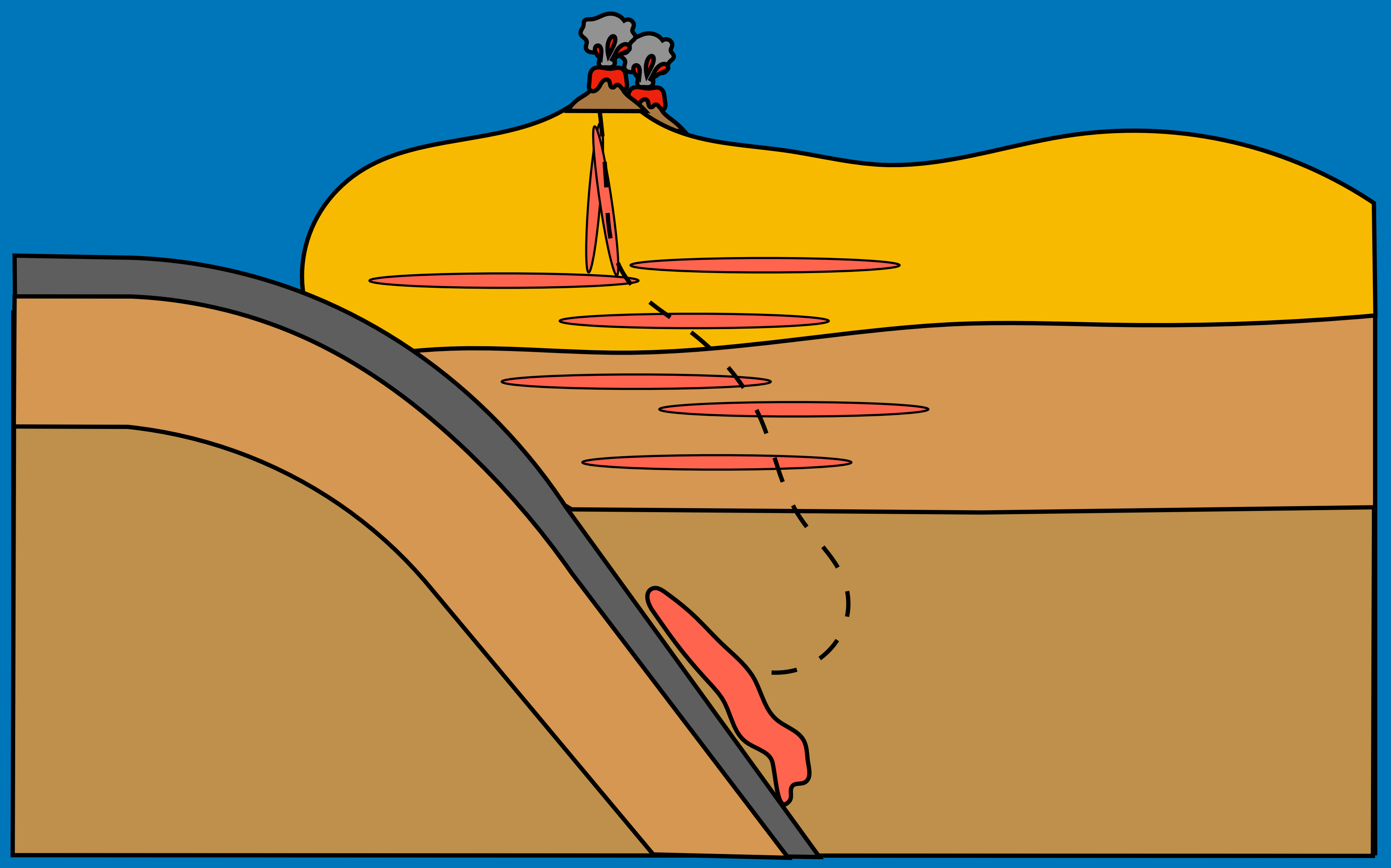
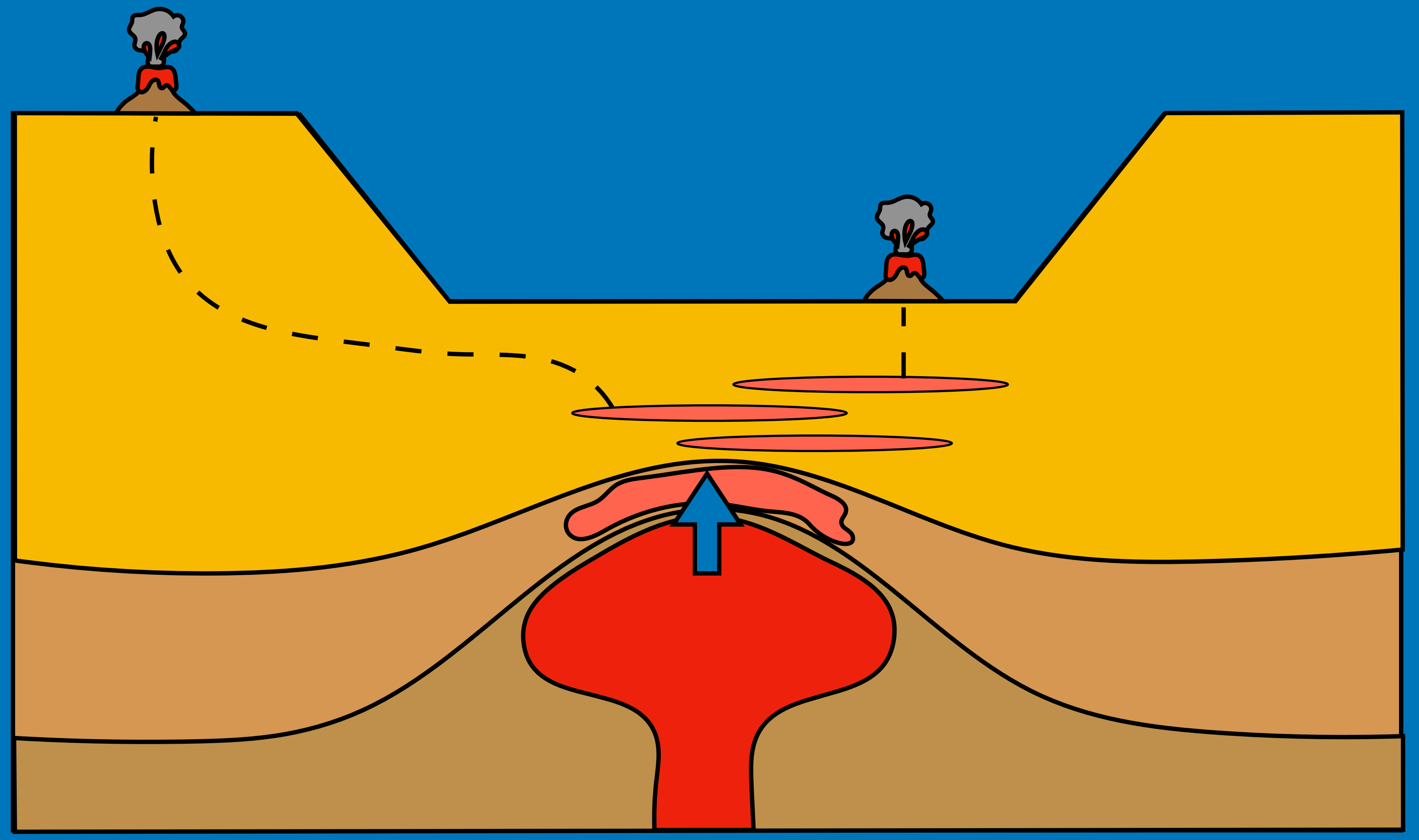




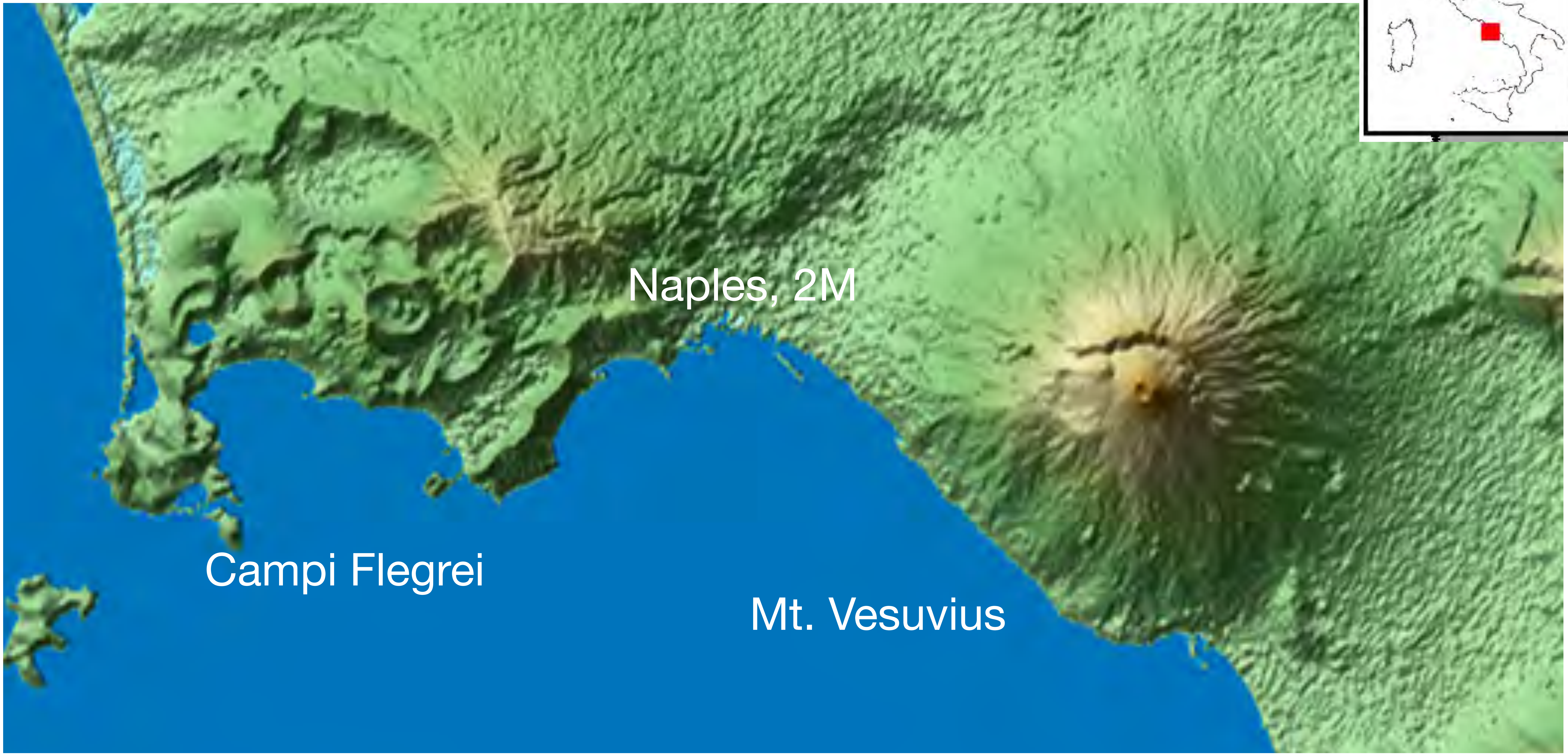
Magma pathways below arc volcanoes and continental rifts

Eleonora Rivalta

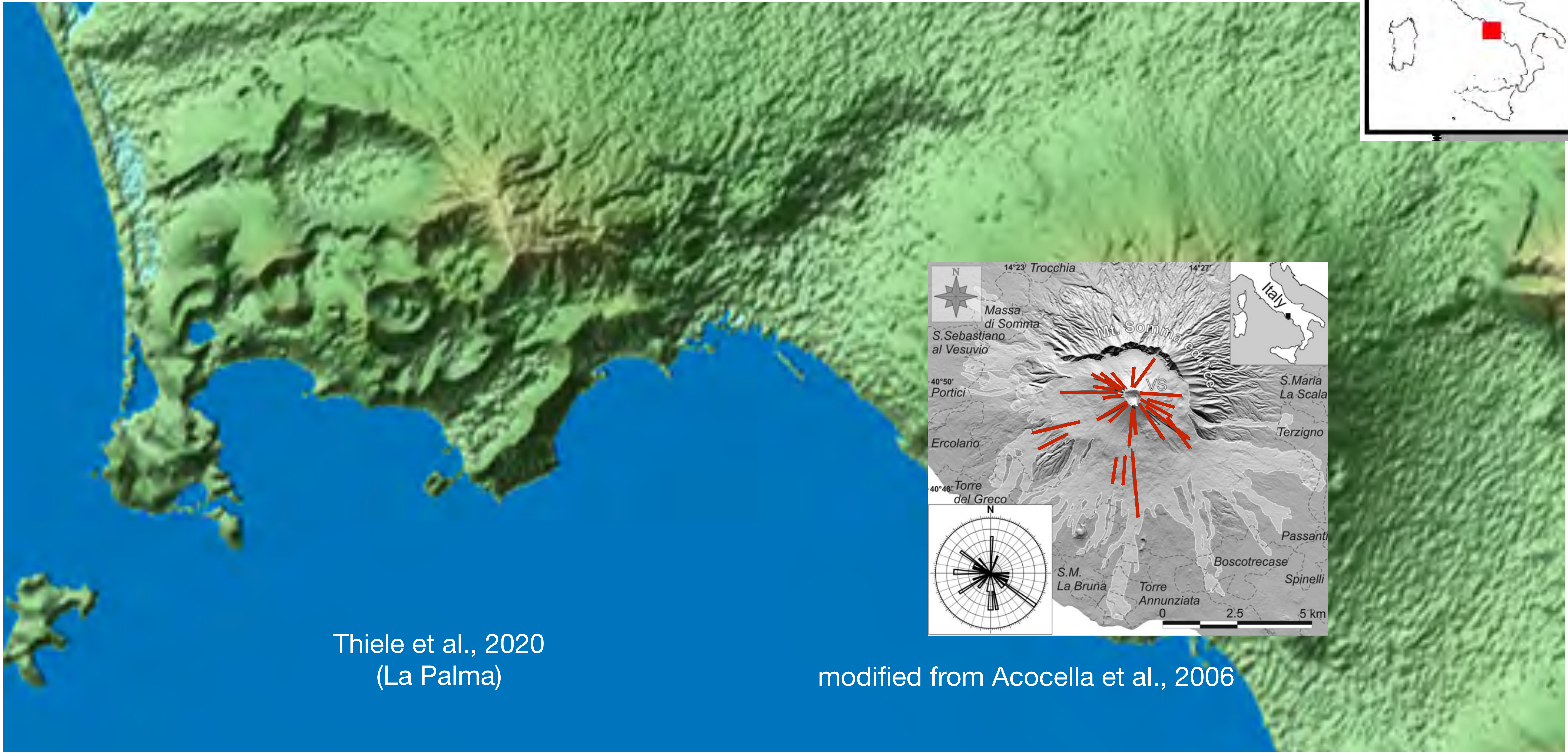
Valentina Armeni, Gaetano Ferrante,
Lorenzo Mantiloni, Timothy Davis,
Francesco Maccaferri, Mehdi Nikkhoo
Luigi Passarelli, Fabio Corbi,
Katy Chamberlain

Virginie Pinel, Torsten Dahm, Valerio Acocella,
Derek Keir, Kyle Anderson, Geoff Kilgour

Eruptive patterns



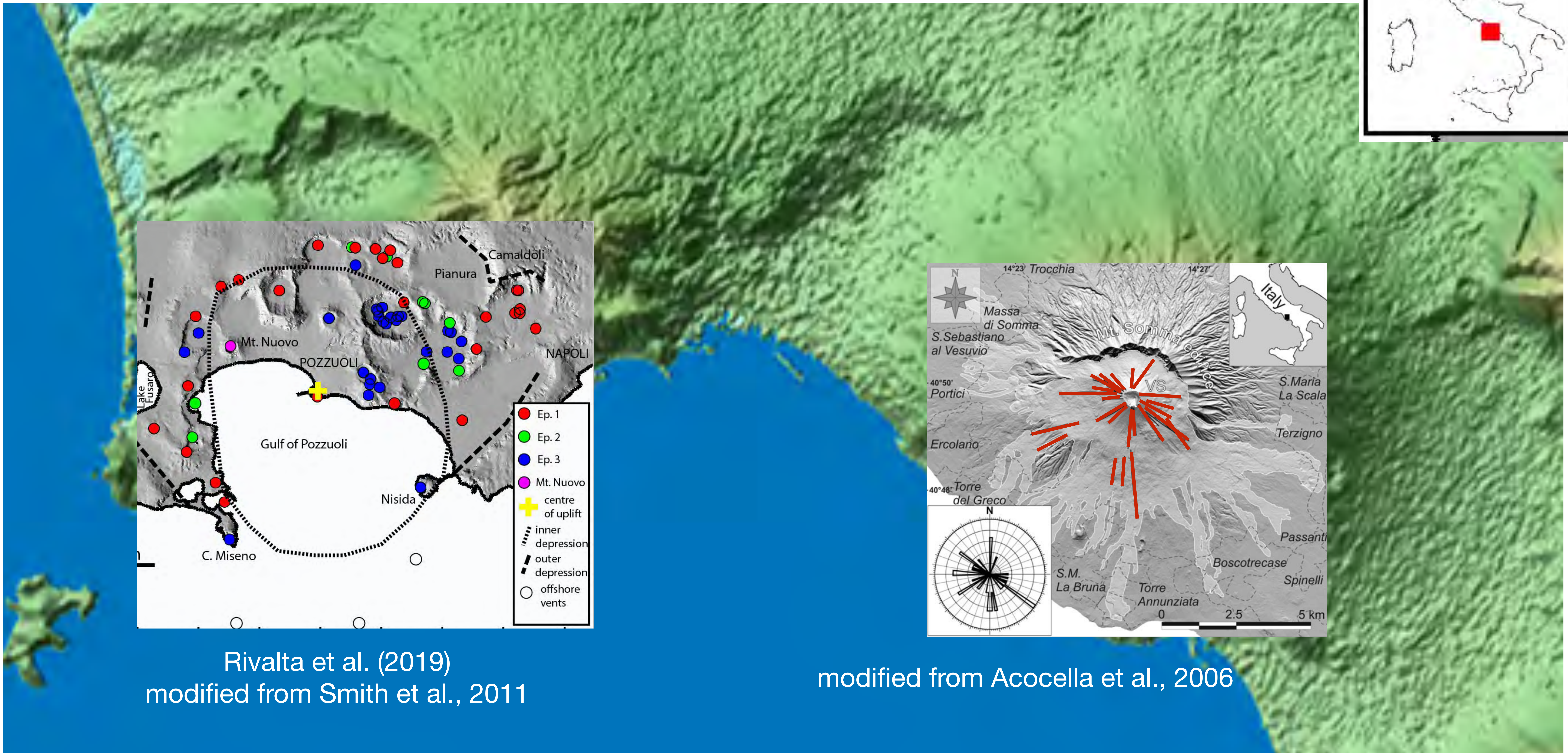
Eruptive patterns



Thiele et al., 2020
(La Palma)

modified from Acocella et al., 2006

Eruptive patterns

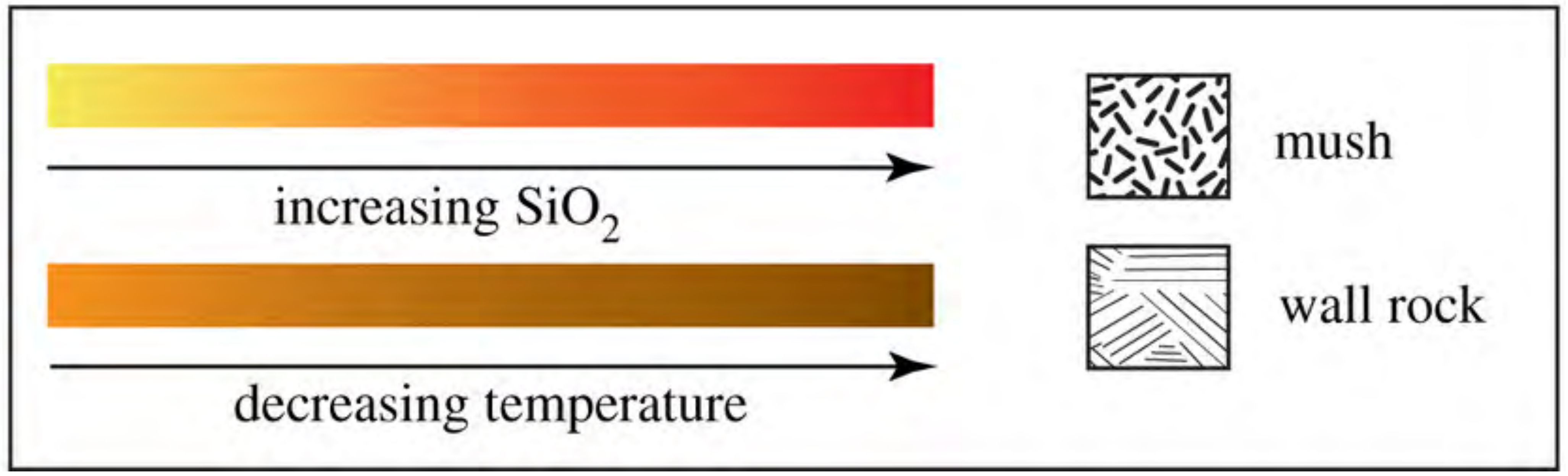


Rivalta et al. (2019)
modified from Smith et al., 2011

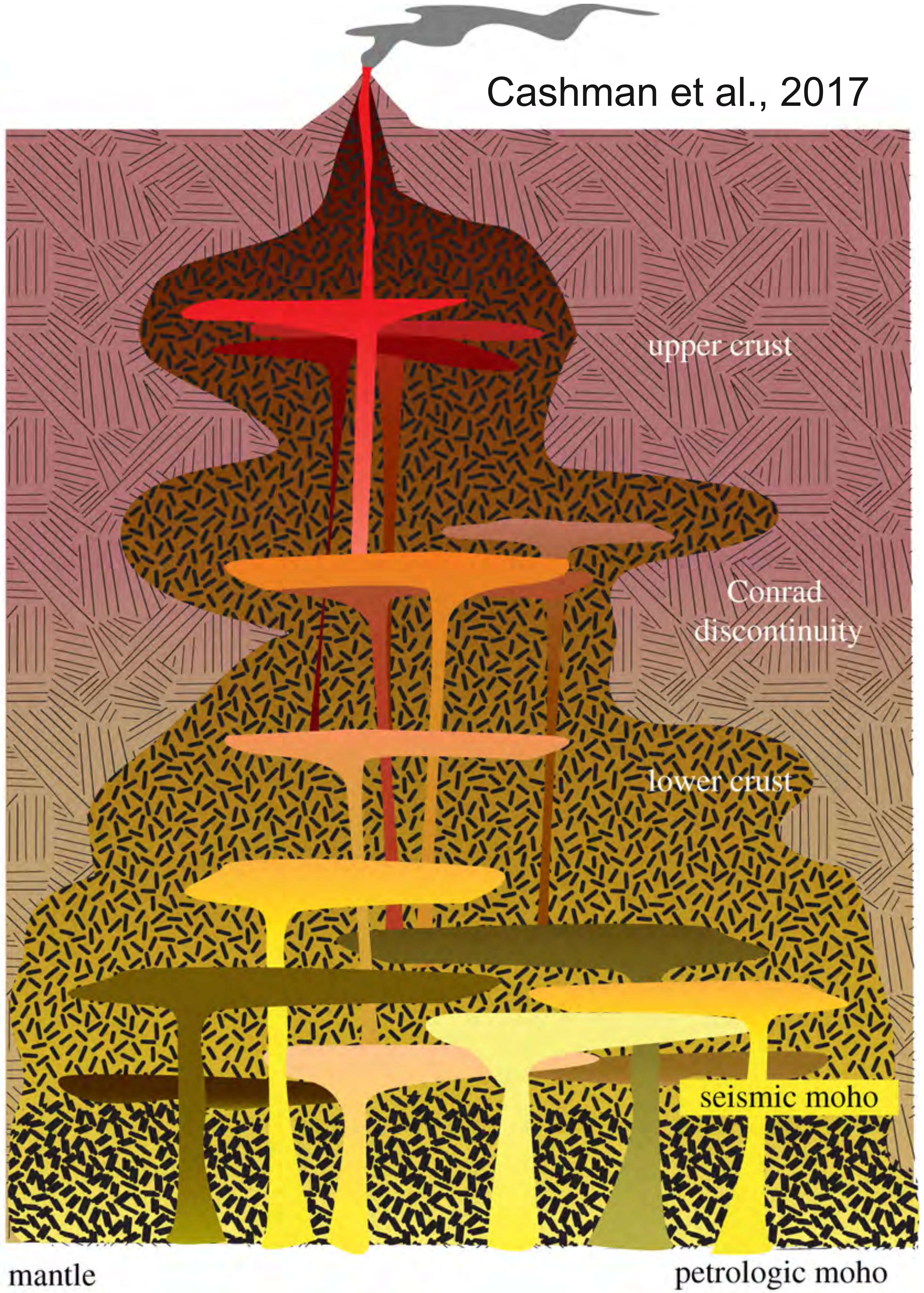
modified from Acocella et al., 2006

Volcanoes fed by a complex, incrementally-grown, mush-dominant storage

- Some magmas ascend and erupt relatively rapidly to create basaltic eruptions
- Most magmas stall during their ascent, recording in their compositions the chemical exchanges with the host rock and other ascending magma batches.

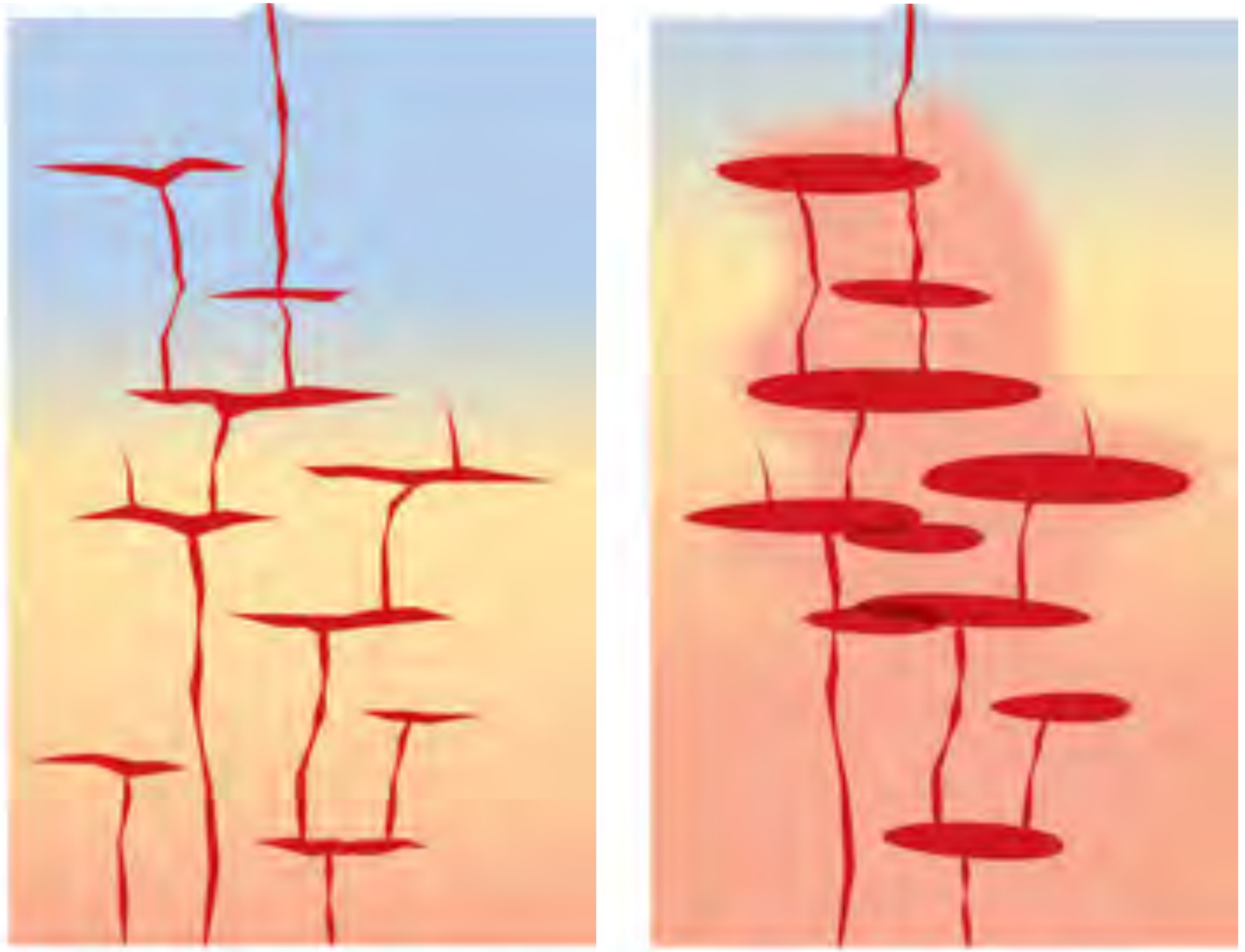


Cashman et al., 2017



What controls magma stalling?

- Crustal structure
- Density/rheology gradients
- Tectonic stresses

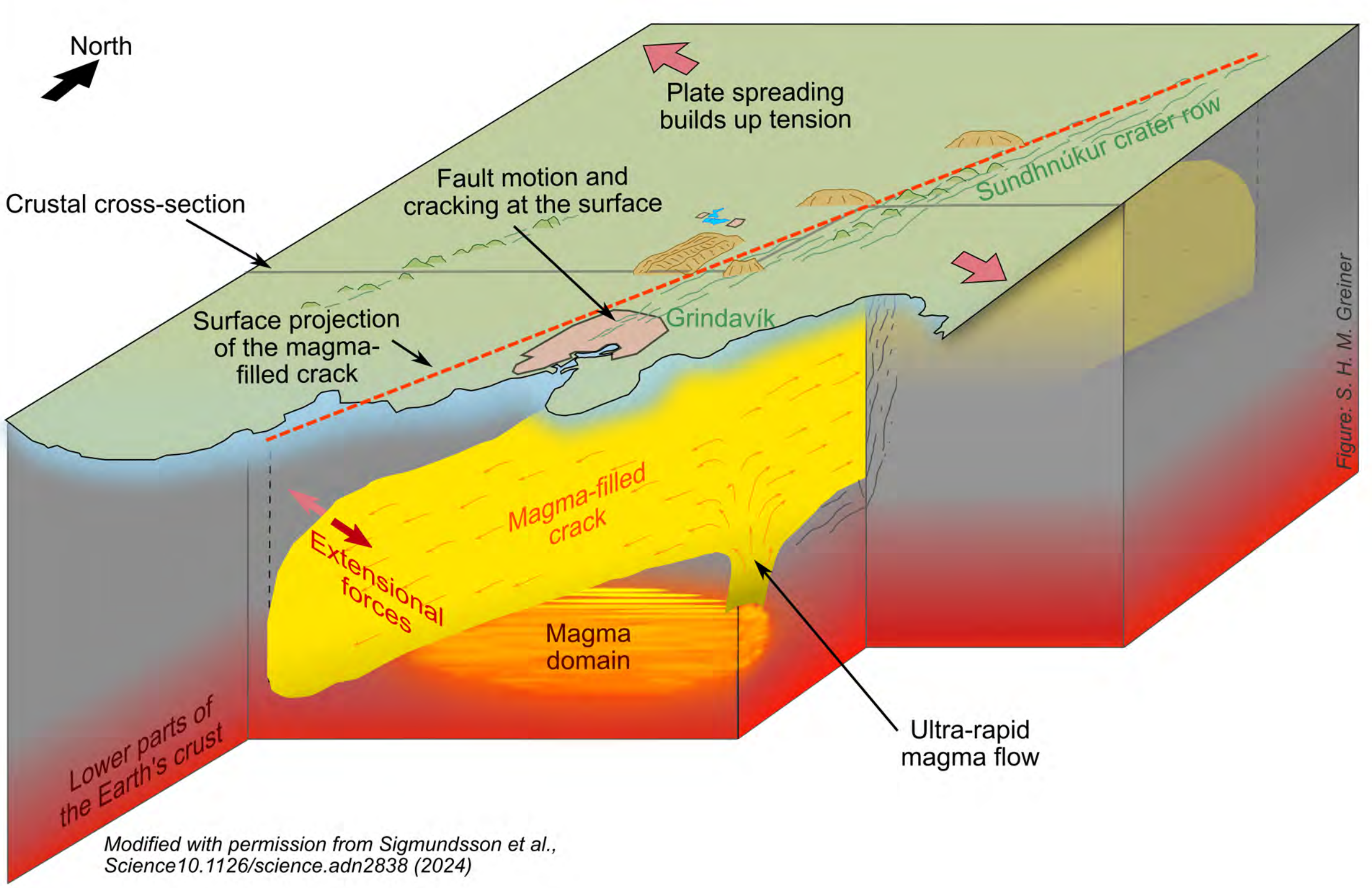


Sparks et al., 2019

Physical principles

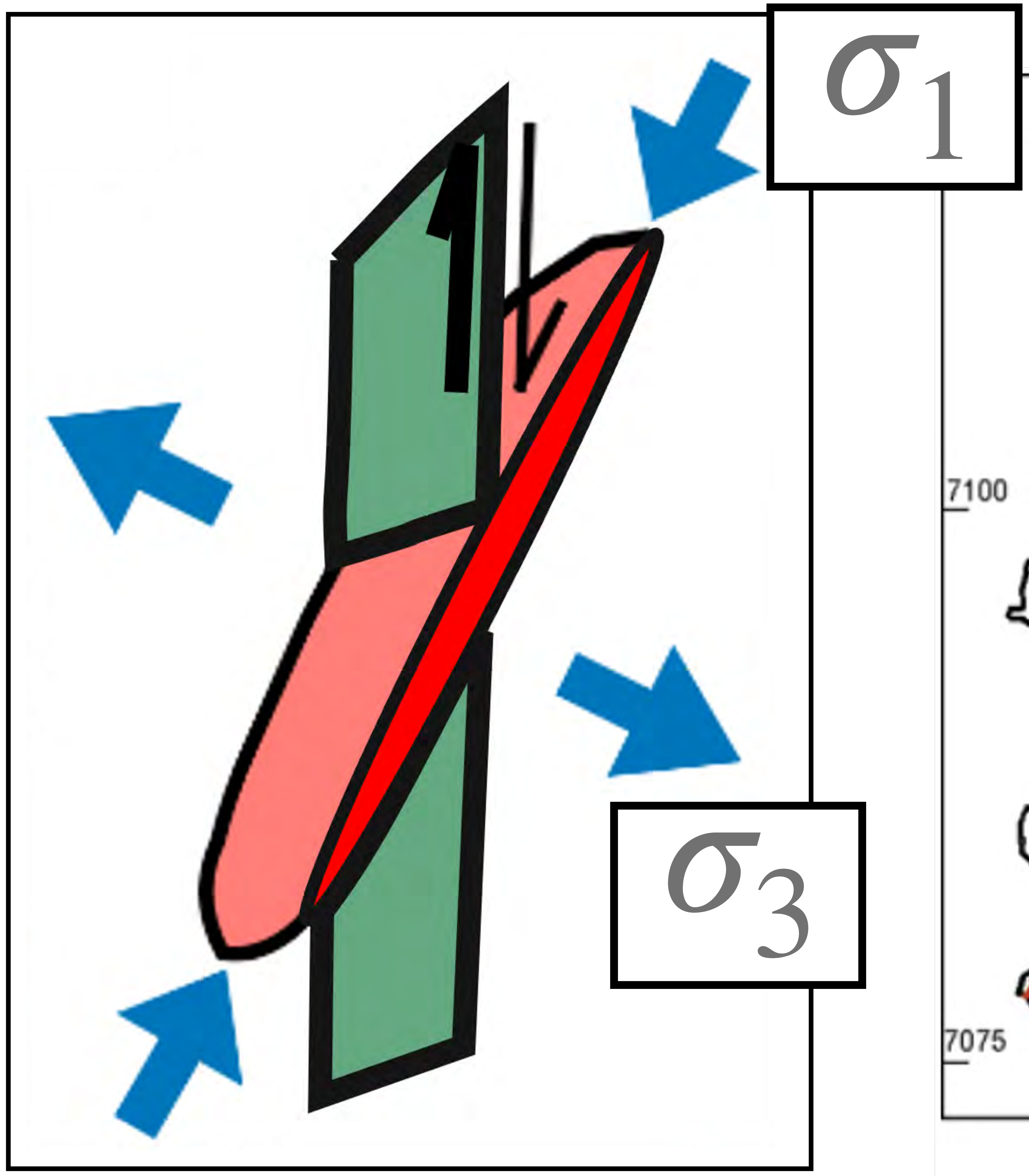
Magma ascent by dyking

Magma ascent by dyking

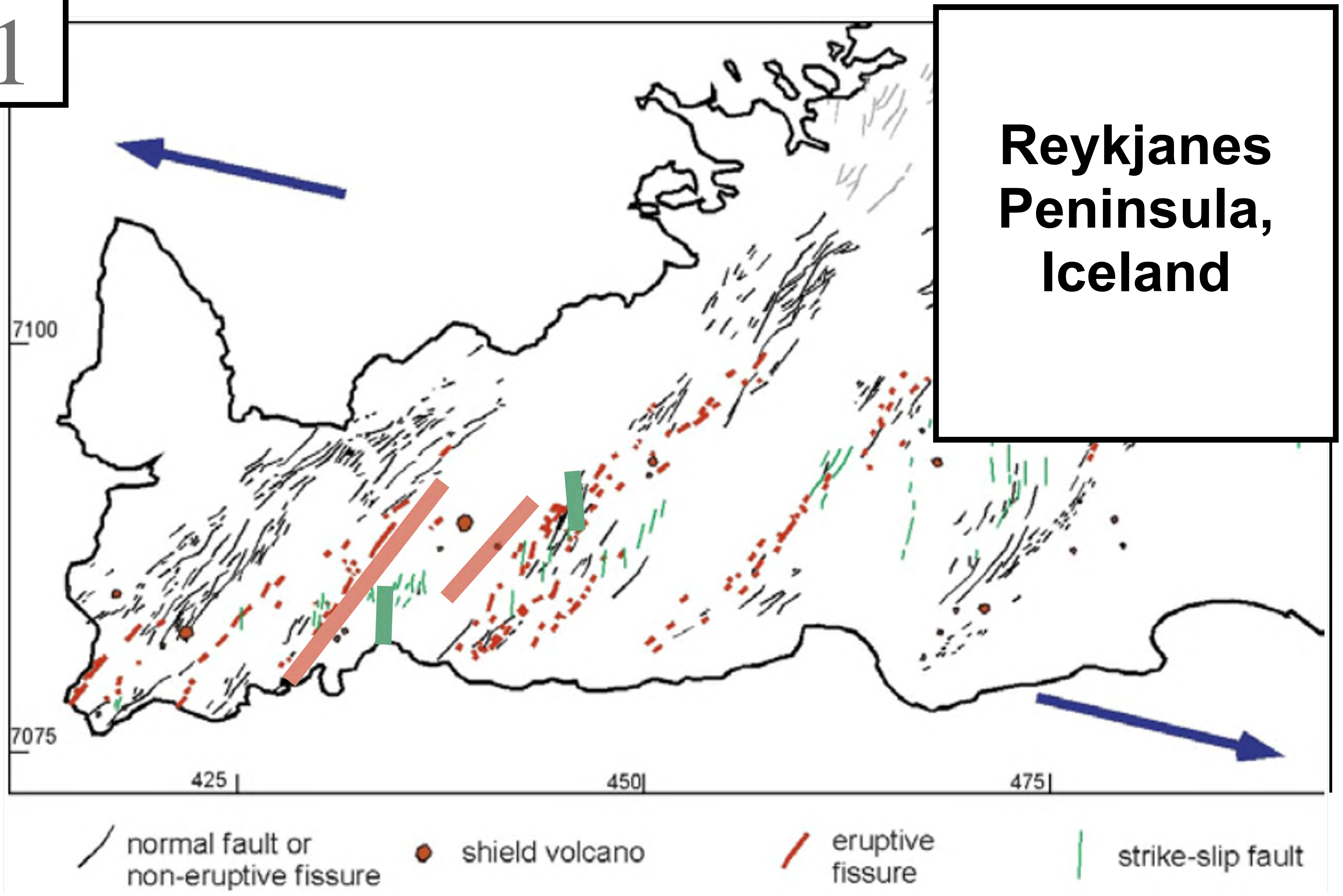


Sigmundsson et al., 2019

Magma ascent by dyking: a form of hydraulic fracturing



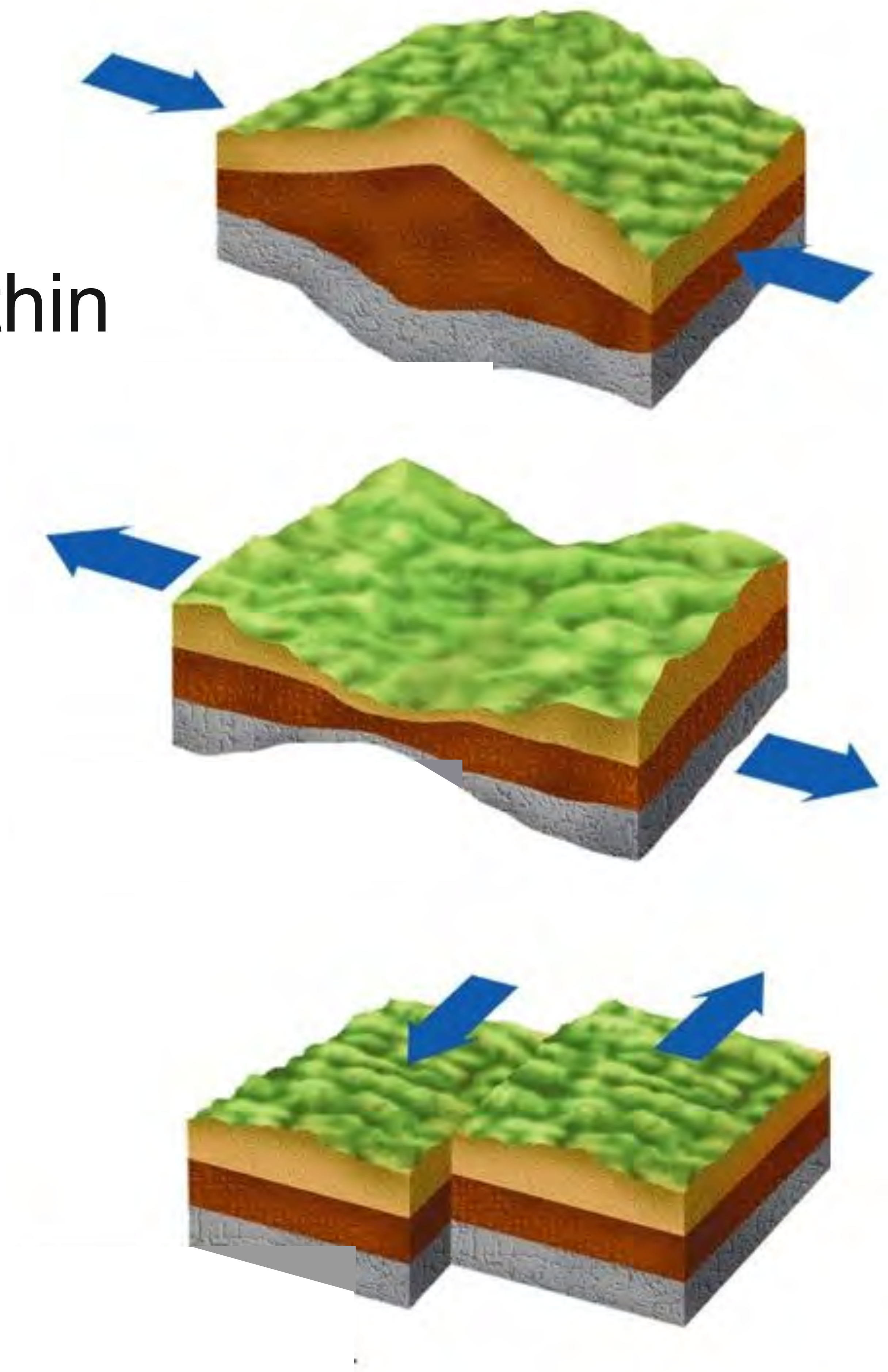
e.g. Anderson, 1937, Pollard, 1987, Dahm, 2000, Roman and Jaupart, 2014



Modified from Stefansson et al., 2006

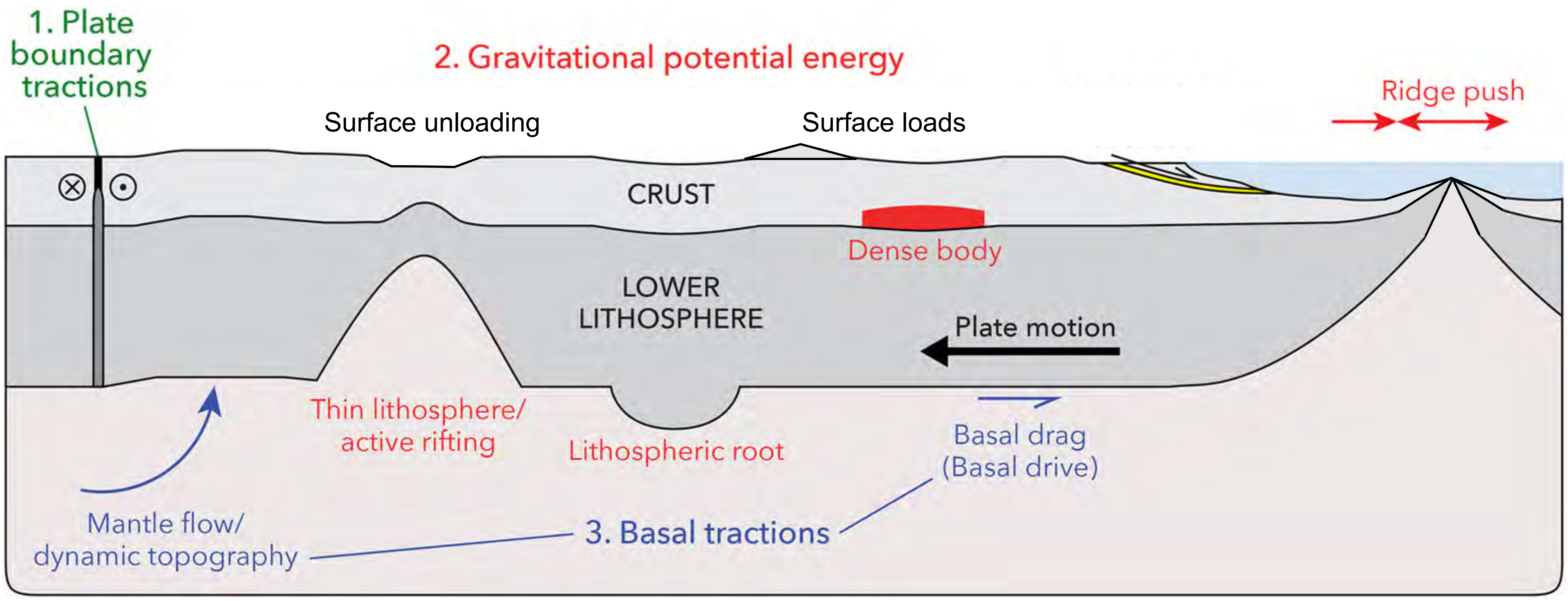
What is the stress field?

- Distribution of internal forces per unit area (pressures and tractions) within the Earth’s crust (or lithosphere).



What is the stress field?

- Distribution of internal forces per unit area (pressures and tractions) within the Earth's crust (or lithosphere).
- Stresses arise from (1) plate motions, (2) gravitational loads imposed by topography resting on the Earth's surface, (3) faulting, (4) fluid migration…
- Heterogeneous in space and time, especially in volcanic regions.



Modified from Lundstern et al., 2024

What is the stress field?

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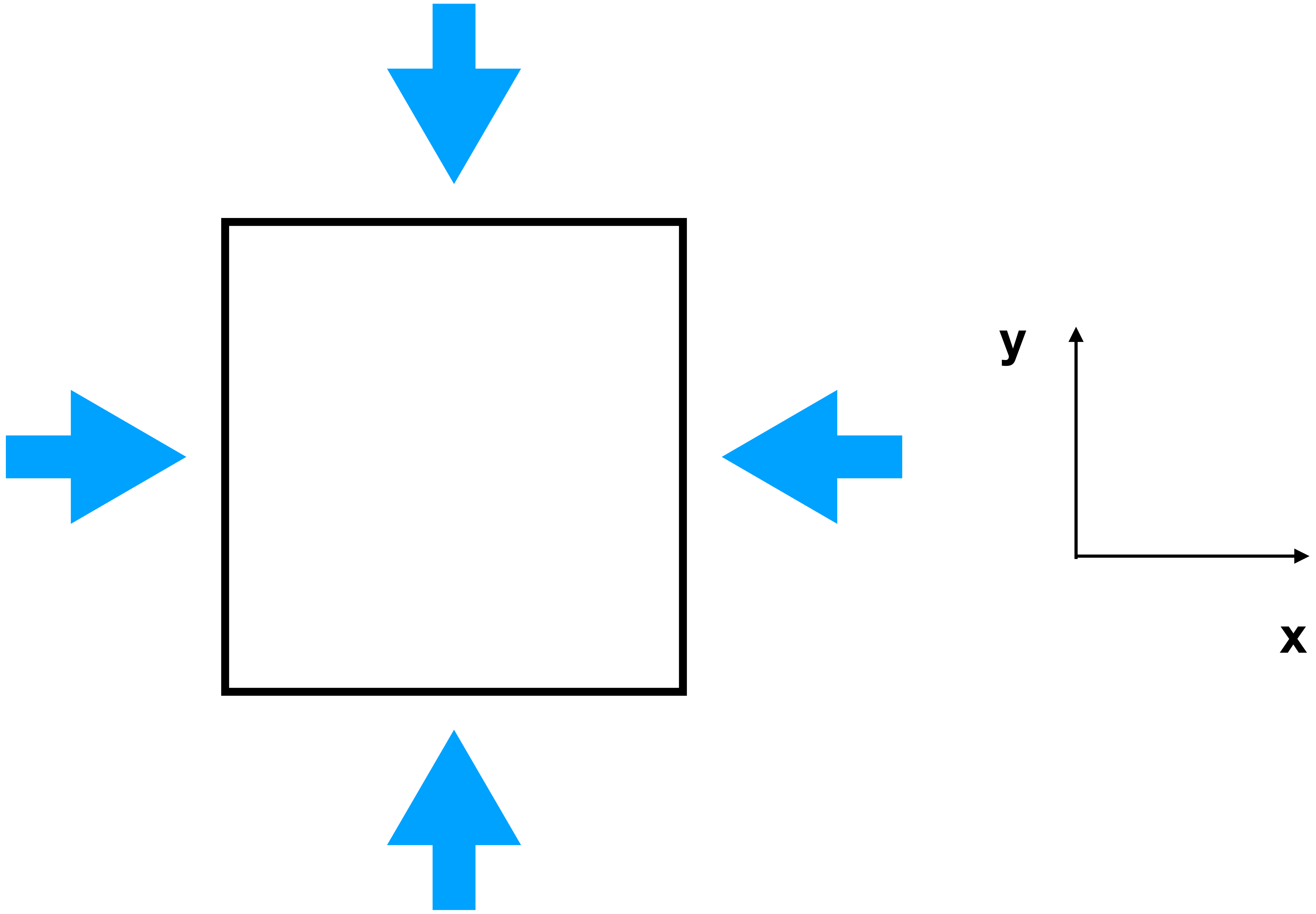
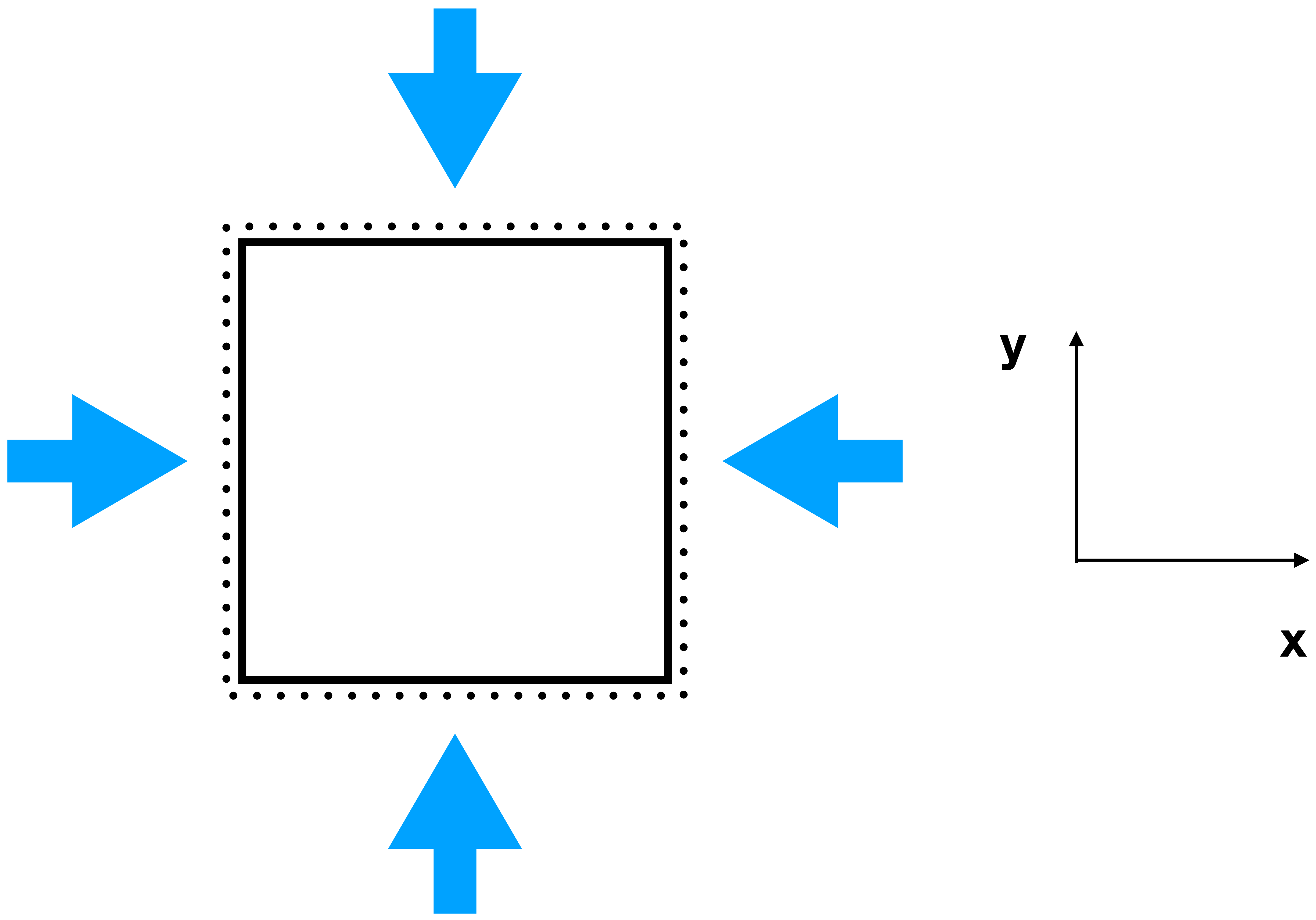
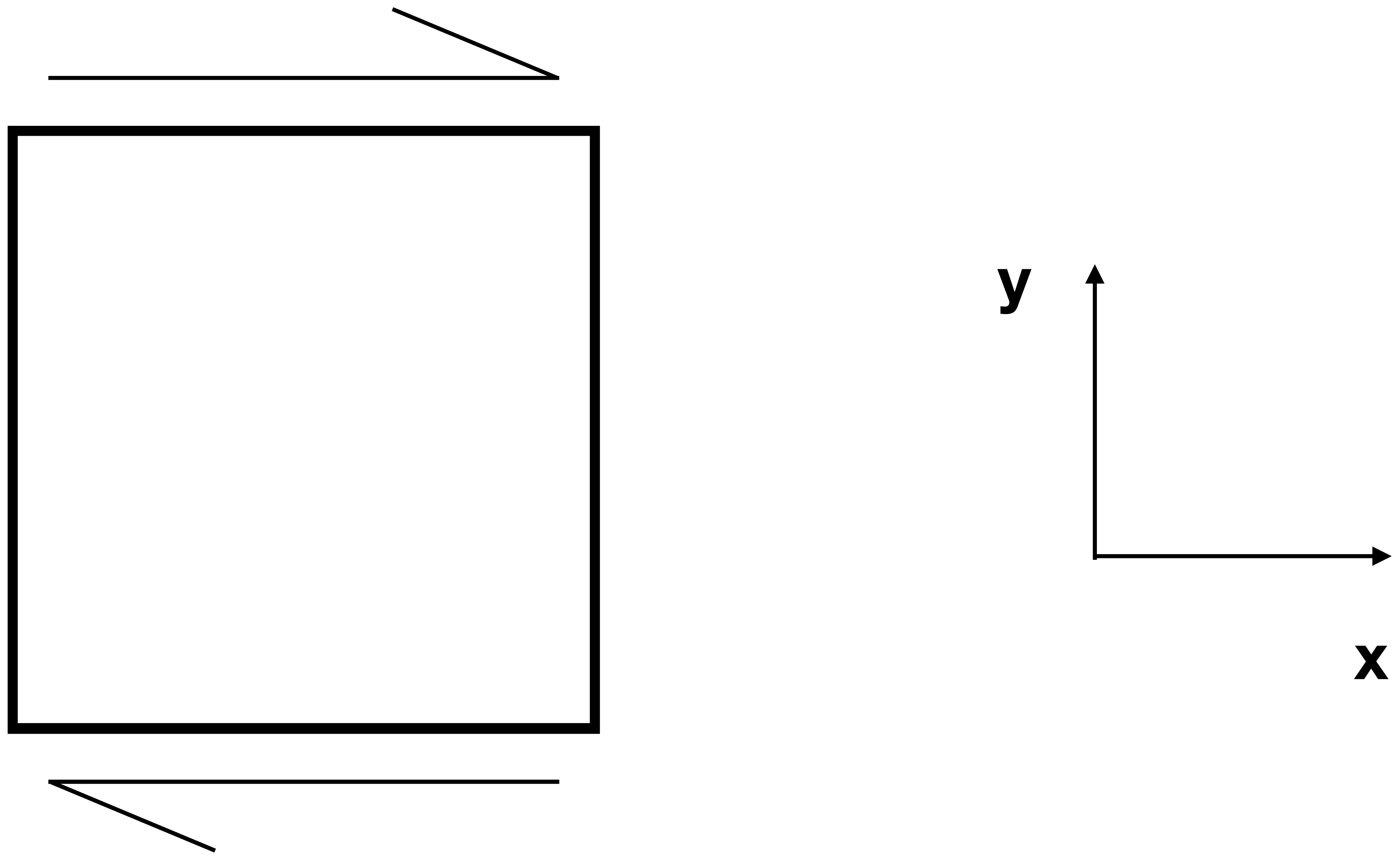


What is the stress field?



What is the stress field?



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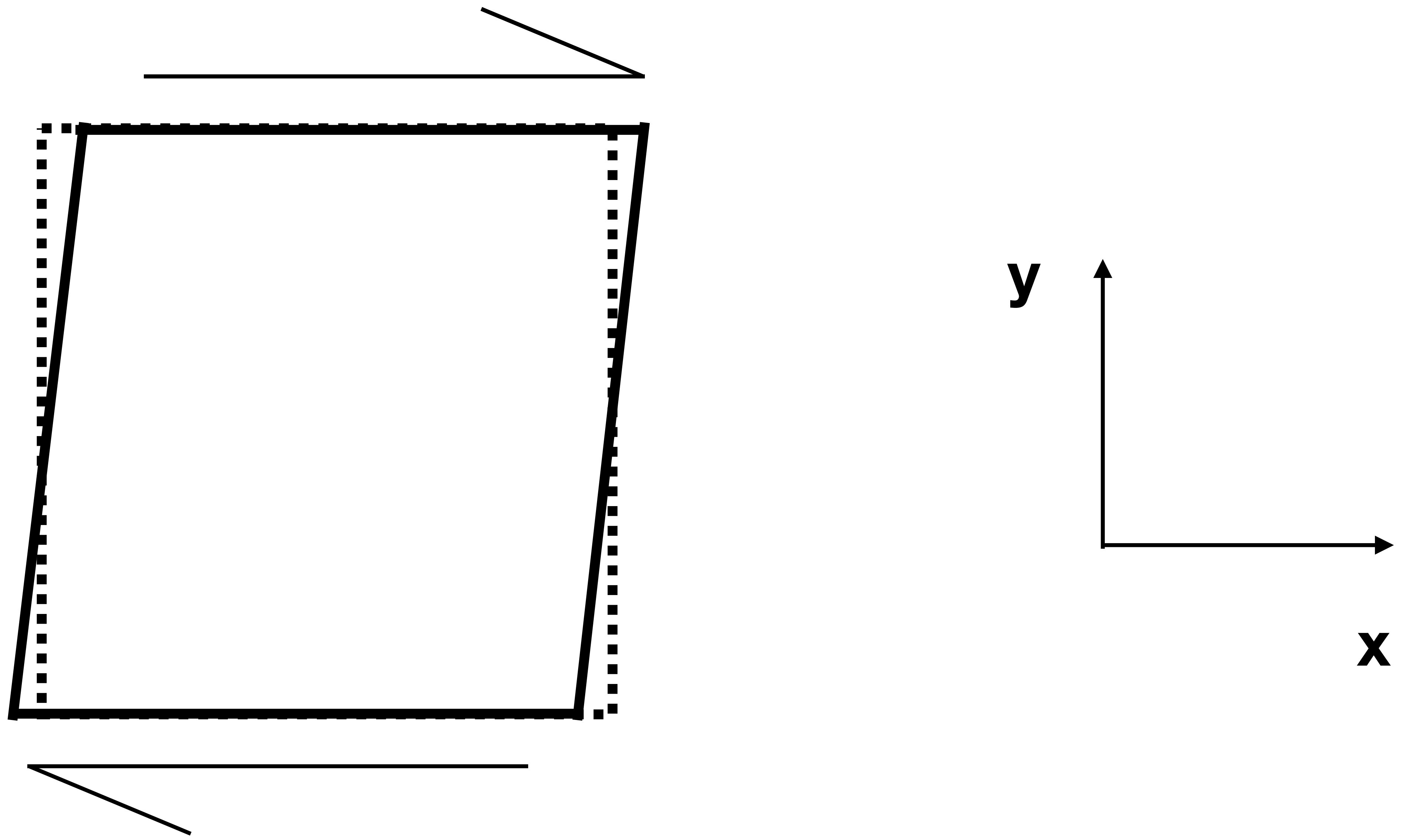
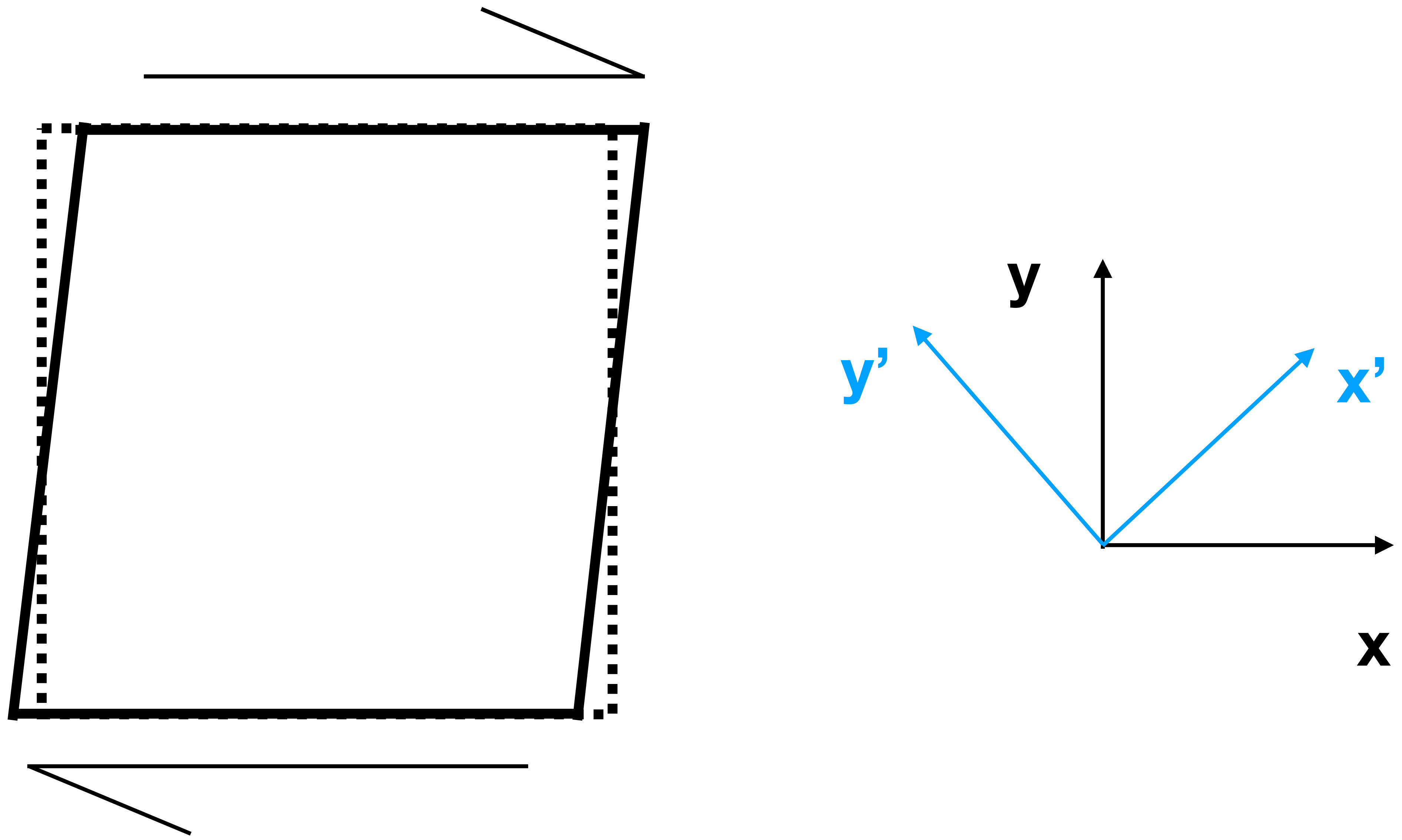
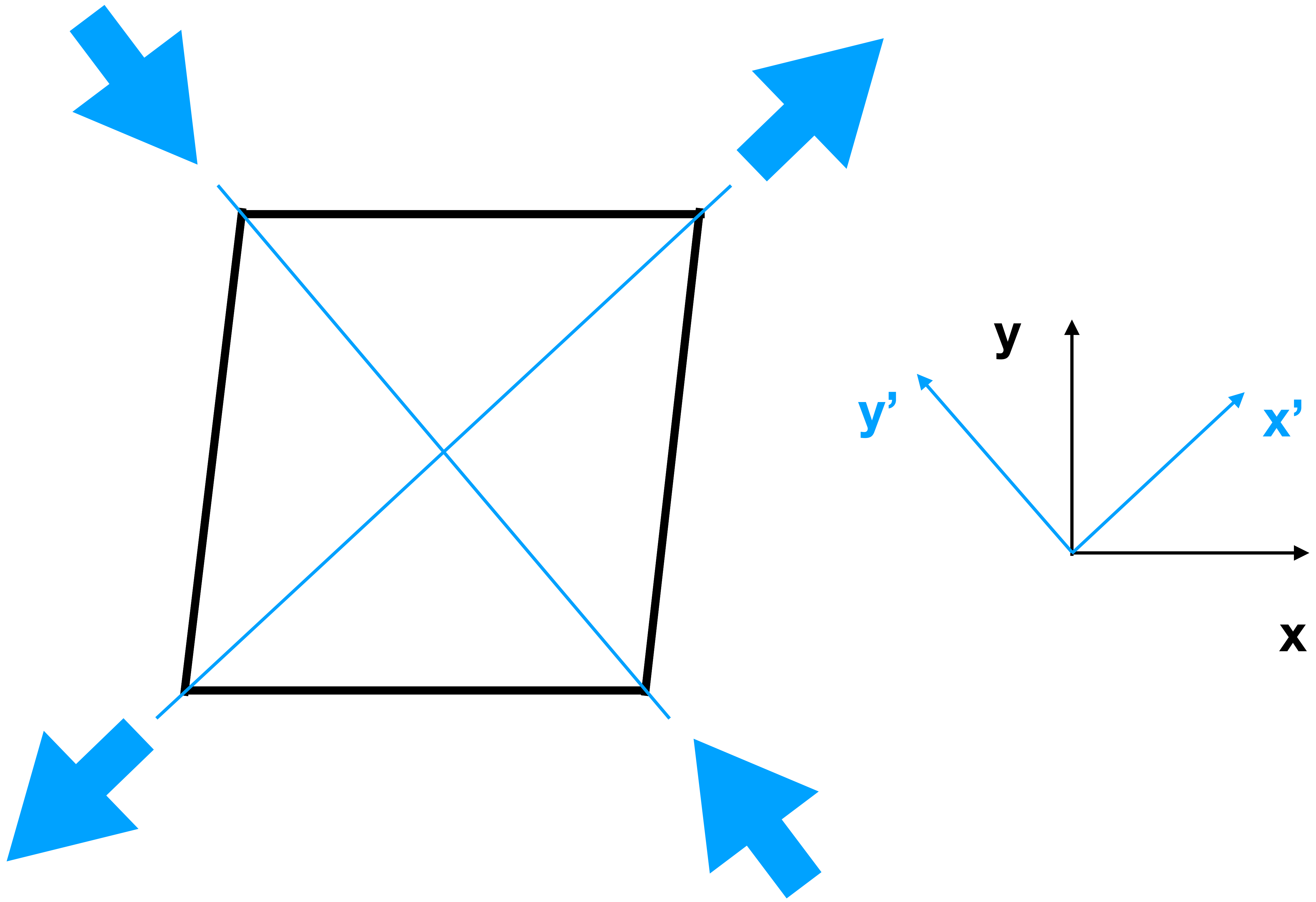


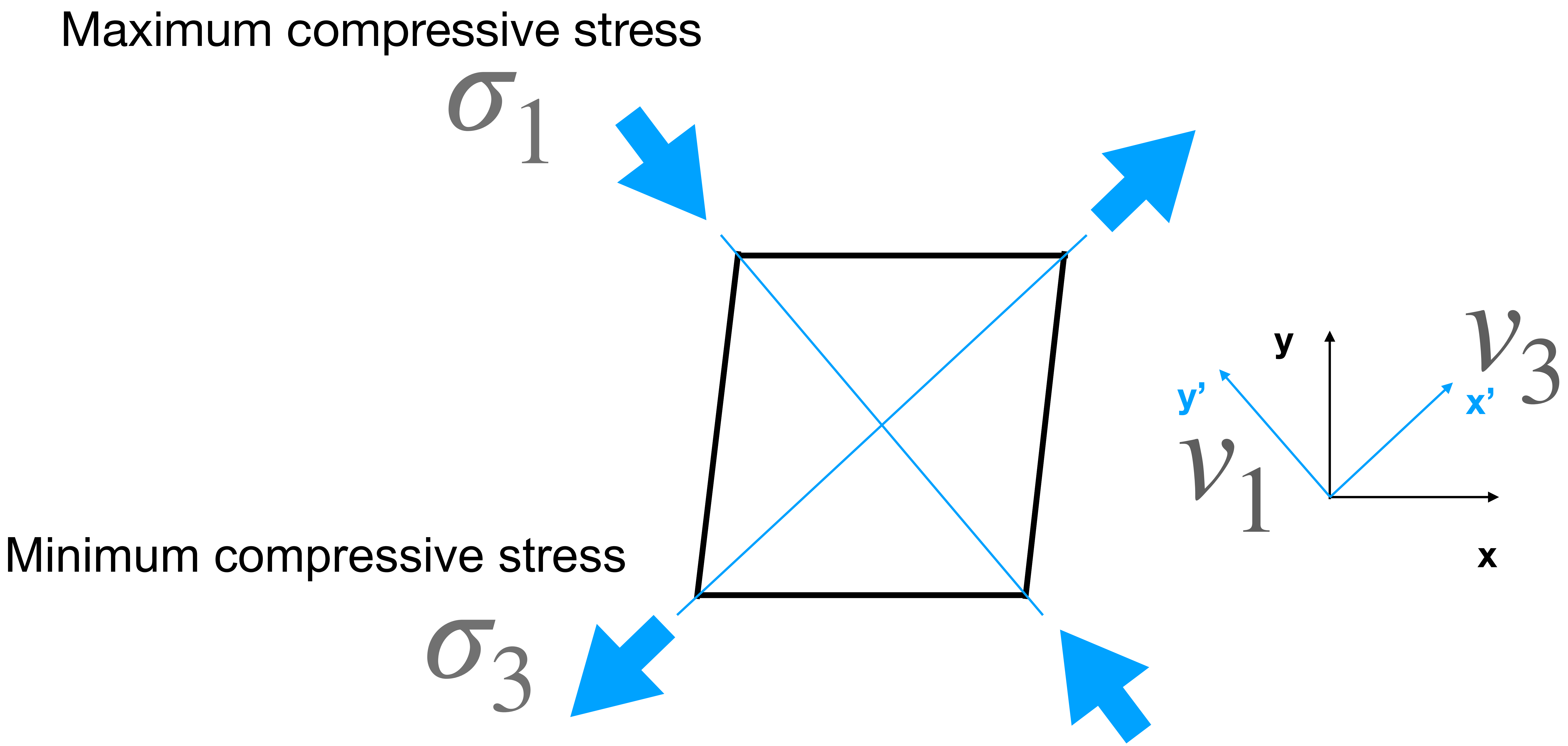
What is the stress field?



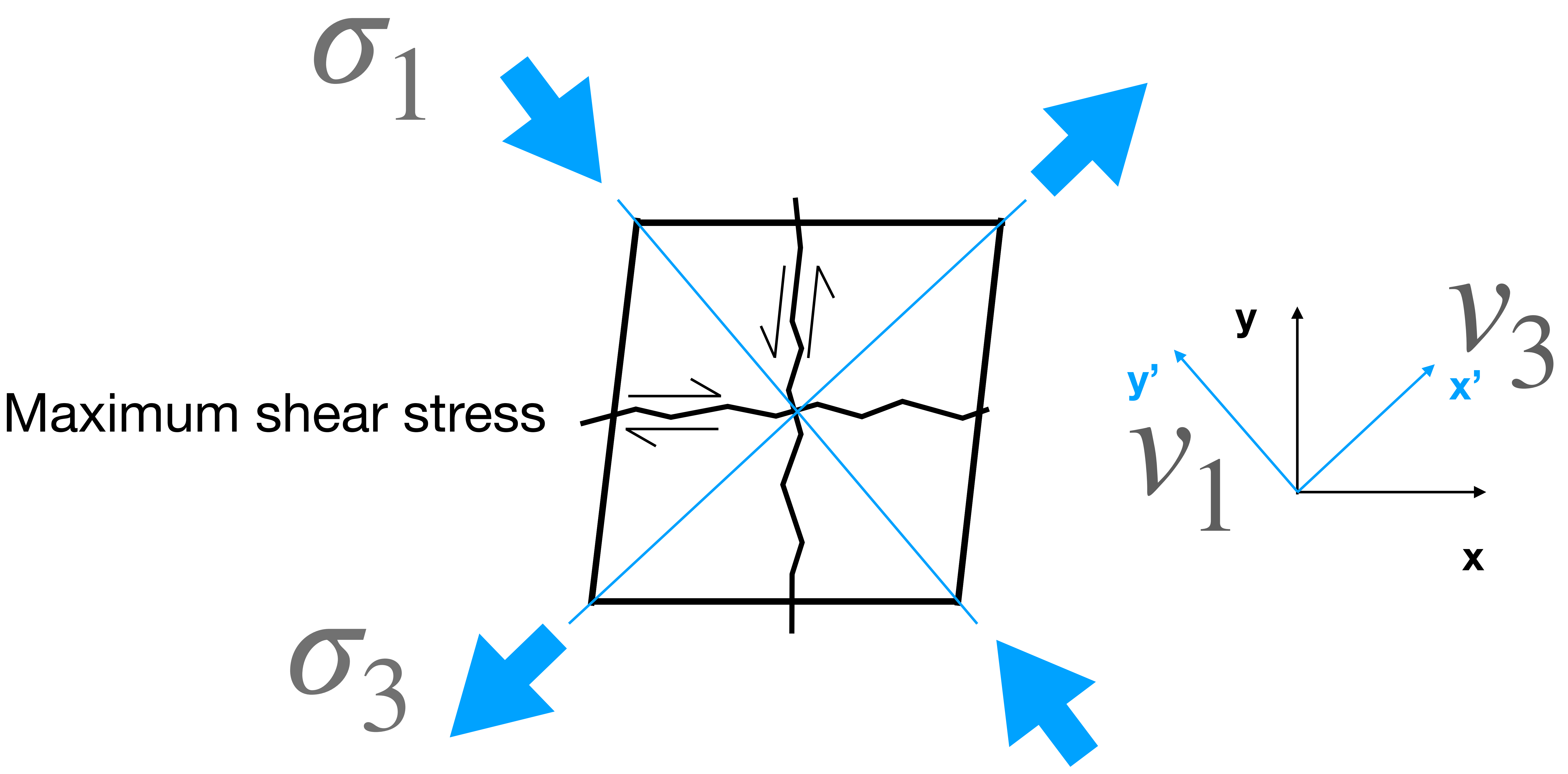
What is the stress field?



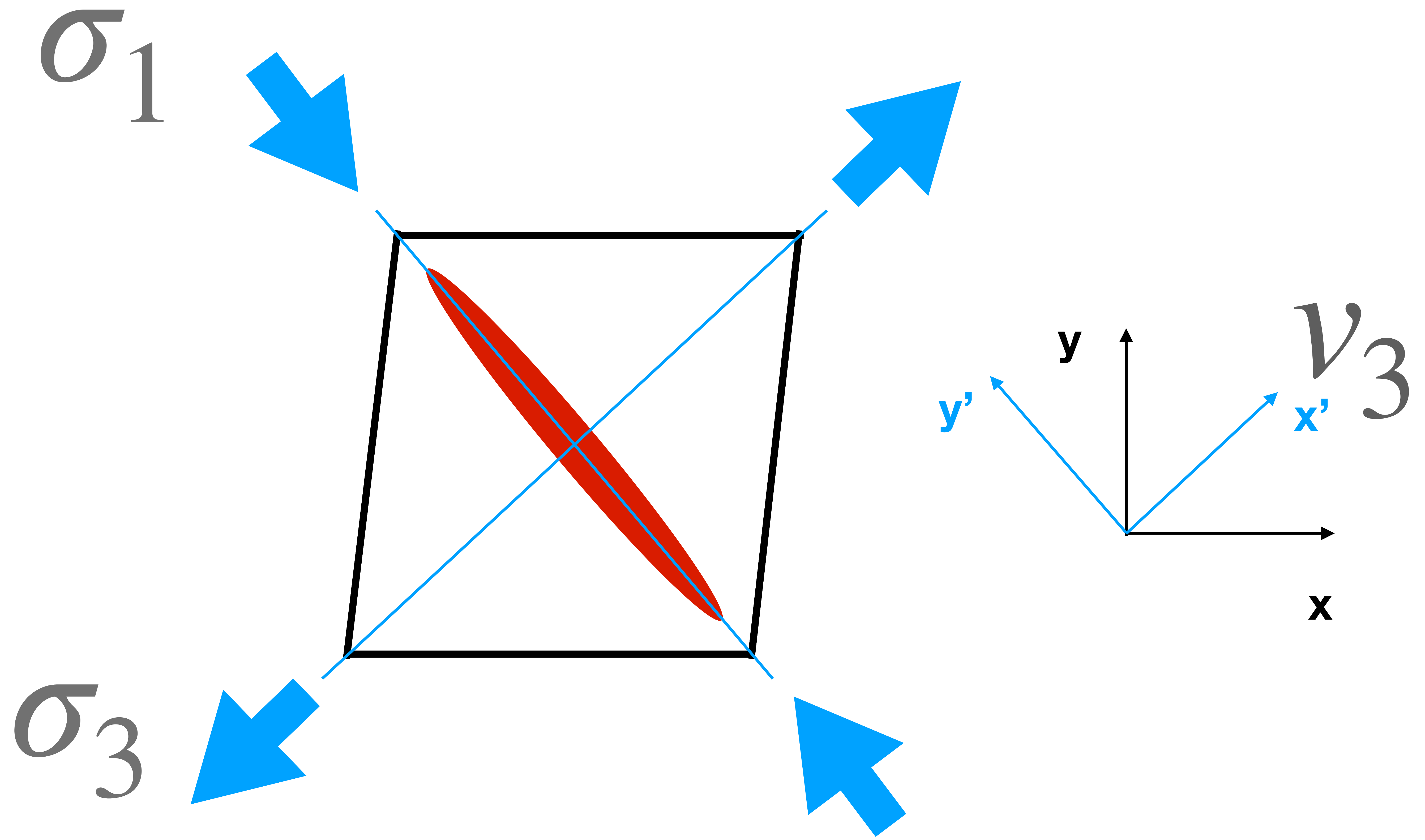
What is the stress field?



What is the stress field?

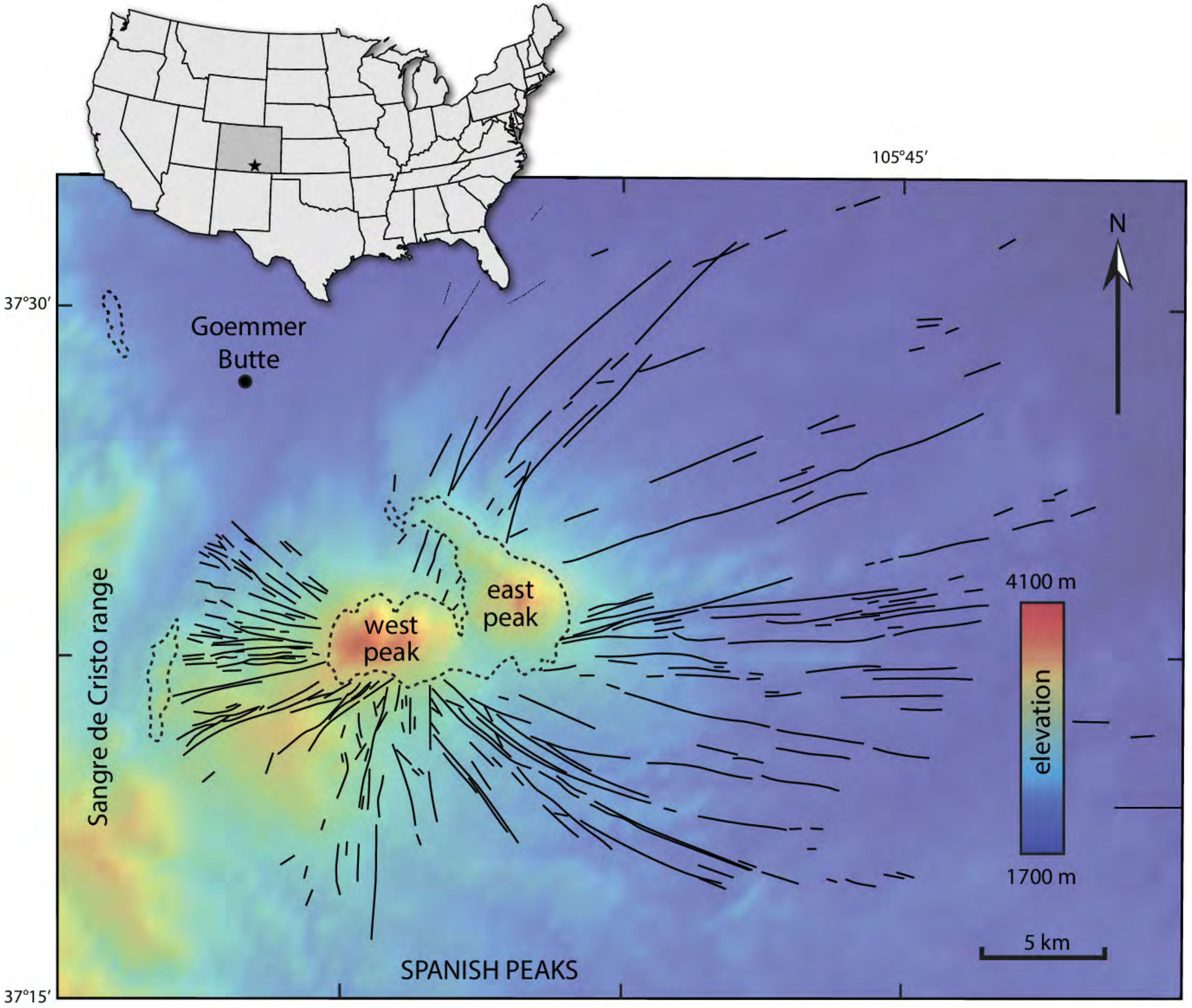


What is the stress field?

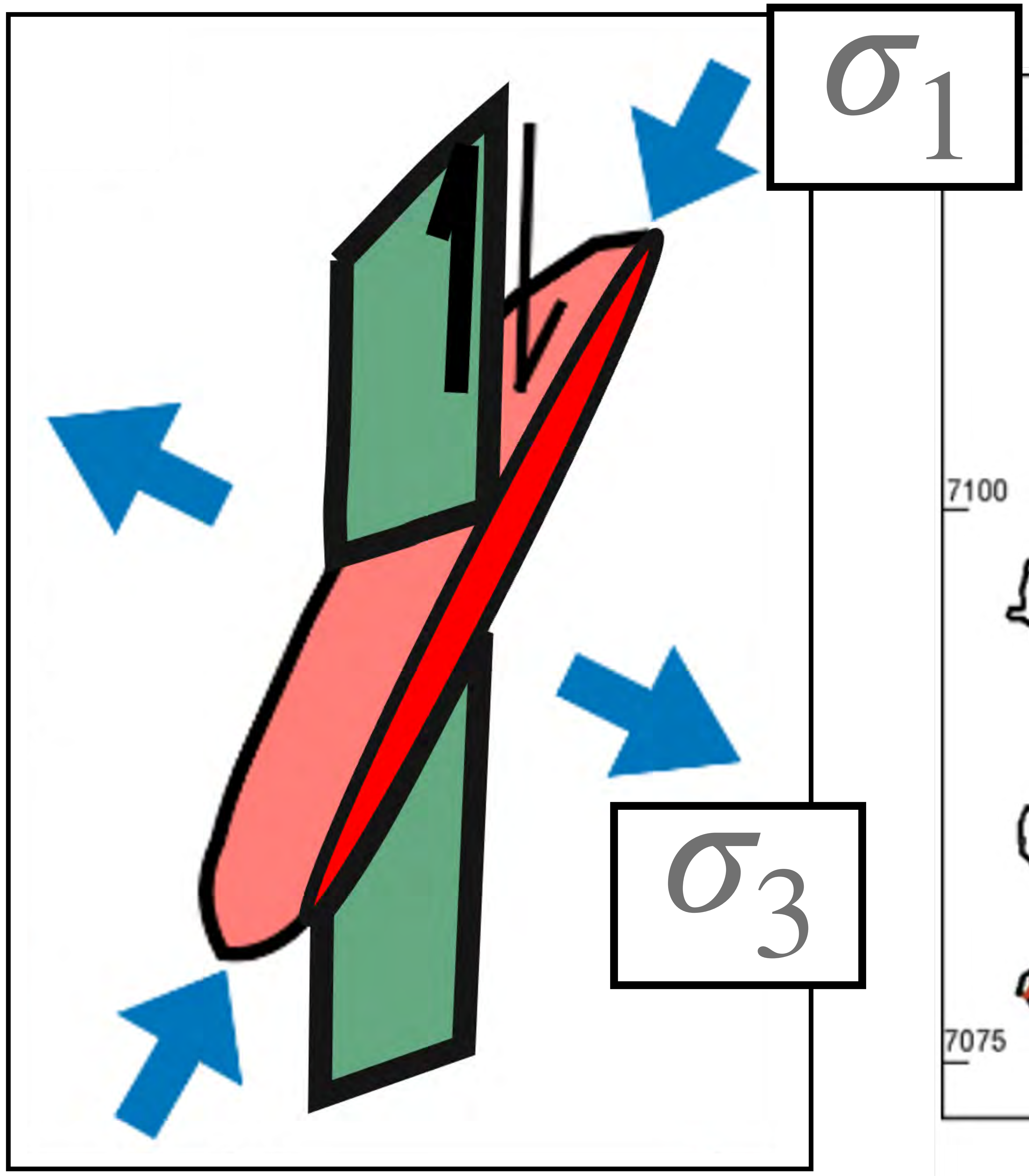


Dike trajectories controlled by the stress field

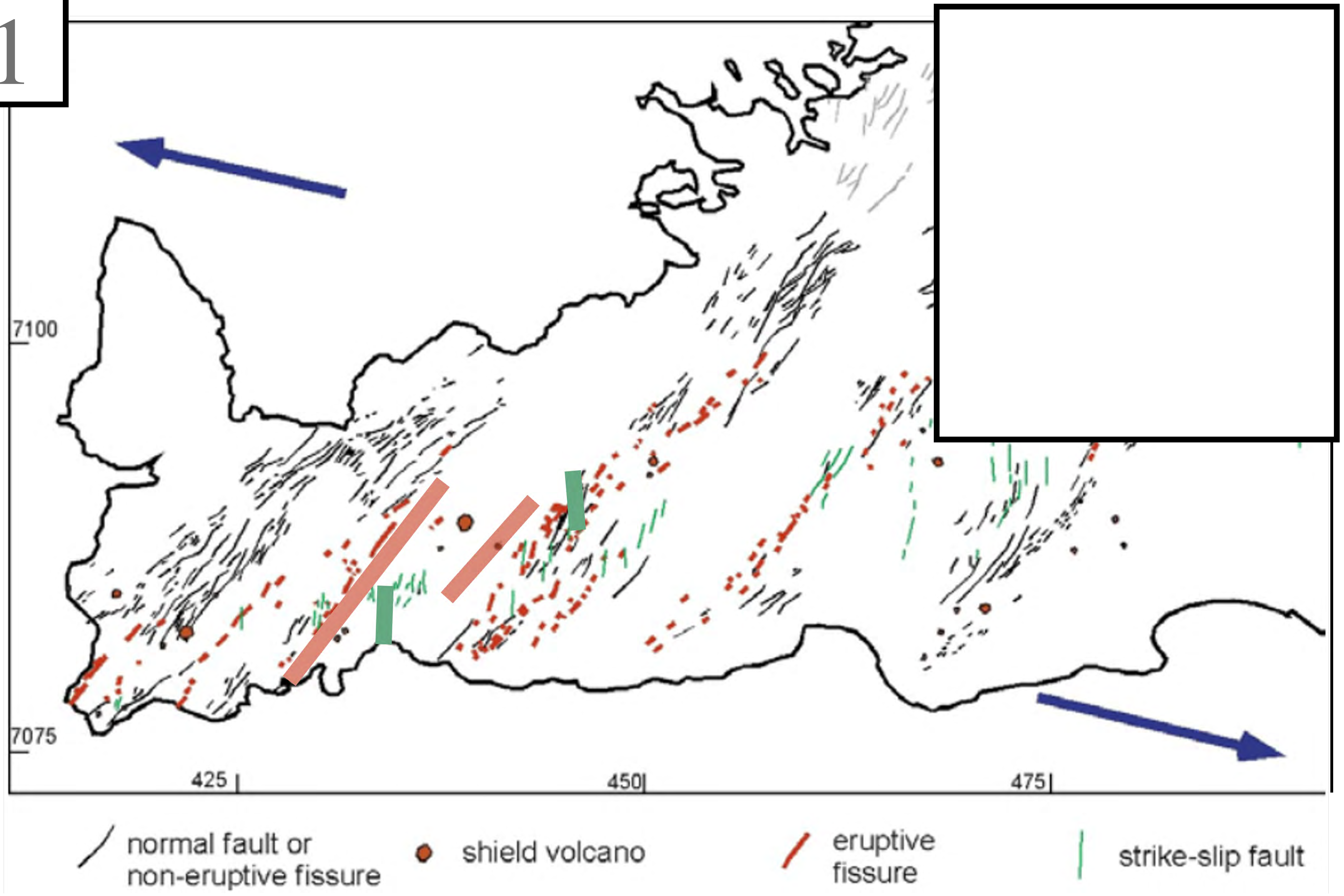
Anderson, 1937
Pollard, 1987
Gudmundsson
Dahm, 2000
Meriaux and Lister, 2002
Roman and Jaupart, 2014



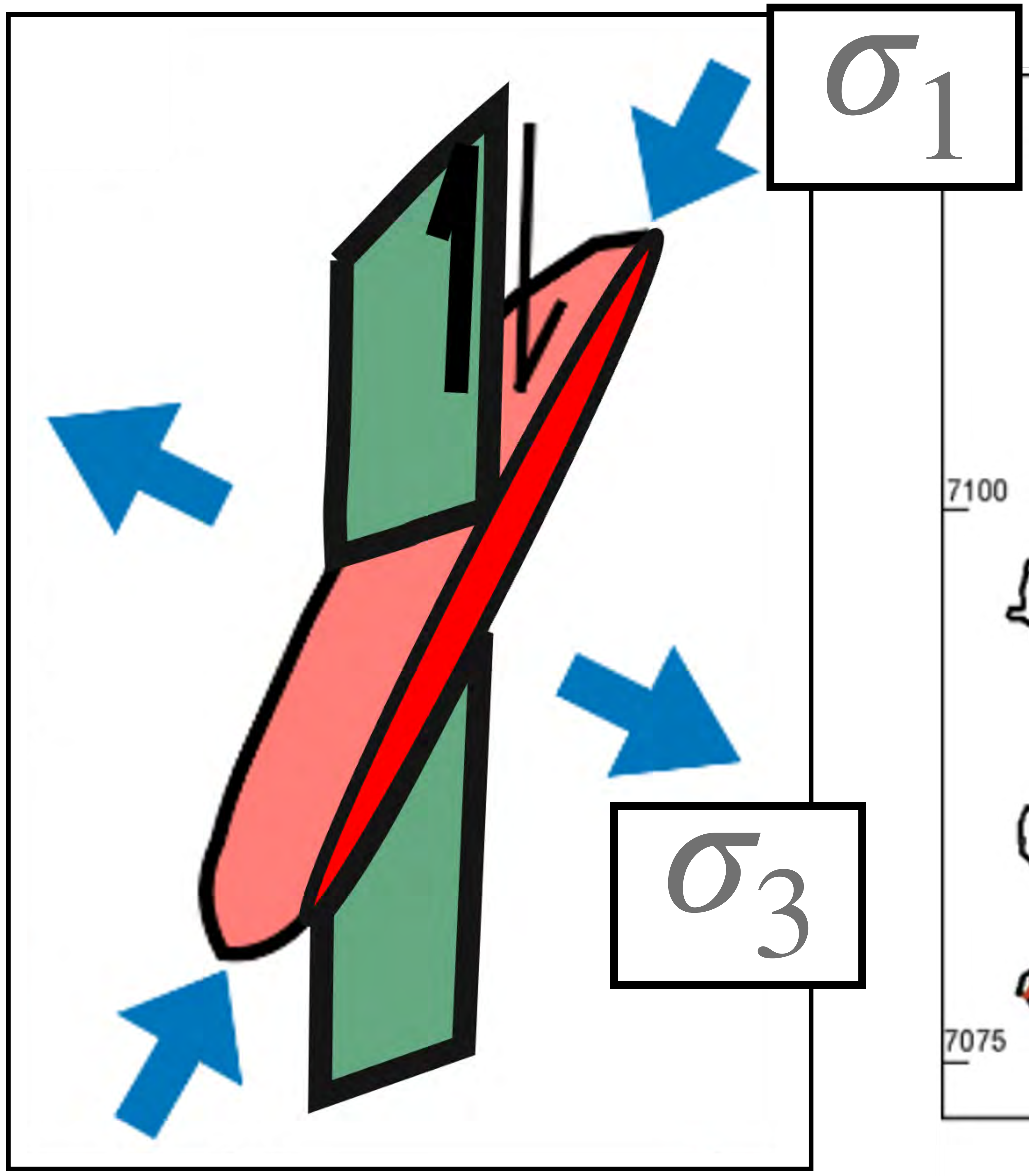
Maerten et al., 2022



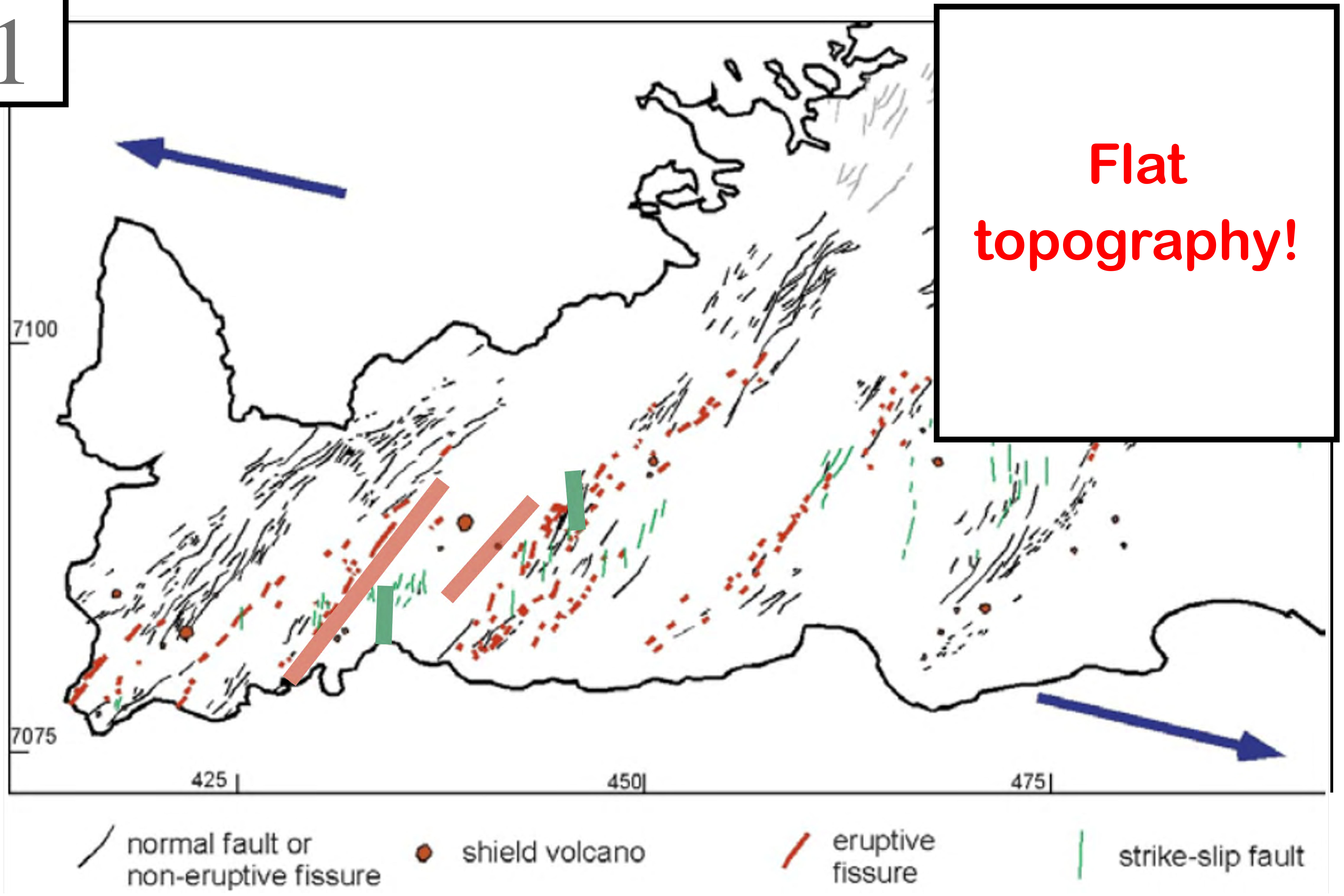
e.g. Anderson, 1937, Pollard, 1987, Dahm, 2000, Roman and Jaupart, 2014



Modified from Stefansson et al., 2006

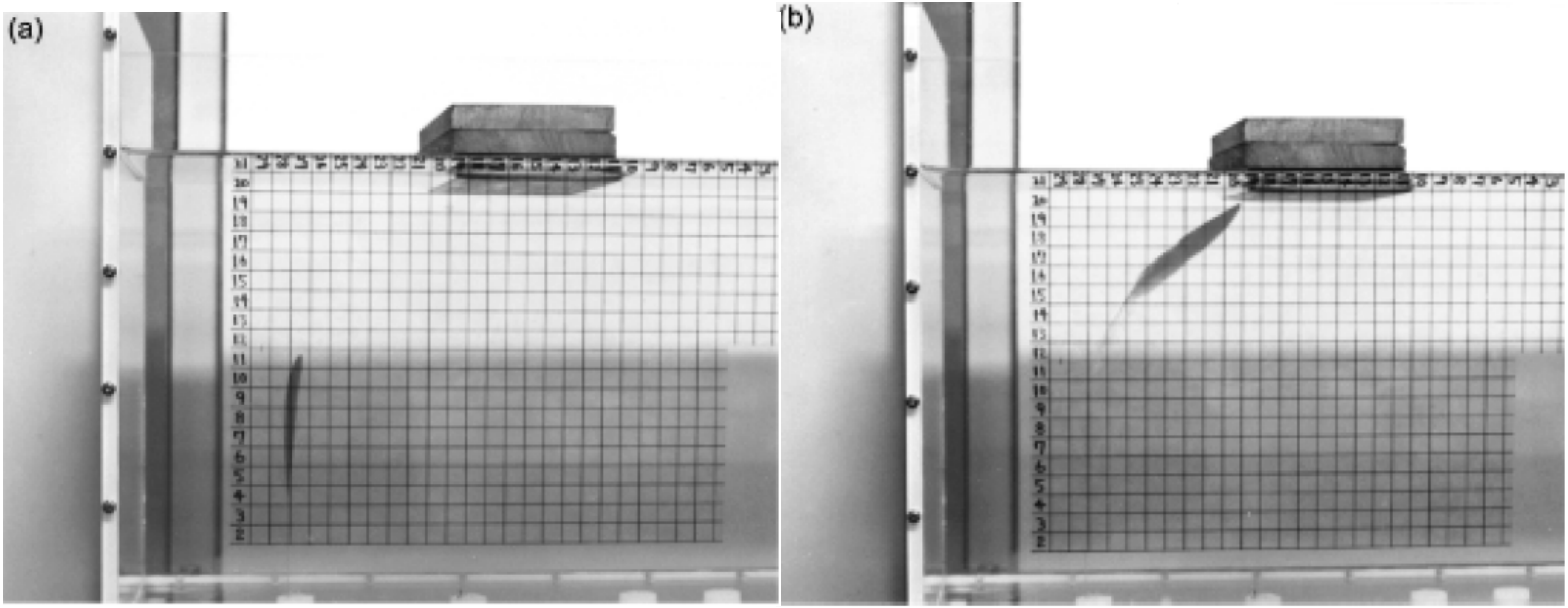


e.g. Anderson, 1937, Pollard, 1987, Dahm, 2000, Roman and Jaupart, 2014



Modified from Stefansson et al., 2006

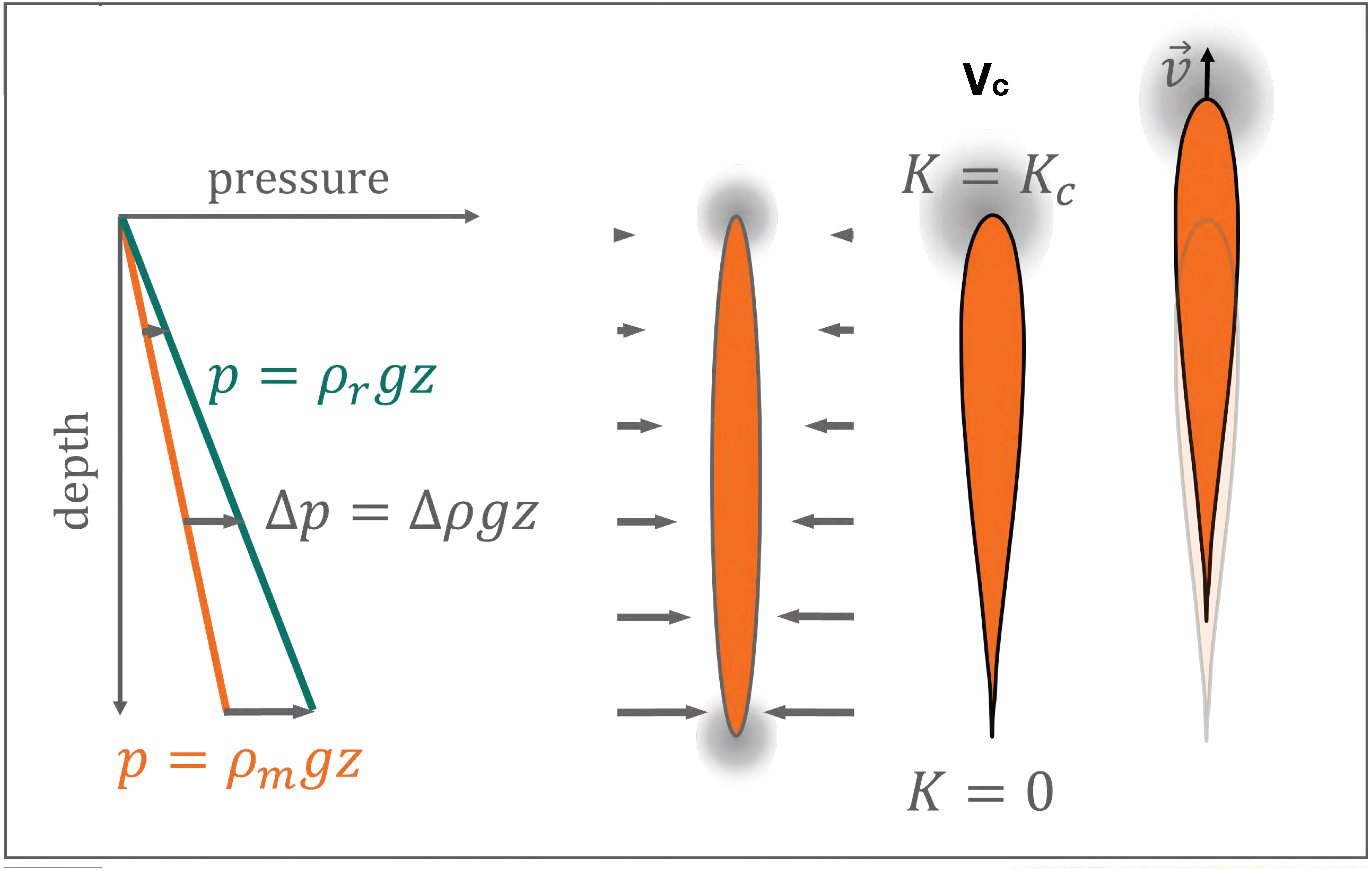
Surface loading



Watanabe et al., 2002

Magma ascent by hydraulic fracturing

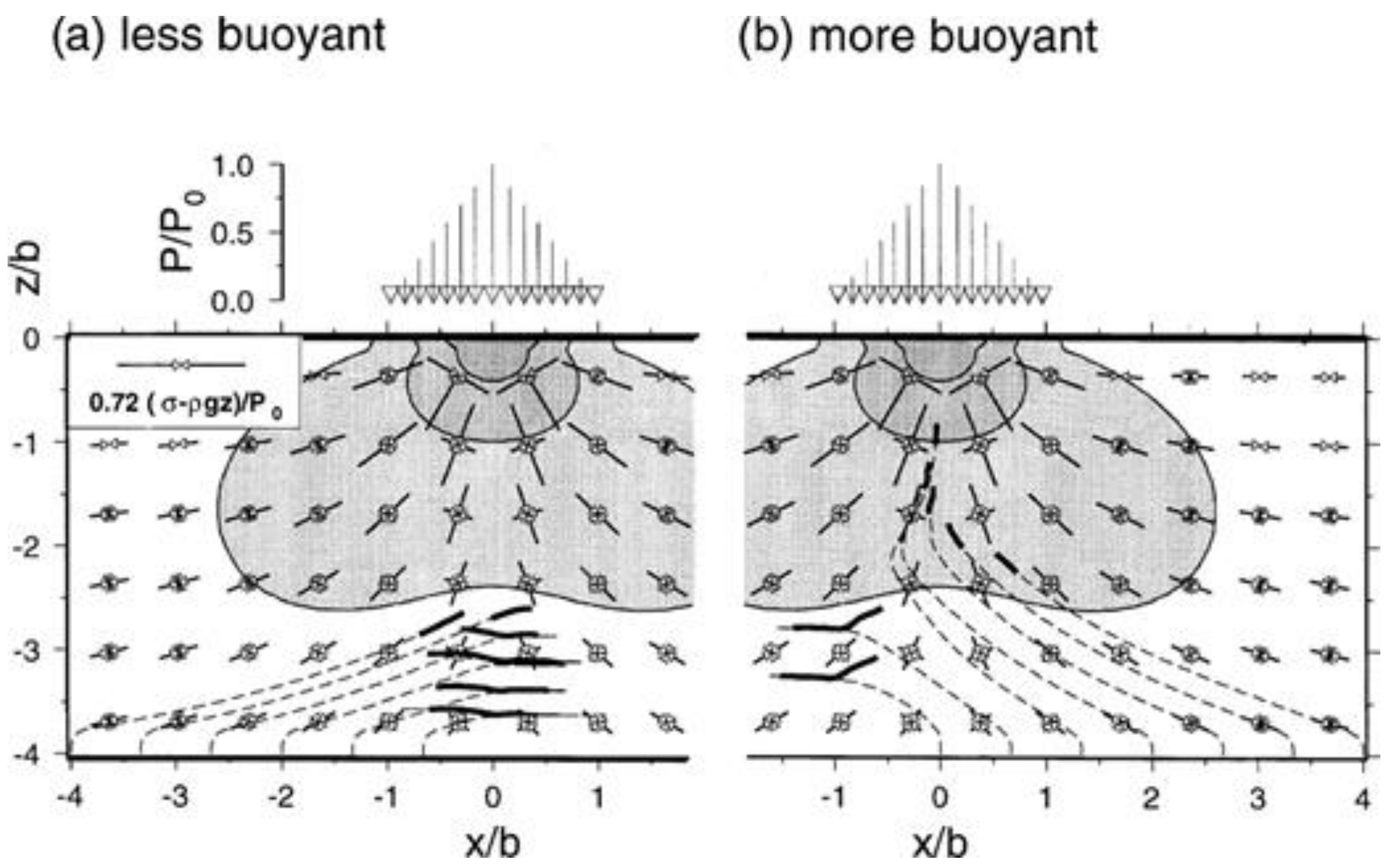
Rivalta et al., Encyclopedia of Volcanoes III edition, under review



Seminal 2D dike propagation models

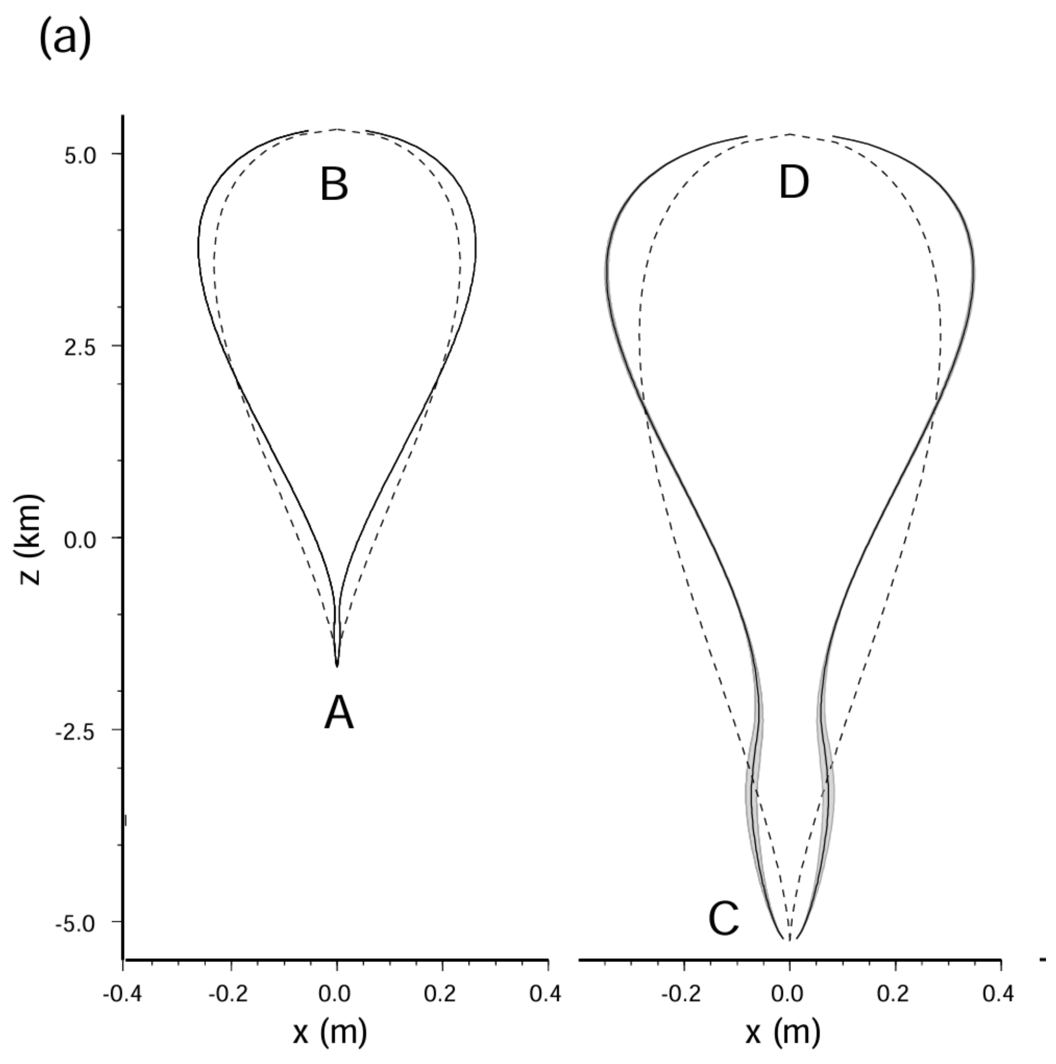
Dike trajectories

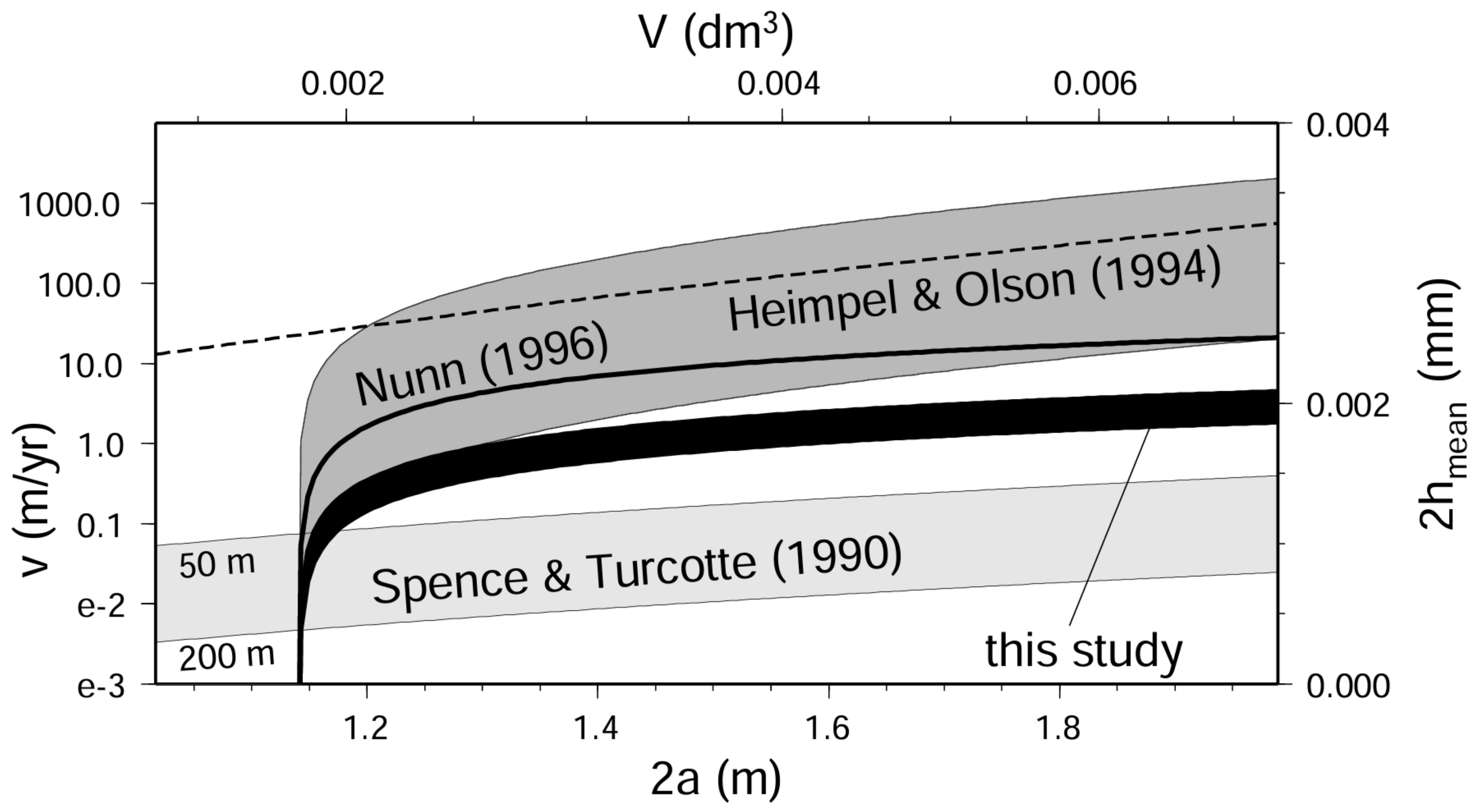
Dahm, 2000
Maccaferri et al., 2010, 2011, 2014, 2015, 2017, 2018, 2019



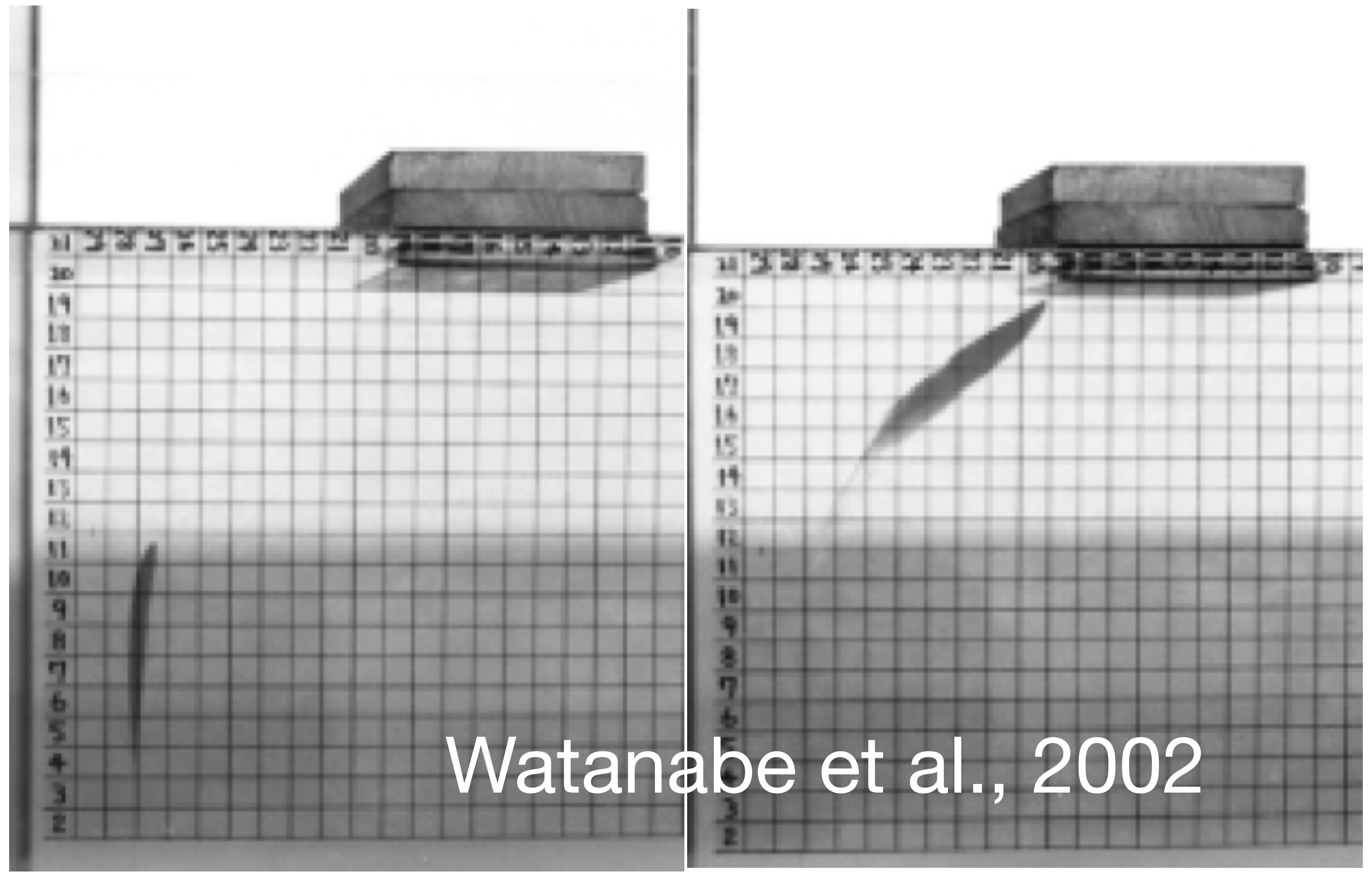
Dike velocity

Dahm, 2000
Roper and Lister, 2007, 2009
Turcotte, Spence, Jaupart, Meriaux, Pinel, Taisne…

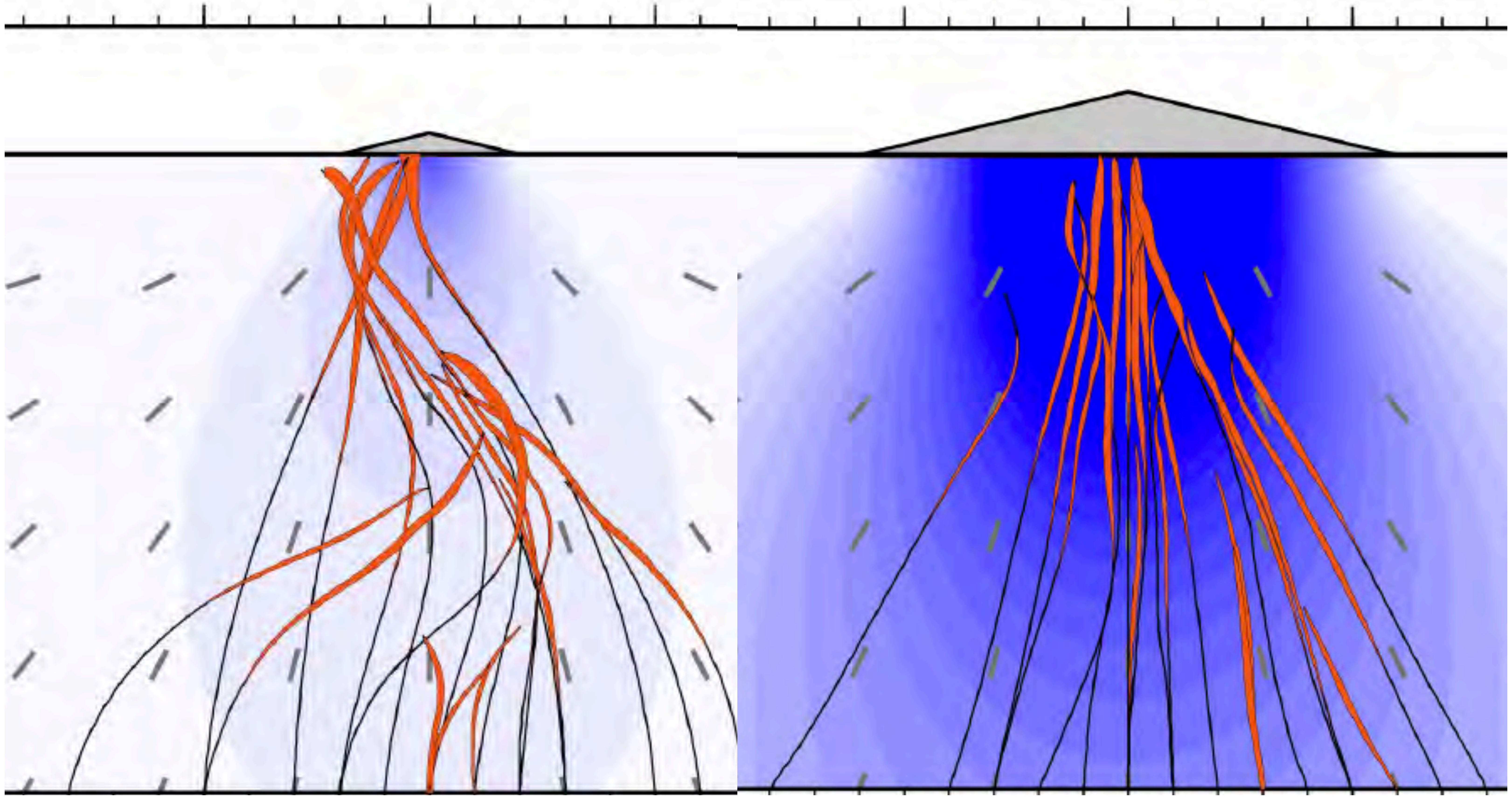




Surface loading



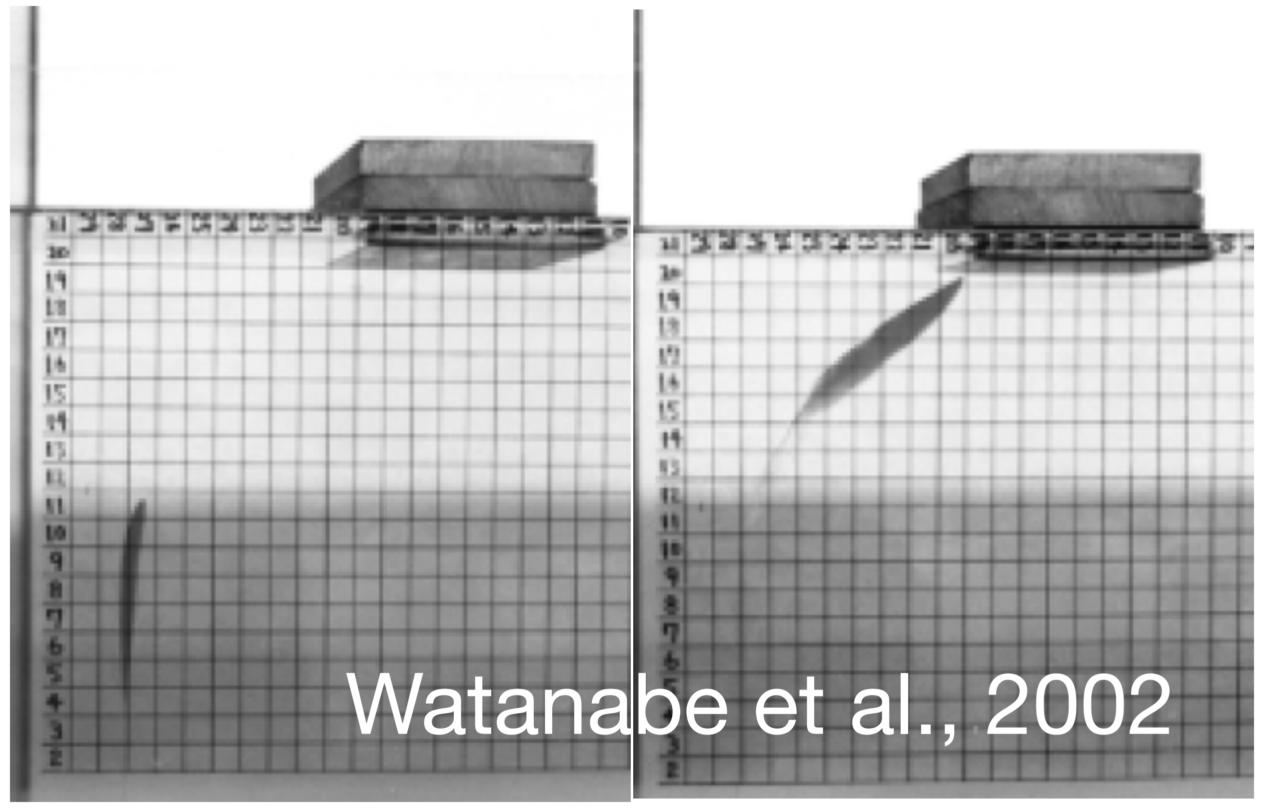
Watanabe et al., 2002



Rivalta et al., in prep.

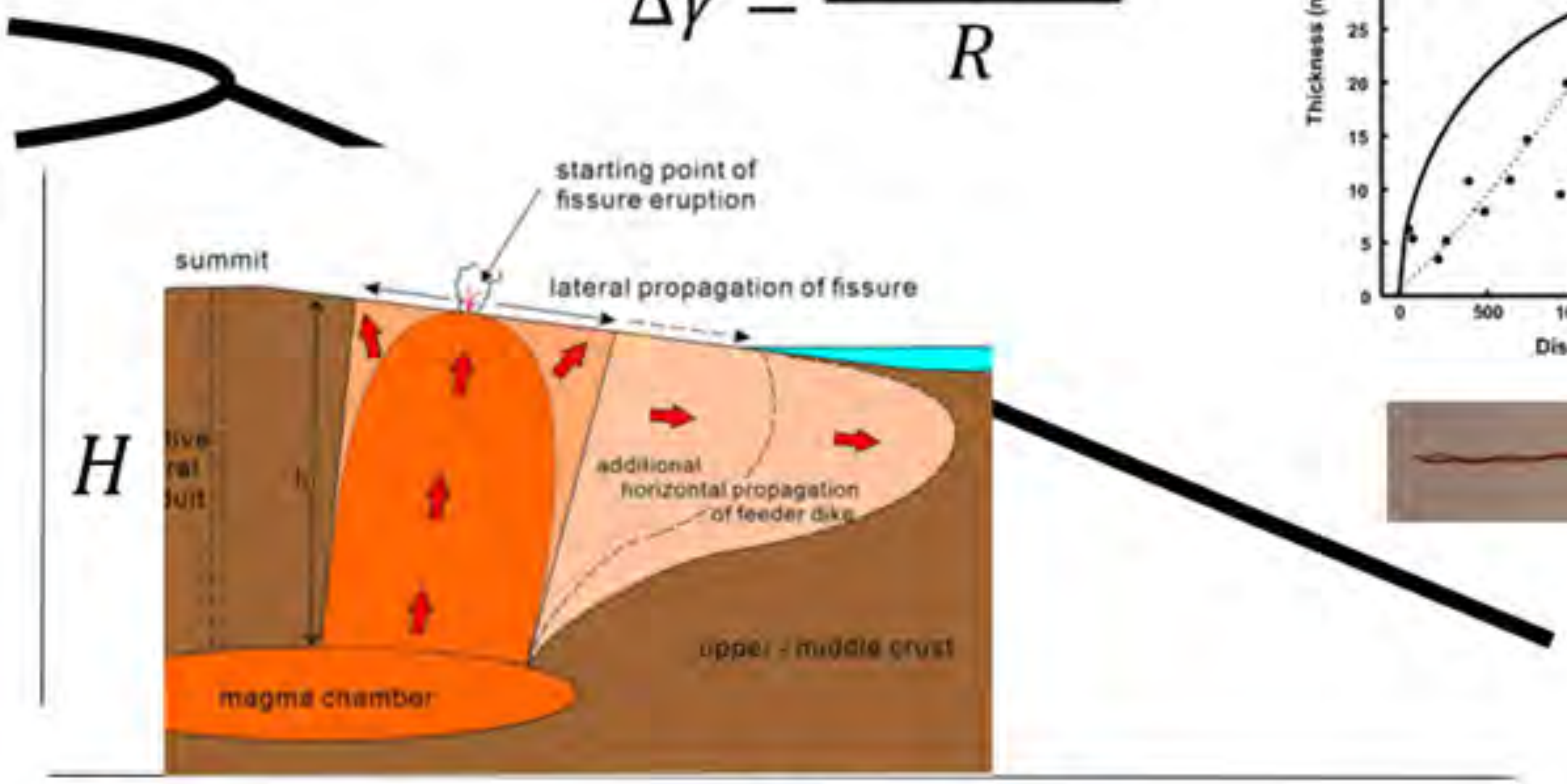
Gaete, Mantiloni & Rivalta

Surface loading


Watanabe et al., 2002

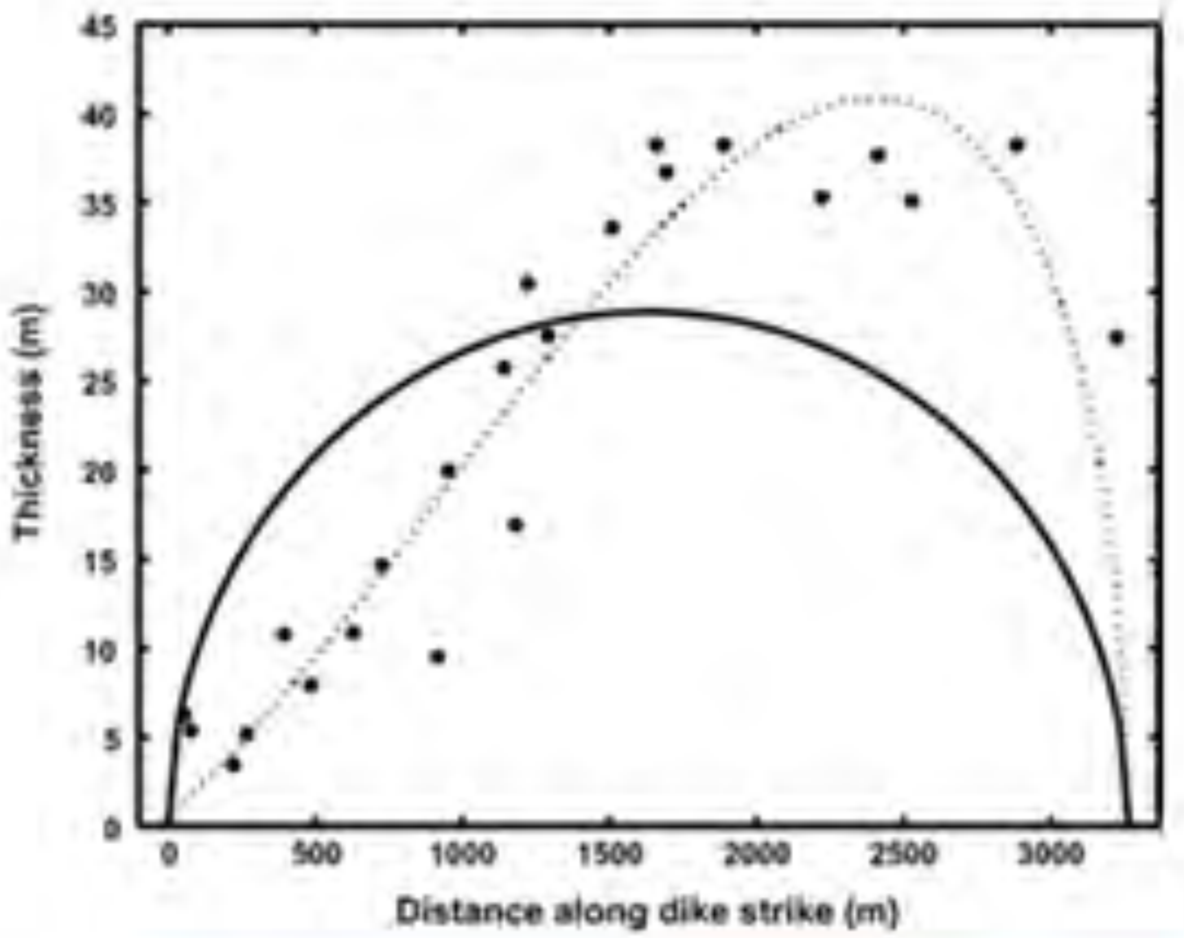
Pinel and Jaupart, 2000
Pinel and Jaupart, 2004
Pinel and Merieaux, 2025

$$\Delta\gamma = \frac{\rho_{Rock}\, g H}{R}$$

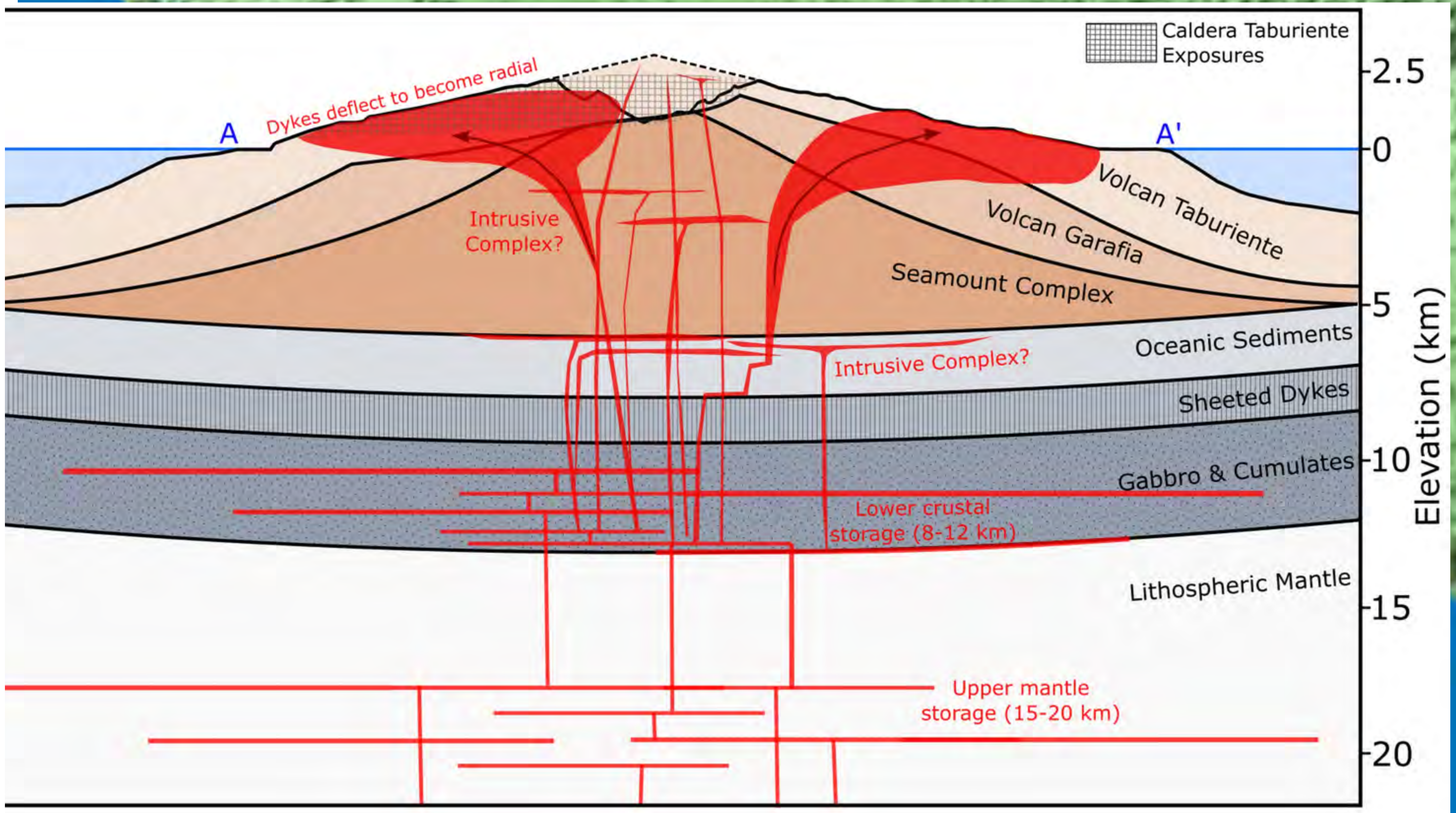


Geshi et al., 2020

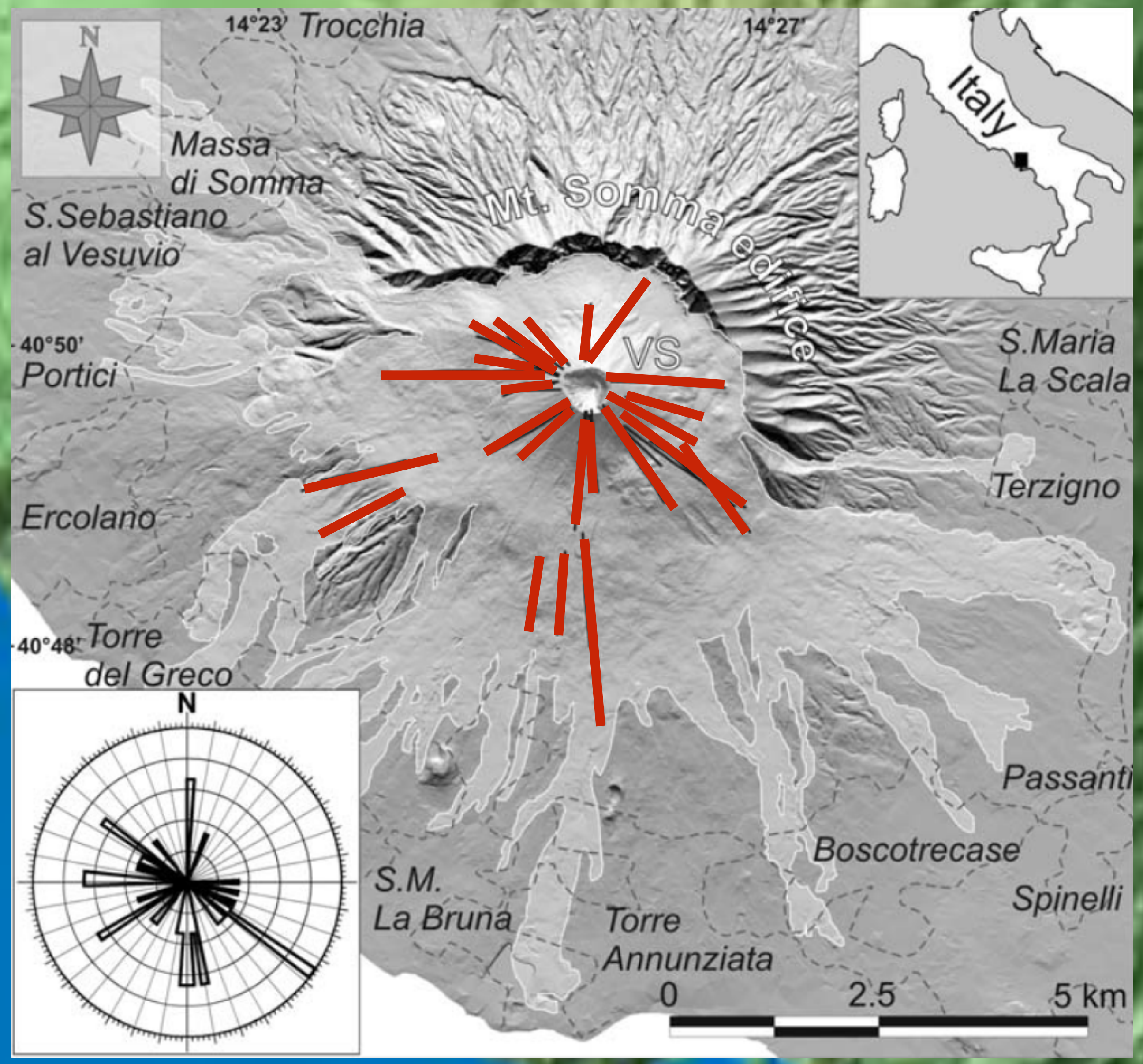
Poland et al., 2008



Radial dikes for stratocones



Thiele et al., 2020
(La Palma)

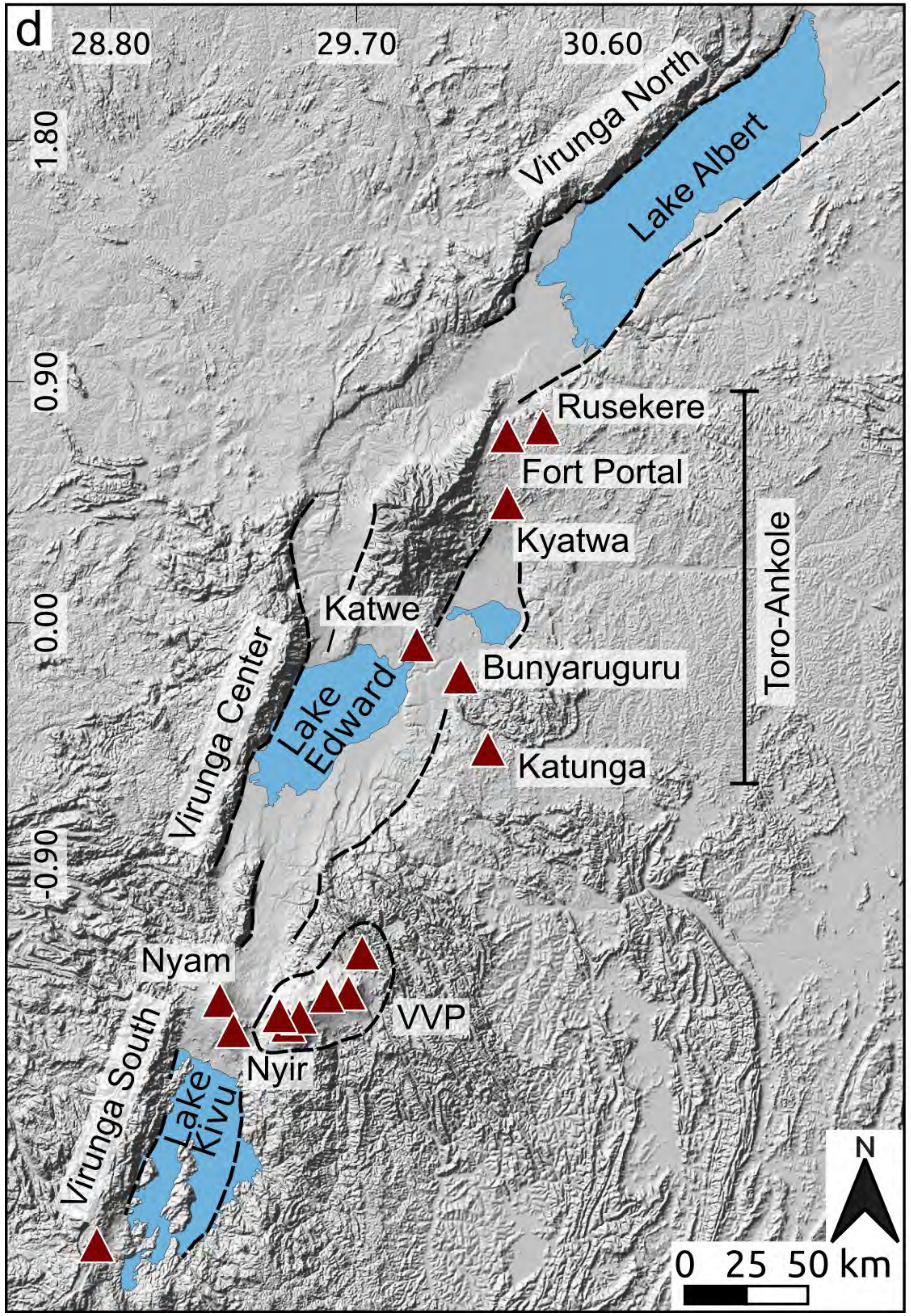


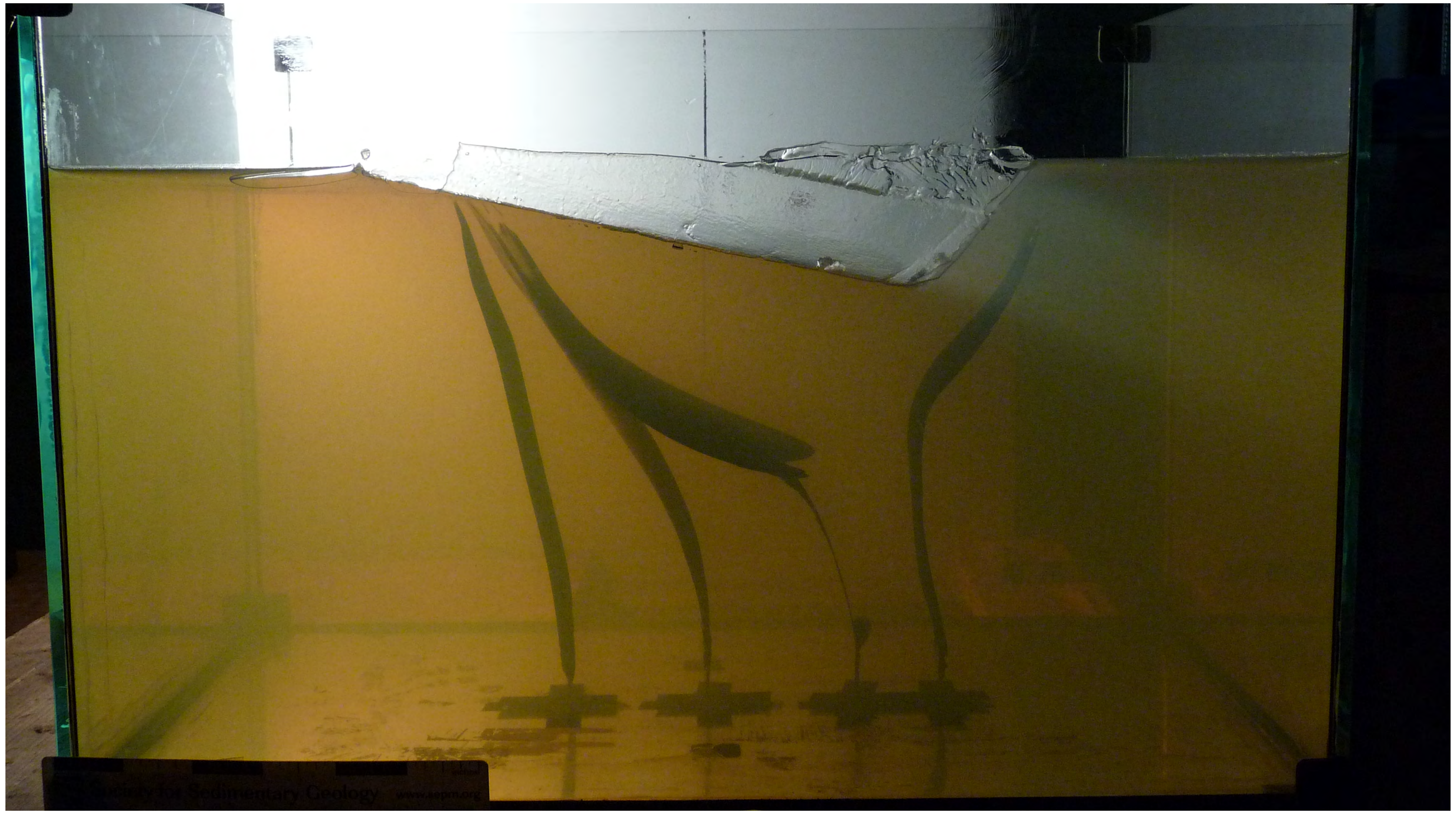
modified from Acocella et al., 2006

Surface unloading: rifts

Rivalta et al.


Sedimentary Geology
www.sepm.org

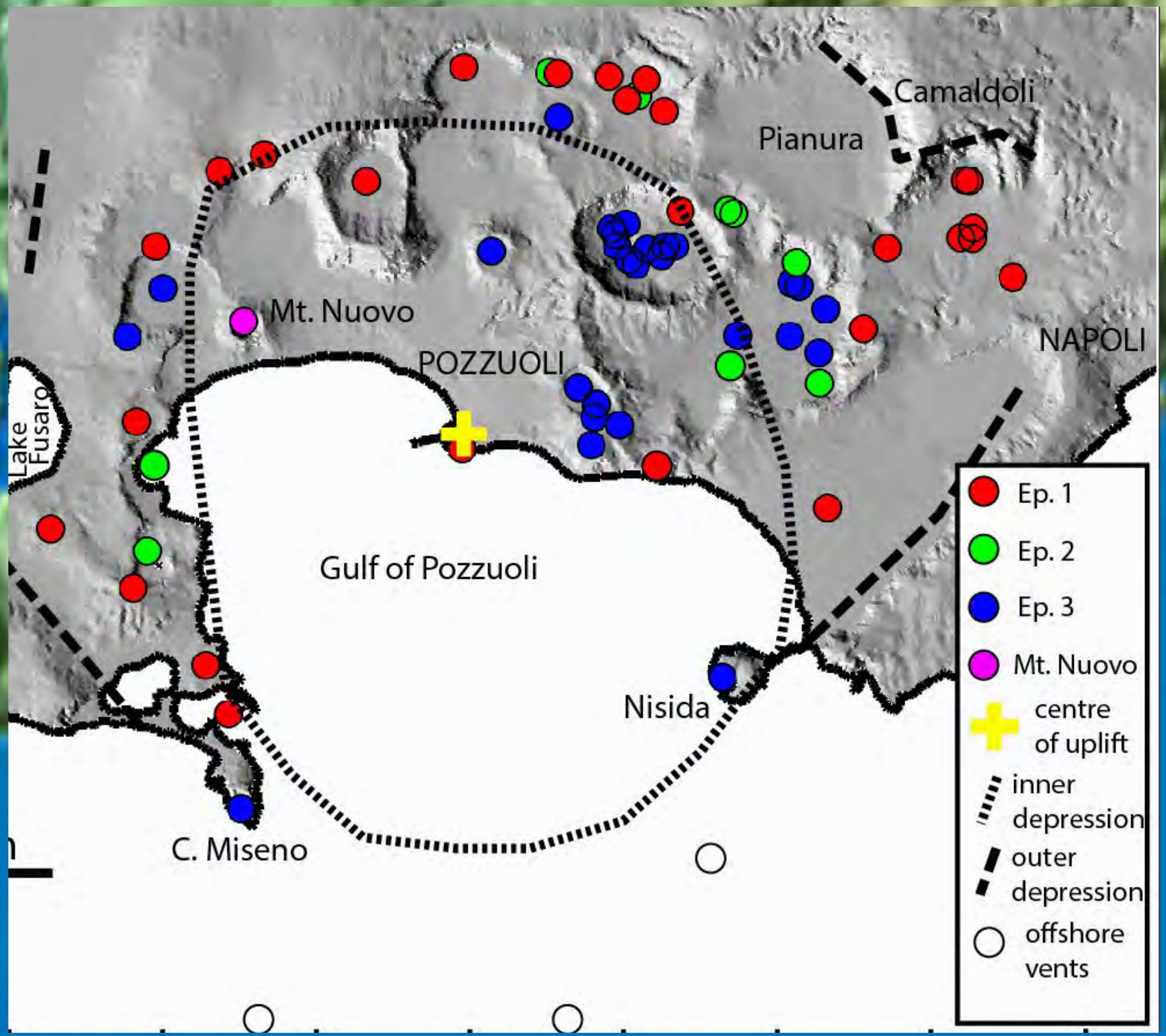




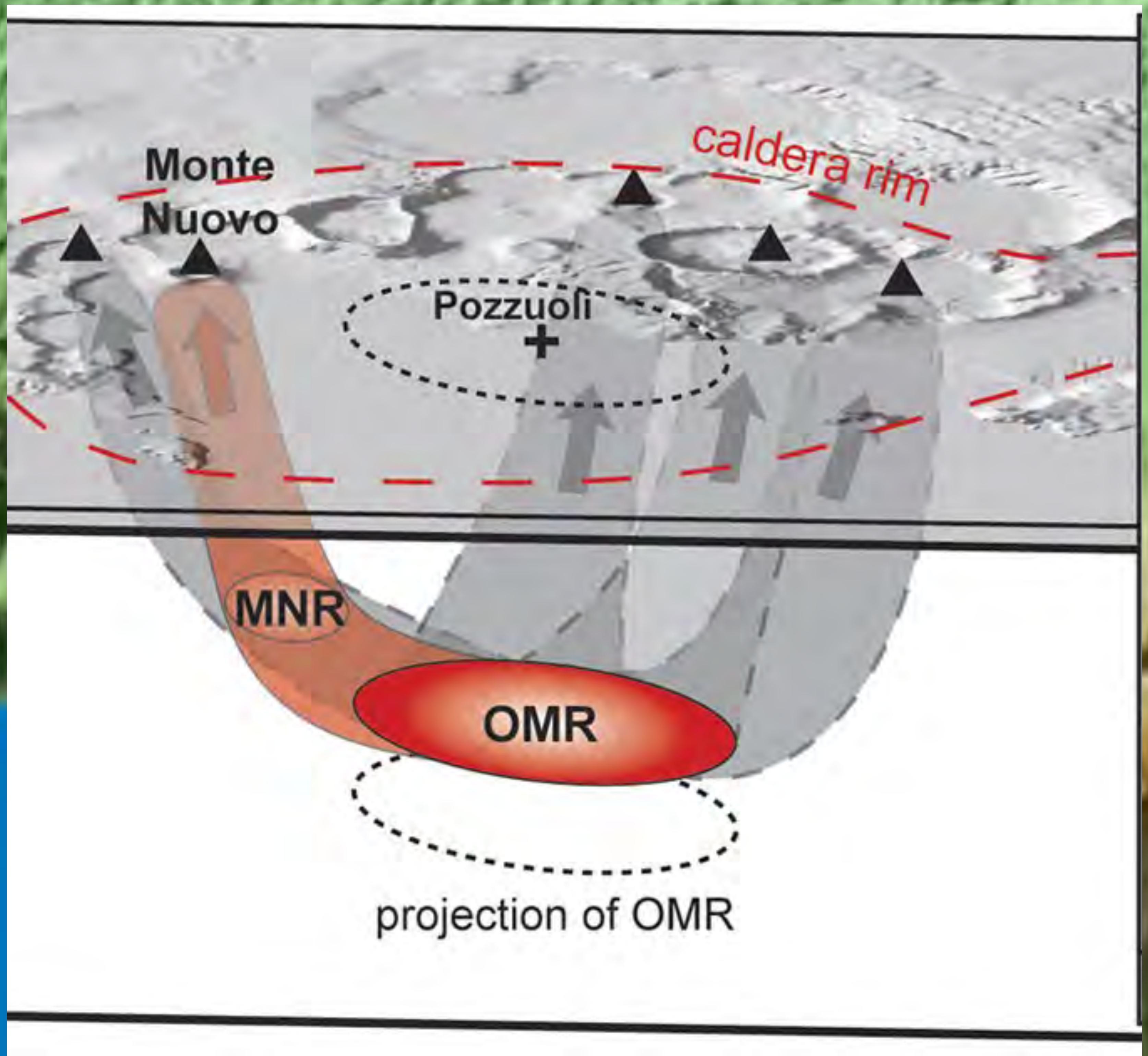
Armeni et al., 2025, accepted

Surface unloading: calderas

Magma “petals” for calderas



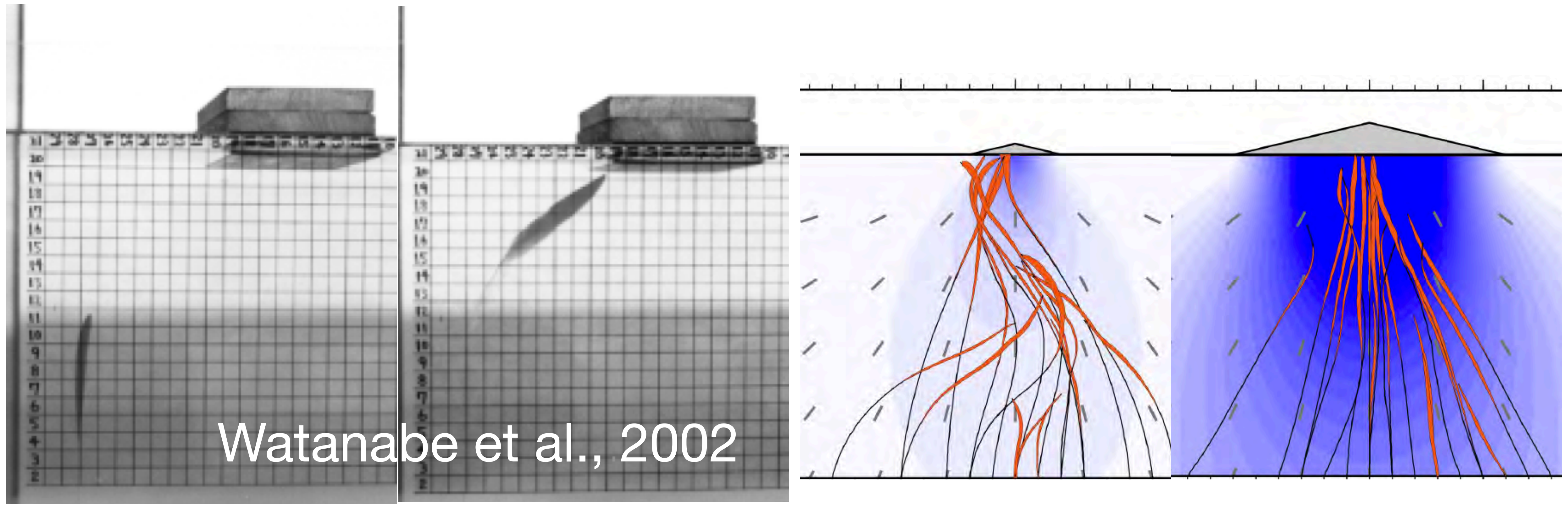
Rivalta et al. (2019)
modified from Smith et al., 2011



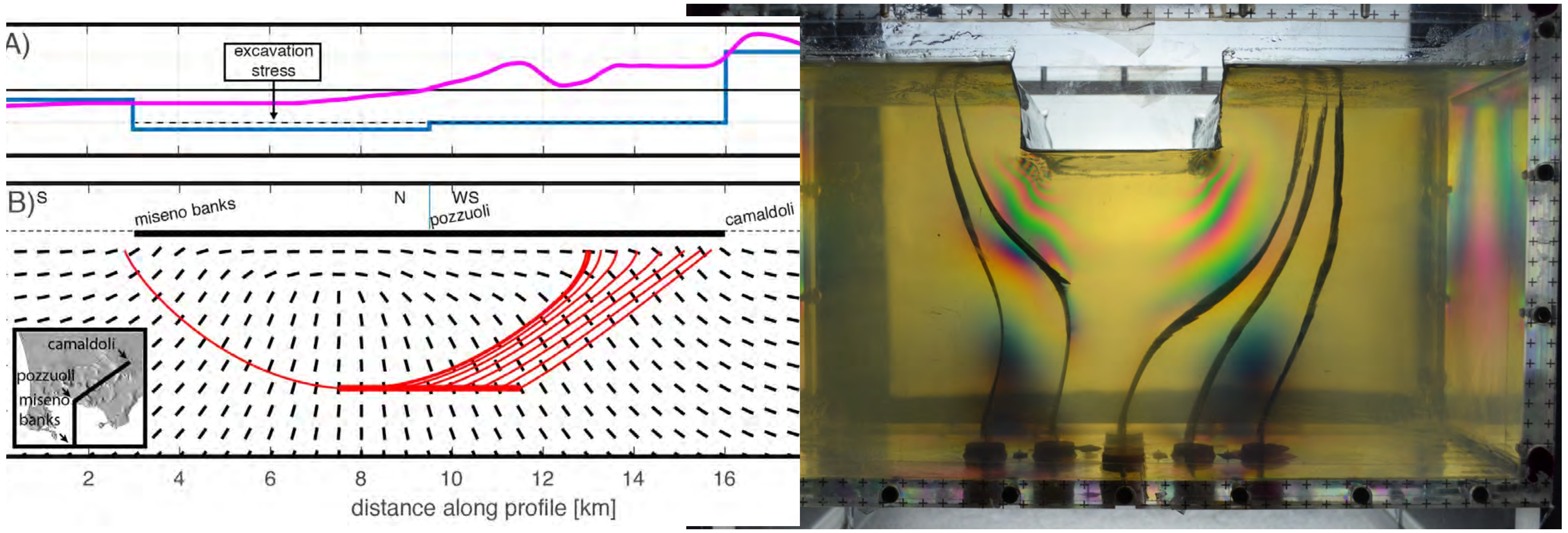
Di Vito et al., 2016

Surface loading

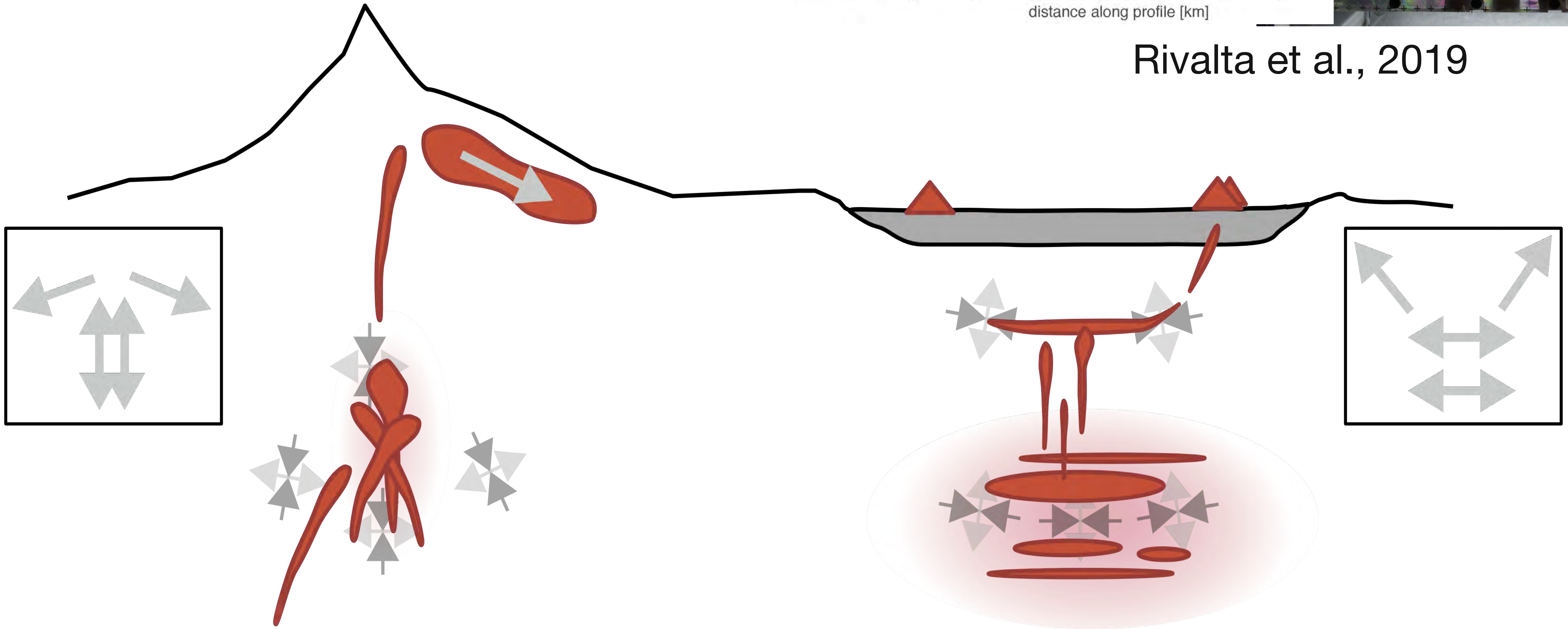
Surface unloading



Watanabe et al., 2002



Rivalta et al., 2019

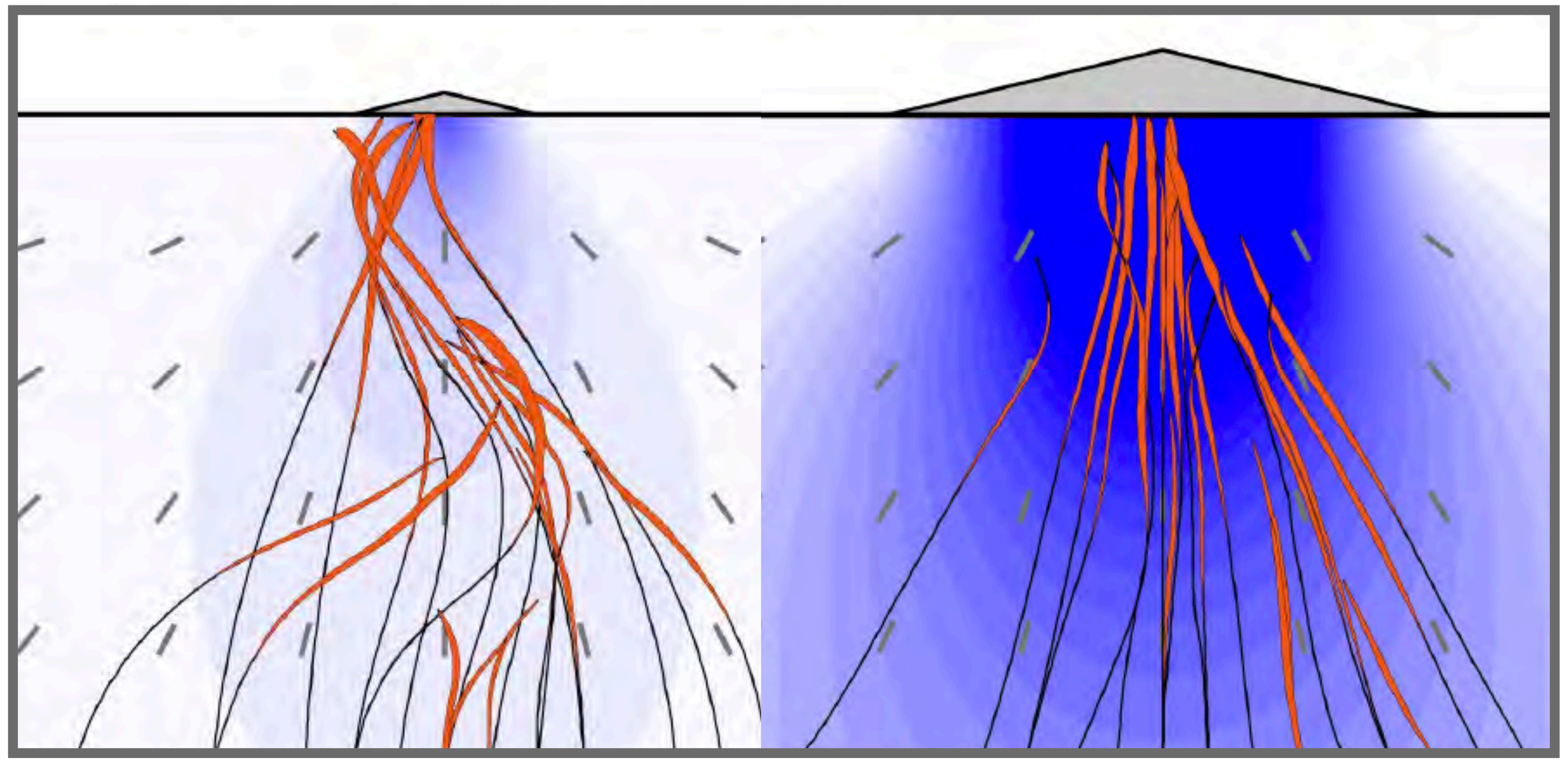


Stress traps

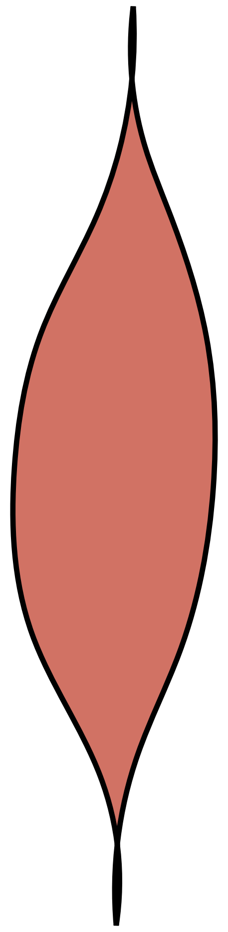
Rivalta and Chamberlain, under review

Stress traps for ascending magmas

Dahm, 2000, Pinel and Jaupart, 2000,
Watanabe et al., 2002, Kervyn et al., 2009,
Maccaferri et al. 2011



Vertical trapping



Buoyancy overridden by topographic loading
compressing dike upper tip

Stress traps for ascending magmas

Dahm, 2000, Pinel and Jaupart, 2000,
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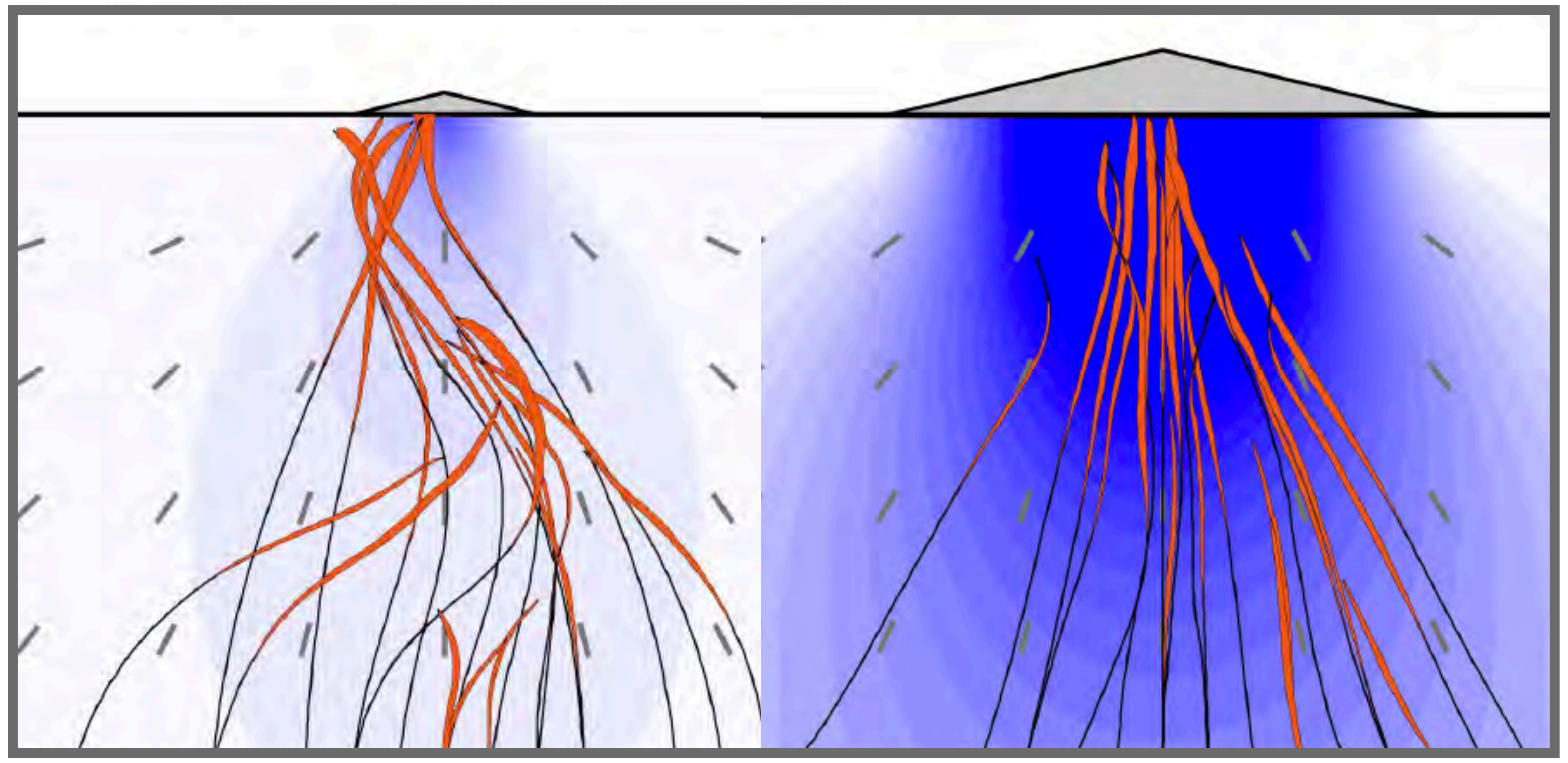
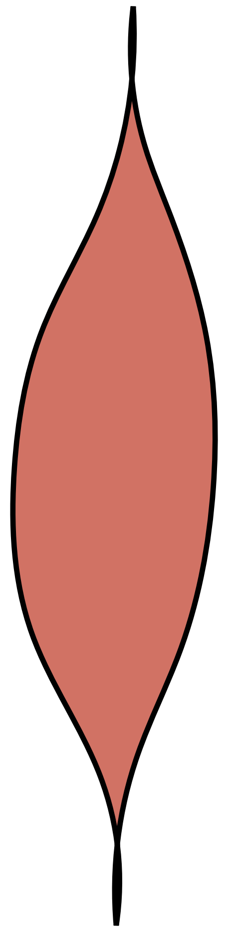


Vertical trapping

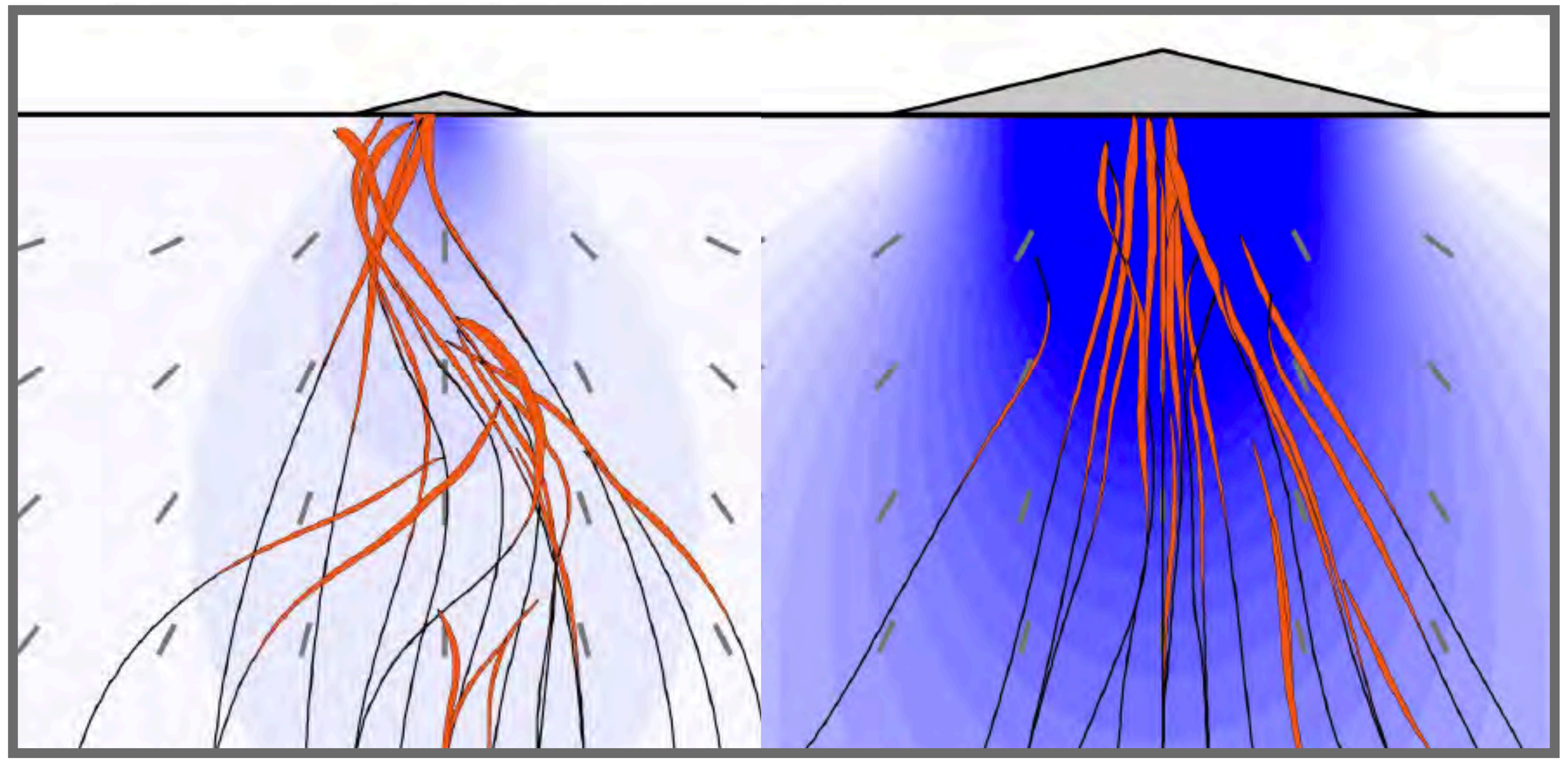


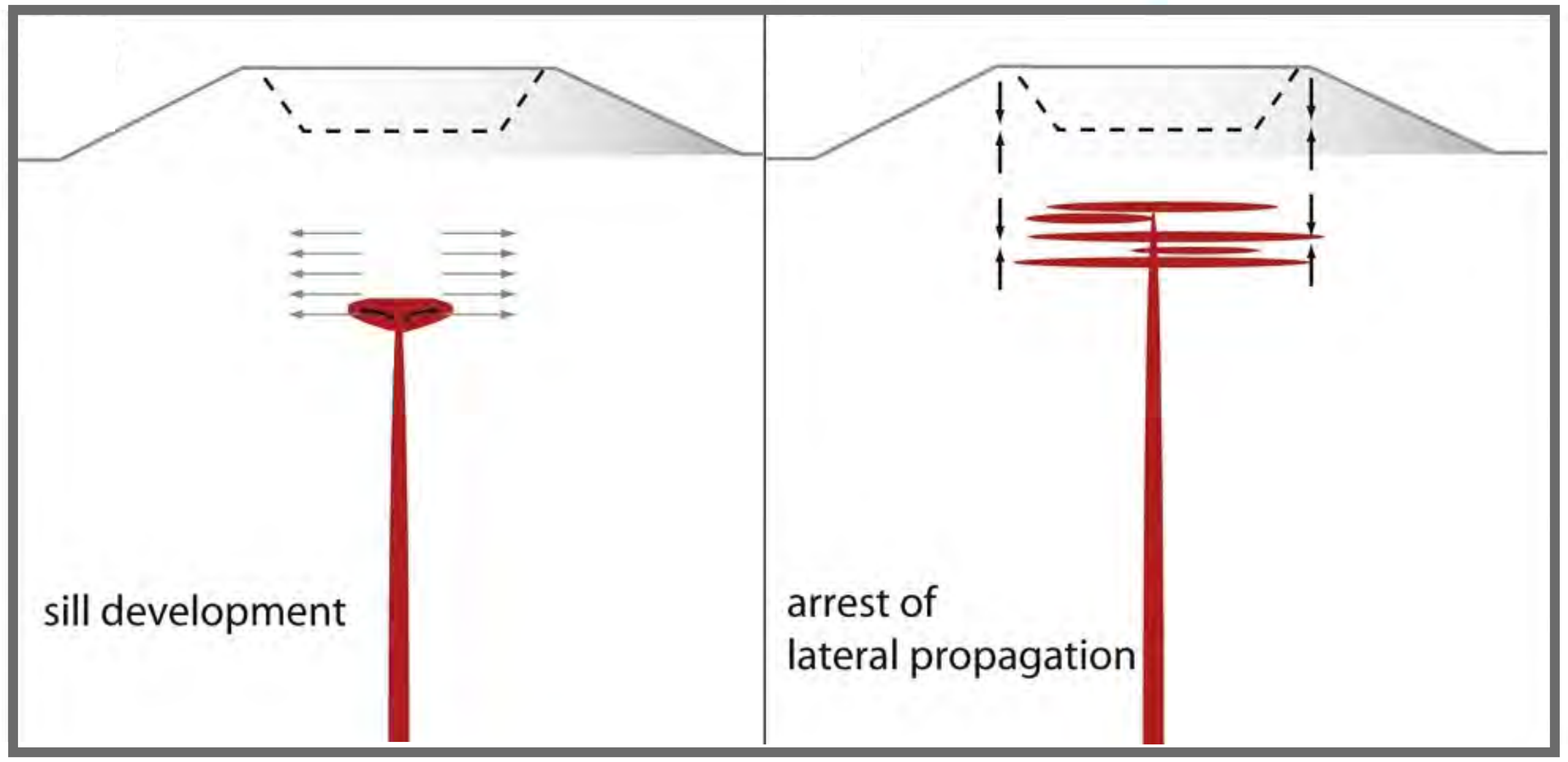
Buoyancy overridden by topographic loading
compressing dike upper tip
Escape factor:
develop buoyancy, magma chamber pressure

Stress traps for ascending magmas

Dahm, 2000, Pinel and Jaupart, 2000, Watanabe et al., 2002, Kervyn et al., 2009, Maccaferri et al. 2011

Maccaferri et al., 2014
Corbi et al., 2015, 2016





Vertical trapping

Buoyancy overridden by topographic loading compressing dike upper tip
Escape factor:
develop buoyancy, magma chamber pressure

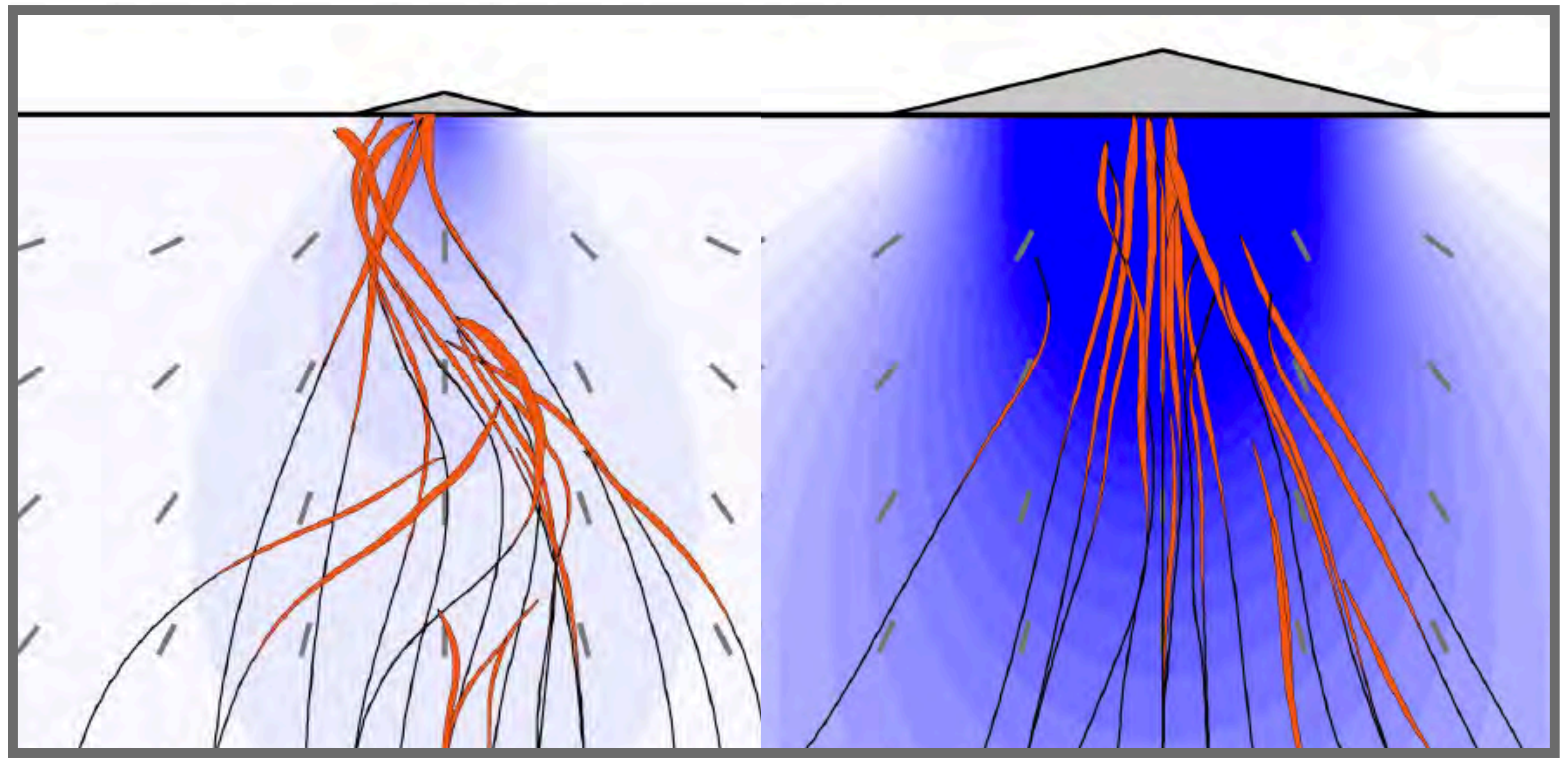
Horizontal trapping

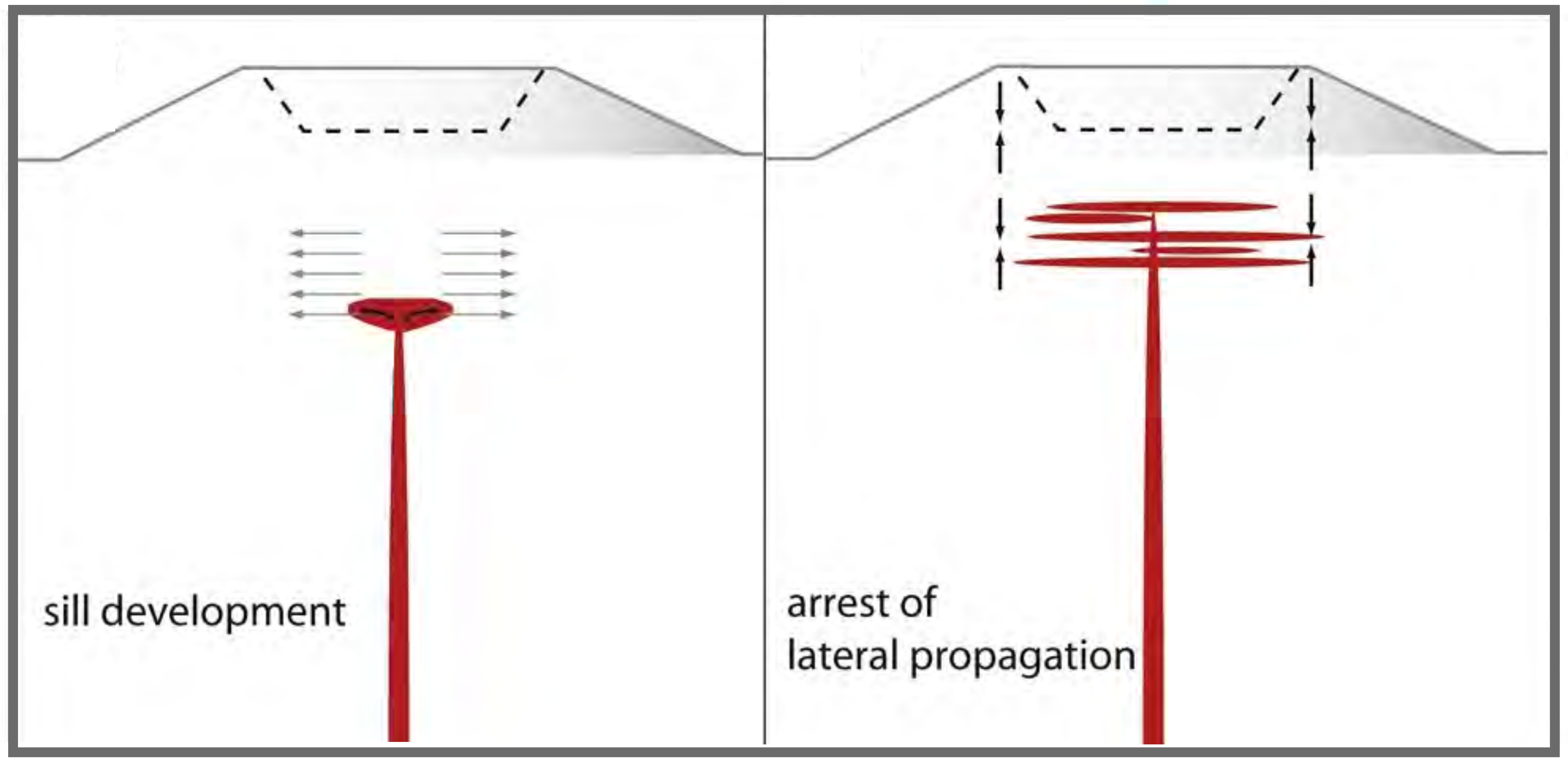
Buoyancy canceled by stress forcing dike to turn into a sill
Escape factor:
supply more volume to escape laterally

Stress traps for ascending magmas

Dahm, 2000, Pinel and Jaupart, 2000, 2004
Watanabe et al., 2002, Kervyn et al., 2009,
Maccaferri et al. 2011

Maccaferri et al., 2014
Corbi et al., 2015, 2016





- Potential for more mixing, more assimilation
- Interaction between successive magma batches

Trapping by crystallization

$$v_{UP} \approx \frac{\Delta\rho^2 V}{\mu\eta} \quad for \quad V > V_c$$

(Further simplified from Davis et al., 2023)

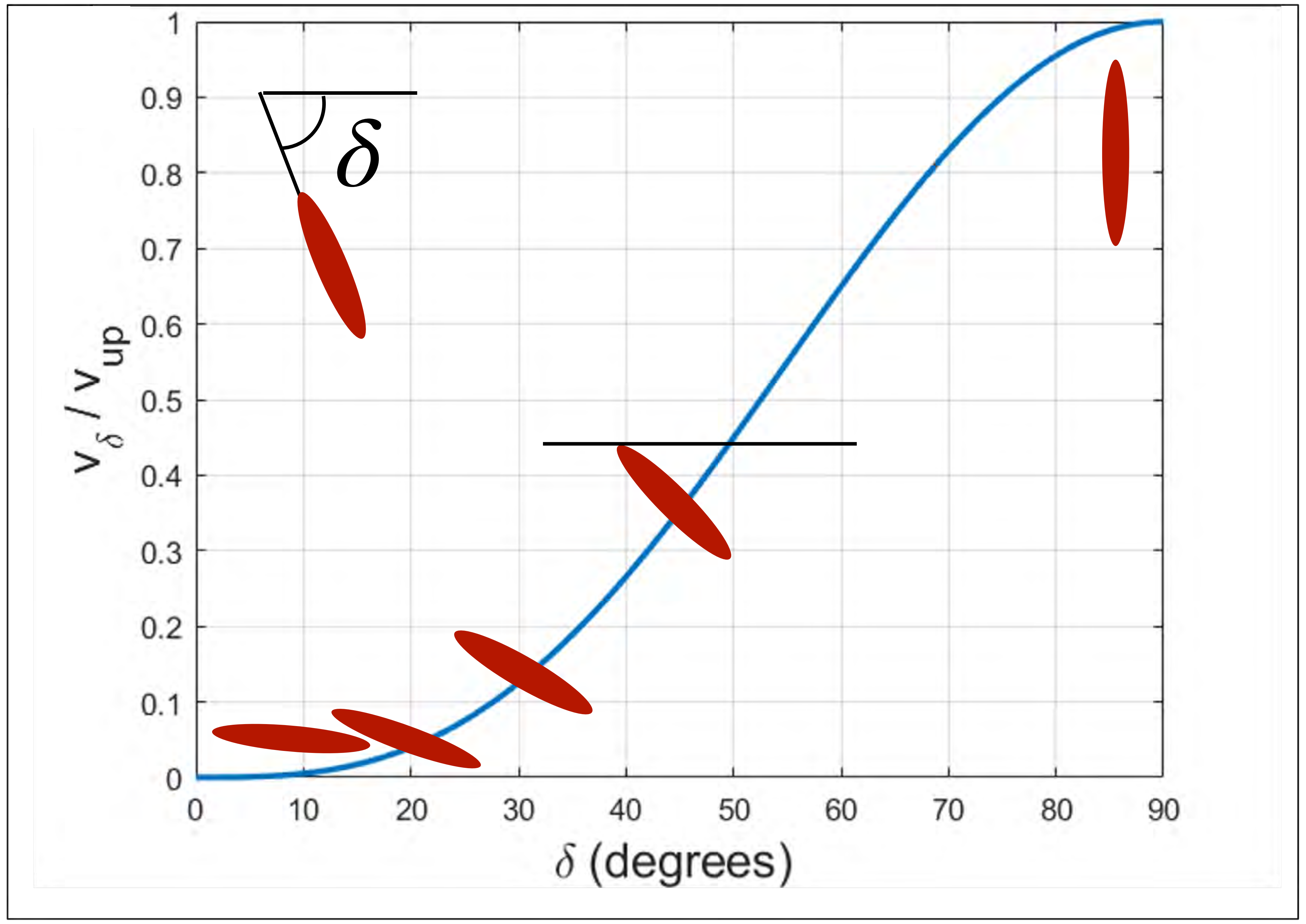
Viscosity increase during ascent
can also lead to trapping

Trapping by crystallization

$$v_{UP} \approx \frac{\Delta\rho^2 V}{\mu\eta} \quad for \quad V > V_c$$

(Further simplified from Davis et al., 2023)

$$v_\delta = v_{UP} \sin^3 \delta$$

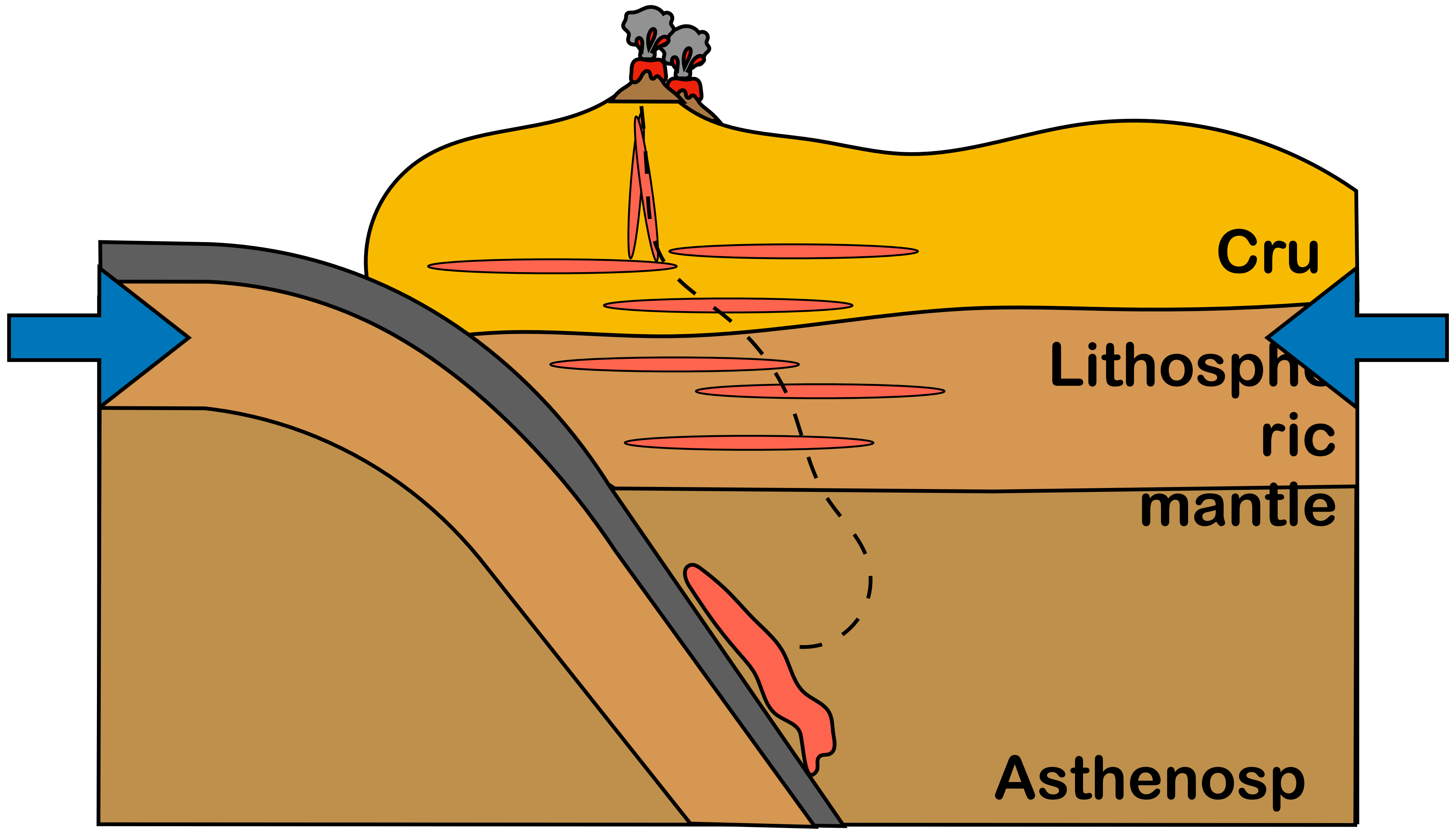


Viscosity increase during ascent
can also lead to trapping

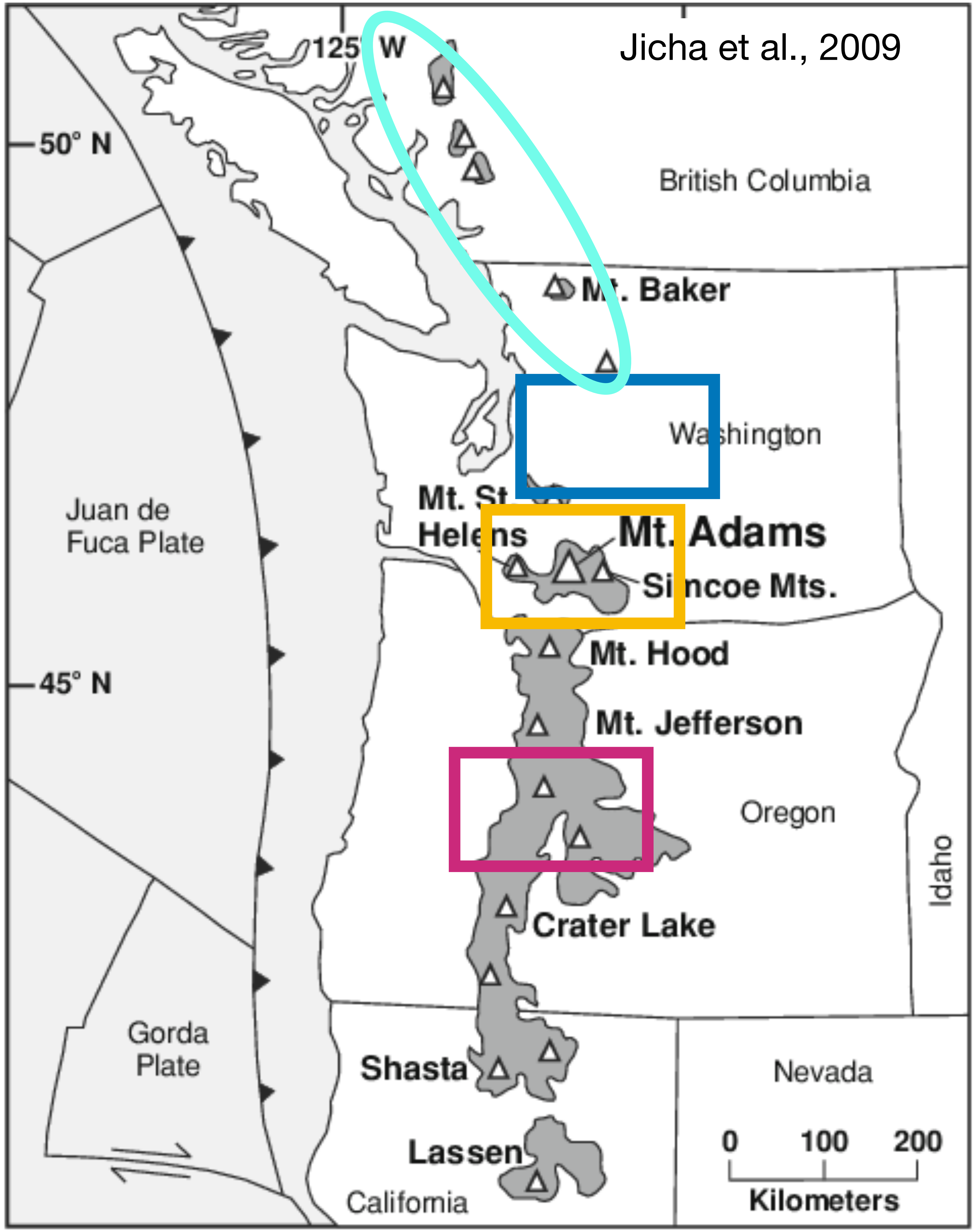
Stress trapping and degassing/crystallization
conspire to trap the magmas!

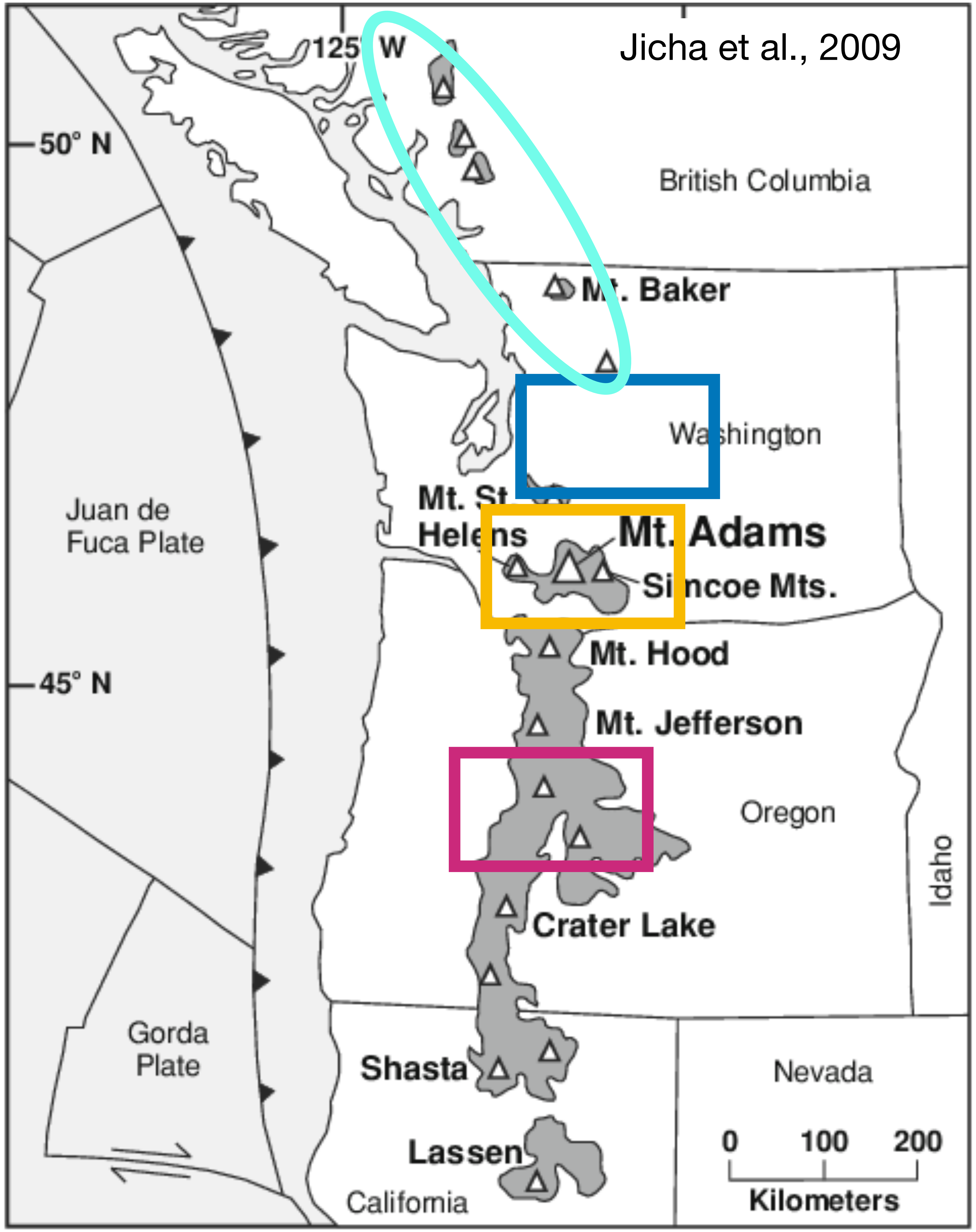
Application
Volcanic arcs

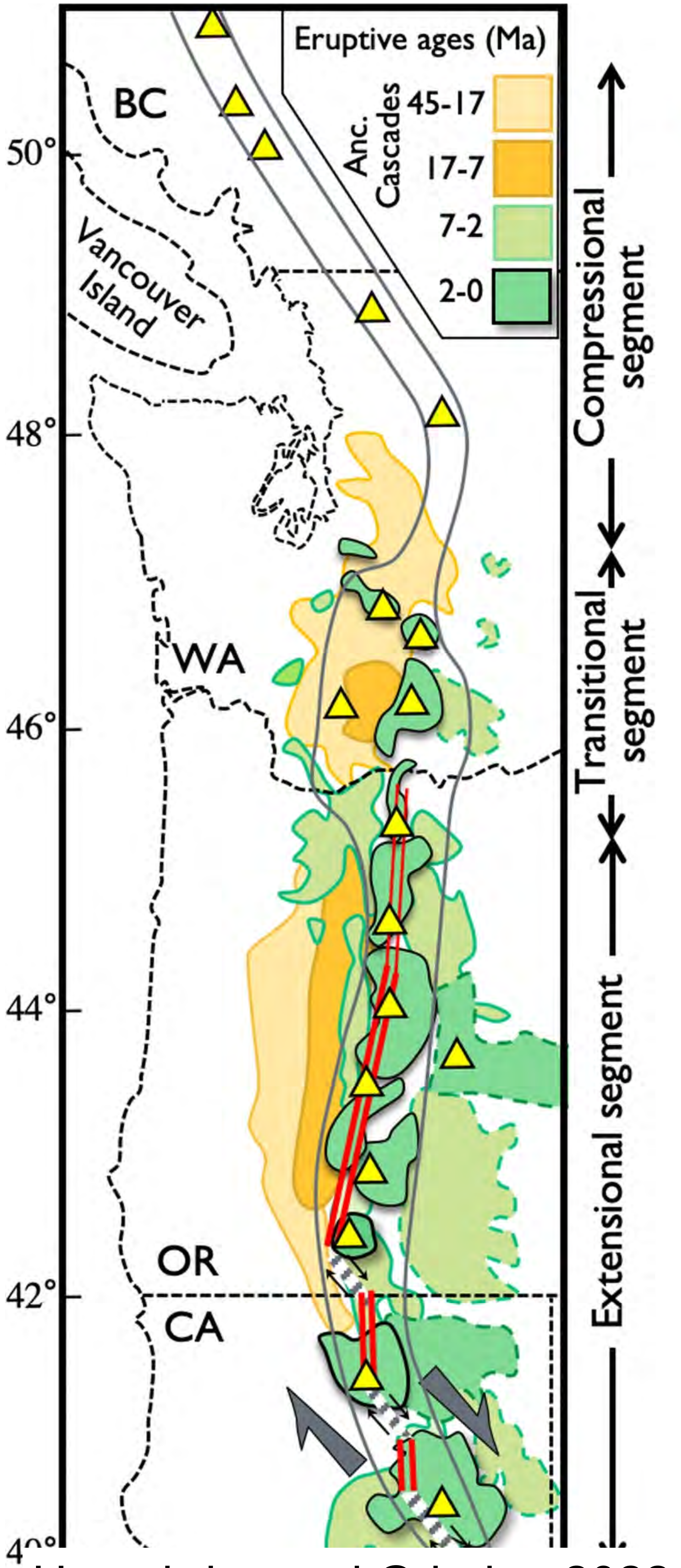
Rivalta and Chamberlain, under review



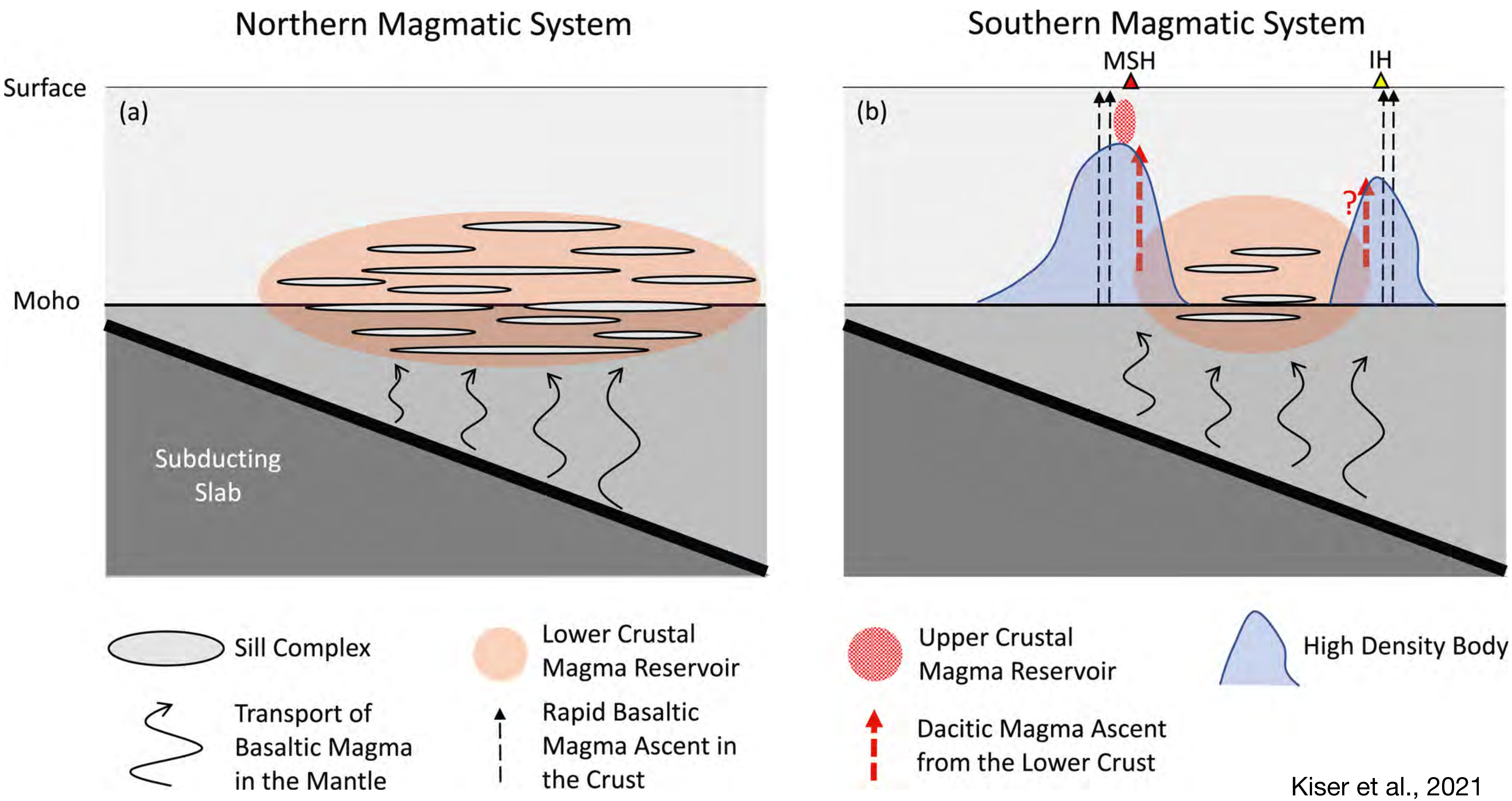
CASCADES ARC: eruptive patterns



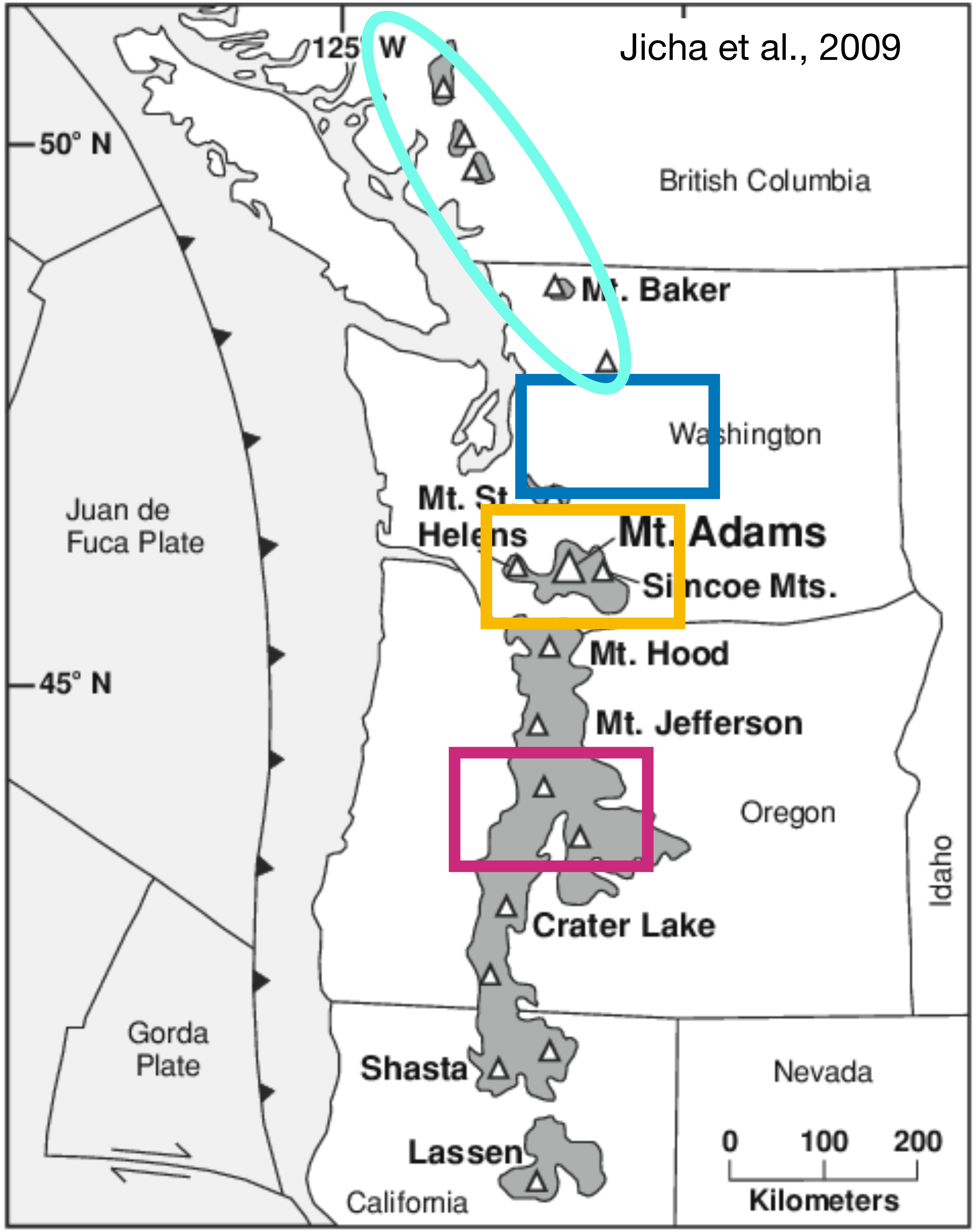




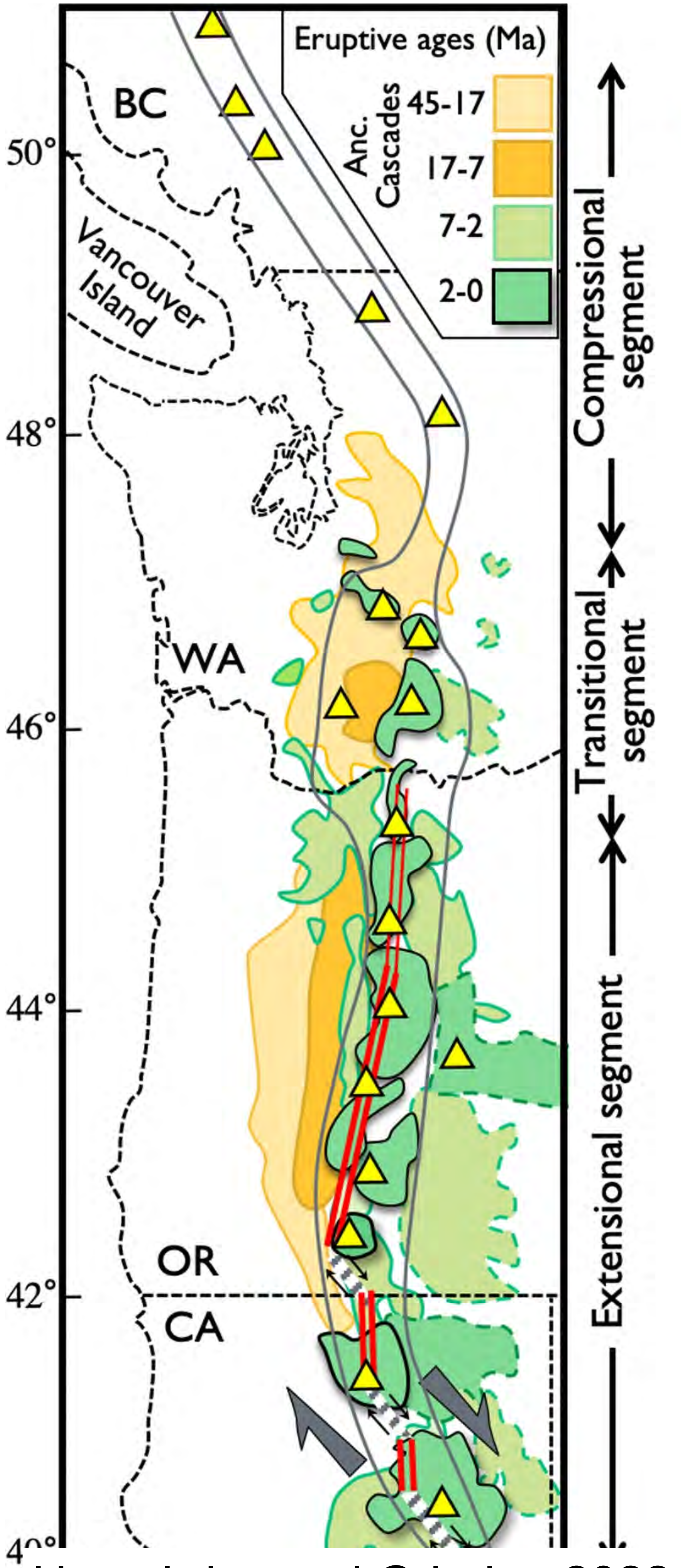
Humphries and Grinder, 2022



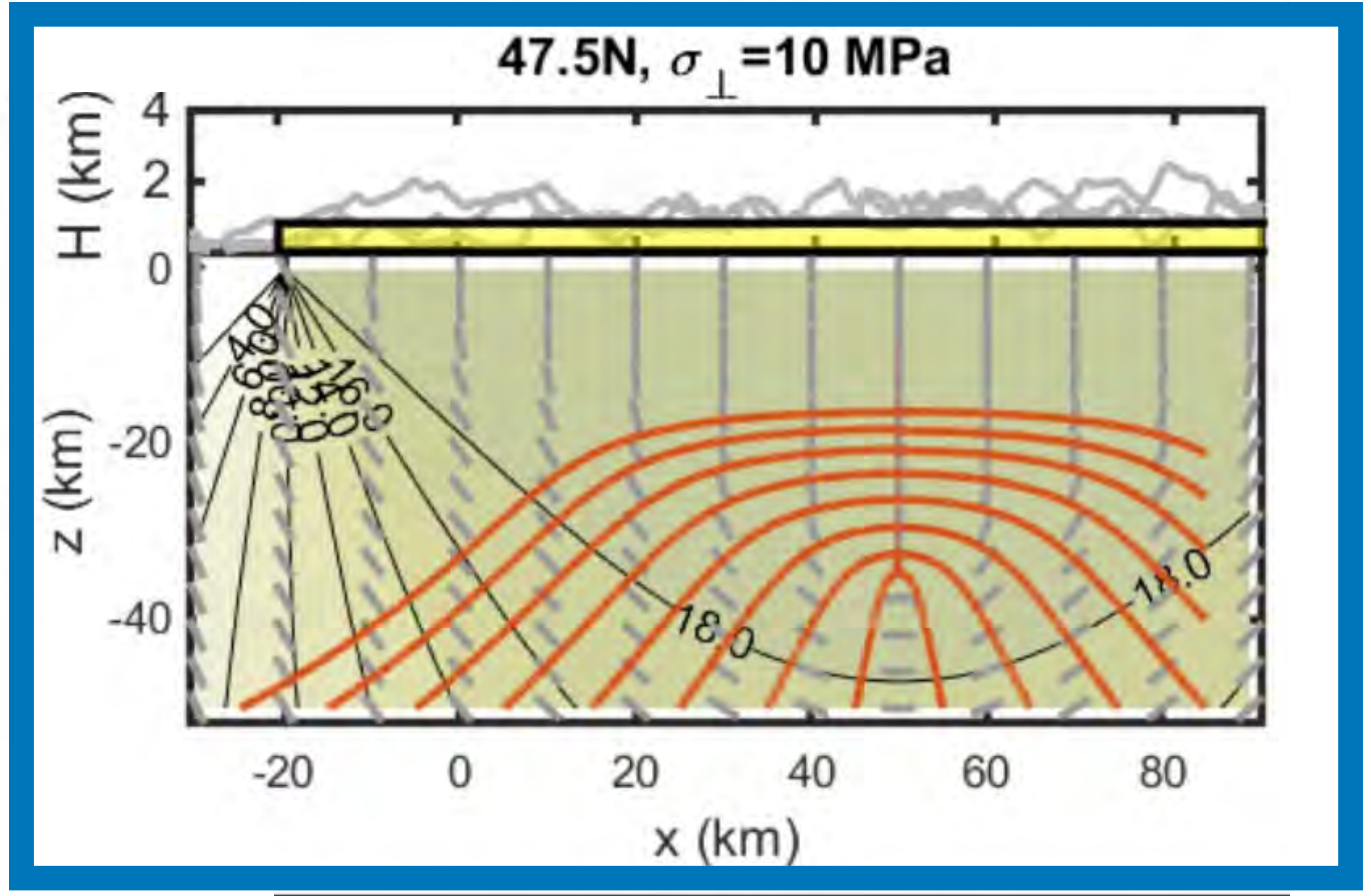
Kiser et al., 2021

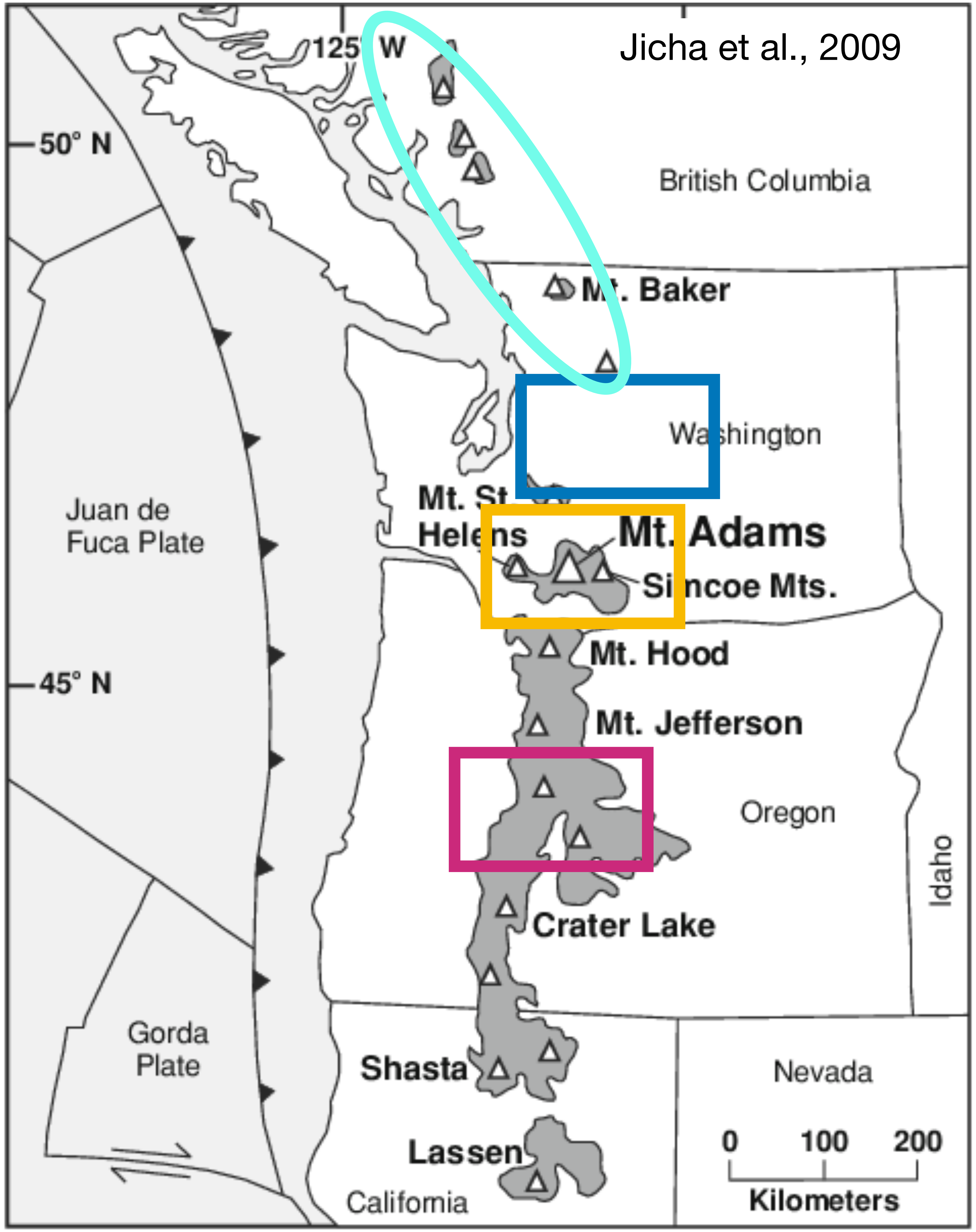


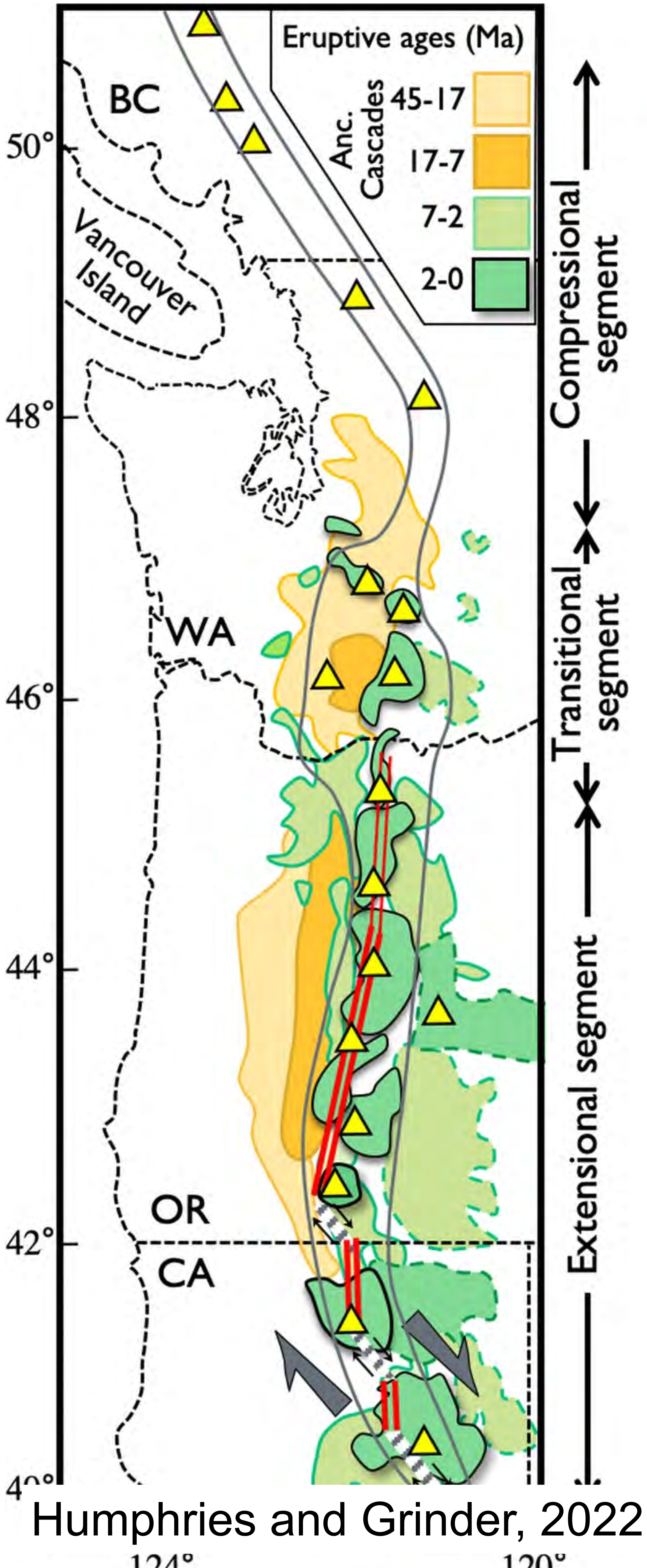
Jicha et al., 2009



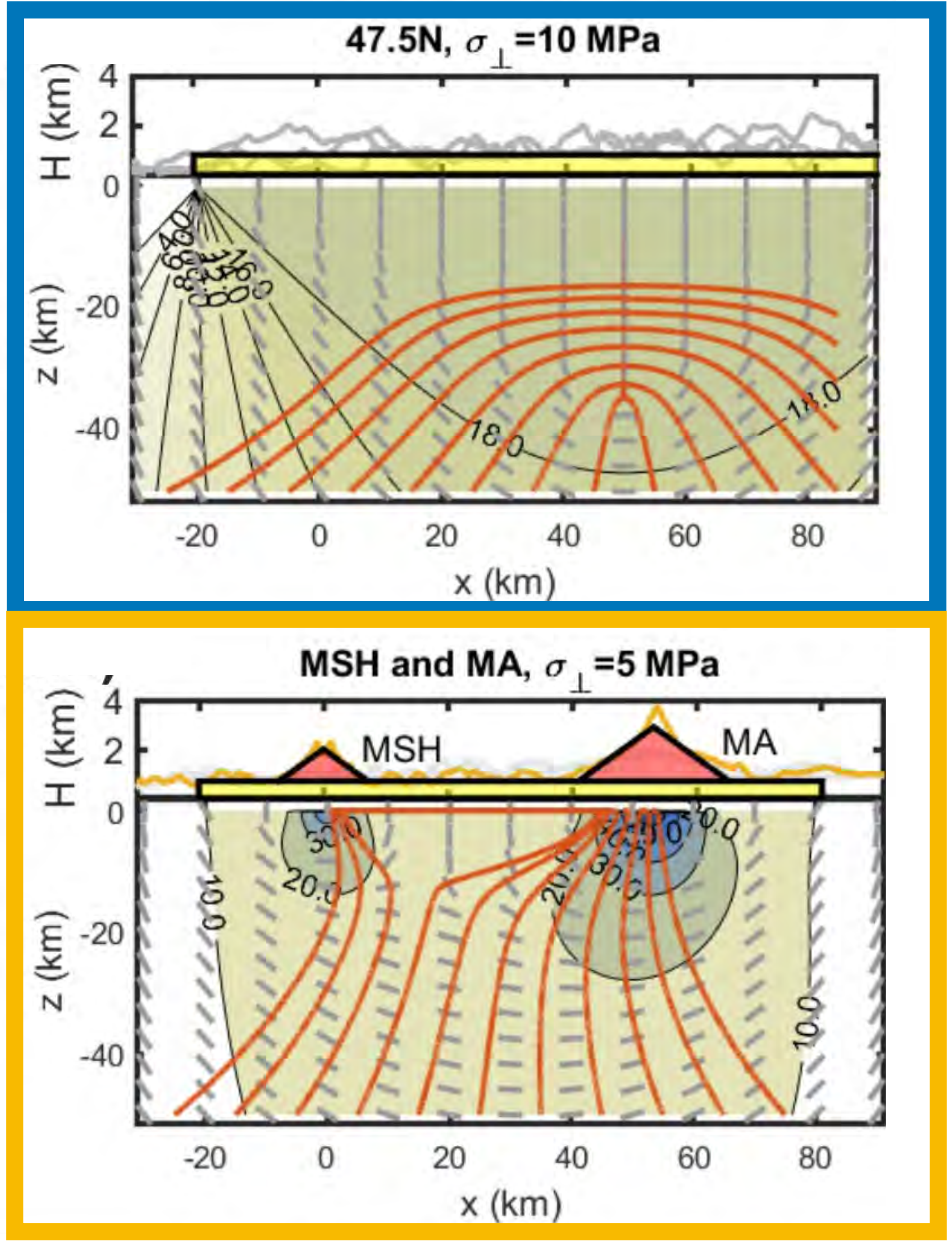
Humphries and Grinder, 2022

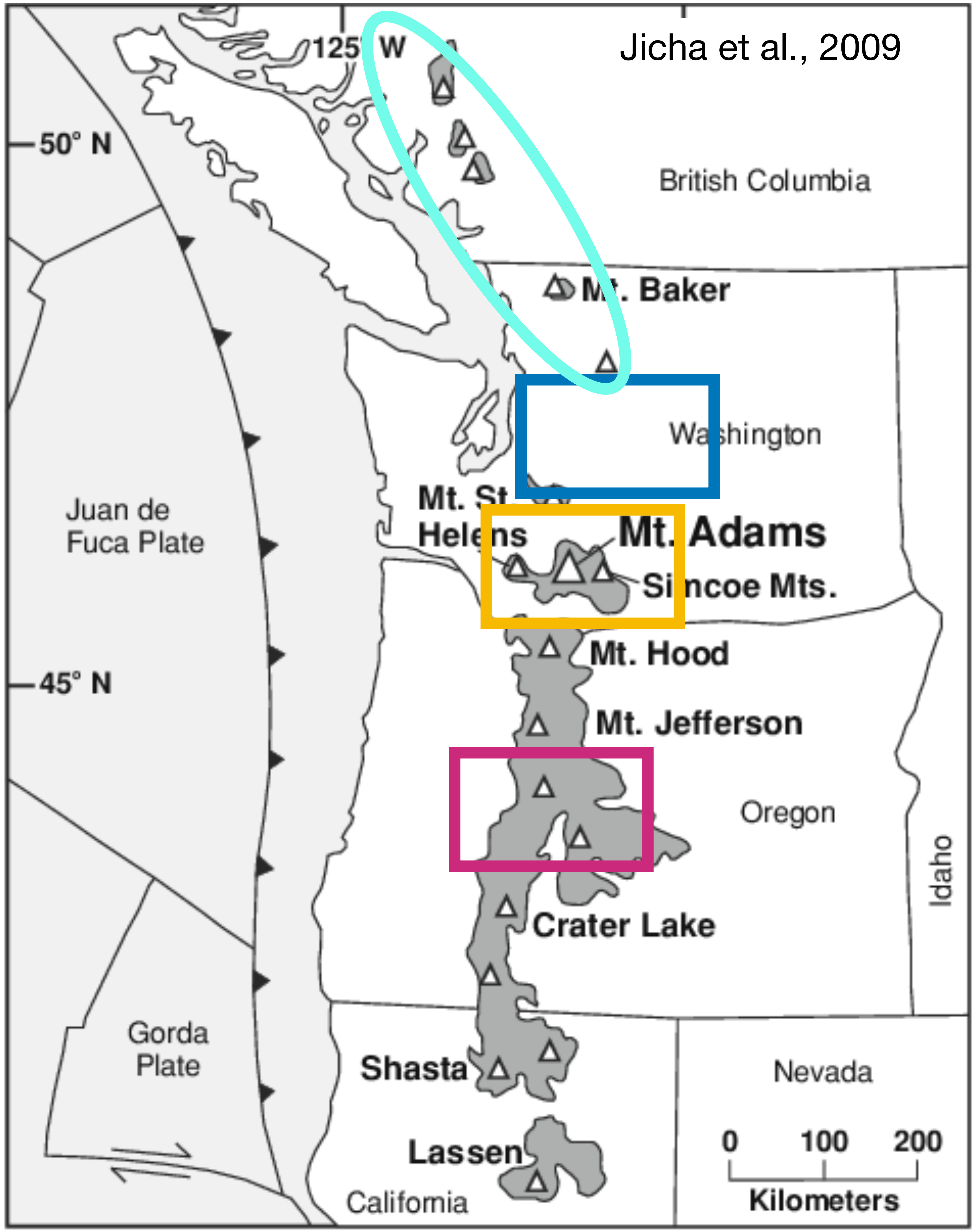


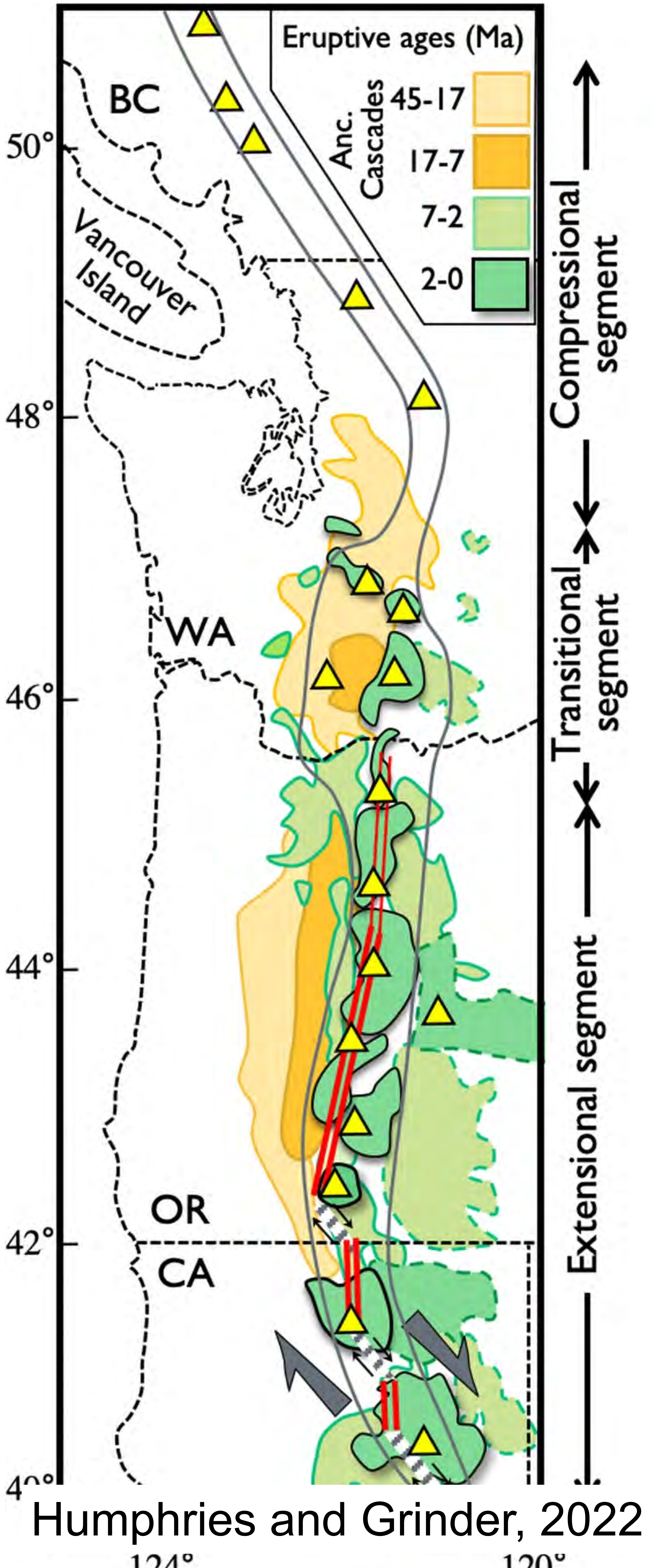


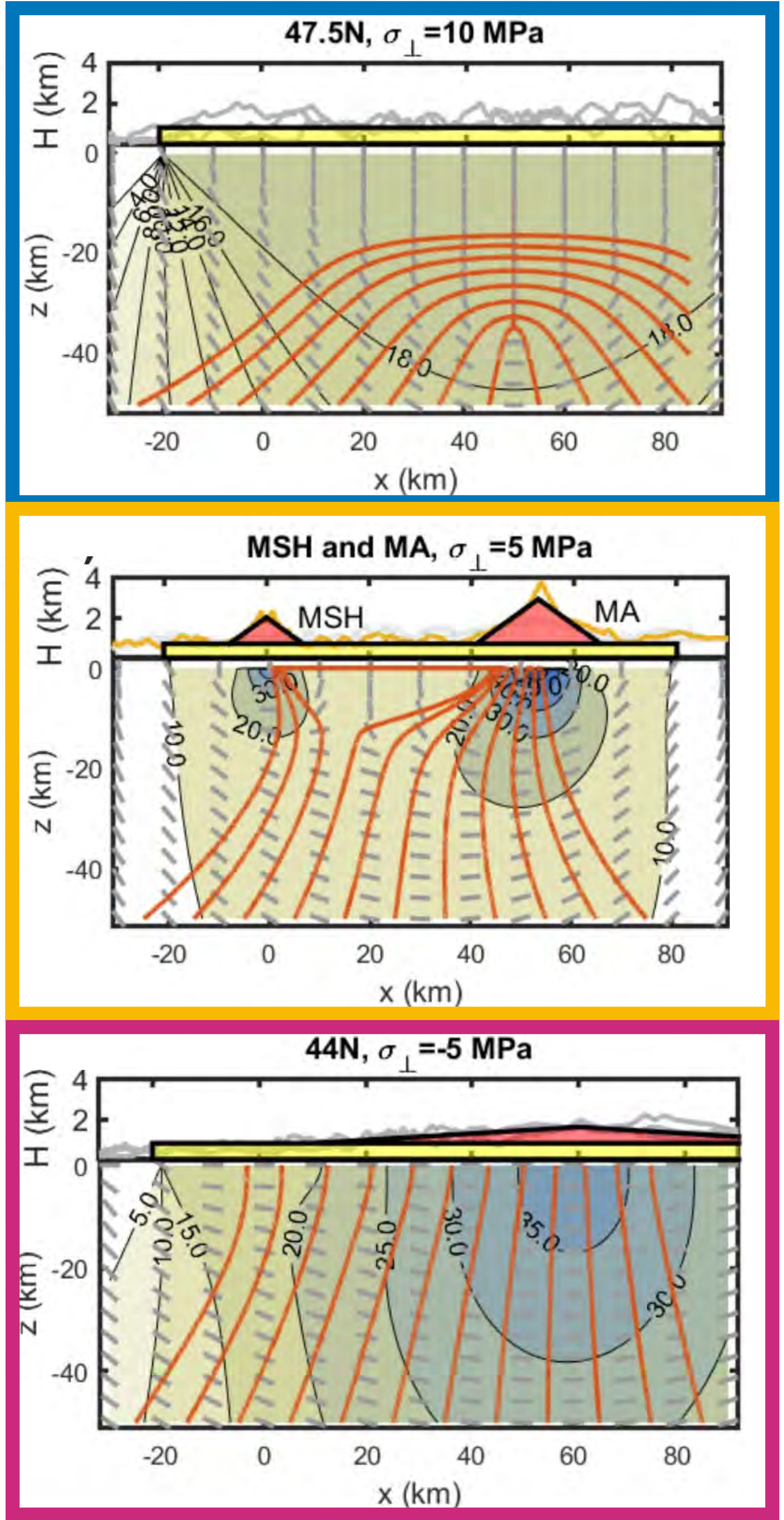


Humphries and Grinder, 2022

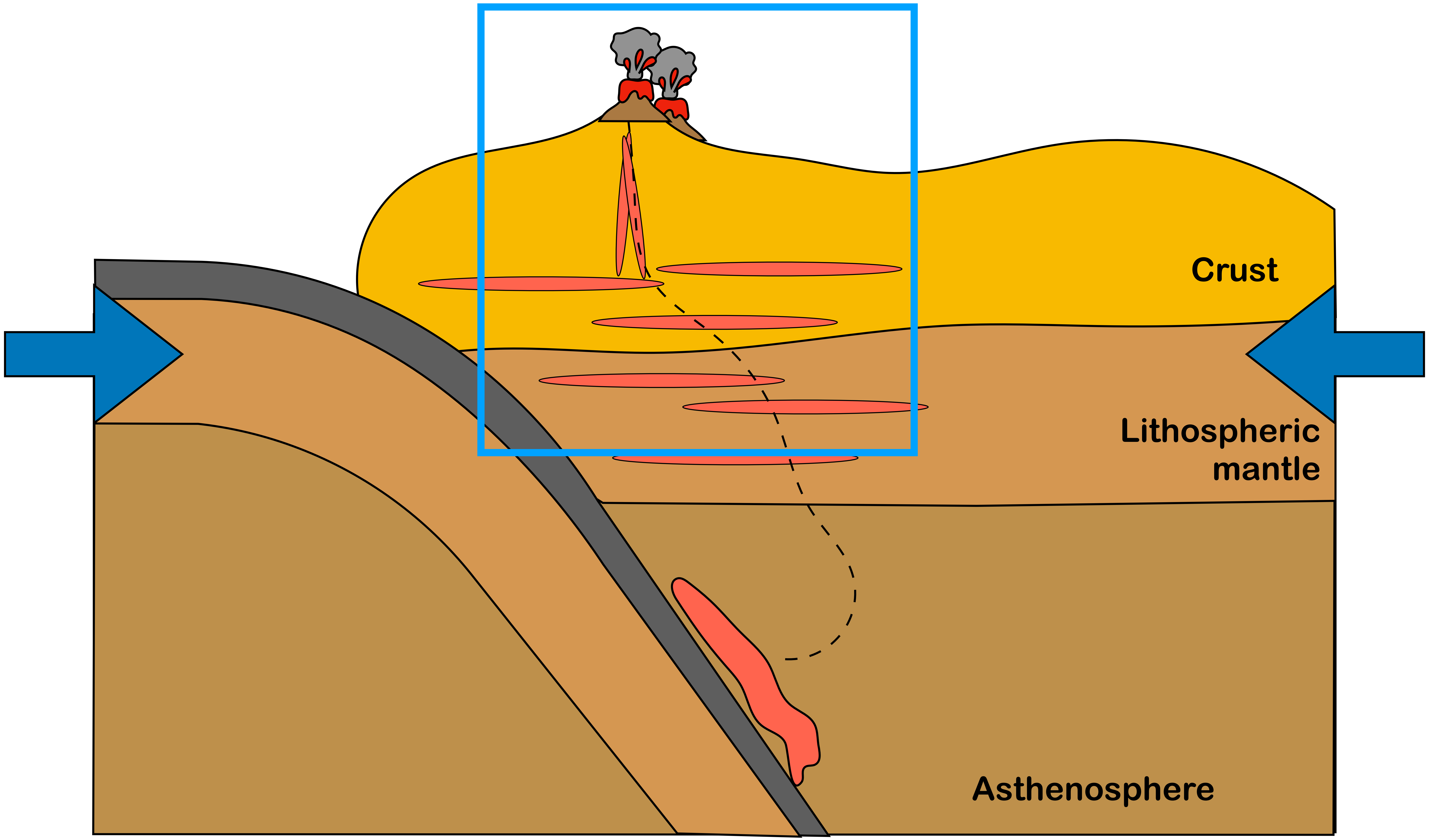



Jicha et al., 2009
125° W
50° N
45° N
British Columbia
Mt. Baker
Washington
Mt. St Helens
Mt. Adams
Simcoe Mts.
Mt. Hood
Mt. Jefferson
Oregon
Crater Lake
Shasta
Lassen
Nevada
Idaho
California
Juan de Fuca Plate
Gorda Plate
0 100 200
Kilometers


Eruptive ages (Ma)
Anc. Cascades
45-17
17-7
7-2
2-0
BC
Vancouver Island
WA
OR
CA
50°
48°
46°
44°
42°
124°
120°
Compressional segment
Transitional segment
Extensional segment
Humphries and Grinder, 2022

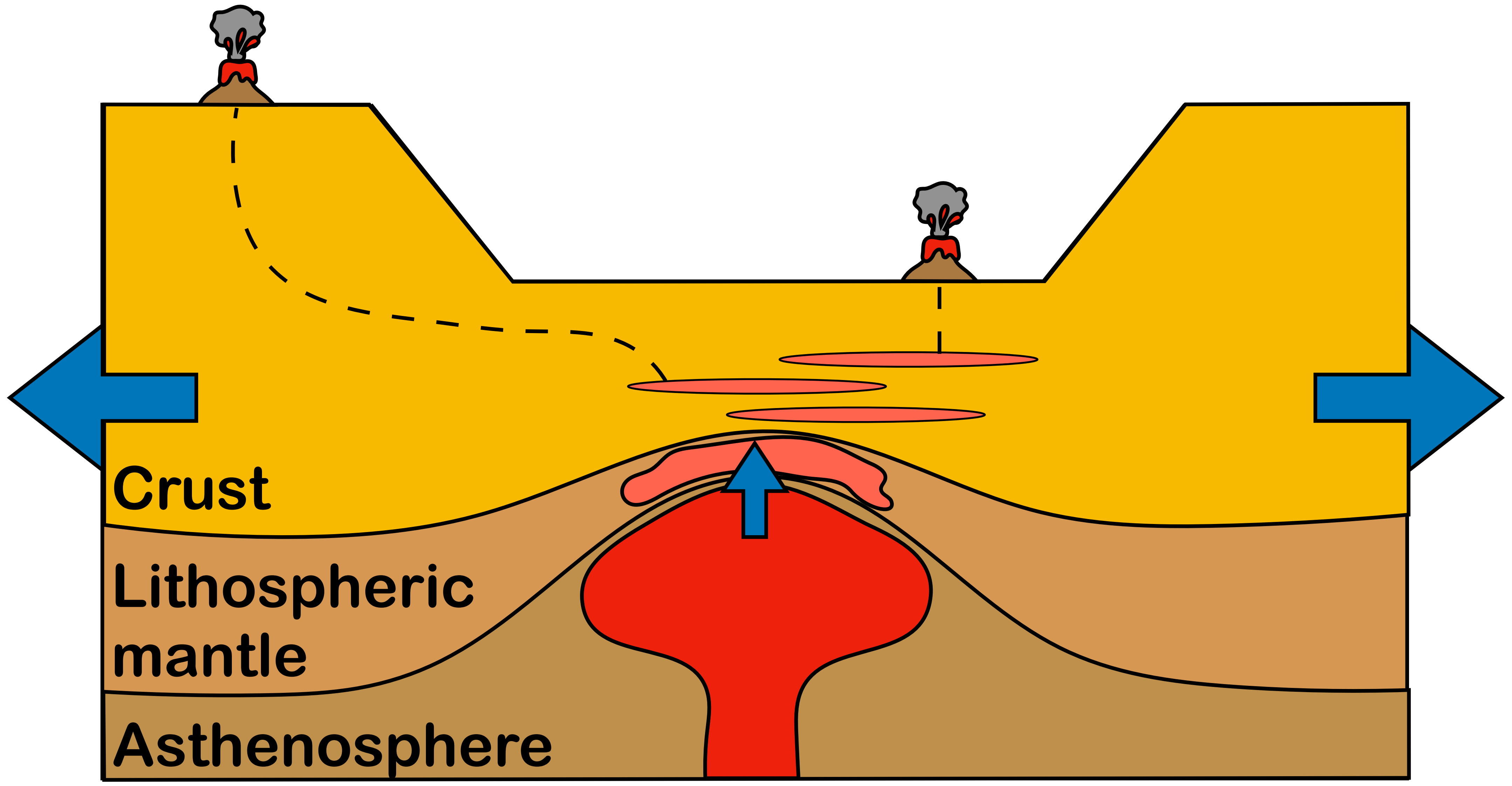

47.5N, σ⊥ =10 MPa
H (km)
z (km)
x (km)
MSH and MA, σ⊥ =5 MPa
MSH
MA
44N, σ⊥ =-5 MPa

Arc volcanism:
Tectonic compression + formation of topographic loads

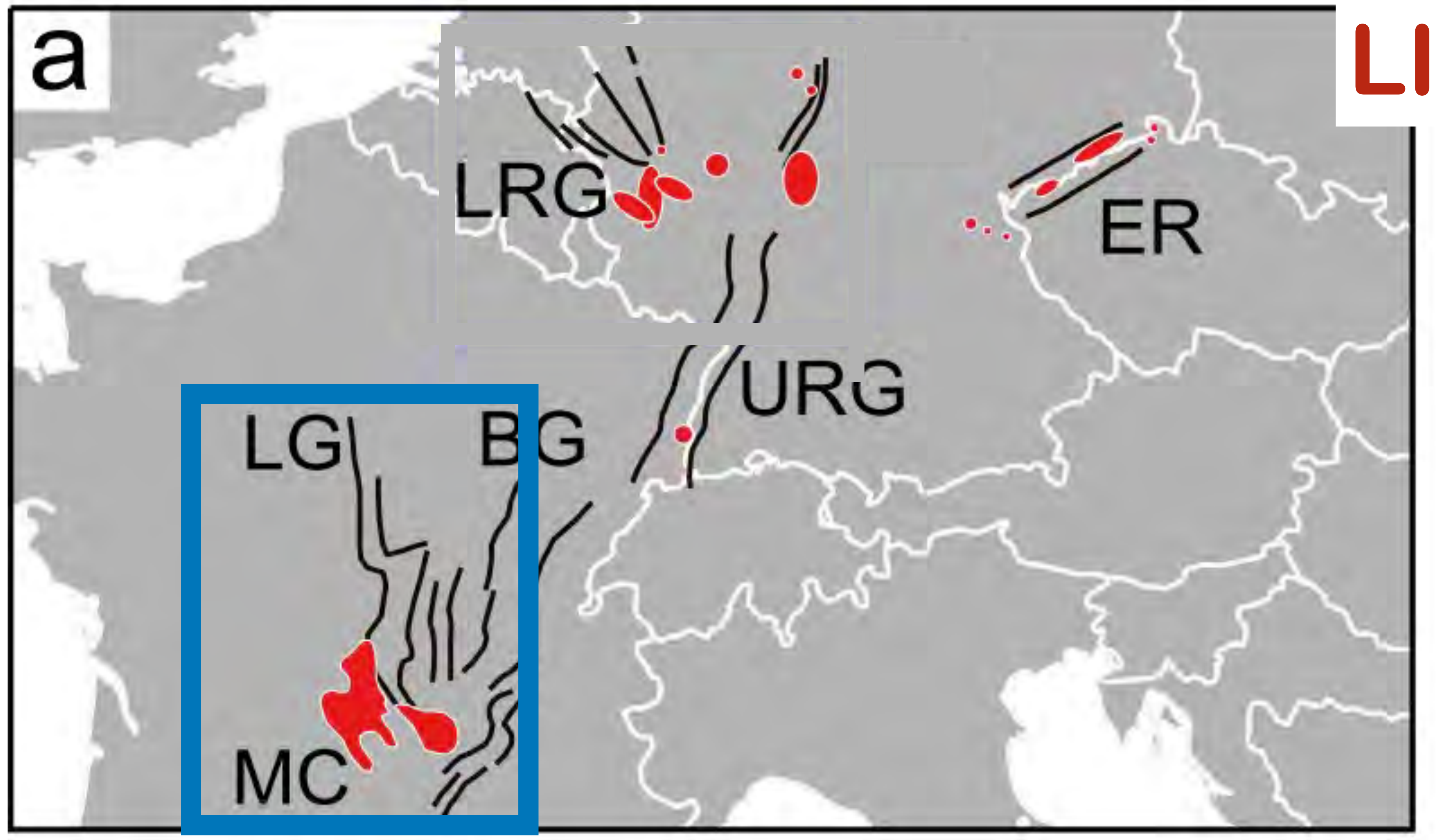


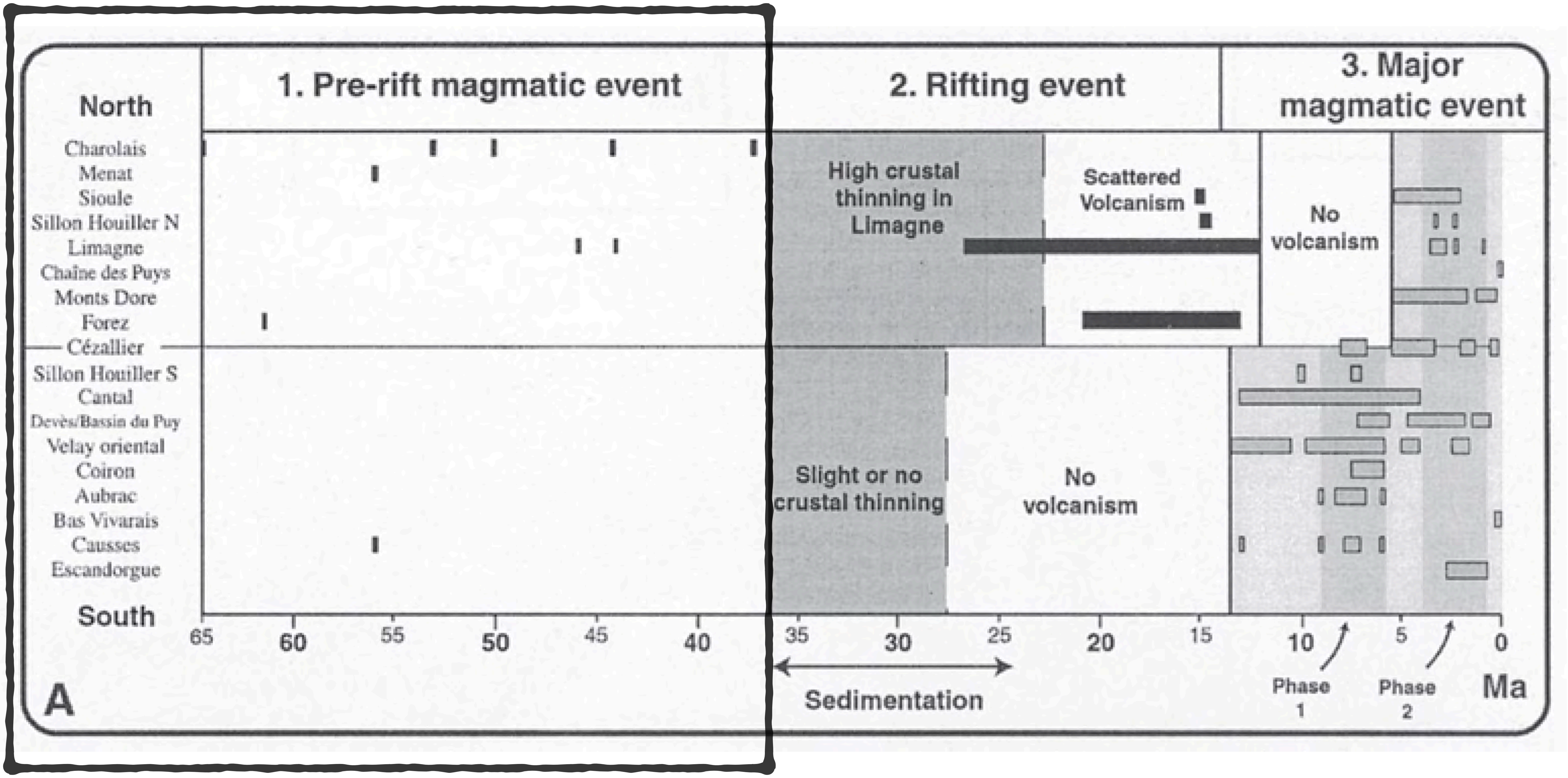
Application:
Continental rifts

Rivalta and Chamberlain, submitted



LIMAGNE GRABEN

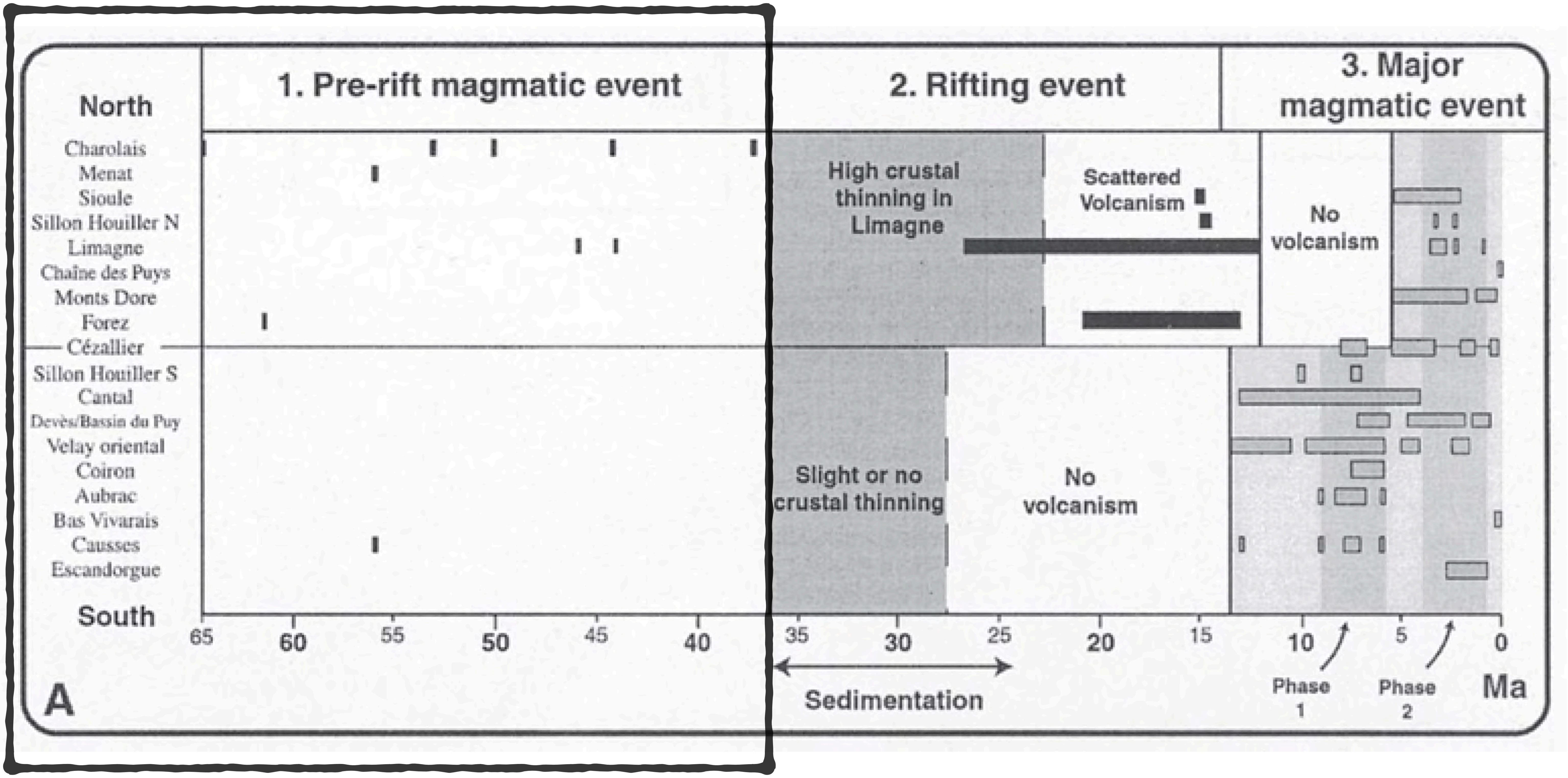


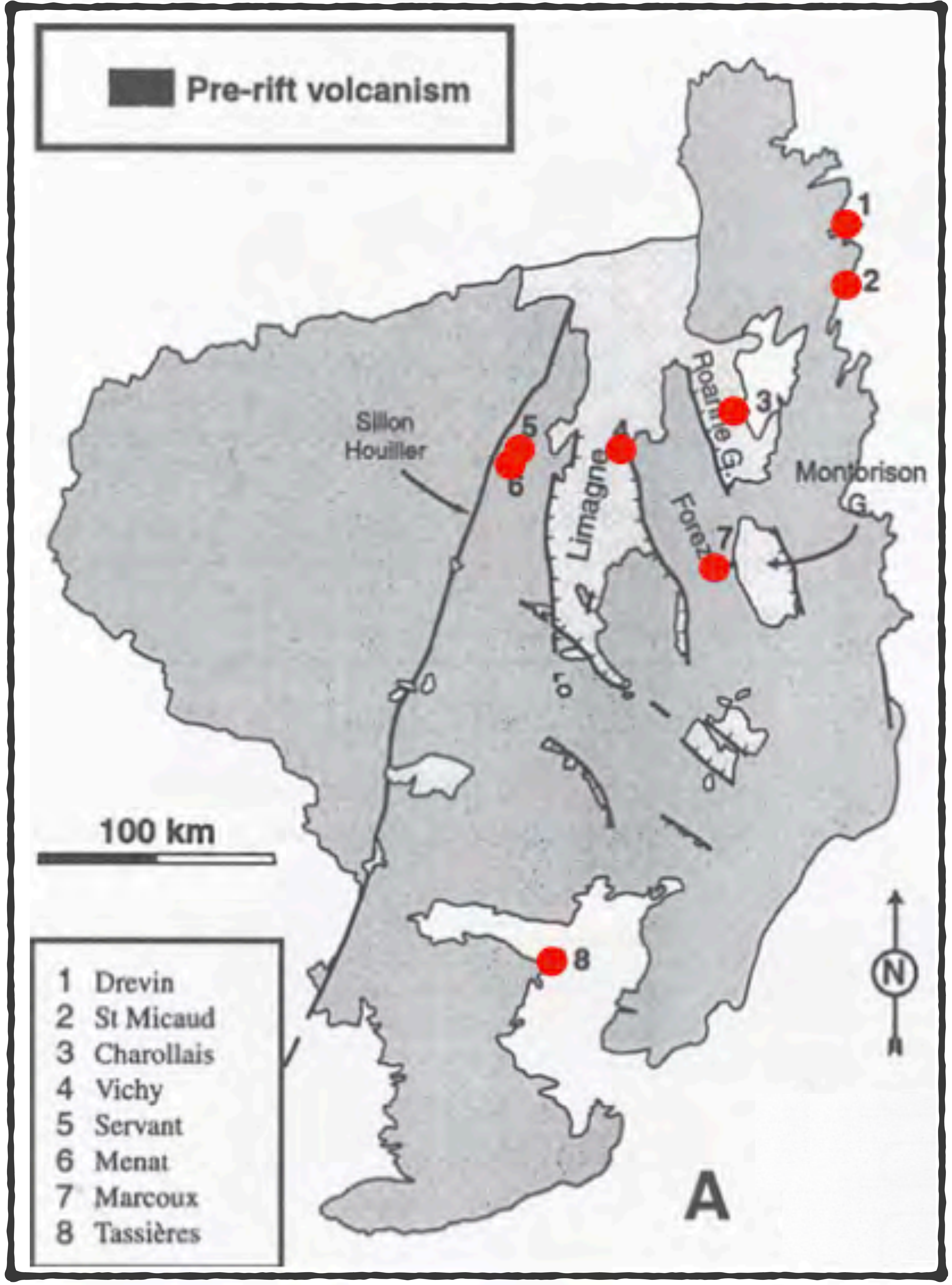


Modified from Michon and Merle, 2001

LIMAGNE GRABEN

Pre-rift: Widespread, spotty volcanism



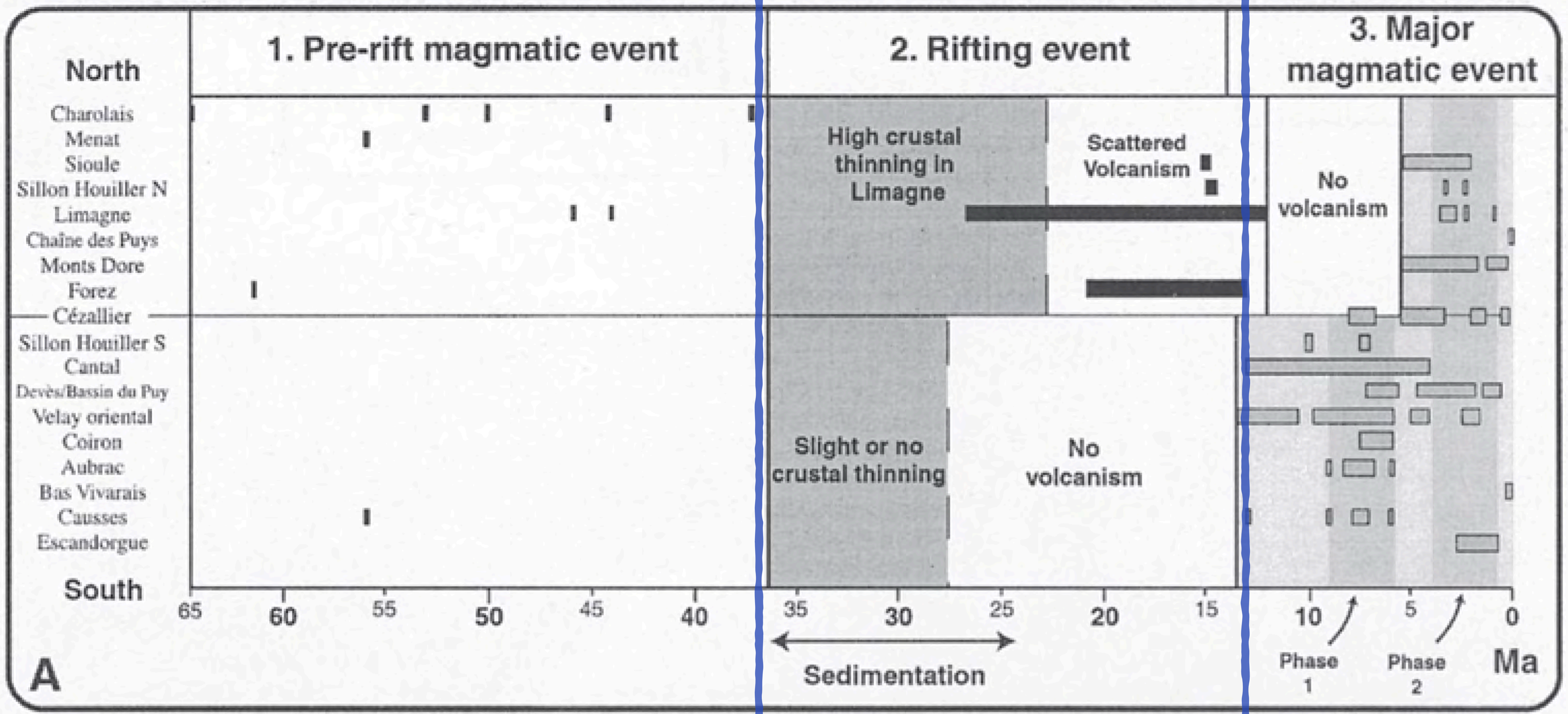


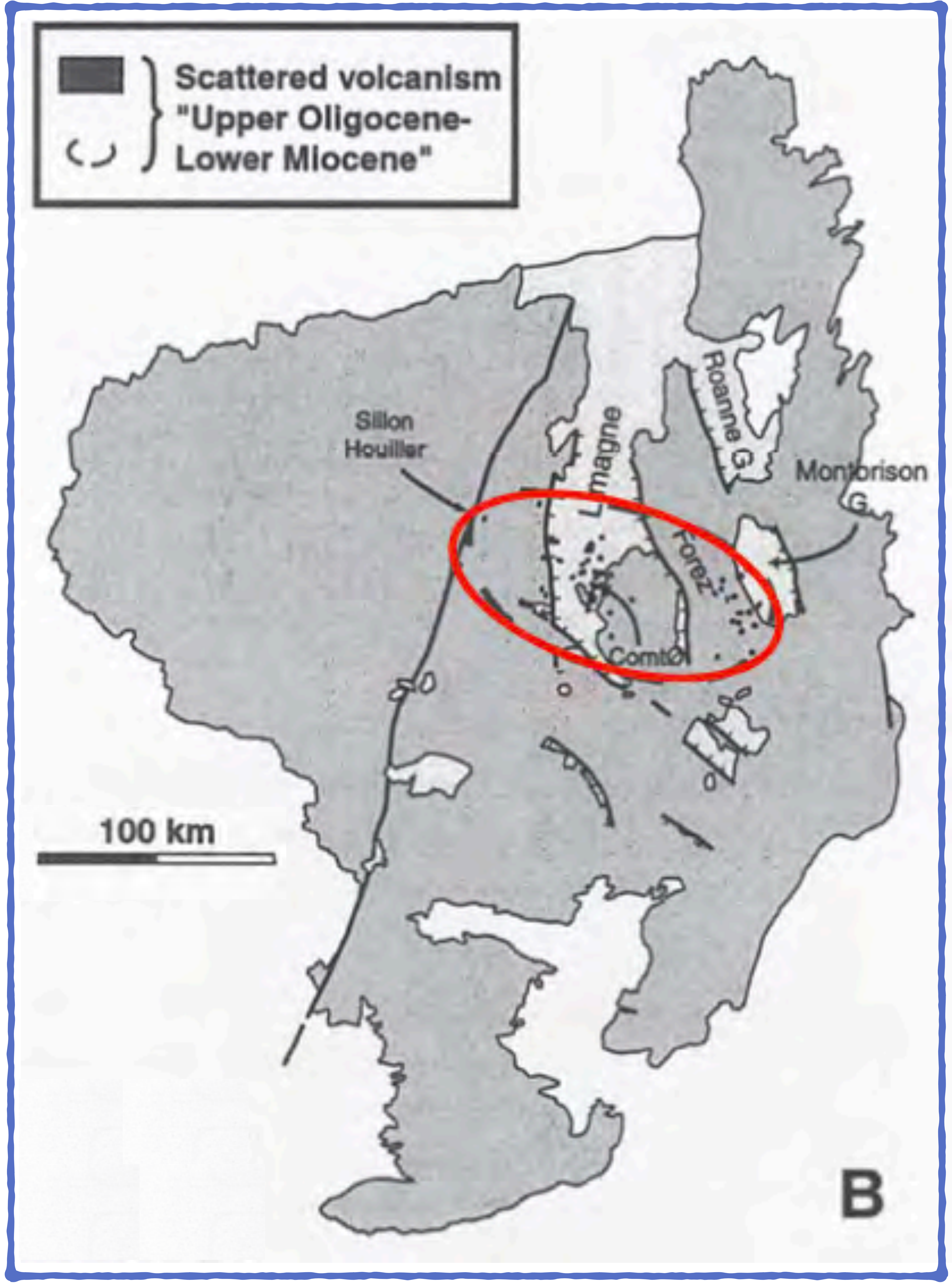
Modified from Michon and Merle, 2001

LIMAGNE GRABEN

Pre-rift: Widespread, spotty volcanism

Rifting: Scattered, in-rift volcanism





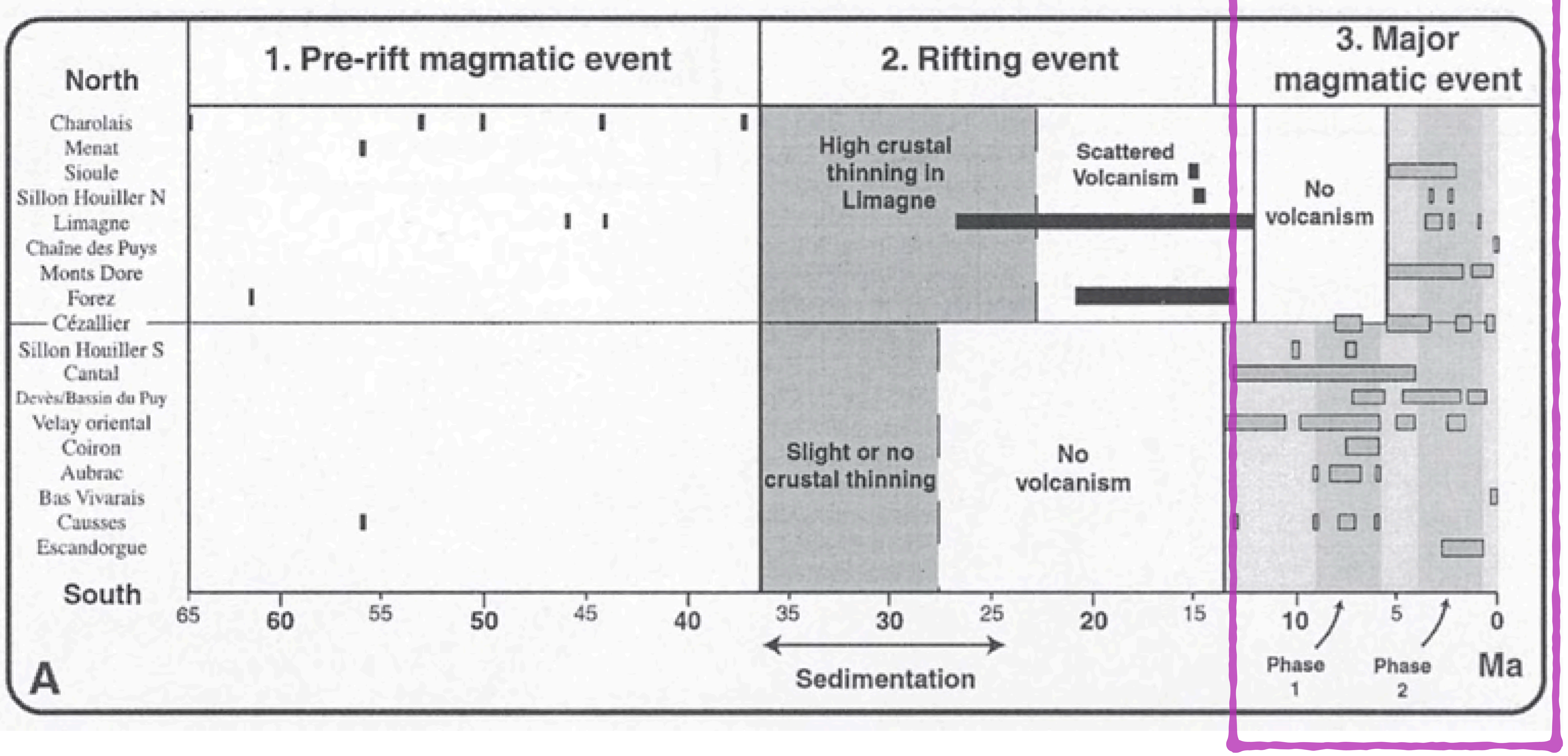
Modified from Michon and Merle, 2001

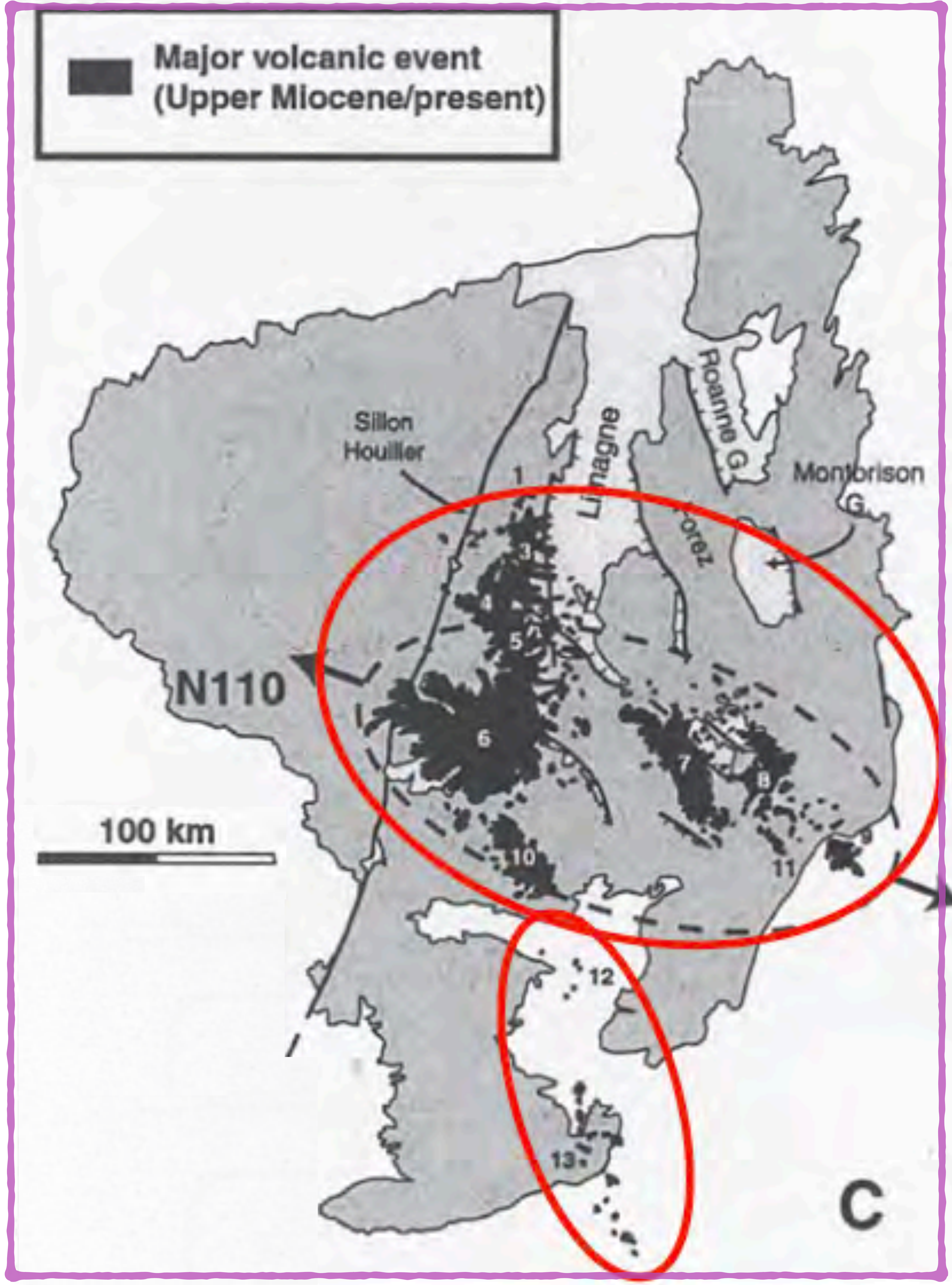
LIMAGNE GRABEN

Pre-rift: Widespread, spotty volcanism

Rifting: Scattered, in-rift volcanism

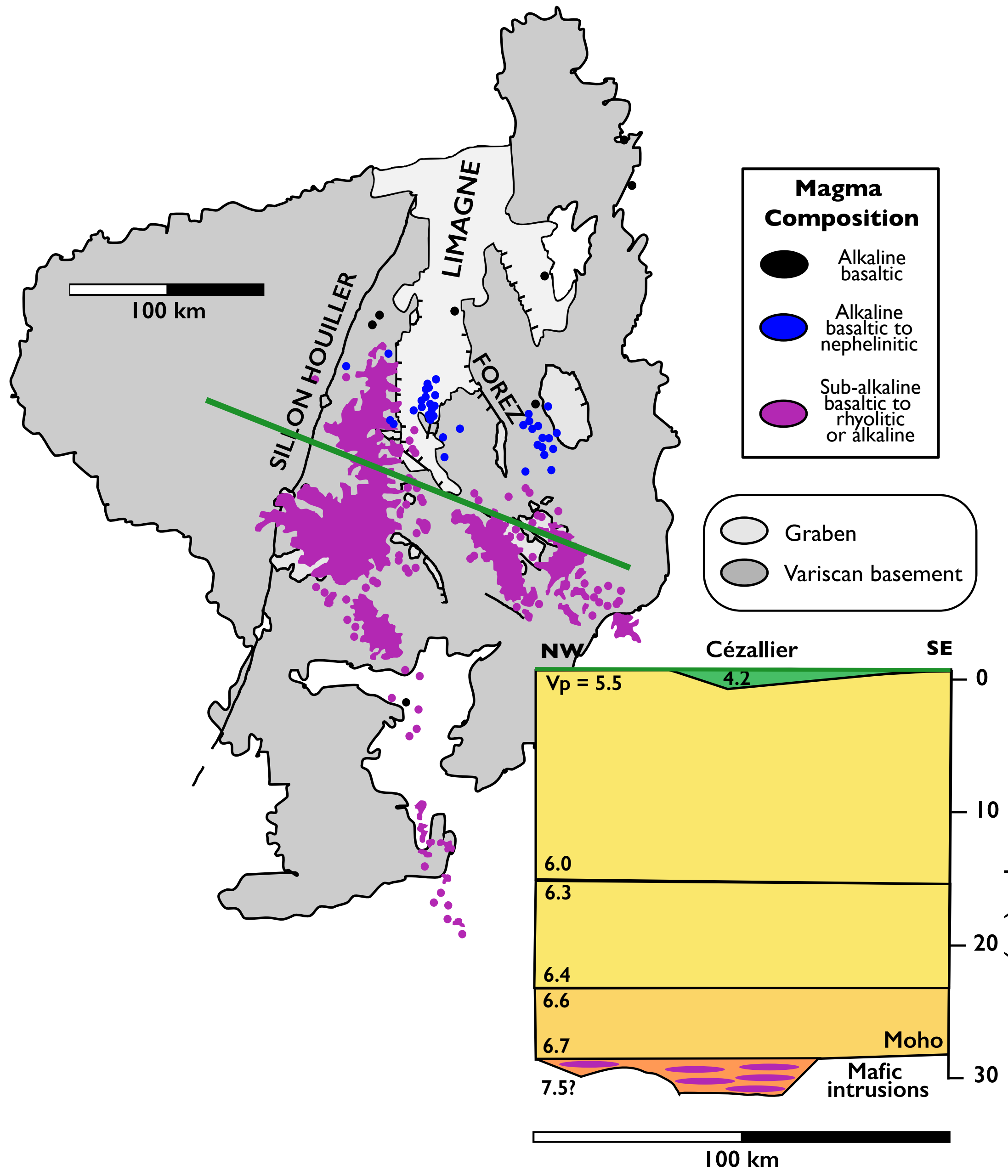
Rifting: Scattered, off-rift volcanism





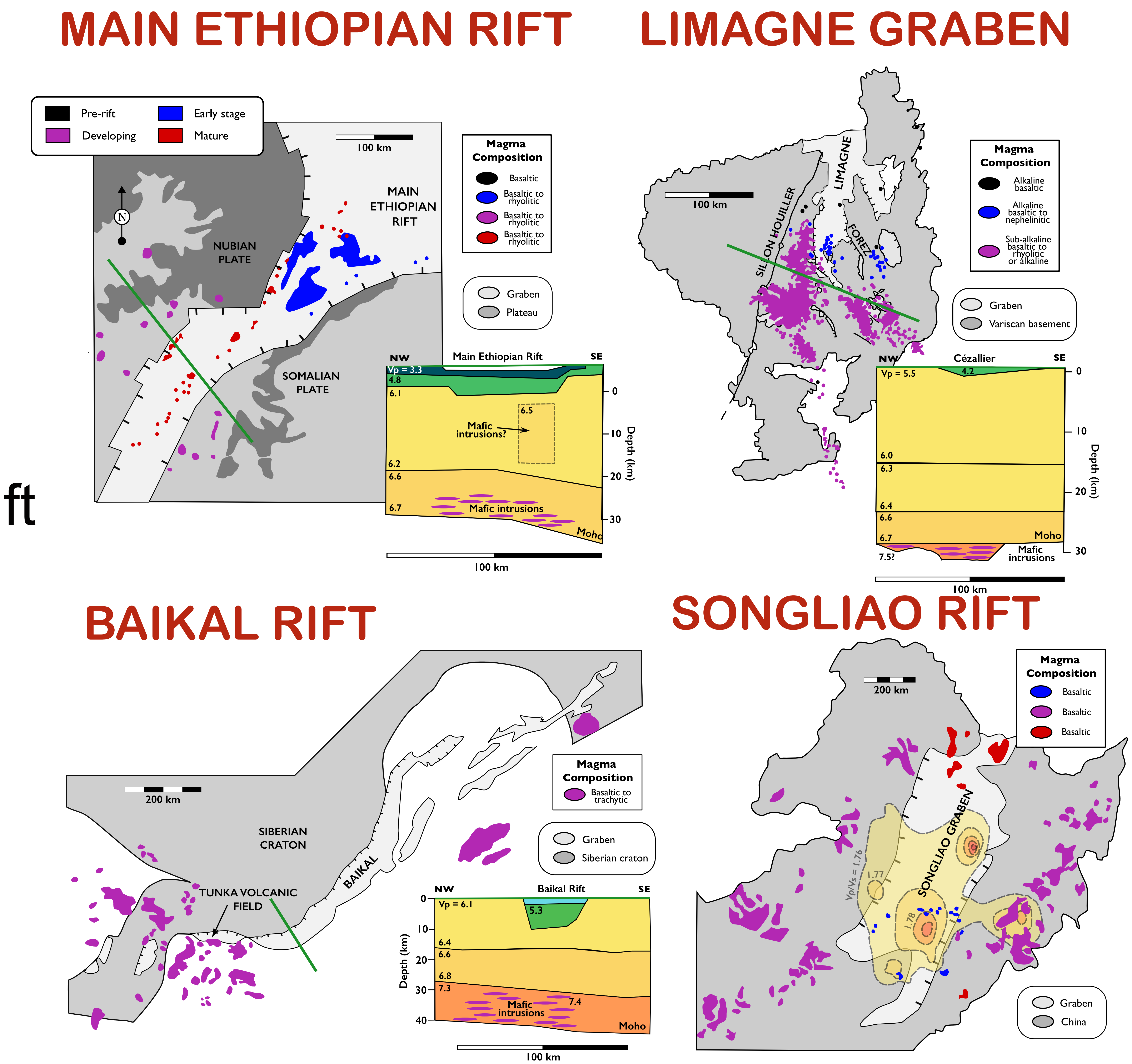
Modified from Michon and Merle, 2001

LIMAGNE GRABEN



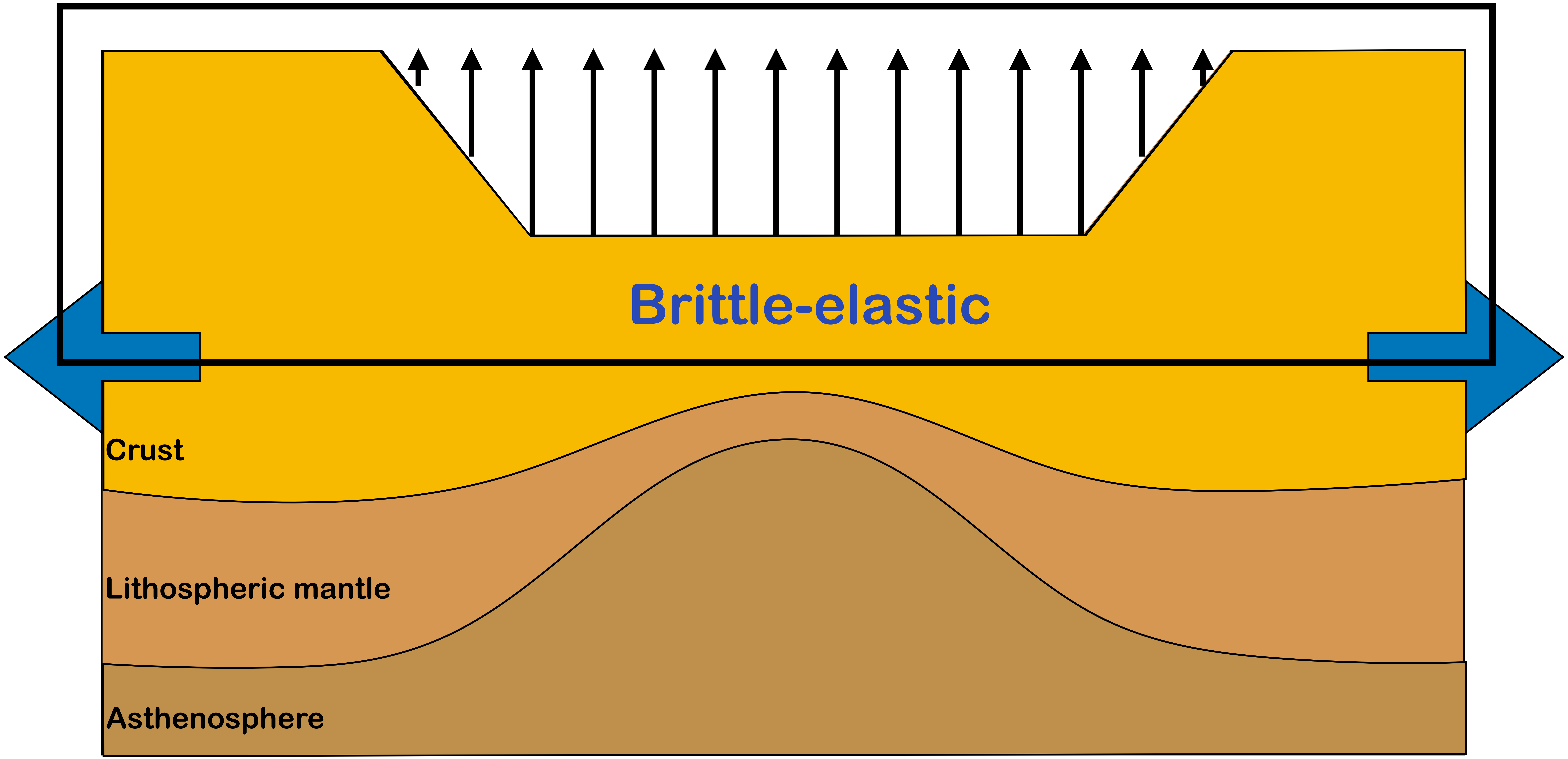
PATTERNS of RIFT VOLCANISM

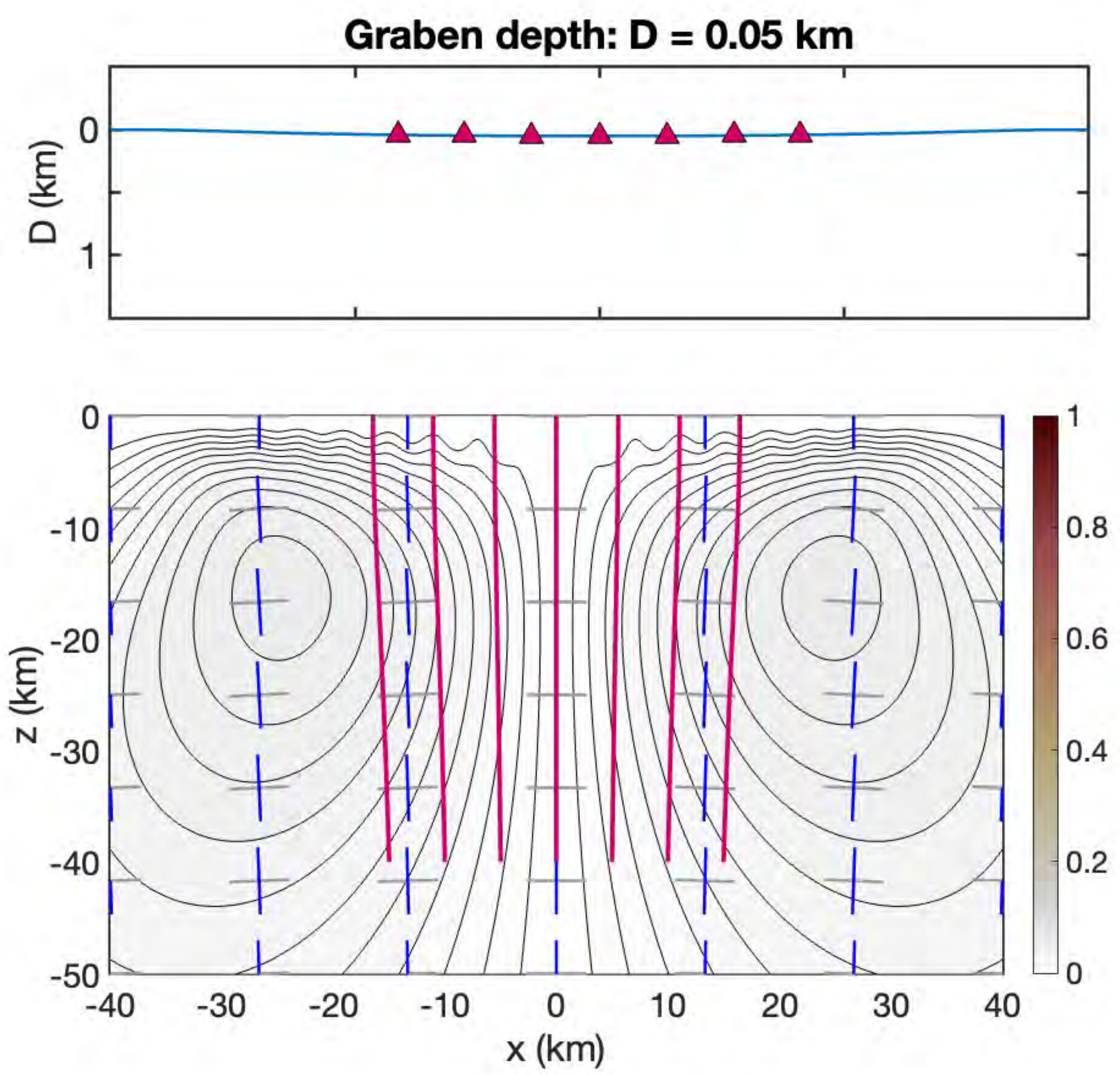
1. Widespread volcanism
2. Scattered, in-rift focused, off-rift
3. Lower crustal sills

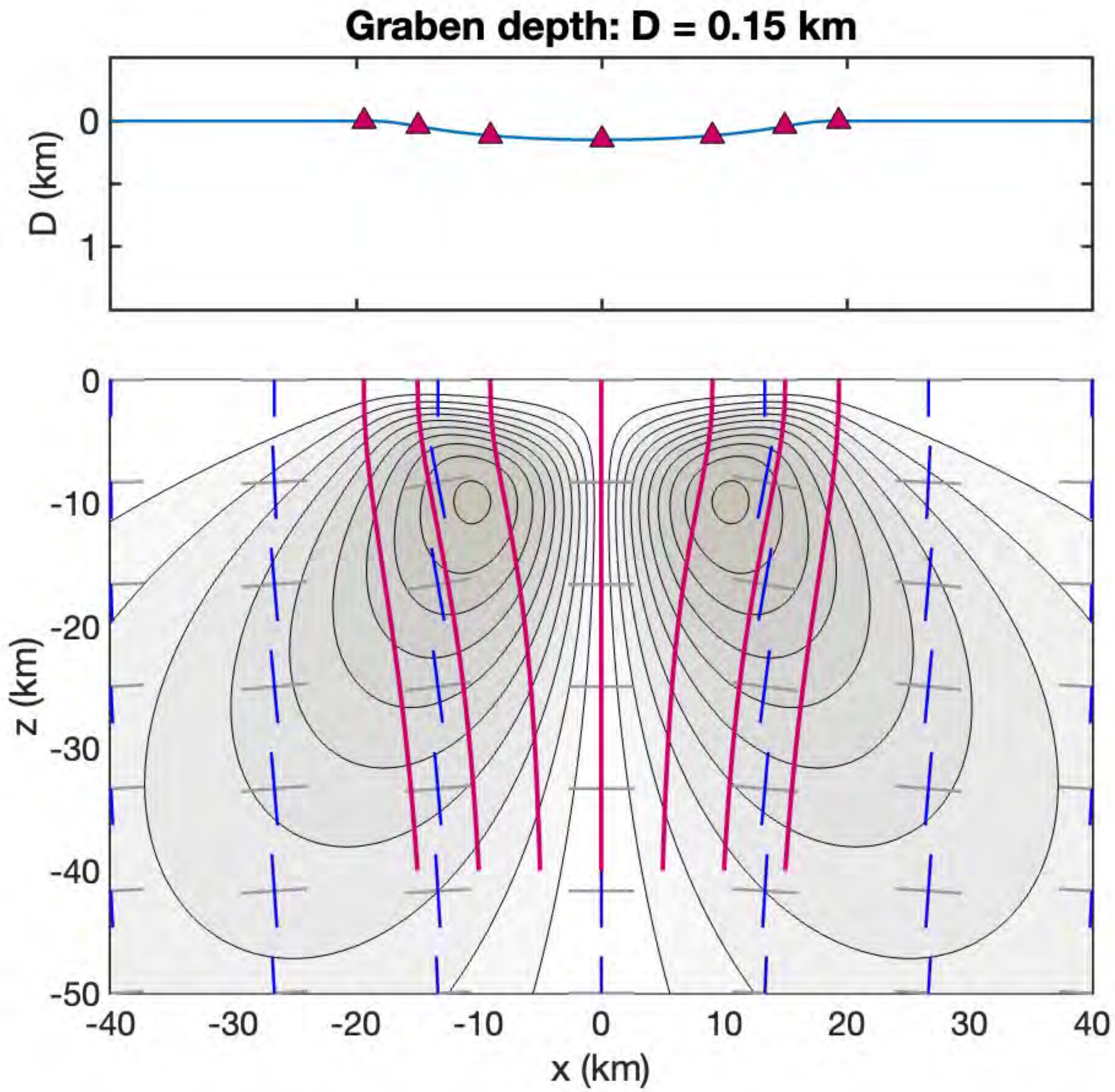


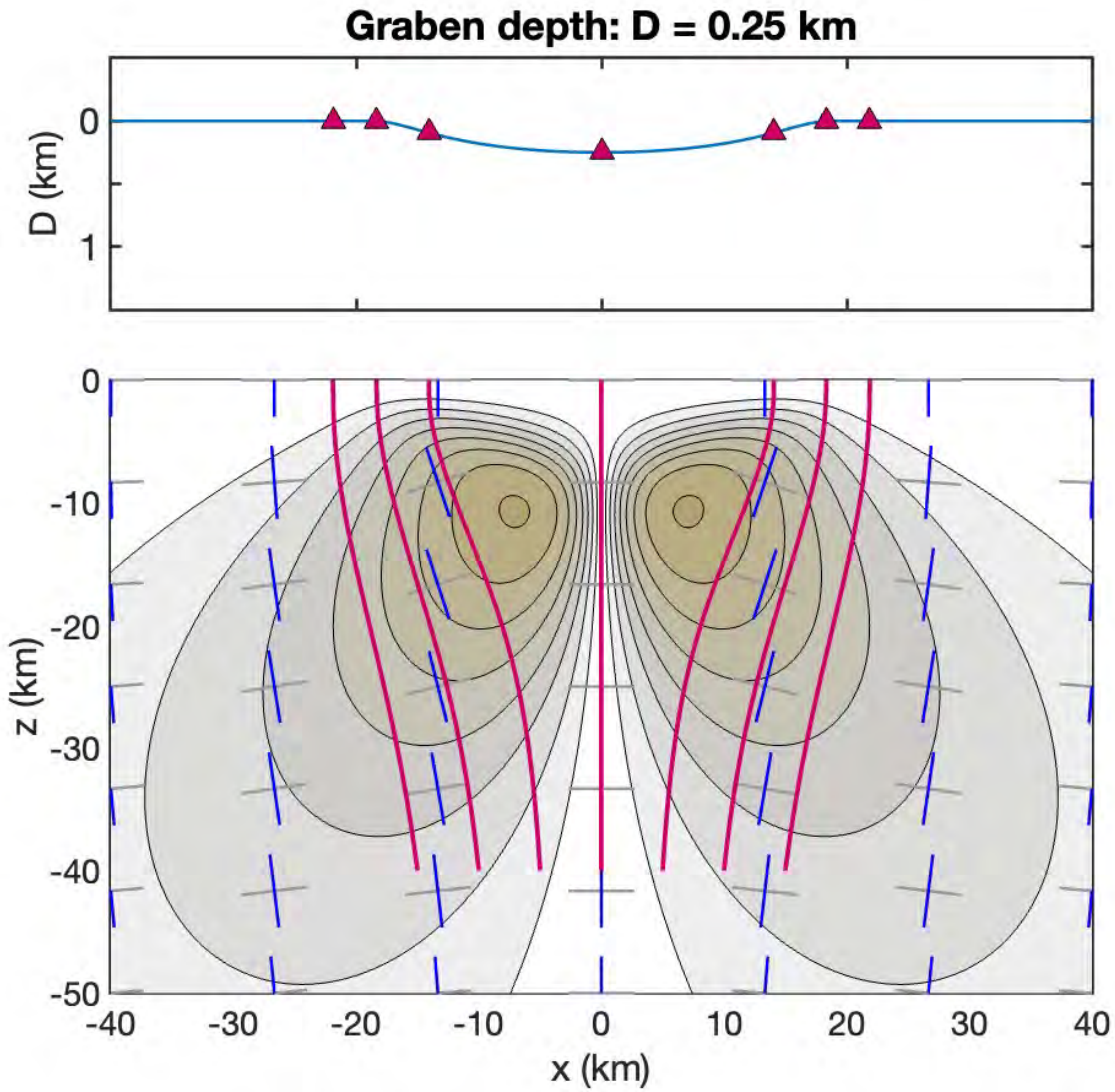
Modified from Ferrante et al., 2024

Tectonic stretching + formation of a topography depression

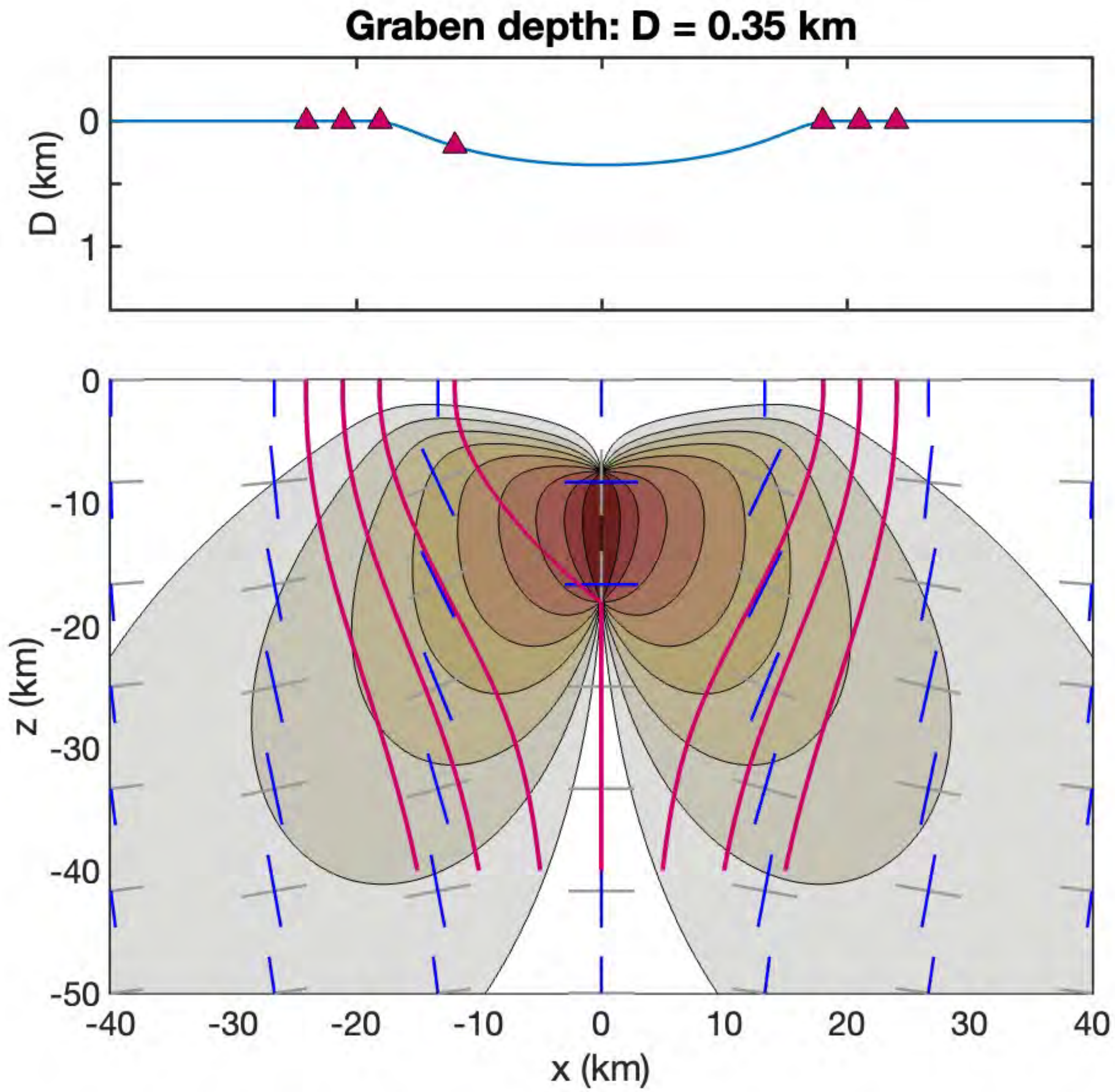



Graben depth: D = 0.05 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
x (km)
-40
-30
-20
-10
0
10
20
30
40
1
0.8
0.6
0.4
0.2
0

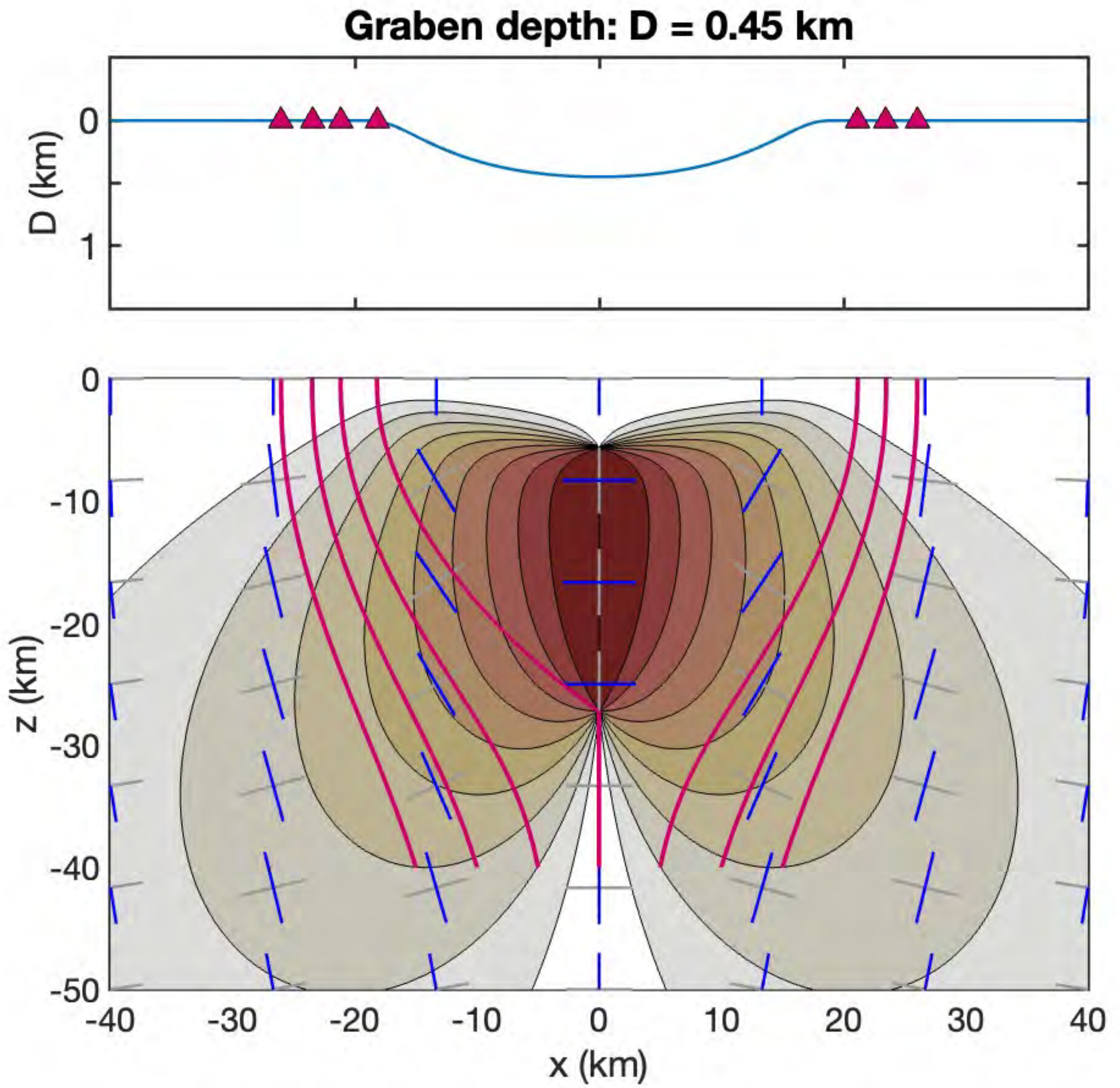

Graben depth: D = 0.15 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
x (km)
-40
-30
-20
-10
0
10
20
30
40



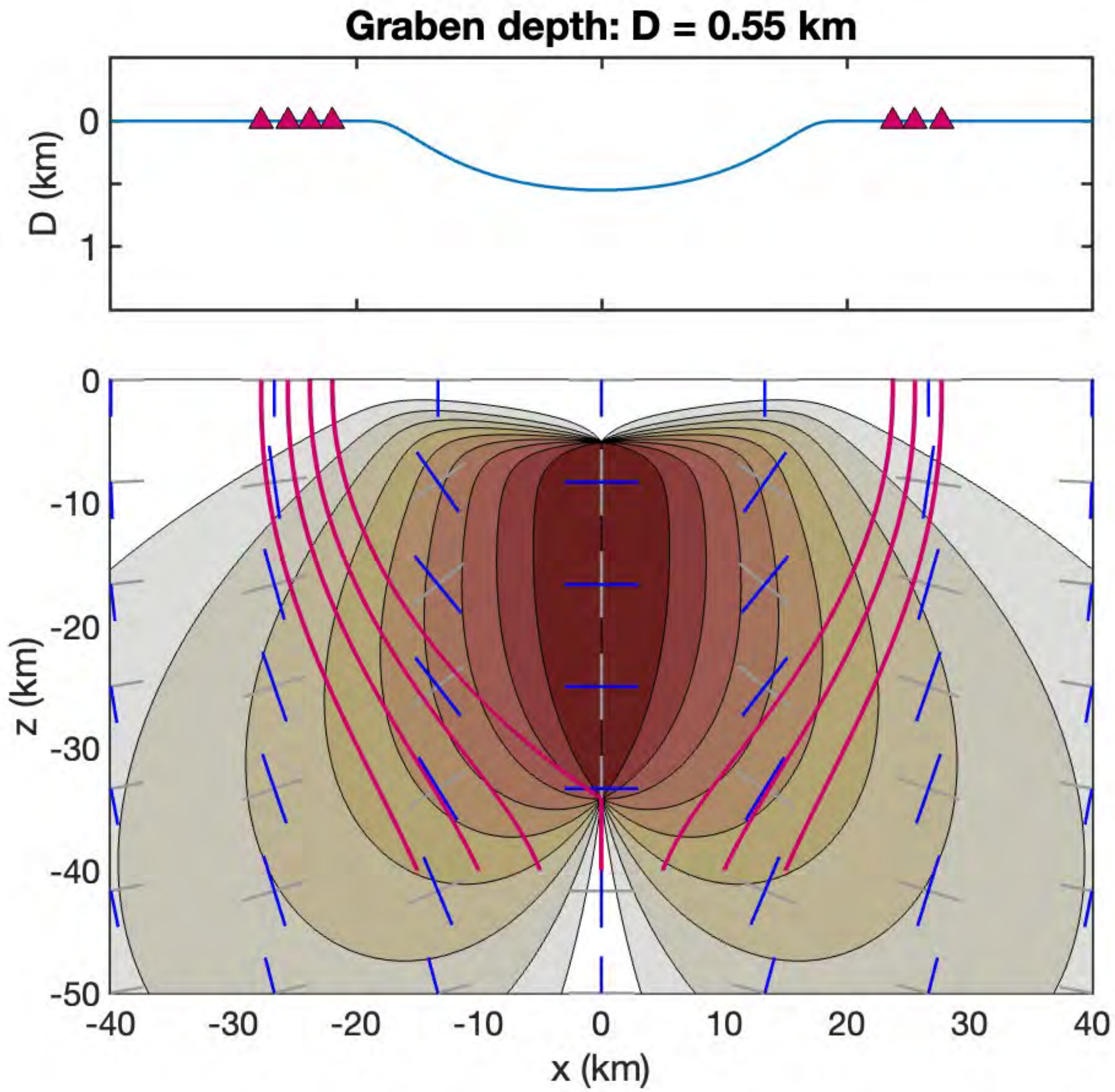
Graben depth: D = 0.25 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)



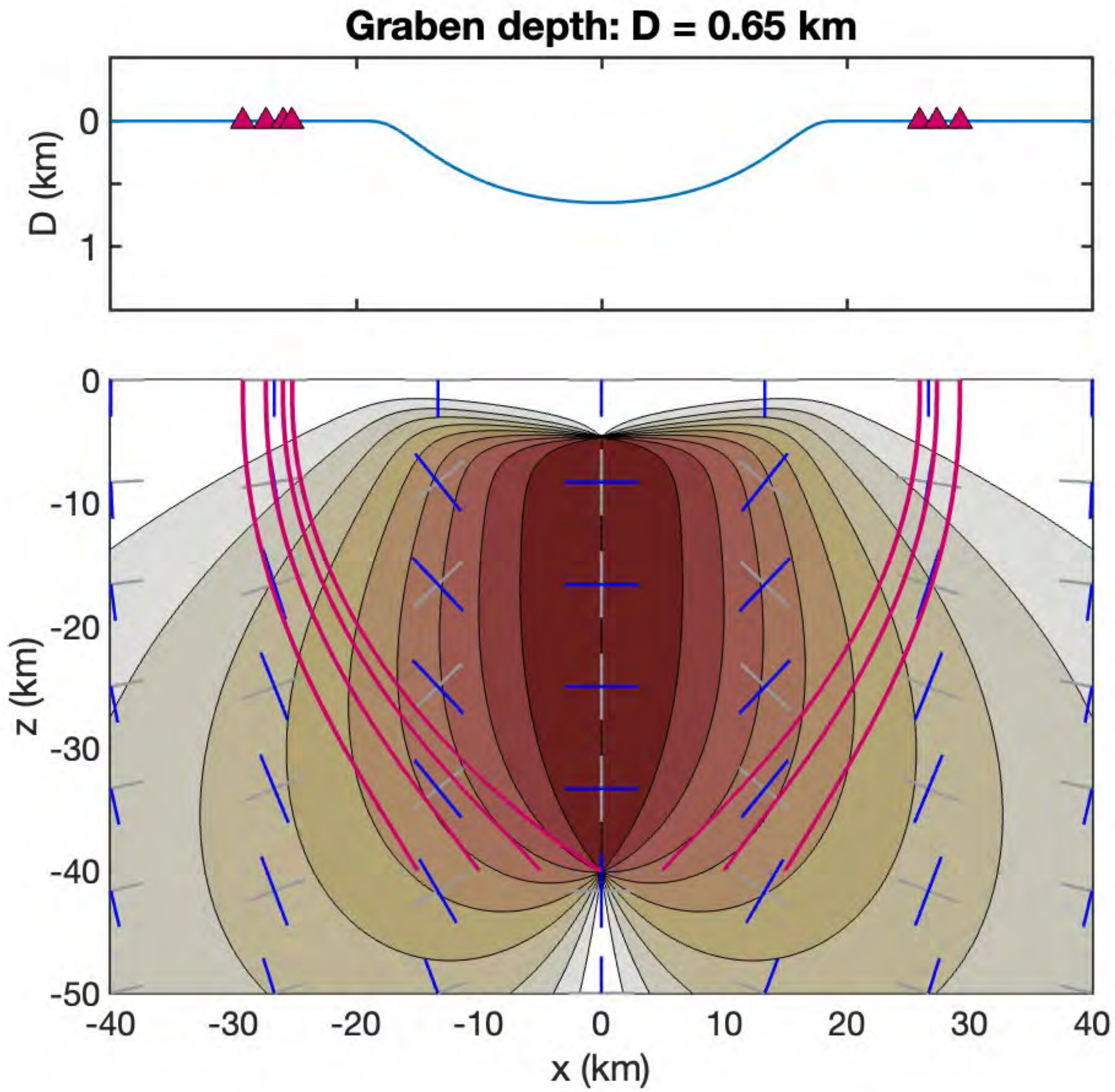
Graben depth: D = 0.35 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

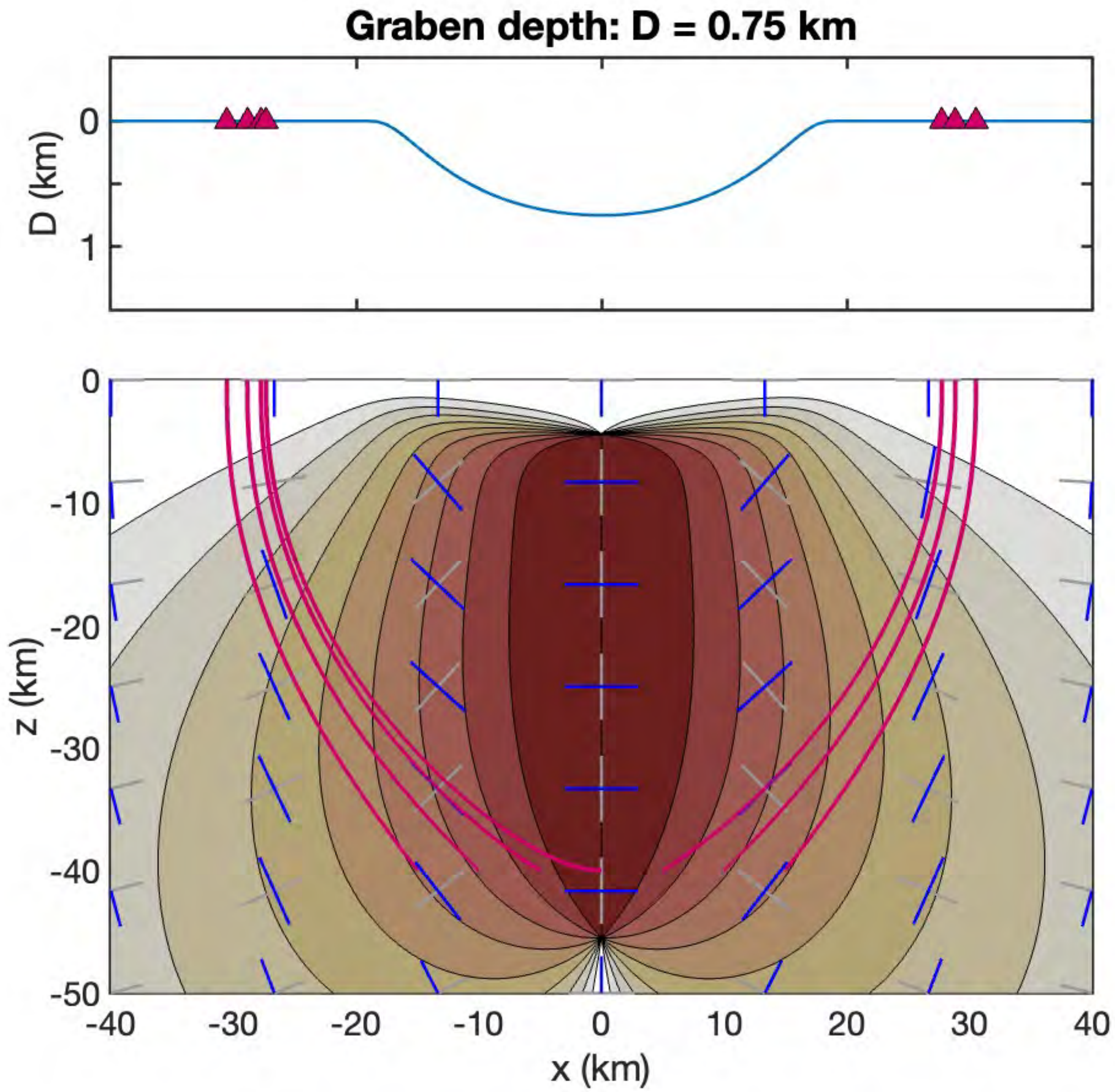


Graben depth: D = 0.45 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

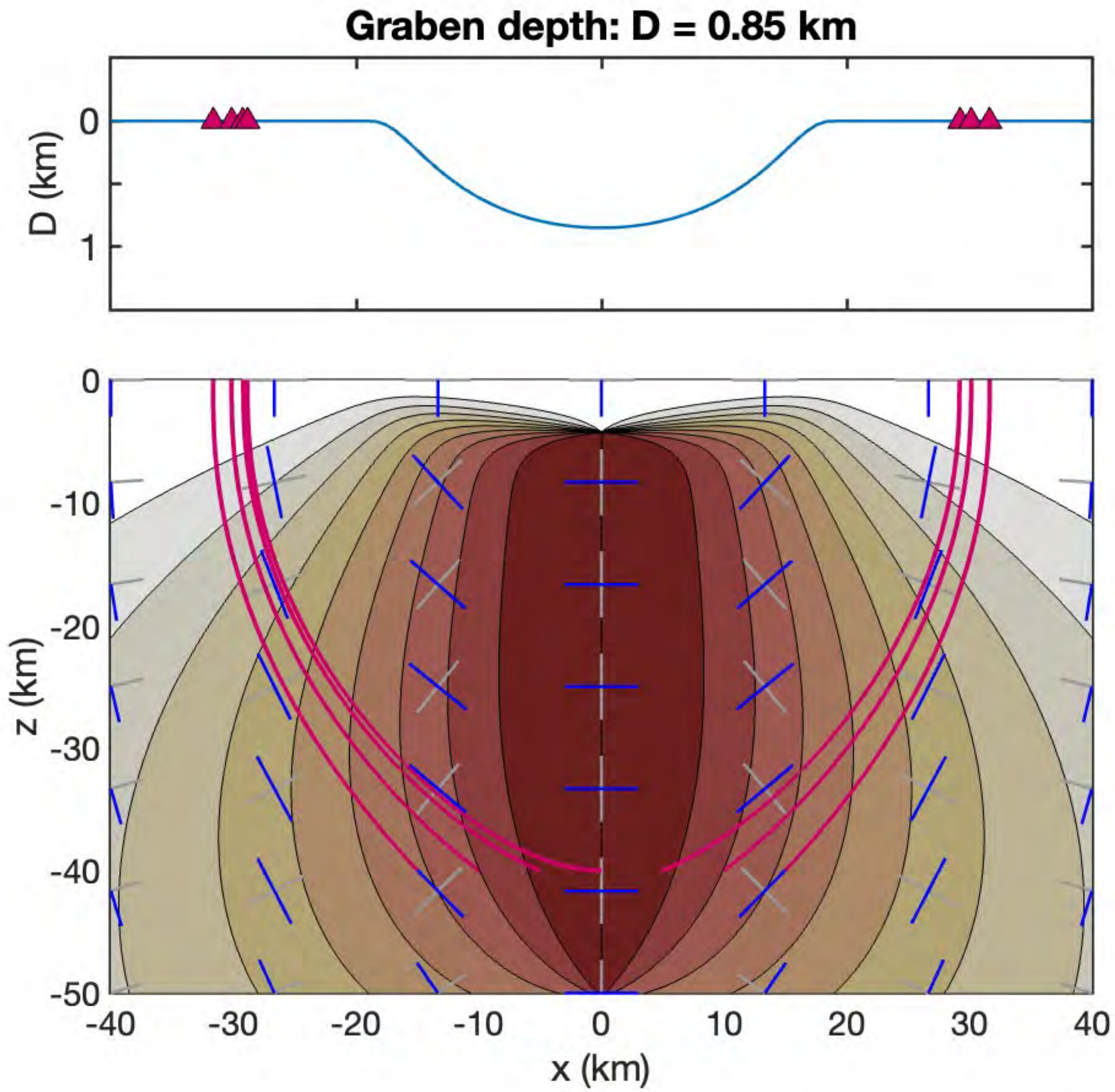


Graben depth: D = 0.55 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

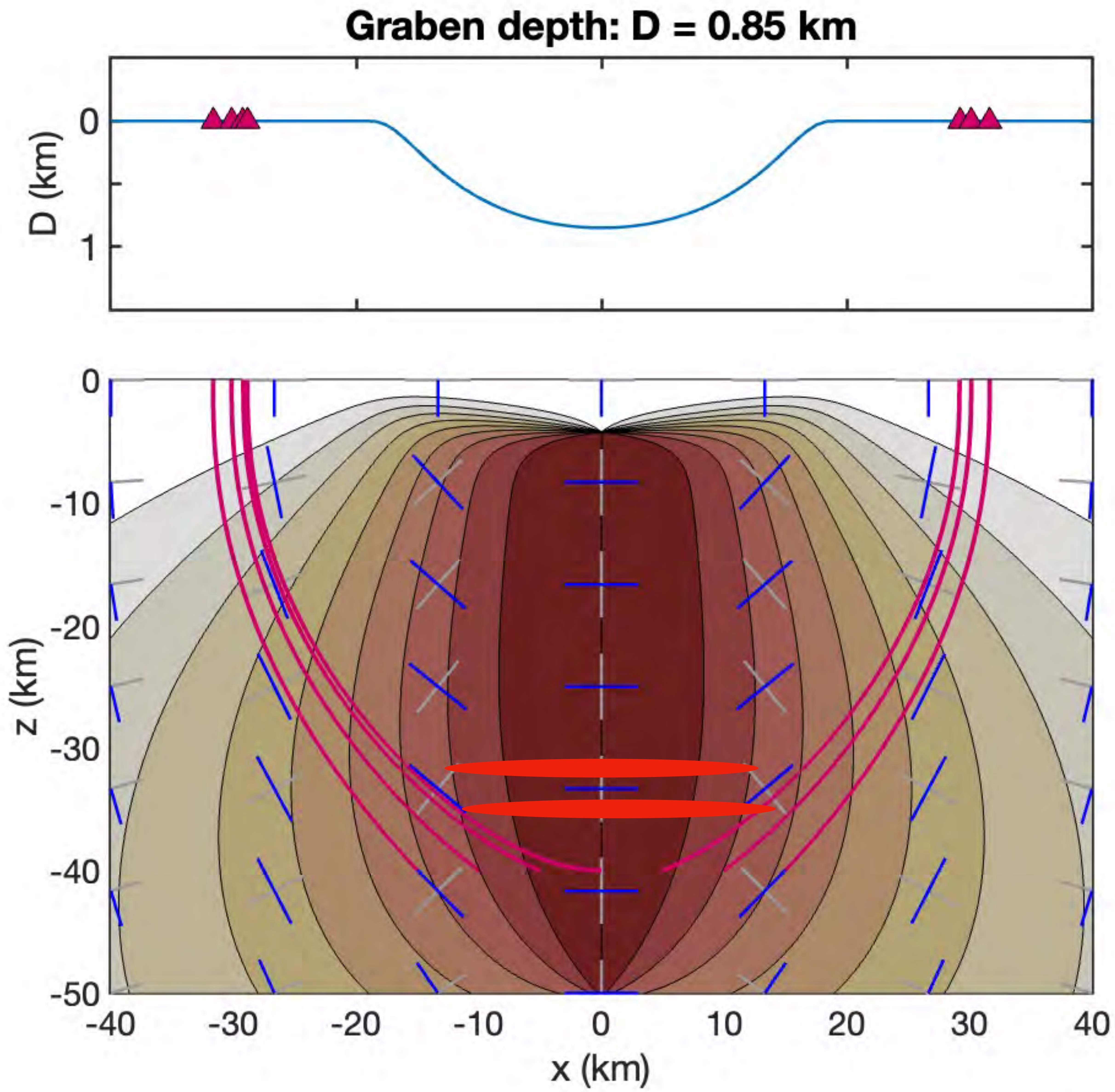

Graben depth: D = 0.65 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

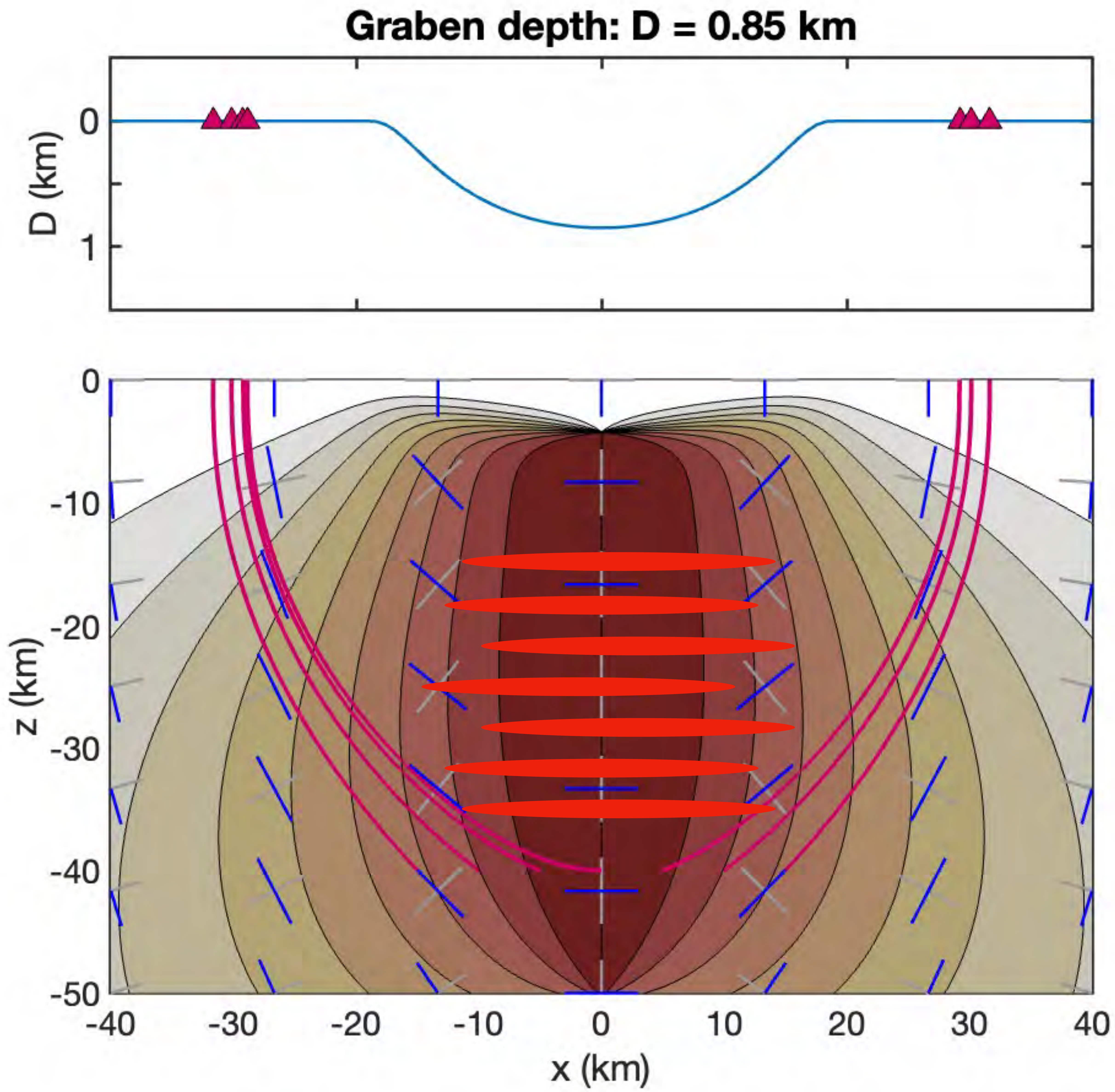


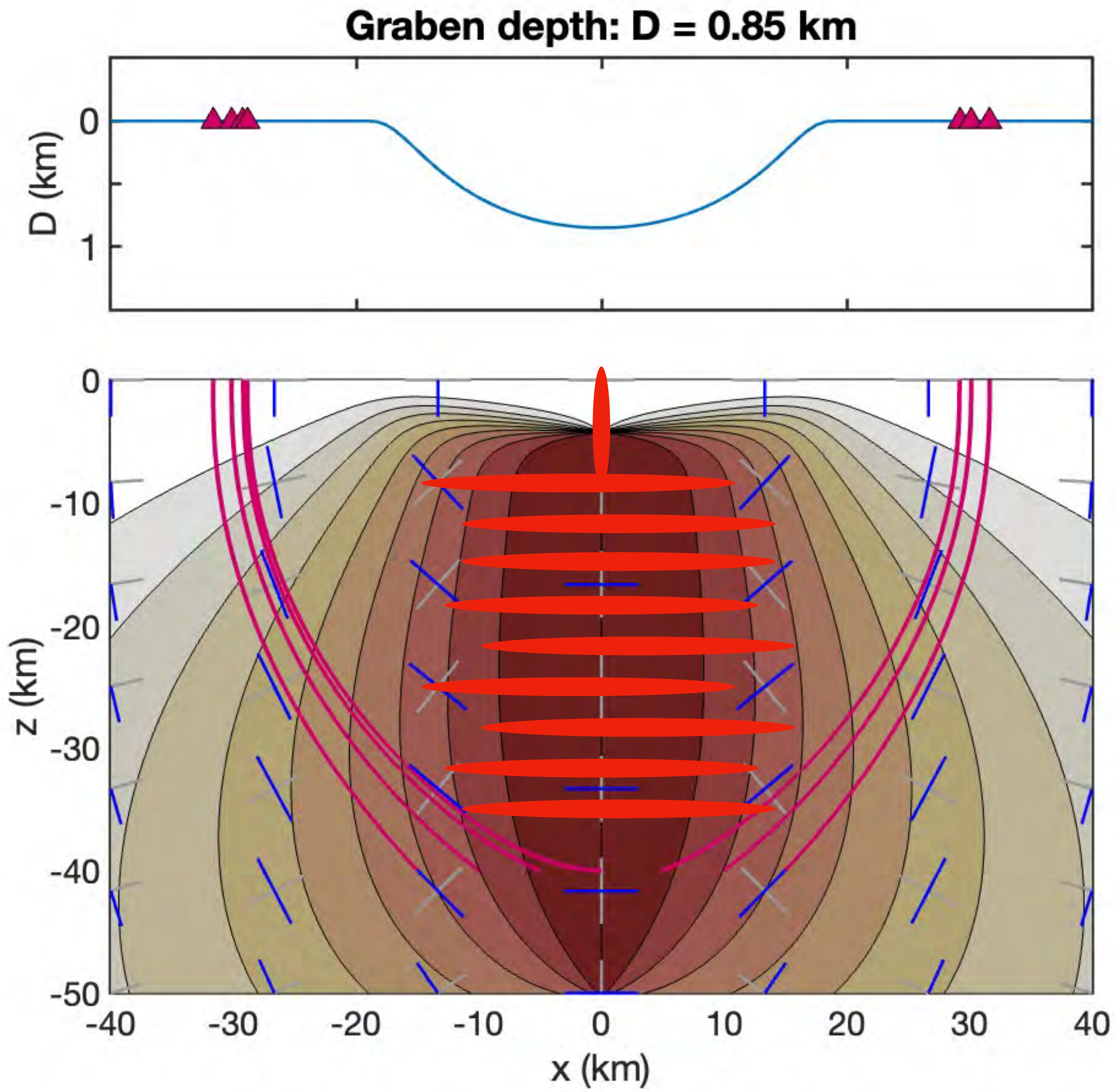
Graben depth: D = 0.75 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)



Graben depth: D = 0.85 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

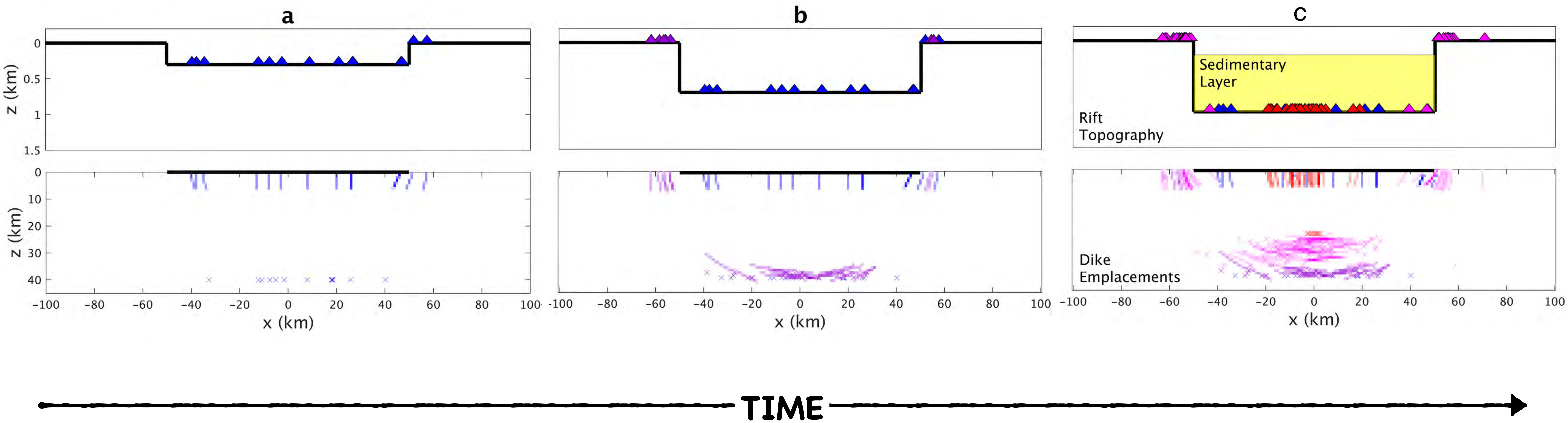

Graben depth: D = 0.85 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)


Graben depth: D = 0.85 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
x (km)
-40
-30
-20
-10
0
10
20
30
40



Graben depth: D = 0.85 km
D (km)
0
1
z (km)
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
40
x (km)

Evolution of Rift Volcanism
(Ferrante et al., 2024)



DIKE INTERACTION

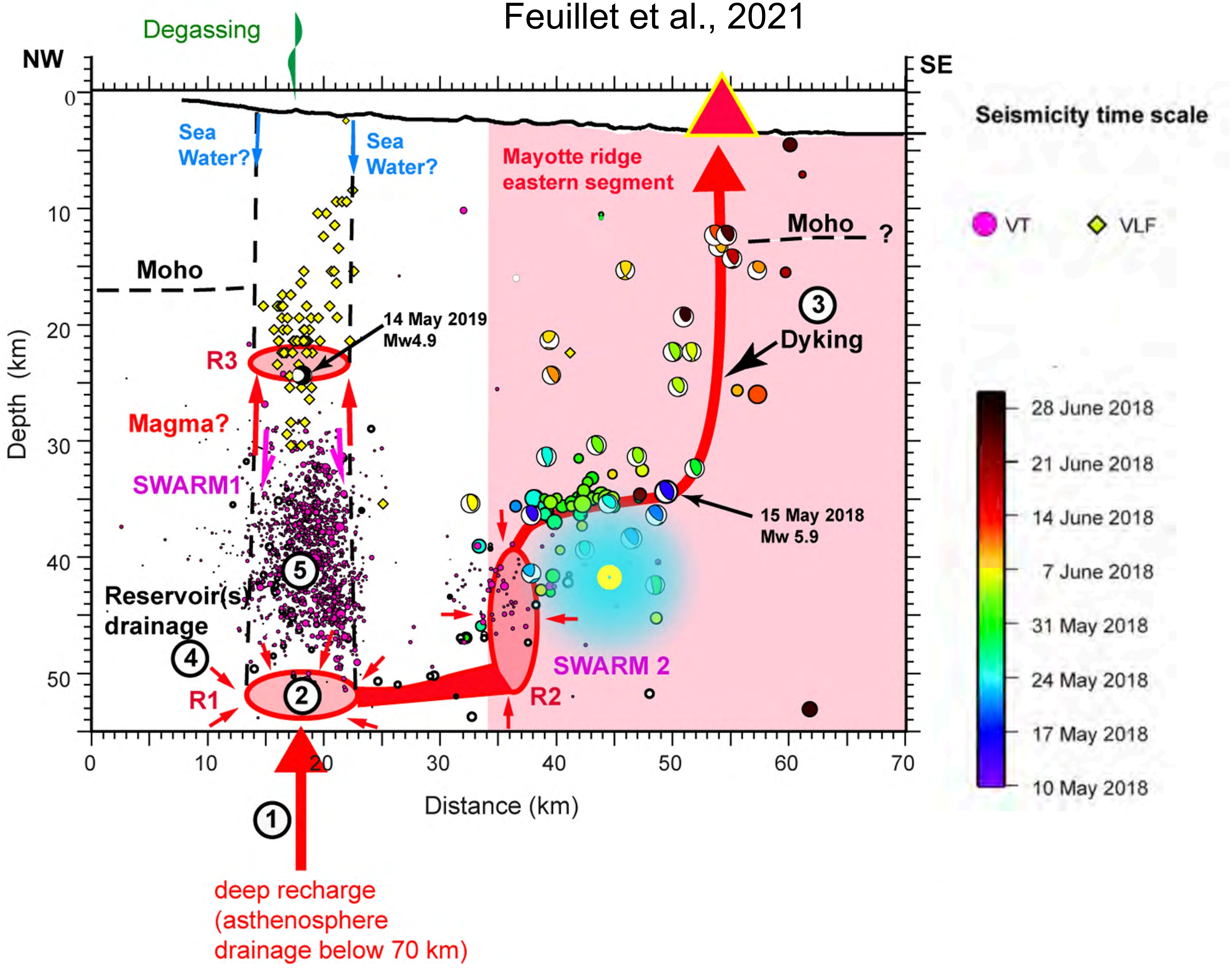
a) monogenetic in-rift volcanism
b) off-rift volcanism + sill stacking
c) axial in-rift volcanism

Modified from Ferrante et al., 2024

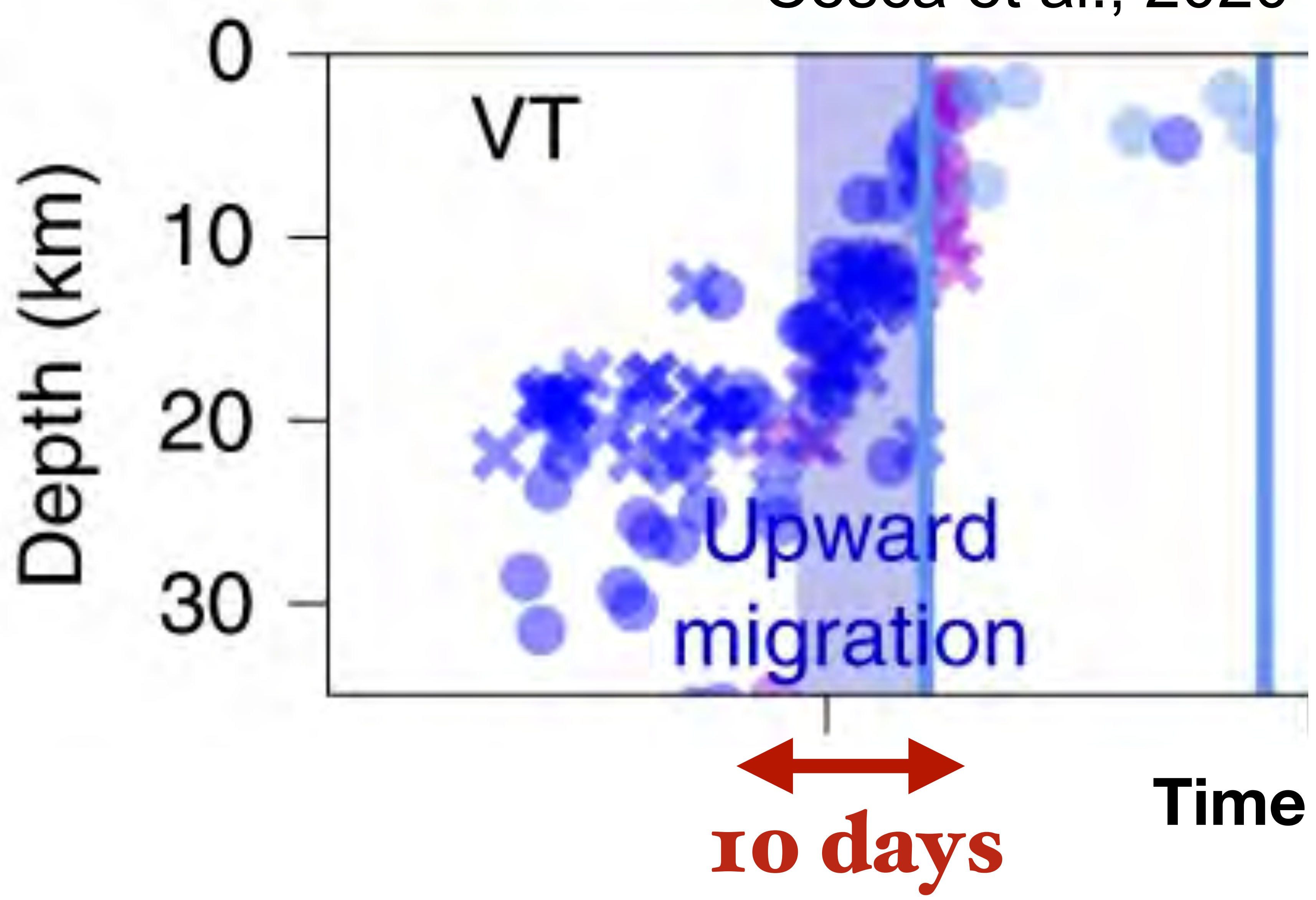
Open questions

How deep?

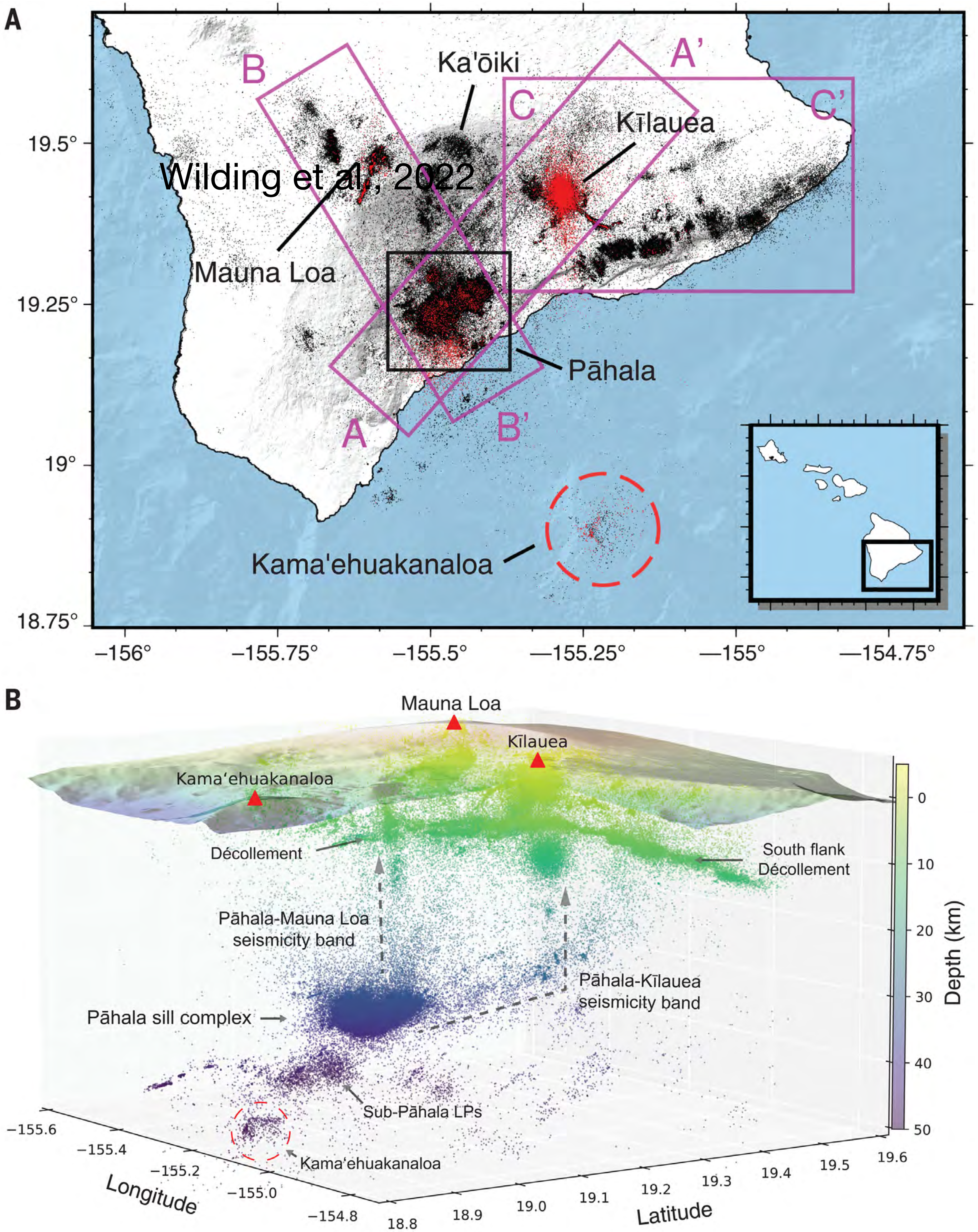
Feuillet et al., 2021



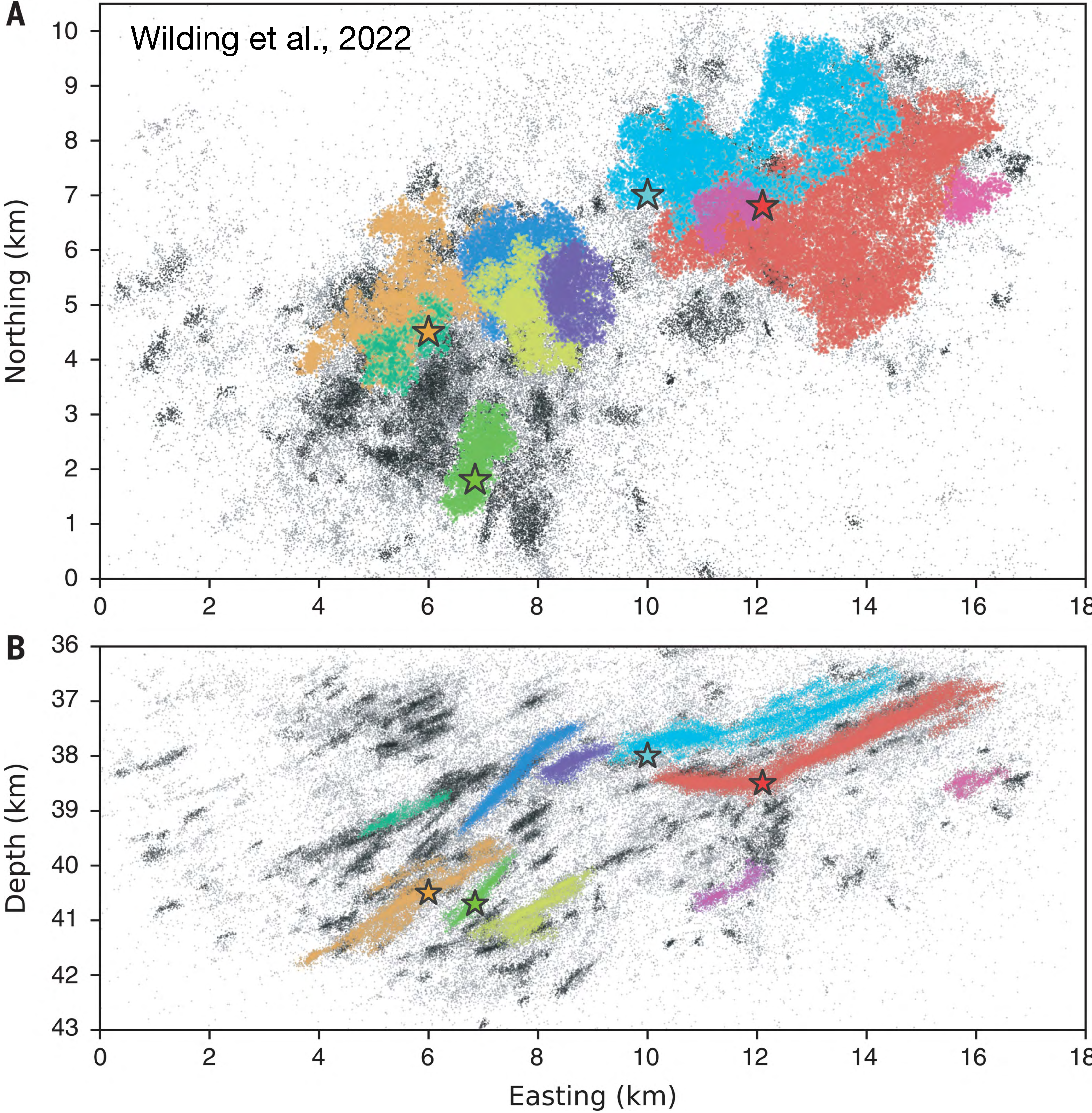
Cesca et al., 2020



- Magma-driven fractures viable in the lithospheric mantle.
- Migration speeds are ~ km/day to few km/h.



A
B
A'
C
C'
B'
A
Ka'ōiki
Kīlauea
Wilding et al., 2022
Mauna Loa
Pāhala
Kama'ehuakanaloa
19.5°
19.25°
19°
18.75°
−156°
−155.75°
−155.5°
−155.25°
−155°
−154.75°
B
Mauna Loa
Kīlauea
Kamaʻehuakanaloa
Décollement
South flank
Décollement
Pāhala-Mauna Loa
seismicity band
Pāhala-Kīlauea
seismicity band
Pāhala sill complex
Sub-Pāhala LPs
Kama'ehuakanaloa
Depth (km)
0
10
20
30
40
50
Longitude
Latitude
−155.6
−155.4
−155.2
−155.0
−154.8
18.8
18.9
19.0
19.1
19.2
19.3
19.4
19.5
19.6

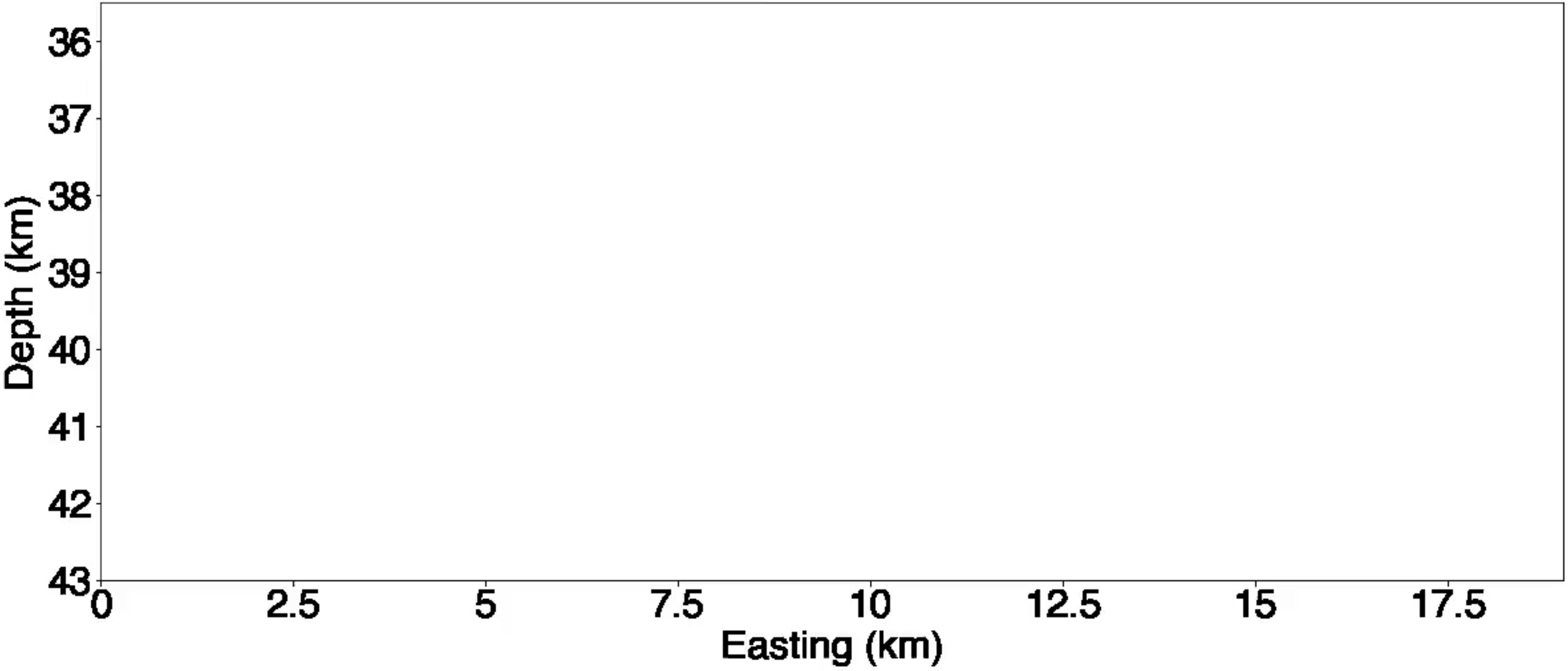


A
Wilding et al., 2022
Northing (km)
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14
16
18
B
Depth (km)
36
37
38
39
40
41
42
43
0
2
4
6
8
10
12
14
16
18
Easting (km)

The magmatic web beneath Hawai'i

- Magma-driven fractures viable in the lithospheric mantle.
- Migration speeds are ~ km/day to few km/h.

Wilding et al., 2022

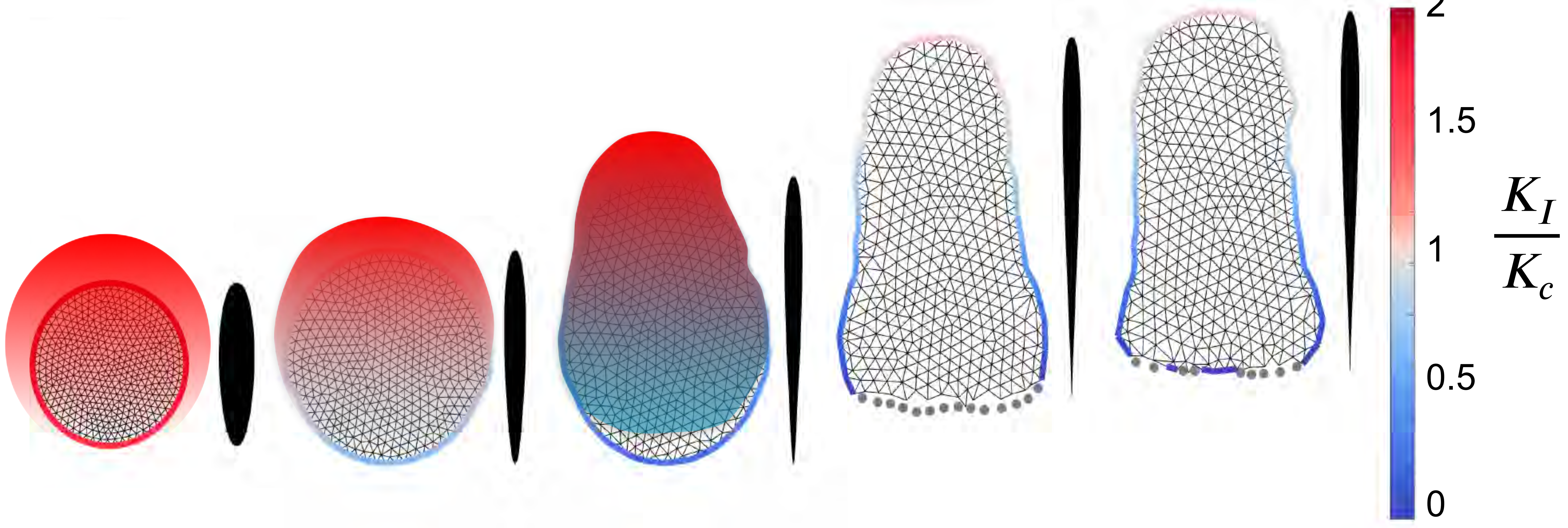


On our way to full 3D dike propagation models

Dike trajectories:

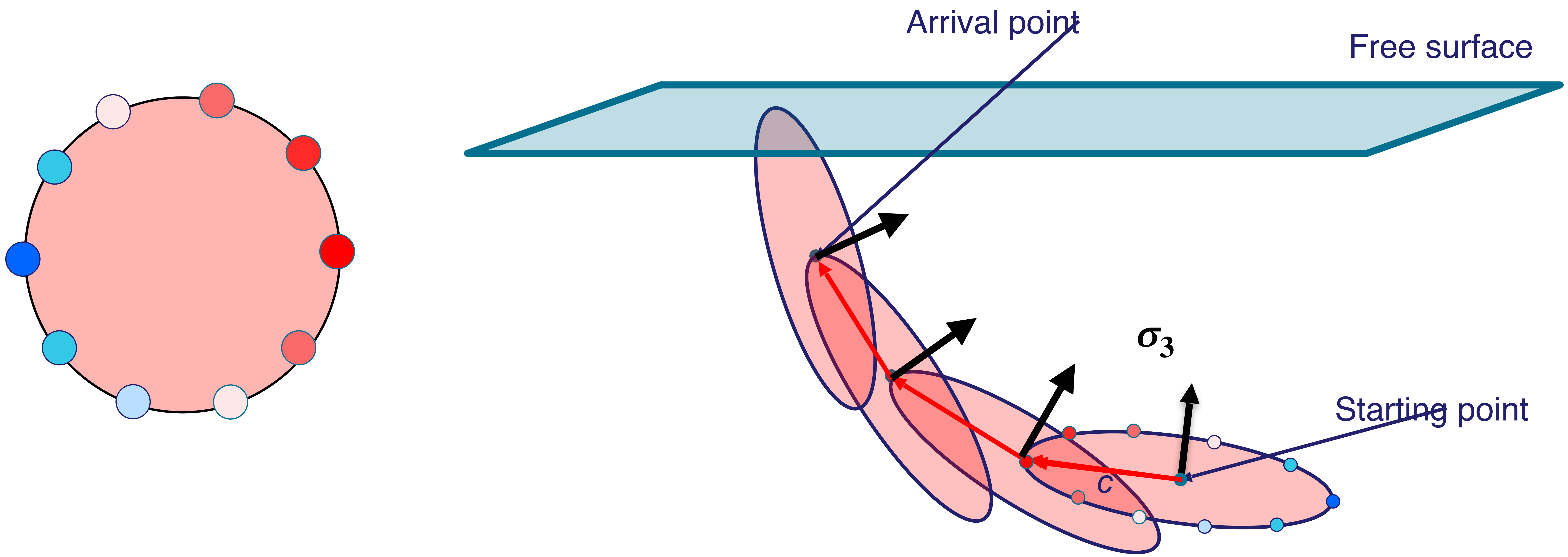
TIM

Davis et al., 2020
Davis et al., 2021



SAM

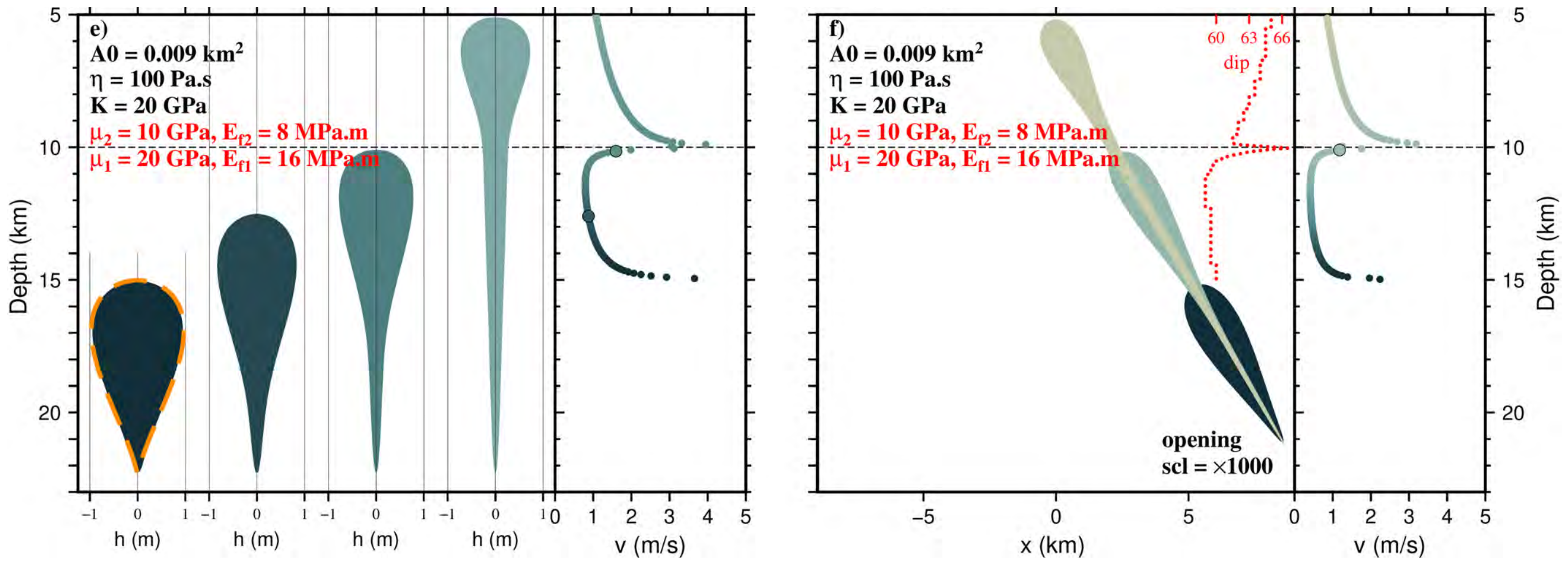
$\perp \sigma_3$



Mantiloni et al., 2023

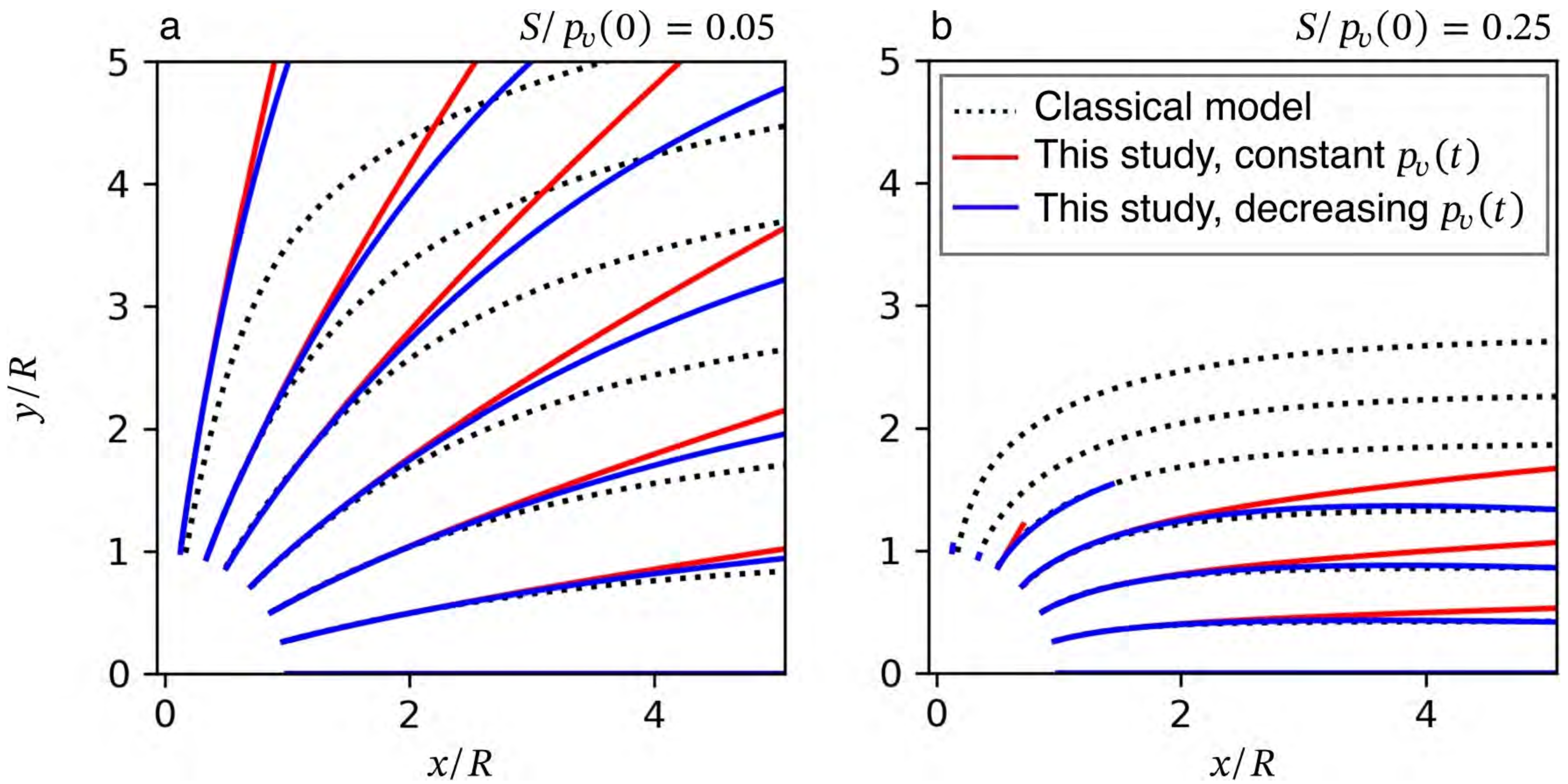
Trajectory + velocity coupling (2D)

Furst et al., 2023
Furst et al. 2024



+ coupling with chamber

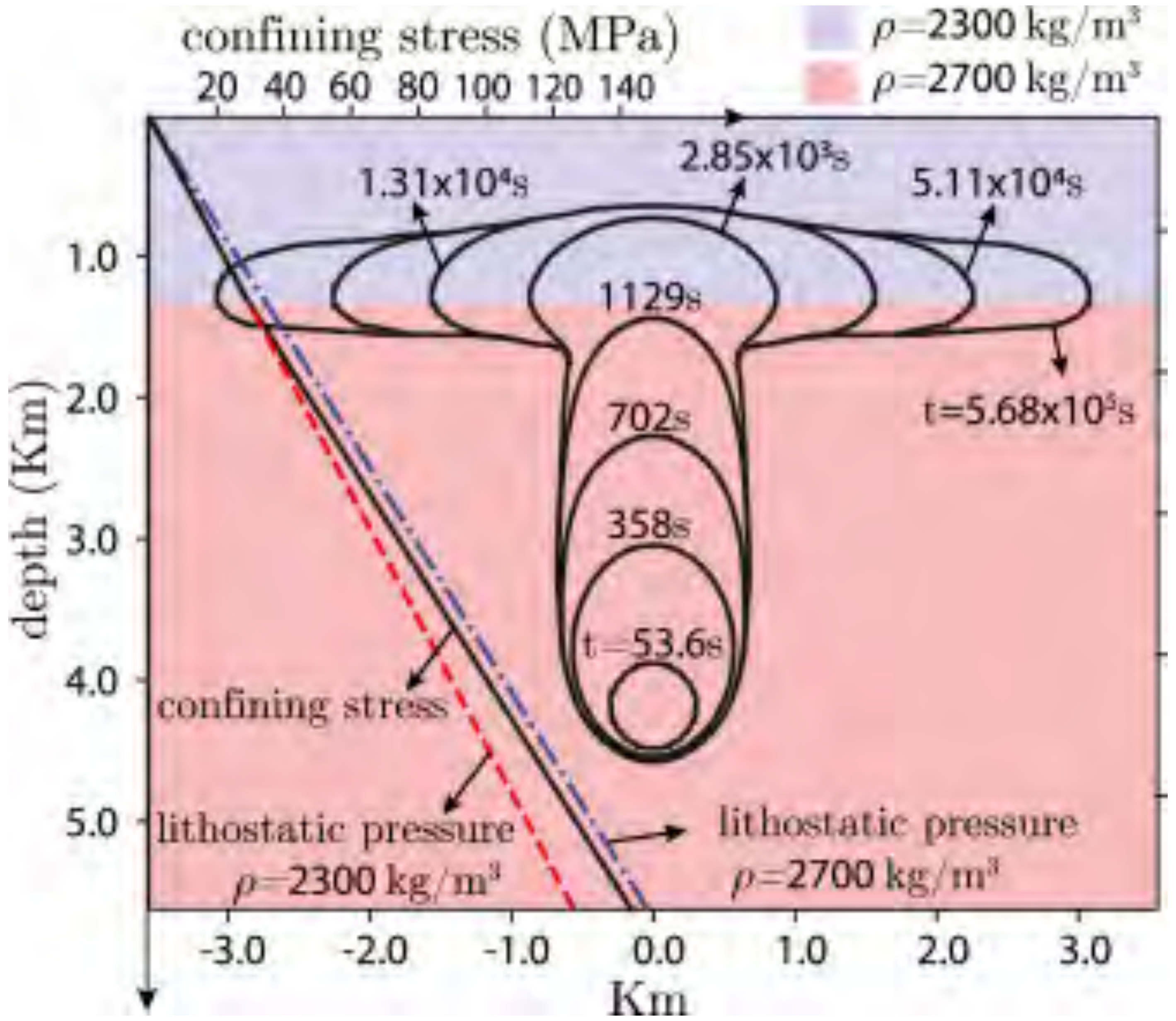
Blackstone et al., 2023

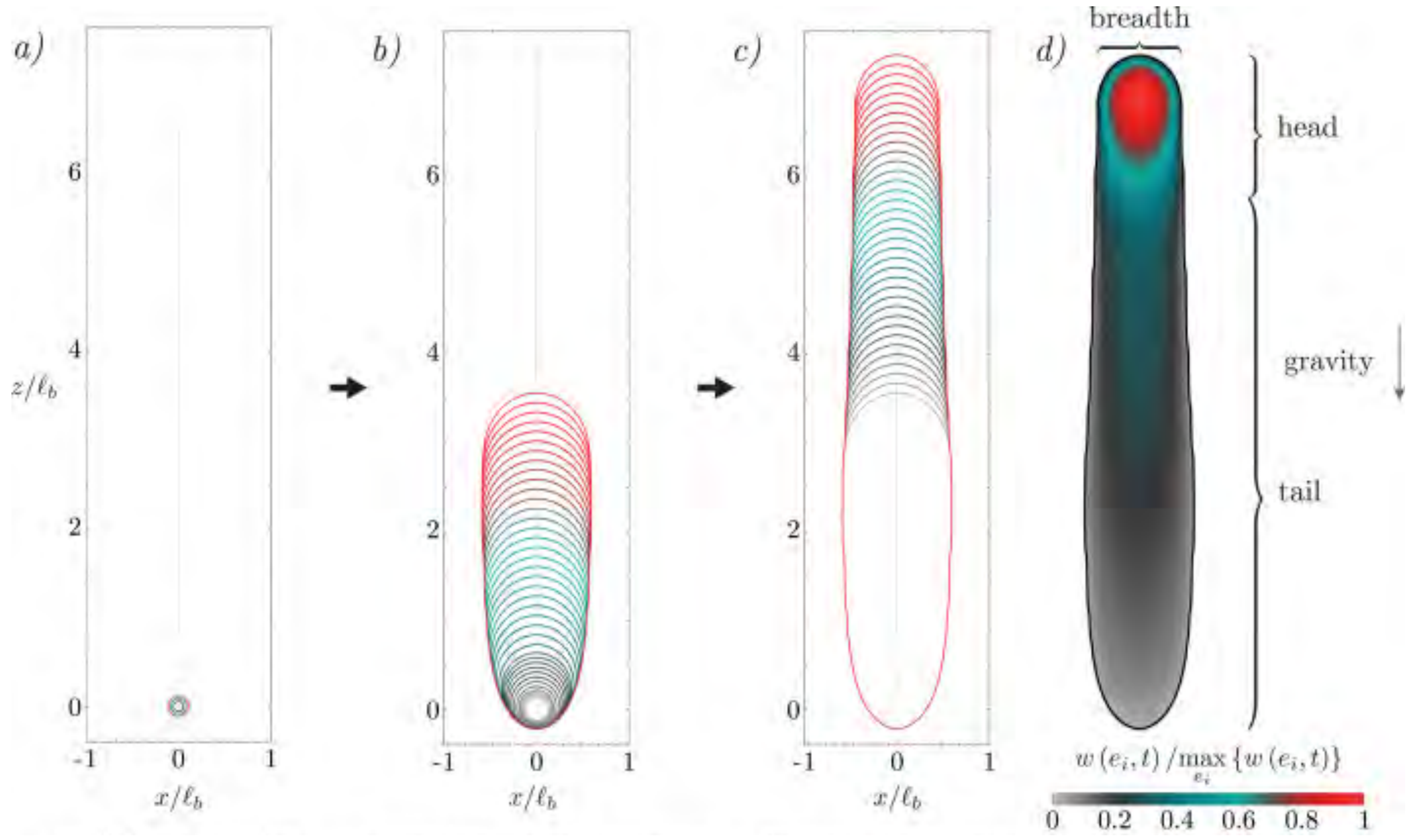


Dike velocity: 3D (planar) coupled fluid flow-fracture models

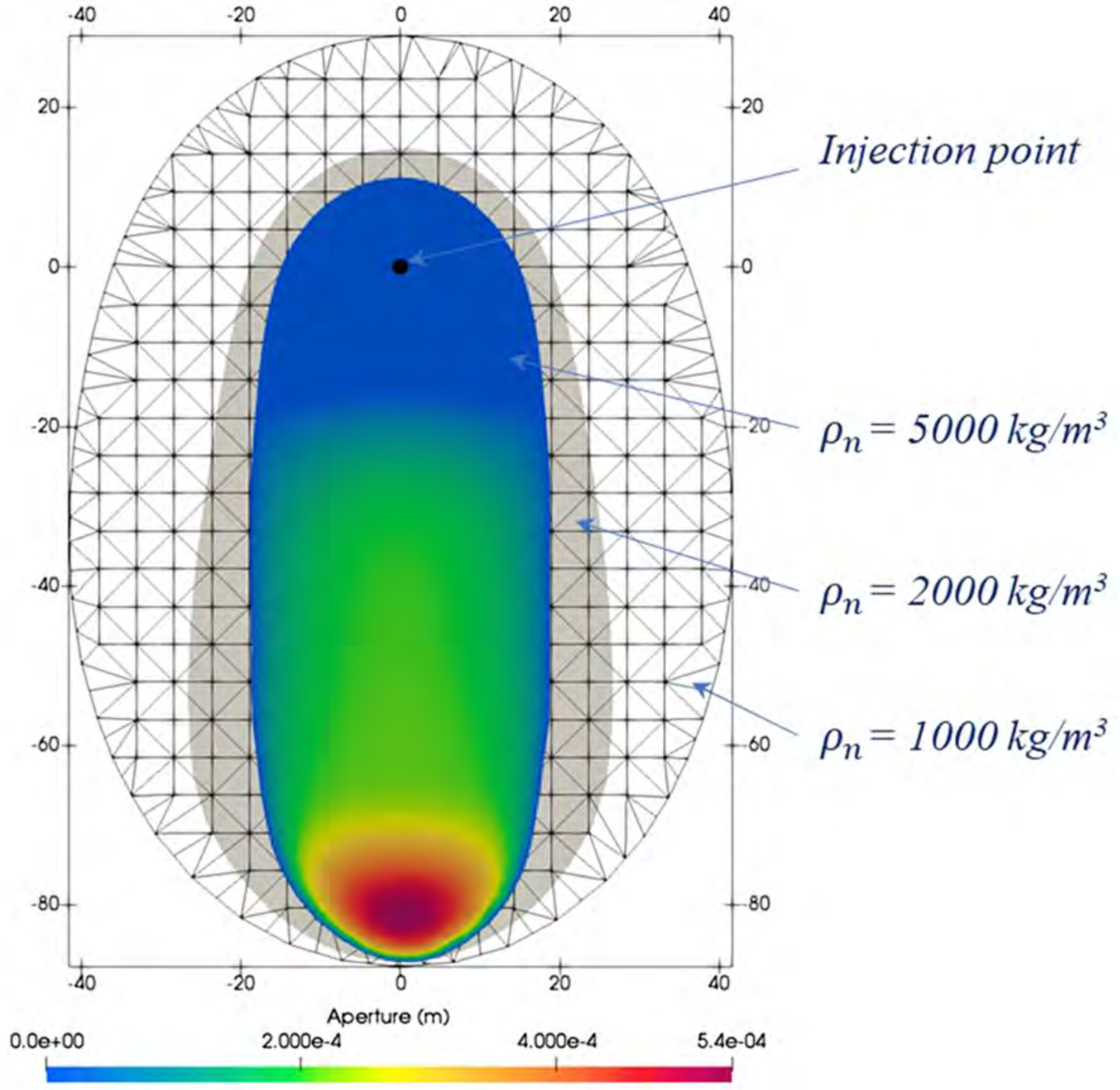
PyFrac

Zia and Lecampion, 2020
Möri and Lecampion
Peruzzo and Lecampion



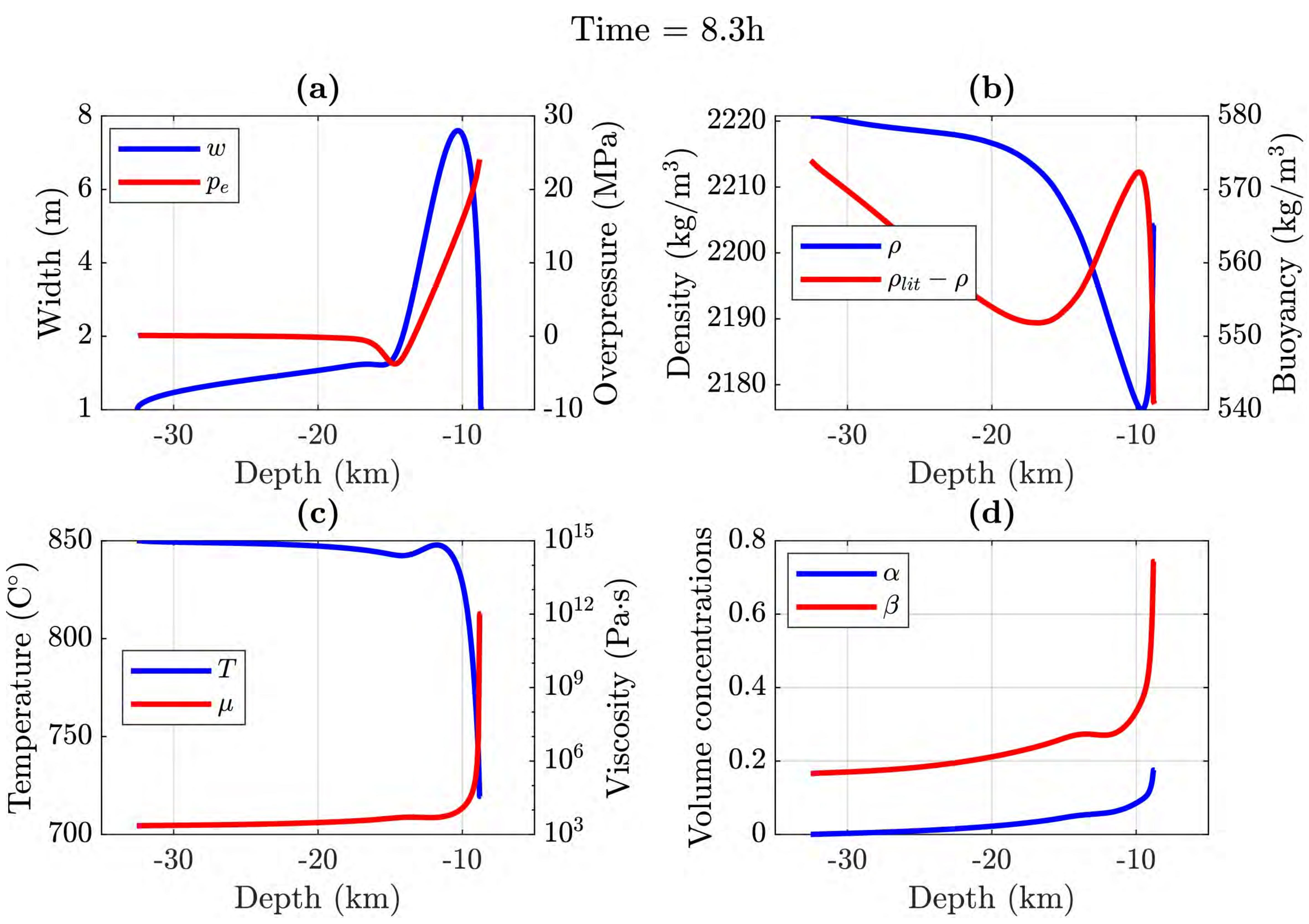


Salimzadeh et al., 2020

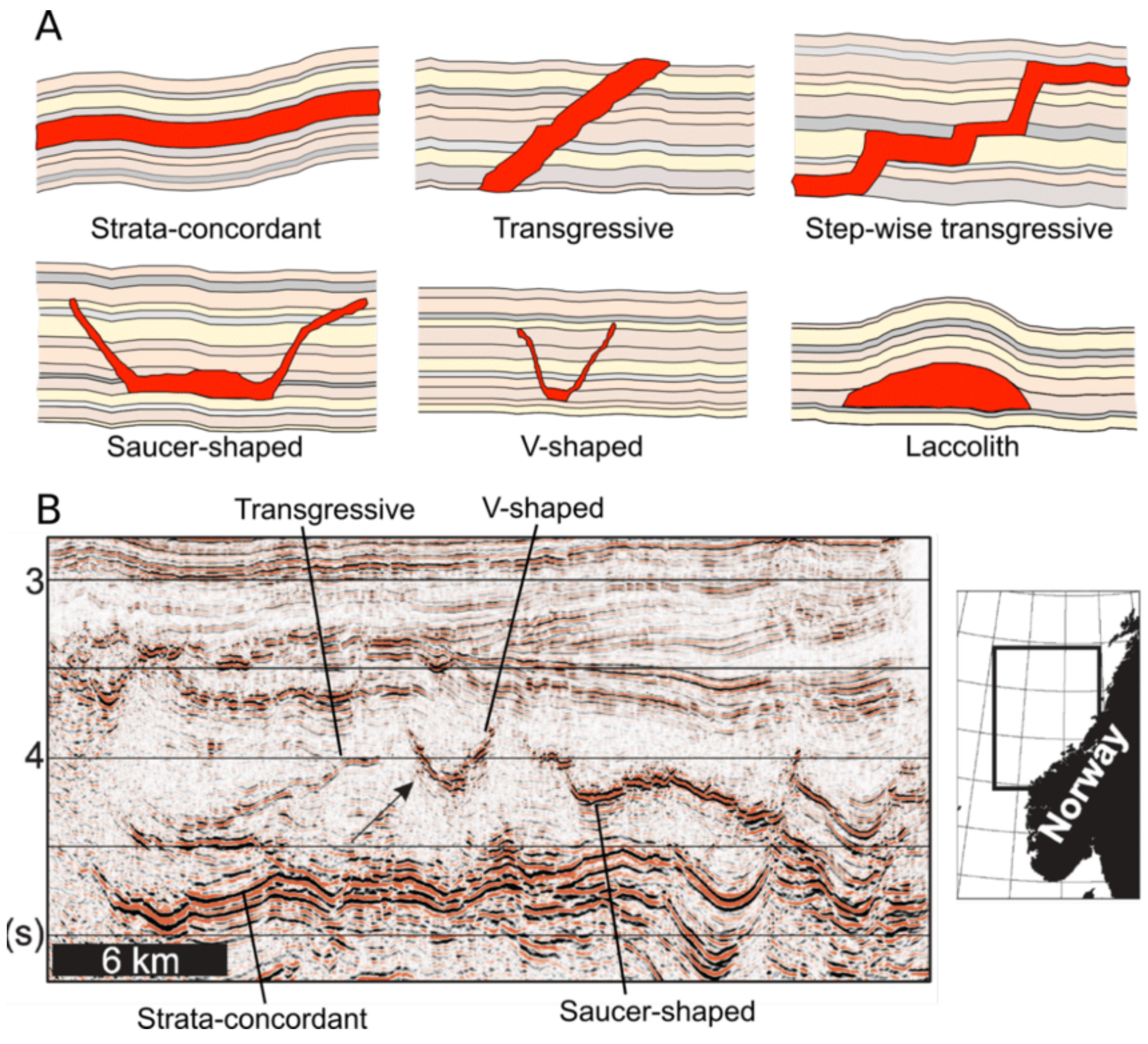


Magma properties

Rock rheology



Abdullin et al., 2024

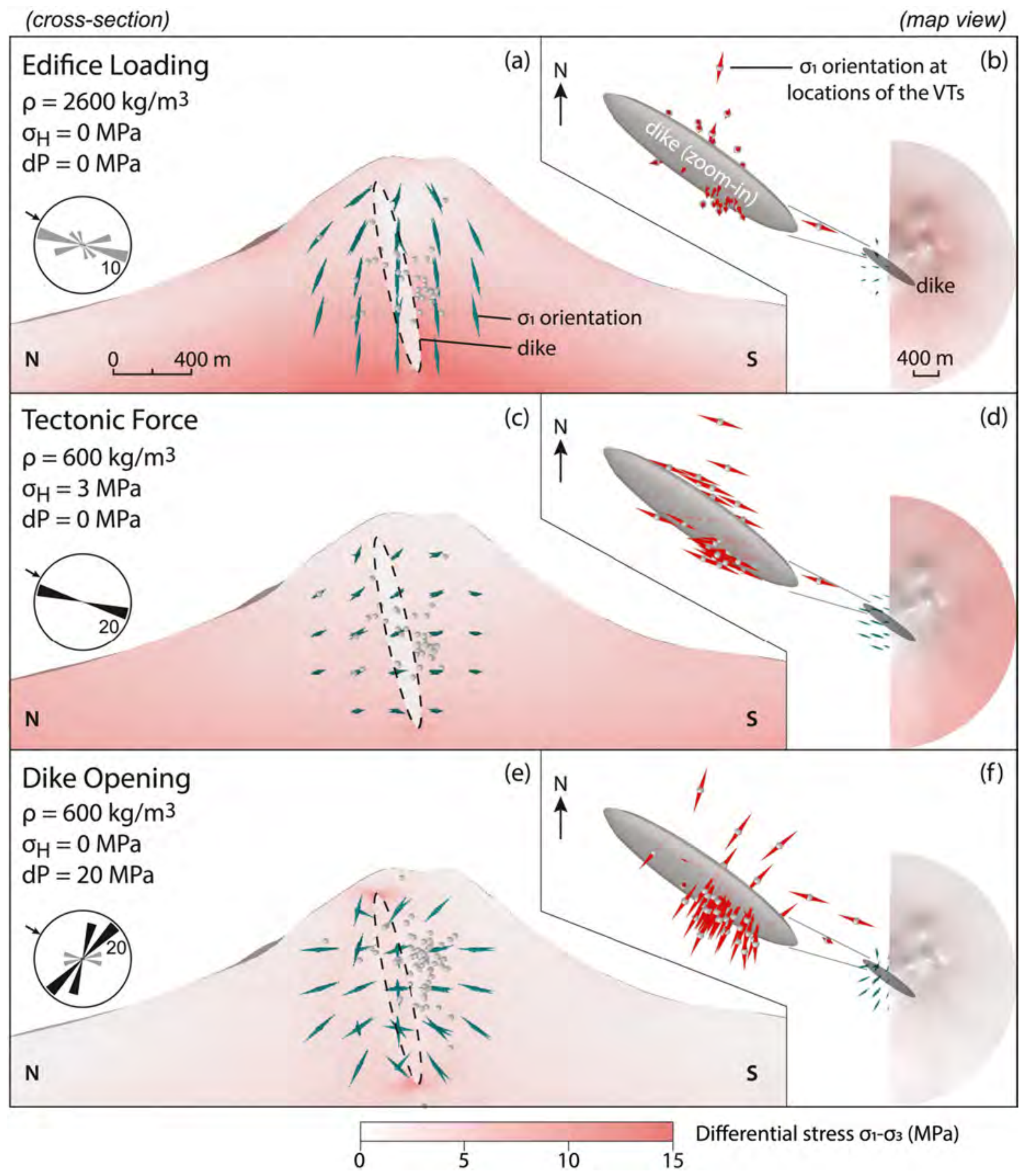


Galland et al., 2018

How can we constrain the stress field?

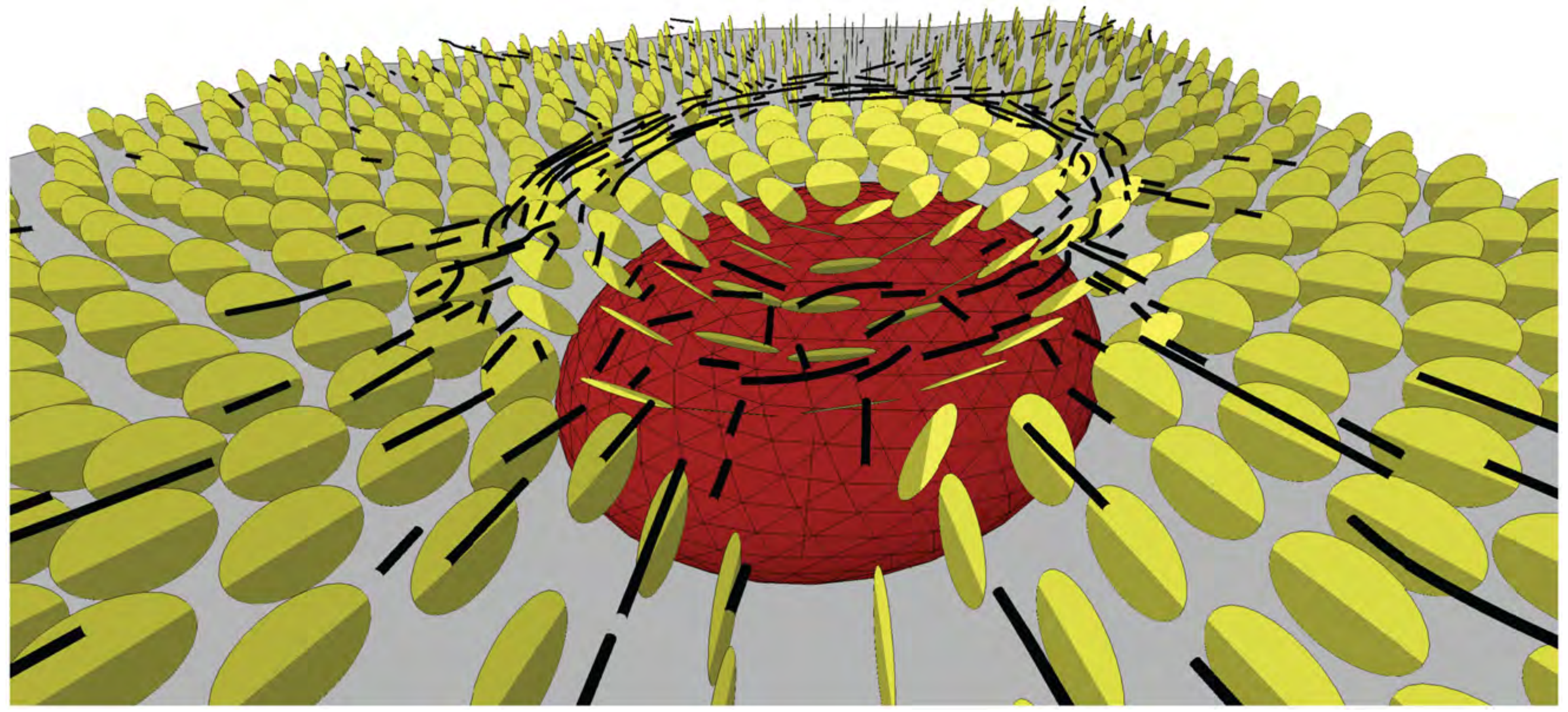
Focal Mechanisms

Zhan et al. 2022



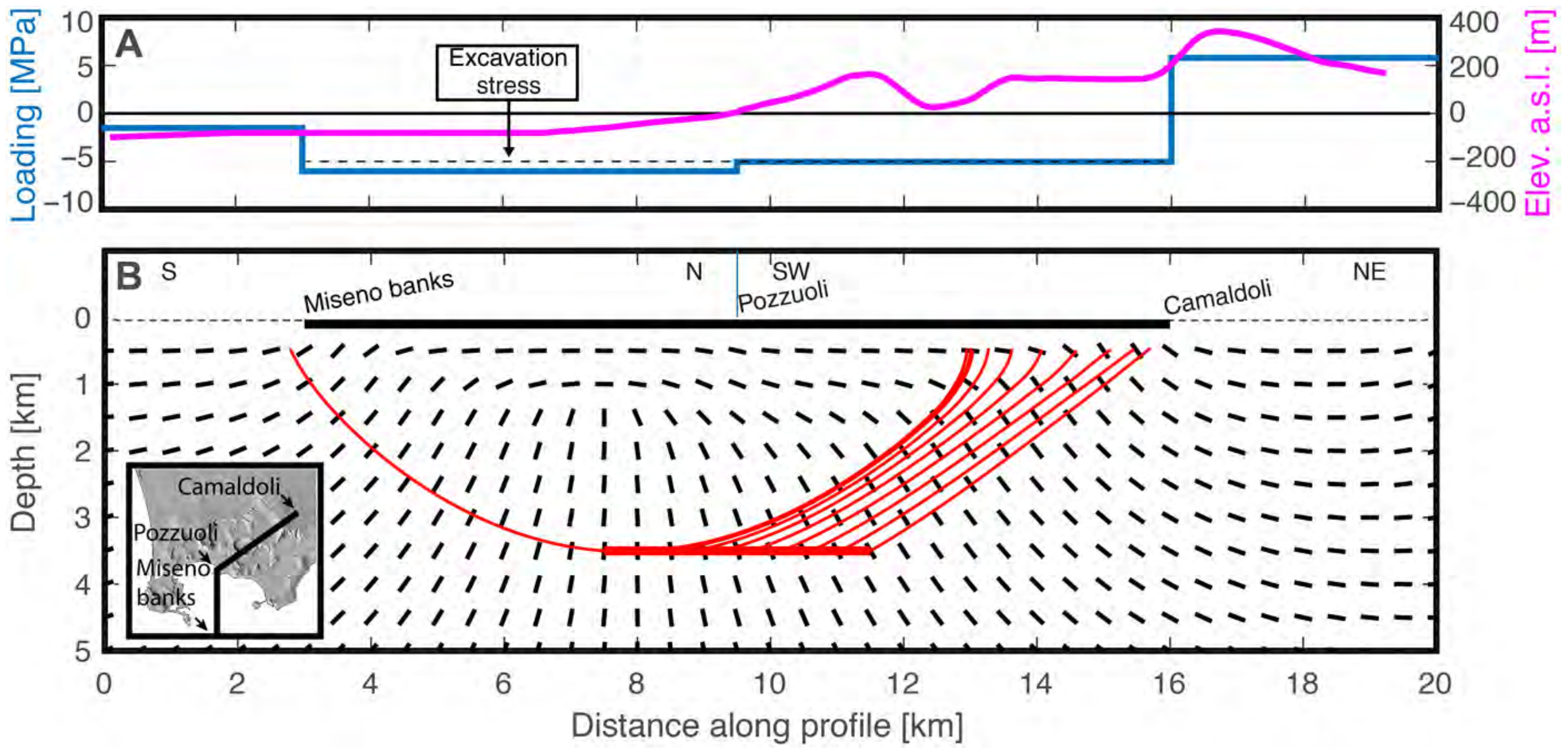
Orientation of dikes

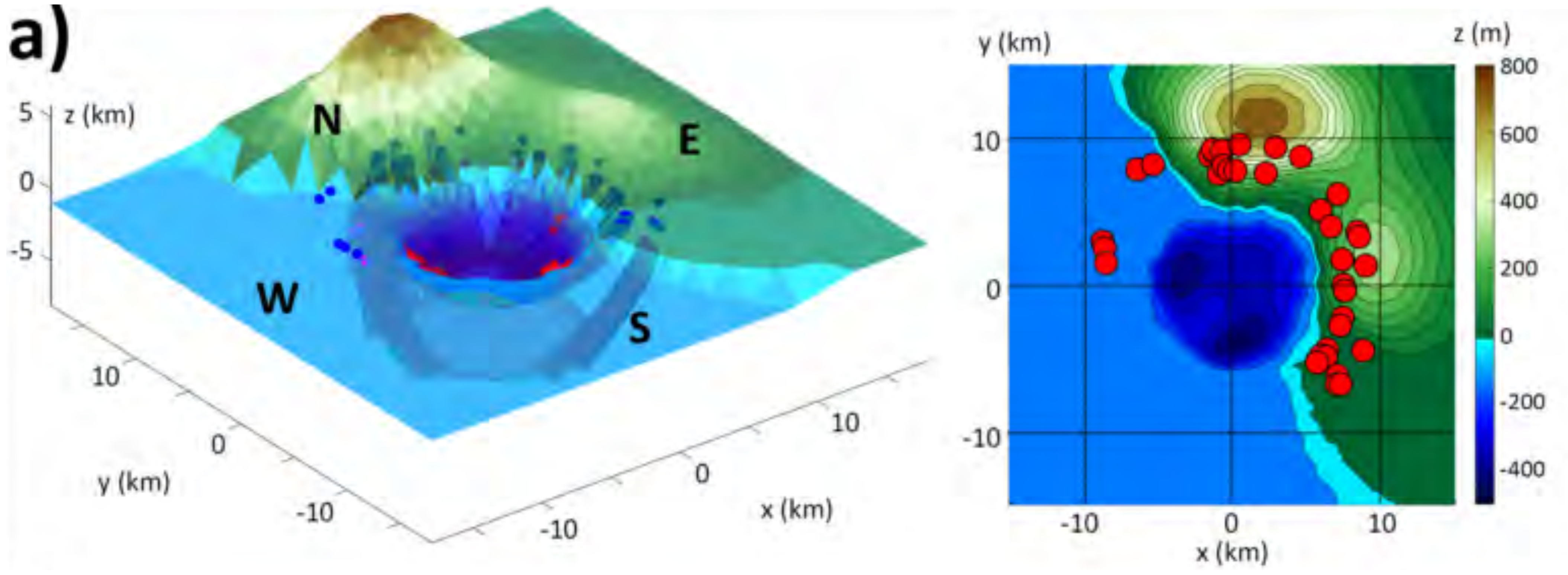
Marten et al., 2022



Eruptive vent patterns

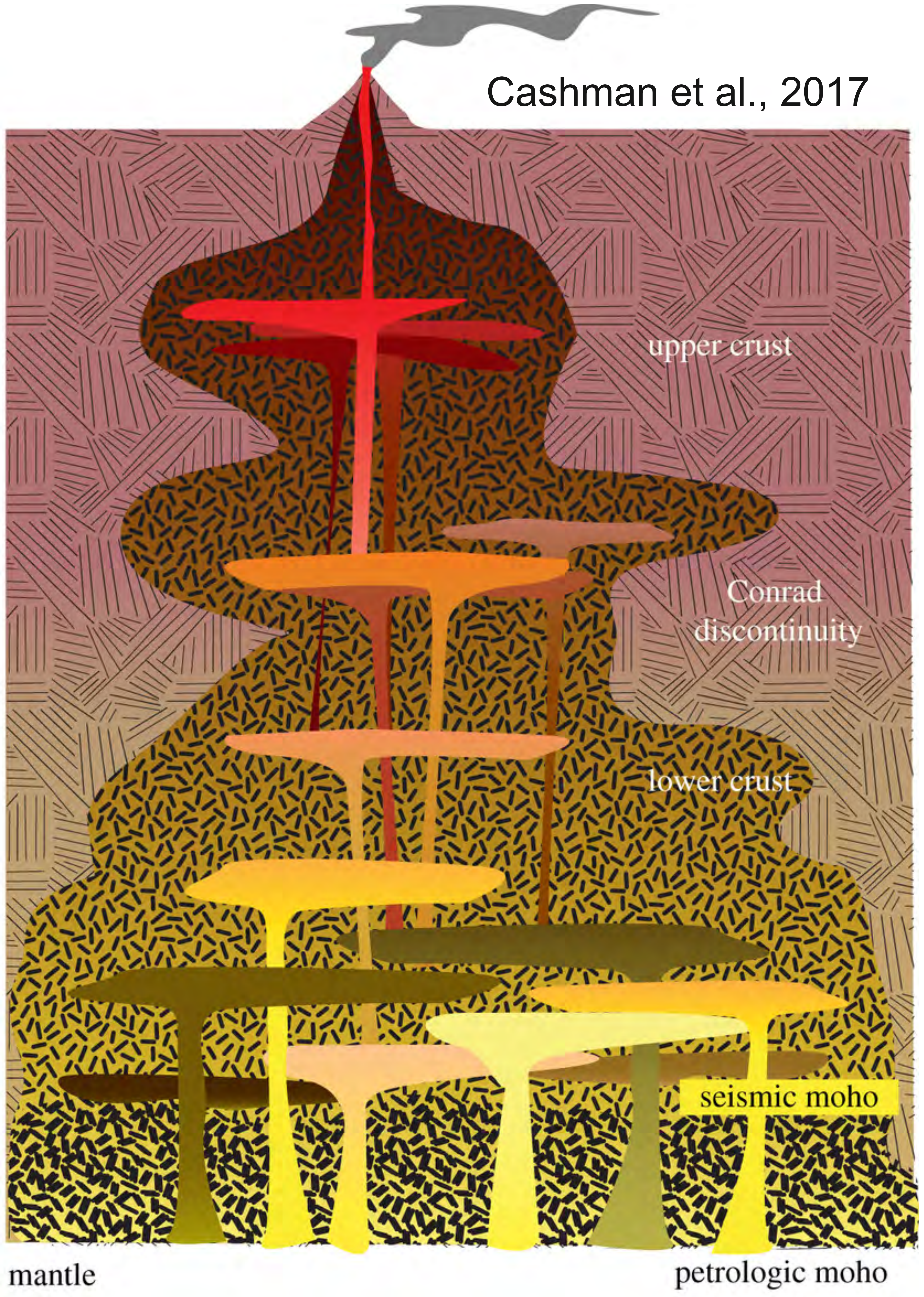
Rivalta et al., 2019
Mantiloni et al., 2024





Conclusions

- Elastic stress models reproduce broad vent and sill patterns in different contexts
- Vertical trapping (loading) and horizontal trapping (unloading) provide opportunity for magma evolution, host rock assimilation and interaction between successive magma batches
- A better understanding of rock and magma rheology at high pressure and temperature and under different strain rates is crucial to clarify transition from porous flow to magma-driven fractures



Thank you for your attention!