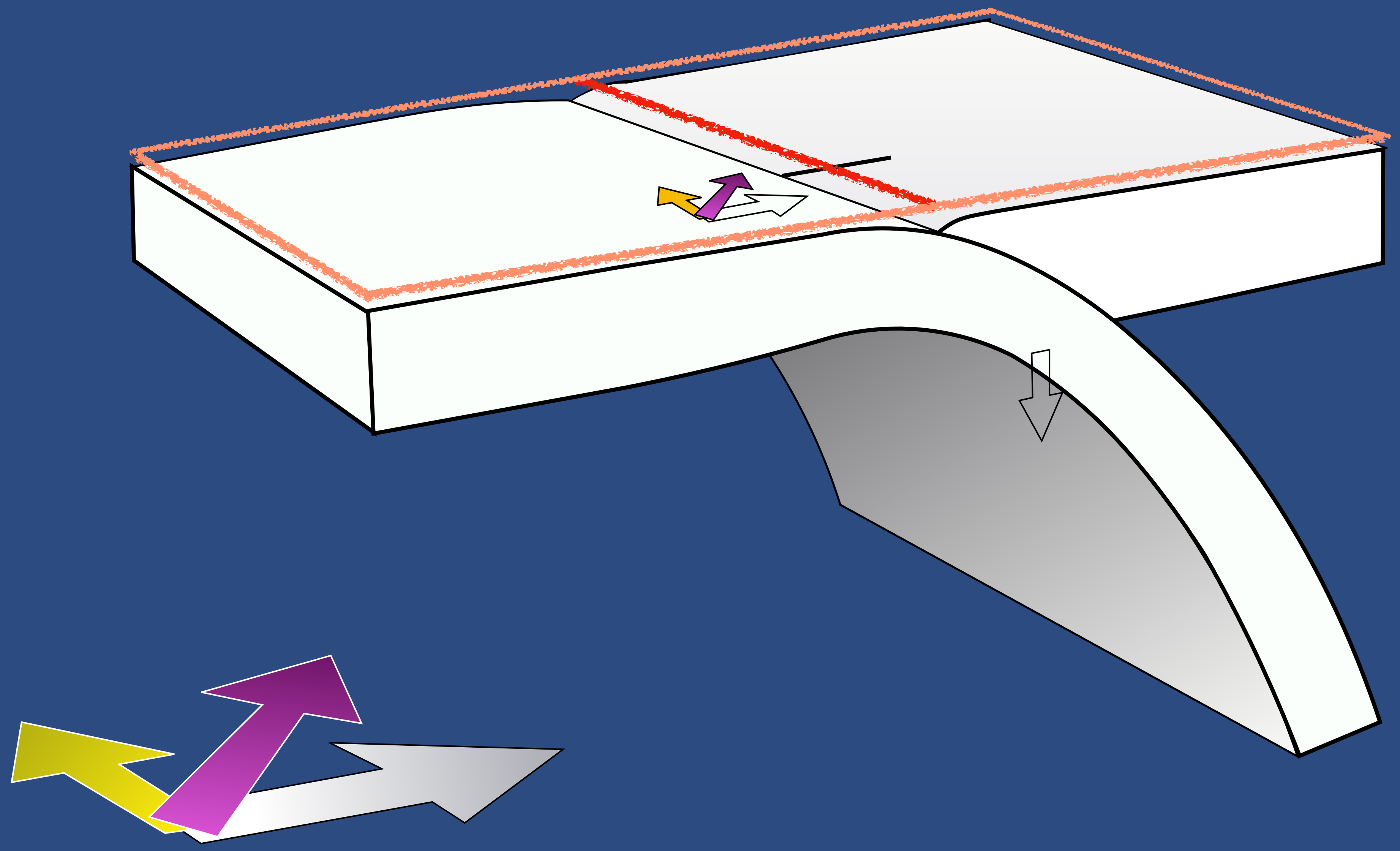

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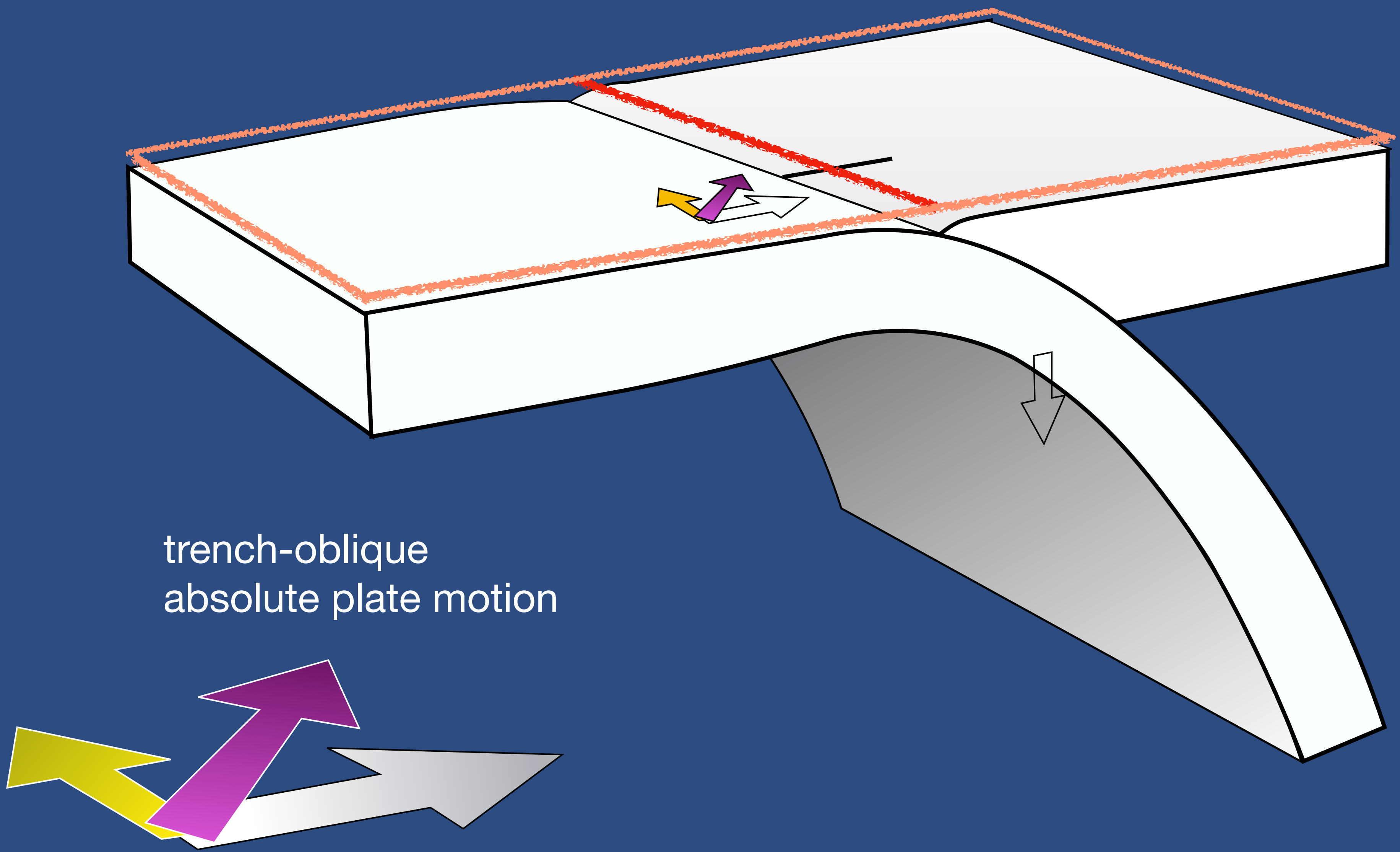

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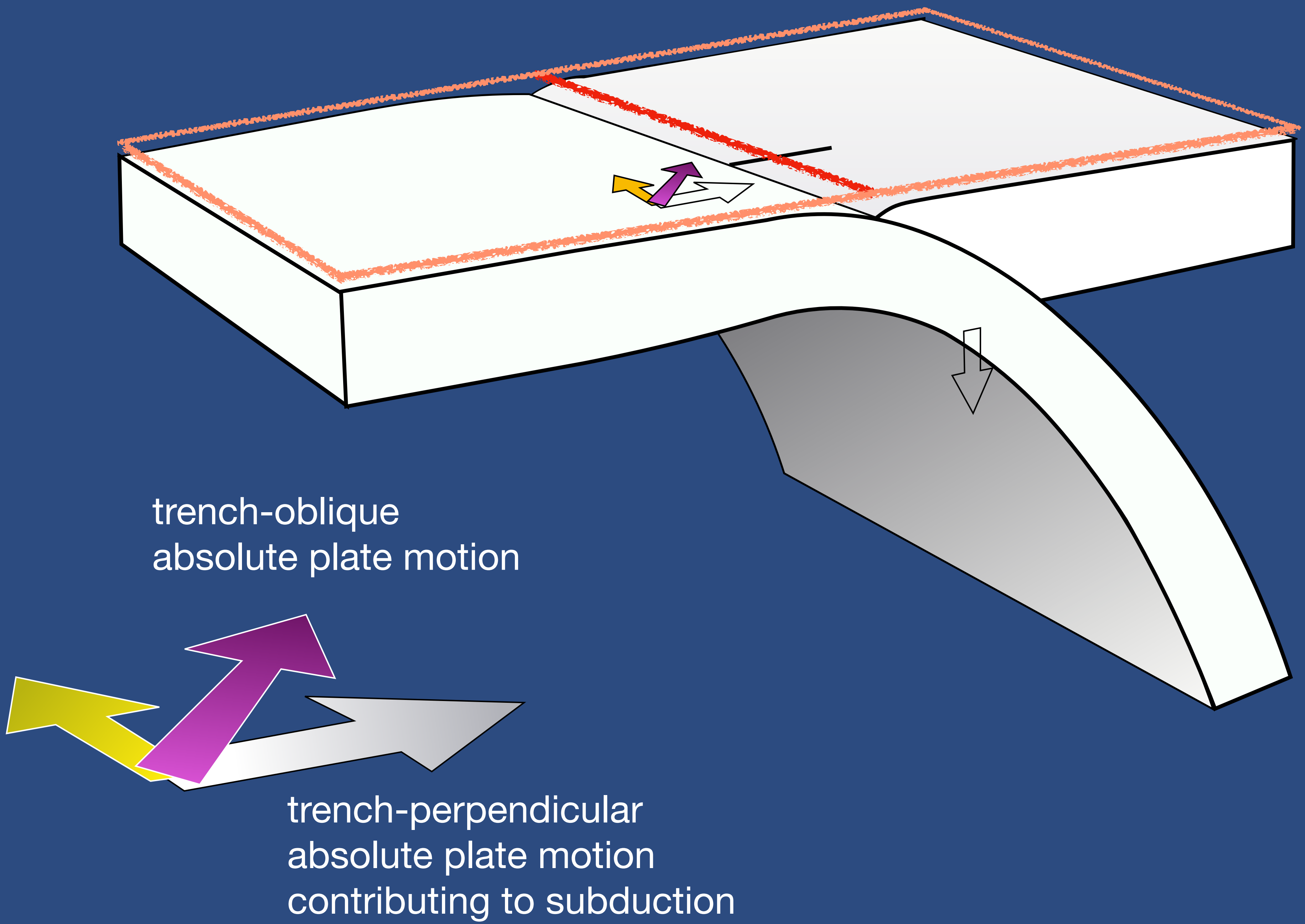

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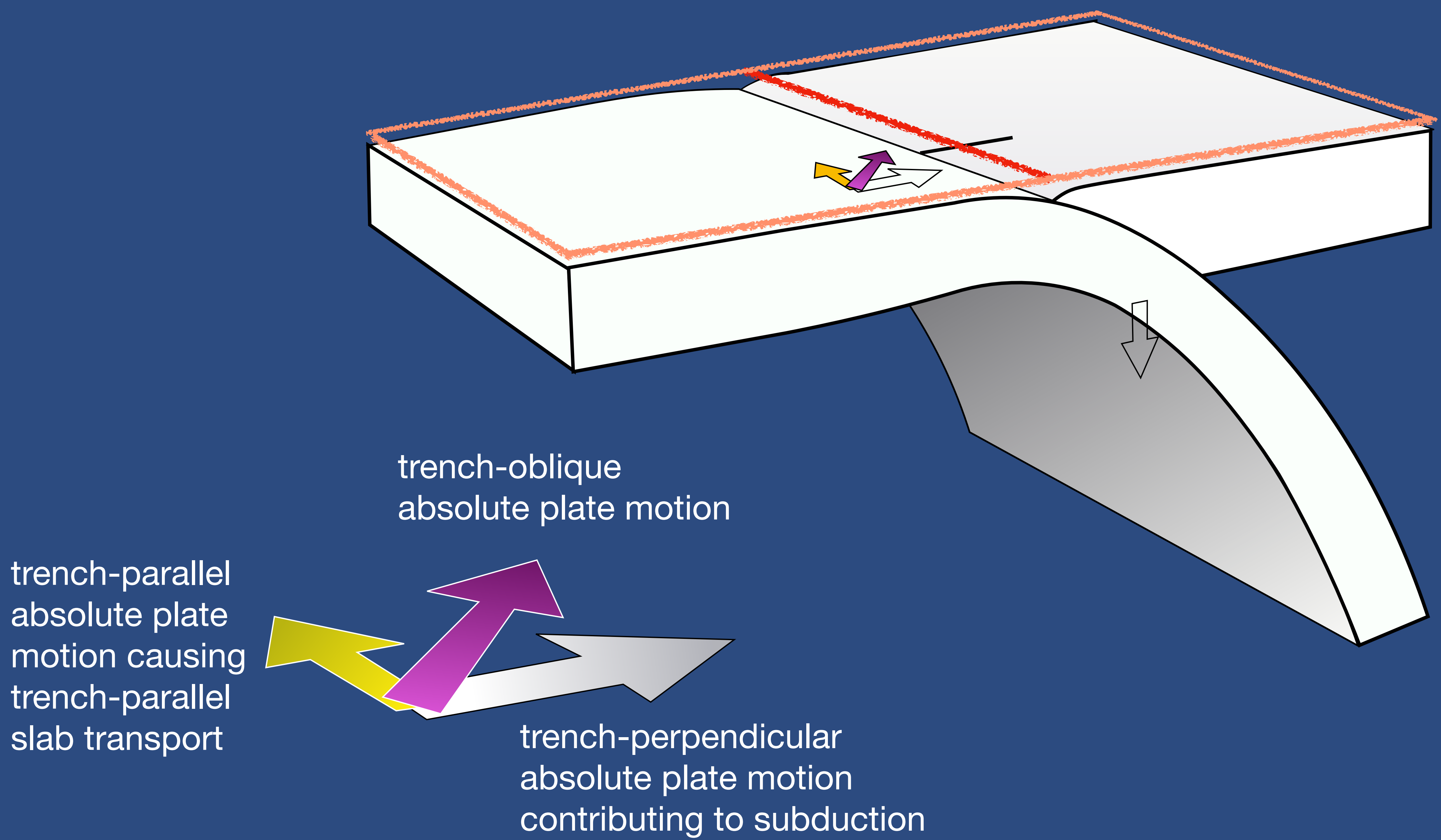

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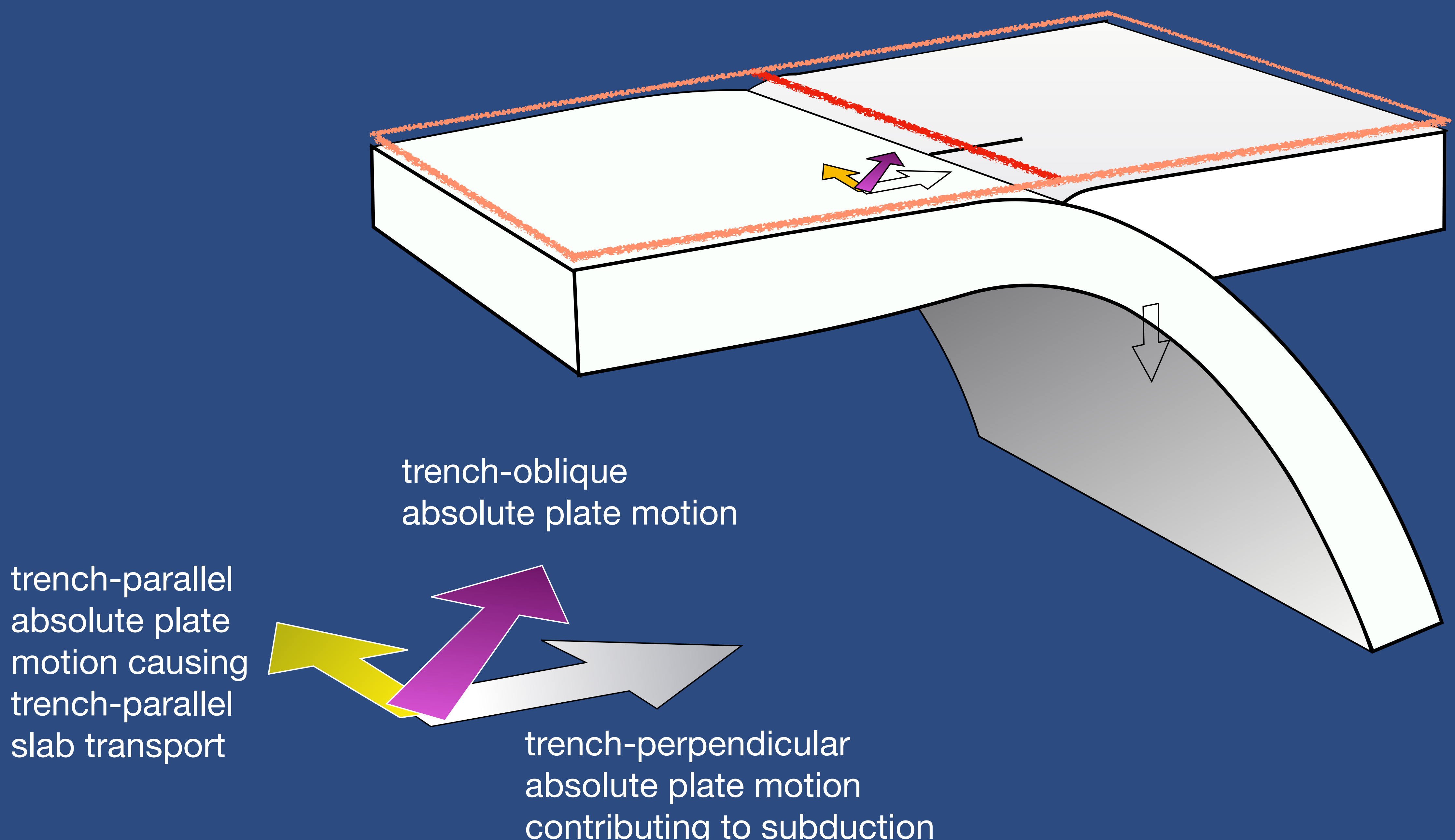
Slab dragging



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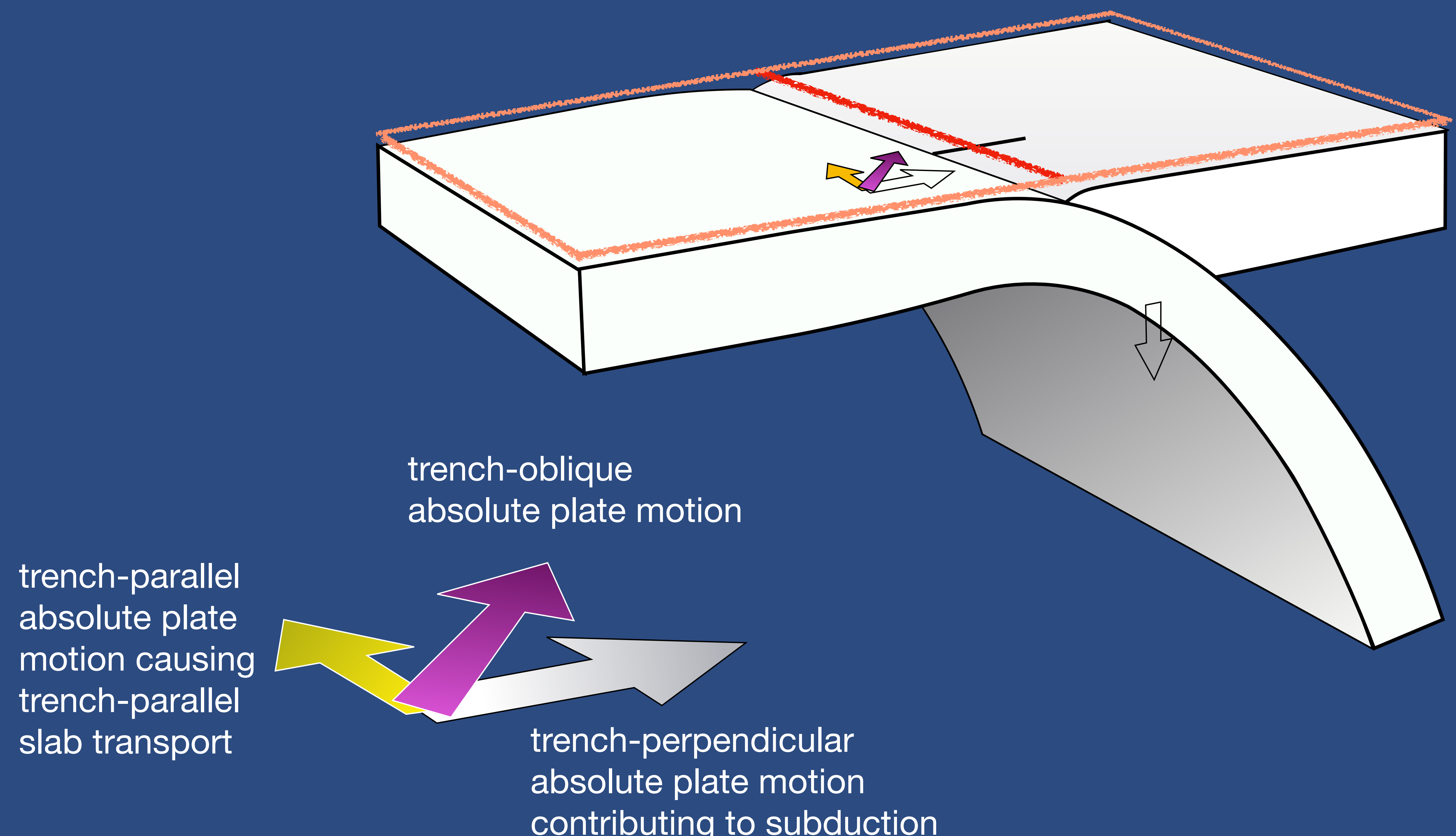
Slab dragging = **lateral transport of the slab forced by, and in the direction of, the absolute motion of the subducting plate** (Spakman et al. 2018).



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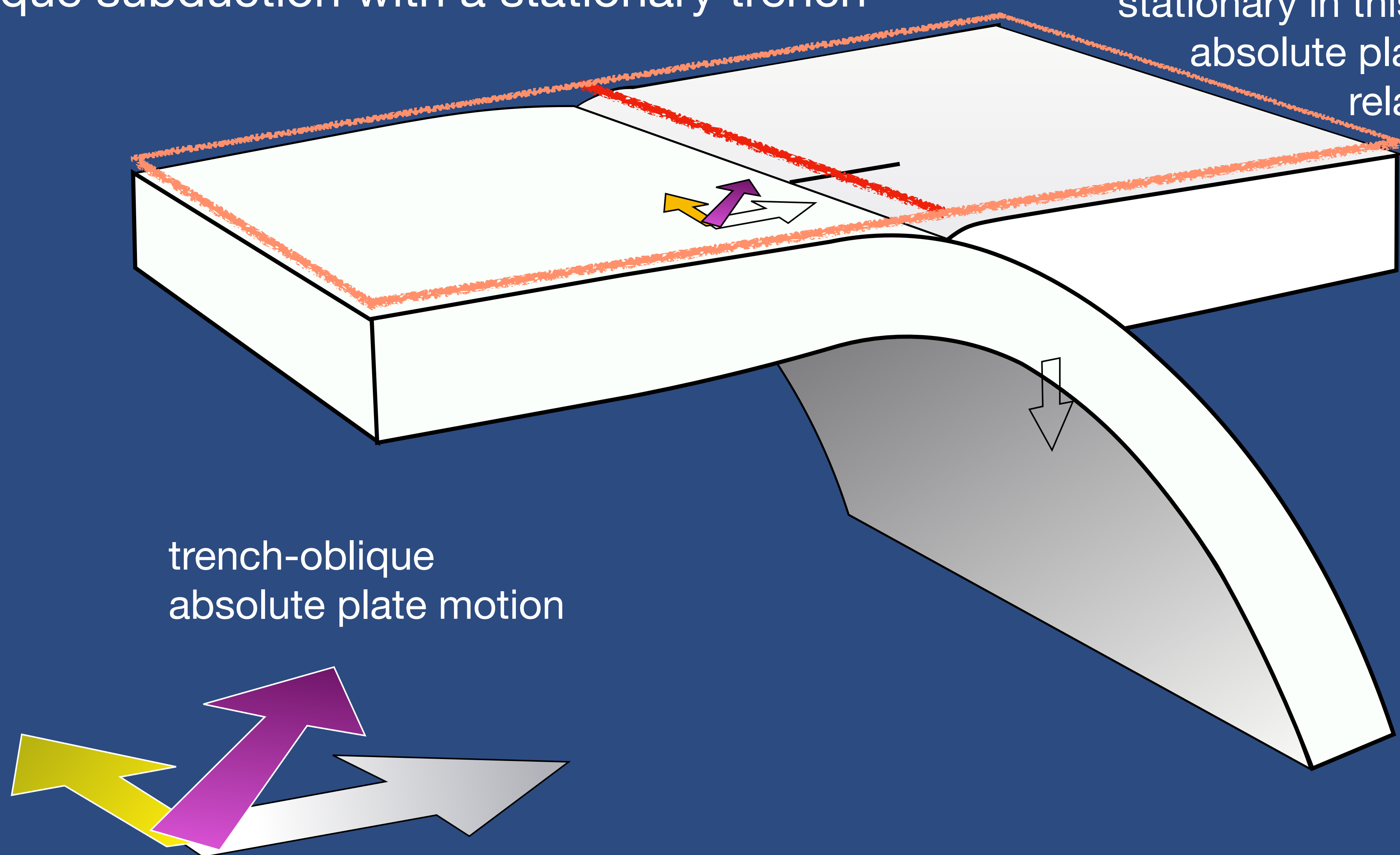
Example: Oblique subduction with a stationary trench

The upper plate is assumed mantle stationary in this example, hence absolute plate motion equals relative plate motion



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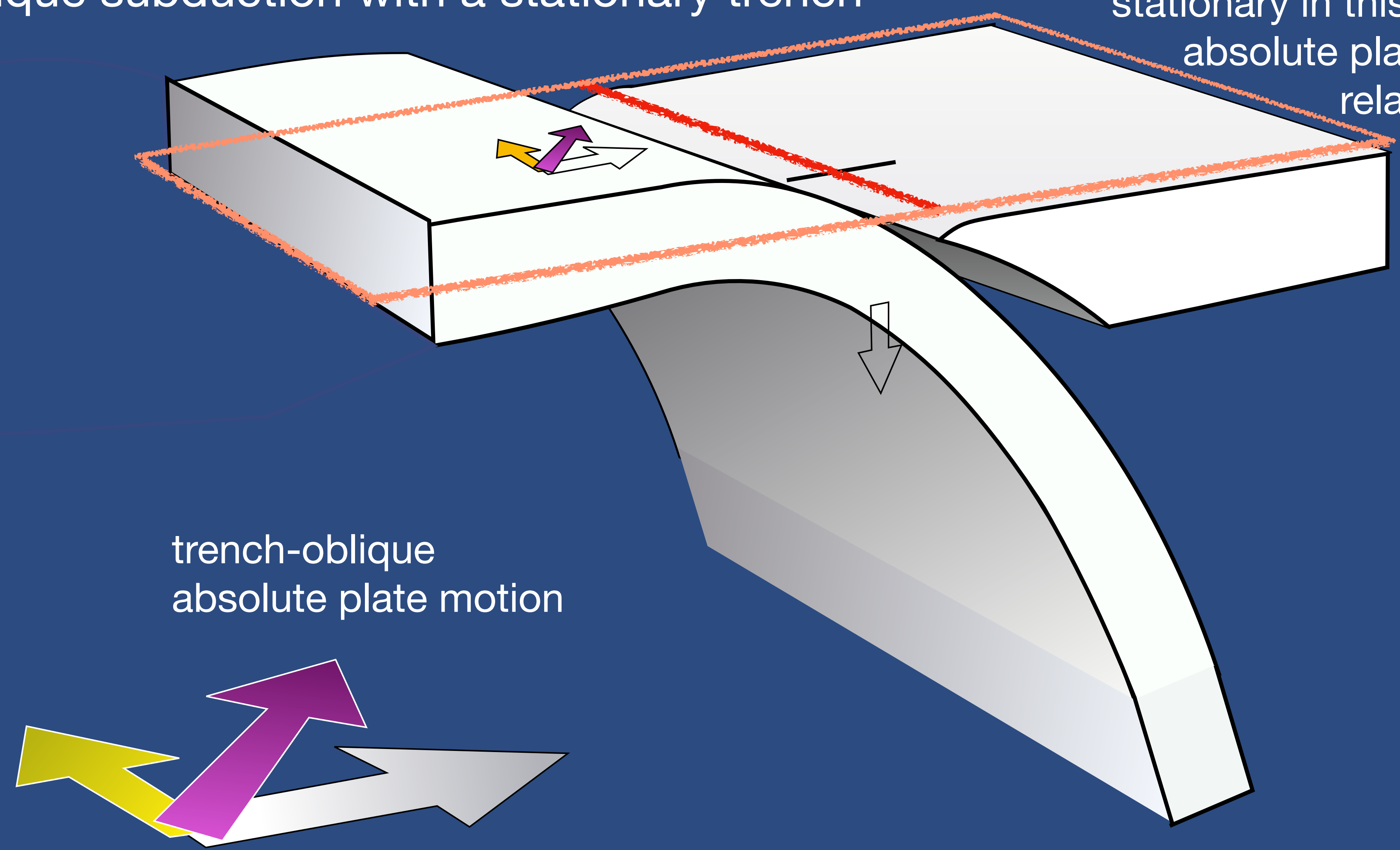

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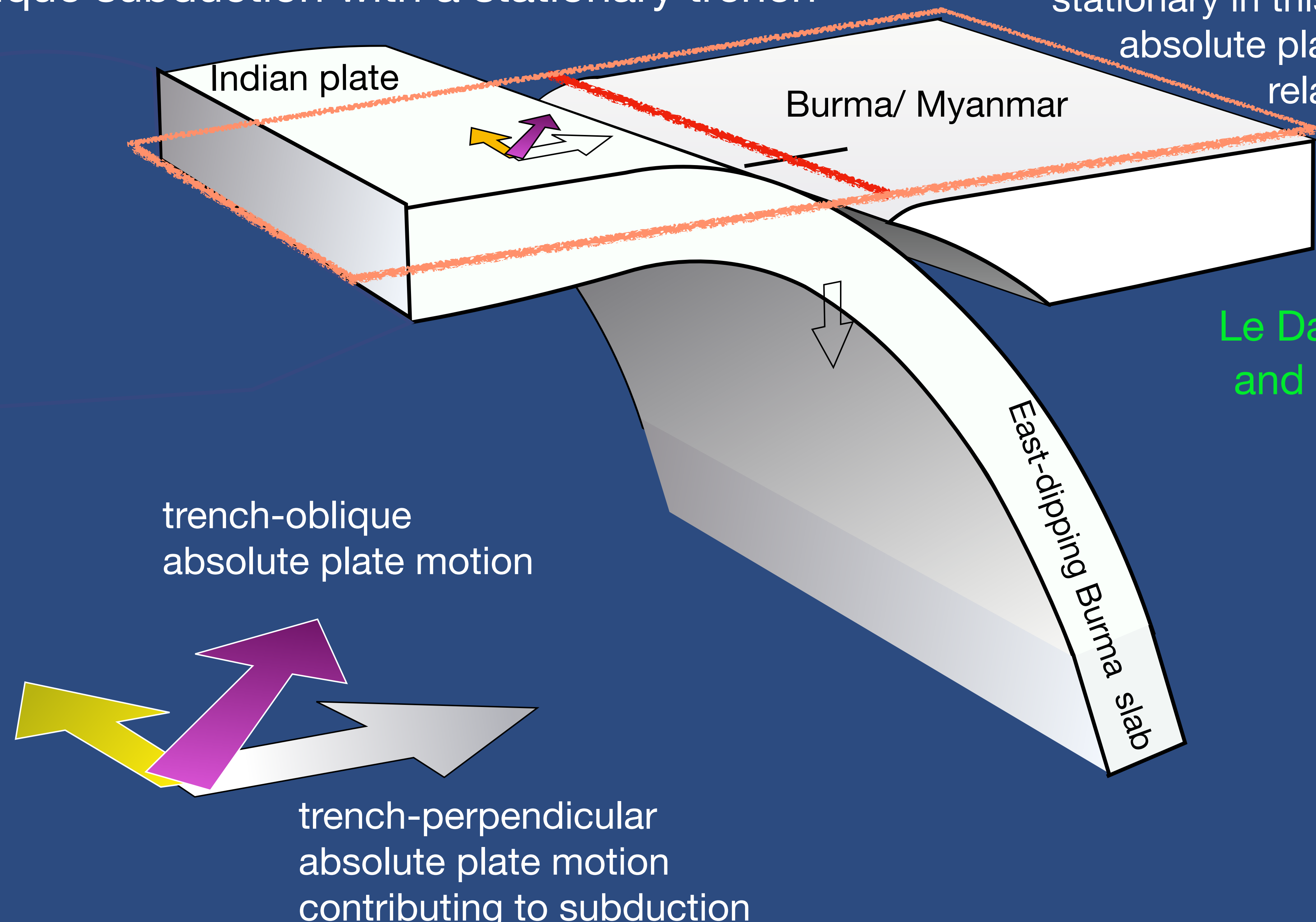

Le Dain, Tapponier and Molnar 1984

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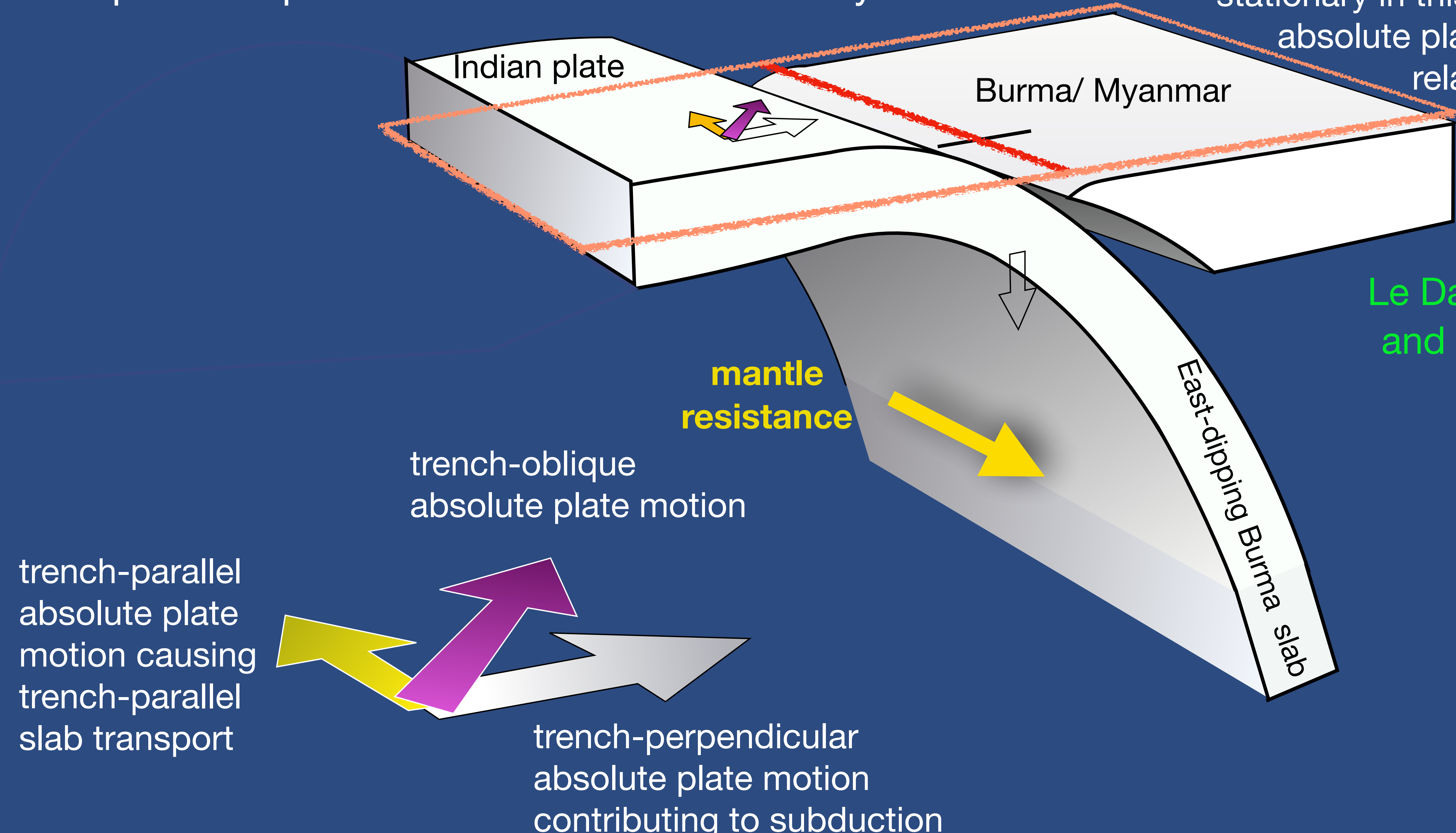
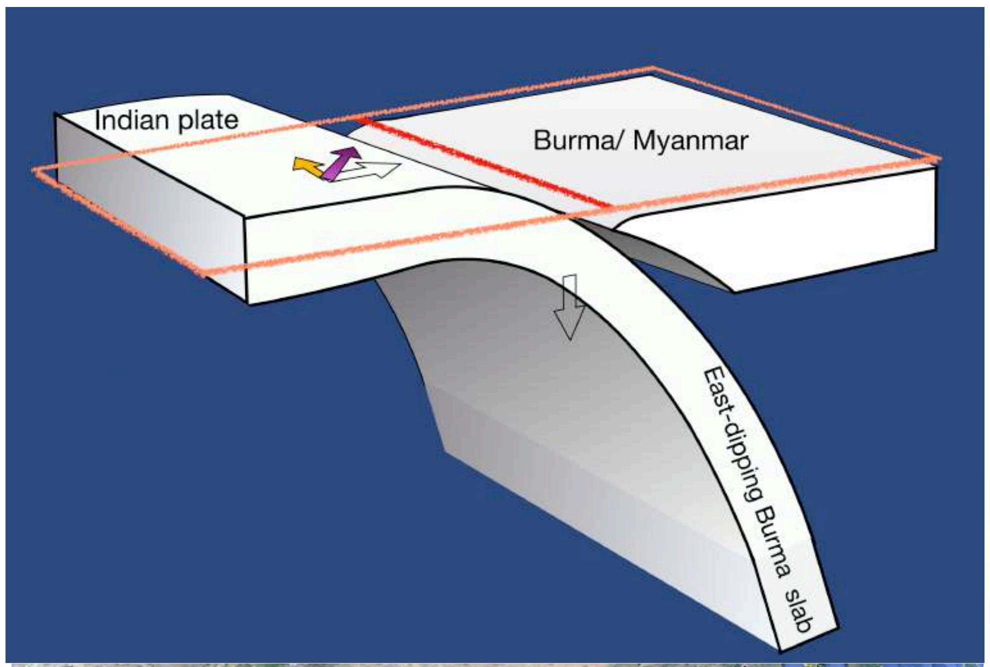
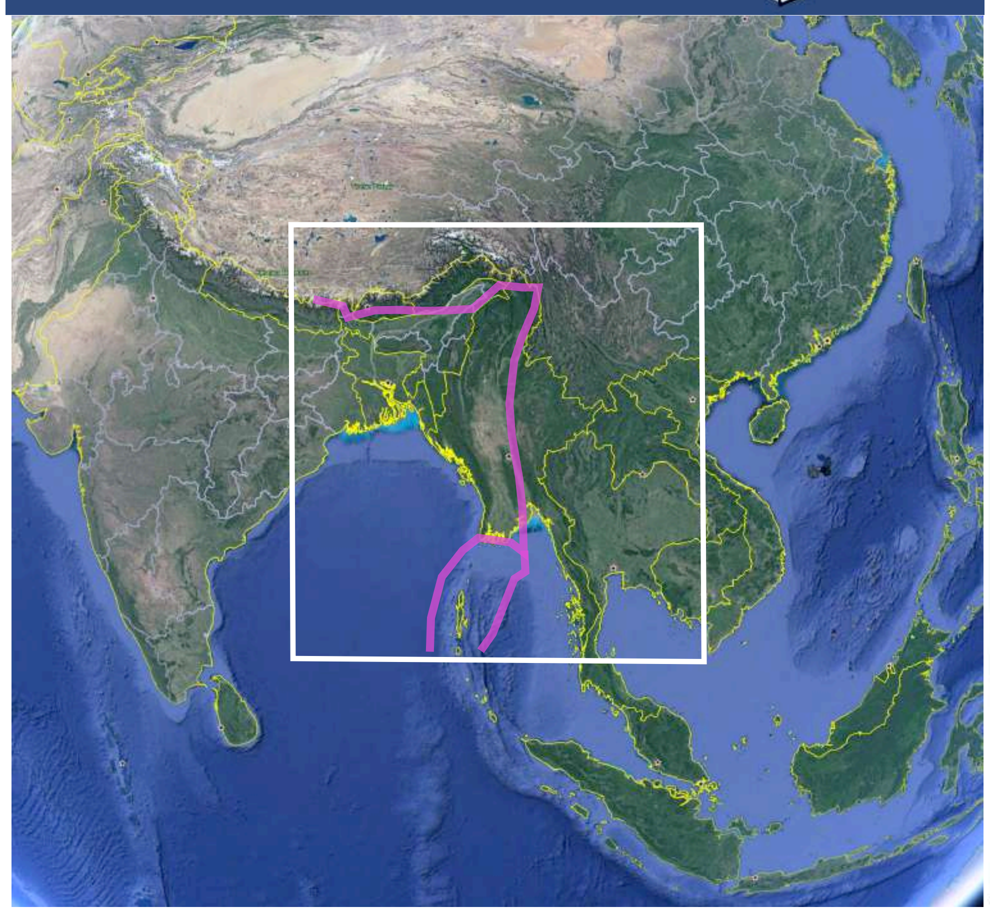
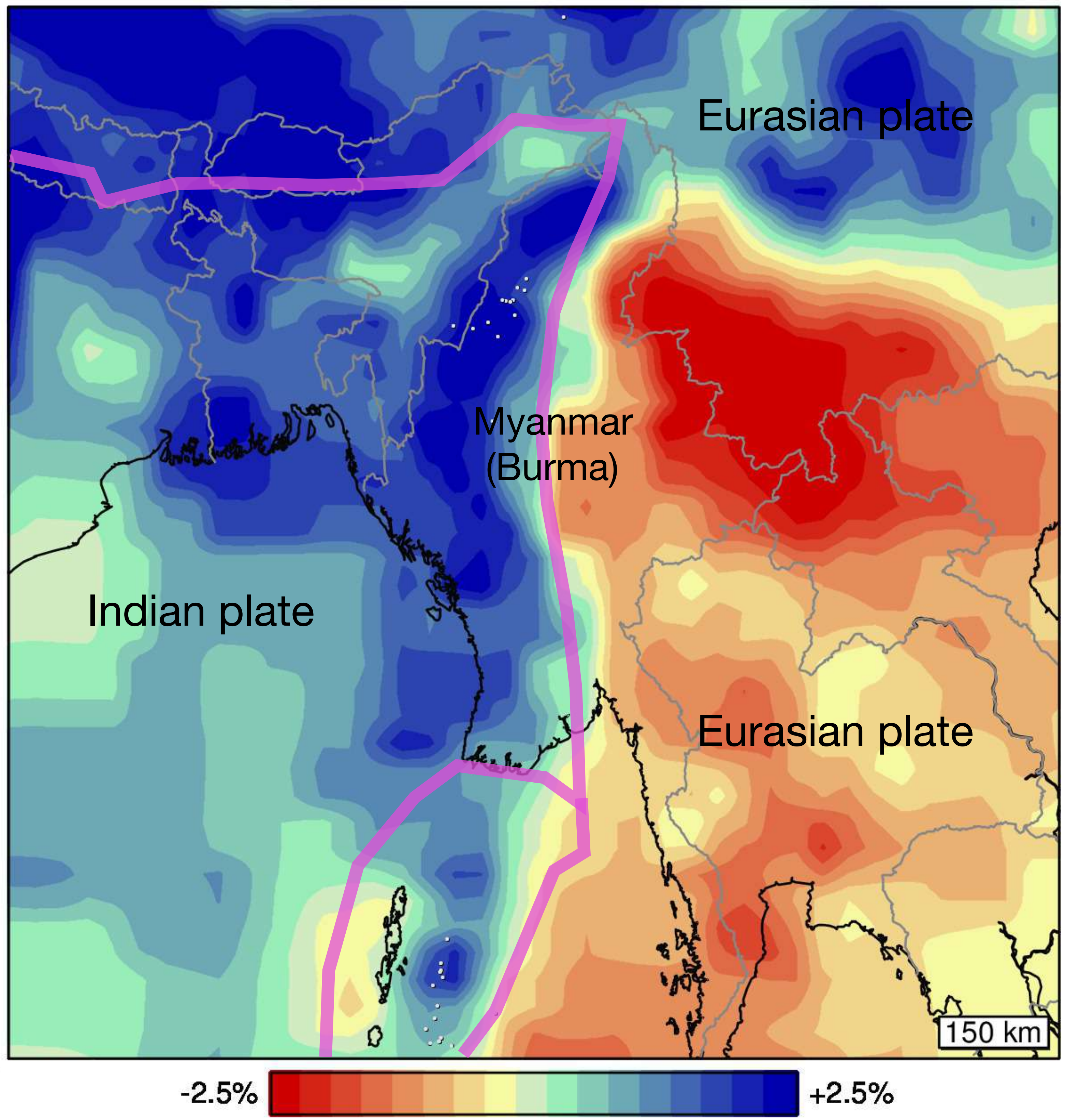


Le Dain, Tapponier and Molnar 1984

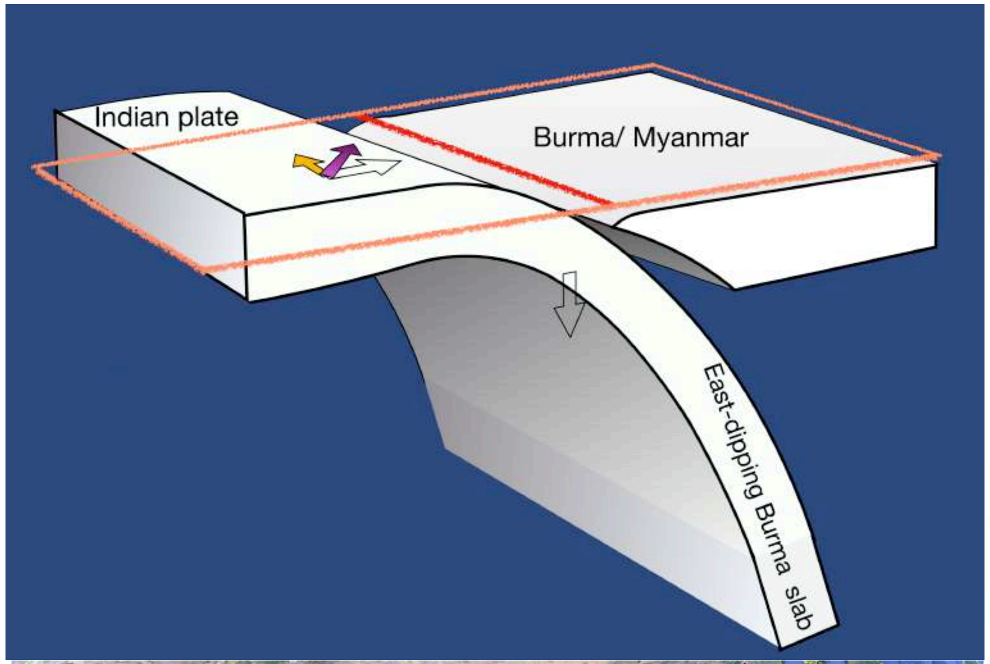
Dragging of the Burma slab by the absolute motion of the Indian plate

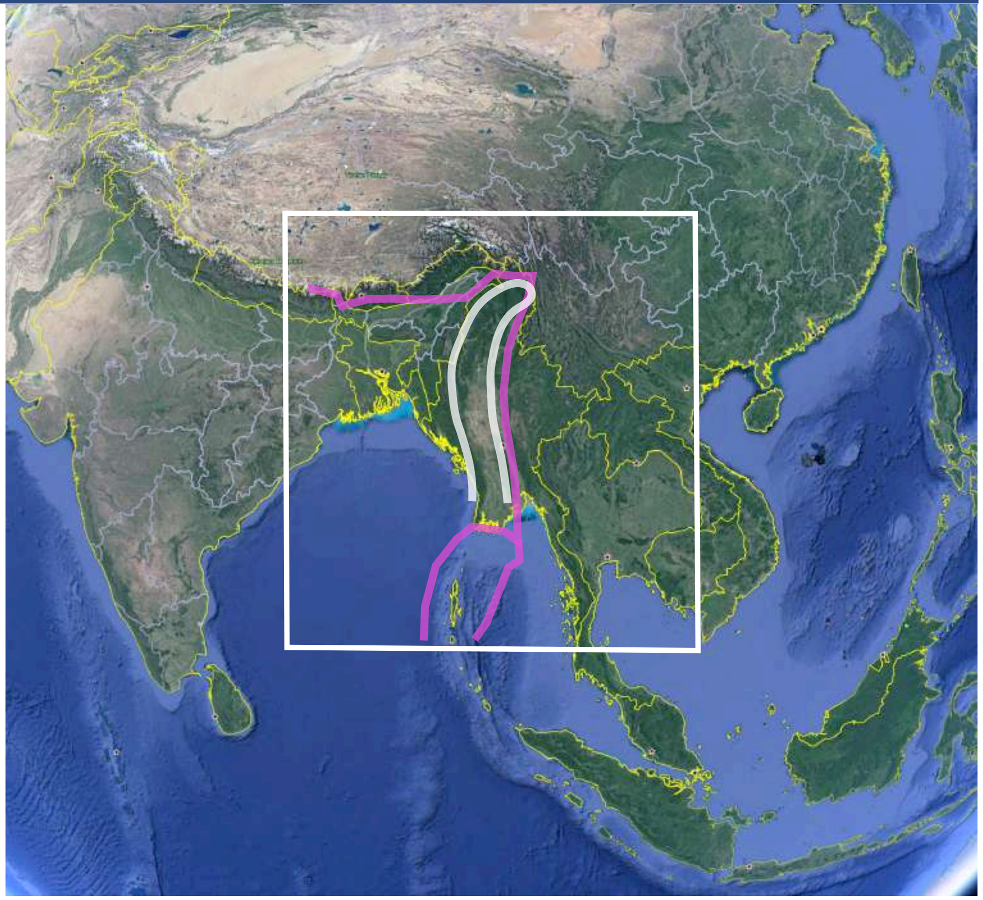


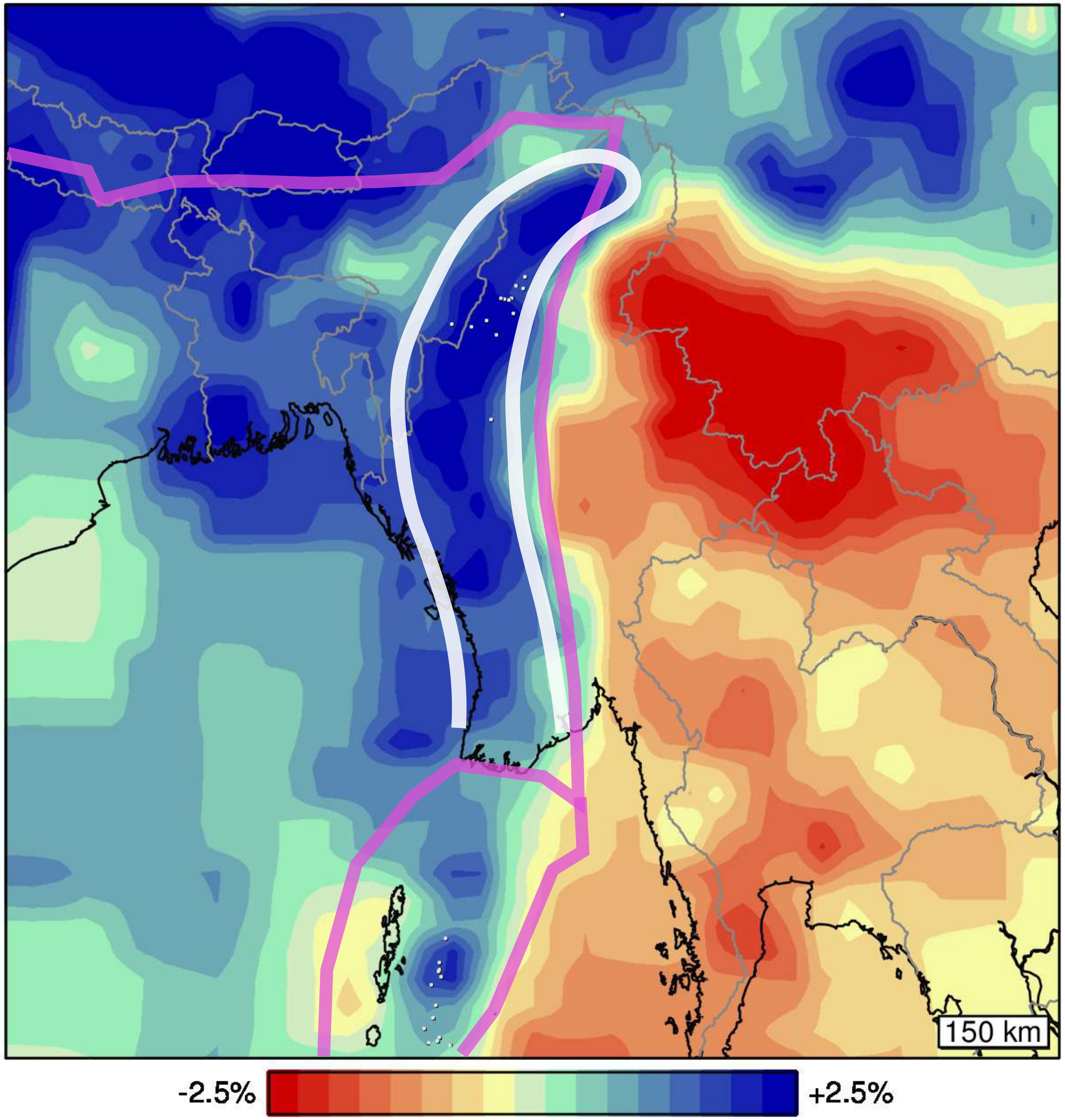




Dragging of the Burma slab by the absolute motion of the Indian plate





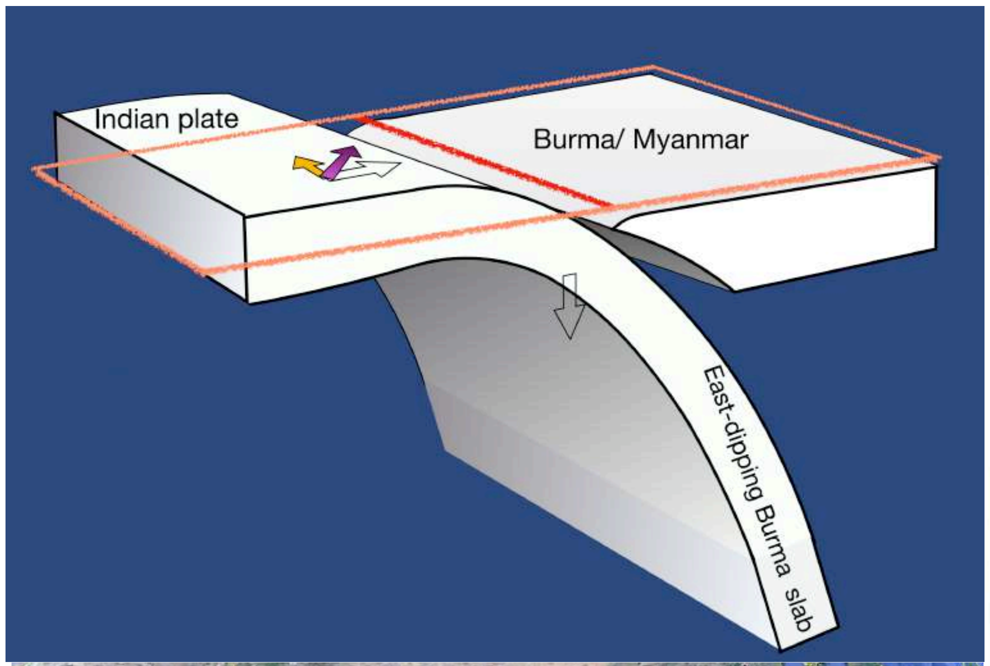


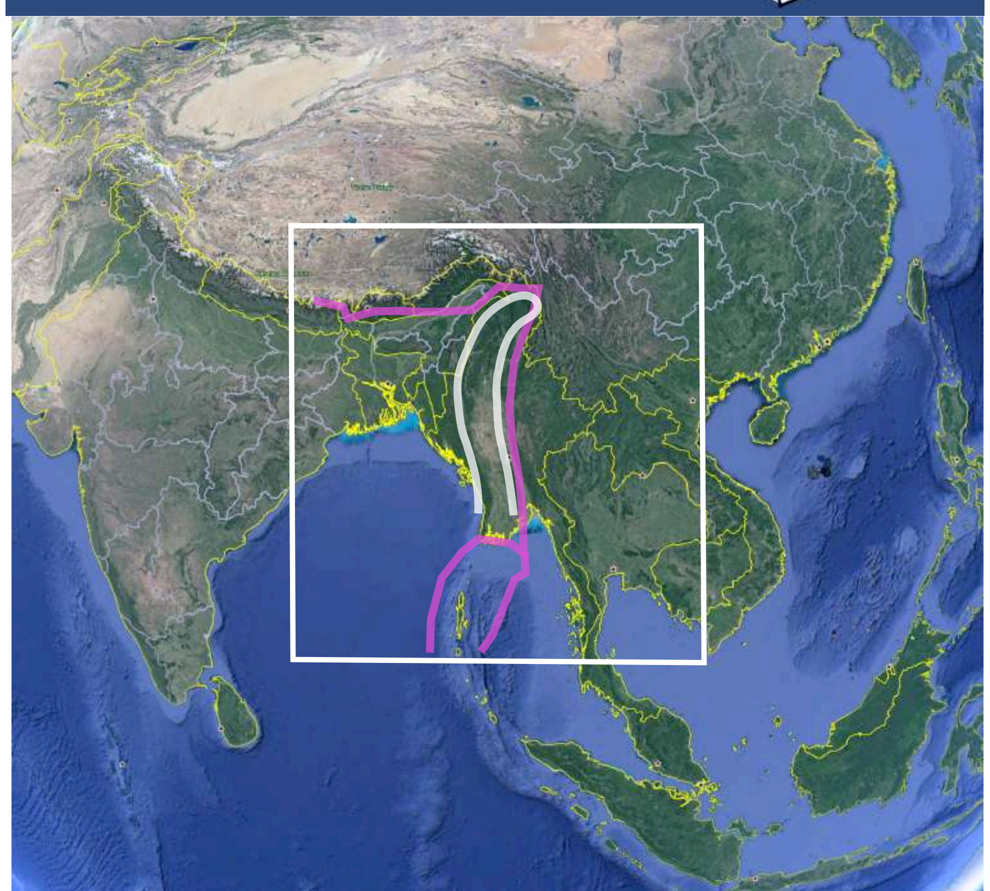
Dragging of the Burma slab by the absolute motion of the Indian plate

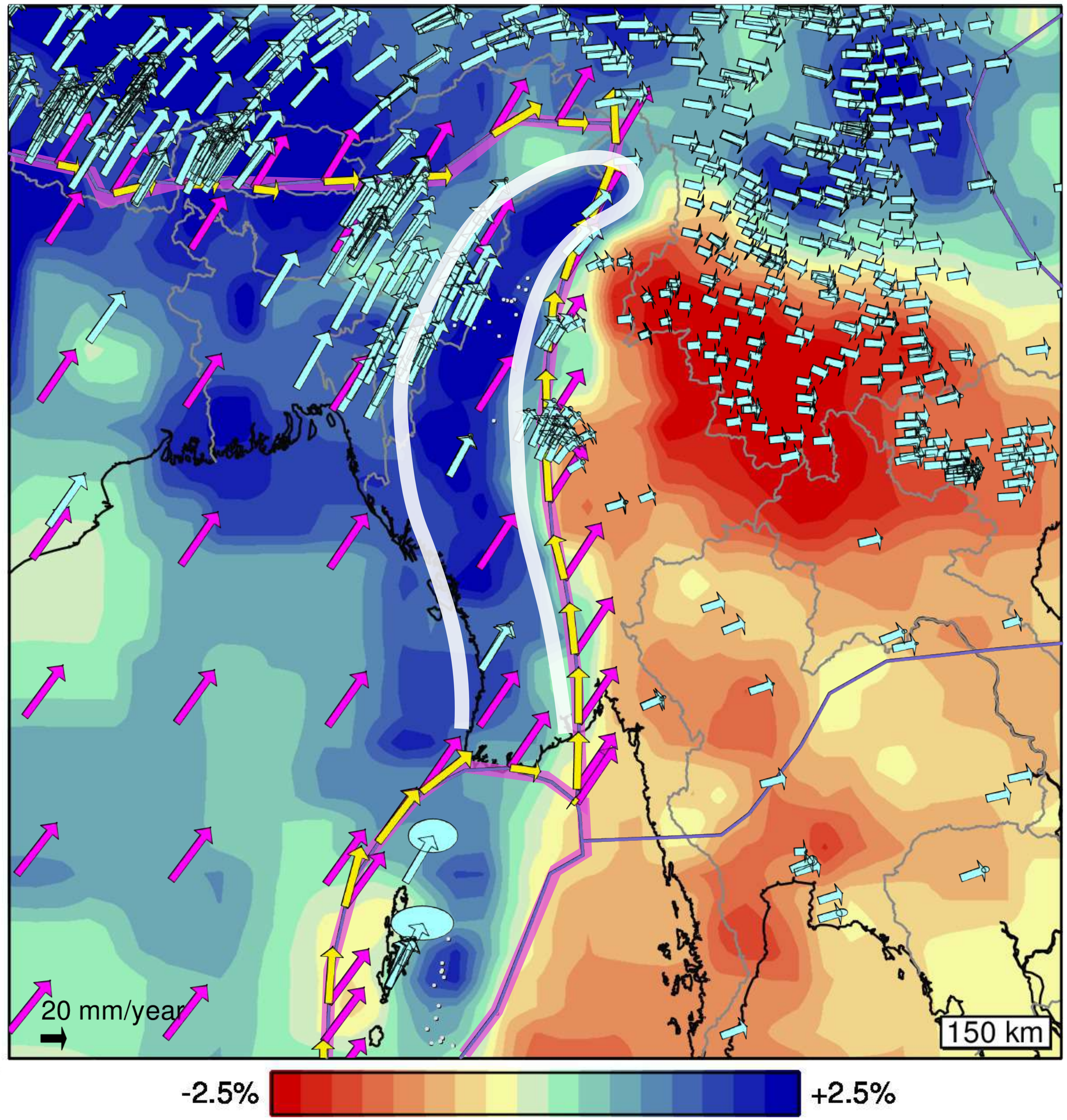
Magenta: absolute motion of Indian plate

Yellow: Indian motion parallel to plate boundary

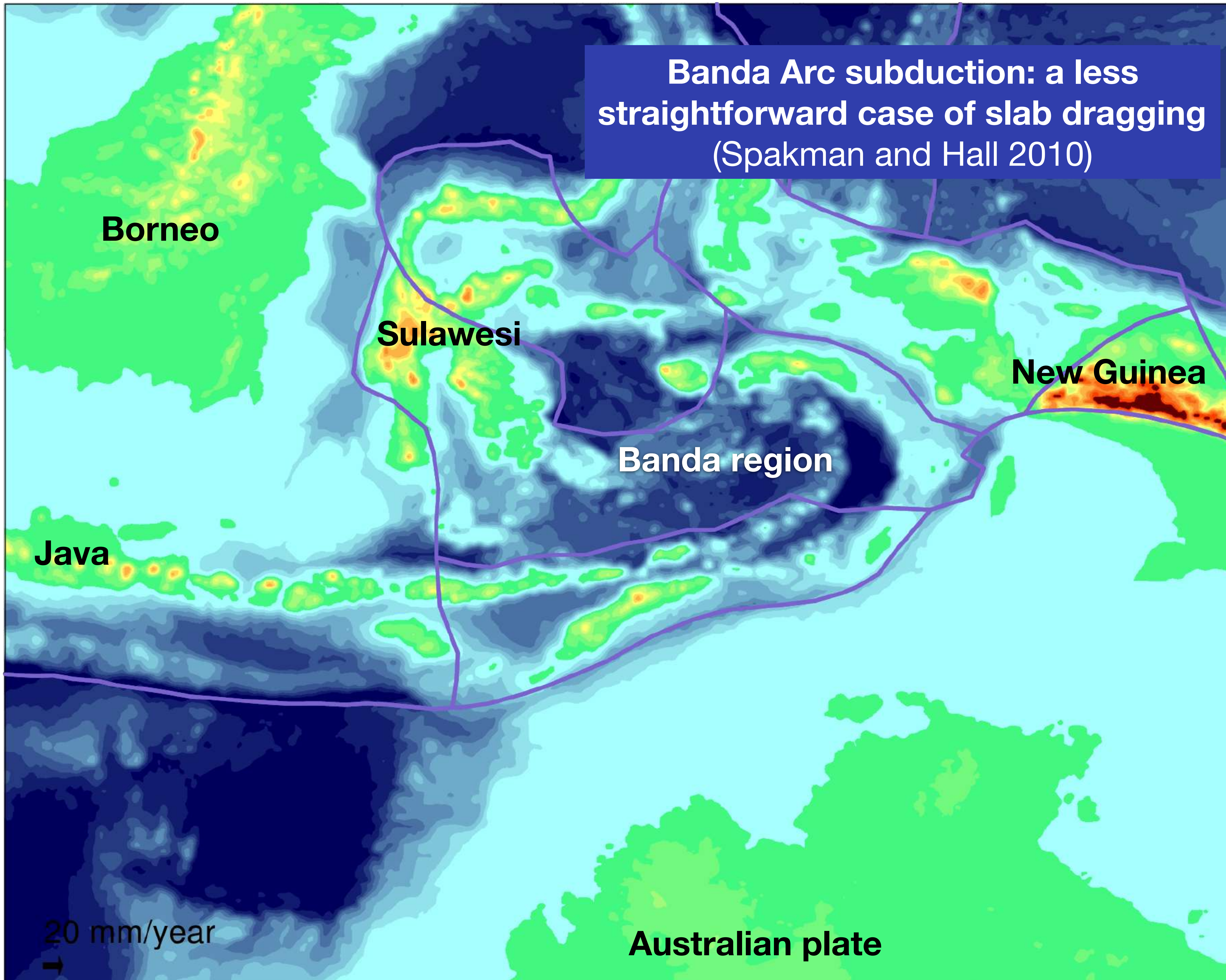
Blue: GPS motions

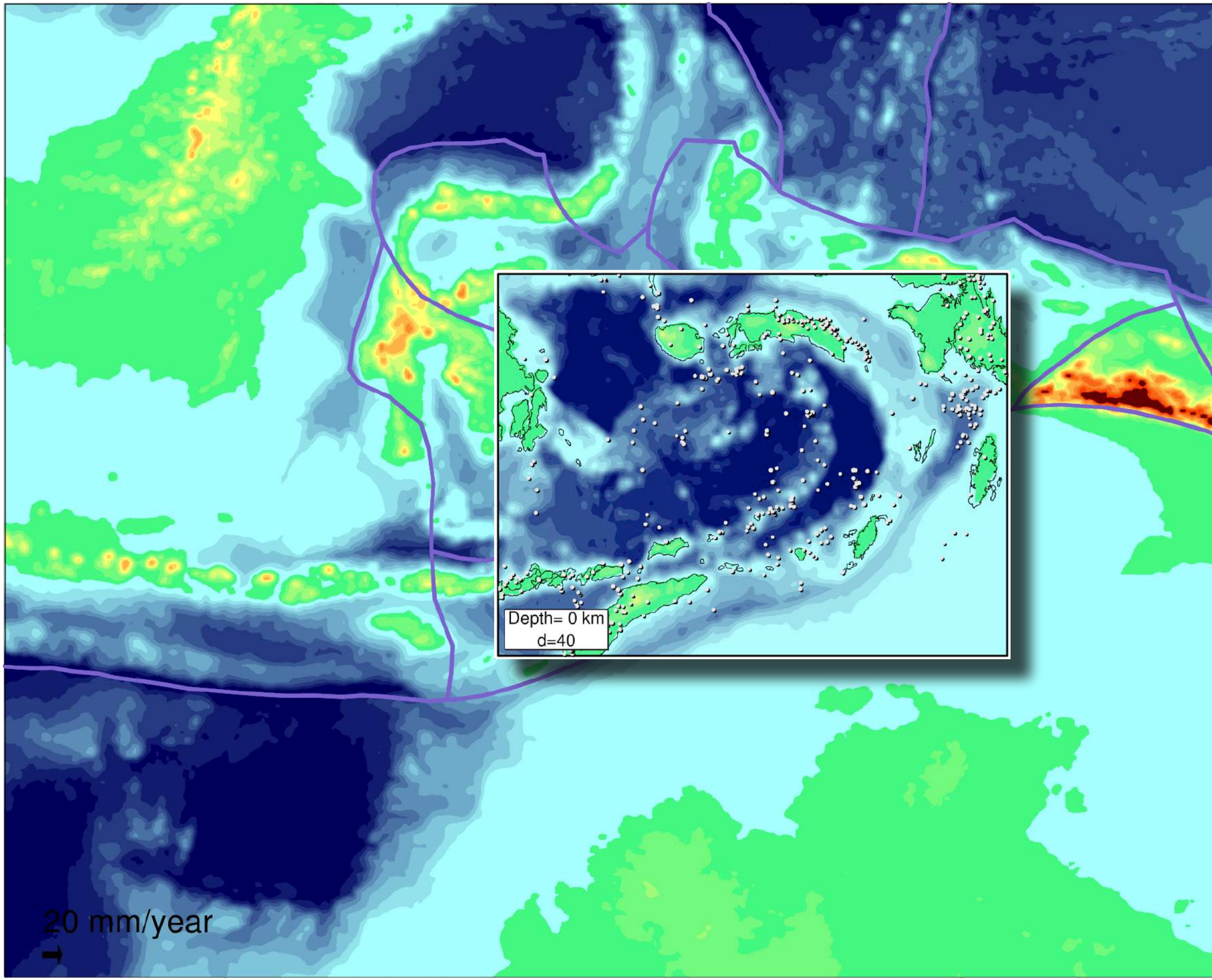


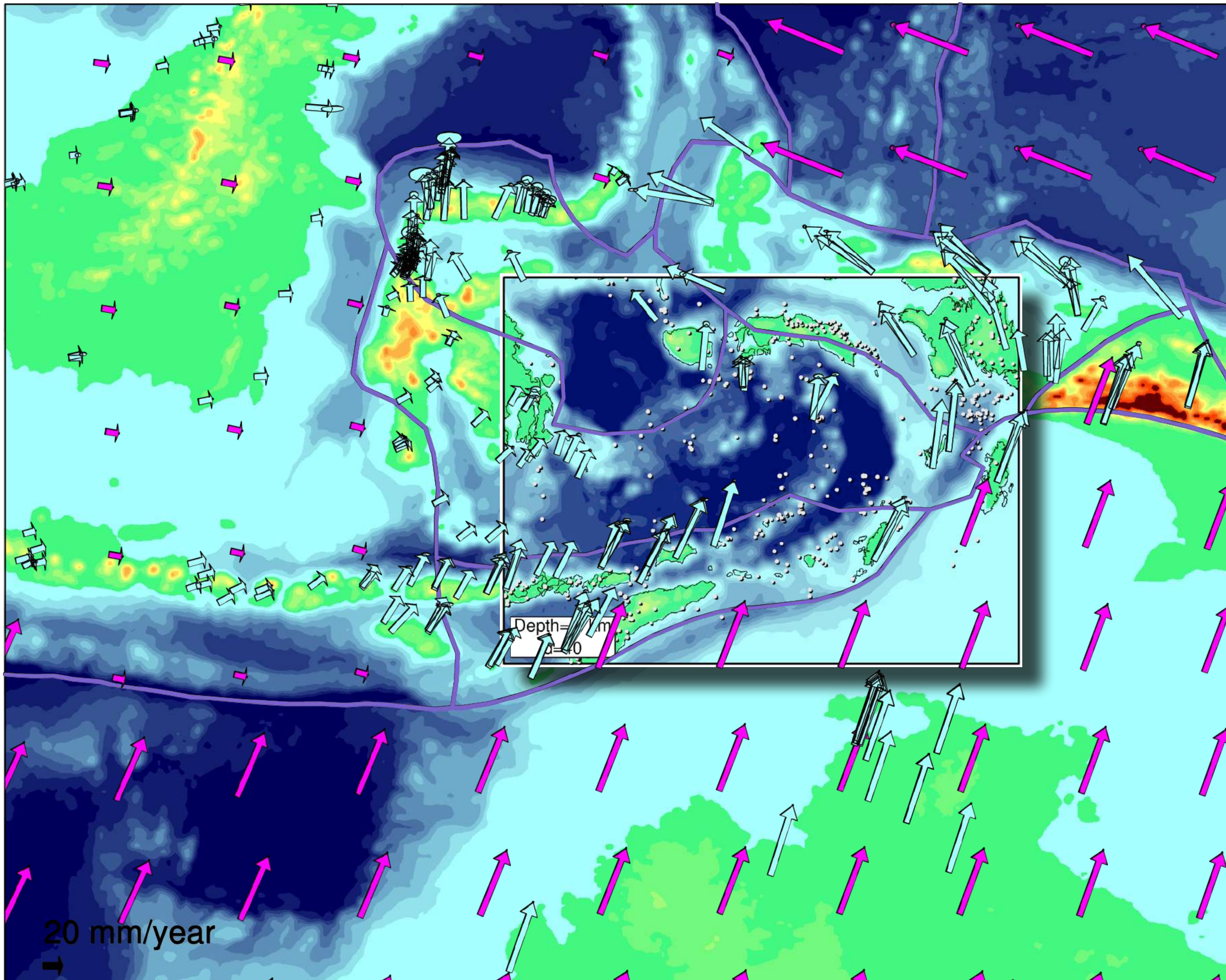




Banda Arc subduction: a less straightforward case of slab dragging
(Spakman and Hall 2010)

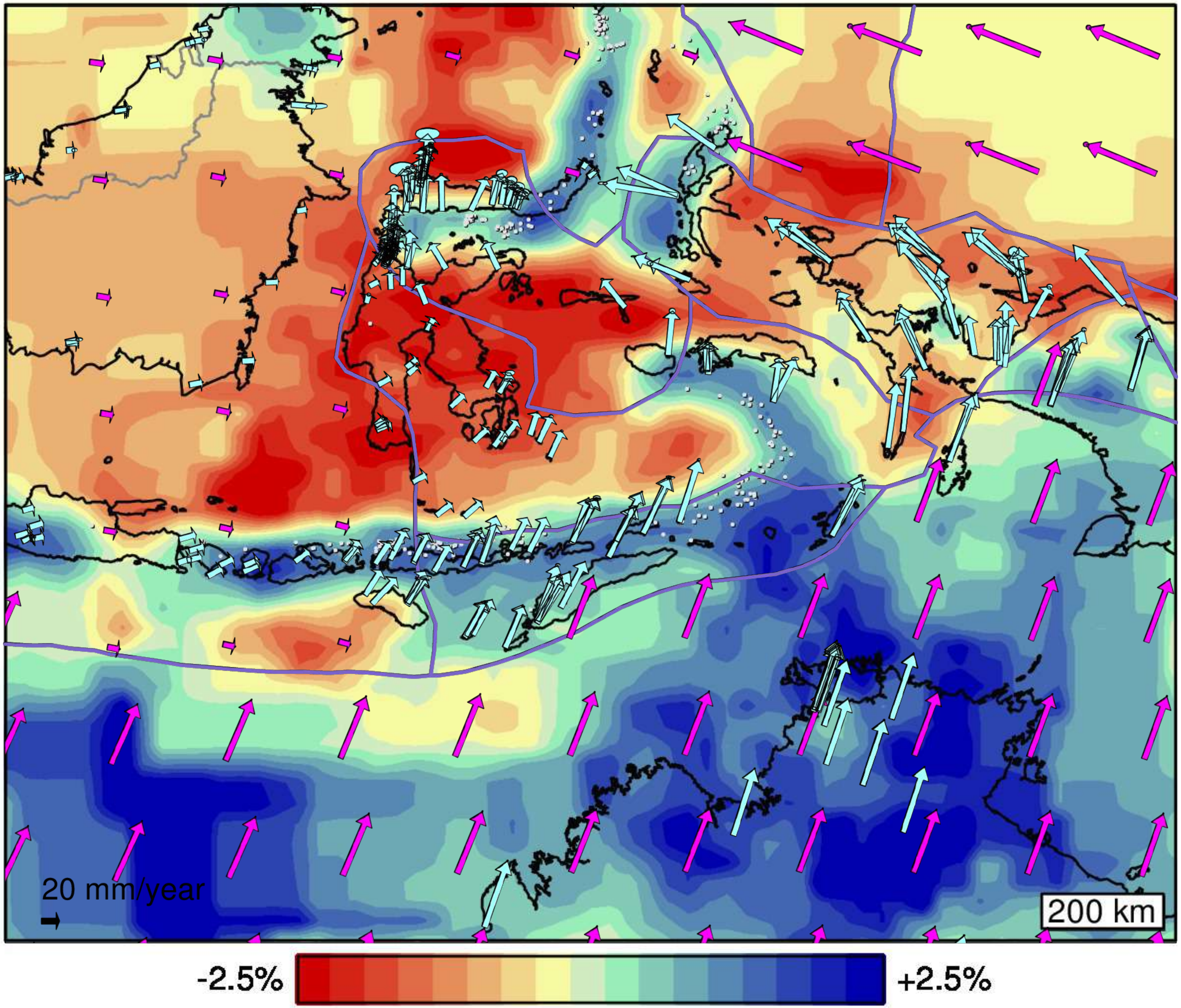



Depth= 0 km
d=40
20 mm/year

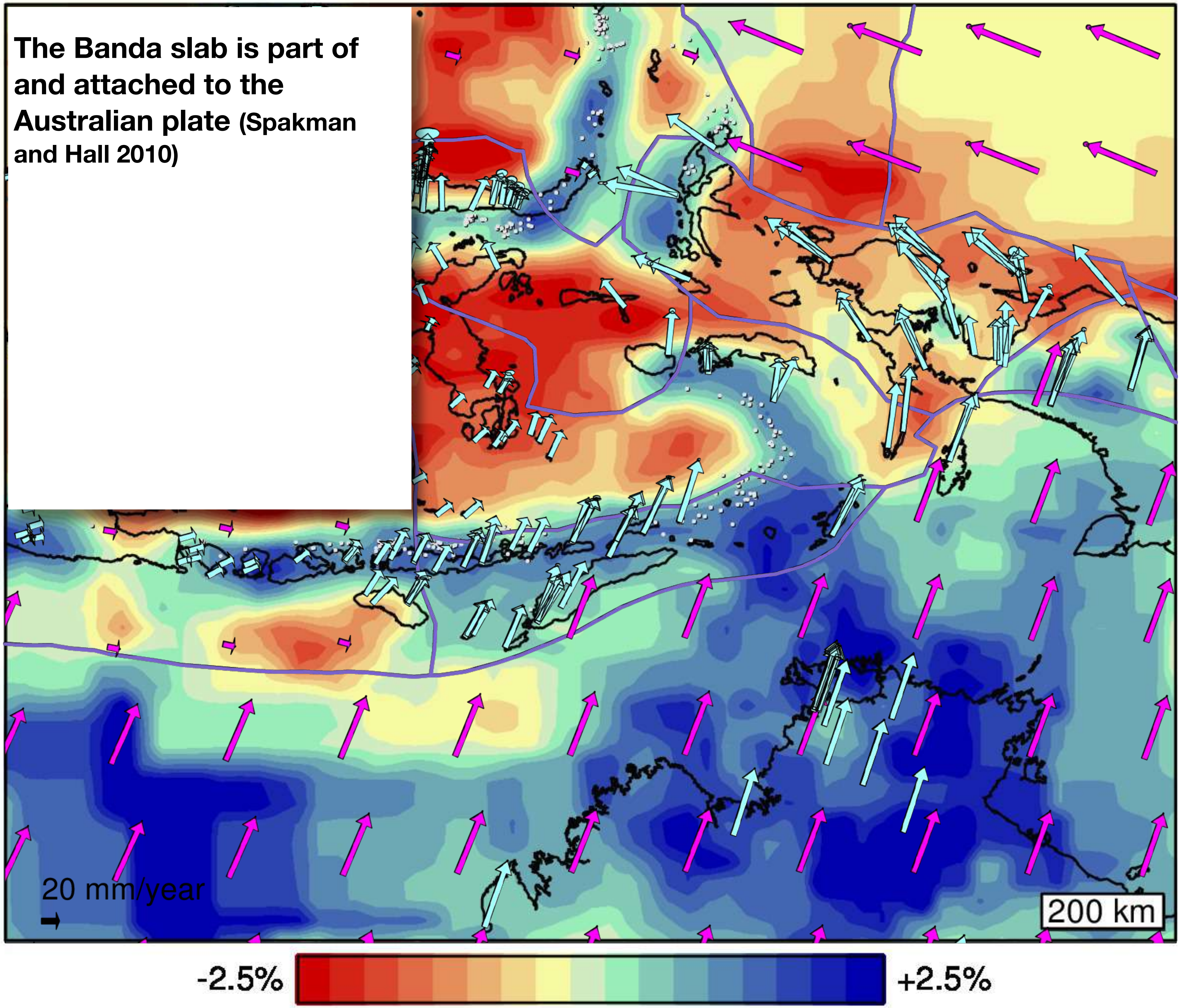


Absolute plate motions and GPS

Mantle structure and crustal motions



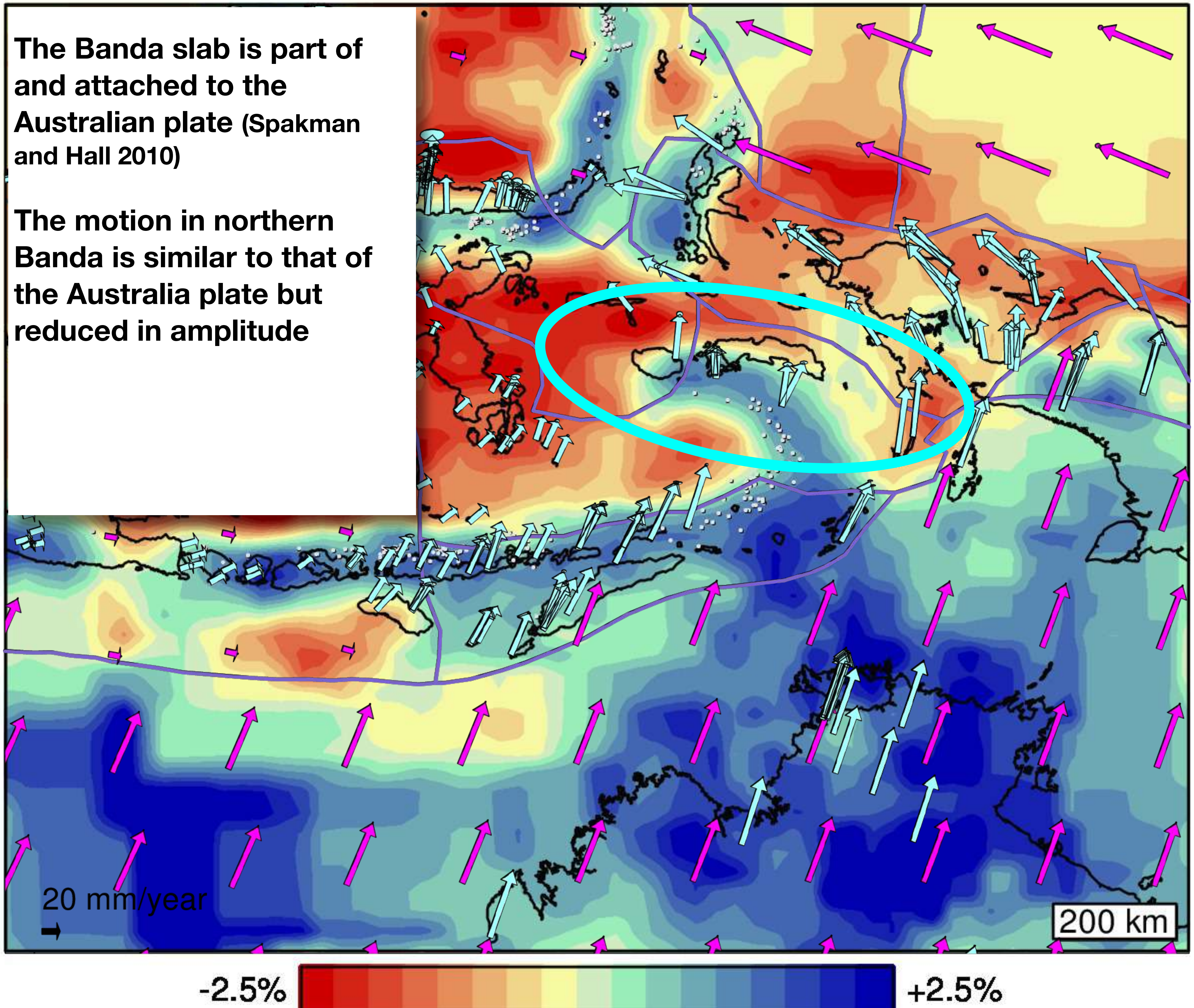
Mantle structure and crustal motions



Mantle structure and crustal motions

The Banda slab is part of and attached to the Australian plate (Spakman and Hall 2010)

The motion in northern Banda is similar to that of the Australia plate but reduced in amplitude



Mantle structure and crustal motions

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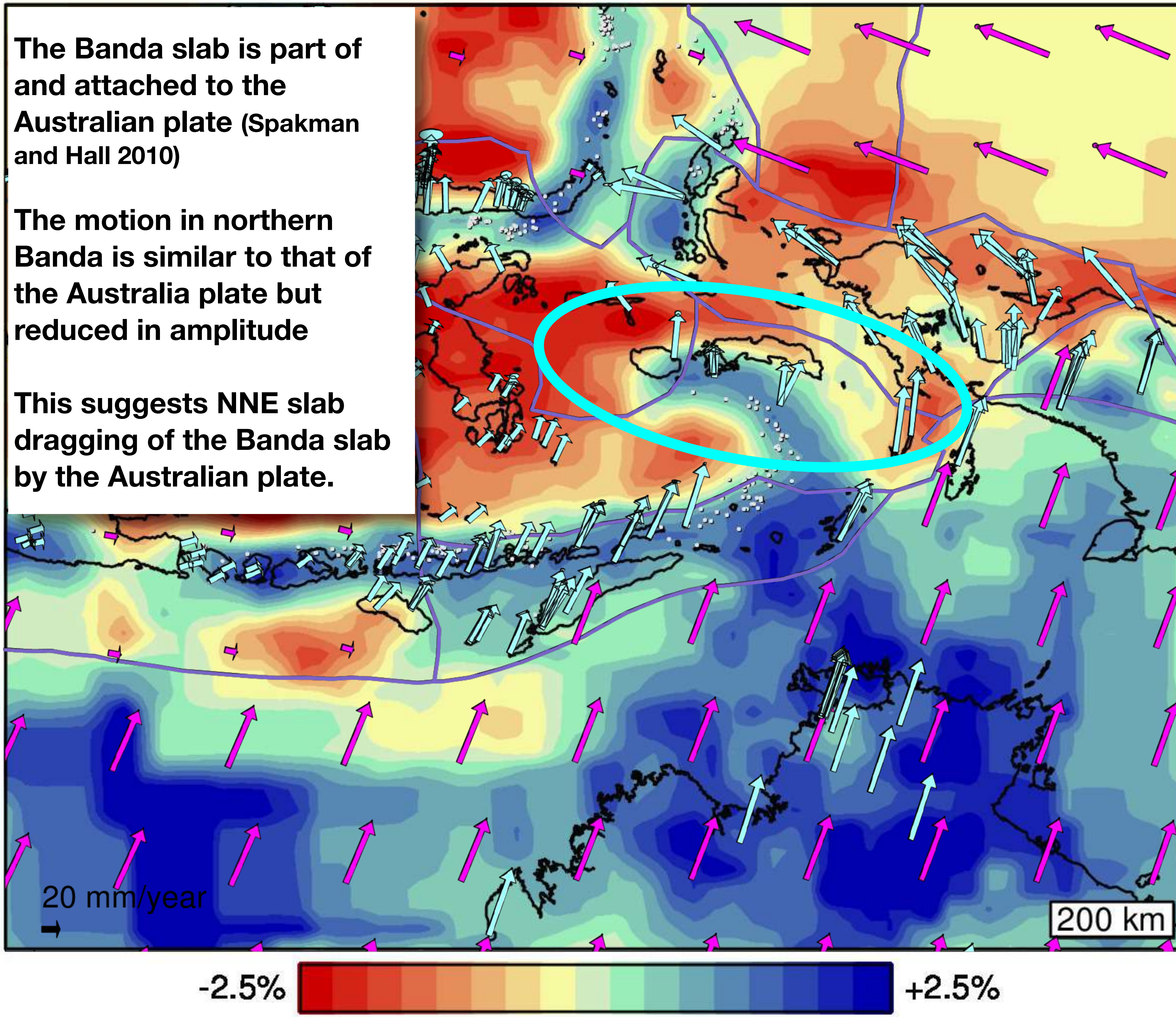
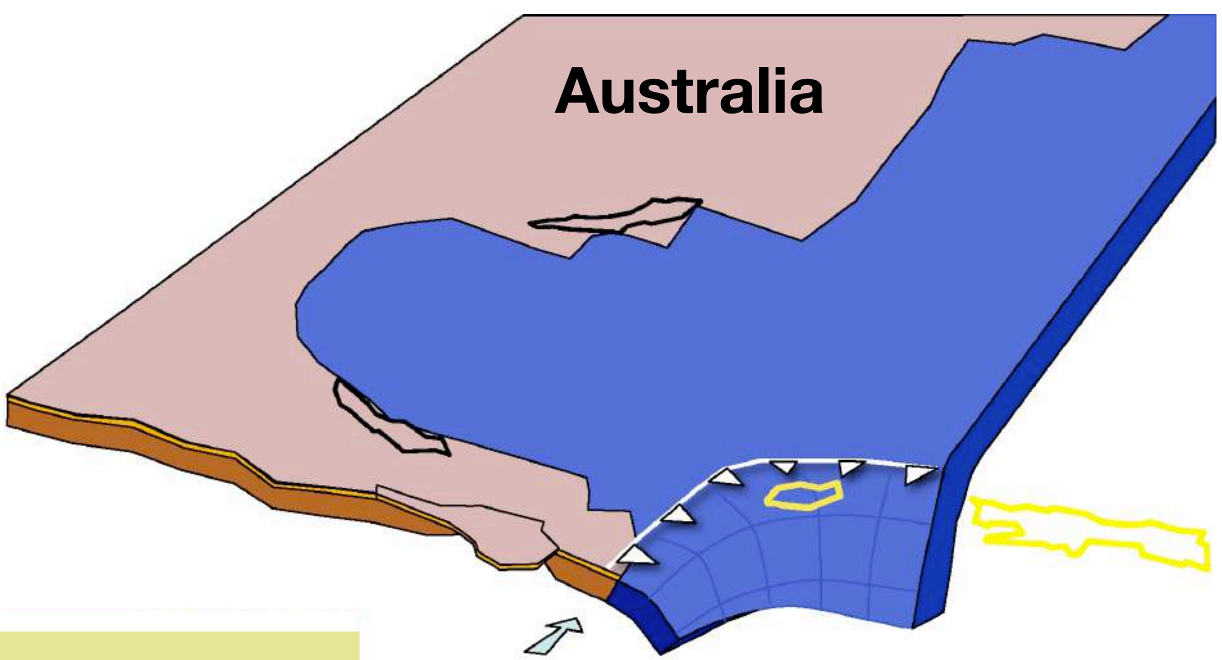
This suggests NNE slab dragging of the Banda slab by the Australian plate.



The necessity of using a mantle frame for identifying the style of subduction is perhaps best illustrated with Banda subduction evolution (Spakman and Hall, 2010)



Banda subduction in an Australia fixed frame

15 Ma

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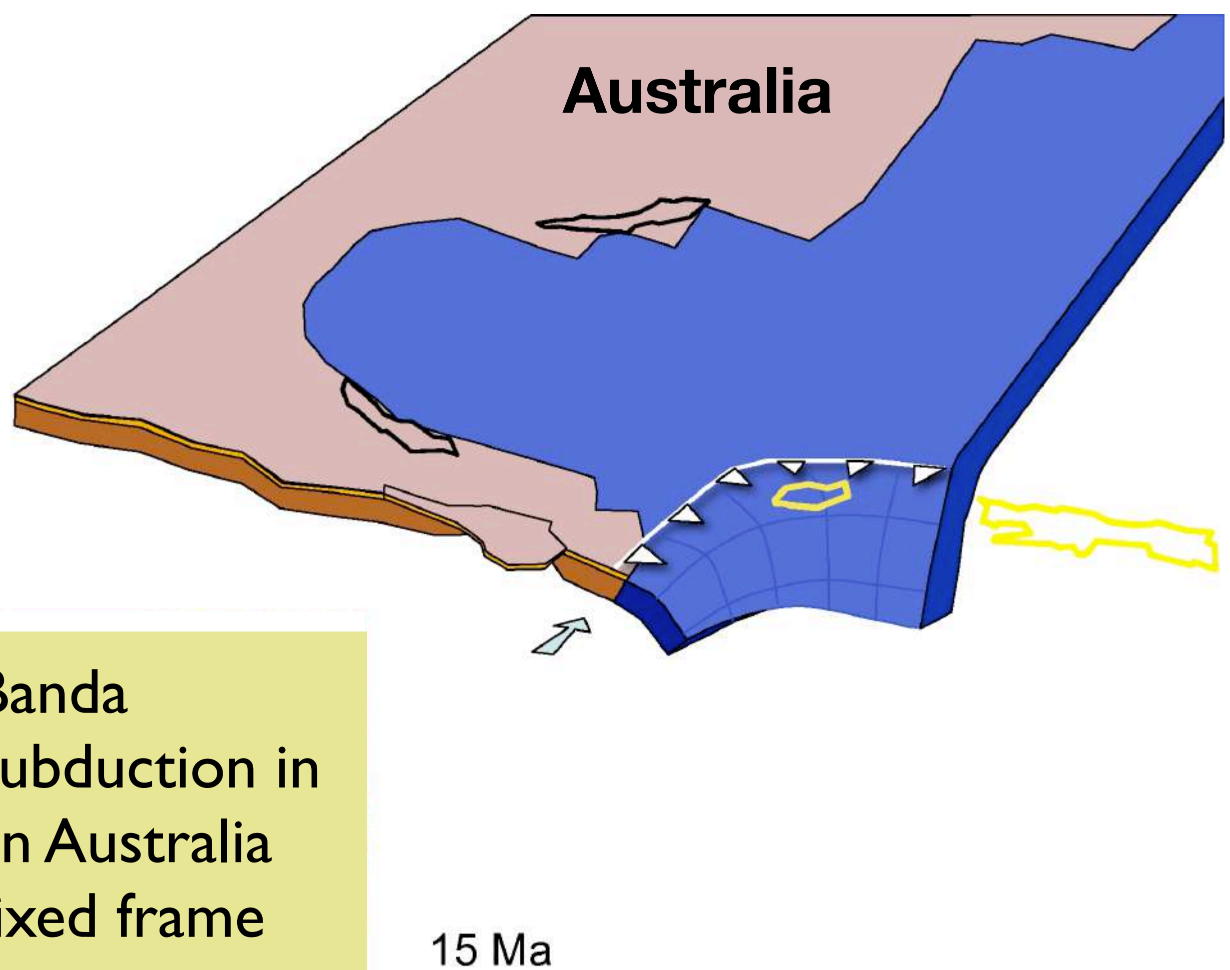
Motions in the Australia-fixed frame suggest rollback to the south and east



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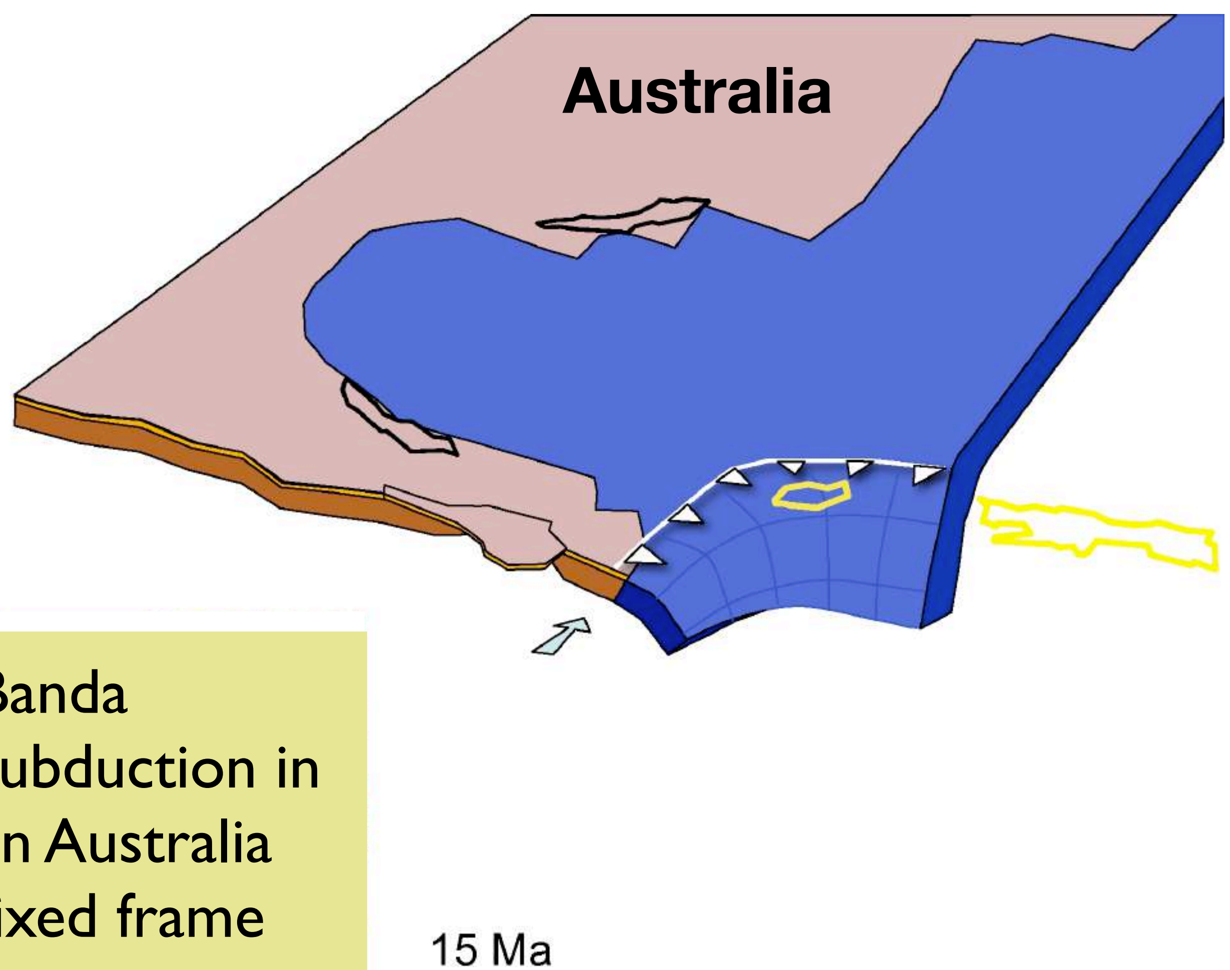
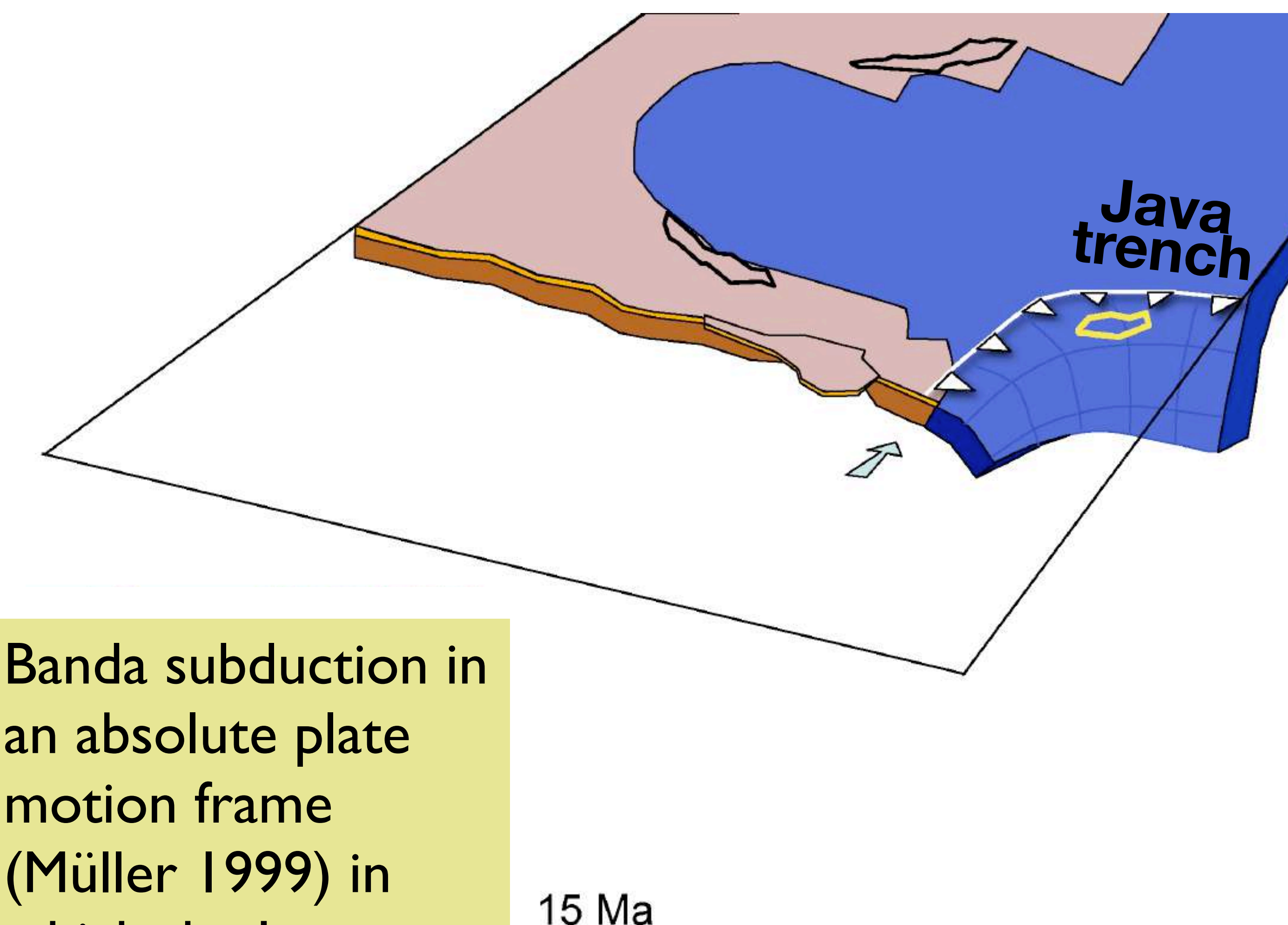


Banda subduction in an Australia fixed frame

In a mantle frame:
Rollback to the east and increasing NNE slab dragging



Banda subduction in an absolute plate motion frame (Müller 1999) in which the Java trench is stationary

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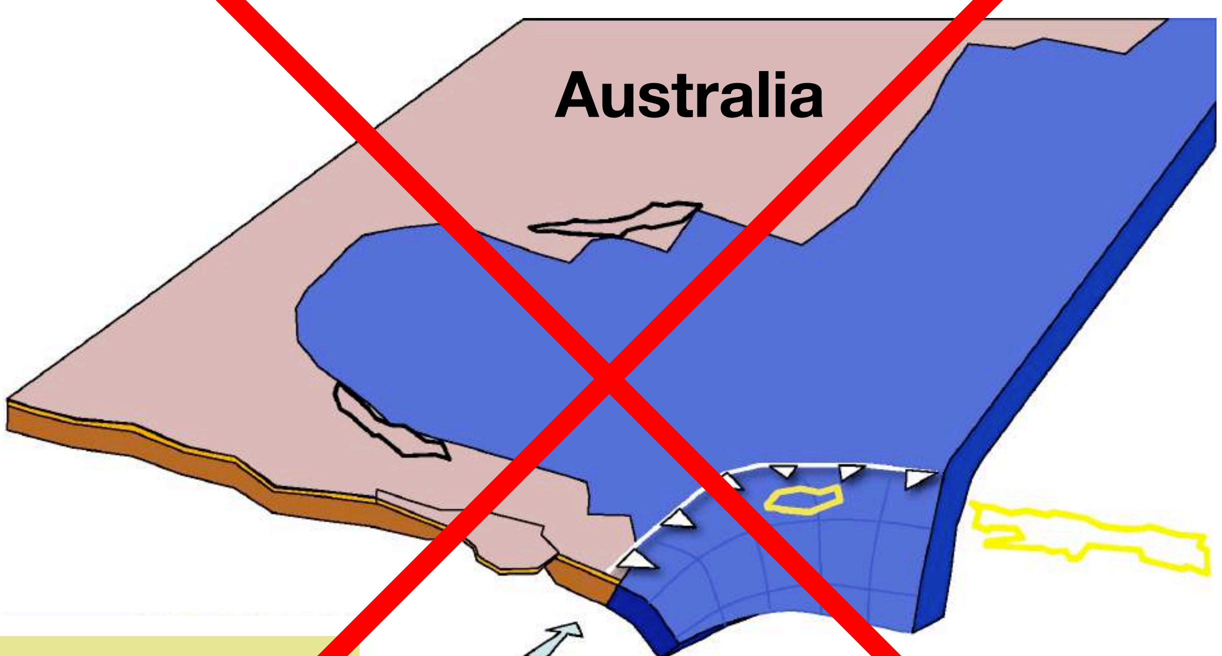

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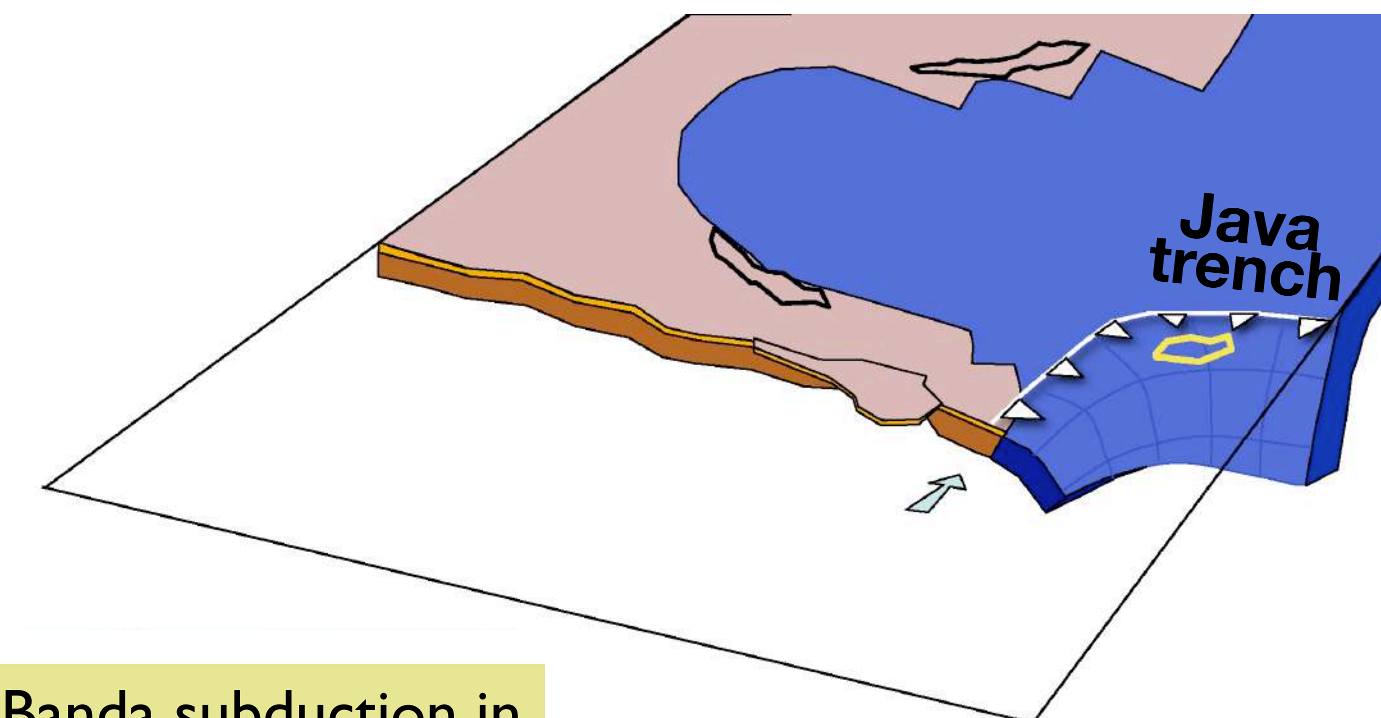
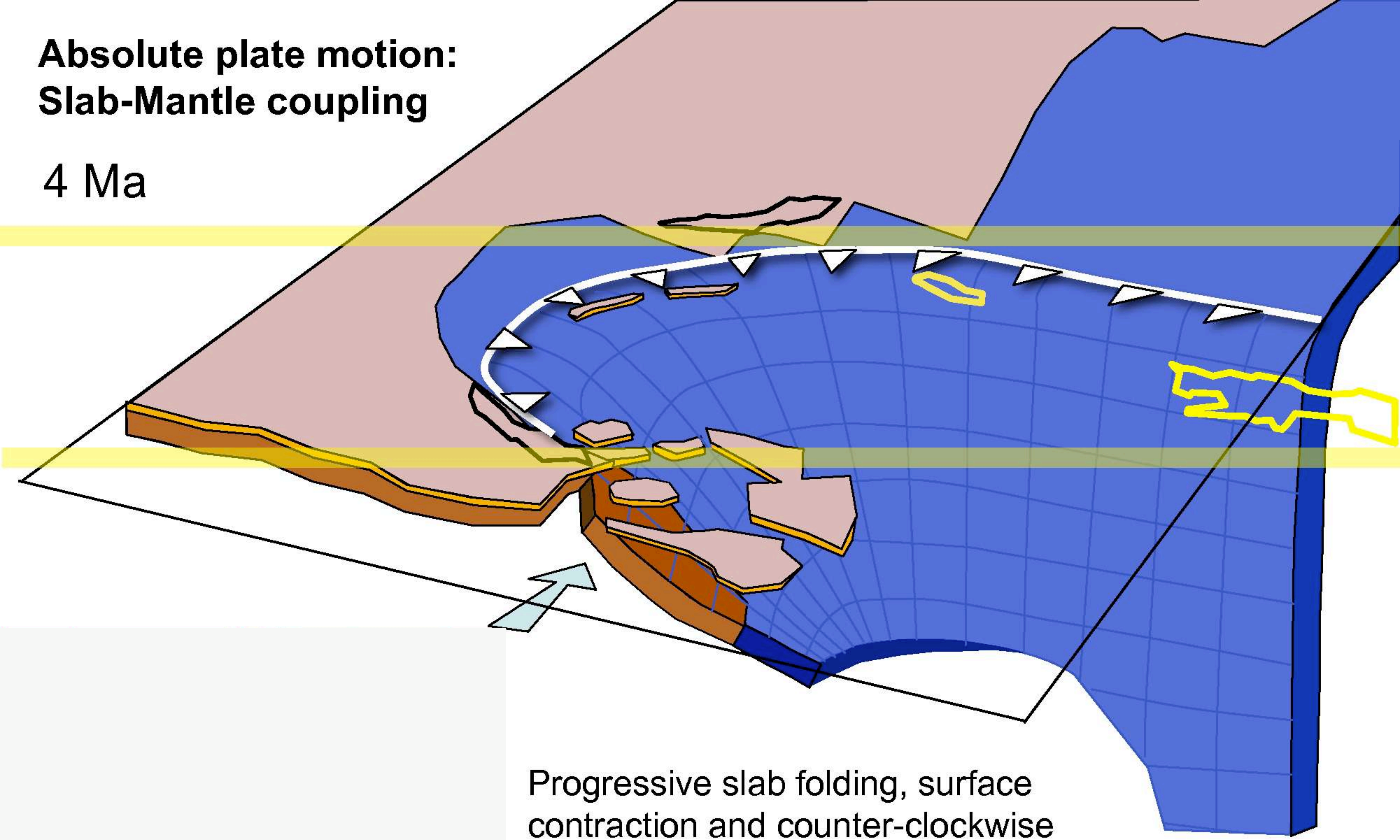


Banda subduction in an absolute plate motion frame (Müller 1999) in which the Java trench is stationary

15 Ma

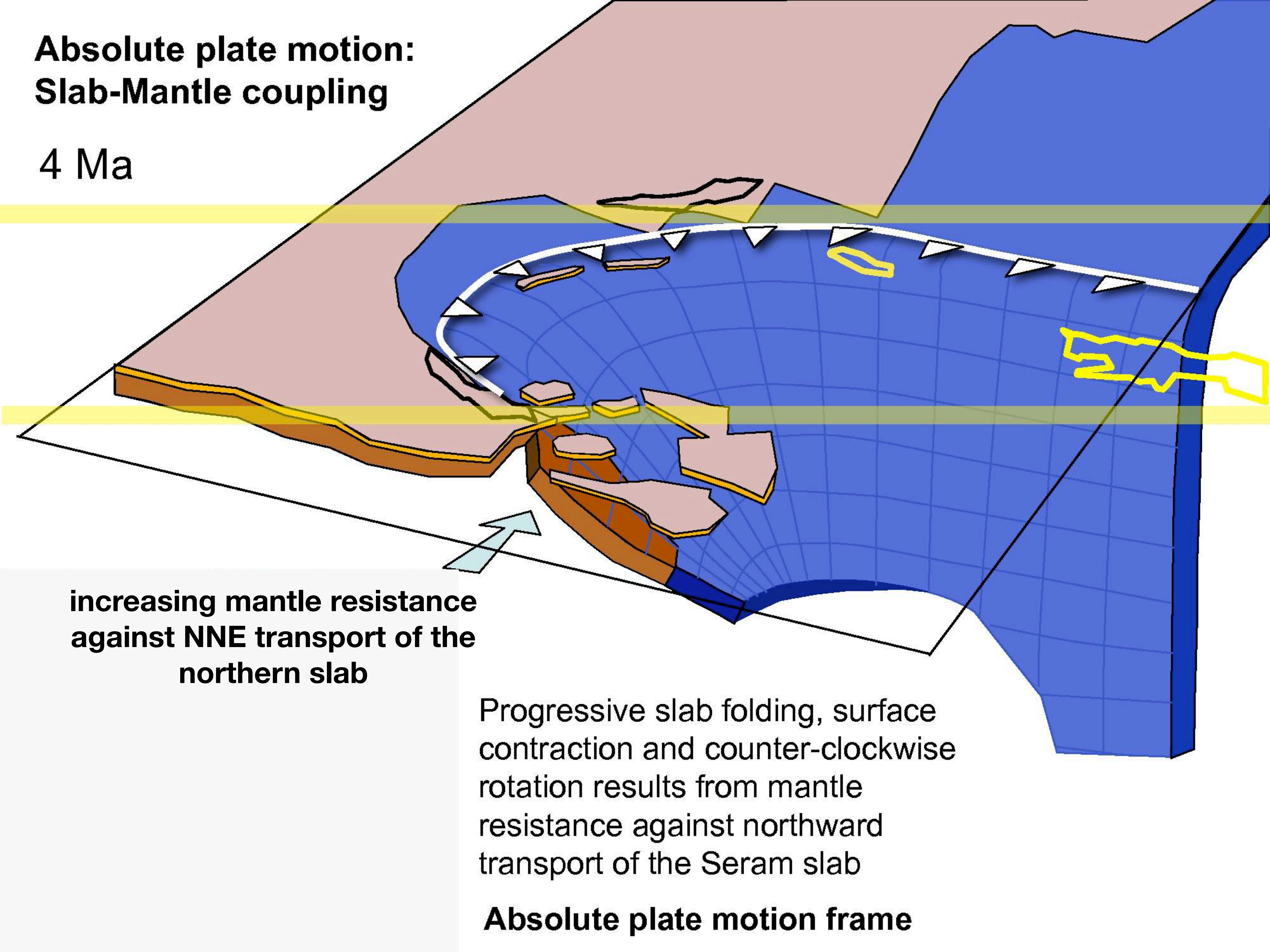
Absolute plate motion:
Slab-Mantle coupling

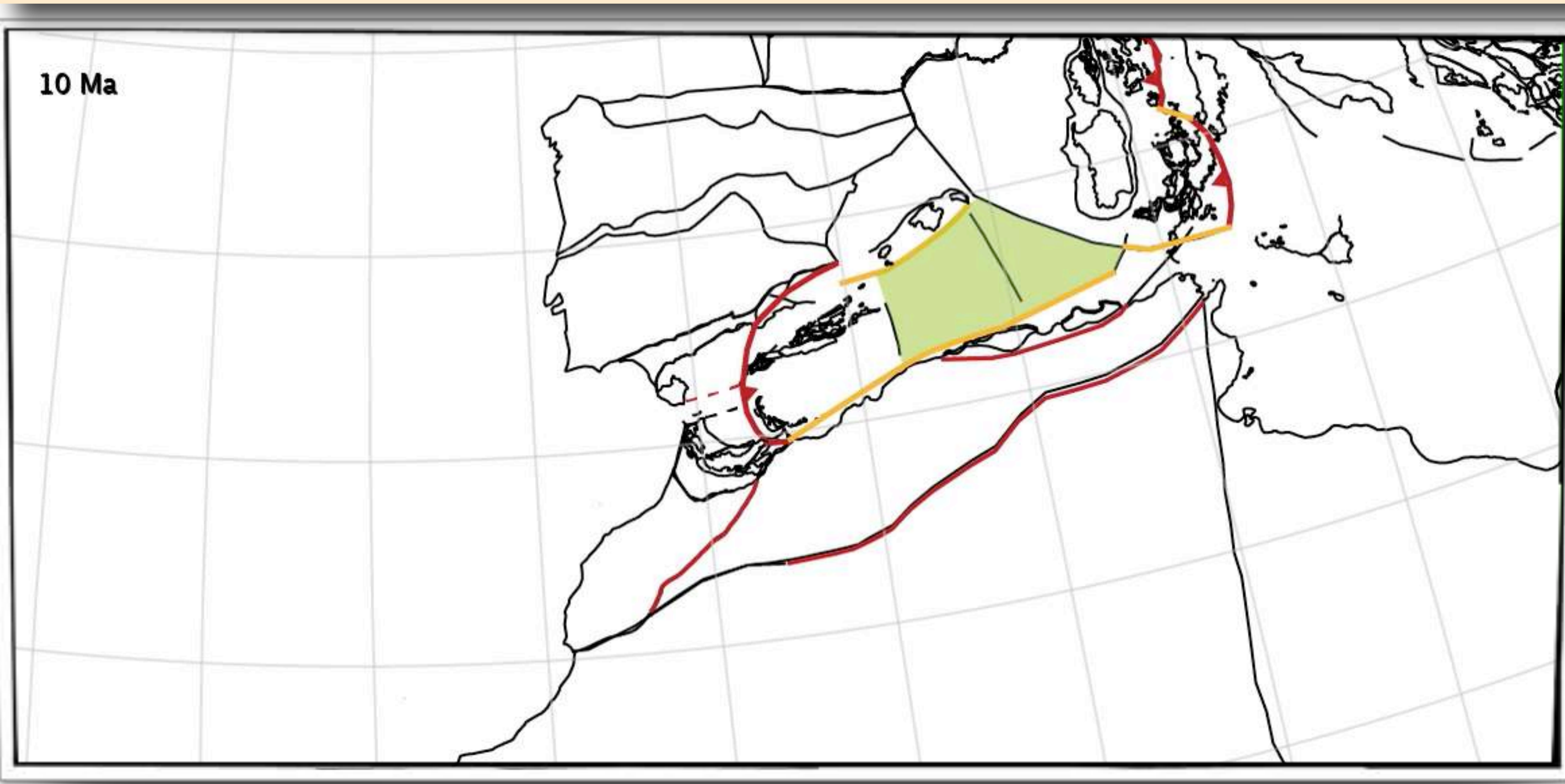
4 Ma



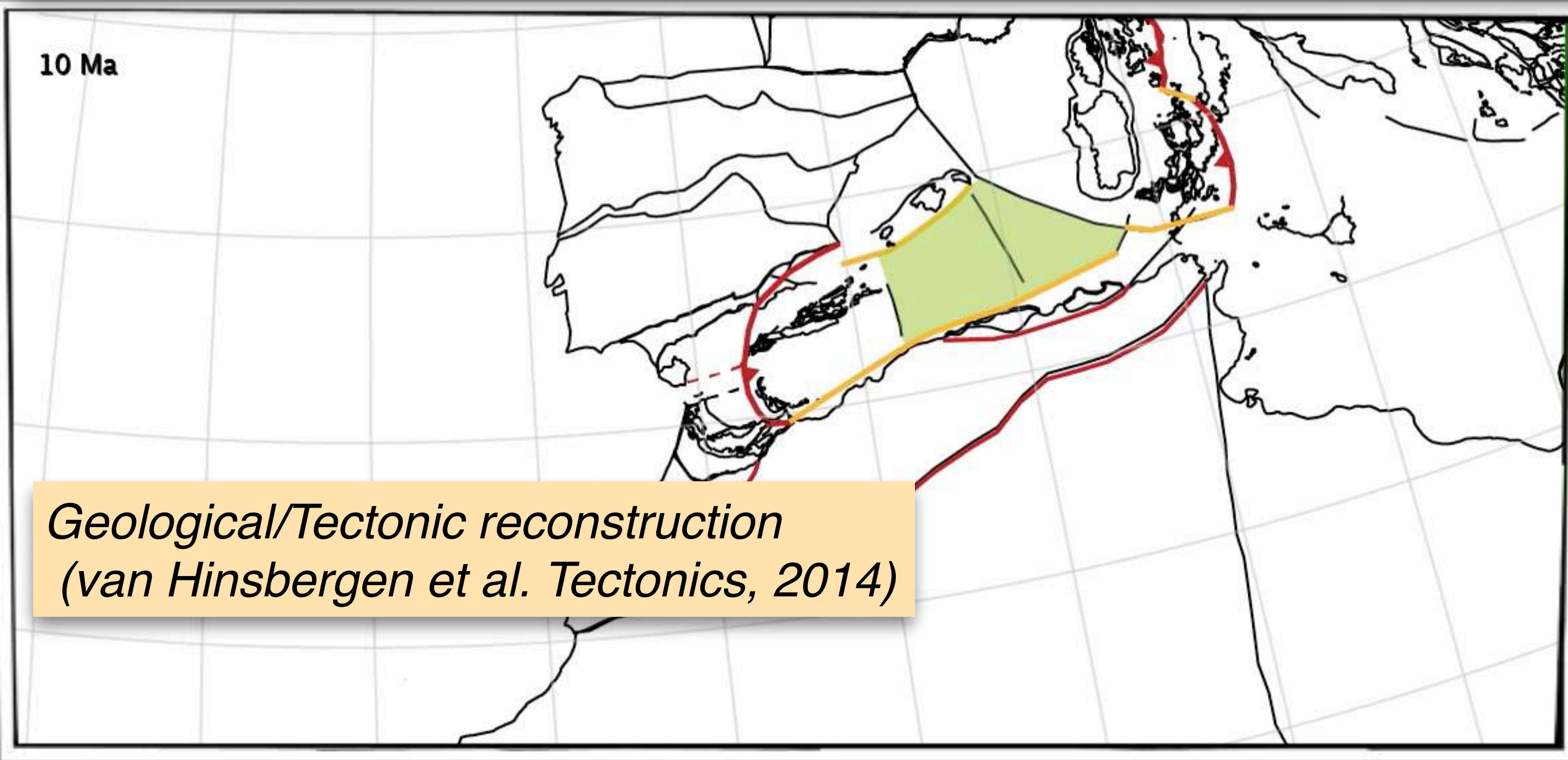
Progressive slab folding, surface contraction and counter-clockwise rotation results from mantle resistance against northward transport of the Seram slab

Absolute plate motion frame


Absolute plate motion:
Slab-Mantle coupling
4 Ma
increasing mantle resistance against NNE transport of the northern slab
Progressive slab folding, surface contraction and counter-clockwise rotation results from mantle resistance against northward transport of the Seram slab
Absolute plate motion frame

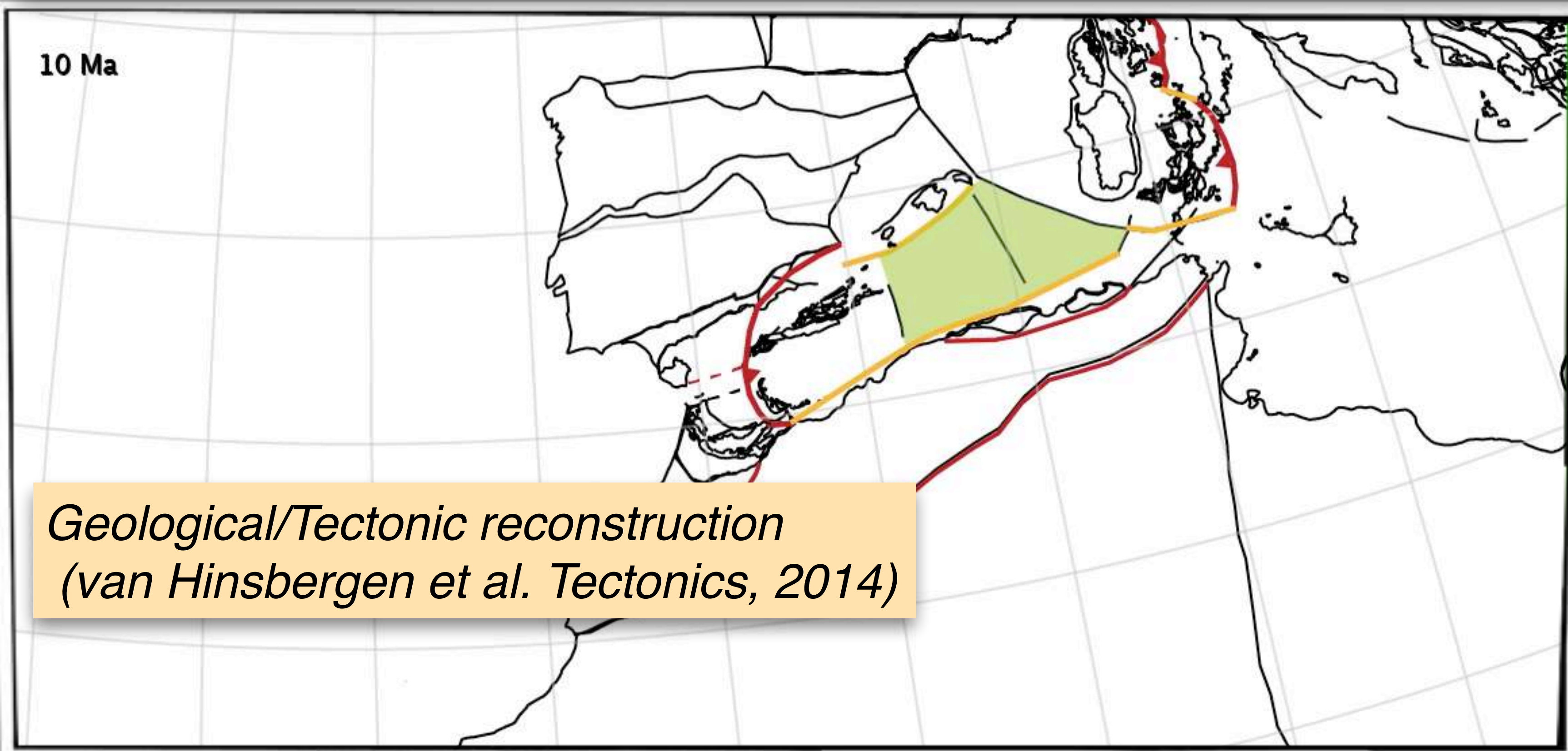

10 Ma

Western Mediterranean tectonic evolution, mantle structure, and the dynamics of slab rollback



Geological/Tectonic reconstruction
(van Hinsbergen et al. Tectonics, 2014)

Western Mediterranean tectonic evolution, mantle structure, and the dynamics of slab rollback



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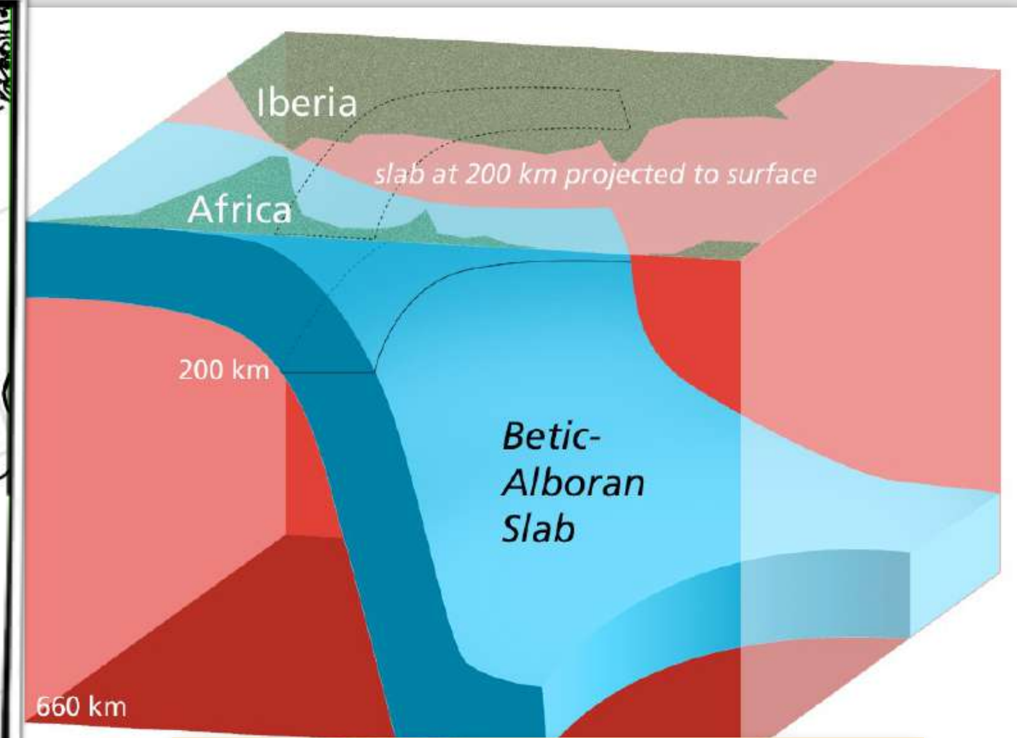
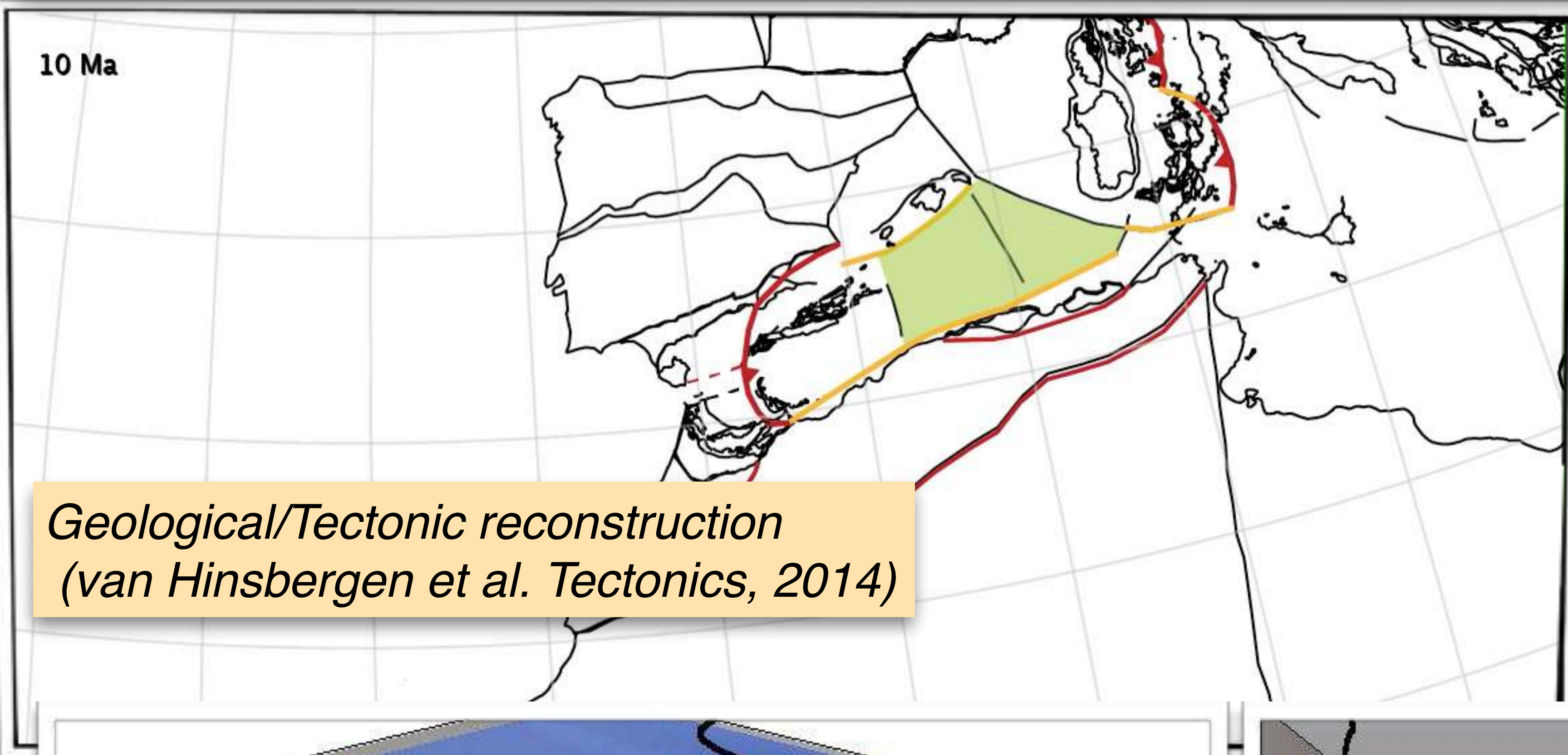
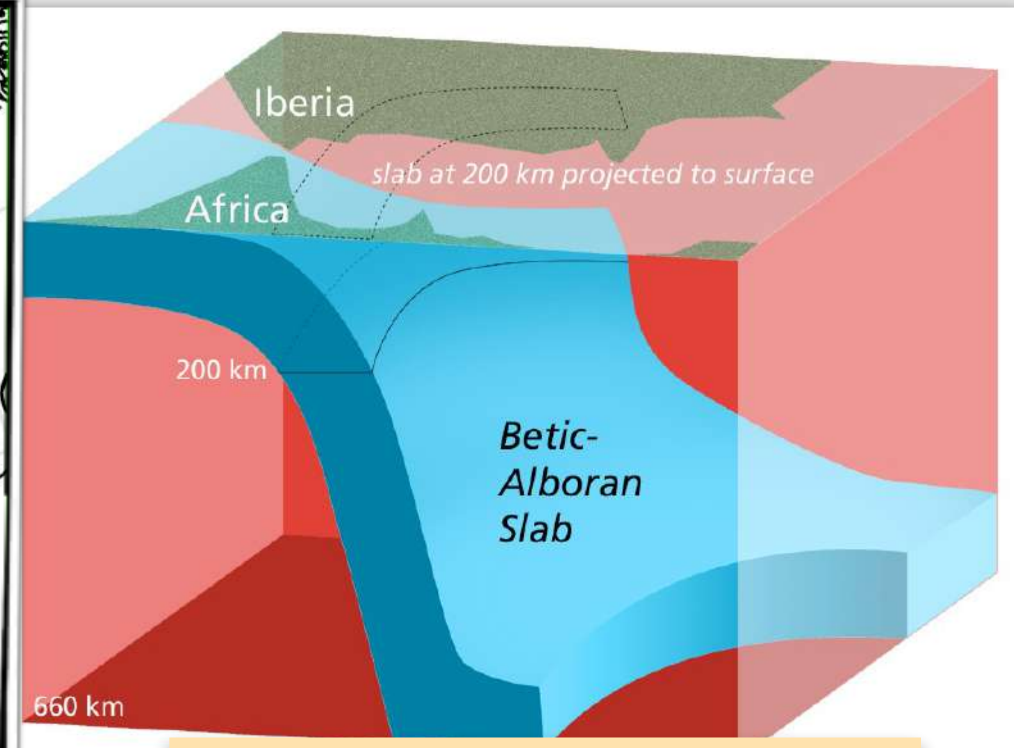


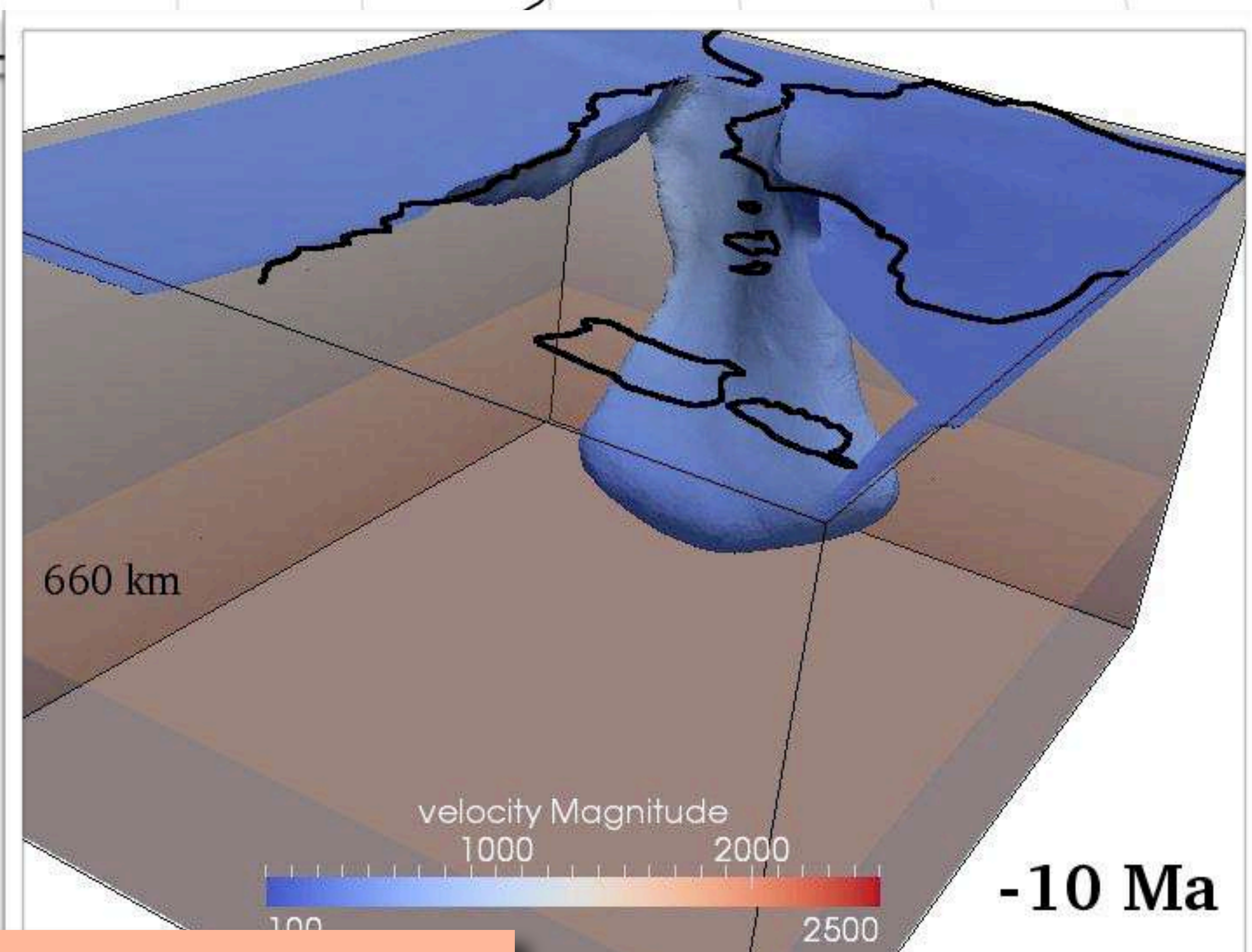
Tomographic mantle structure

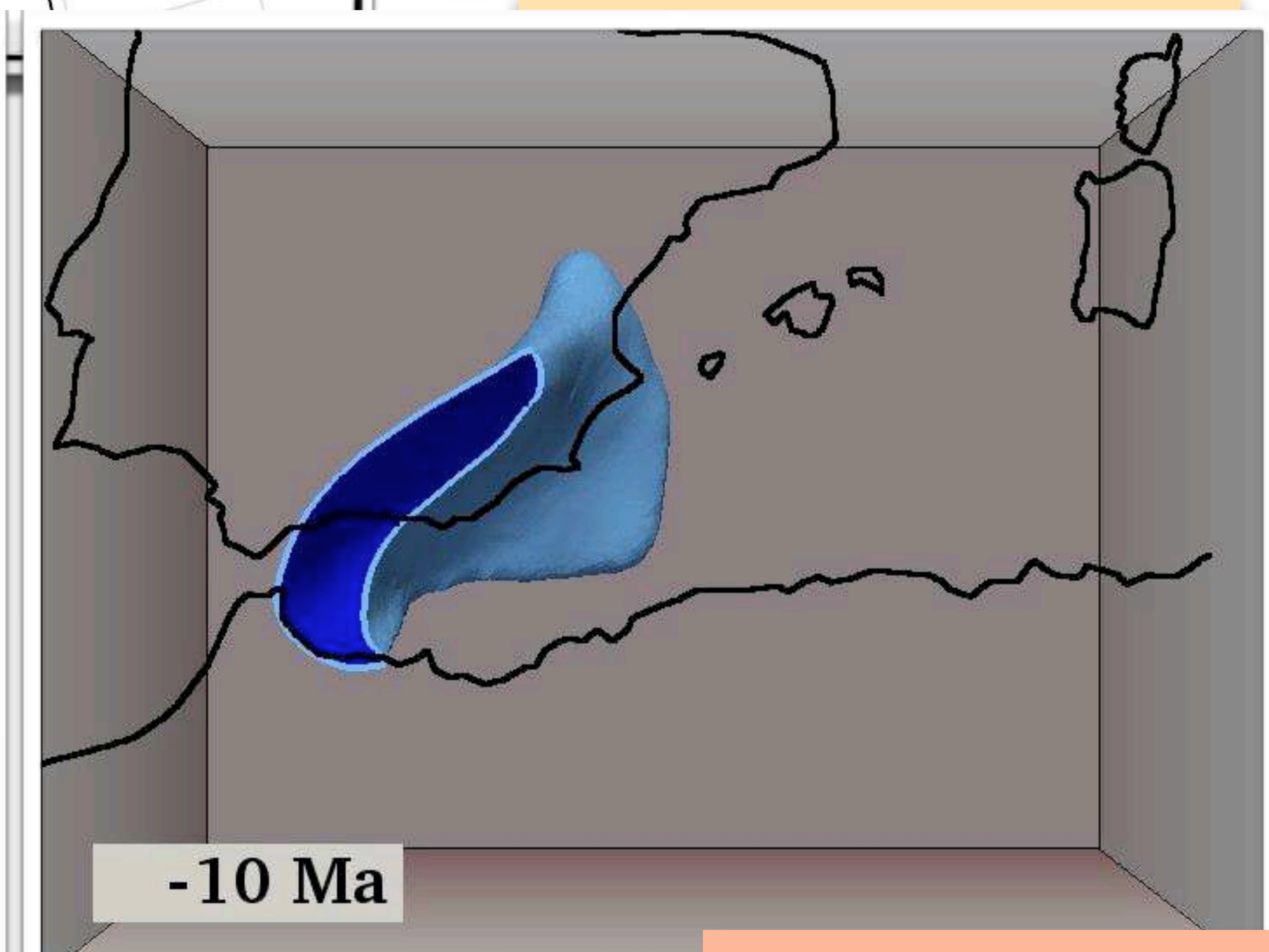
Western Mediterranean tectonic evolution, mantle structure, and the dynamics of slab rollback



Geological/Tectonic reconstruction (van Hinsbergen et al. Tectonics, 2014)





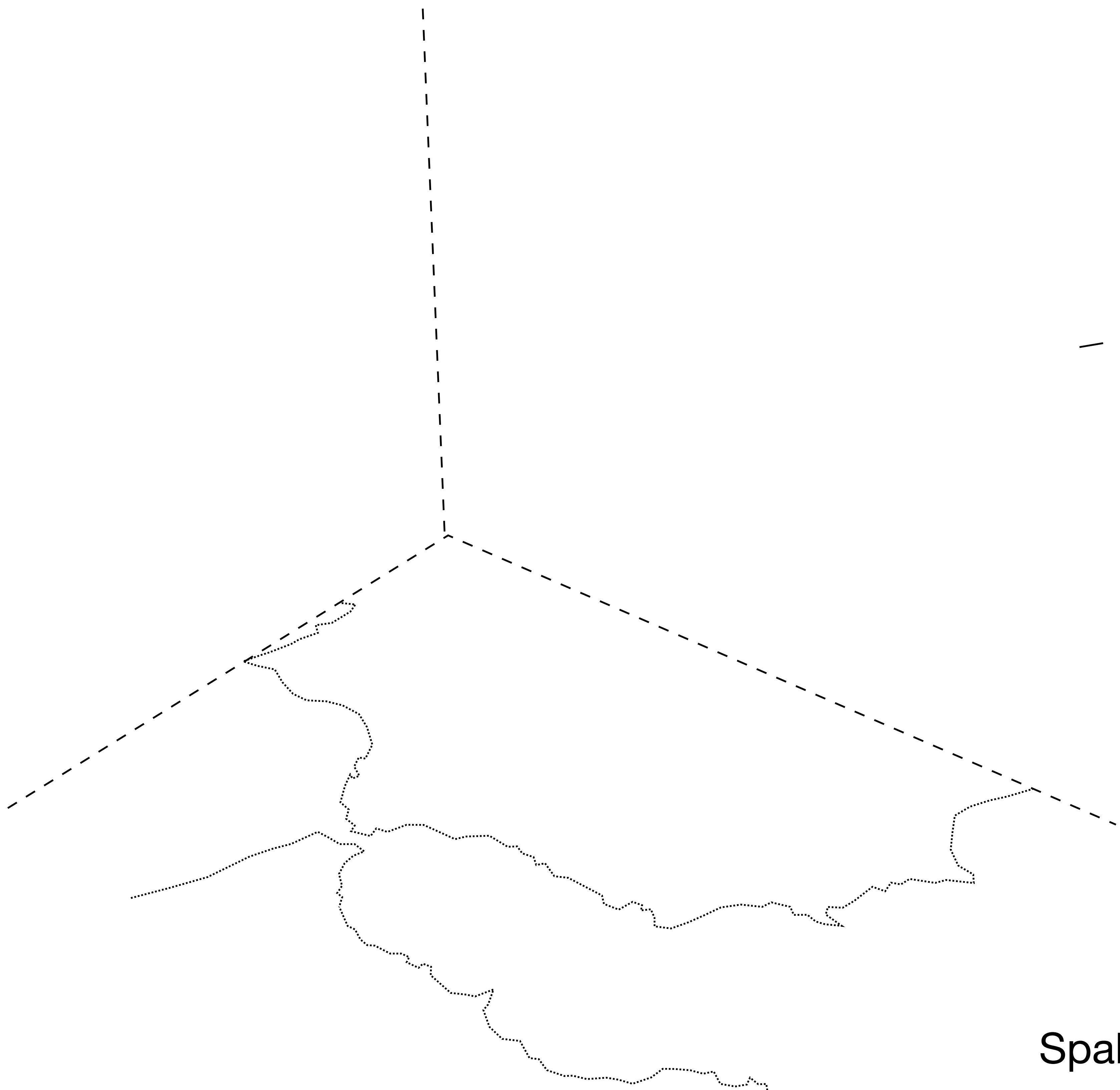


Temperature surface ; color = flow speed

Modelling of the subduction evolution (Chertova et al., 2014)

Temperature surface; view starting at ~ 200 km depth

The combination of various seismological inferences, tectonic reconstruction of the region and dynamic modelling of slab evolution reveals the geometry and connections of the slab to the African and Iberian plates.



Spakman et al. 2018

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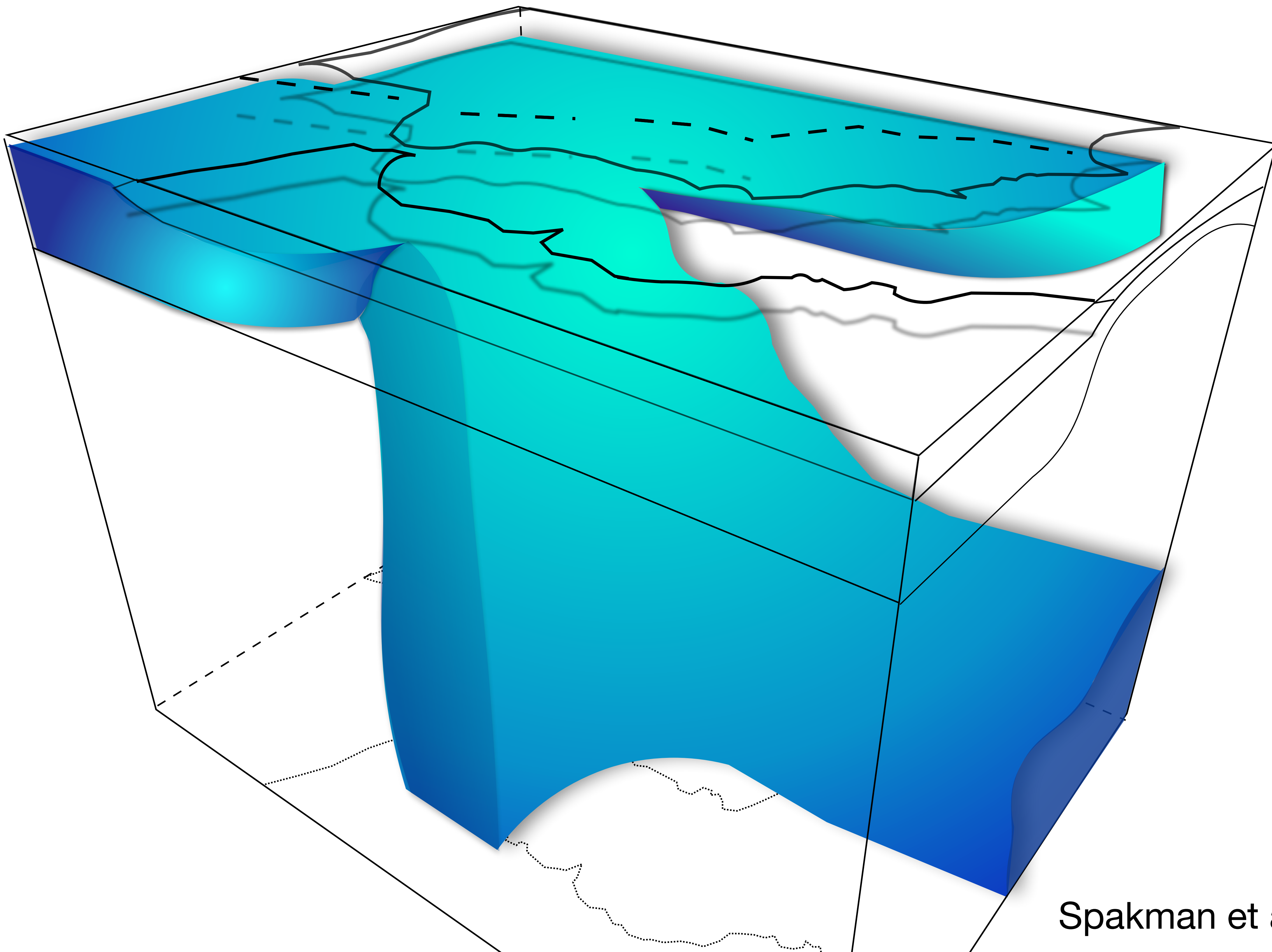

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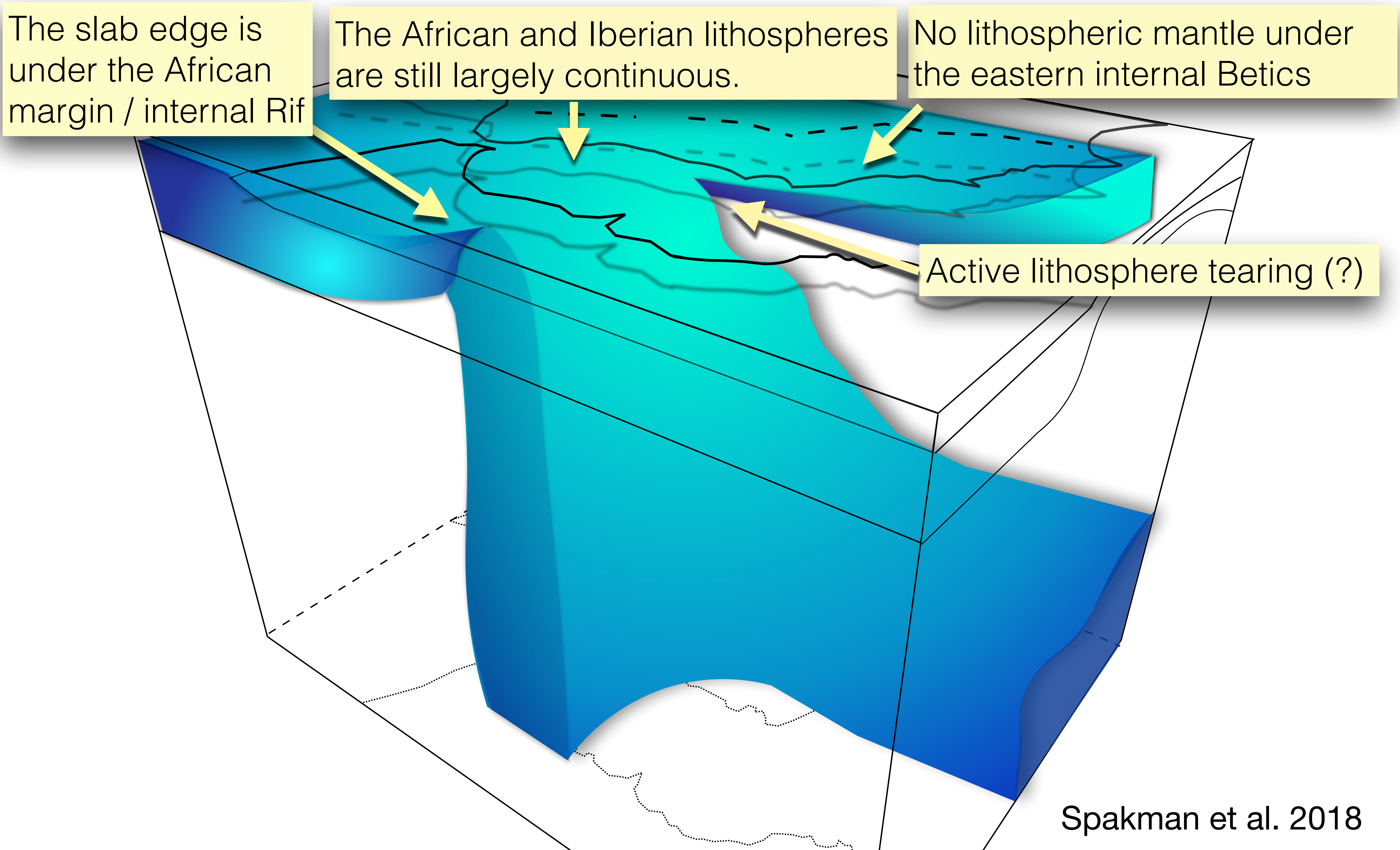

Spakman et al. 2018

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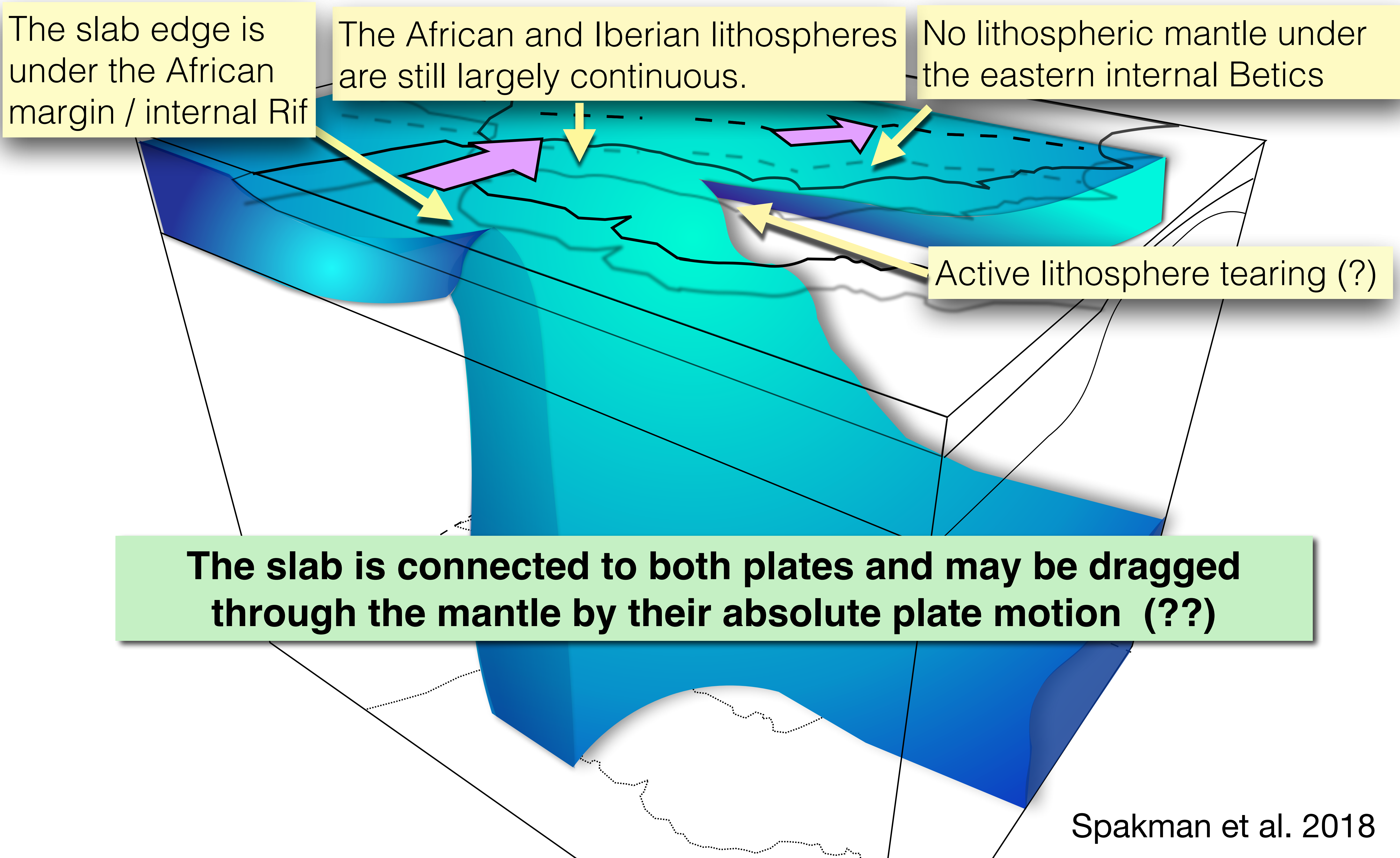
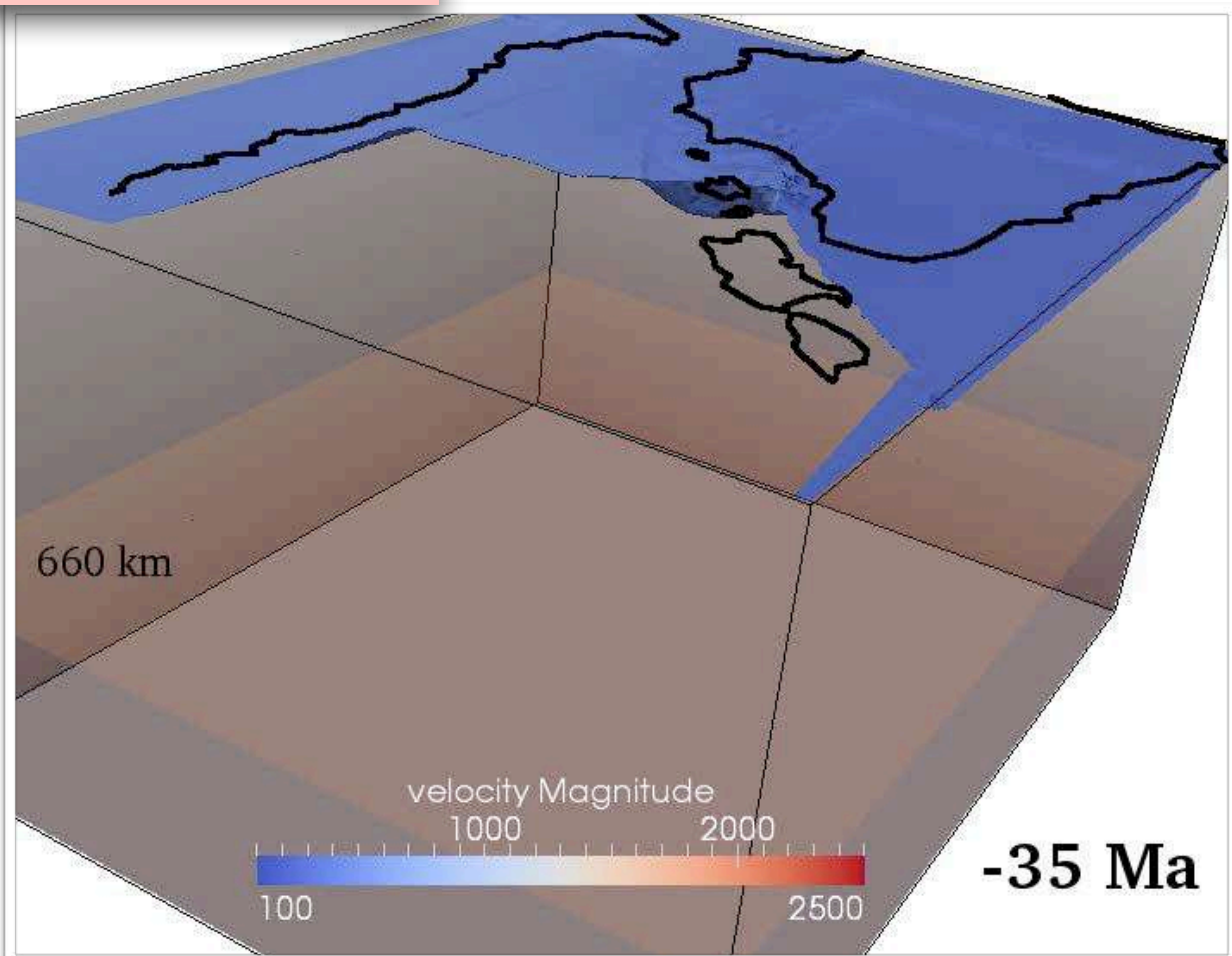


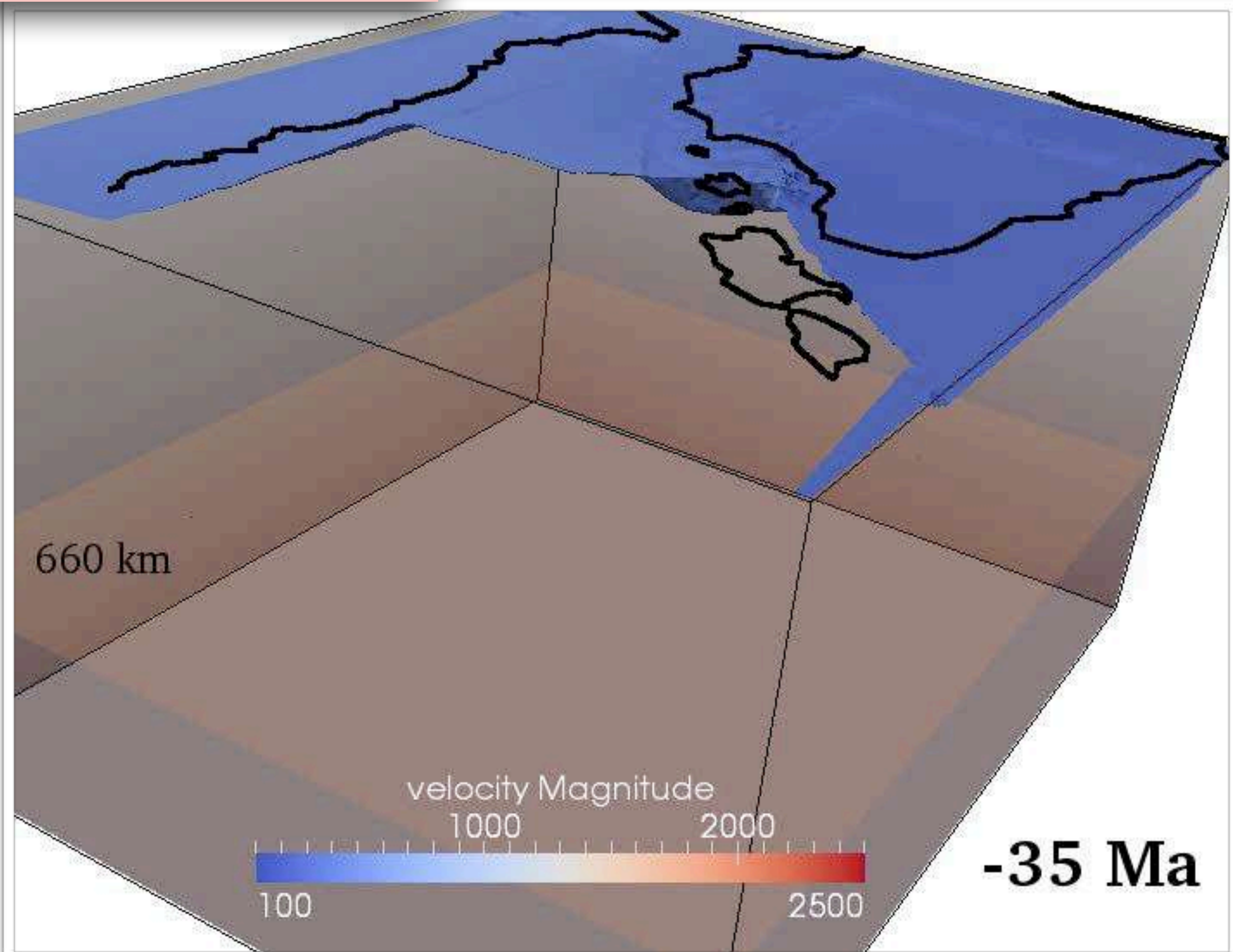
Spakman et al. 2018

Dynamic modelling in a mantle frame reveals slab dragging



View to the SW; Colors = flow speed

Dynamic modelling in a mantle frame reveals slab dragging



View to the SW; Colors = flow speed

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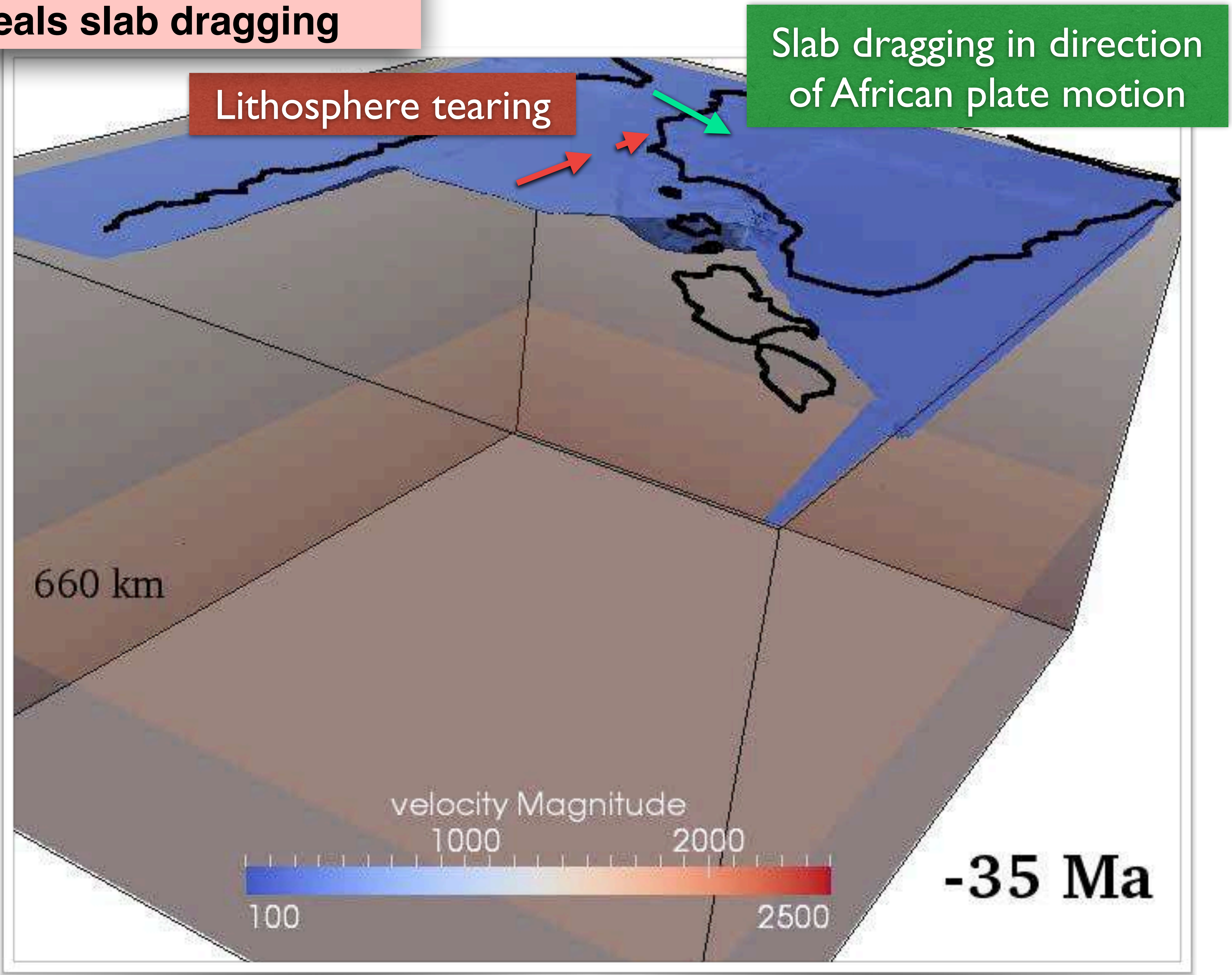
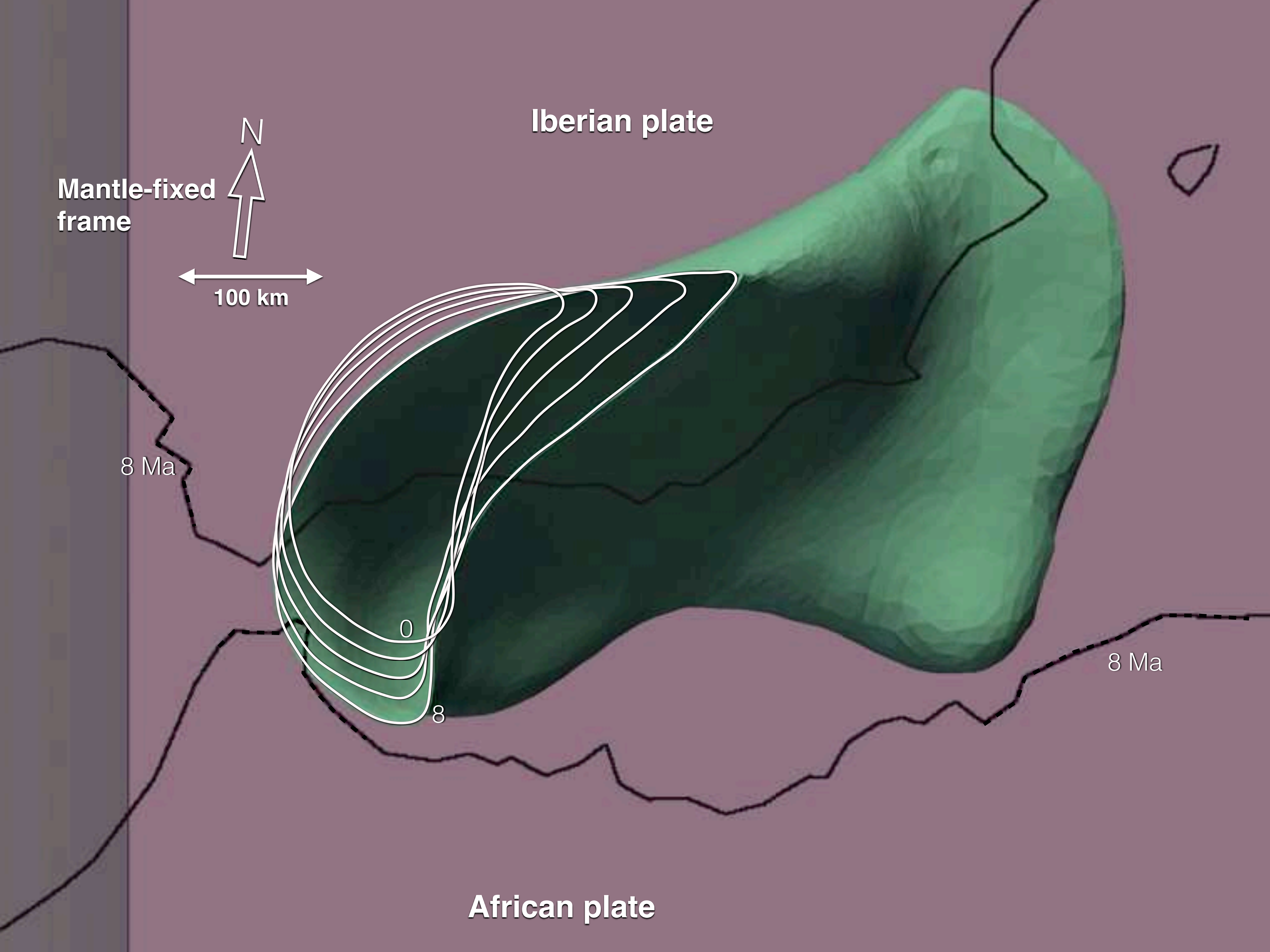
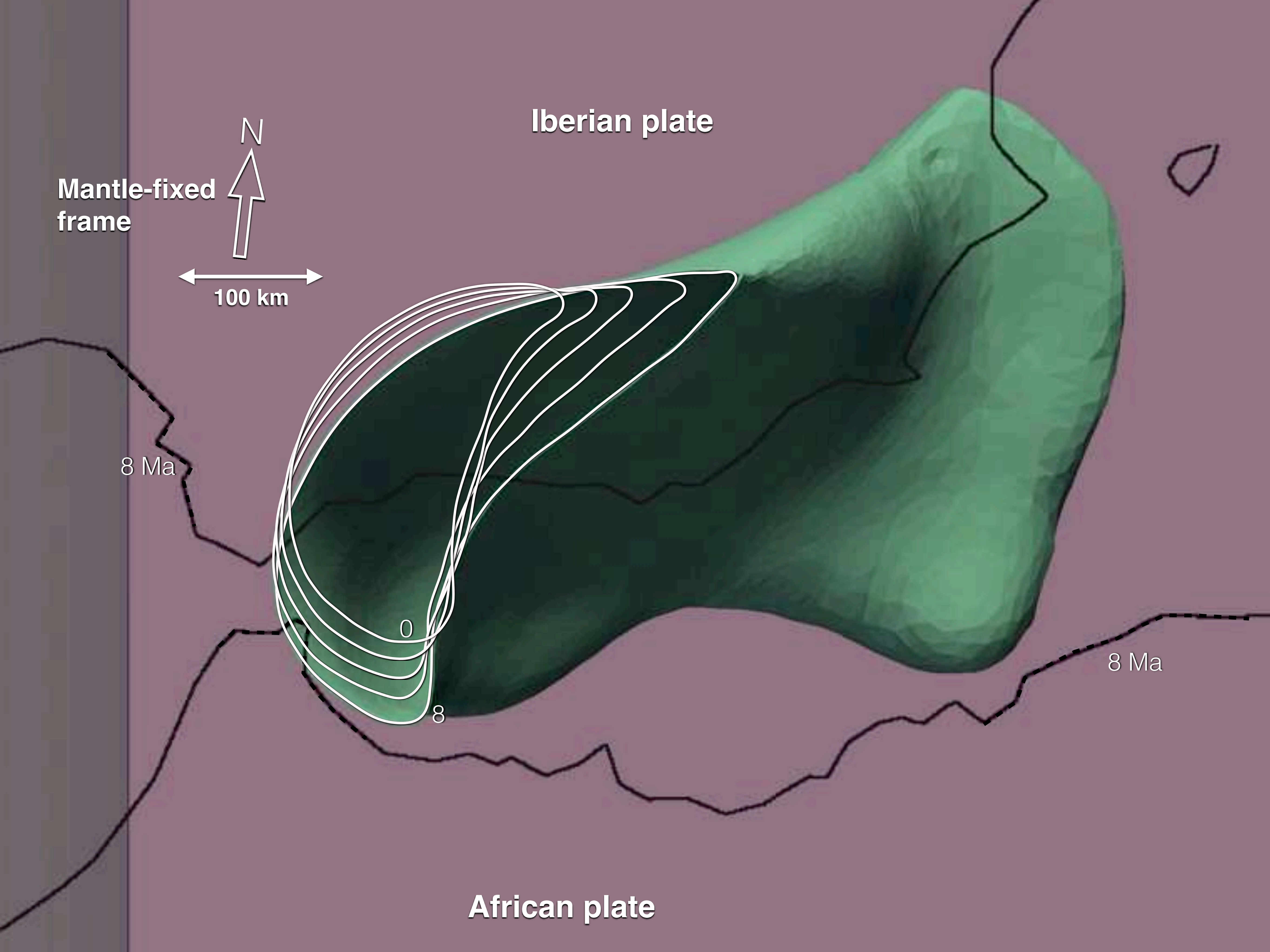
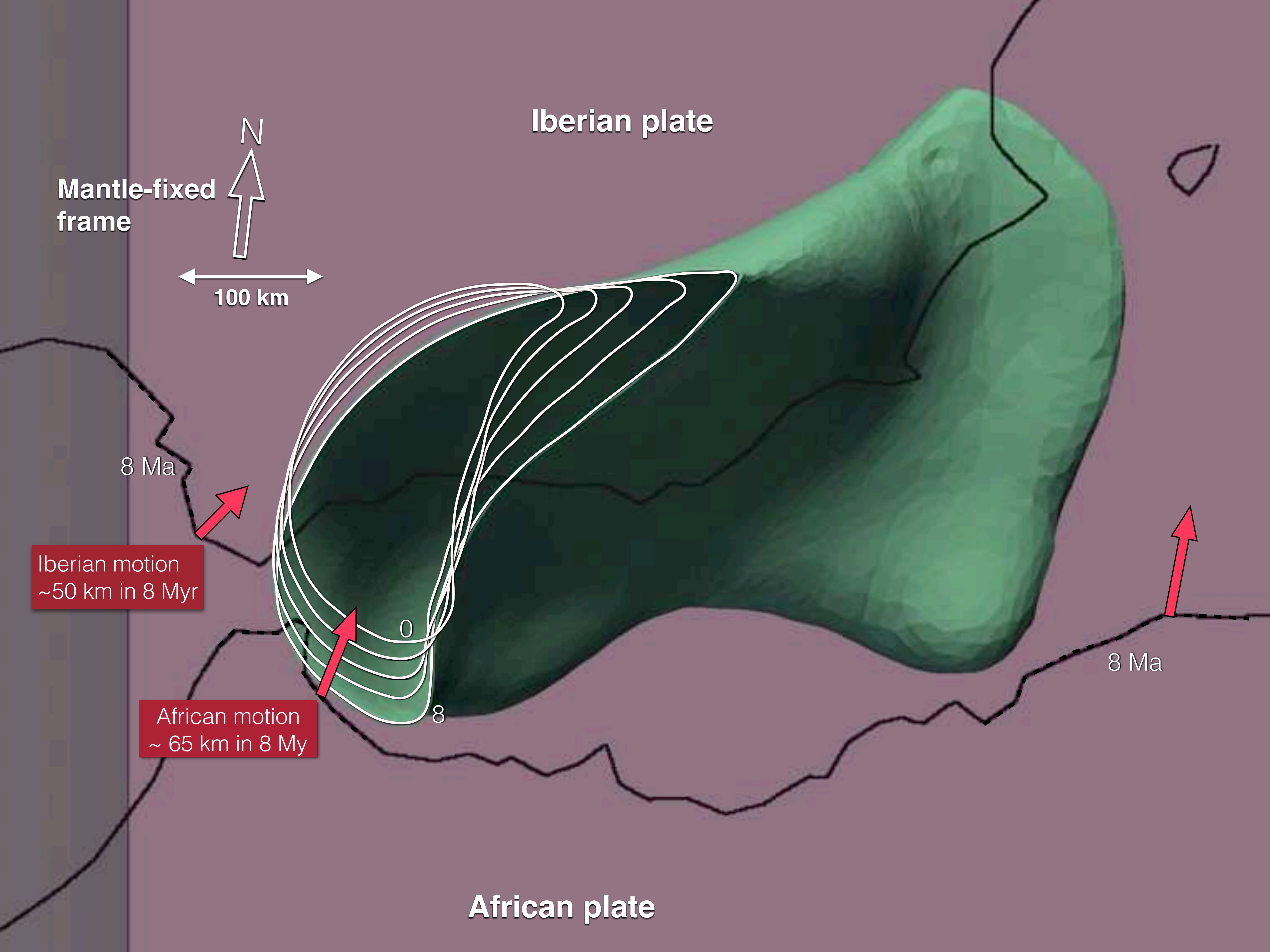


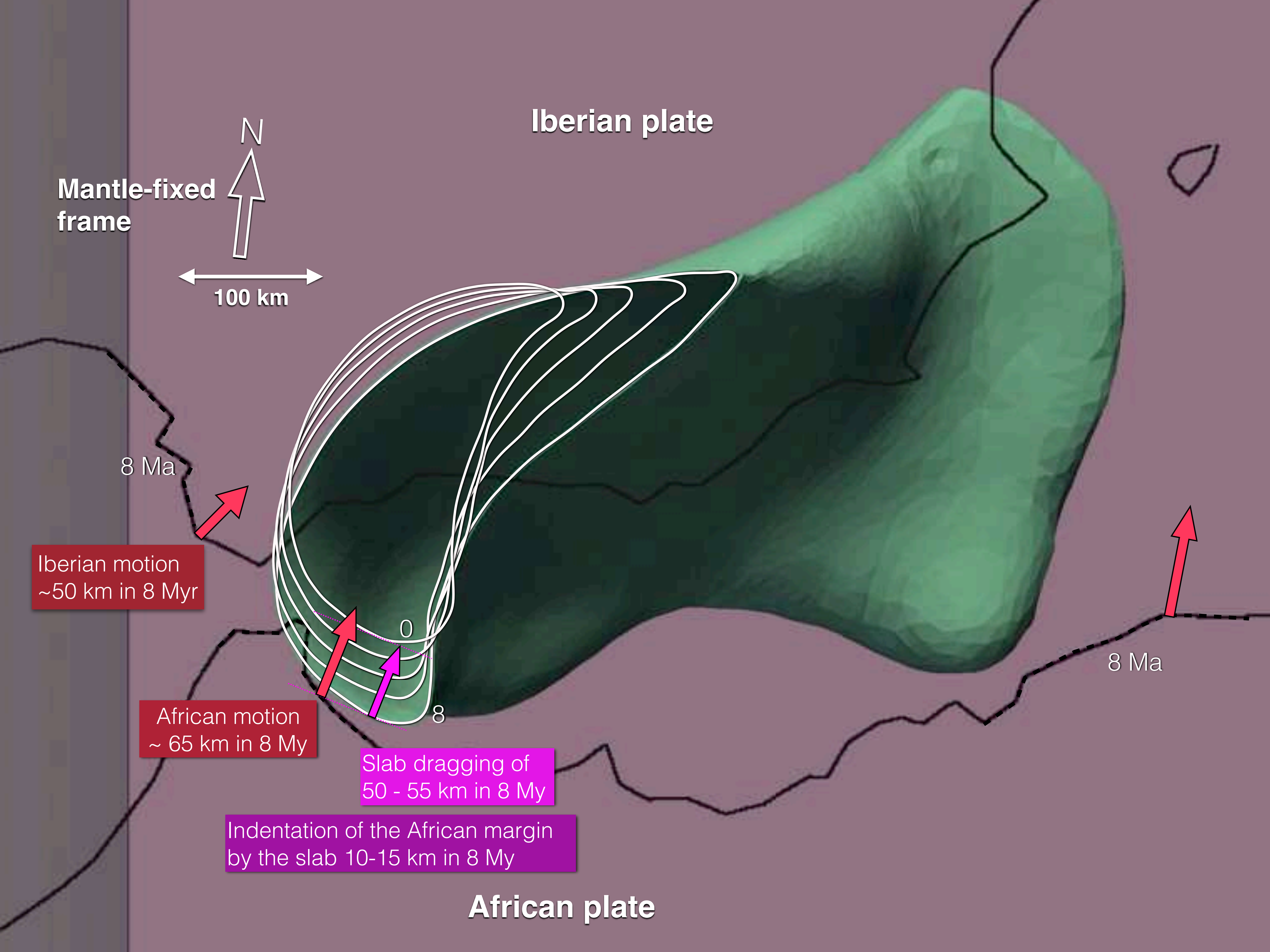
View to the SW; Colors = flow speed

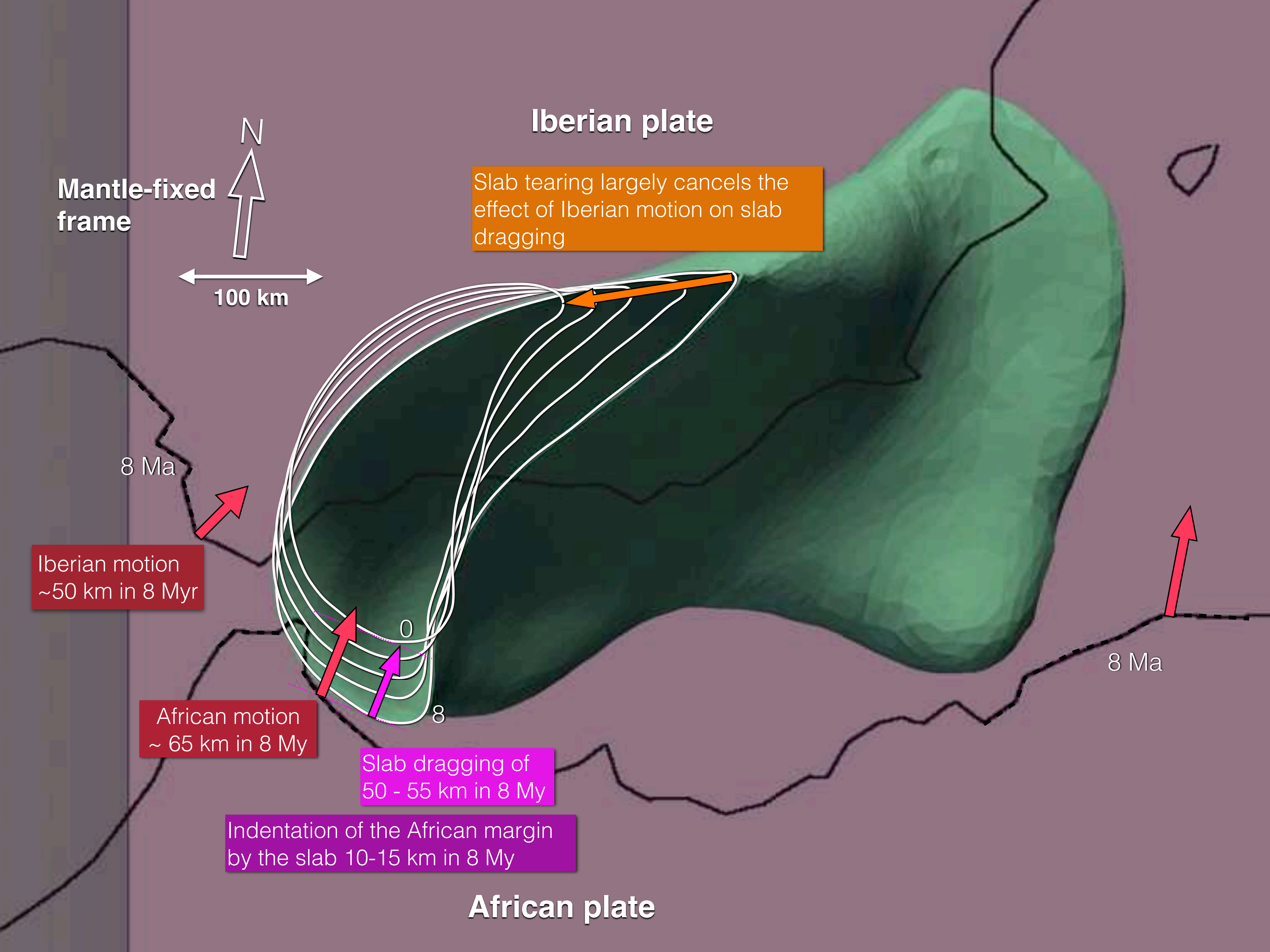

Iberian plate
N
Mantle-fixed frame
100 km
8 Ma
0
8
8 Ma
African plate



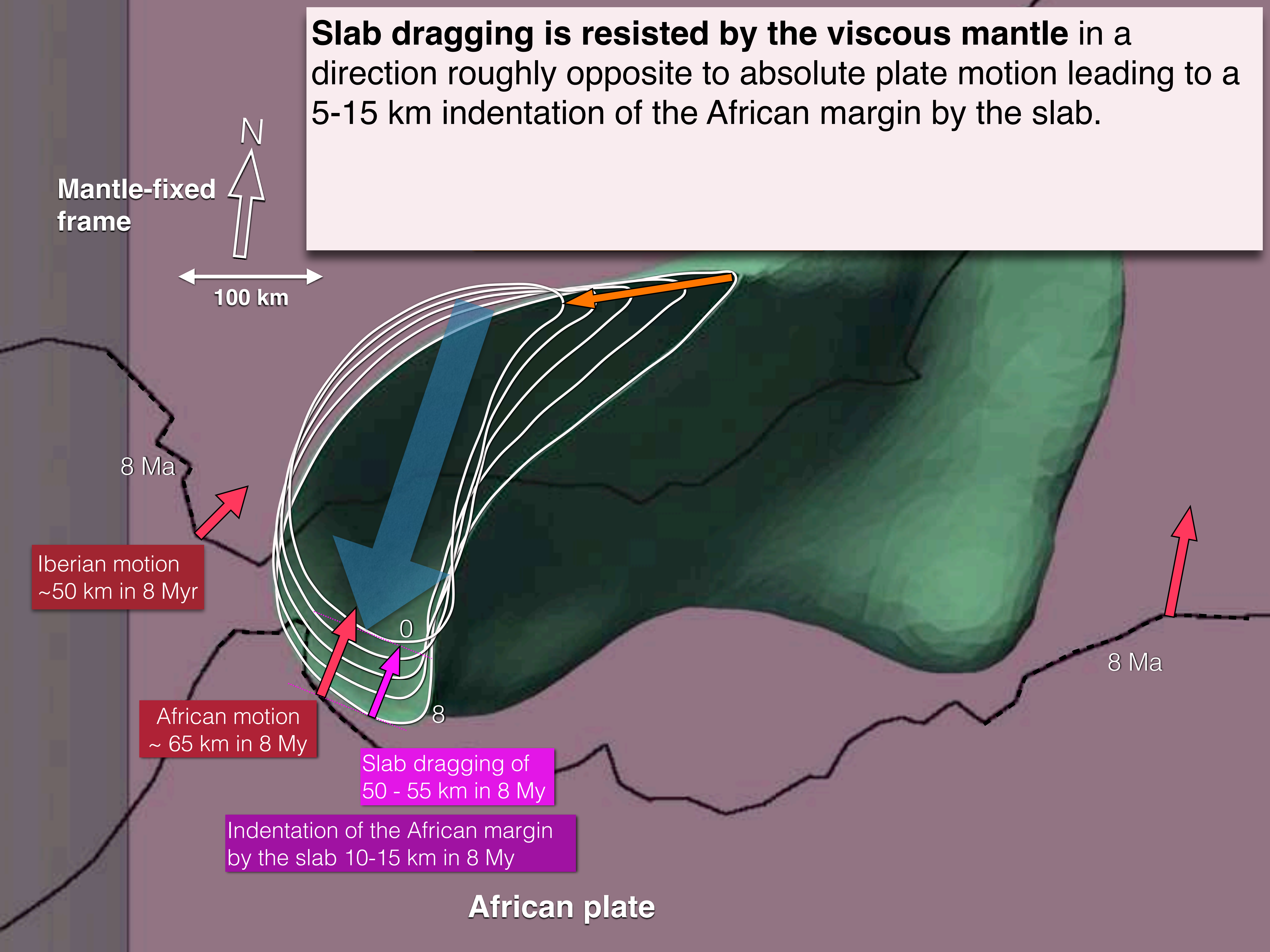
Iberian plate
N
Mantle-fixed frame
100 km
8 Ma
0
8
8 Ma
African plate

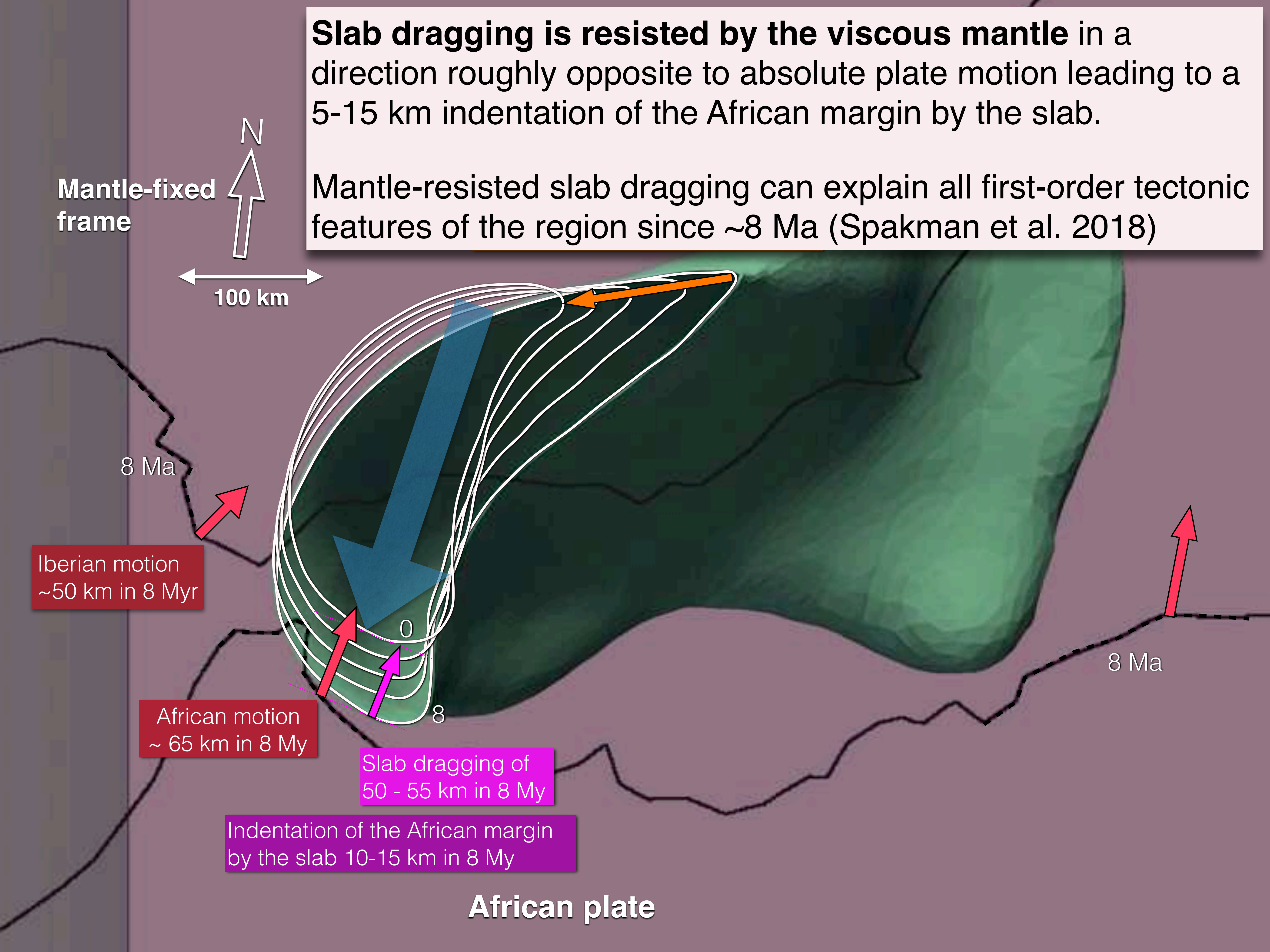

Iberian plate
Mantle-fixed frame
N
100 km
8 Ma
Iberian motion ~50 km in 8 Myr
0
8
African motion ~ 65 km in 8 My
8 Ma
African plate


Iberian plate
N
Mantle-fixed
frame
100 km
8 Ma
Iberian motion
~50 km in 8 Myr
0
8
8 Ma
African motion
~ 65 km in 8 My
Slab dragging of
50 - 55 km in 8 My
Indentation of the African margin
by the slab 10-15 km in 8 My
African plate


Iberian plate
N
Mantle-fixed frame
100 km
Slab tearing largely cancels the effect of Iberian motion on slab dragging
8 Ma
Iberian motion ~50 km in 8 Myr
0
8
8 Ma
African motion ~ 65 km in 8 My
Slab dragging of 50 - 55 km in 8 My
Indentation of the African margin by the slab 10-15 km in 8 My
African plate

Slab dragging is resisted by the viscous mantle in a direction roughly opposite to absolute plate motion leading to a 5-15 km indentation of the African margin by the slab.

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Mantle-resisted slab dragging can explain all first-order tectonic features of the region since ~8 Ma (Spakman et al. 2018)
Mantle-fixed frame
N
100 km
8 Ma
Iberian motion ~50 km in 8 Myr
0
8
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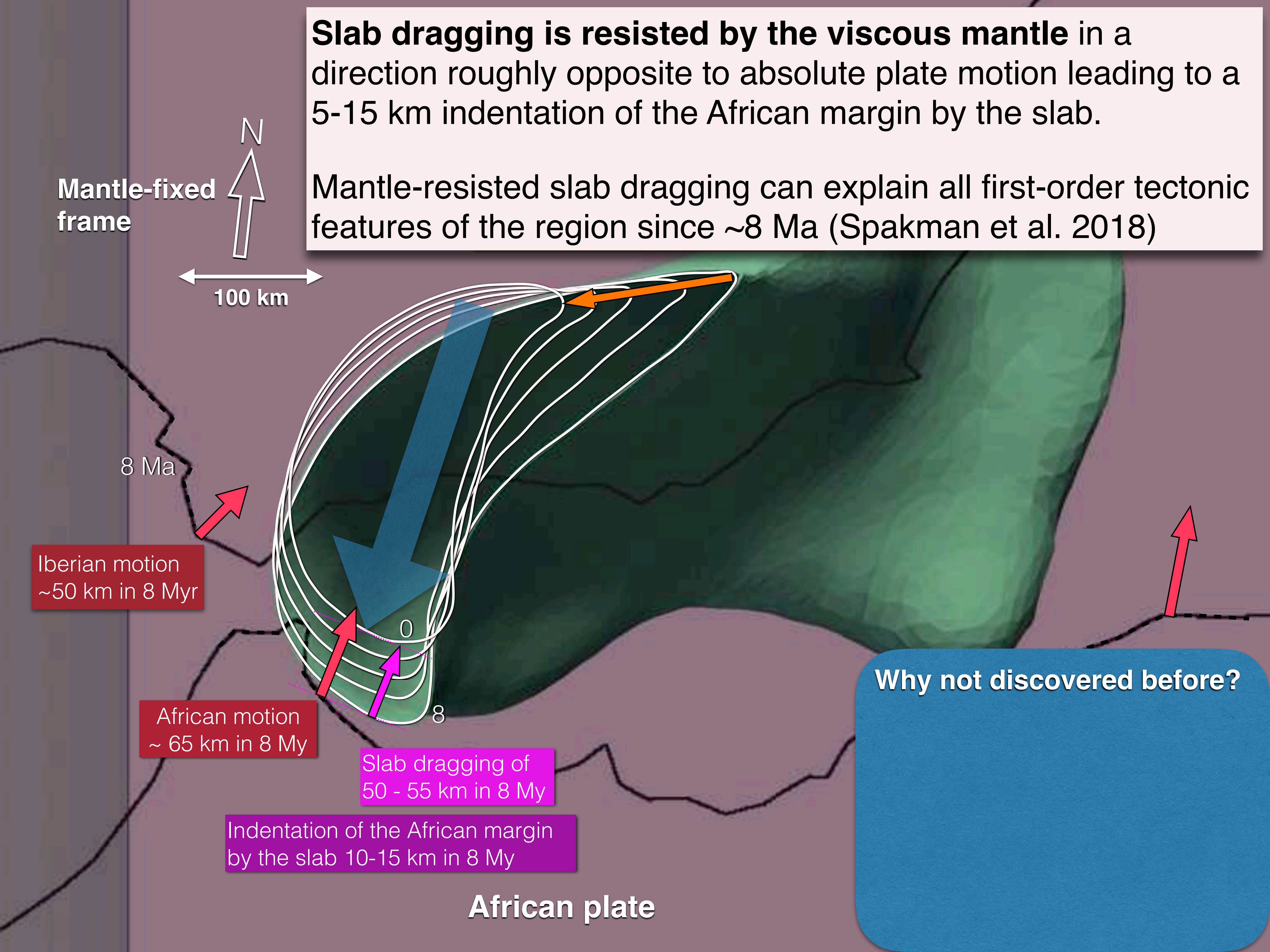
African motion ~ 65 km in 8 My
Slab dragging of 50 - 55 km in 8 My
Indentation of the African margin by the slab 10-15 km in 8 My
African plate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Why not discovered before?

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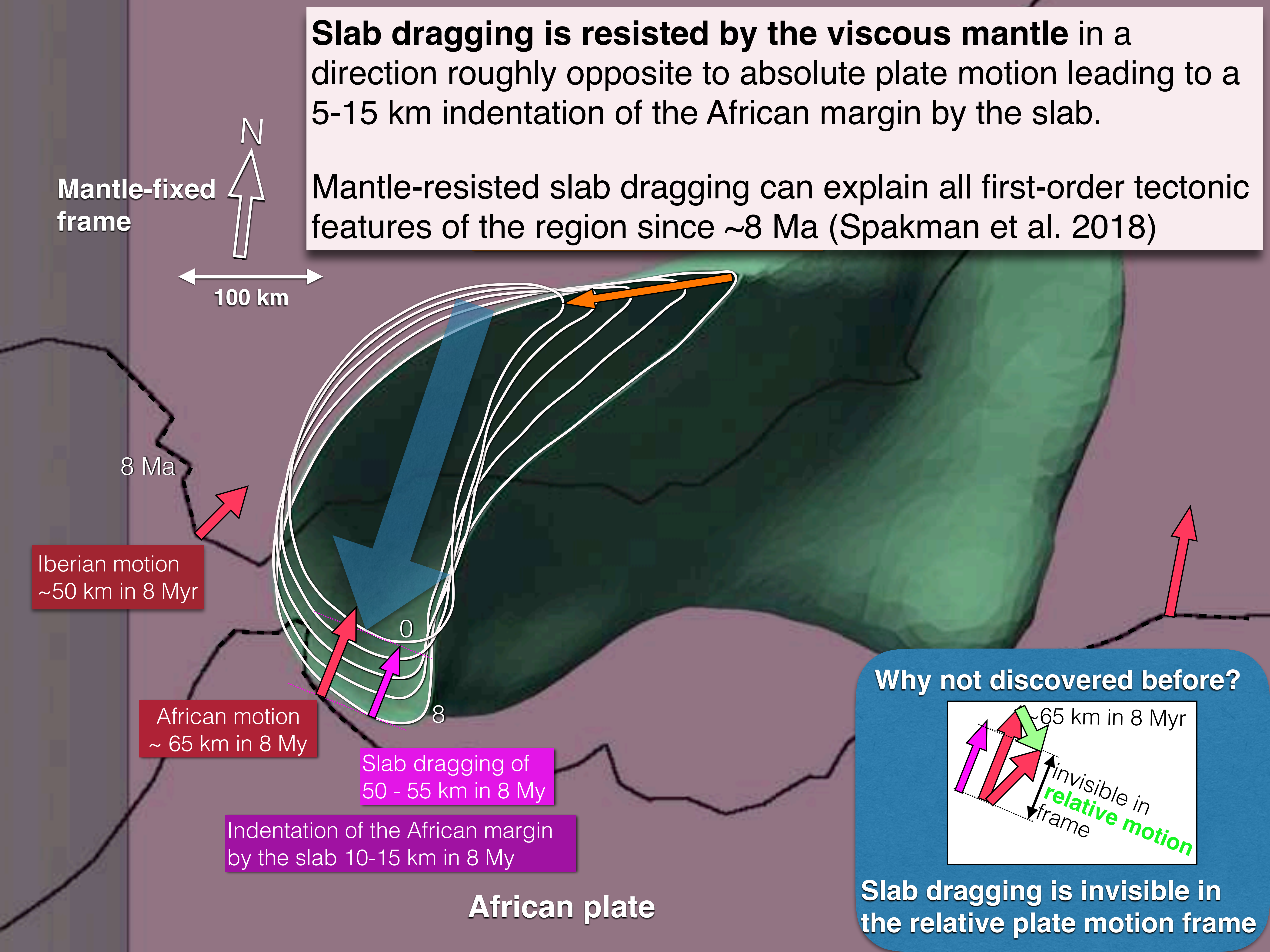
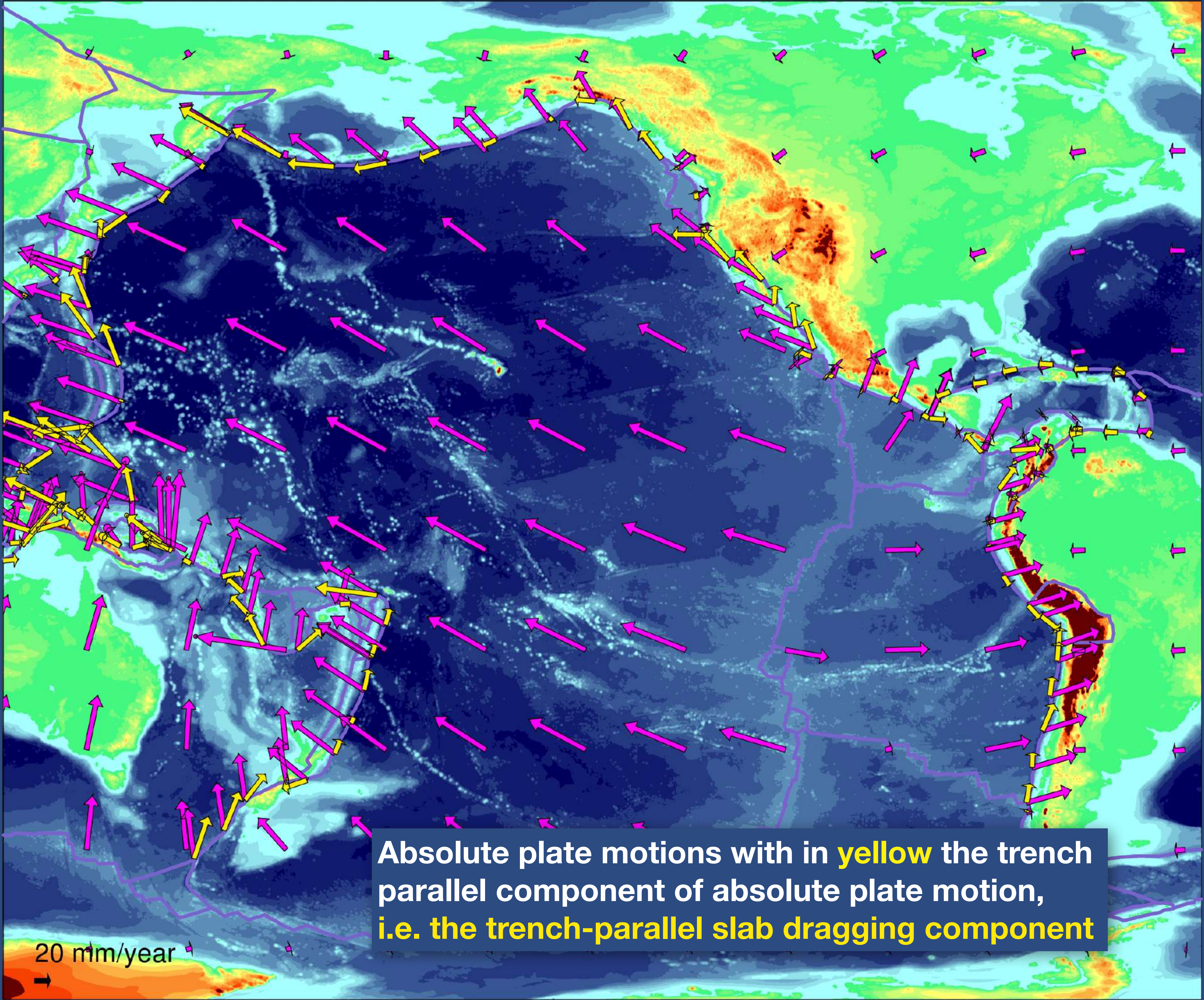


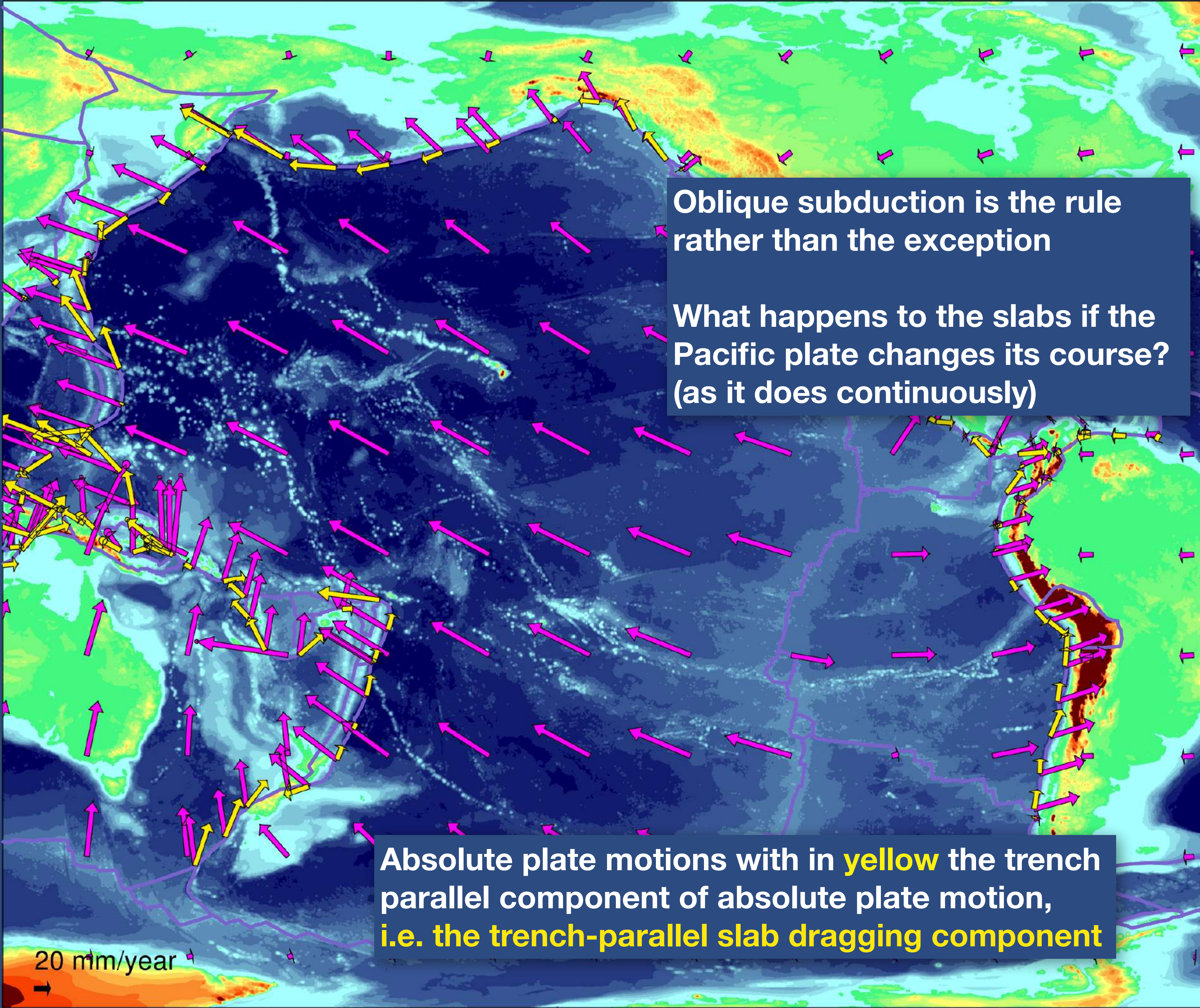
Is dragging of the Burma, Banda, and Gibraltar slabs exceptional because of their peculiar geodynamic setting, or does slab dragging occur more generally?



Absolute plate motions with in yellow the trench parallel component of absolute plate motion, i.e. the trench-parallel slab dragging component

Oblique subduction is the rule rather than the exception

What happens to the slabs if the Pacific plate changes its course? (as it does continuously)



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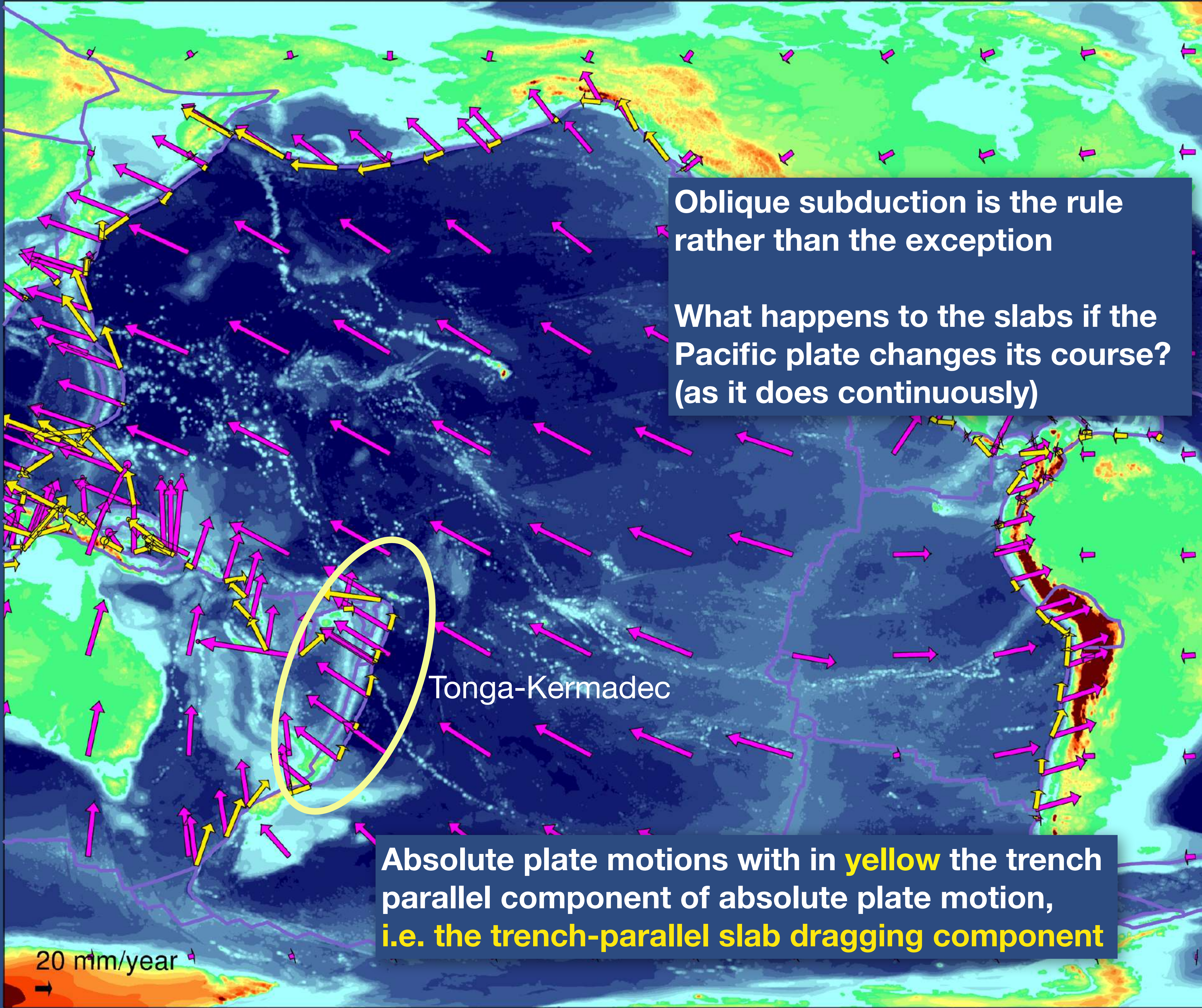

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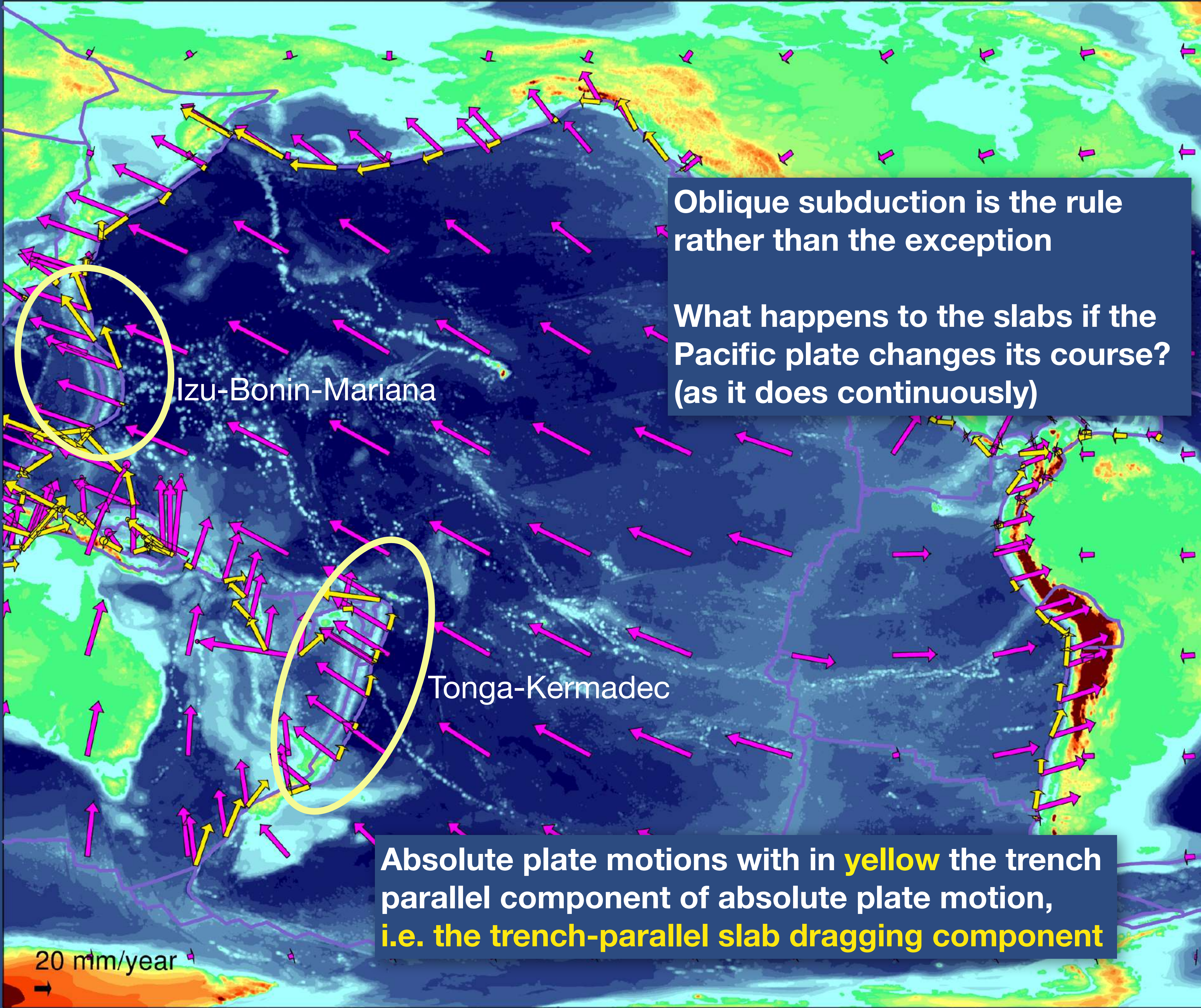

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Izu-Bonin-Mariana

Tonga-Kermadec

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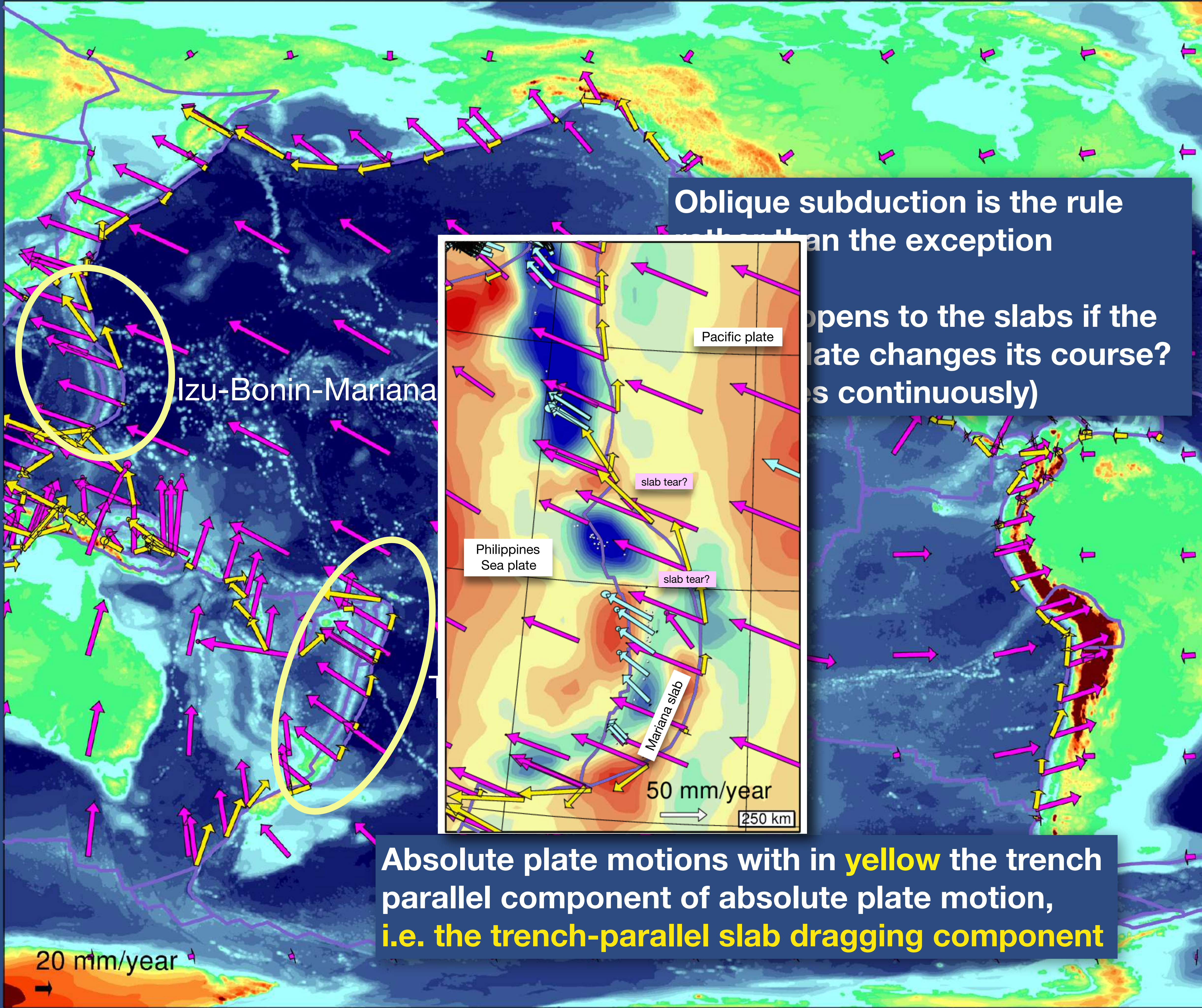
20 mm/year



Oblique subduction is the rule
an the exception
pens to the slabs if the
late changes its course?
s continuously)
Izu-Bonin-Mariana
Pacific plate
Philippines Sea plate
slab tear?
slab tear?
Mariana slab
50 mm/year
250 km
20 mm/year
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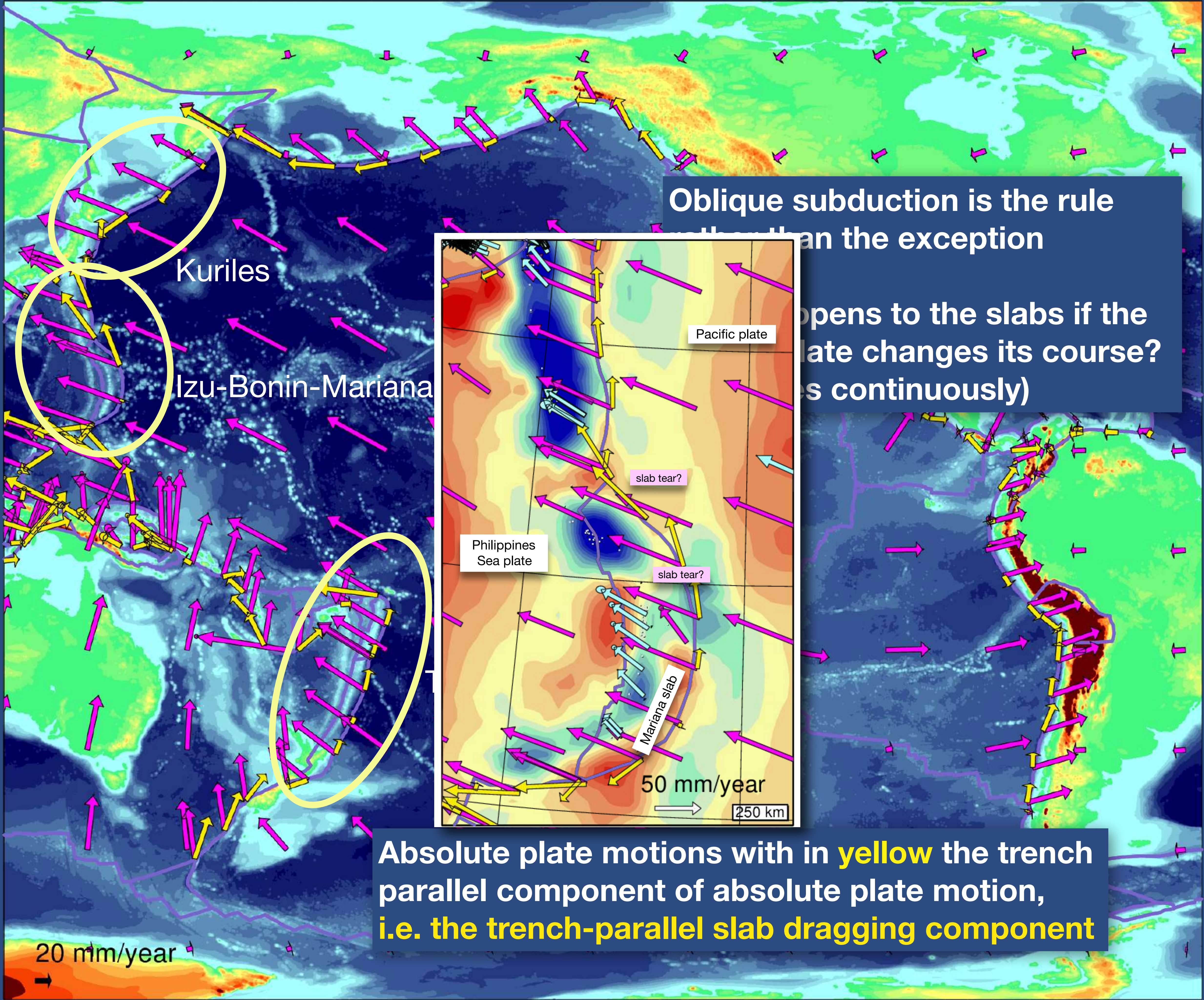

Oblique subduction is the rule
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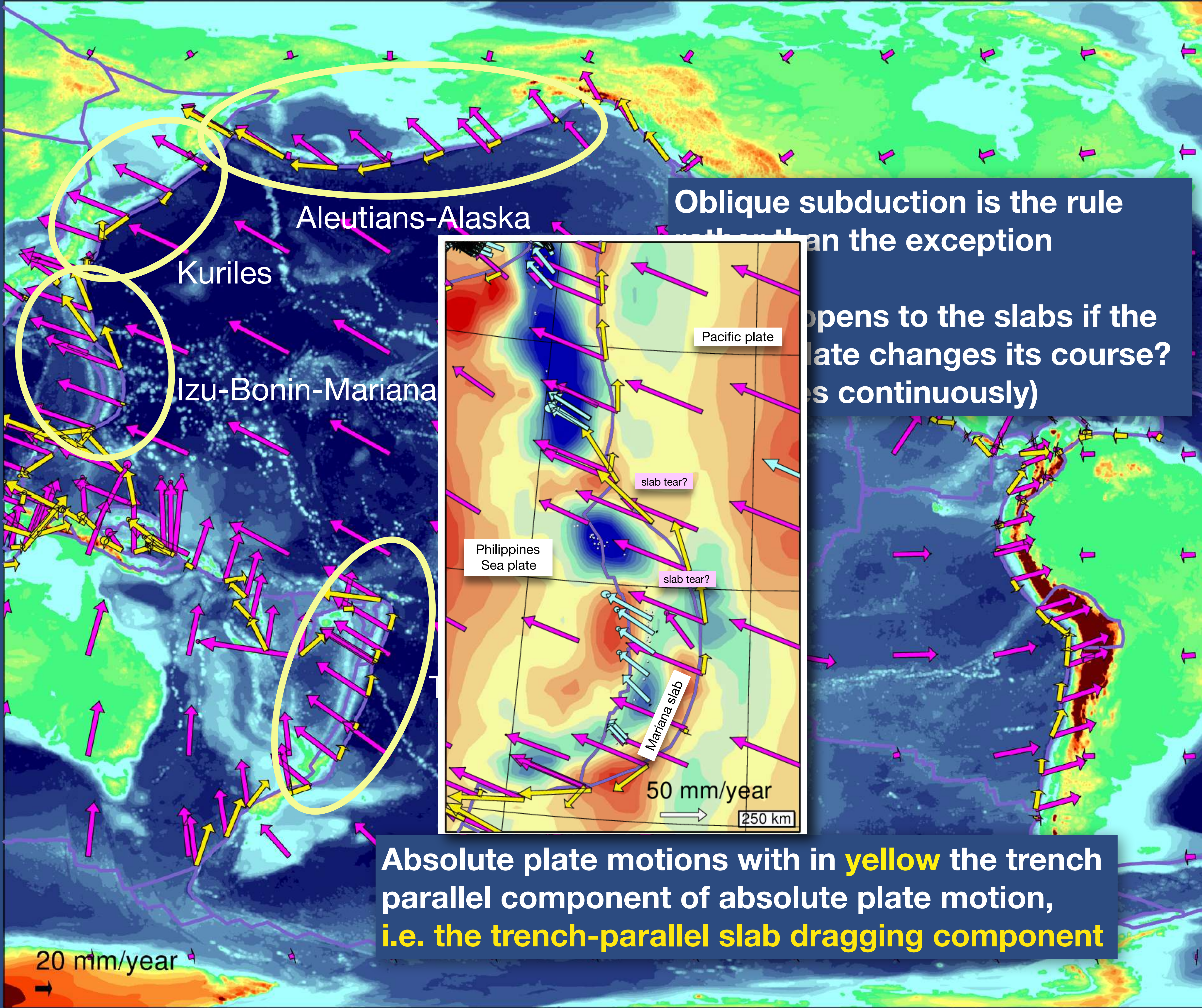

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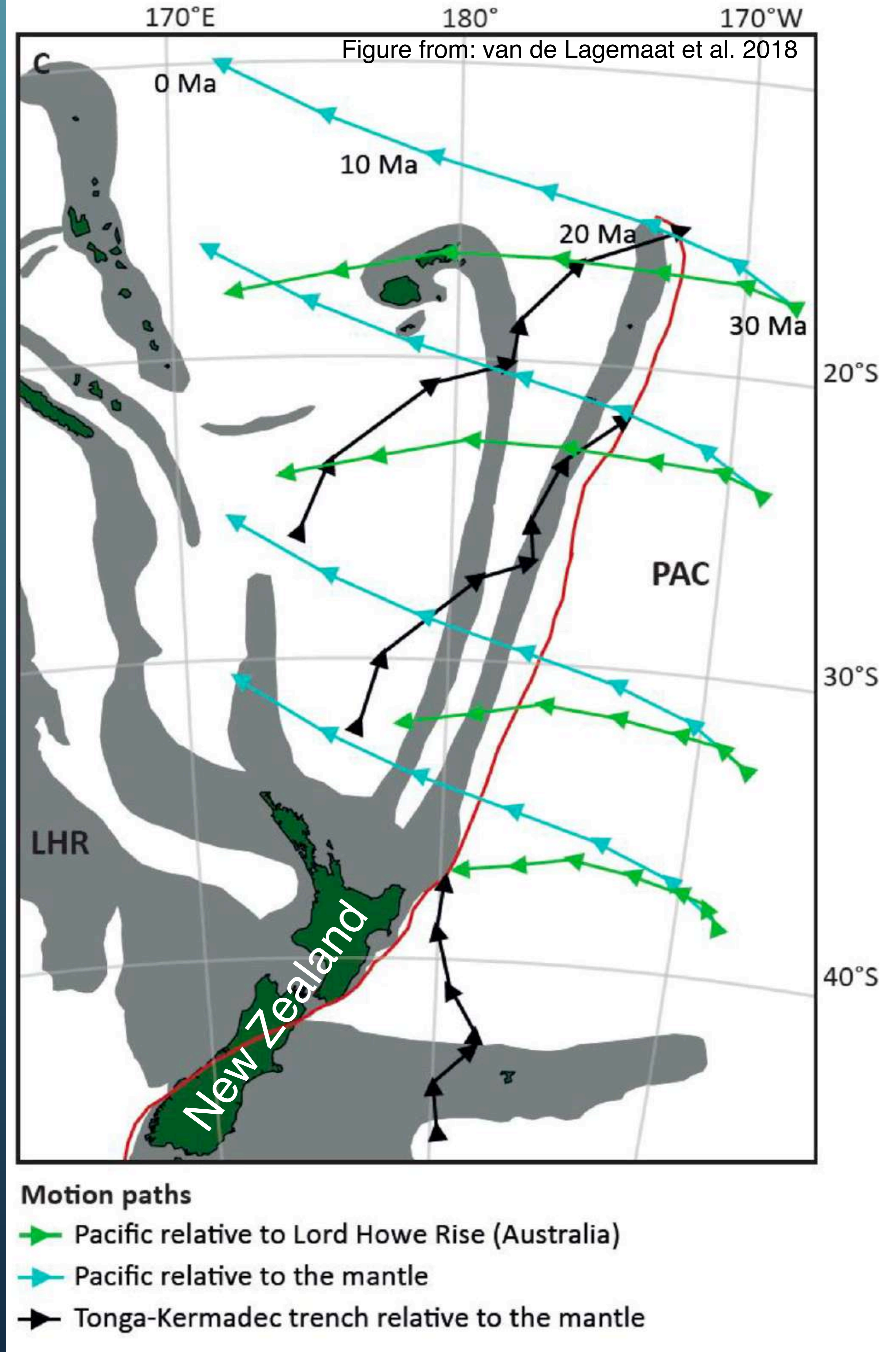
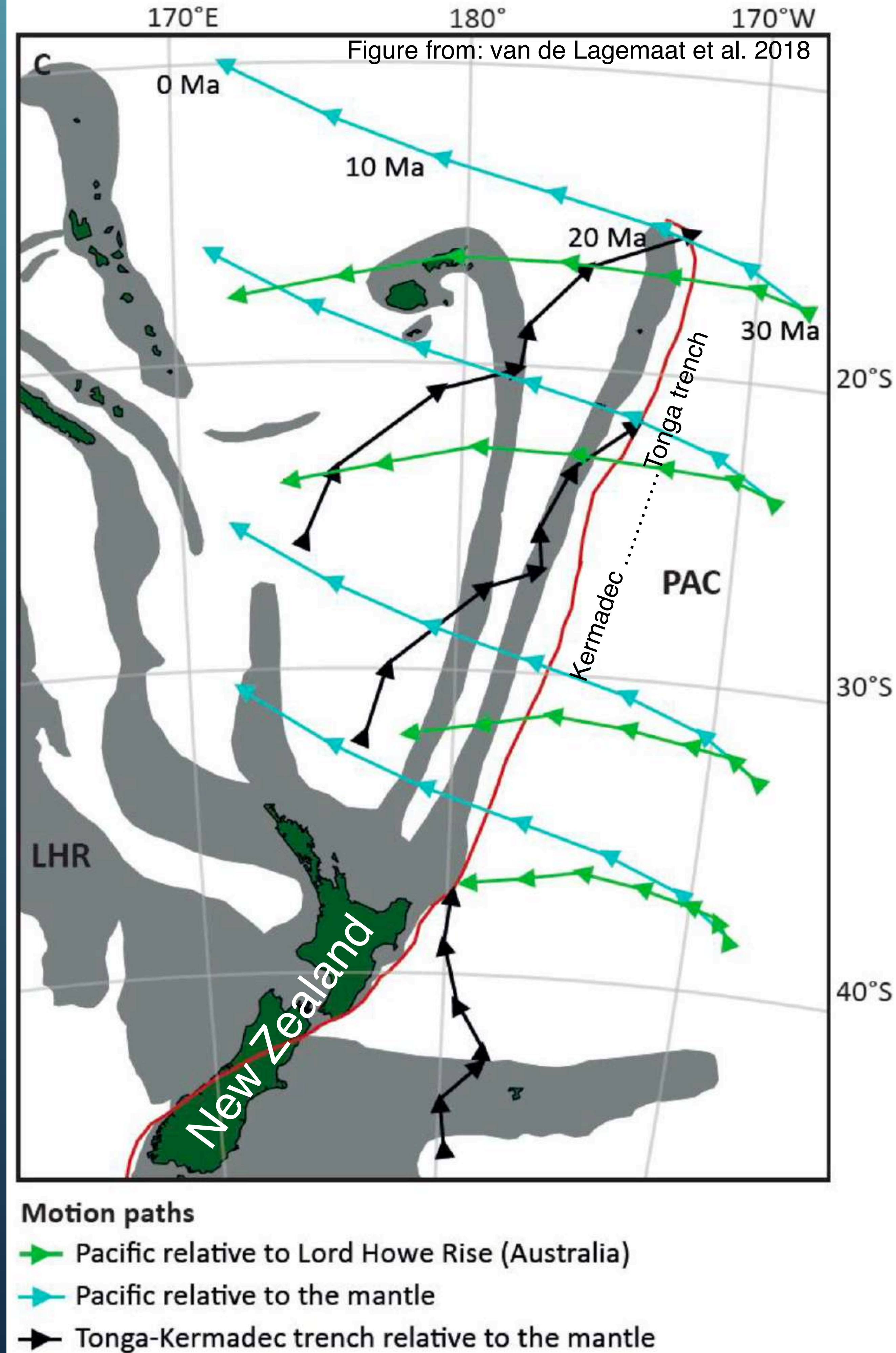

170°E
180°
170°W
Figure from: van de Lagemaat et al. 2018
c
0 Ma
10 Ma
20 Ma
30 Ma
20°S
30°S
40°S
PAC
LHR
New Zealand
Motion paths
Pacific relative to Lord Howe Rise (Australia)
Pacific relative to the mantle
Tonga-Kermadec trench relative to the mantle

Dragging of the Tonga-Kermadec slab by the Pacific plate:



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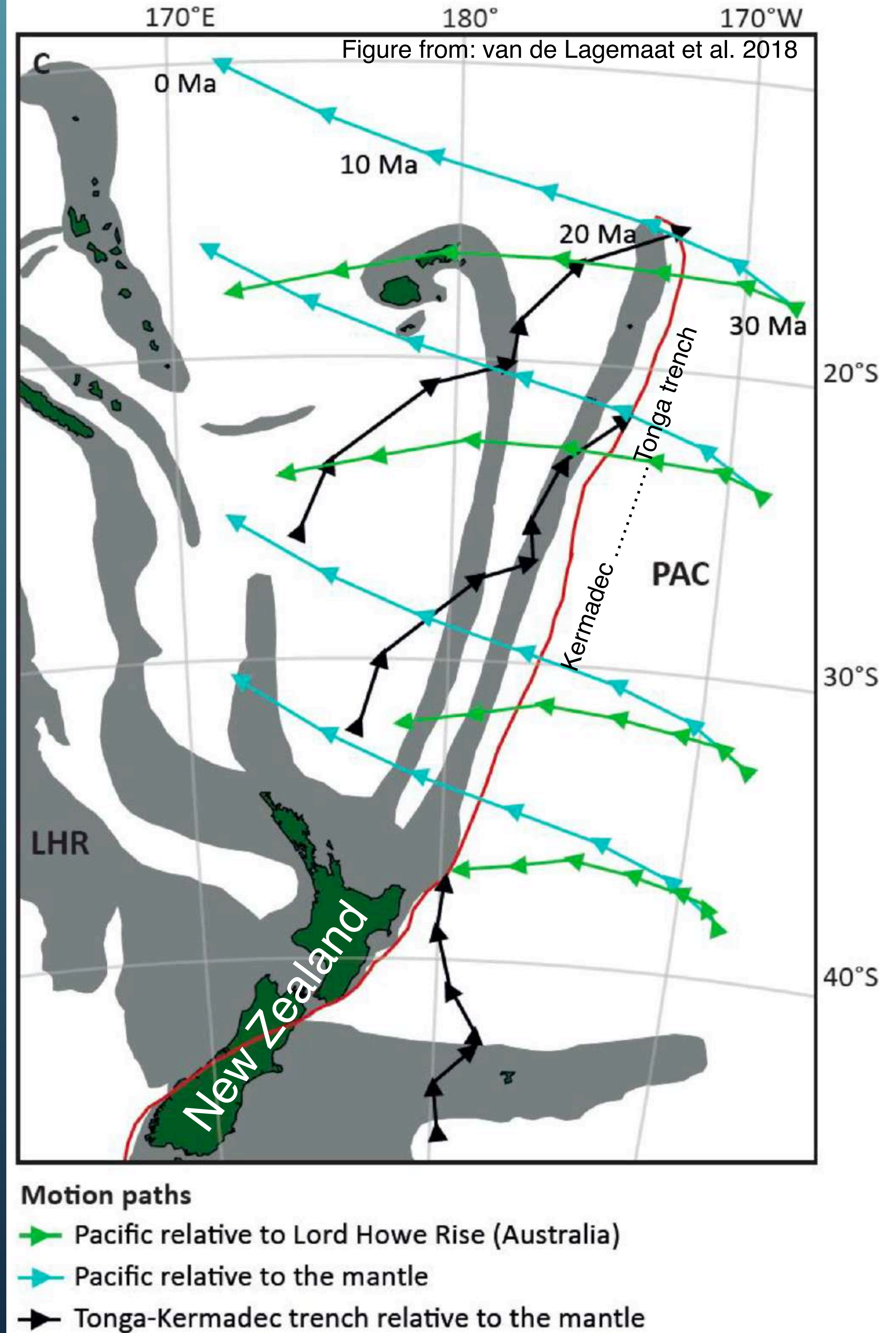

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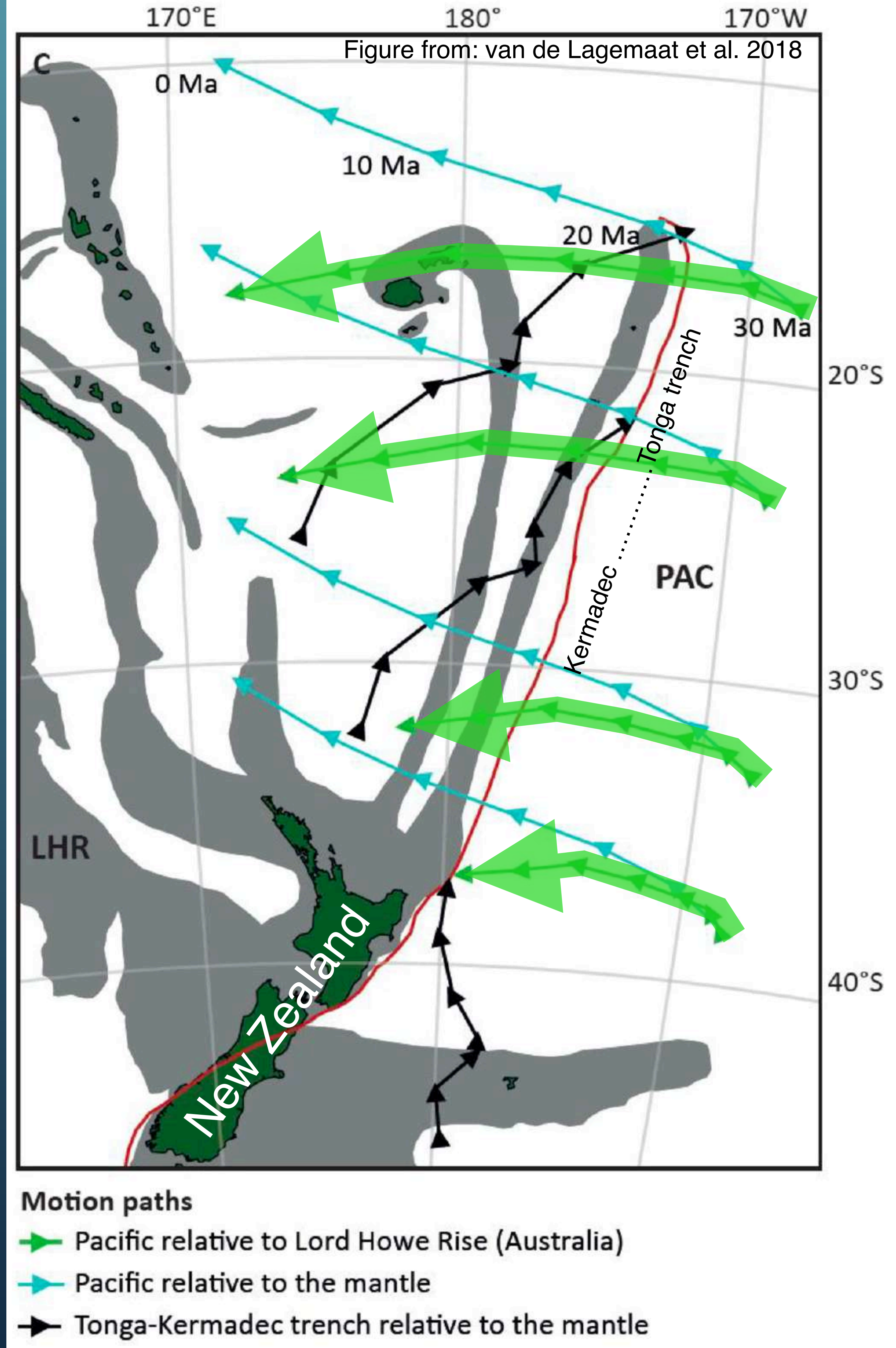

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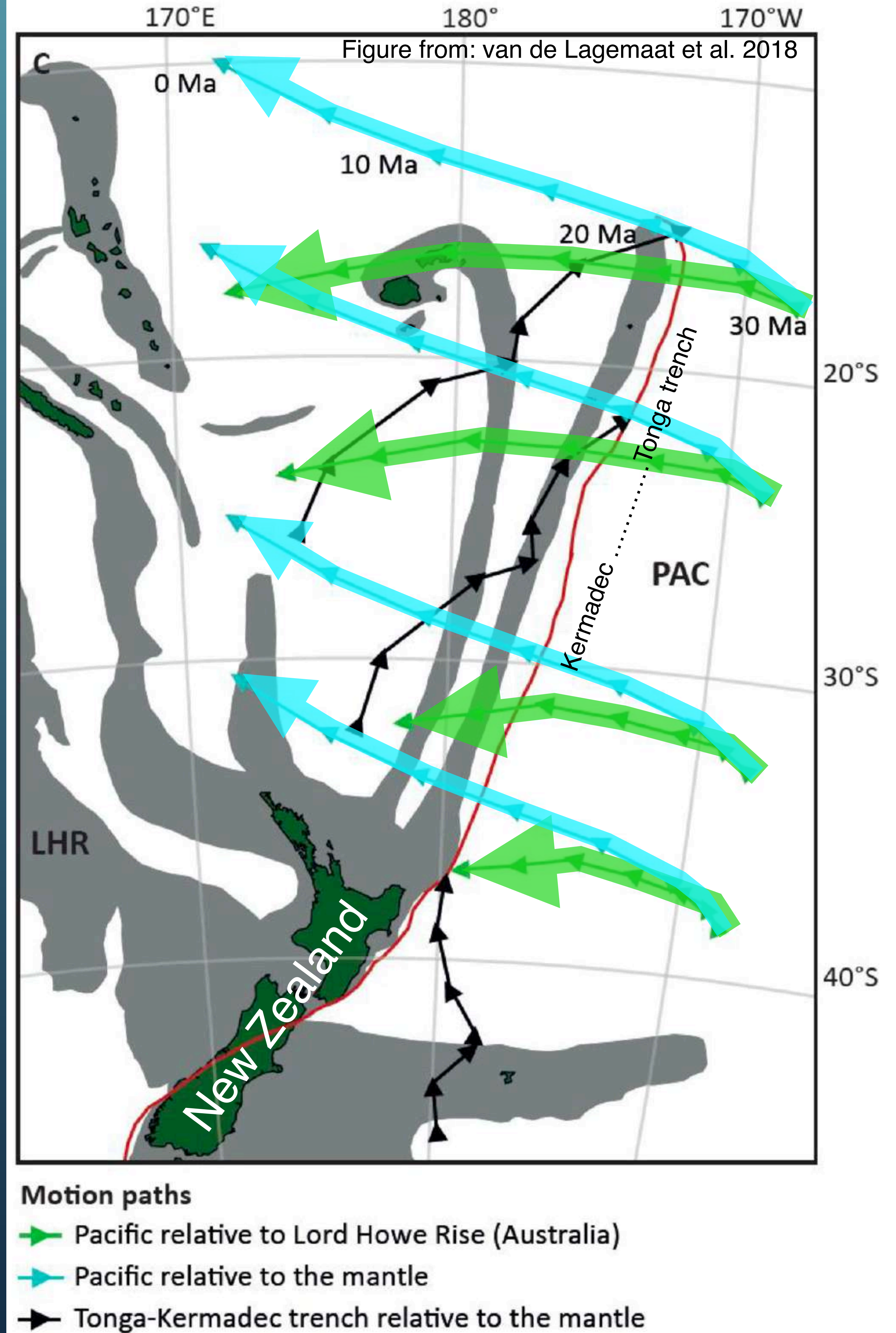

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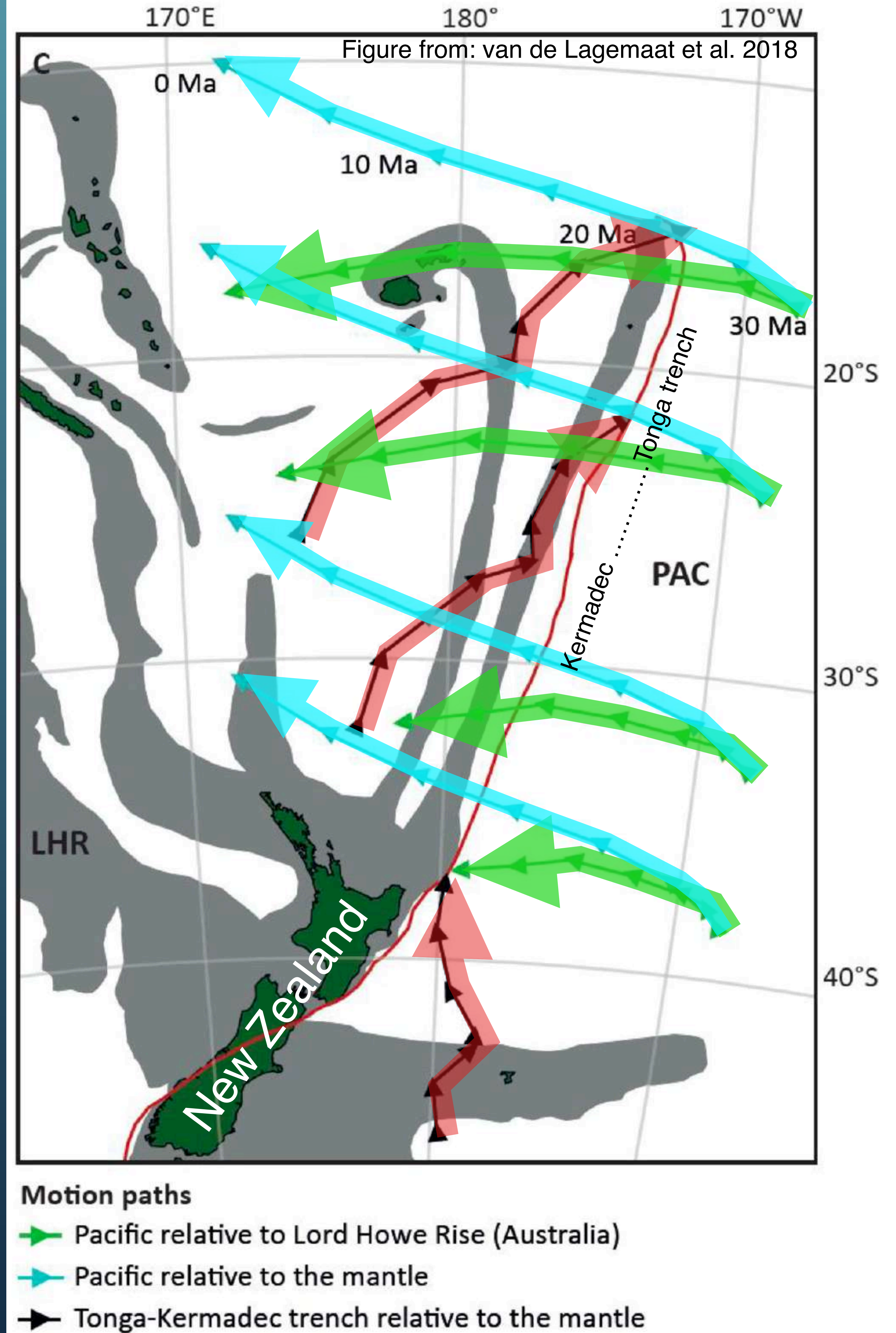

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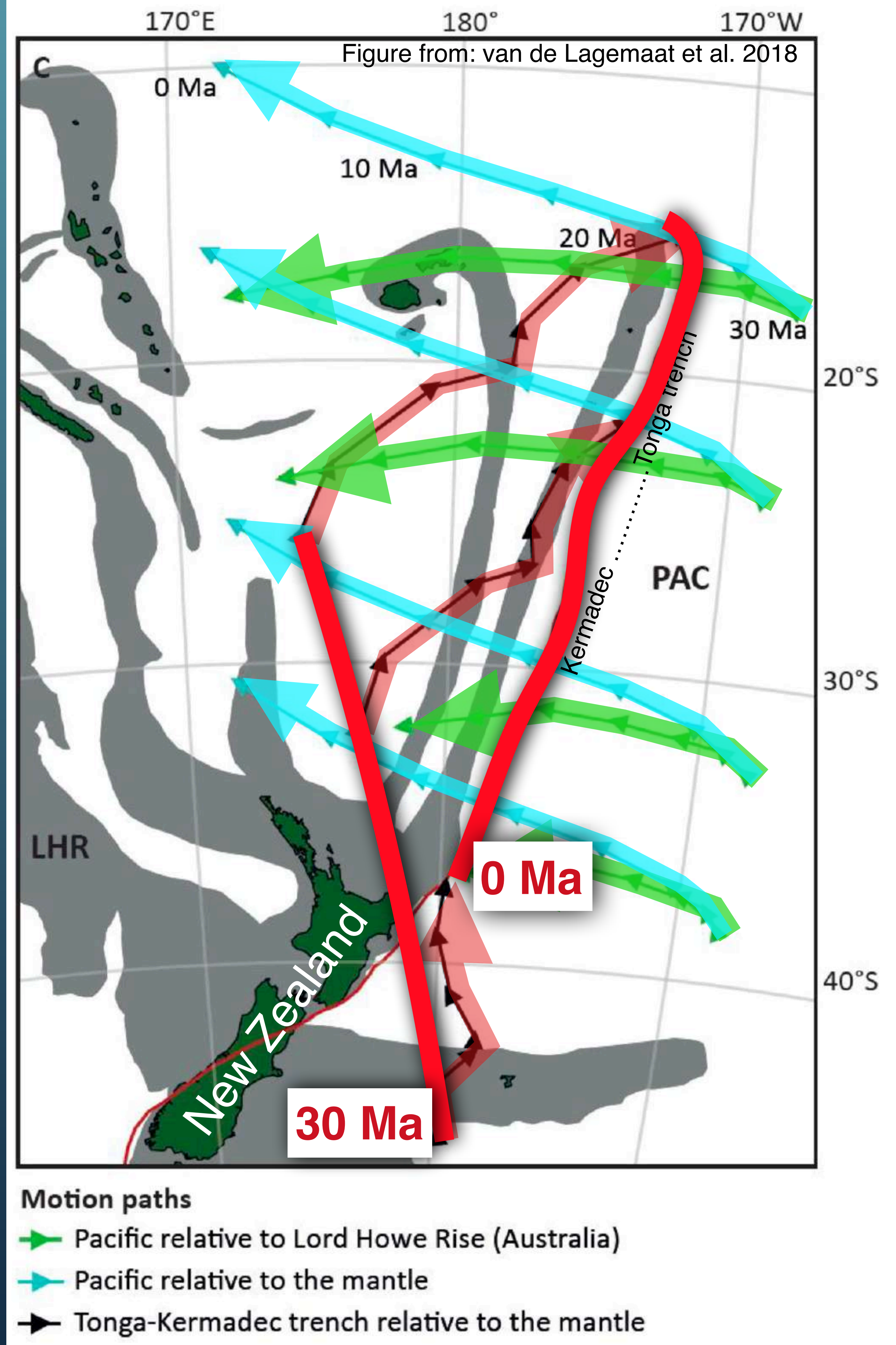

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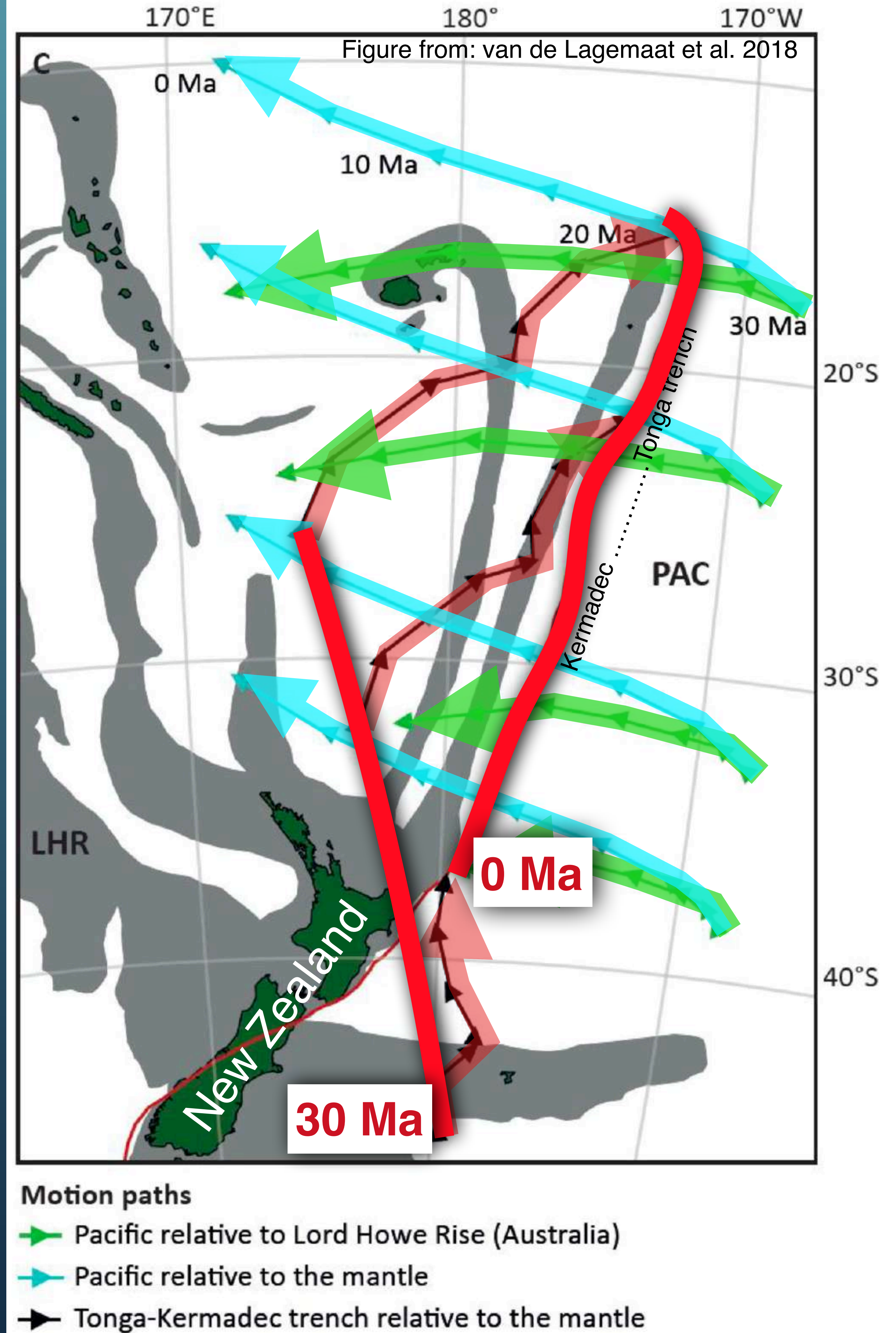
Note: As for the Gibraltar region, the relative motion frame masks large scale slab dragging.

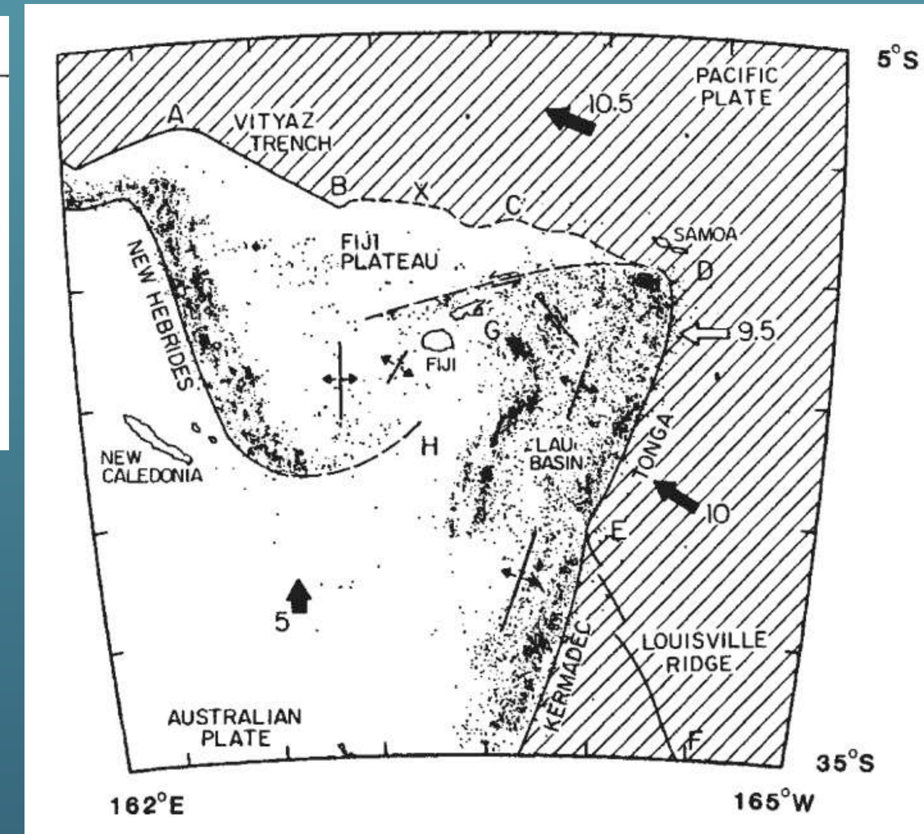


NATURE VOL. 319 13 FEBRUARY 1986

ARTICLES

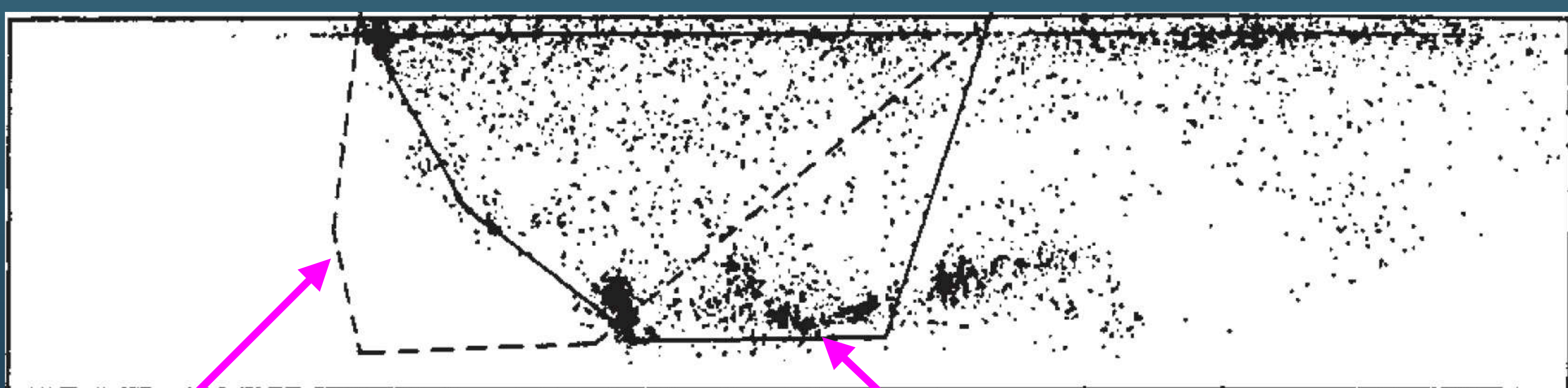
Horizontal shear flow in the mantle beneath the Tonga arc

D. Giardini & J. H. Woodhouse



Observed seismicity along strike of the Tonga-Kermadec slab

N S



Slab outline as predicted from their tectonic reconstruction assuming no internal slab deformation

Slab outlined by present-day seismicity

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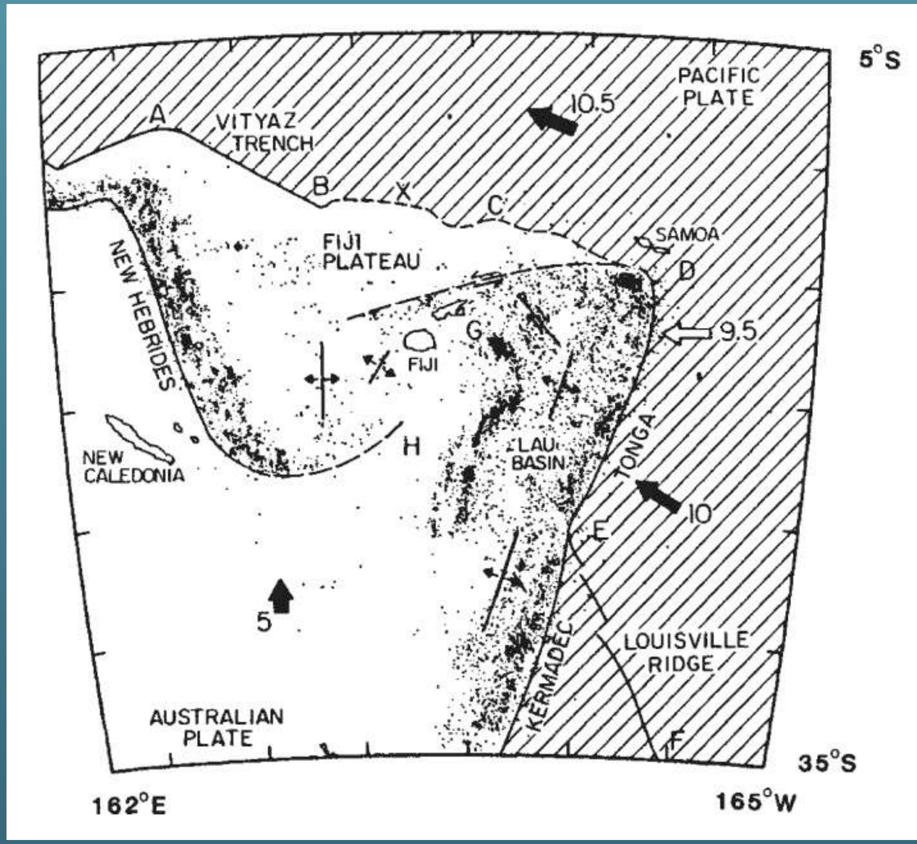

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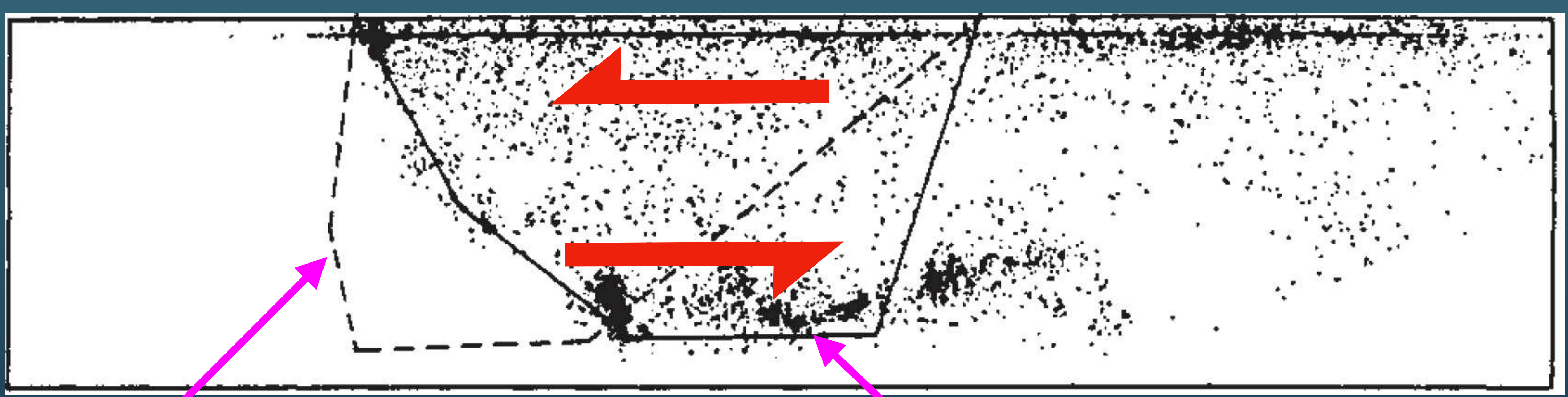

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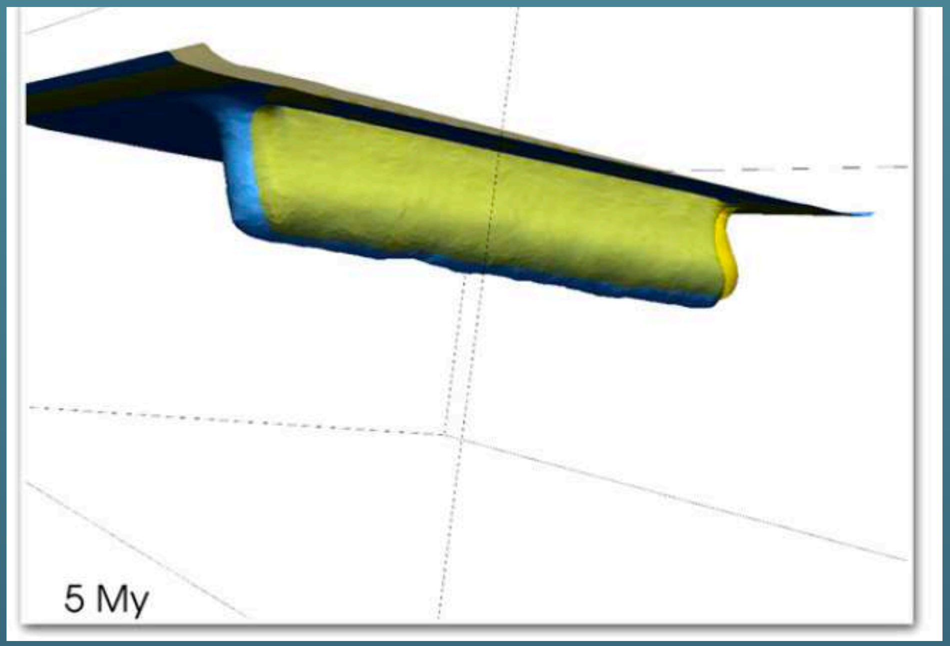

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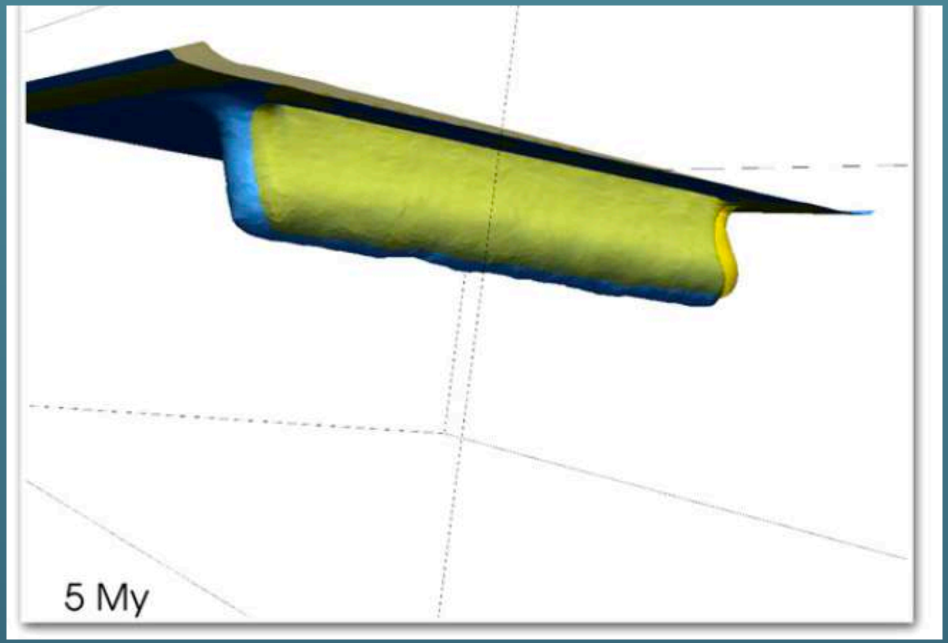

3D slab deformation modelling tracking slab morphology change resulting from an imposed uniform trench-parallel mantle flow

Blue: slab morphology in case there is no forced mantle flow

Yellow: slab morphology when mantle is inflowing from the left at a rate of 3 cm/yr.

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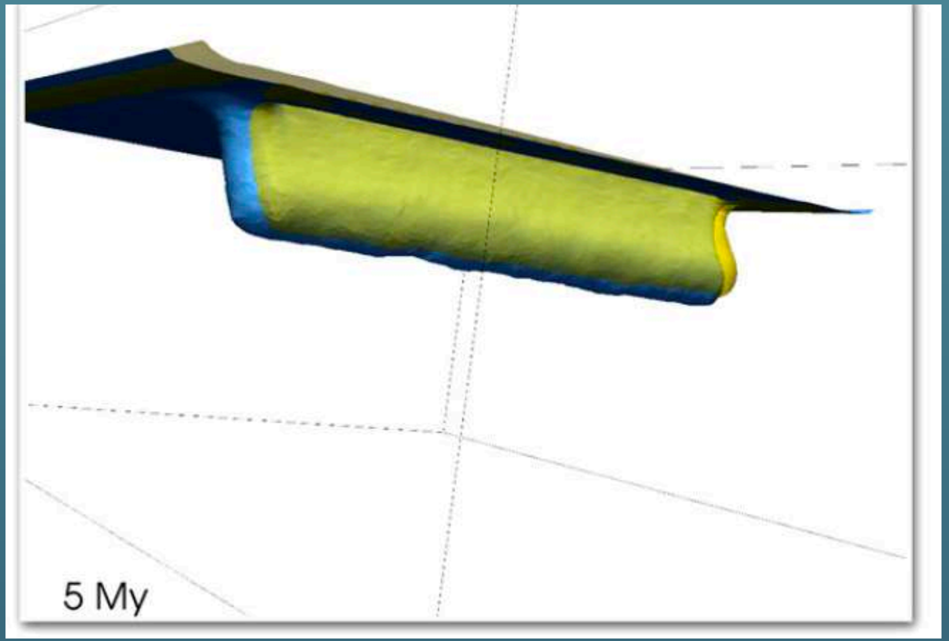

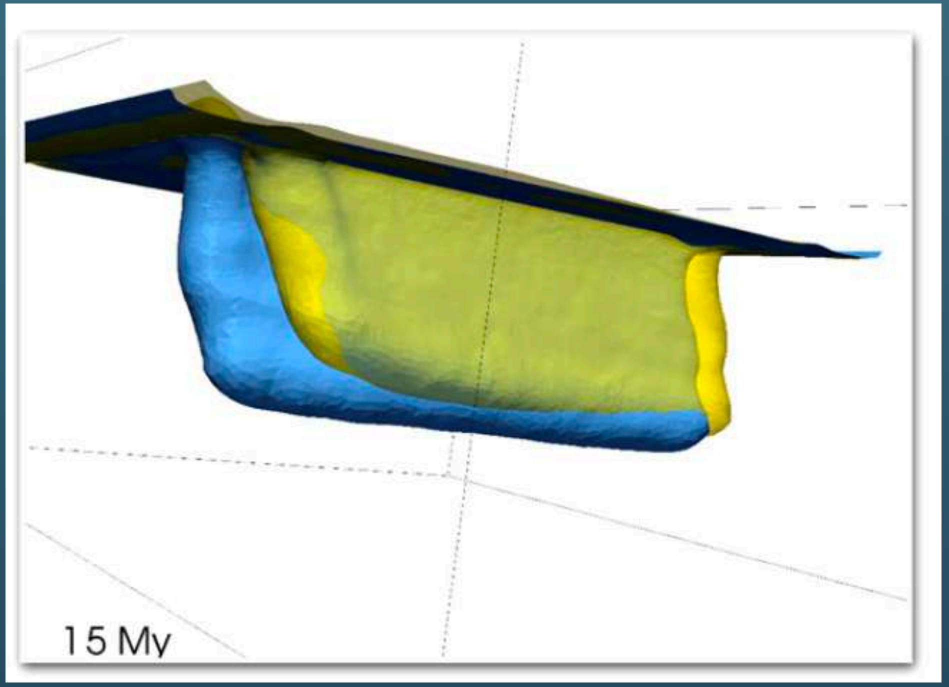

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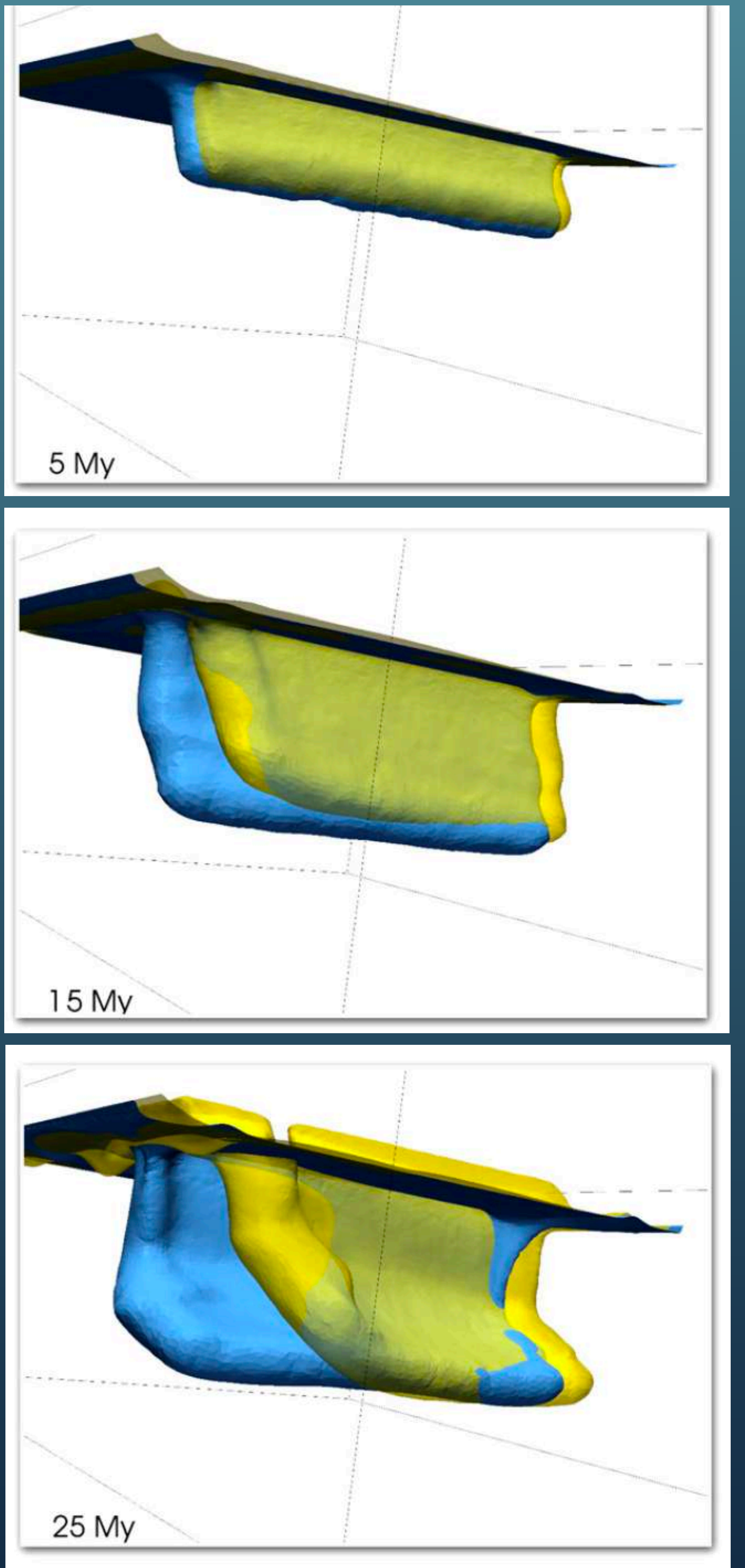

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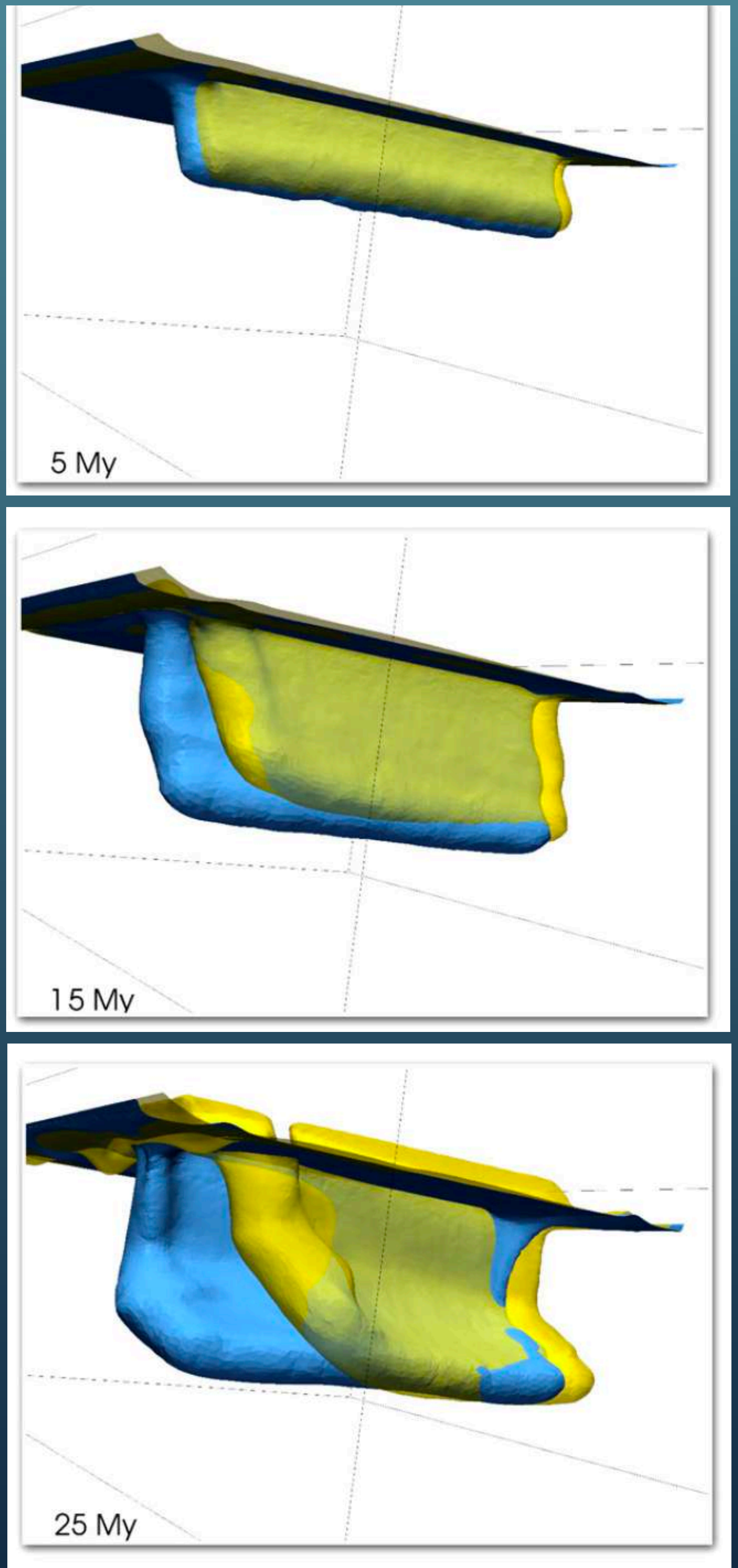

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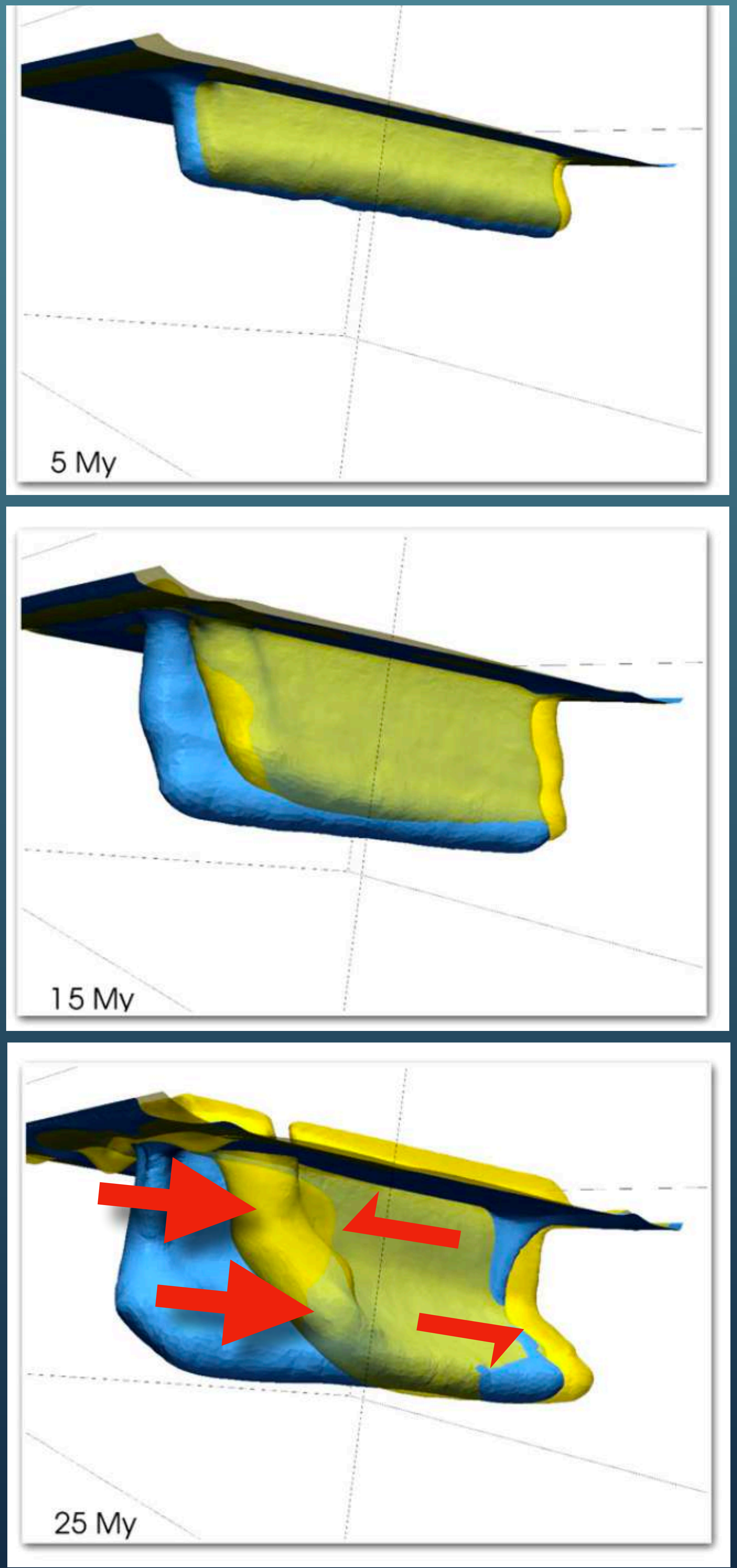
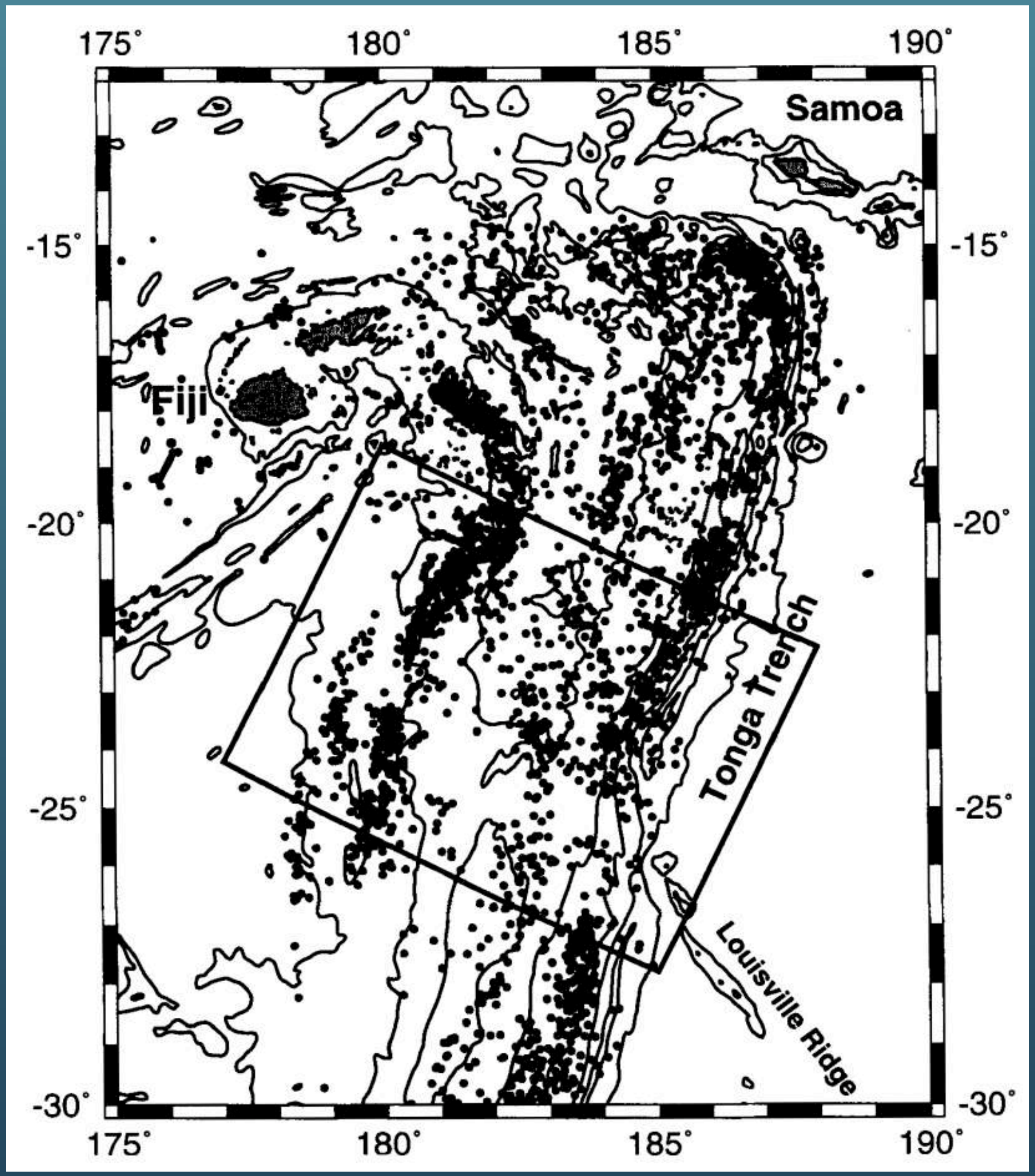
The viscous slab-mantle coupling causes strong trench-parallel deformation, with in addition strong deformation of the slab edge, combining into a complex 3D-state of slab stress.



Nothard et al. 1996 *Distributed deformation in the subducting lithosphere at Tonga*



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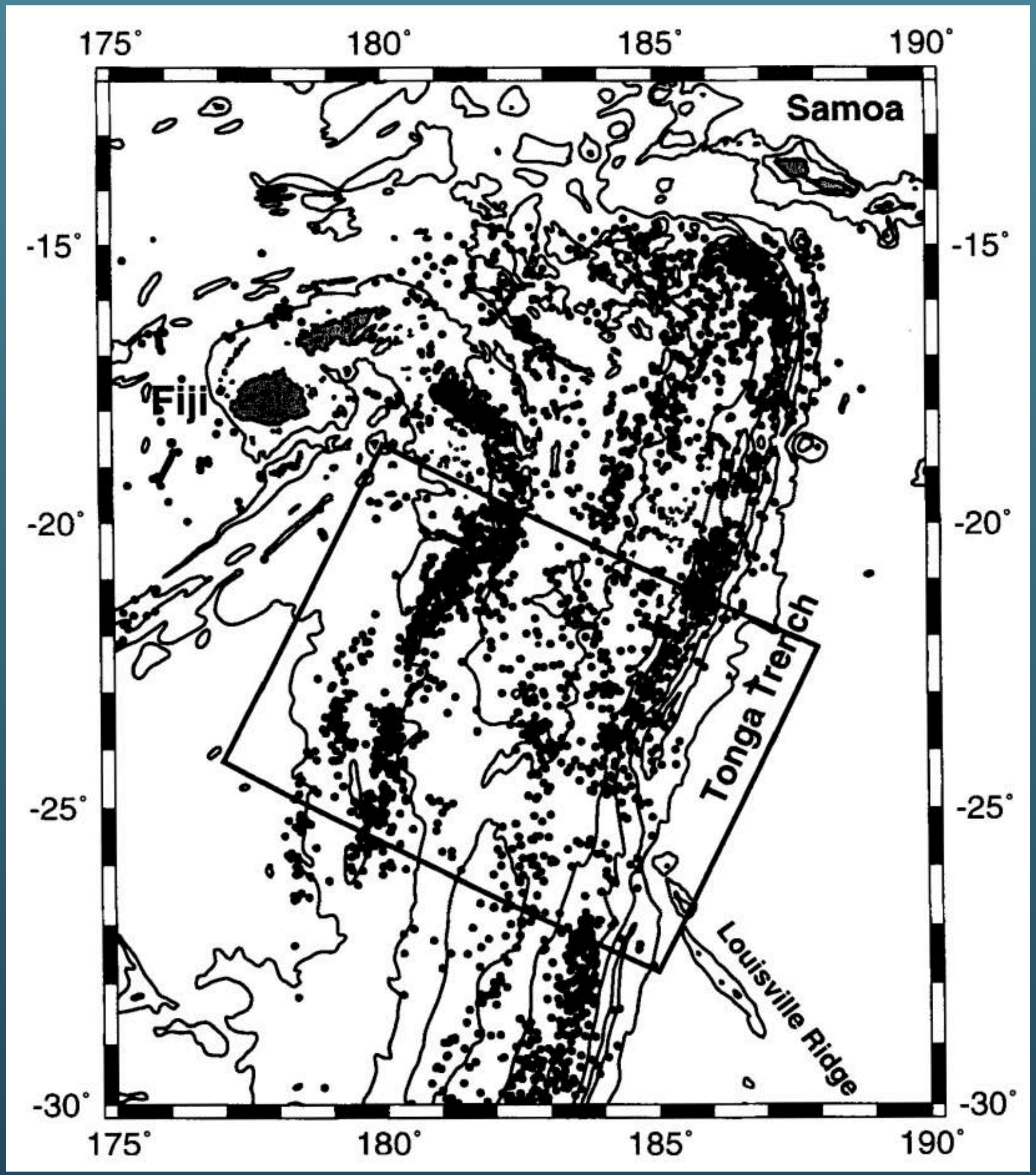

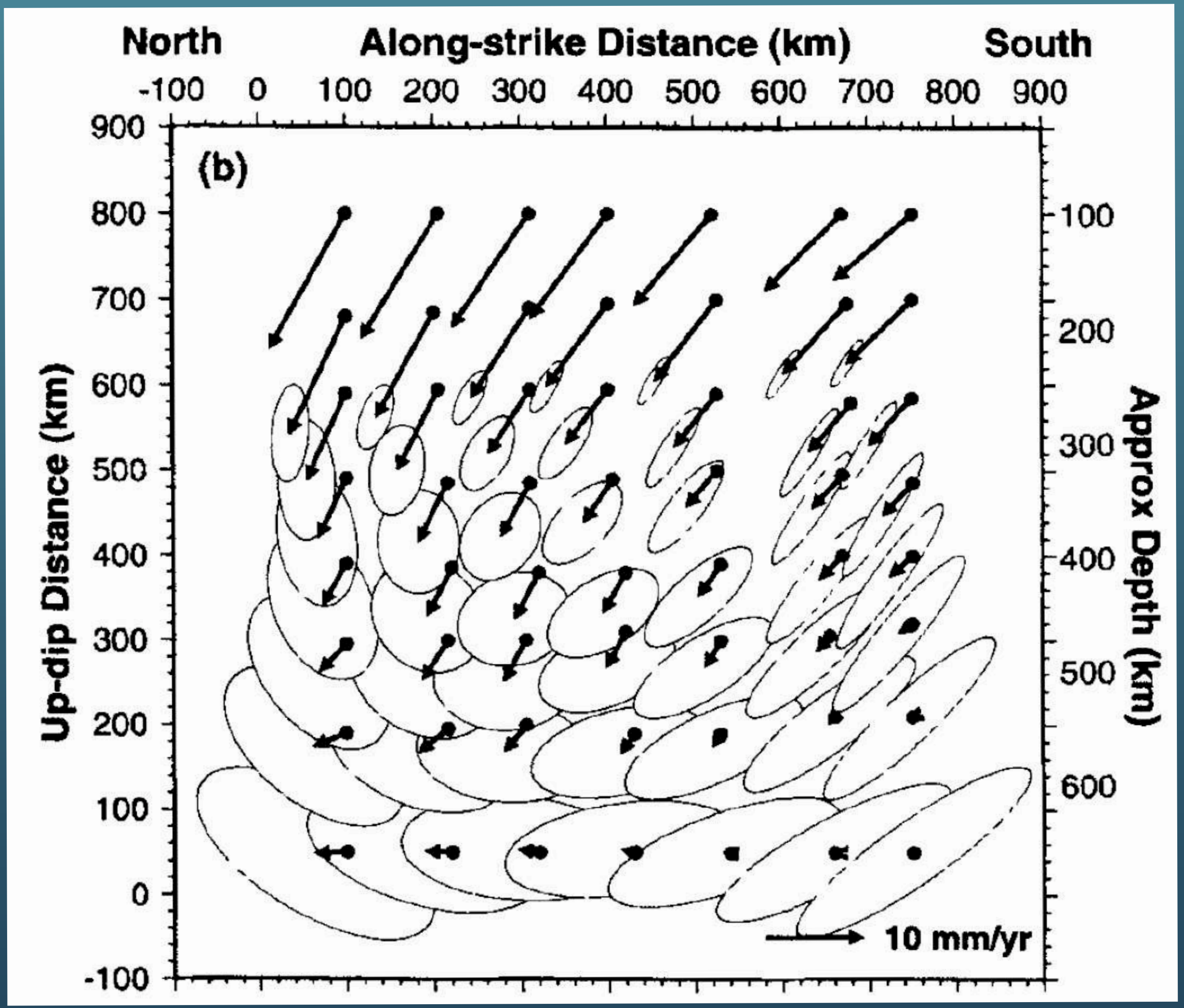

Along-strike motion field in the slab relative to the point to the lower right.

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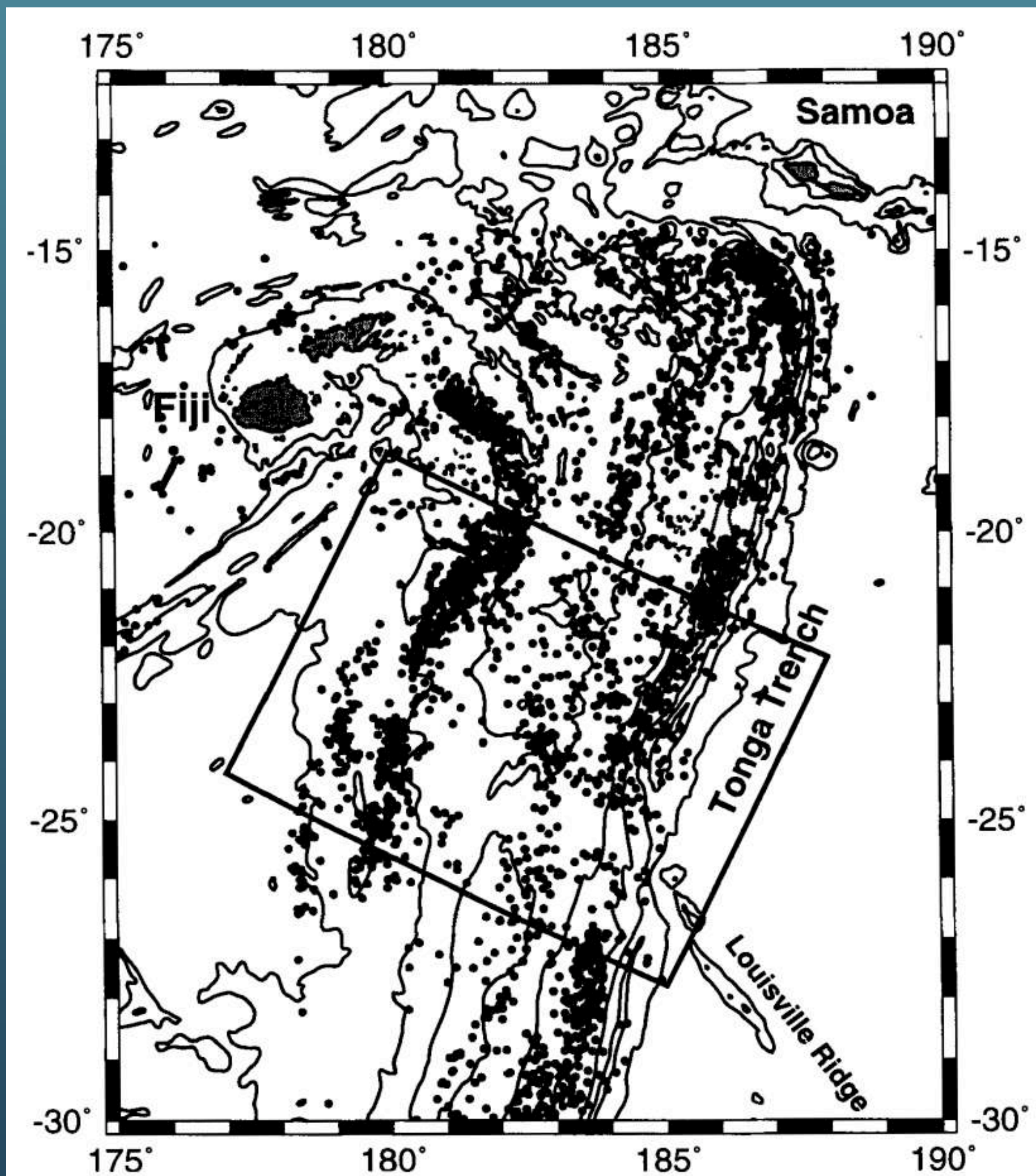

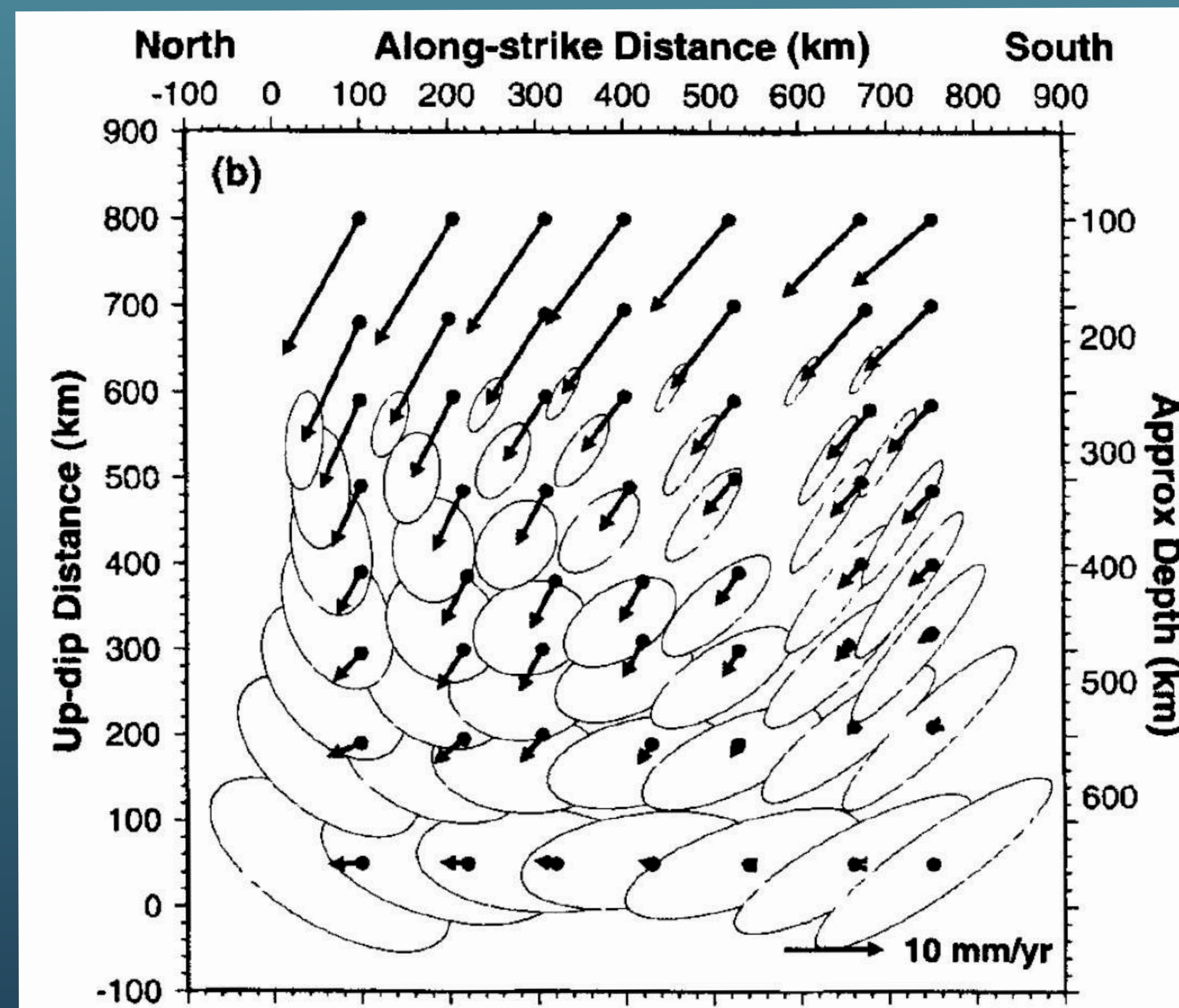

Along-strike motion field in the slab relative to the point to the lower right.

It shows a systematic northward motion component that decreases with depth (although for the lower part mostly within the formal error ellips).

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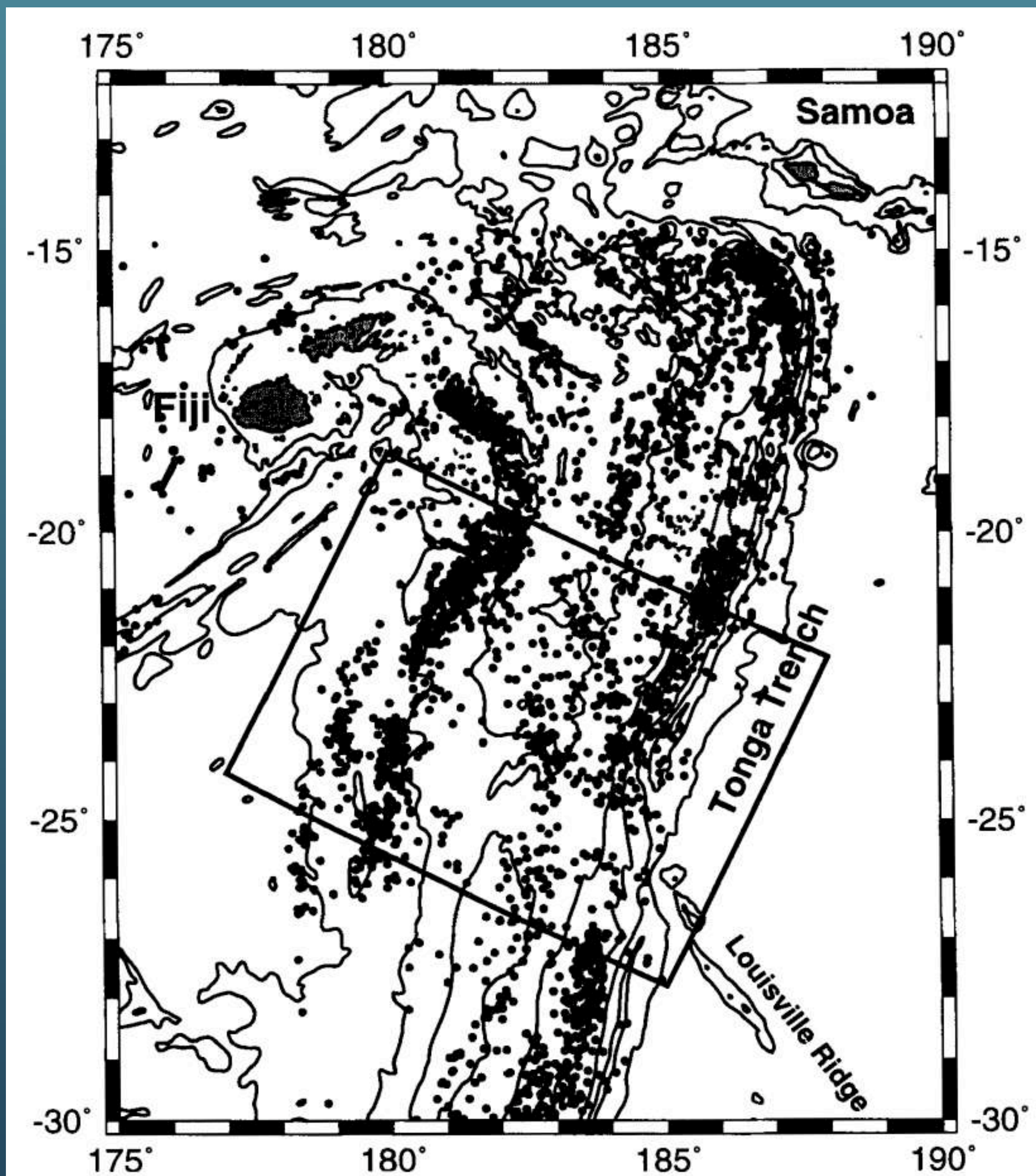
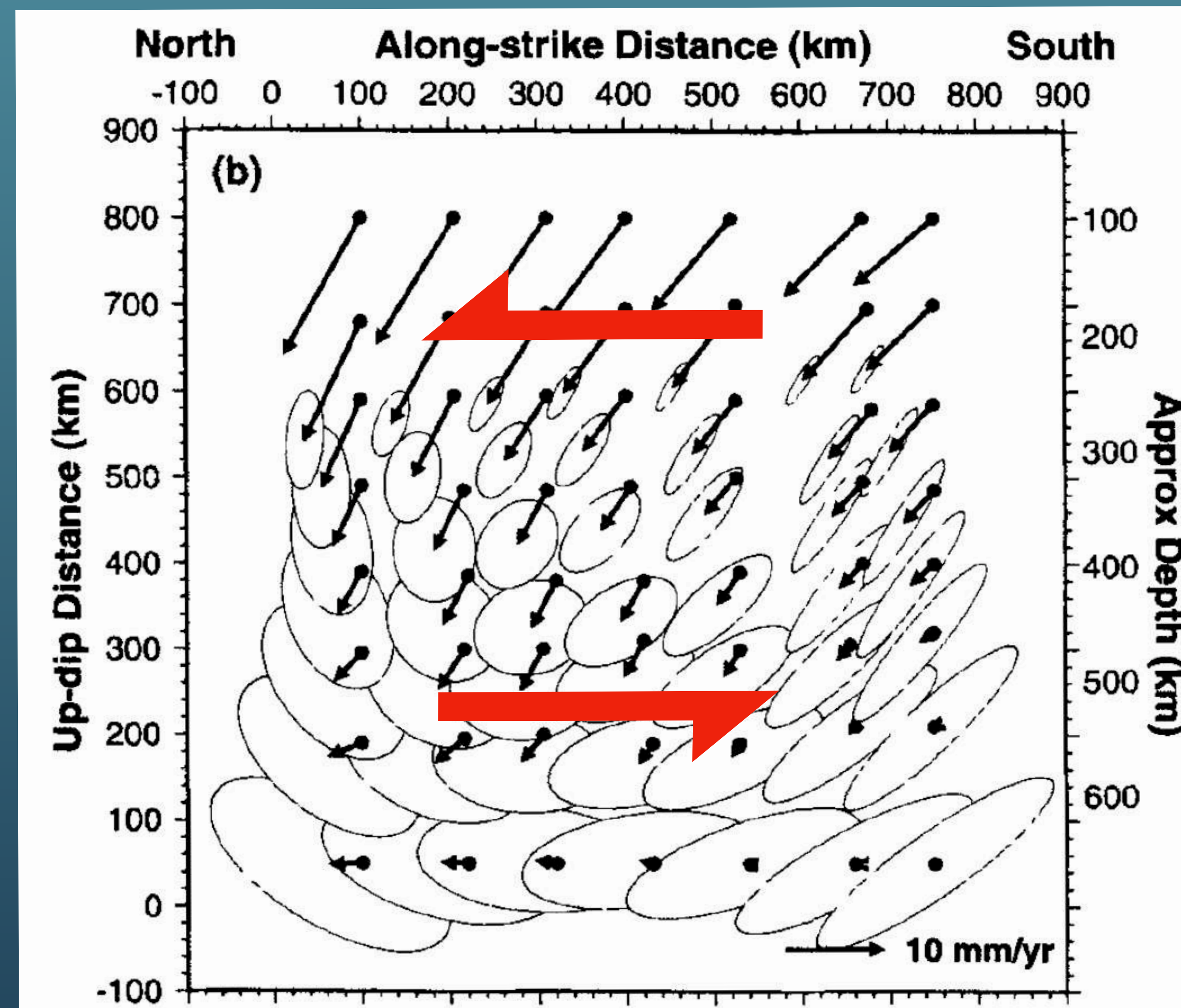


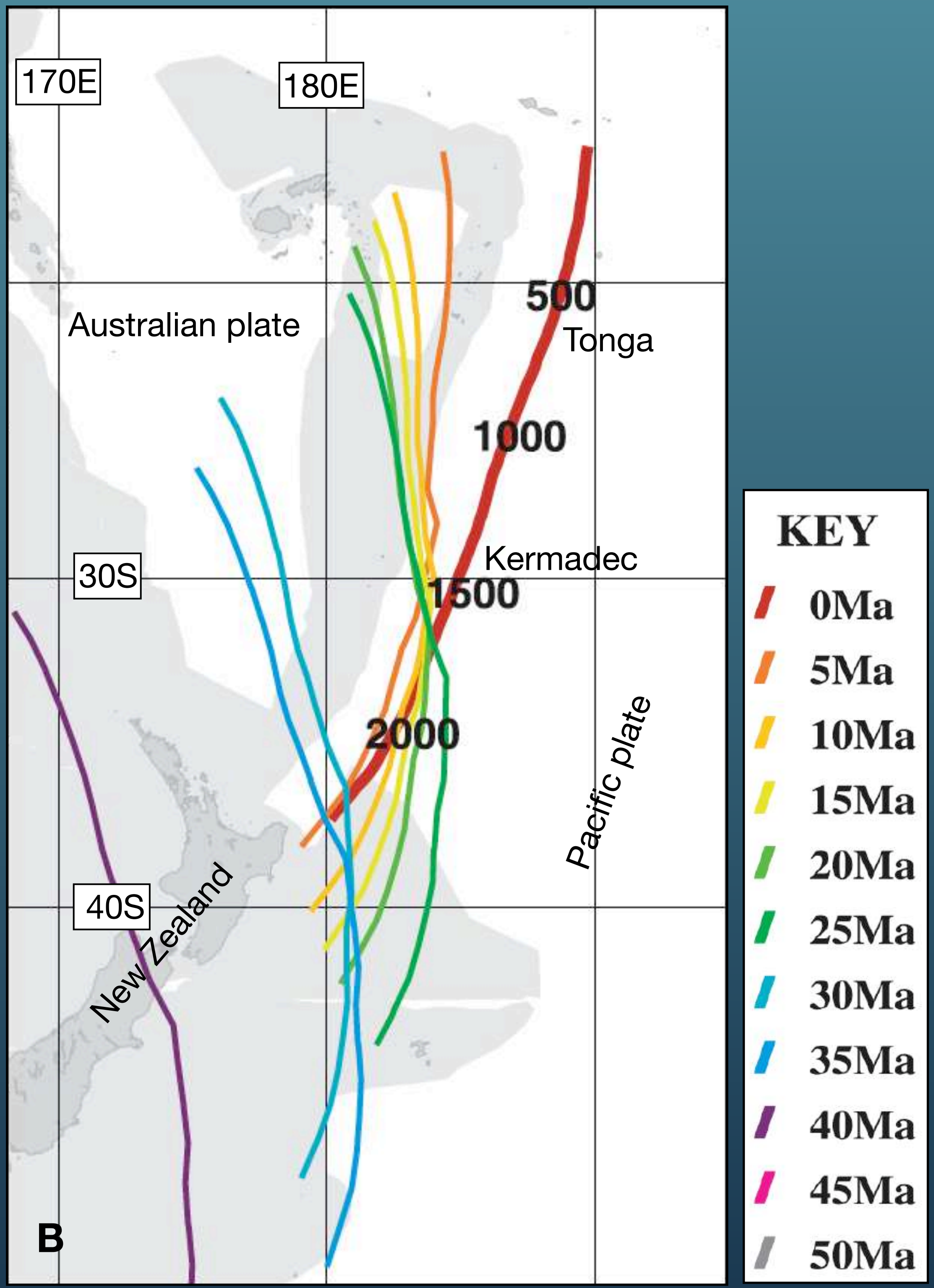


Along-strike motion field in the slab relative to the point to the lower right.

It shows a systematic northward motion component that decreases with depth (although for the lower part mostly within the formal error ellips).

This pattern can be explained by mantle-resisted northward slab dragging that holds back the lower part of the slab relative to the top part leading to a state of strike-parallel shear

Slab dragging of the Tonga-Kermadec slab was in fact recorded earlier (but not interpreted) by placing relative tectonic reconstructions in a mantle frame



Sdrolias and Müller 2006

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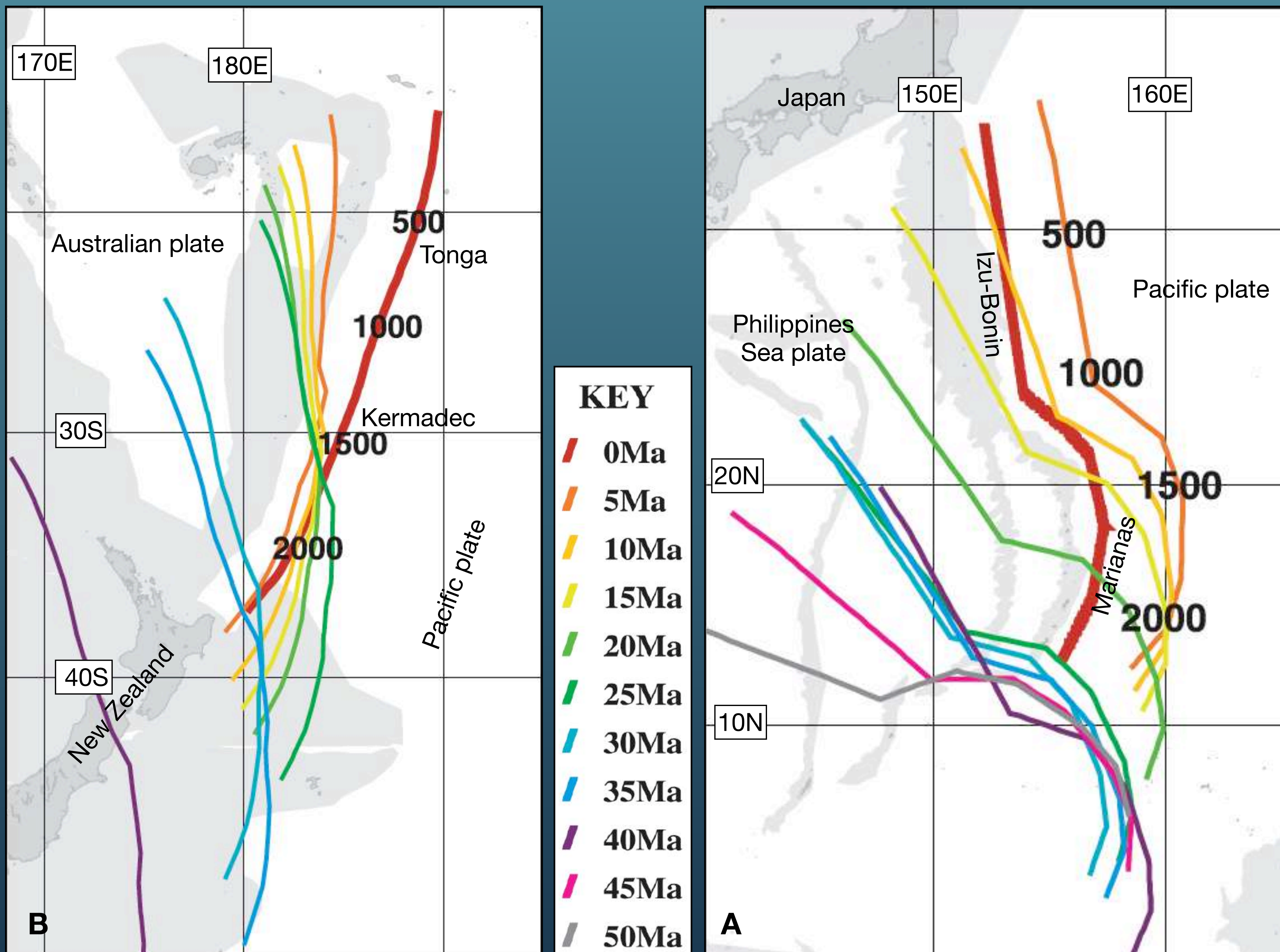
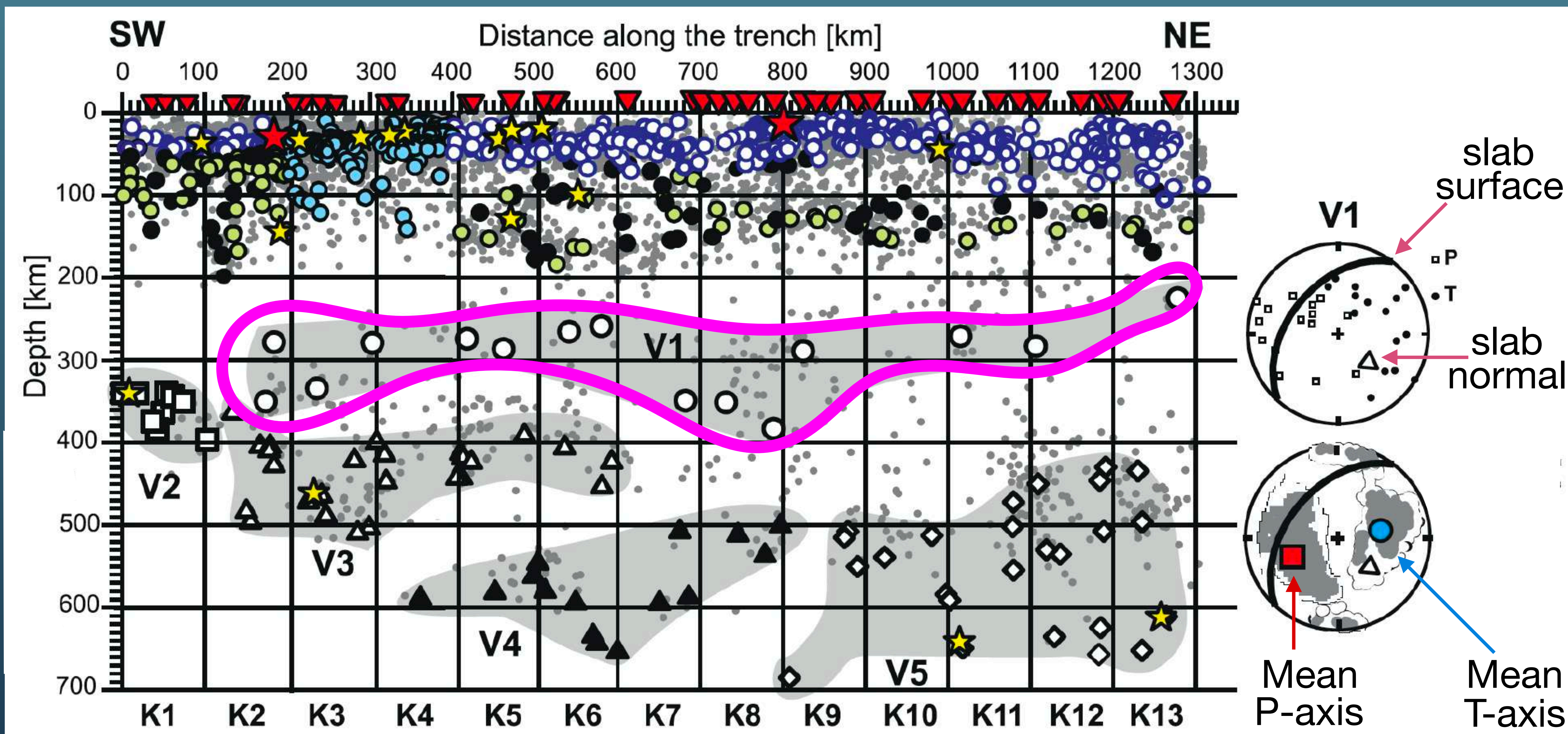


Sdrolias and Müller 2006

… and slab dragging is also predicted for the Izu-Bonin-Mariana subduction

Off-dip oriented P-T axis of major events between 200-400 km along strike of the Kurile slab (Christova 2015)



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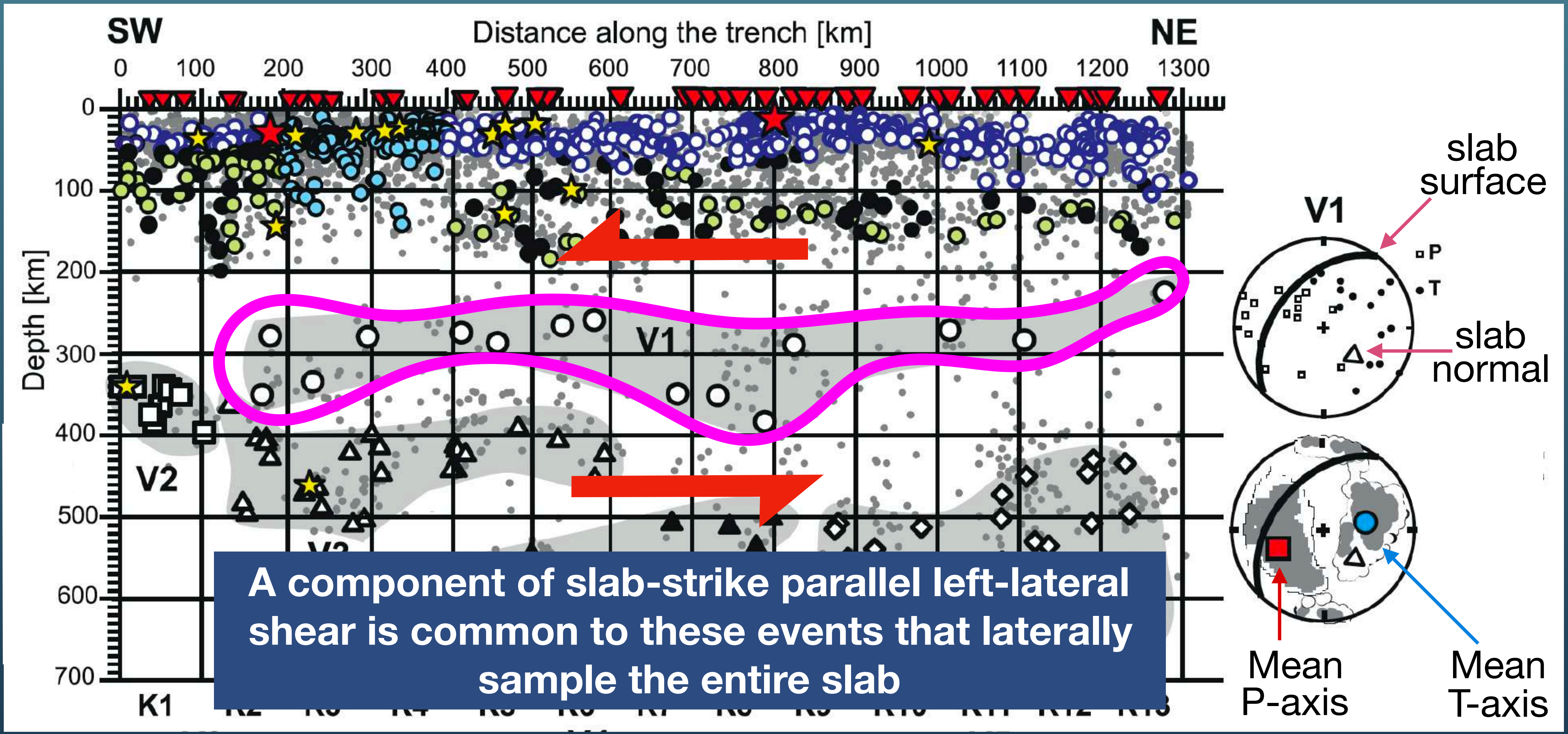
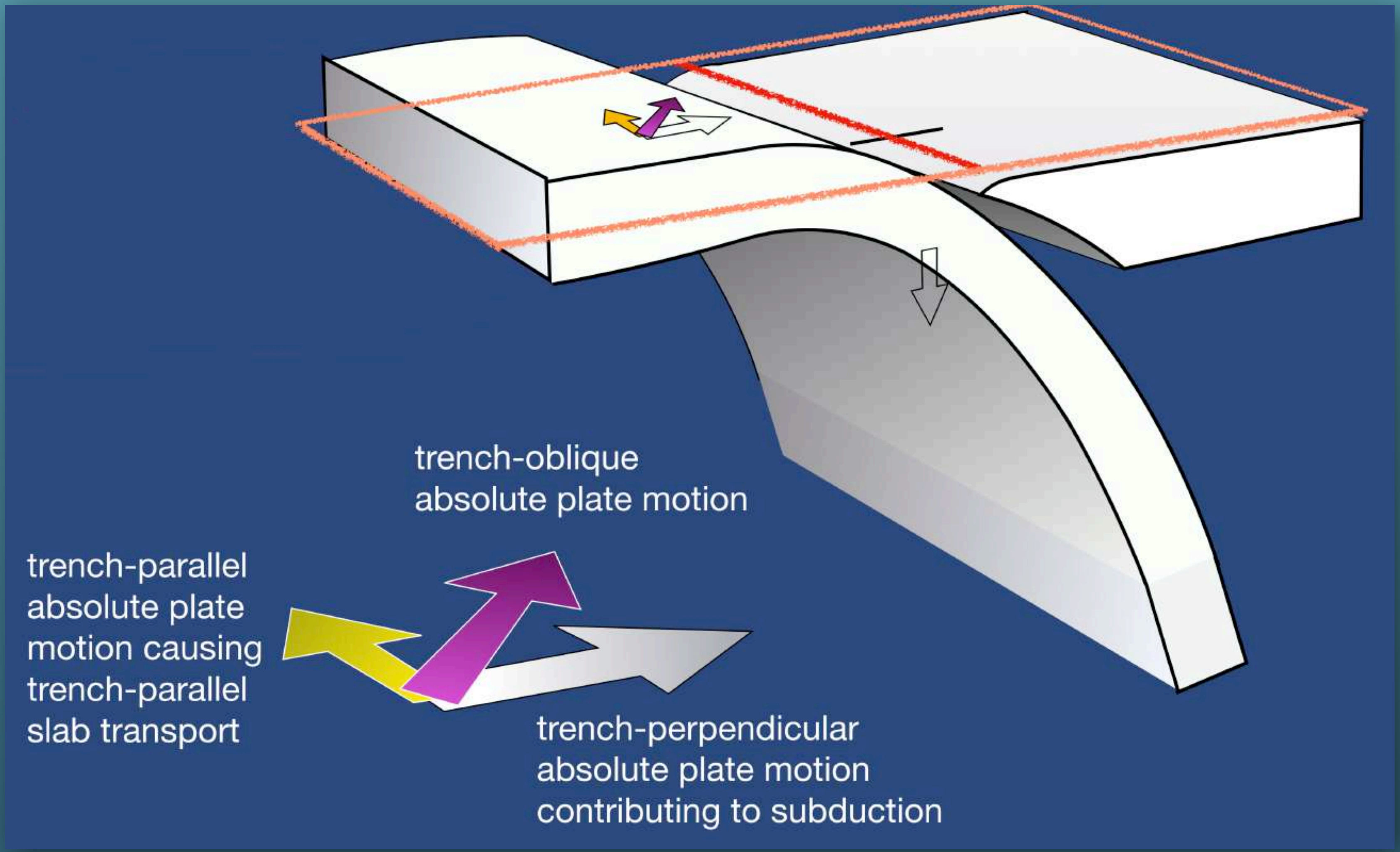


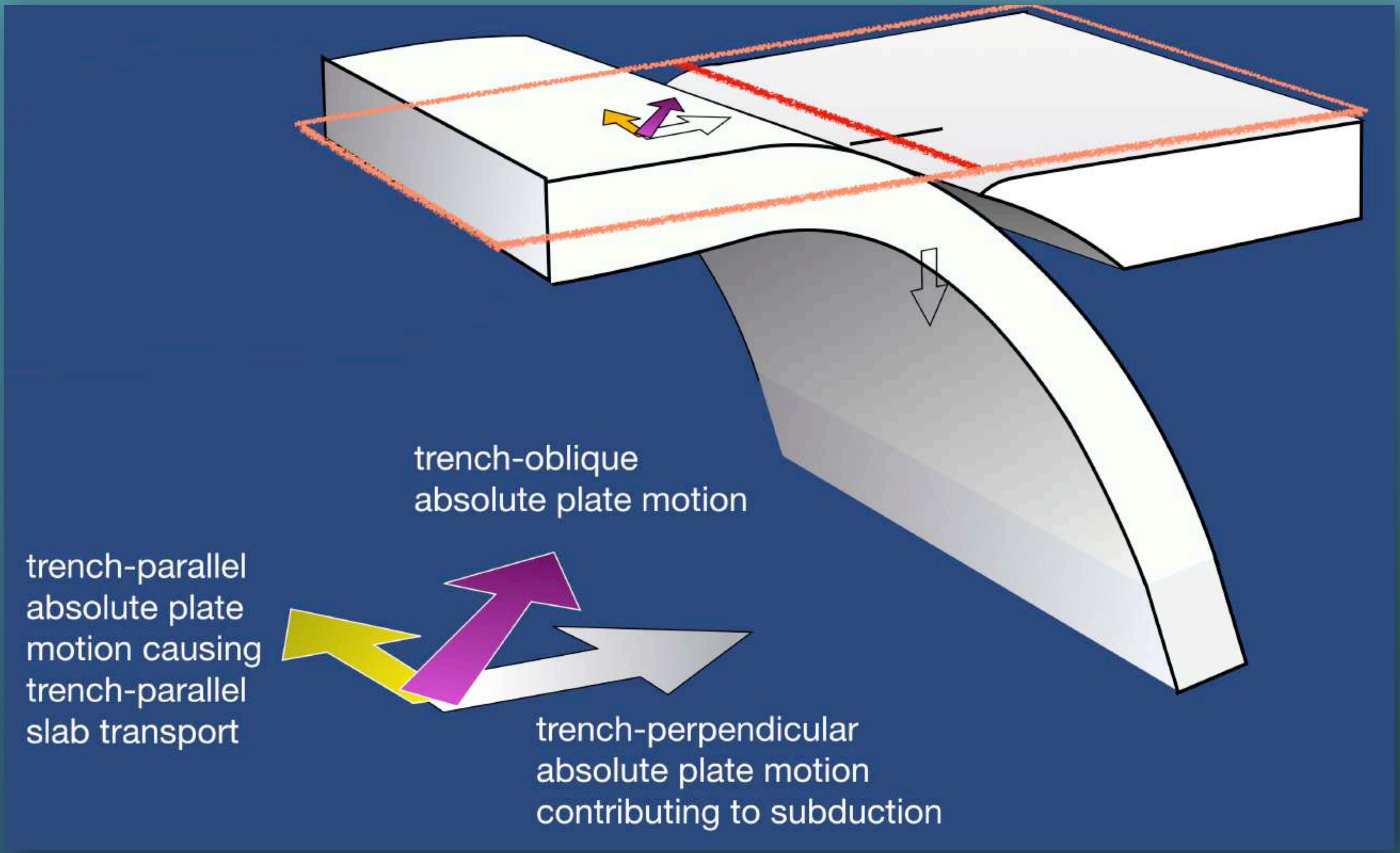
A component of slab-strike parallel left-lateral shear is common to these events that laterally sample the entire slab

Summarizing…



Summarizing…

Slab dragging occurs globally and has been largely overlooked since the discovery of plate tectonics



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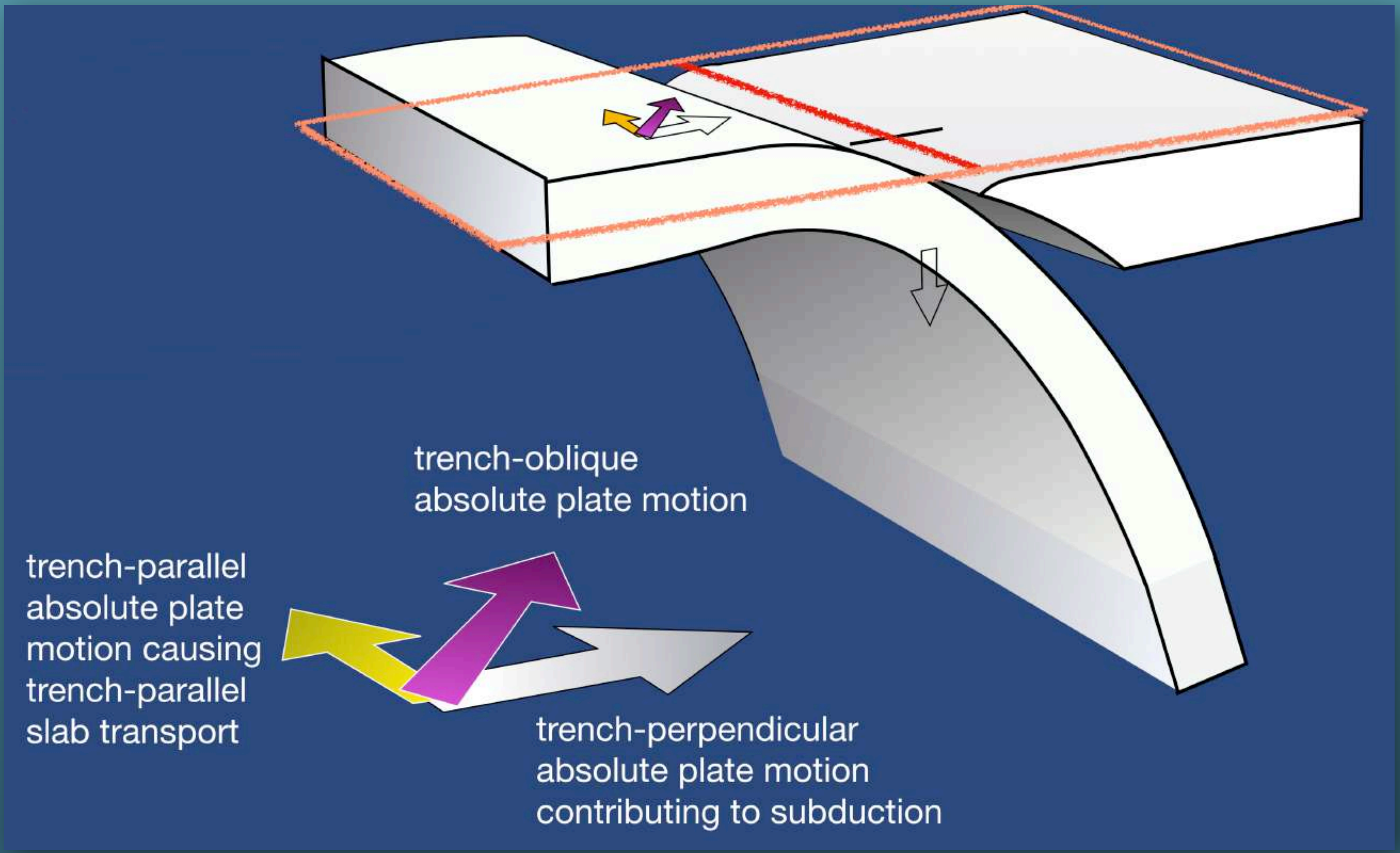

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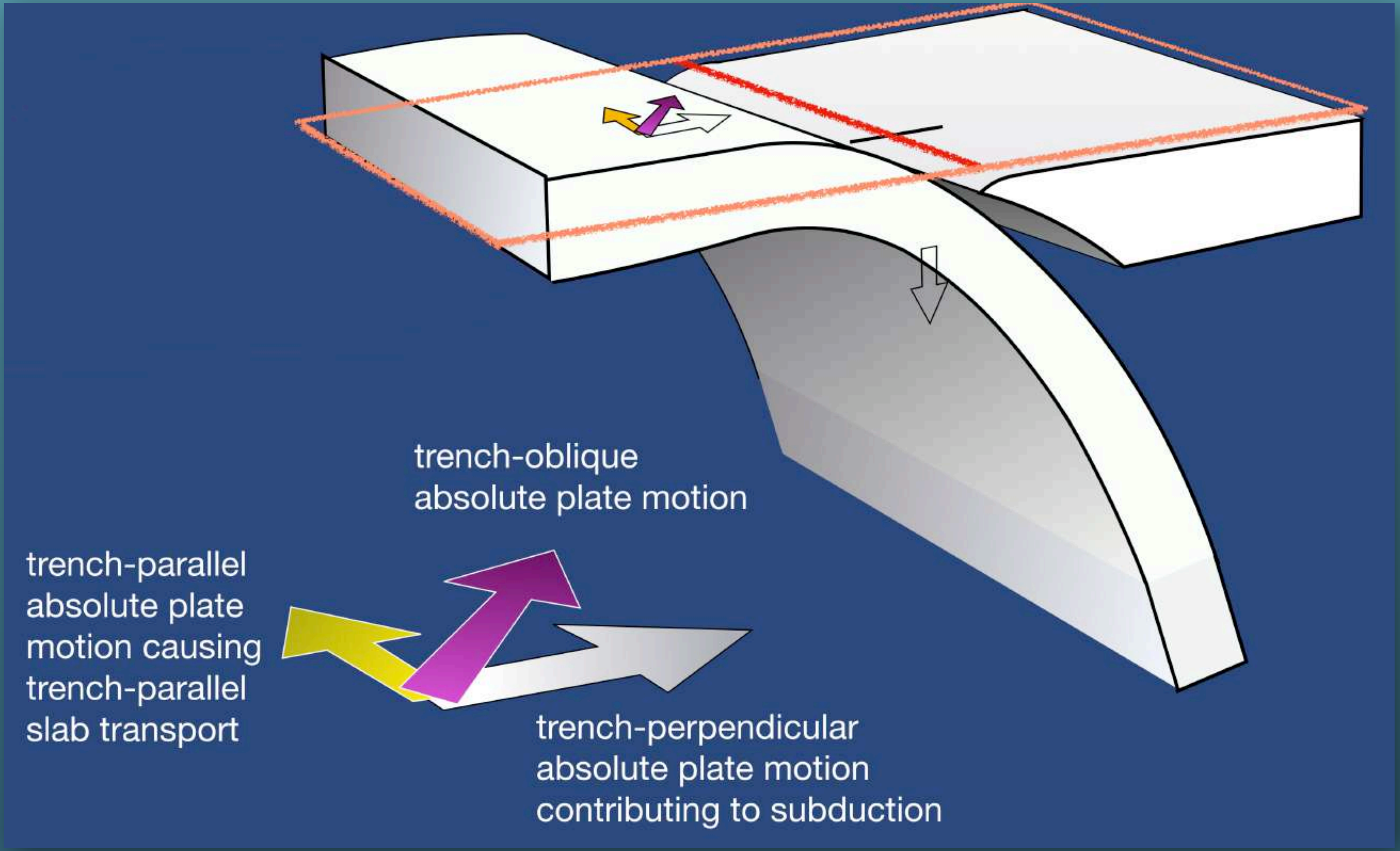

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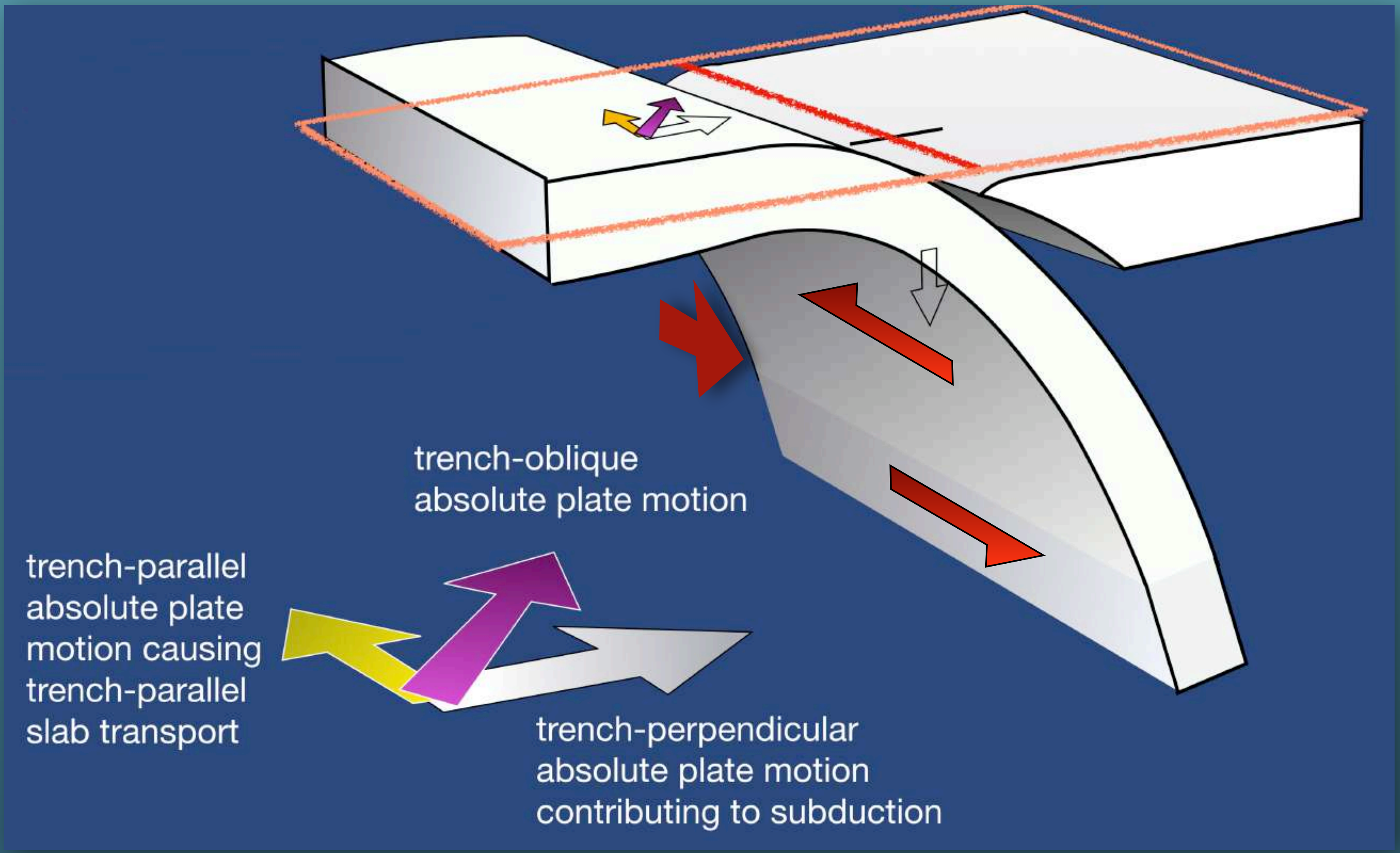
Slab dragging occurs in the direction of the absolute plate motion of the subducting plate

It contributes to the trench-normal component of subduction and causes the trench-parallel component of slab motion

Summarizing…



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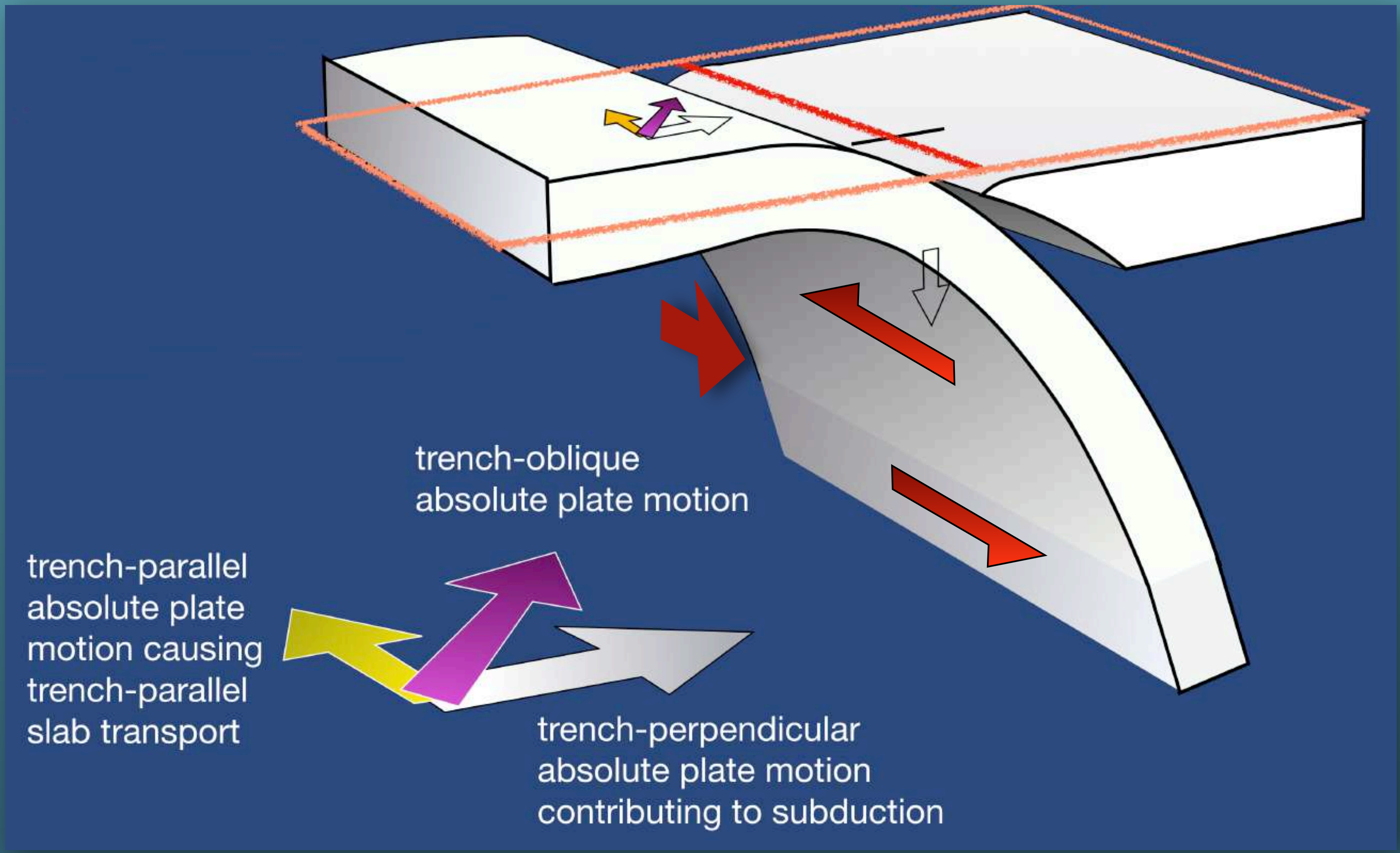

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Slab dragging may have a much wider impact on subduction plate boundaries. Conceptually, it may help shape subduction arcs, it may underlie vertical segmentation of the slab, and may have a significant impact on the tectonic evolution of the crust overhead.