ISTerre

Institut de Recherche pour le Développement FRANCE

EAIFR ICTP—East African Institute for Fundamental Research

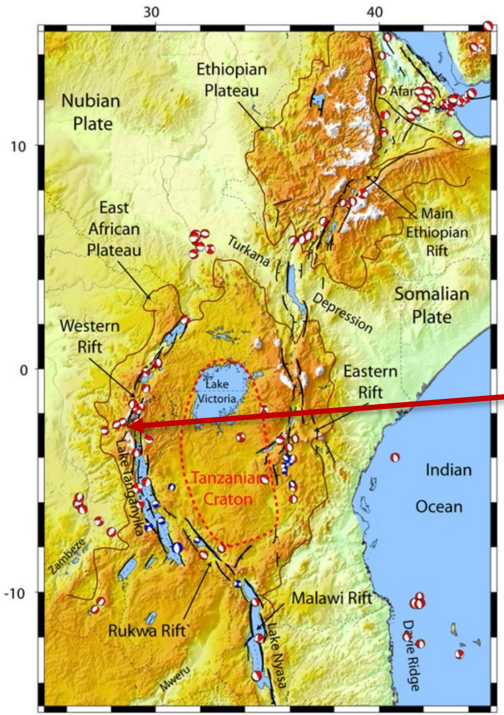
E-DOORs

unesco International Geoscience Programme

Towards a better understanding of subsurface magma propagation using numerical and analogue models, application to recent eruptions of Nyiragongo volcano

Virginie Pinel, C. Mériaux, S. Furst, F. Maccaferri, A. Gaete & M. M. H. Mohamed

Competition between vertical and lateral propagation in rift zones



East African Rift Zone
~5000-km long

DRC &Western Rwanda, **Lake Kivu**

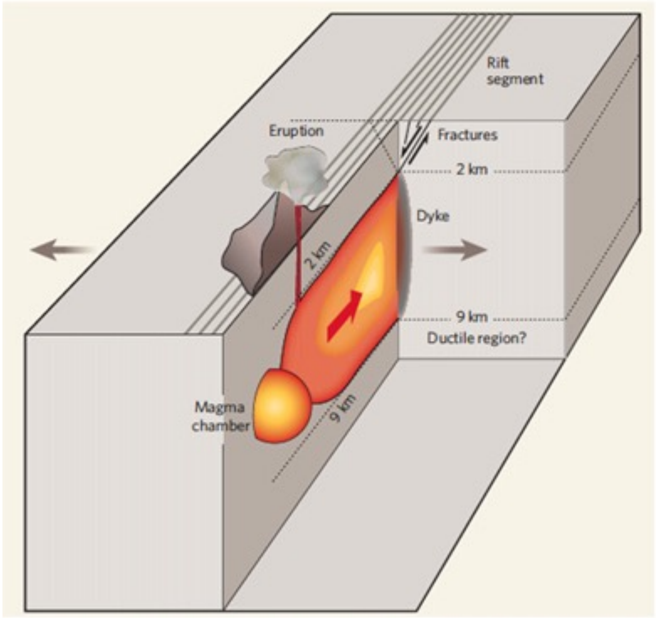
Rift direction N20°E, Extension N110°E

Spreading rate: 2.8 mm/yr

(Stamps et al., 2008)

Average vertical extension 10MPa

(Stamps et al., 2010)

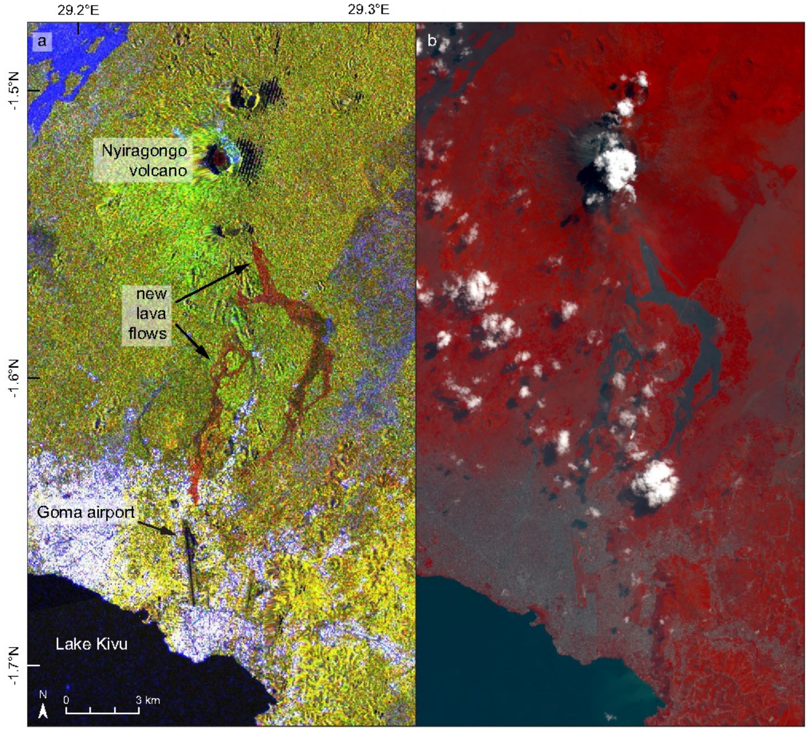


From Rivalta et al, 2015

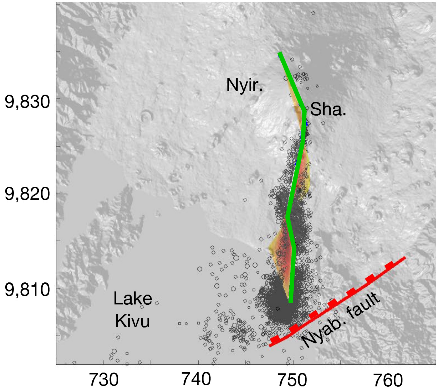
Extension + magmatic activity

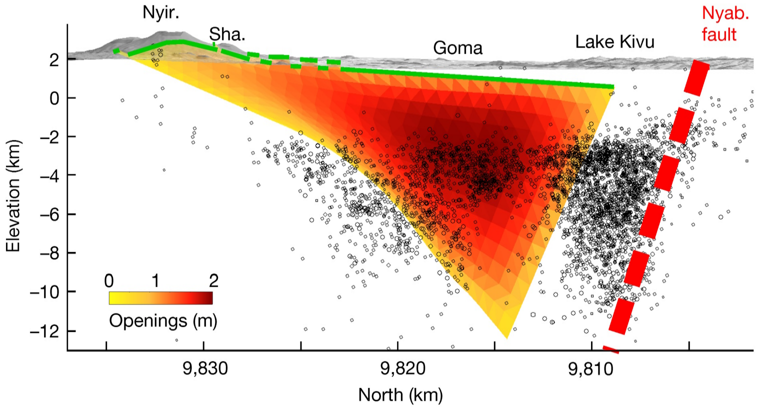
Nyiragongo volcano, DRC: 20 km of lateral propagation

1977, Jan. 2002, **May 2021**



From Poland, 2022

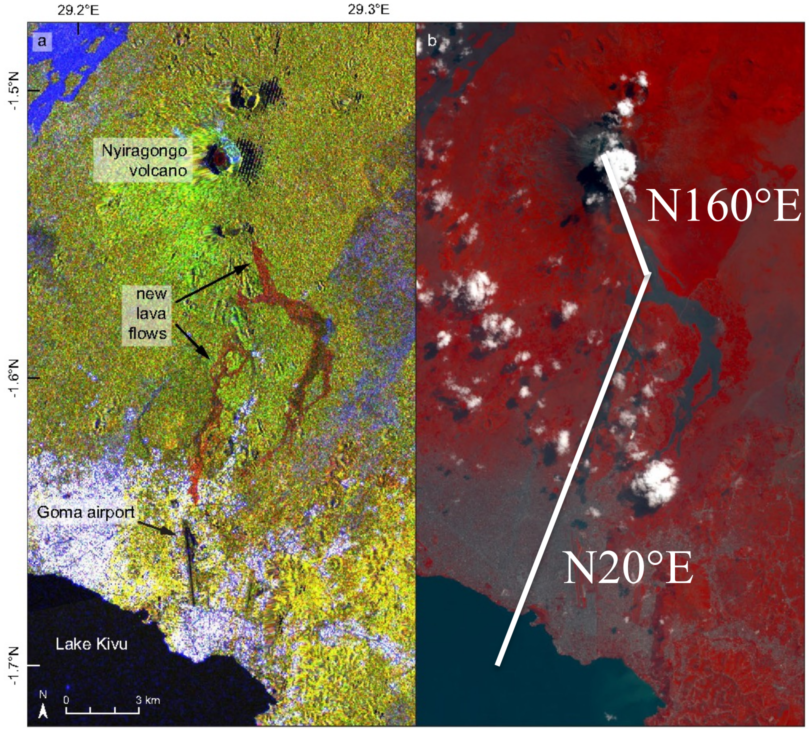




From Smittarello et al, Nature, 2022

Nyiragongo volcano, DRC: 20 km of lateral propagation

1977, Jan. 2002, May 2021



From Poland, 2022

Key questions:

- **will the magma reach** the surface?
- **where?**
- **when?**

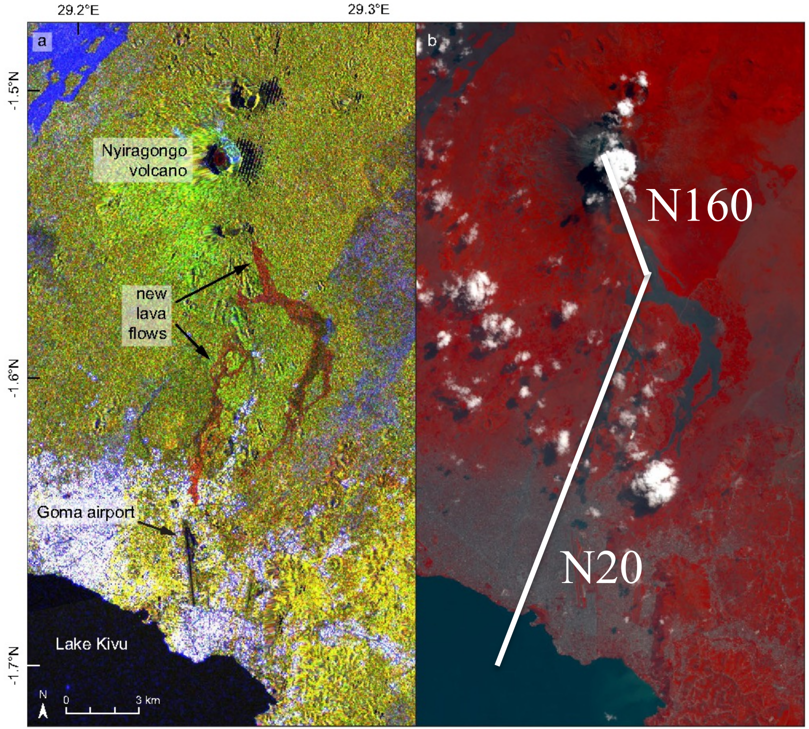
1. What controls the magma path and velocity?

2. Direction of propagation

→ lateral versus vertical

Nyiragongo volcano, DRC: 20 km of lateral propagation

1977, Jan. 2002, **May 2021**



From Poland, 2022

Key questions:

will the magma reach the surface?

where?

when?

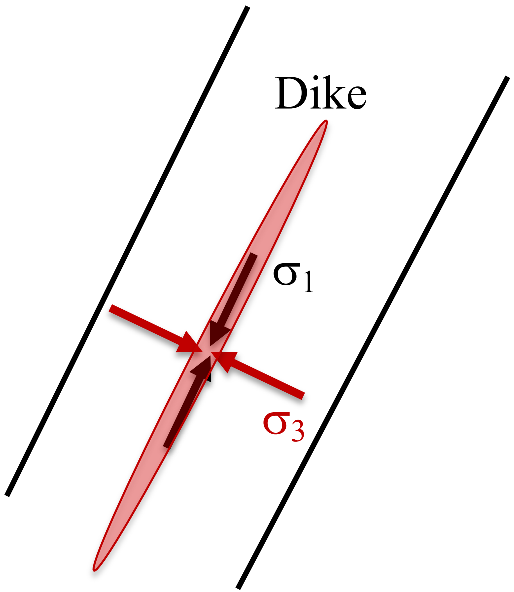
1. What controls the magma path and velocity?

2. Direction of propagation

→ lateral versus vertical

Dikes orientation is function of the local stress field

When the deviatoric stress field is large dykes should open perpendicular to the minimum compressive stress σ_3 *(Anderson, 1951)*

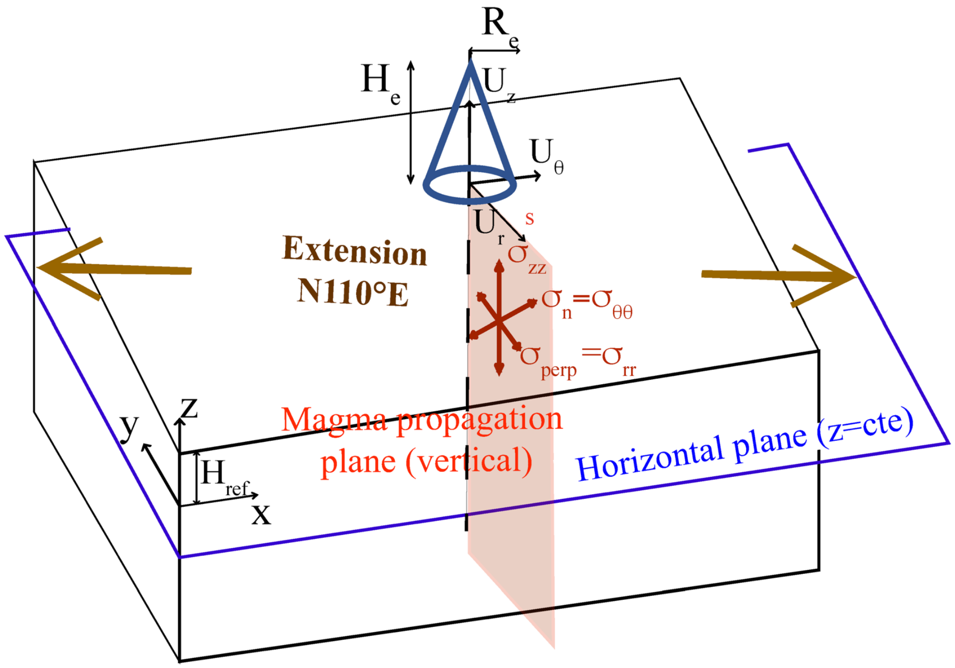


Modeling strategy for Nyiragongo case

3D stress field calculation:
-Lithostatic reference state
-Extension (N110°E)
-Edifice load

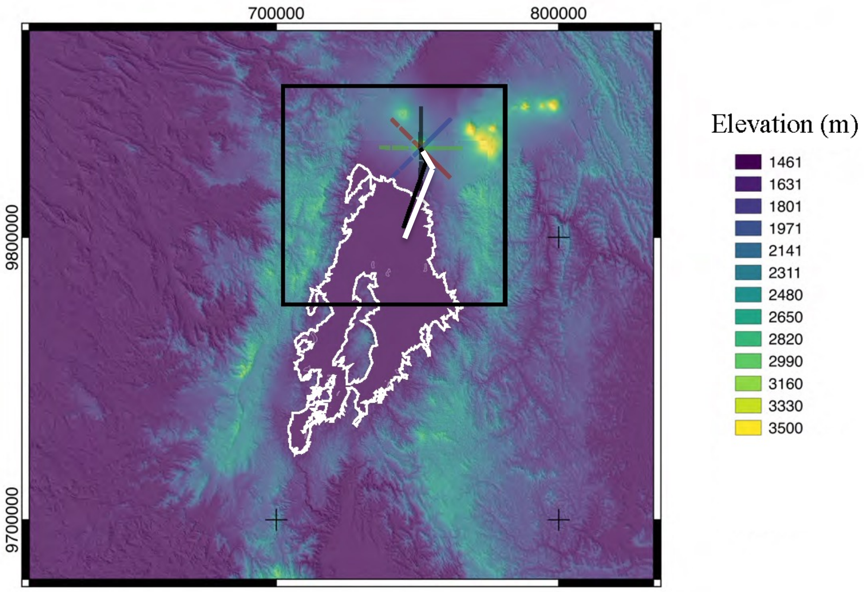
*Stress in horizontal plane
--> Dyke orientation

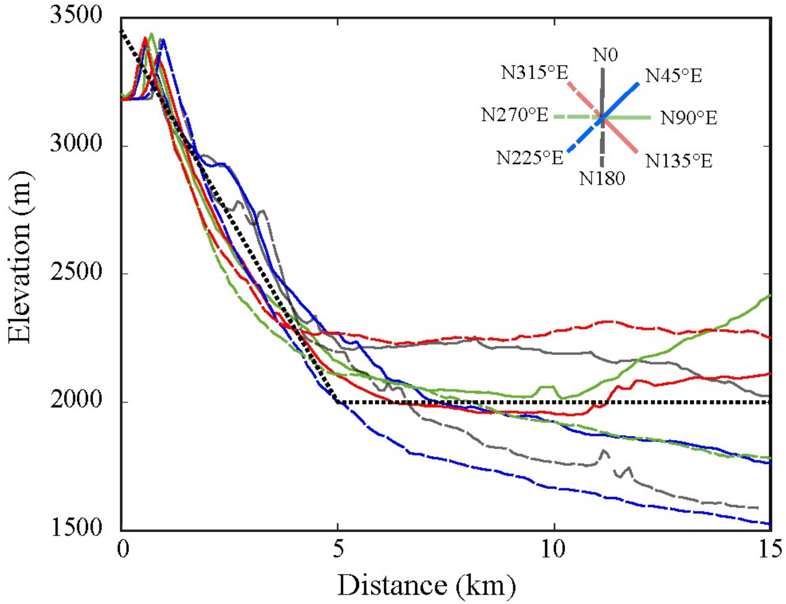
*Stress in vertical plane
--> Direction of propagation



Analytical solution
Conical load applied at H_{ref}=2km

Nyiragongo volcano topography



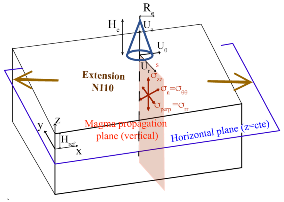


Nyiragongo edifice: 3470 m a.s.l.
Maximum water depth in Lake Kivu: 475 m

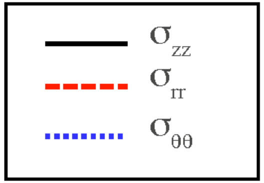
Nyiragongo topography
can be approximated by a **conical load**
(radius Re=5 km, He=1450 m lying above Href=2000m)

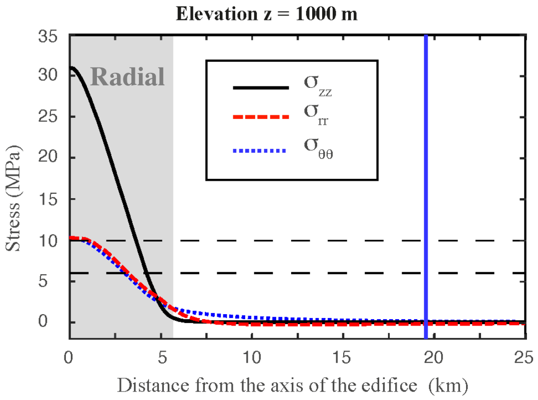
Topography decreases more towards the South, South-West

Edifice load effect is dominant at shallow level beneath the volcano

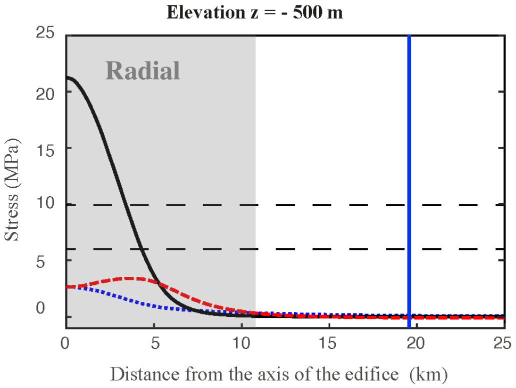


Analytical solution

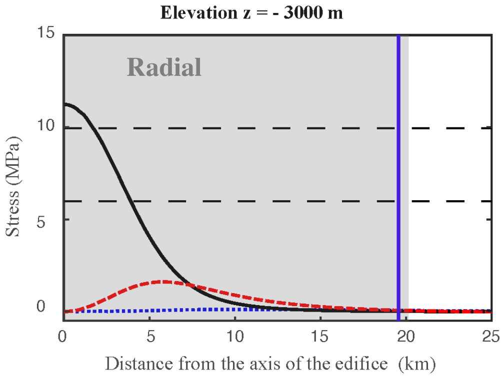




Depth = 0.2*R_e



Depth = 0.5*R_e

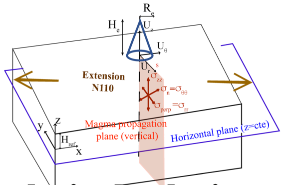


Depth = R_e

Increasing depth

Pinel & Mériaux, 2025

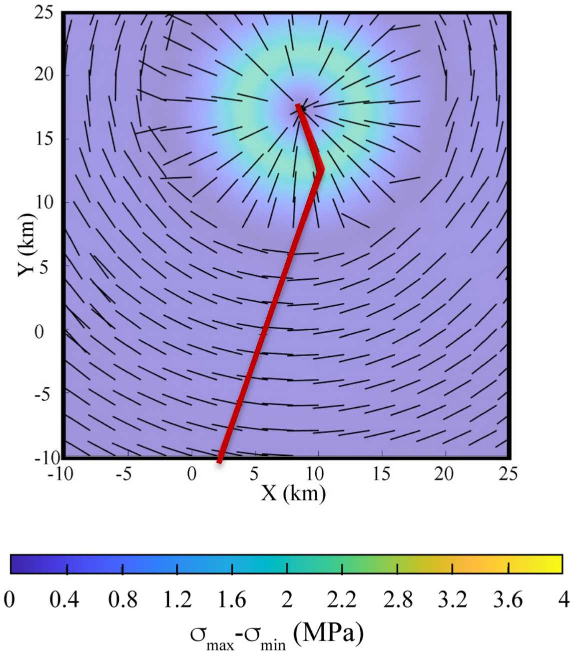
Dyke orientation: Maximum compressive stress direction in horizontal planes

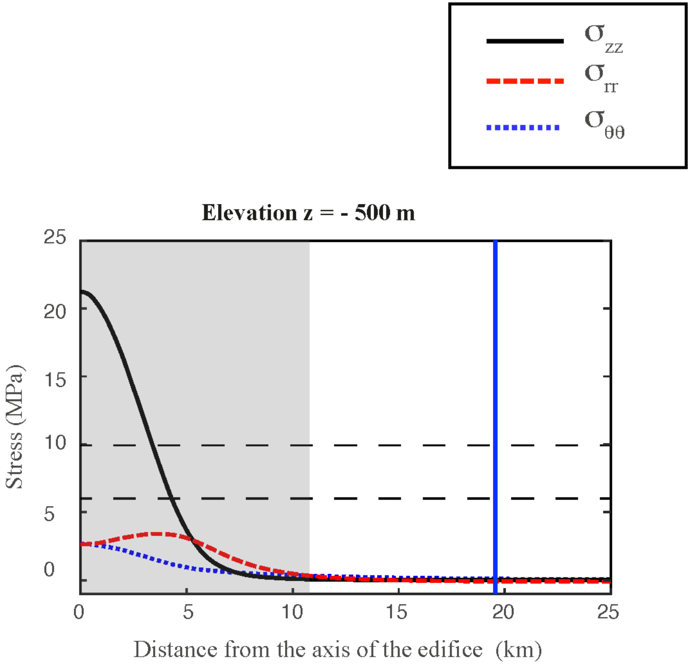


Analytical solution

No extension

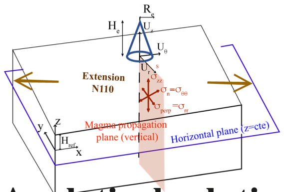
z=-500 m





Pinel & Mériaux, 2025

Dyke orientation: Maximum compressive stress direction in horizontal planes



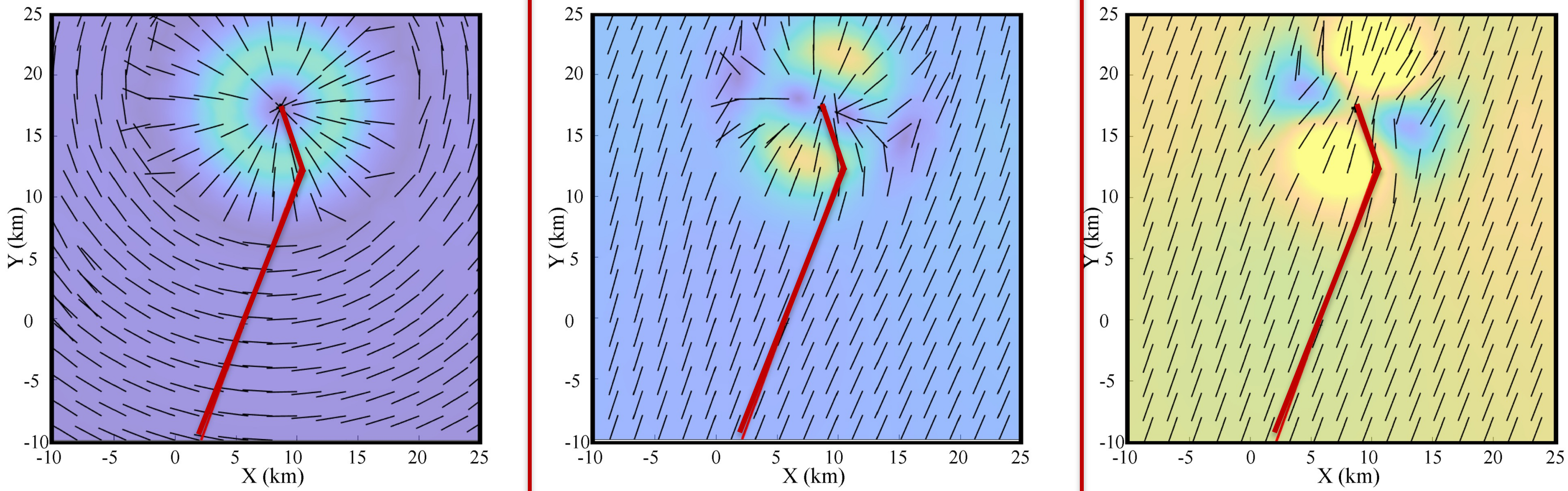
Analytical solution

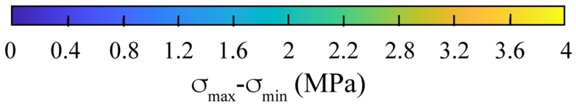
No extension

Uniform Extension
N110°E, σ=1 MPa

Uniform Extension
N110°E, σ=3MPa

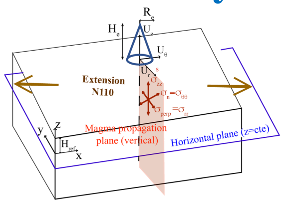
Z=-500 m



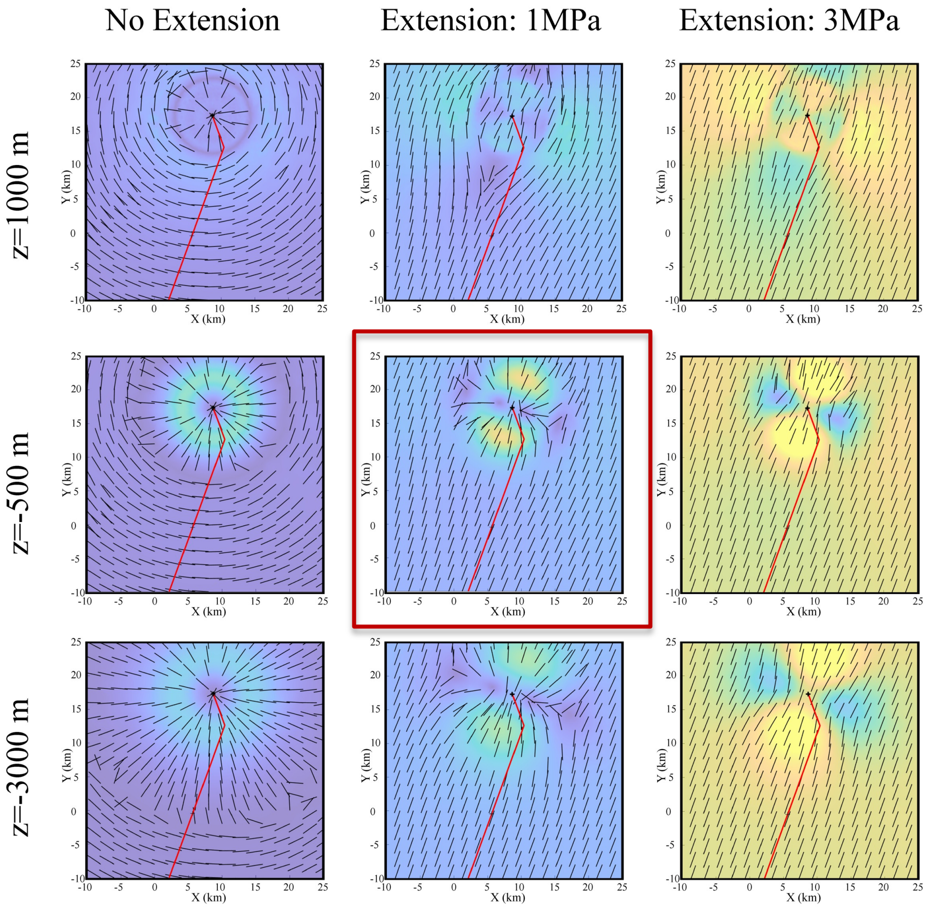


Pinel & Mériaux, 2025

Dyke orientation: Maximum compressive stress direction in horizontal planes



Analytical solution

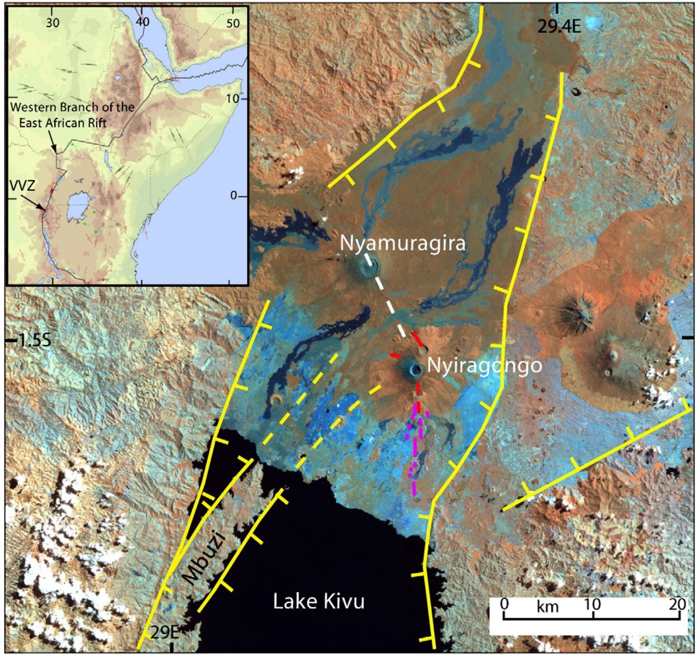


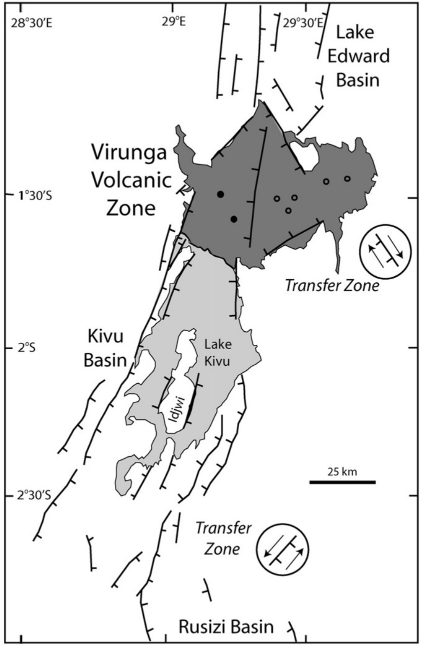
An extension of 0.5 to 2 MPa, at a depth of between 500 m and -3000 m

→ Consistent dyke orientation

Pinel & Mériaux, 2025

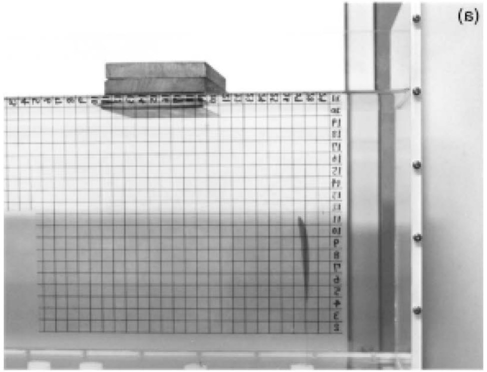
But tectonic stress is more complex
Local faults

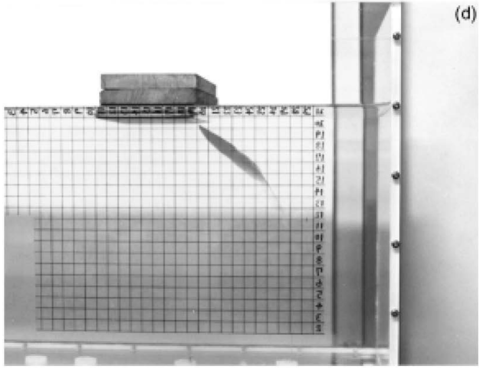


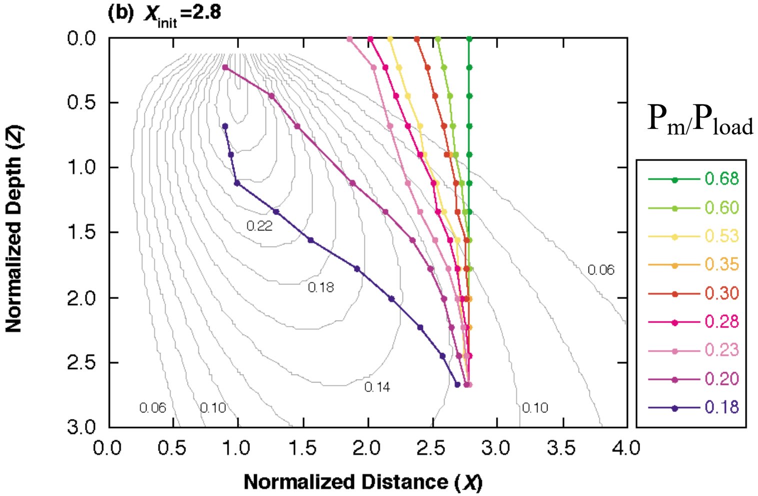


From Wadge & Burt , 2011

Orientation also depends on the magma driving pressure







Local stress field influences the magma path: $R=\sigma_{xy}/P_m$

If R>0.2 deflection

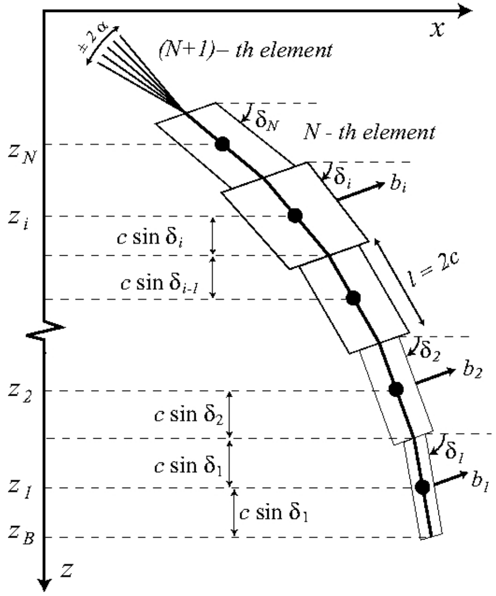
From Watanabe et al, 2002

2D quasi-static model → path

A buoyant isolated crack modelled by BEM

The orientation that maximizes
the total energy release is chosen.

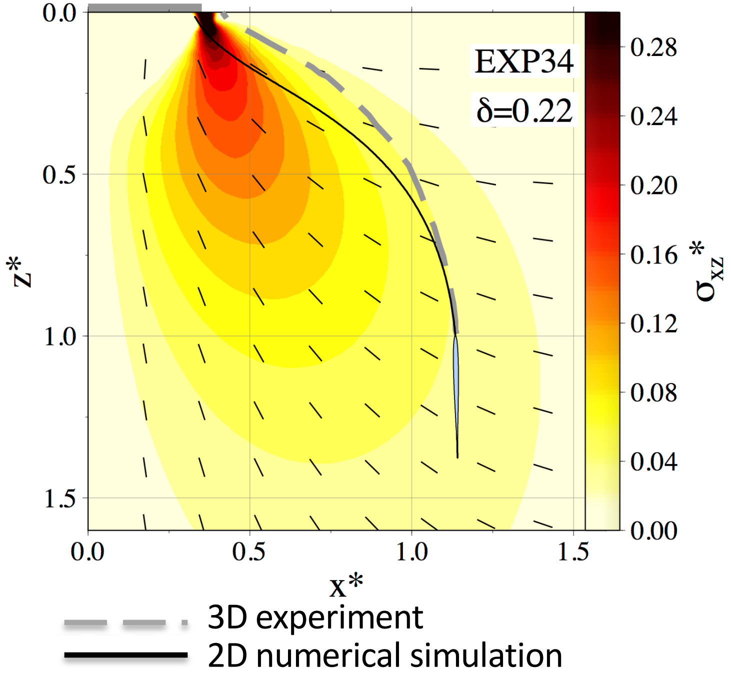
(strain + gravitational energy)

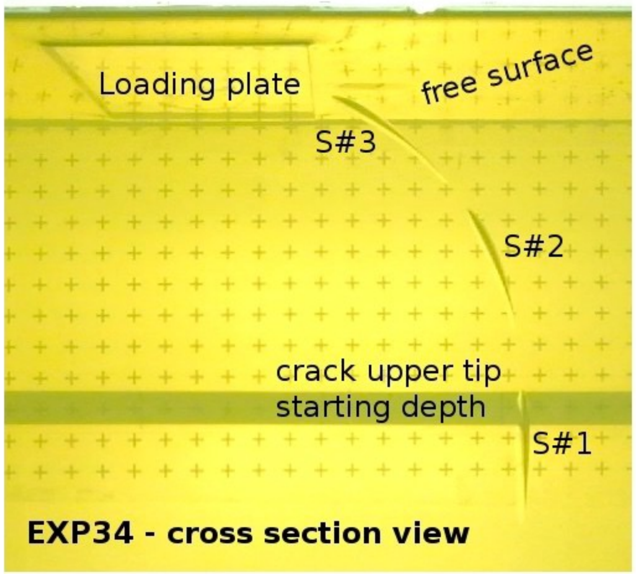


From Maccaferri et al, JVGR, 2011

Comparing numerical and analogue models

Criterion $\delta=\sigma_{xy}/(P_m{}^*L^*)$



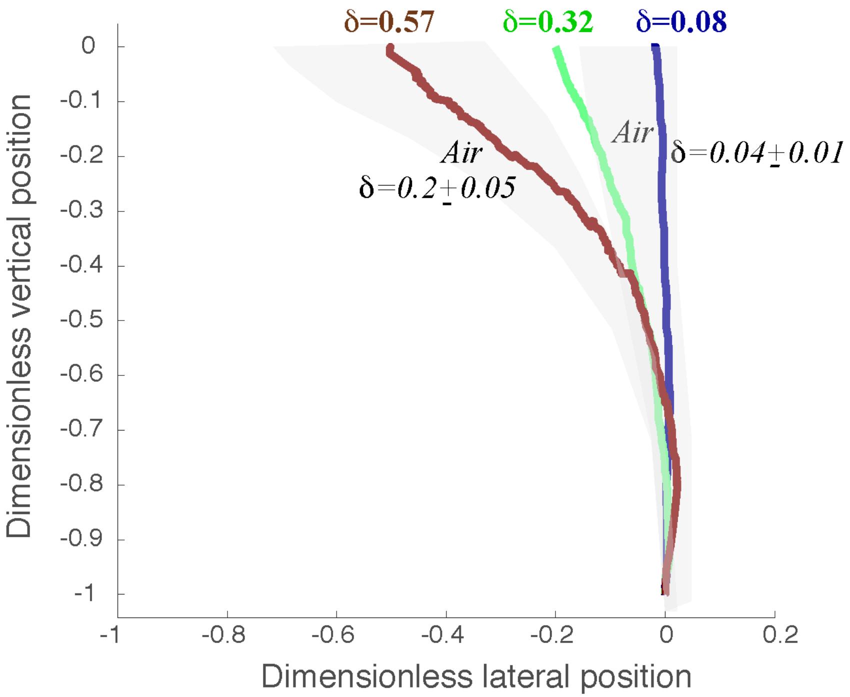


From Maccaferri et al, 2019

Influence of fluid viscosity…

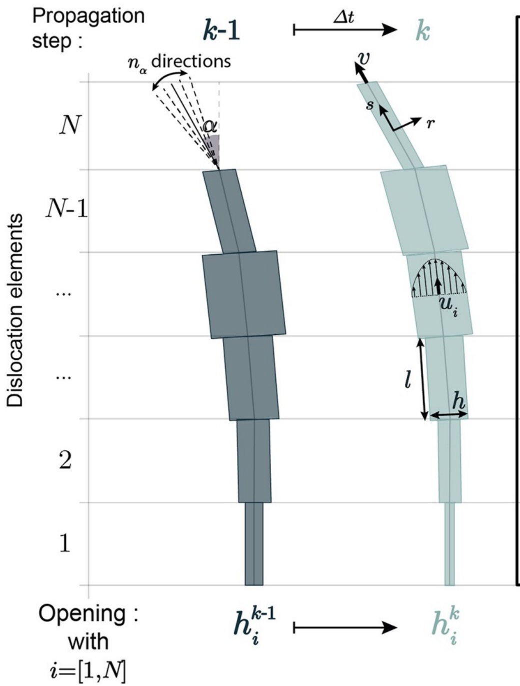
Injection of silicon oil
50 000 more viscous than air

Criterion $\delta=\sigma_{xy}/(P_m*L^*)$



Deflection decreases when viscosity increases

New dynamical models with full coupling



2D Volume variation :

$\Delta V_N = l(h_N^k - h_N^{k-1})$

$\Delta V_{N-1} = l(h_{N-1}^k - h_{N-1}^{k-1})$

...

...

$\Delta V_2 = l(h_2^k - h_2^{k-1})$

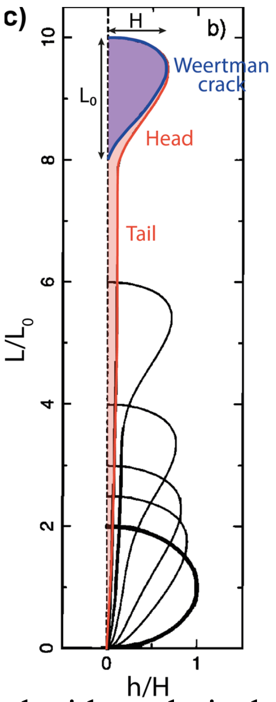
$\Delta V_1 = l(h_1^k - h_1^{k-1})$

$$\Delta E = \Delta E_f \cdot l + \Delta E_v$$

$$v = \frac{\Delta E - \Delta E_f \cdot l}{\eta \cdot D'}.$$

With

$$\Delta E_f = K_c^2 \frac{1 - nu}{2G}.$$



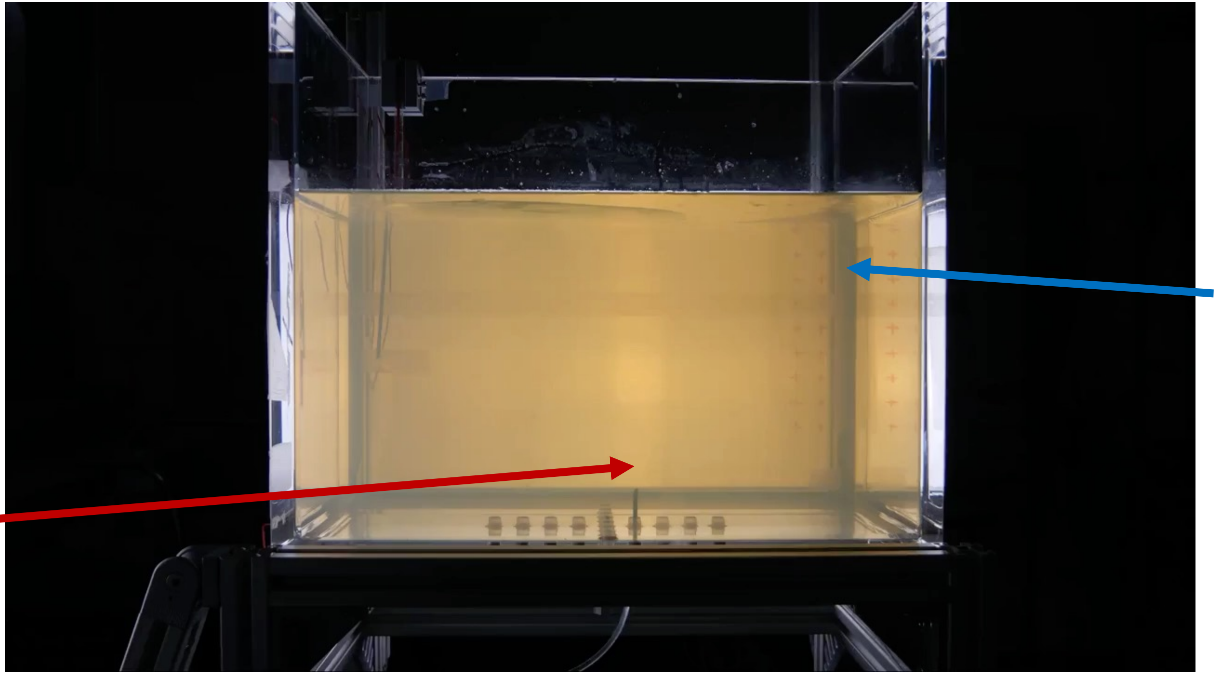
Validated with analytical solutions for the viscous contribution

(strain + gravitational energy + viscous energy → velocity)

From Furst et al., JGR, 2023

Validation by oil injection inside gelatin

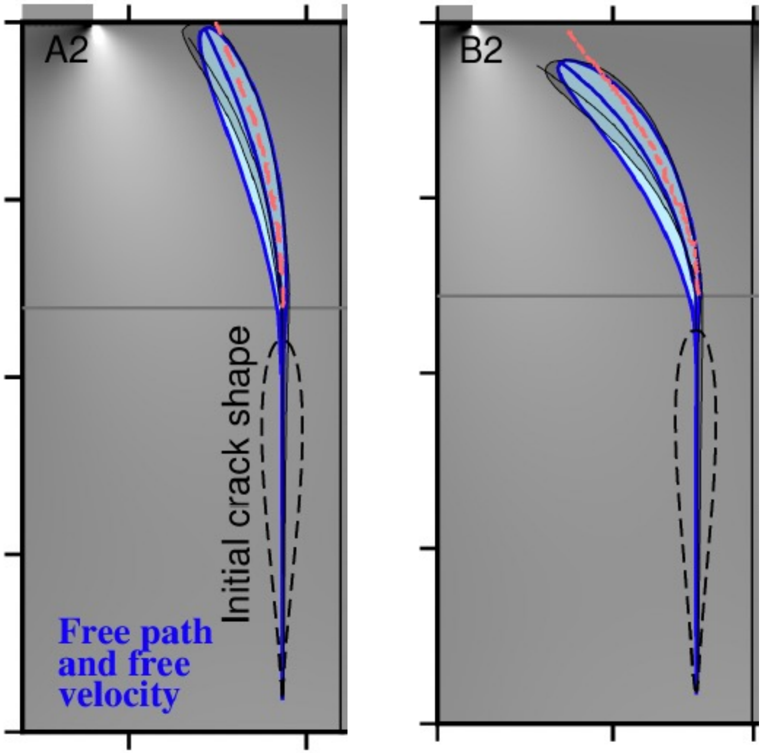
→ trajectories, velocities



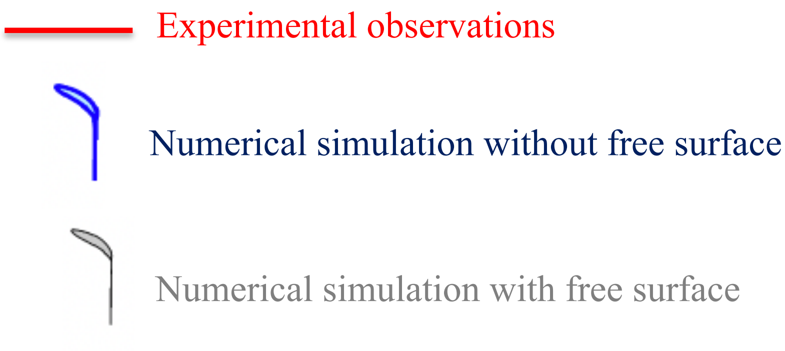
Elastic medium
(E, ν, K_c, ρ)
Salty gelatin/crust

Fluid
(μ, ρ)
Silicon oil/magma

Path consistency

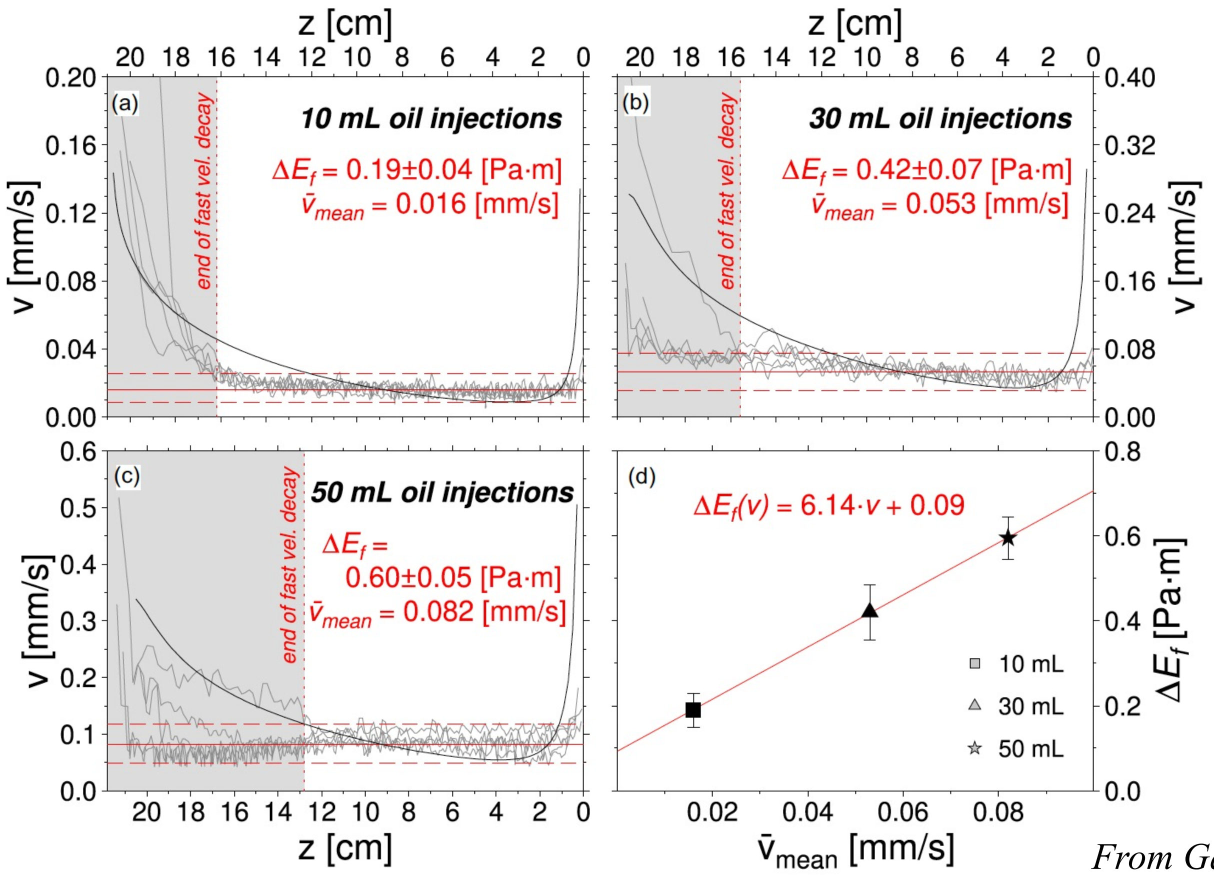


Oil viscosity 0.97 Pas



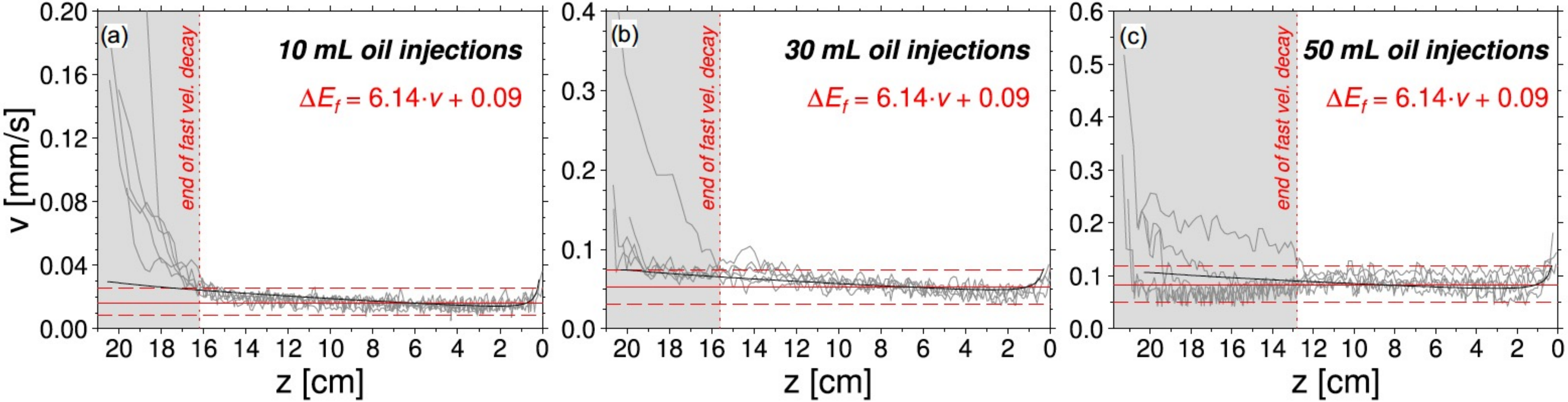
From Furst et al., Volcanica, 2024

Fracture toughness depends on velocity



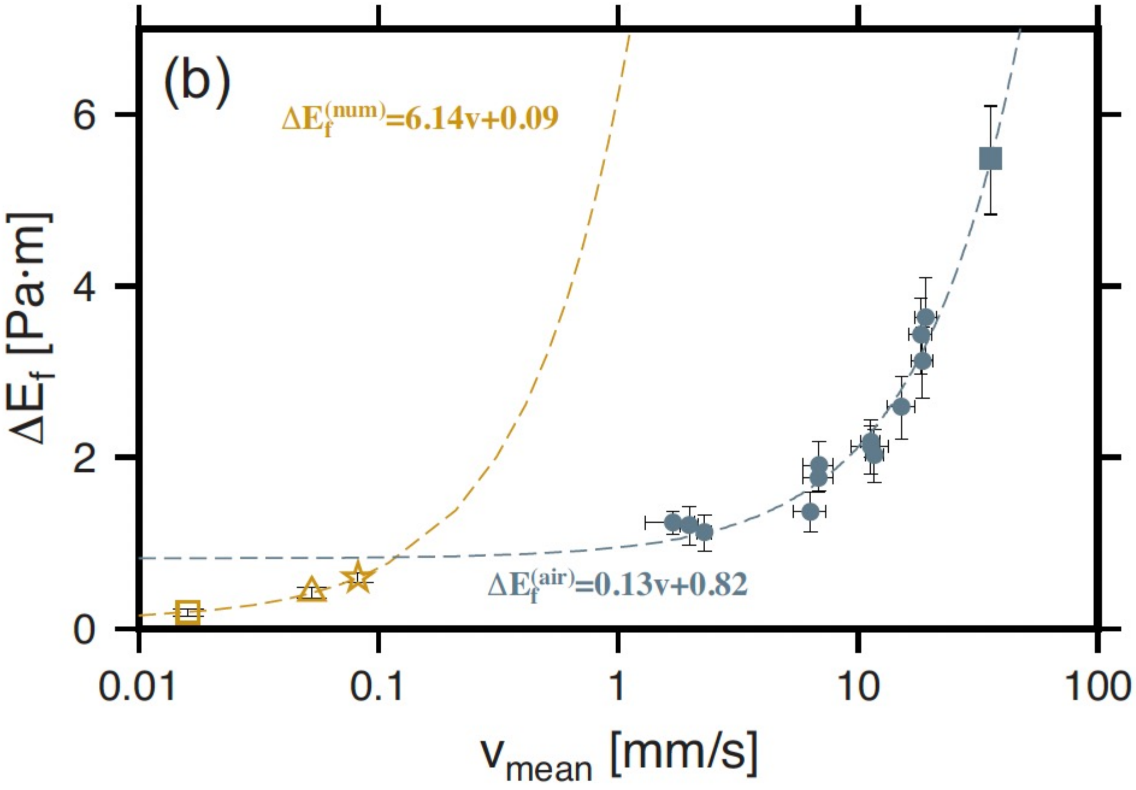
From Gaete et al., GJint, 2025

Kc(v) need to be an input of the numerical simulation



From Gaete et al., GJint, 2025

We need to constrain Kc=f(v) for the magma velocities



From Gaete et al., GJint, 2025

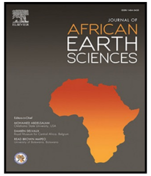
Conclusions on orientation of propagation

First order of magma path given by the local stress field at Nyiragongo volcano

r < 5km edifice load

r > 5 km rift extension

Pinel & Mériaux, 2025



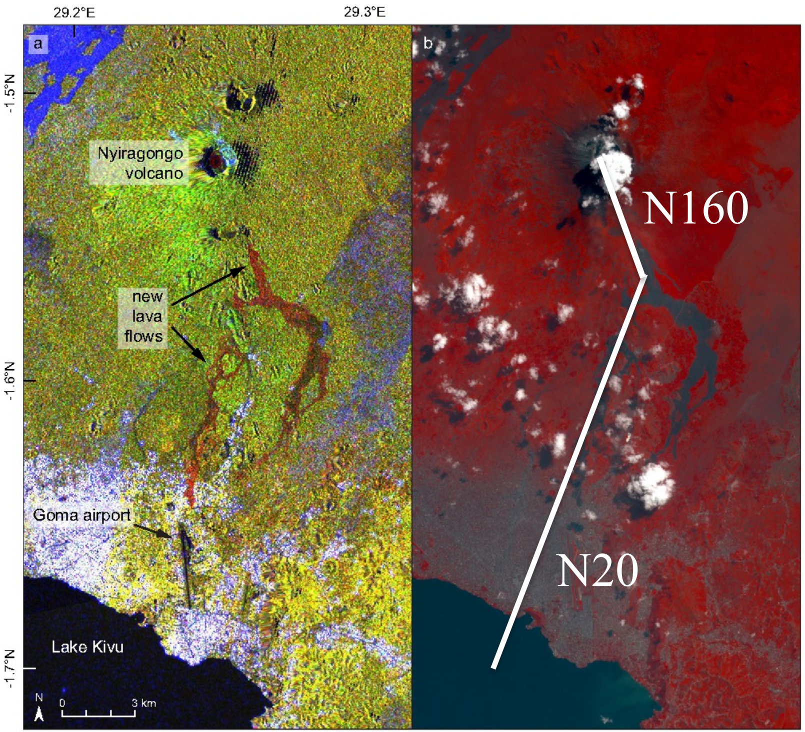
Moving forward:

-We need a better stress field characterization (faults)

-2D models of magma propagation can improve the path prediction and provide information on the velocity but a better characterization of the crustal fracure toughness is needed

Nyiragongo volcano, DRC: 20 km of lateral propagation

1977, Jan. 2002, **May 2021**



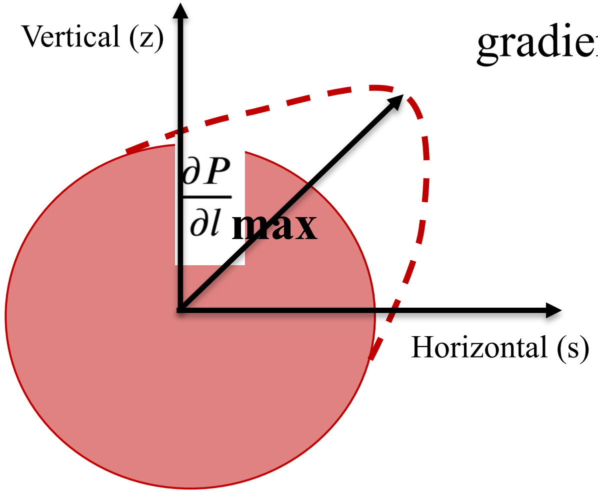
From Poland, 2022

Orientation→ magma path
r < 5km edifice load
r > 5 km rift extension

Direction of propagation
→ lateral versus vertical

Theoretical principle

A penny shaped crack will propagate in a direction corresponding to the **maximum pressure gradient** (quasi static case)→ maximum stress intensity factor K_I



Internal pressure gradient

Buoyancy

External stress field

$$\frac{\partial P}{\partial l} = \frac{\partial P_{buoy}}{\partial l} - \frac{\partial \sigma_n}{\partial l}$$

Promote magma ascent

Vertical effect

$$\frac{\partial P_{buoy}}{\partial s} = 0,$$

$$\frac{\partial P_{buoy}}{\partial z} = (\rho_c - \rho_m)g,$$

Promote magma propagation towards maximum value of extension

Vertical + lateral effect

Tada et al. 2000

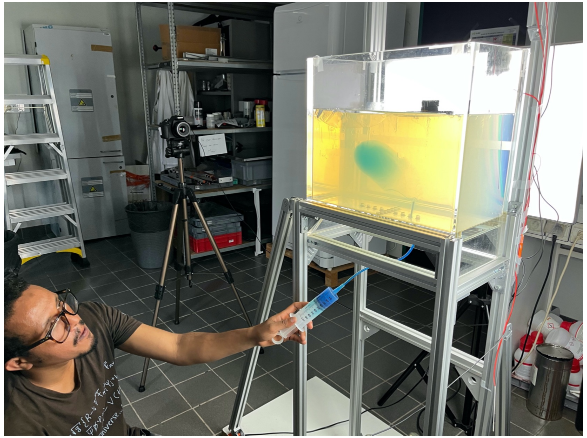
Davis et al., 2021

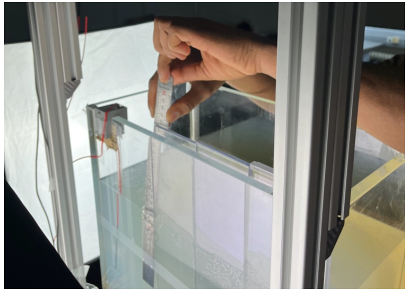
This approach neglects the potential effects of:

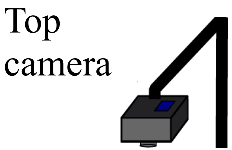
- the dyke non-isotropic shape
- magma flow

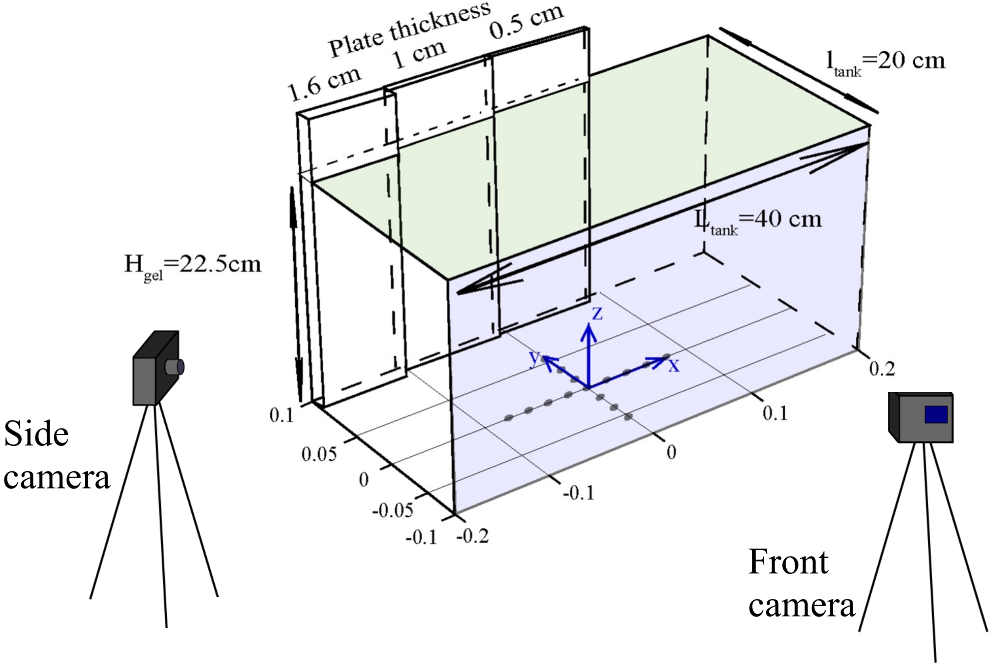
→ Need for validation

Experimental validation: Oil injection inside gelatin









Measured gelatin properties:

-density *($1000<\rho_{gel}<1104$ kg/m^3)*

-Young's modulus *($1250<E_{gel}<2193$Pa)* *(Smittarello et al. 2021)*

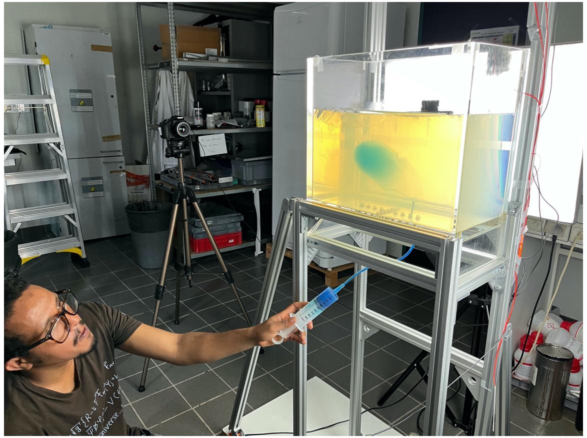
-ν close to 0.5

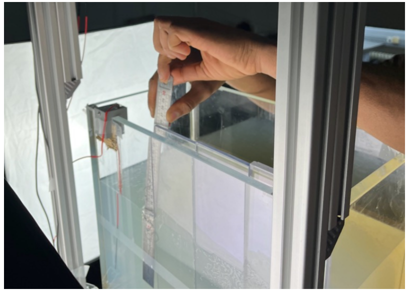
Known oil properties:

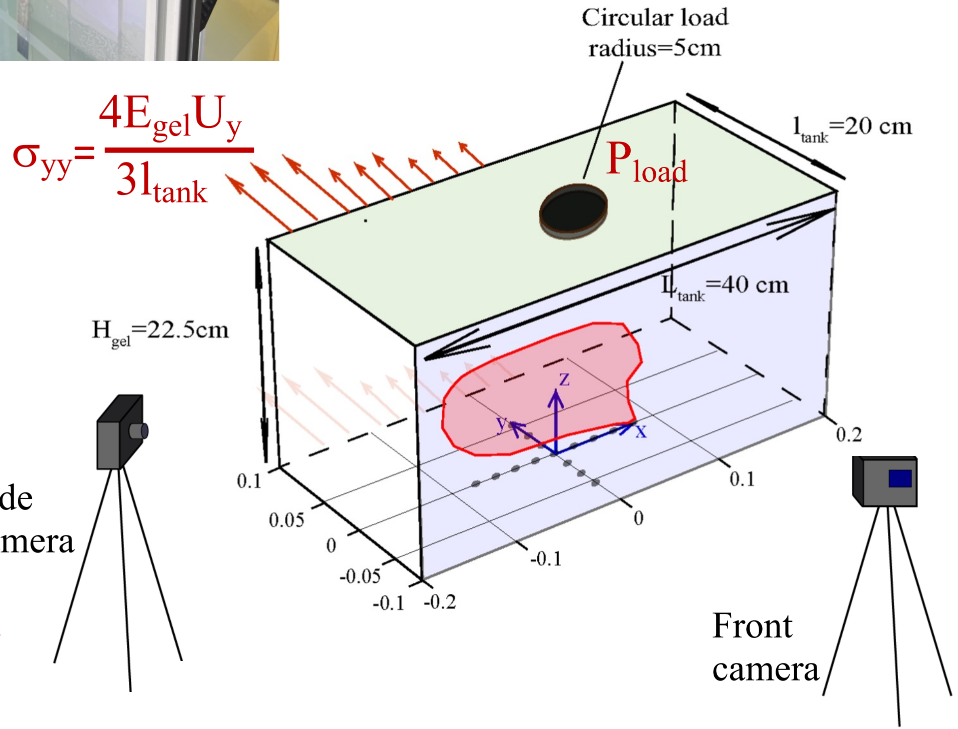
-density *($\rho_{oil}=871$ kg/m^3)*

-viscosity *($\mu_{oil}=1.74*10^{-3}$ Pas)*

Experimental validation: Oil injection inside gelatin







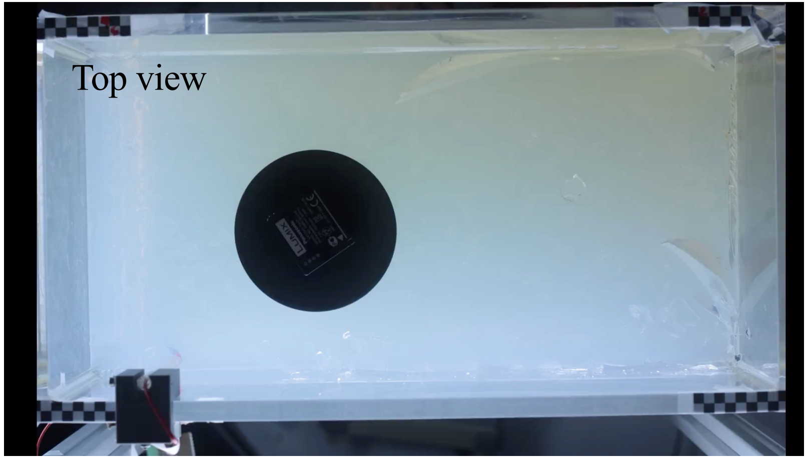
Extension imposed by removing lateral plates

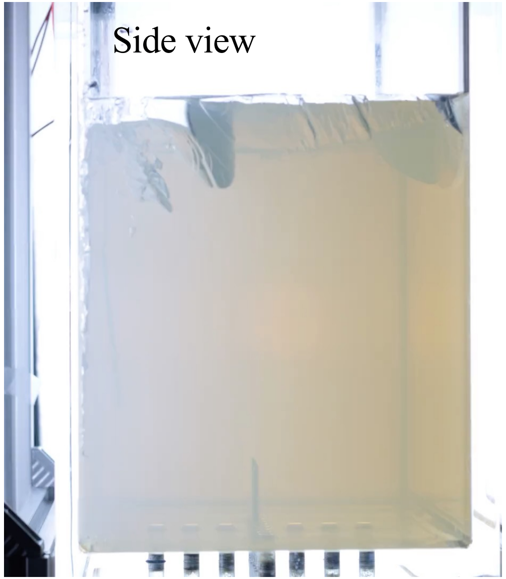
Varying:

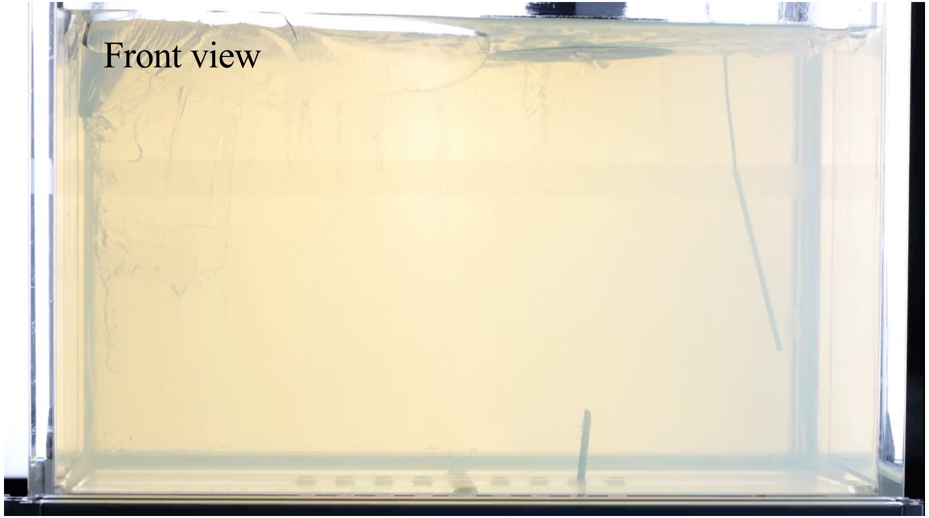
- surface load (P_{load})
- extension amount (σ_{yy})
- density contrast ($\Delta\rho$)→ buoyancy

Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m
P_{load} = 138 Pa
$\Delta\rho$=129, E= 2193 Pa

Film accelerated *1200
True duration: 36 min



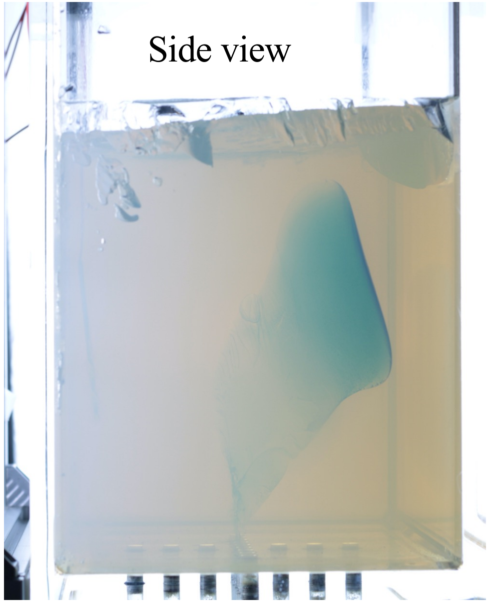


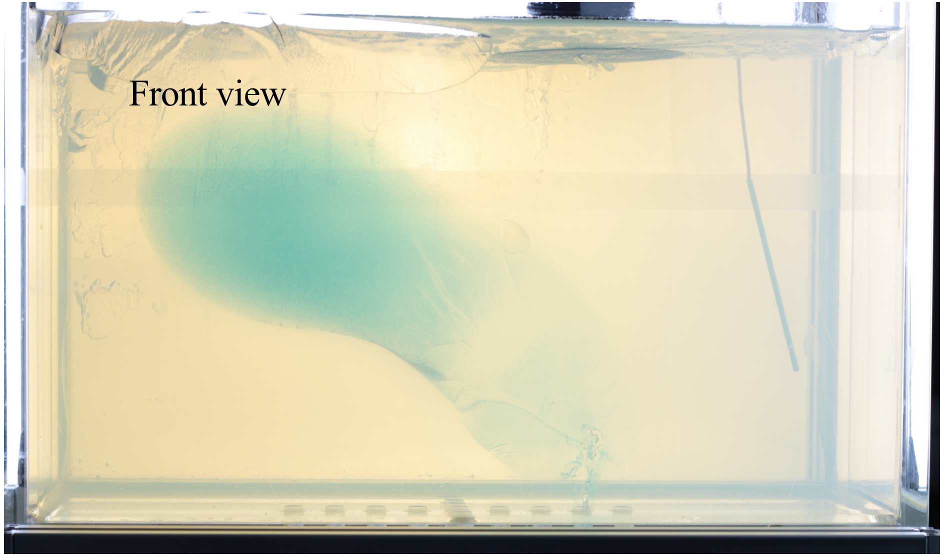


Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m

P_{load} = 138 Pa

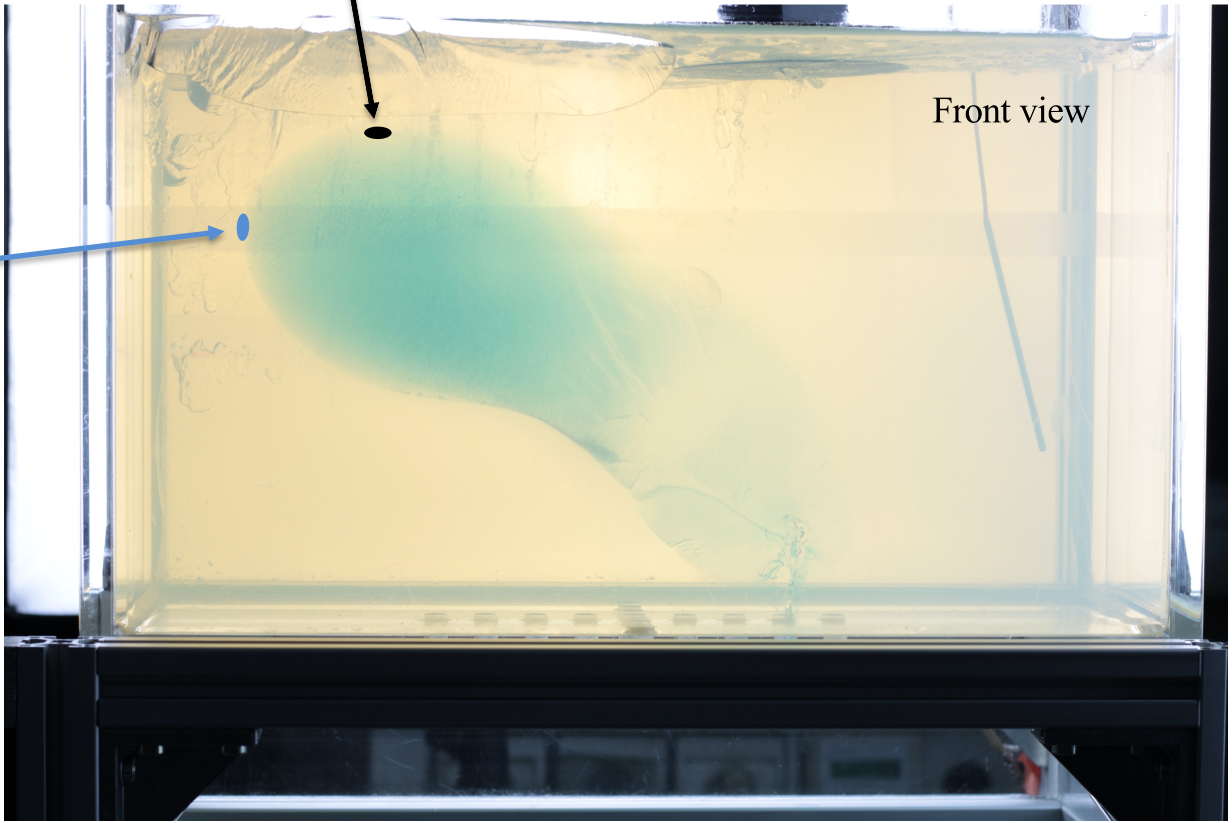
$\Delta\rho$=129, E= 2193 Pa





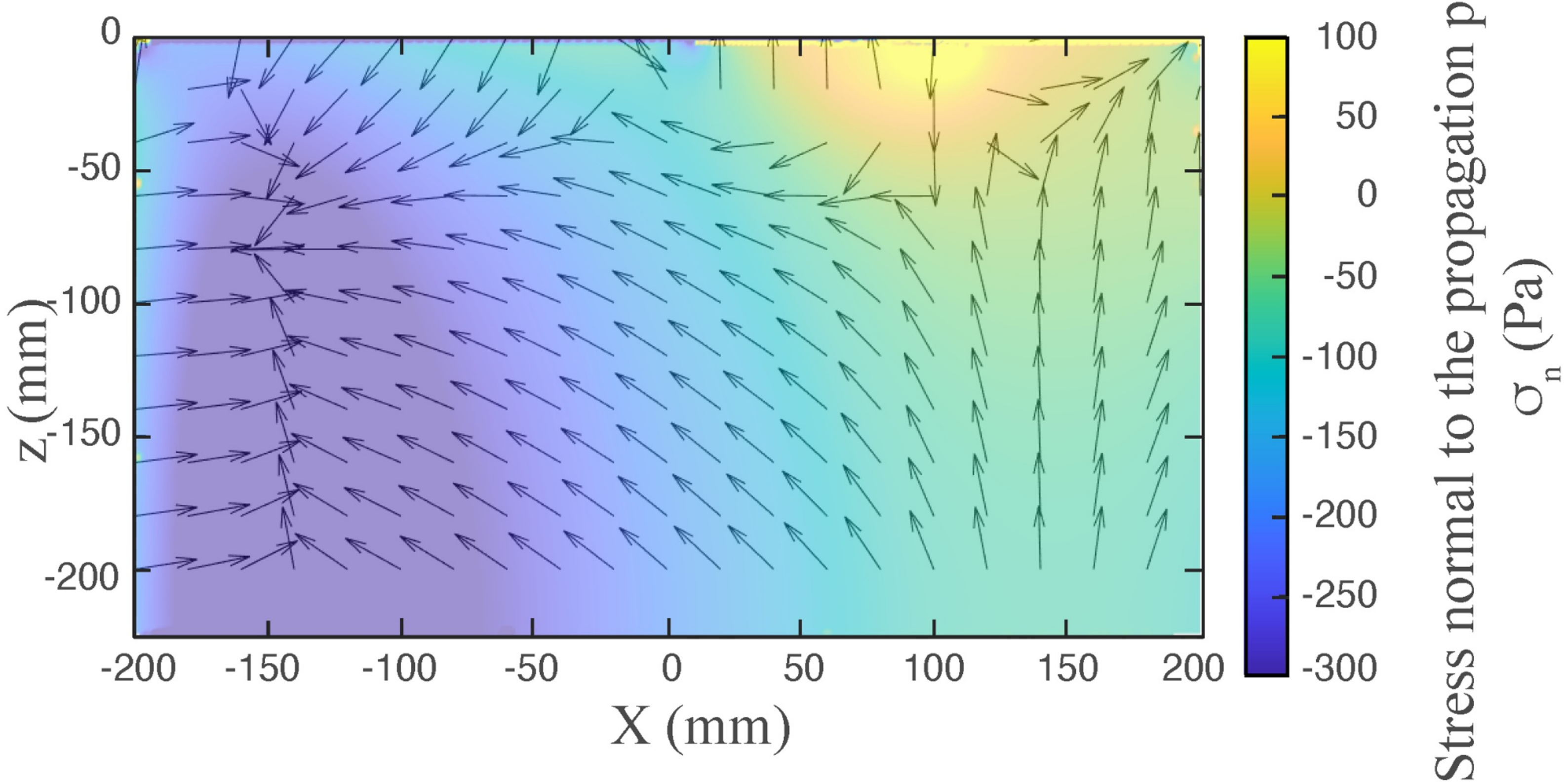
Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m
P_{load} = 138 Pa
$\Delta\rho$=129, E= 2193 Pa

Surface not reached



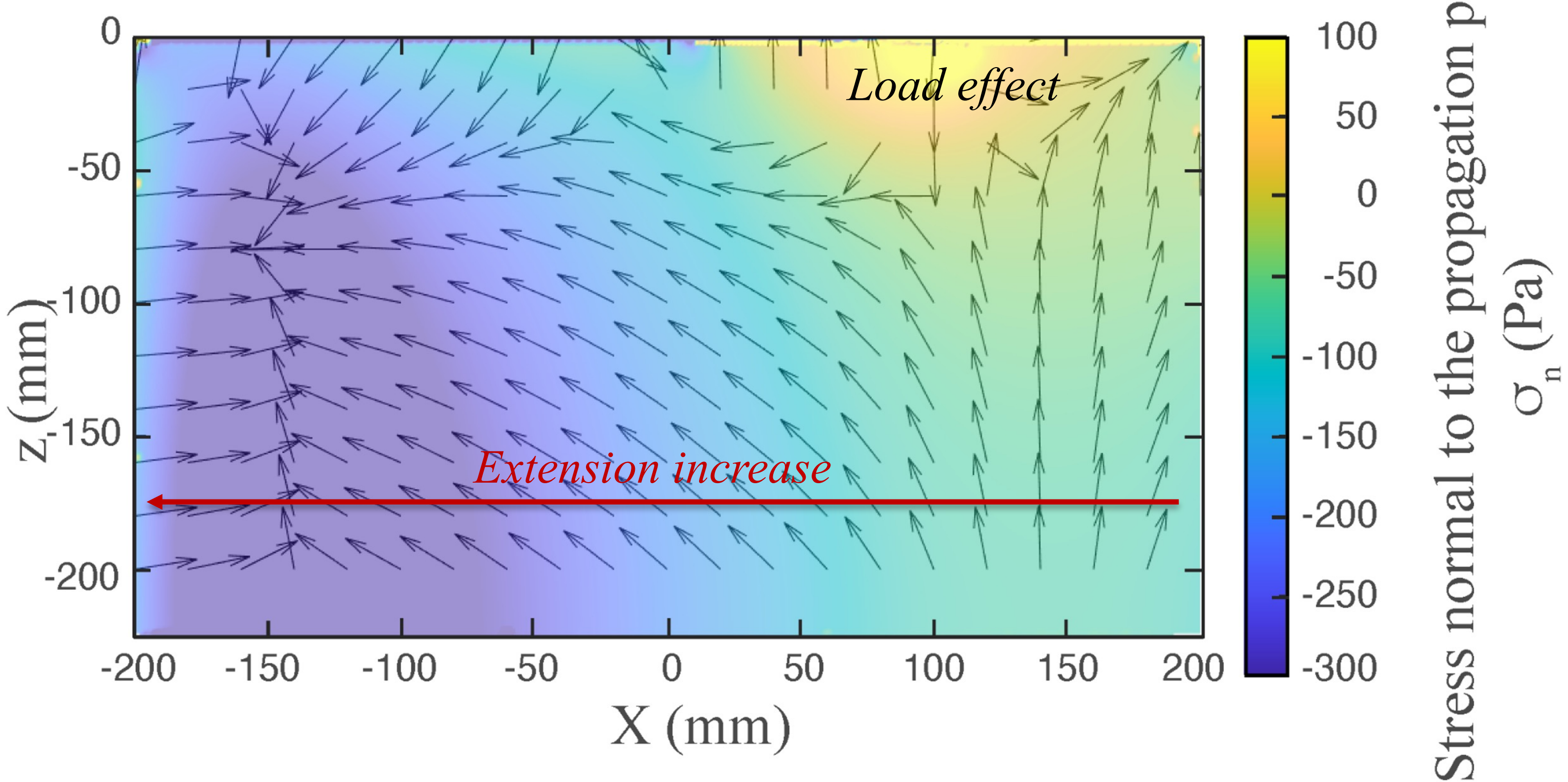
Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m
P_{load} = 138 Pa
$\Delta\rho$=129, E= 2193 Pa

Tank stress field modelled with COMSOL
Mid-plane Y=0



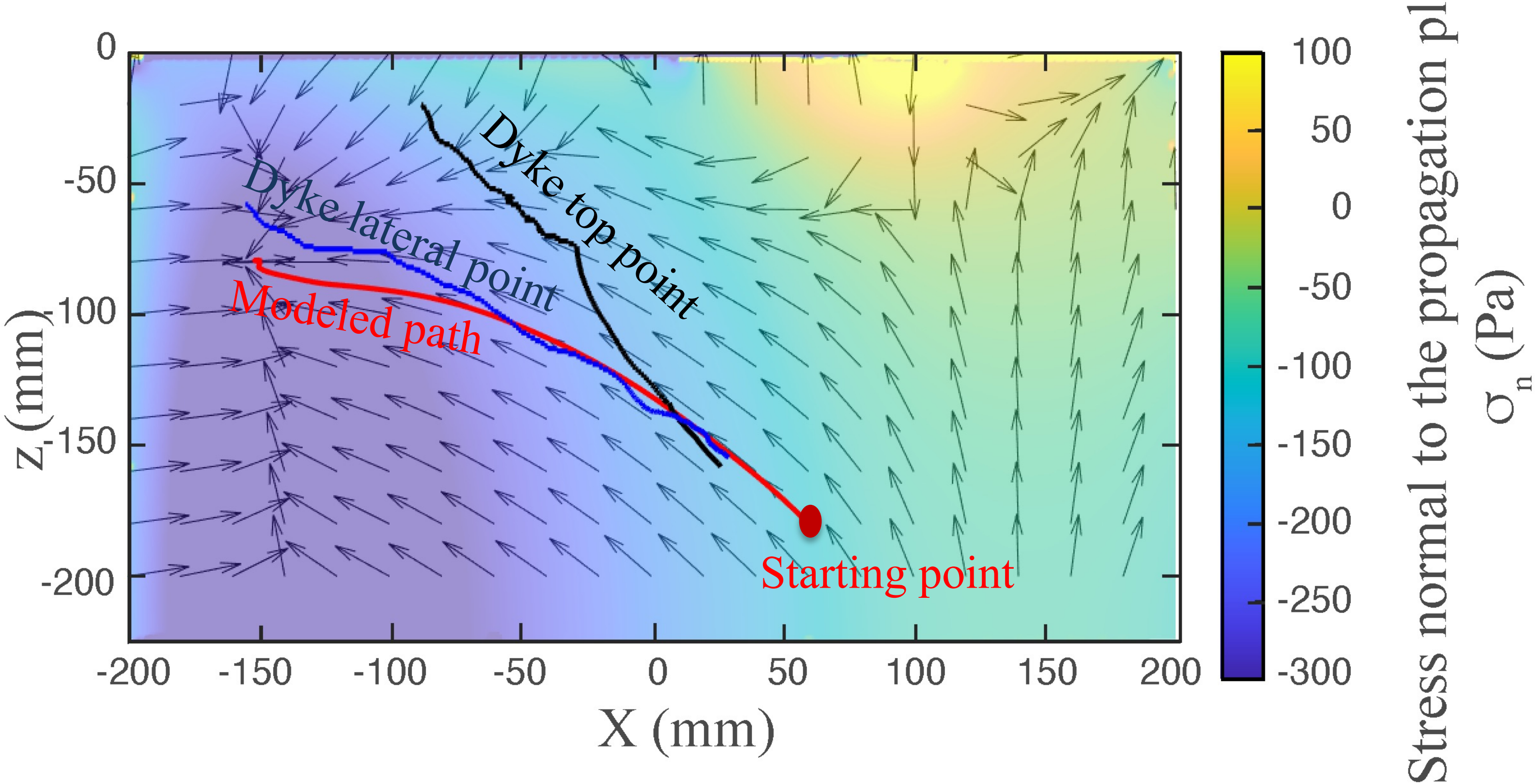
Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m
P_{load} = 138 Pa
$\Delta\rho$=129, E= 2193 Pa

Tank stress field modelled with COMSOL
Mid-plane Y=0



Extension σ_{yy}=234Pa, $d\sigma_{yy}/dx$=975Pa/m
P_{load} = 138 Pa
$\Delta\rho$=129, E= 2193 Pa

Tank stress field modelled with COMSOL
Mid-plane Y=0



Experimental results: 3 other cases

Extension: $d\sigma_{yy}/dx$=826Pa/m

Extension: $d\sigma_{yy}/dx$=600Pa/m

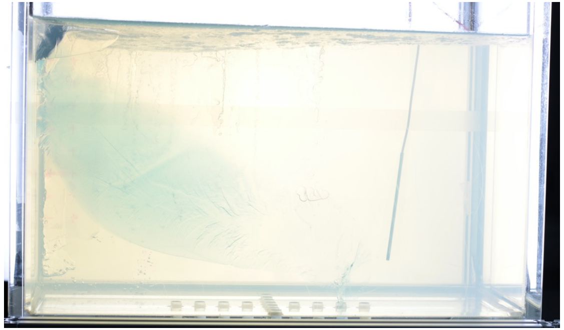
No extension

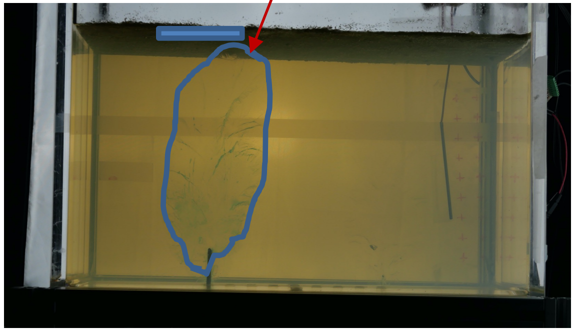
Extension increase

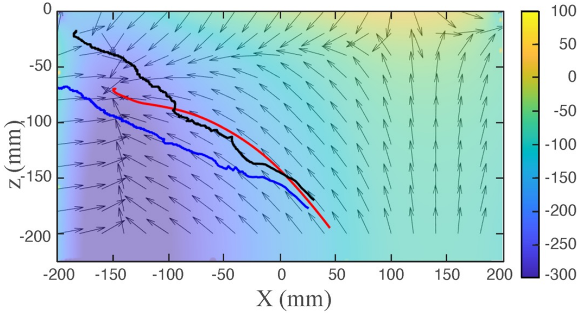
No load
$\Delta\rho$=129 kgm^{-3}
Surface not reached

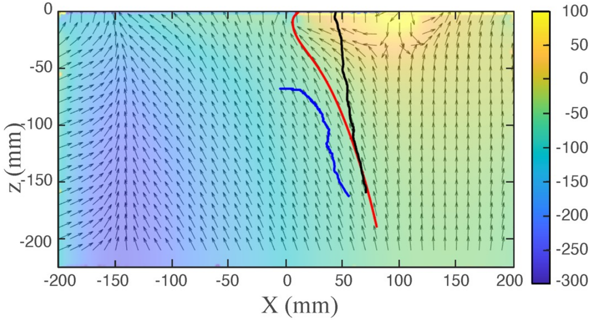
P_{load}=138 Pa
$\Delta\rho$=233 kgm^{-3}
Surface reached

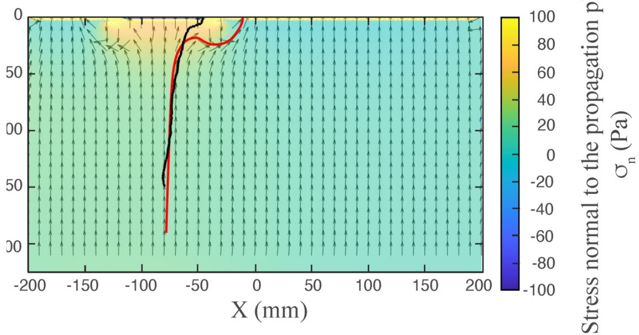
P_{load} =133 Pa
$\Delta\rho$=131 kgm^{-3}
Surface reached







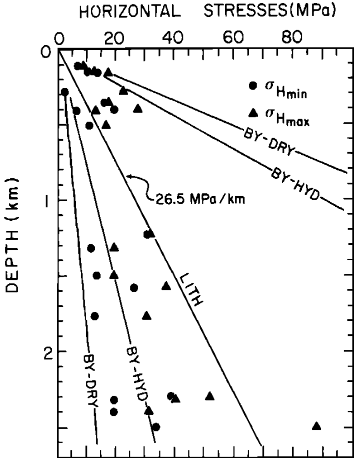




External stress field gradient calculation for Nyiragongo case study

- extension N110°E

A Vertical gradient



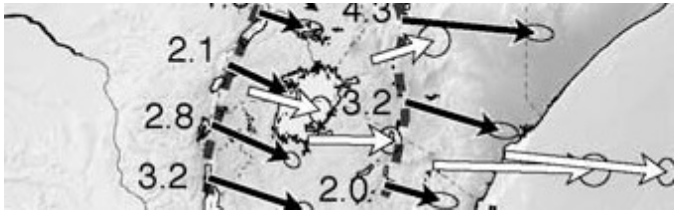
(Brace & Kohlstedt., 1980)

$$\frac{\partial \sigma_n}{\partial z}$$

between 1400Pa/m and 2500 Pa/m

→ may inhibit vertical ascent

A lateral gradient estimated from displacement gradient



(Stamps et al., 2008)

Spreading rate locally increasing towards the South (lateral gradient around 2.2 $\mu m yr^{-1} km^{-1}$)

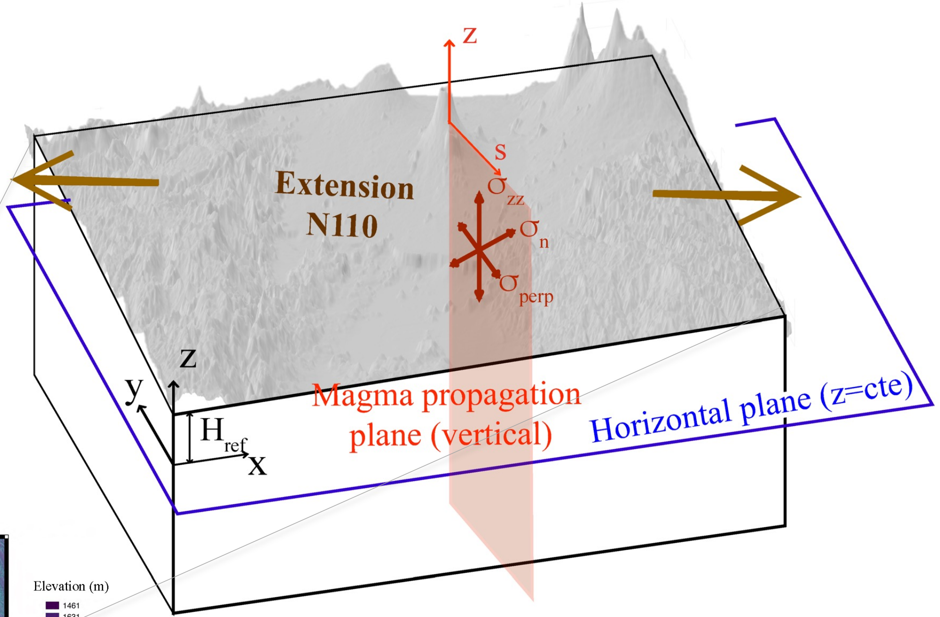
several orders of magnitude smaller

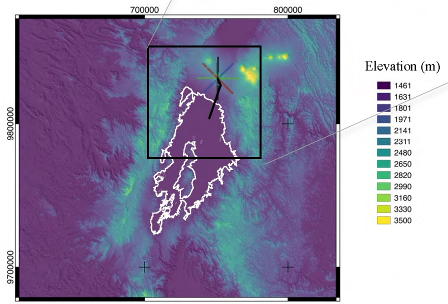
-topography + lake loading effects estimated using a numerical model

Modeling strategy

3D stress field calculation:
-Lithostatic reference state
-Extension (N110)
-**Topographic load + water load**
applied at H_{ref}=1.461 km (lake level)

σ_n: Stress normal to the vertical propagation plane





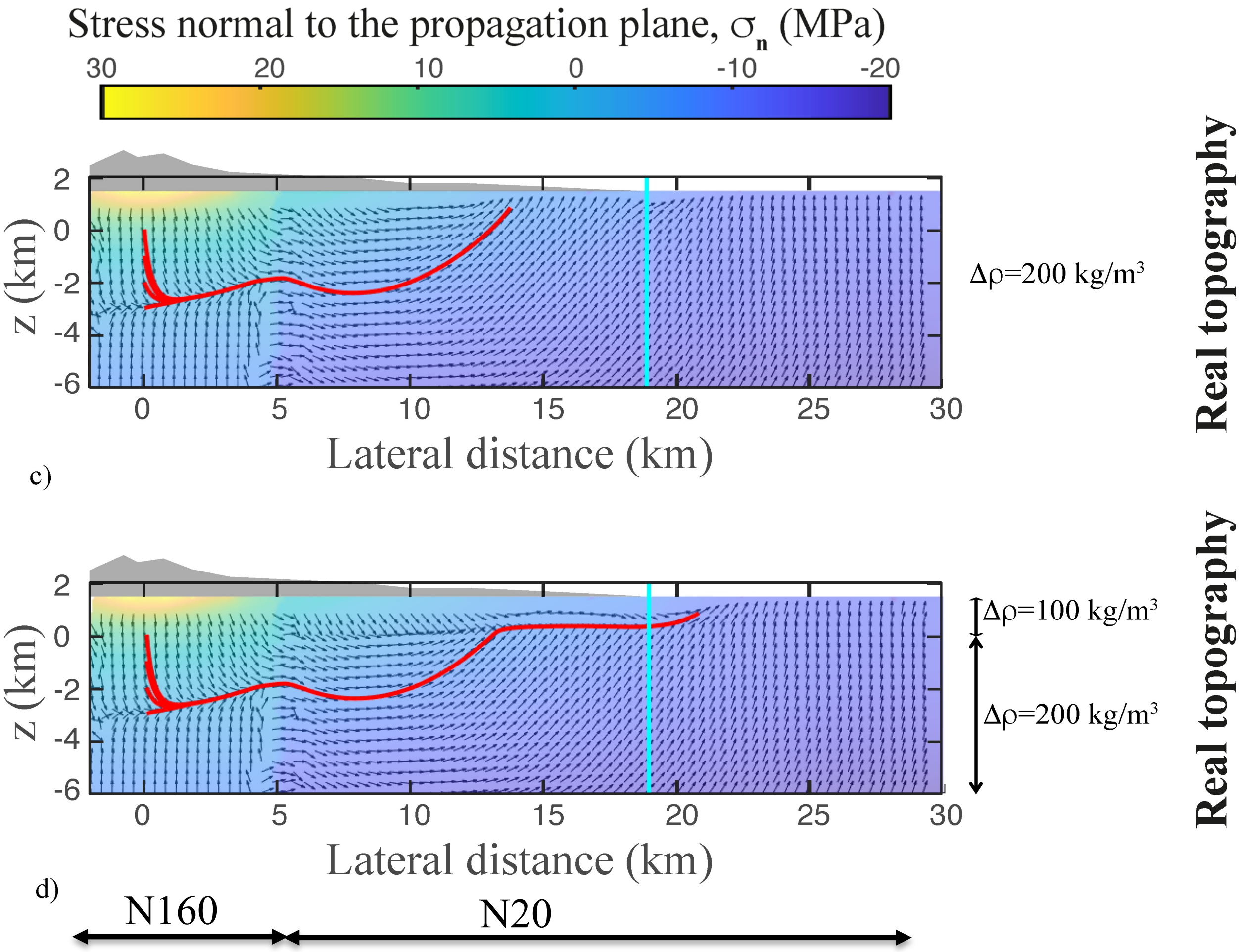
SRTM DEM
+ bathymetry of Lake Kivu
(Lahmeyer, 1998; Ross et al., 2014)

Numerical solution
(COMSOL, 80*80*80 km^3 domain)
Zero displacement condition bottom + lateral boundaries

Lateral propagation also requires reduced buoyancy at shallow depth

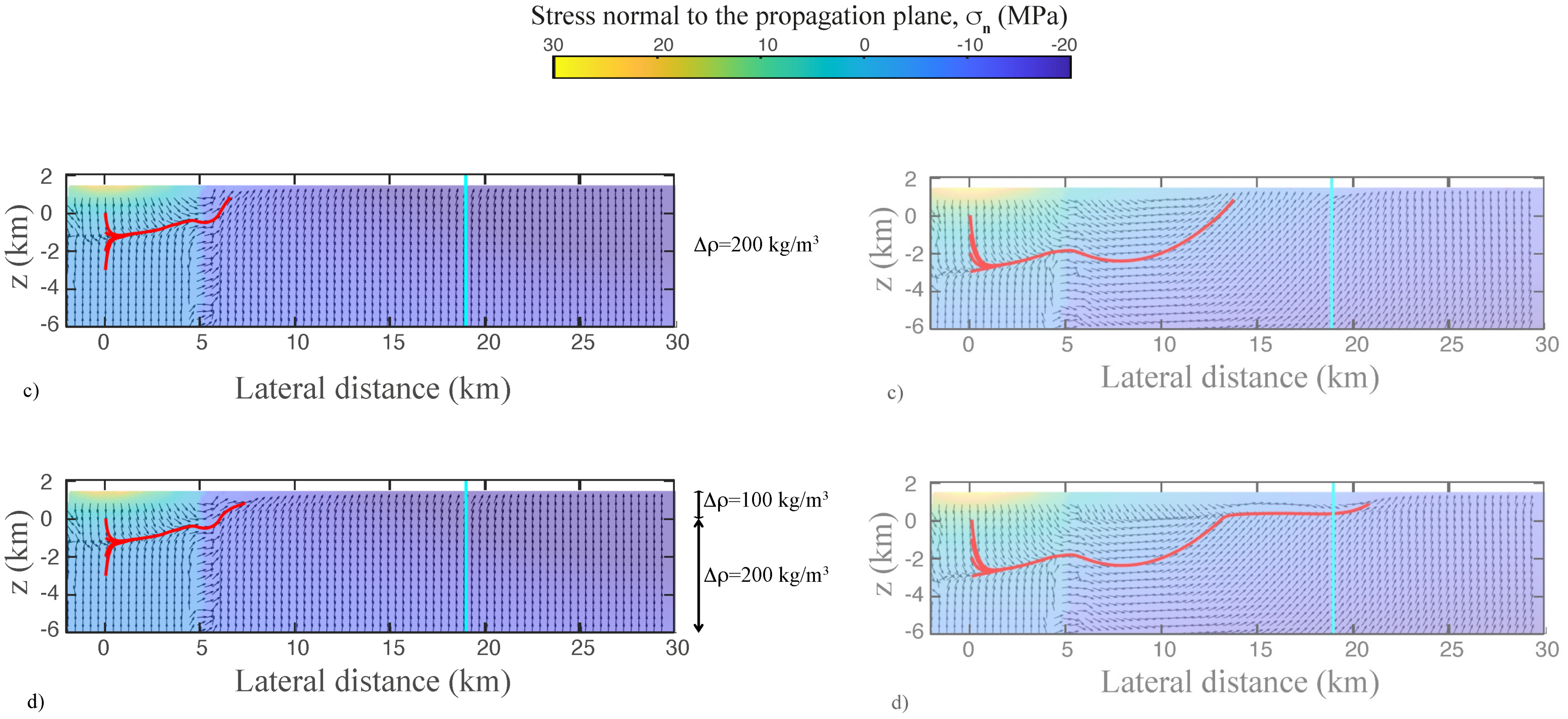
Extension gradient:

- Vertical: -2500Pa/m
  15MPa at 6 km depth
- Horizontal: +0.002 Pa/m



Pinel et Mériaux, 2025

The vertical gradient of the extension is really needed



Without vertical gradient **With vertical gradient**

Lateral propagation is favored by:

- **depth-dependent extension**
- **reduced magma buoyancy at shallow depth**

- downslope towards Lake Kivu
- slight increase in rift extension towards the south

Conclusions on direction of propagation

Rift zone are prone to magma lateral propagation

→ Magma may or may not reach the surface

→ If magma does reach the surface, it may be very far away (several tens of km) from its source

This must be taken into account when assessing volcanic hazards and associated risks.

Modeling the gradient of magma overpressure → direction of magma propagation

Validated by analogue modeling

Applied to Nyiragongo volcano

→ **deviatoric stress in extension increases with depth in rift zones**

→ **magma buoyancy** is **reduced** at shallow depth around Lake Kivu

General conclusion

Combining analogue experiments and numerical models is a good way to better understand magma propagation

We need :

- **To better characterize the local stress field**
- **To better characterize crustal properties (fracture toughness)**

ISTerre

IRD Institut de Recherche pour le Développement FRANCE

EAIFR ICTP—East African Institute for Fundamental Research

E-DOORs

unesco International Geoscience Programme

Thank you for your attention...