MAGMA TRANSPORT THROUGH THE UPPER CRUST

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Iceland

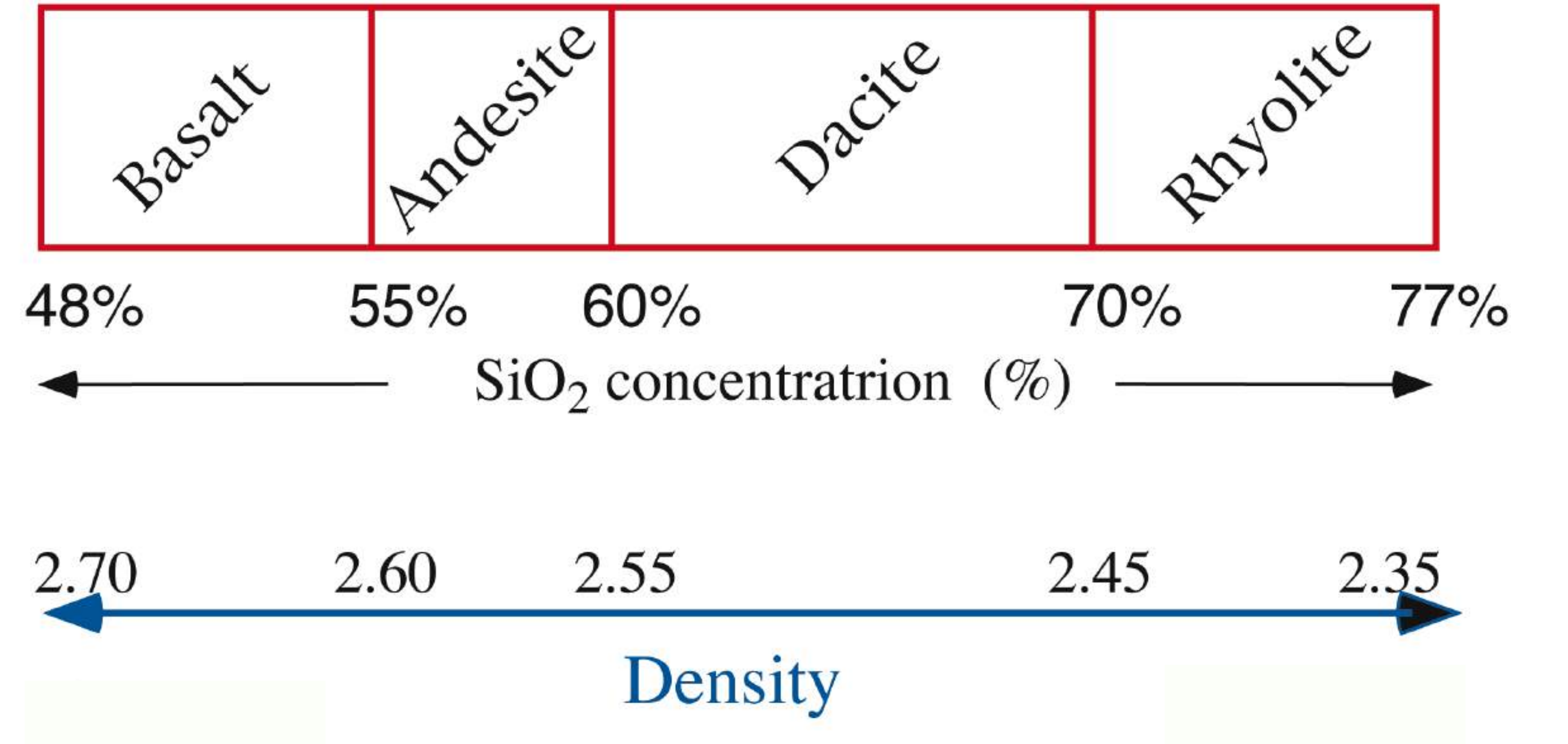
1. Magma transport and storage in the upper crust

2. Basics of dyke propagation.
   Importance and relevance of stratification.

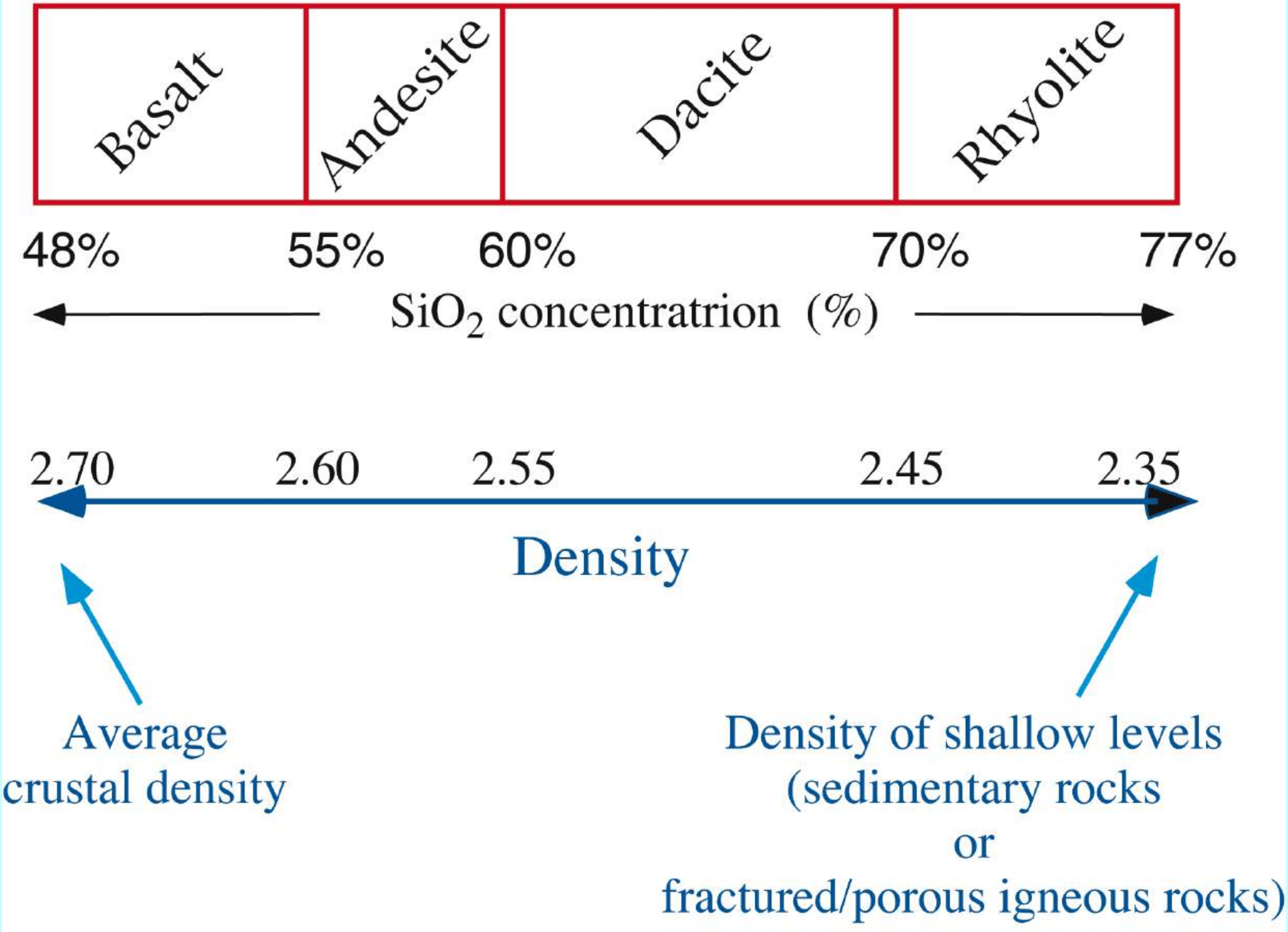
3. Dyke penetration through layers of different densities

4. Sill (reservoir) formation

5. Effect of volatiles : precursor phases prior to an eruption



Basalt
Andesite
Dacite
Rhyolite
48%
55%
60%
70%
77%
SiO2 concentratrion (%)
2.70
2.60
2.55
2.45
2.35
Density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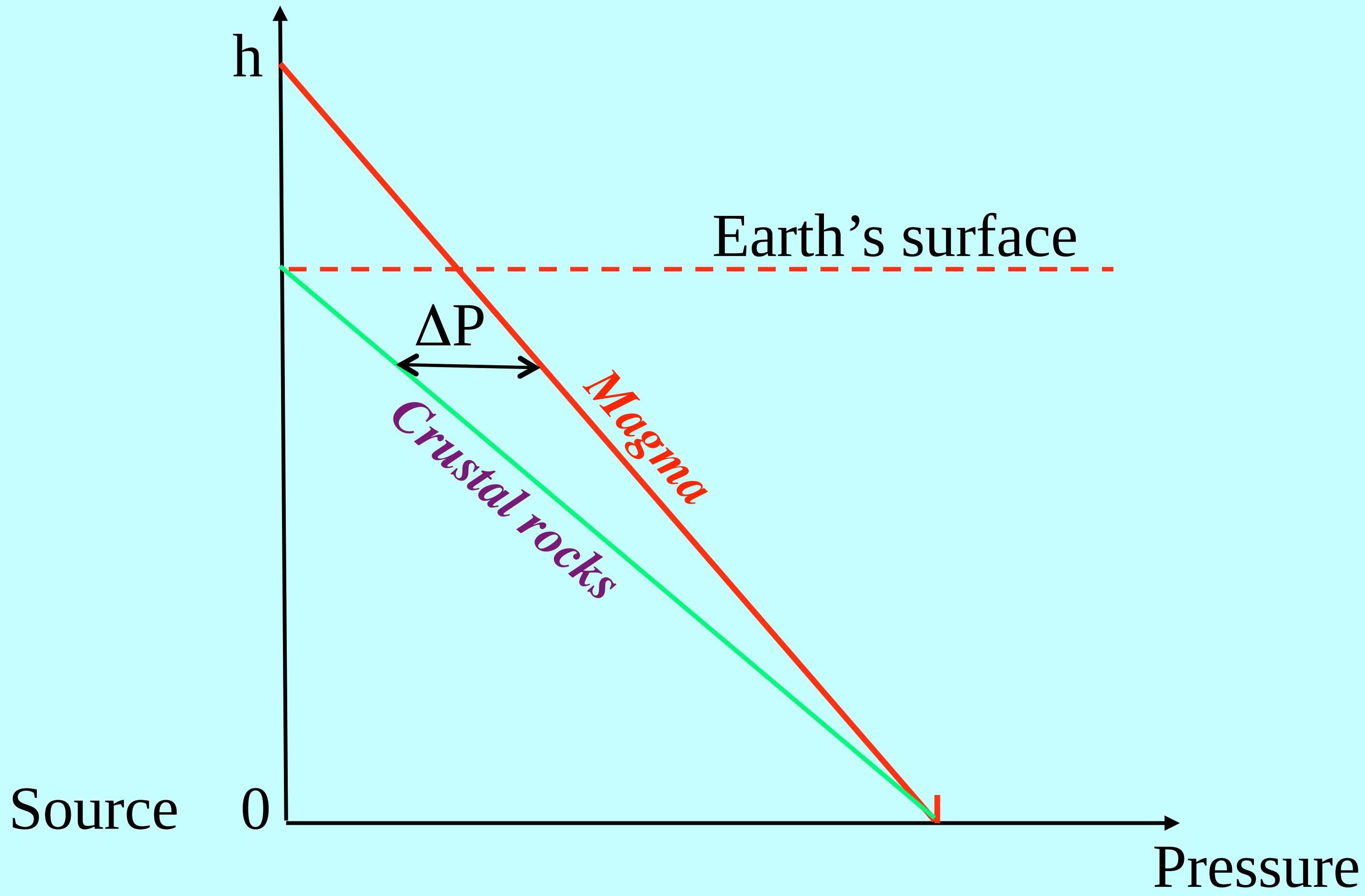
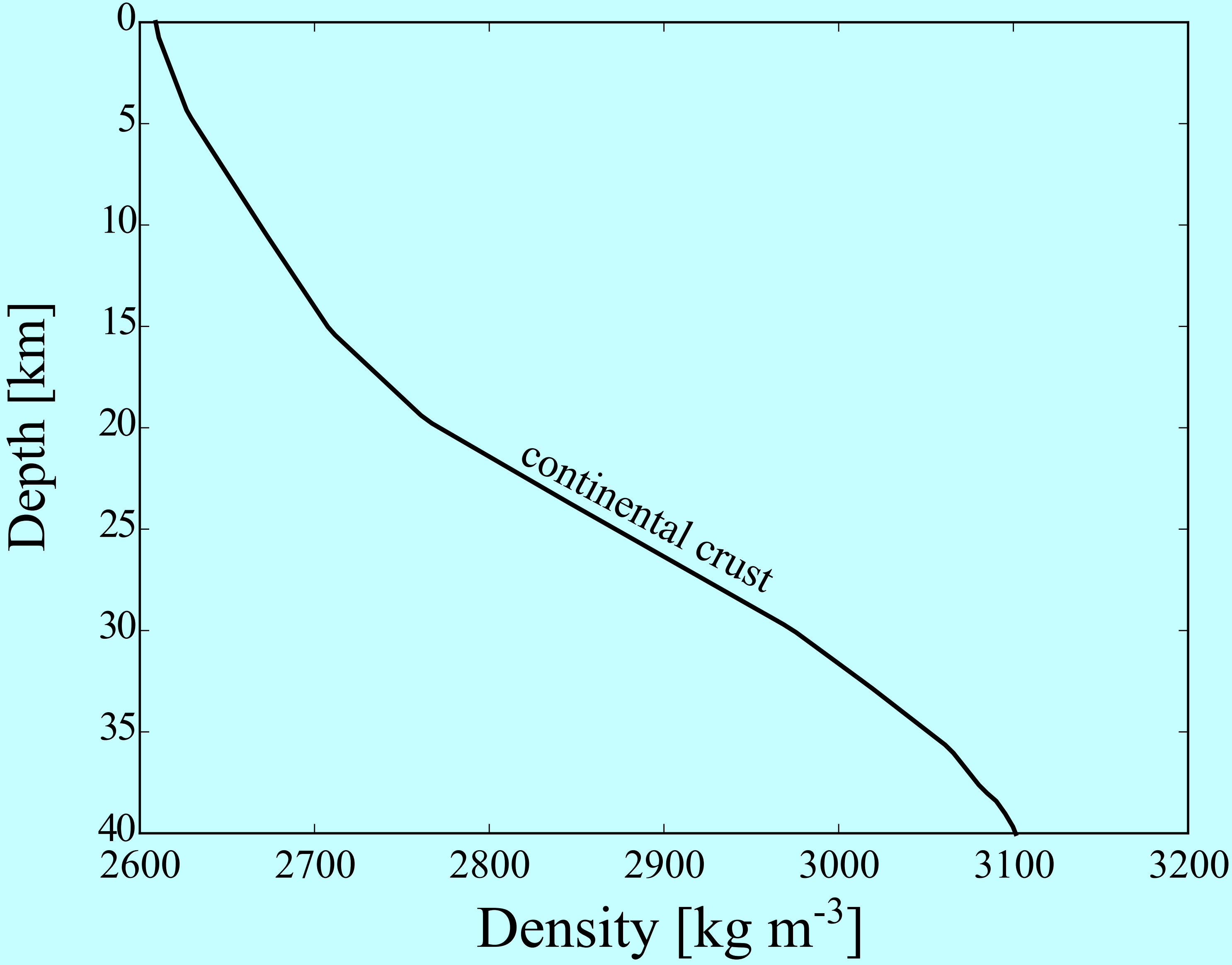
2.55
2.45
2.35
Density
Average crustal density
Density of shallow levels (sedimentary rocks or fractured/porous igneous rocks)

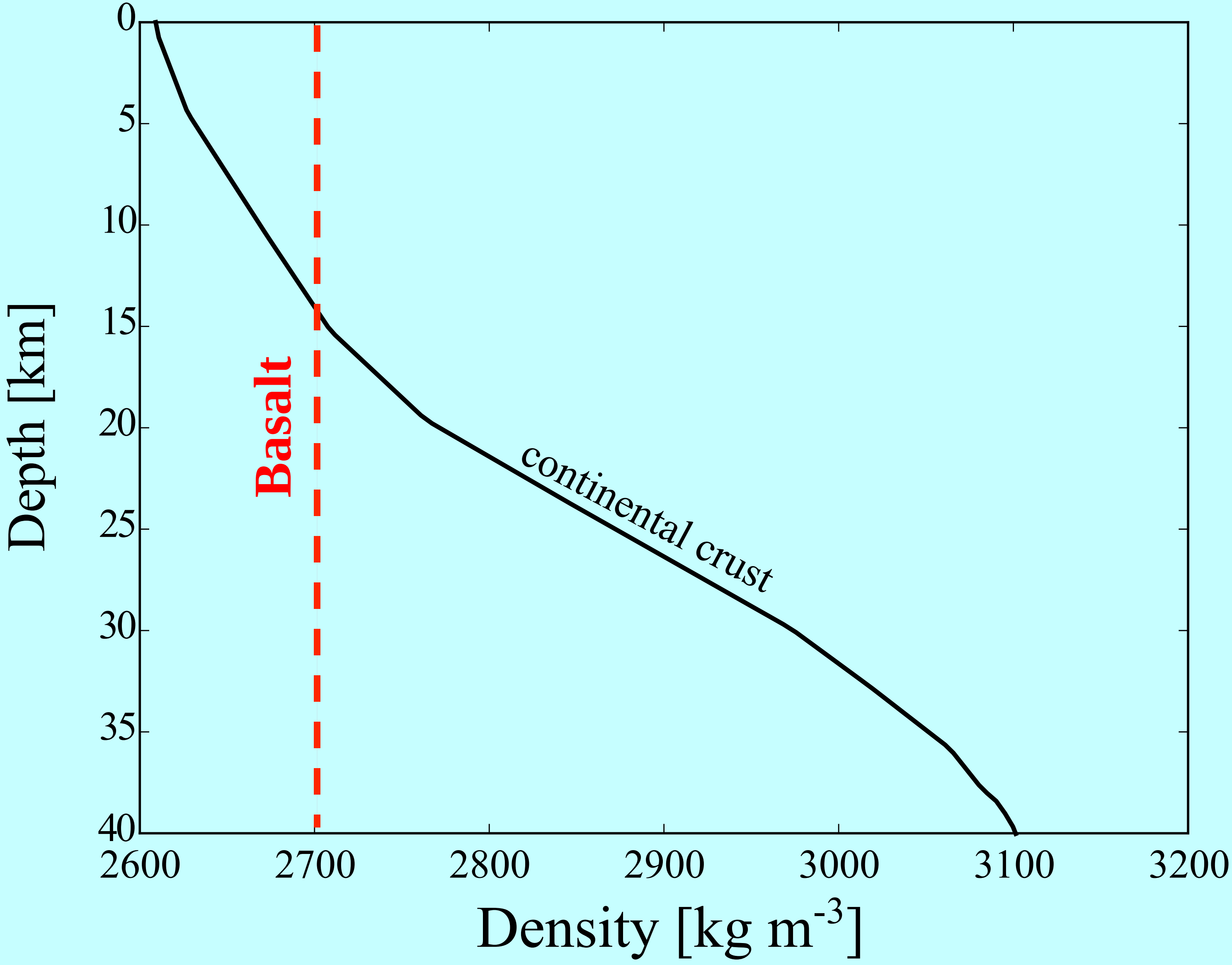


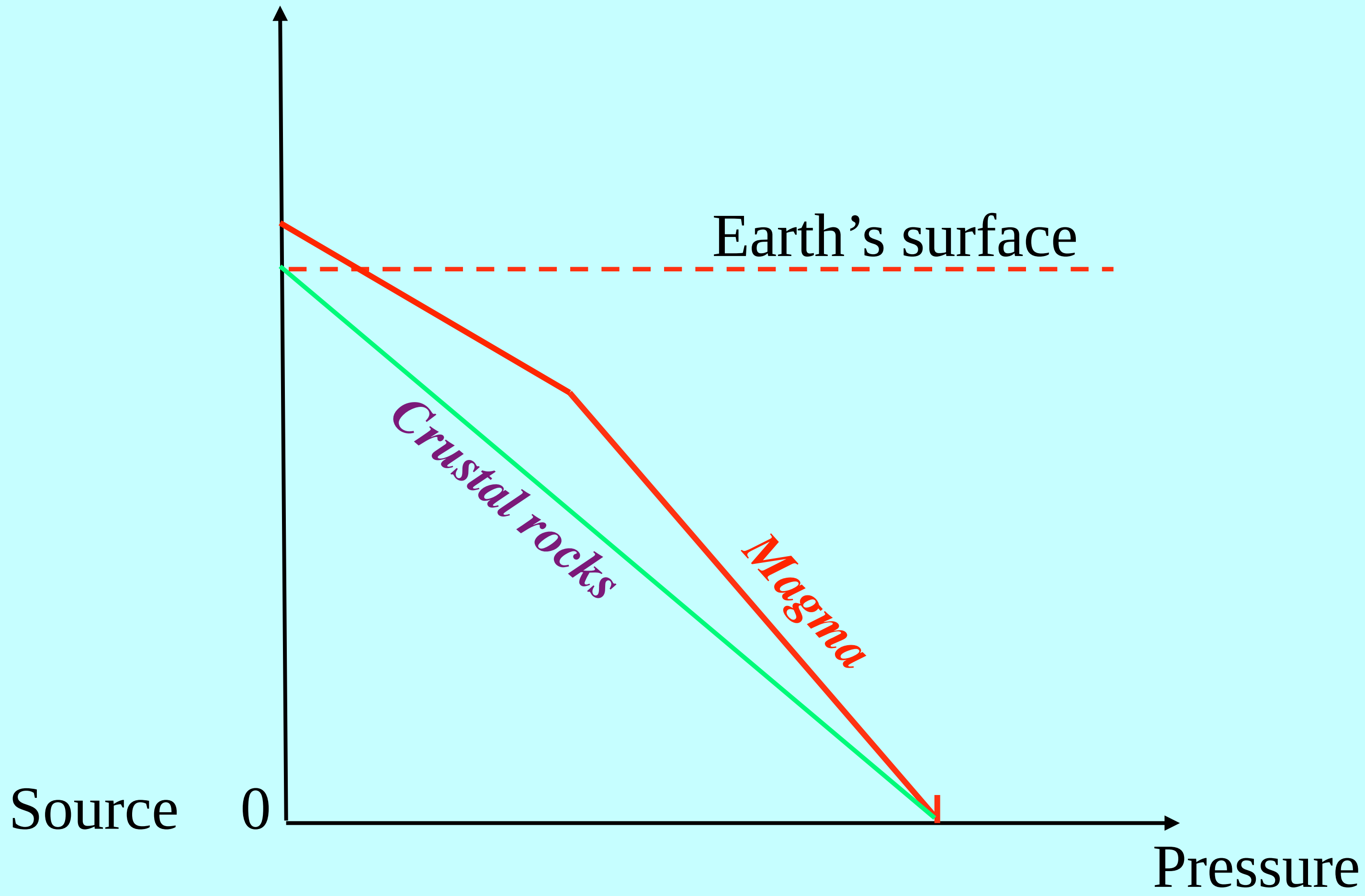
Magma pressure $\Delta P = (\rho_r - \rho_m)\, g\, z$

Average crustal density distribution

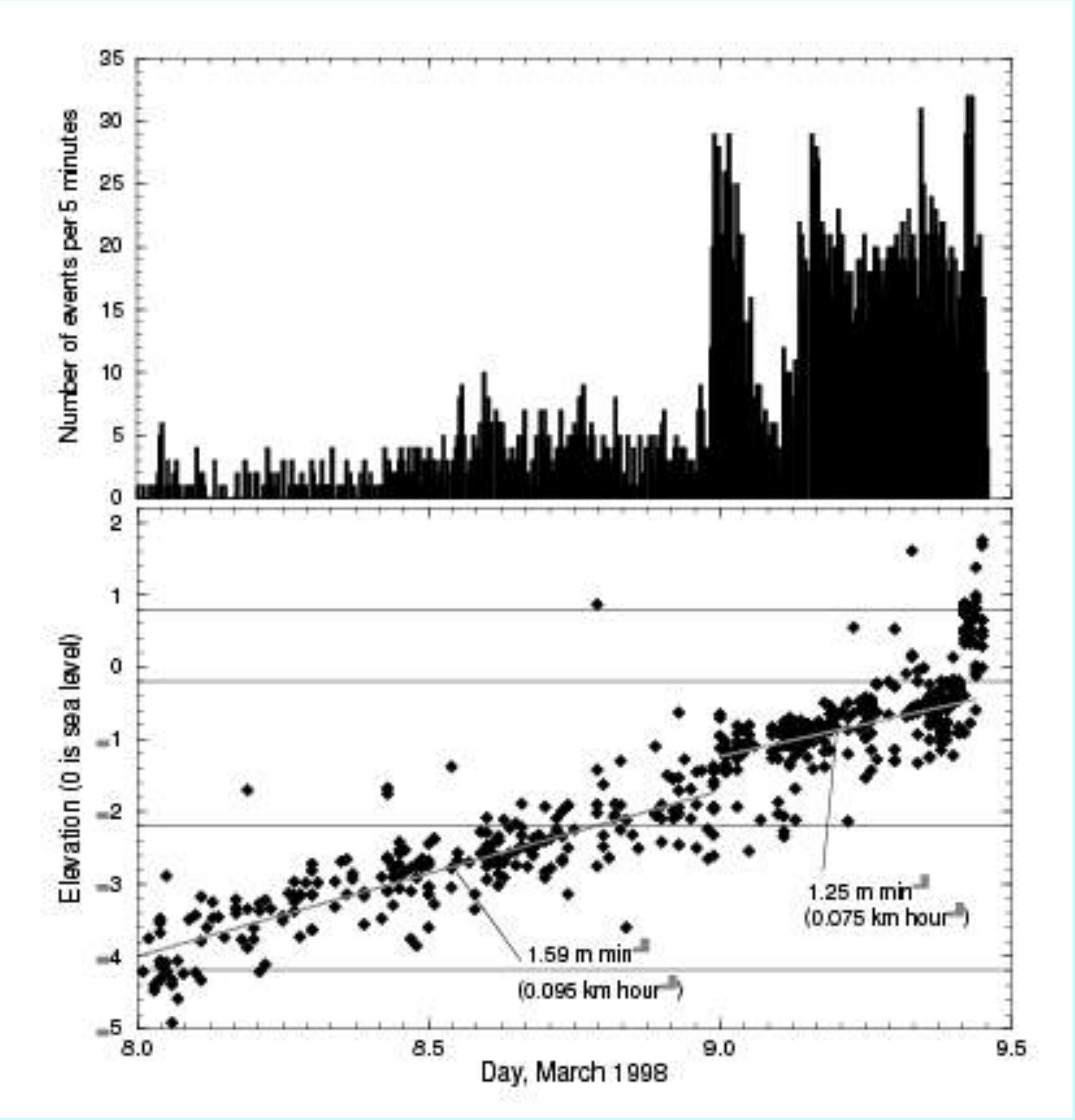


Average crustal density distribution



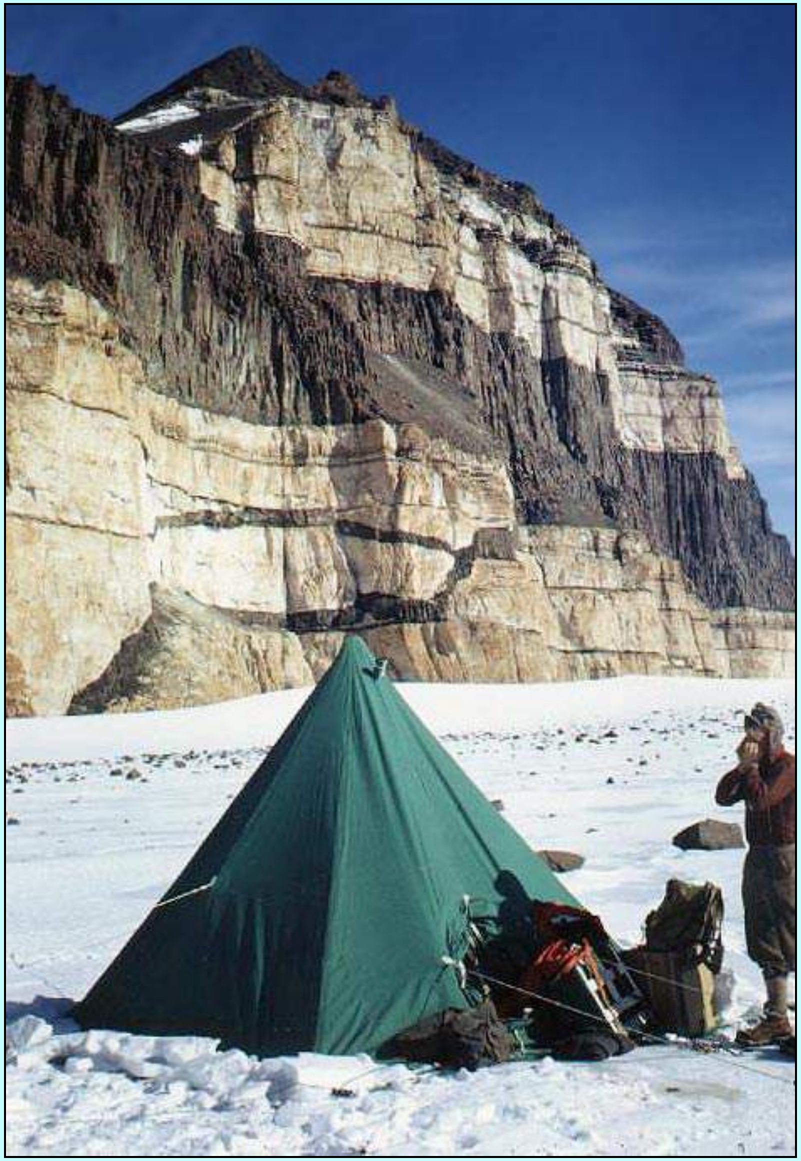

Earth’s surface
Crustal rocks
Magma
Source
0
Pressure

Iceland



Piton de la Fournaise, 1998

Piton de la Fournaise, Reunion Island



Ferrar dolerites, Antarctica

Sill emplacement

Big Bend National Park, Texas

Along bedding plane

FLOW THROUGH A DYKE

$\neq$

FLOW THROUGH AN OPEN CHANNEL

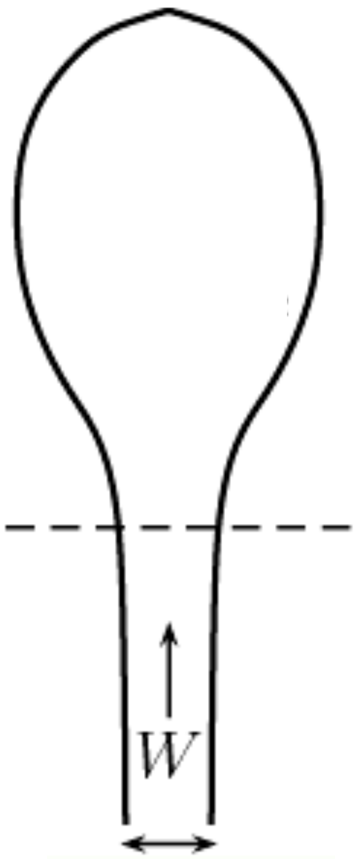
Open channel (2-D)

Volume flux $\quad Q \sim (\nabla P)\, a^3/\mu$

Velocity $\quad \mathbf{c} \sim (\nabla P)\, a^2/\mu \sim Q$

Structure of a dyke

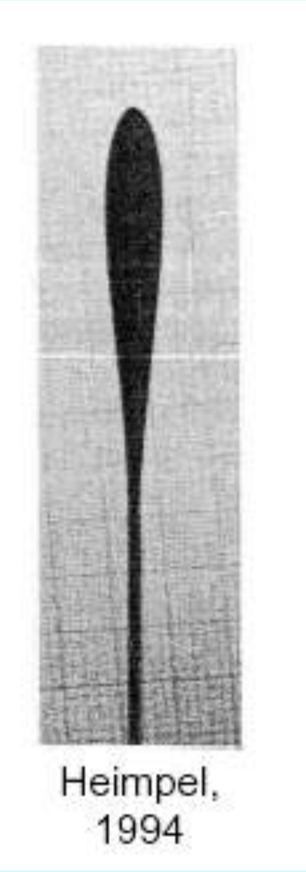
Heimpel, 1994

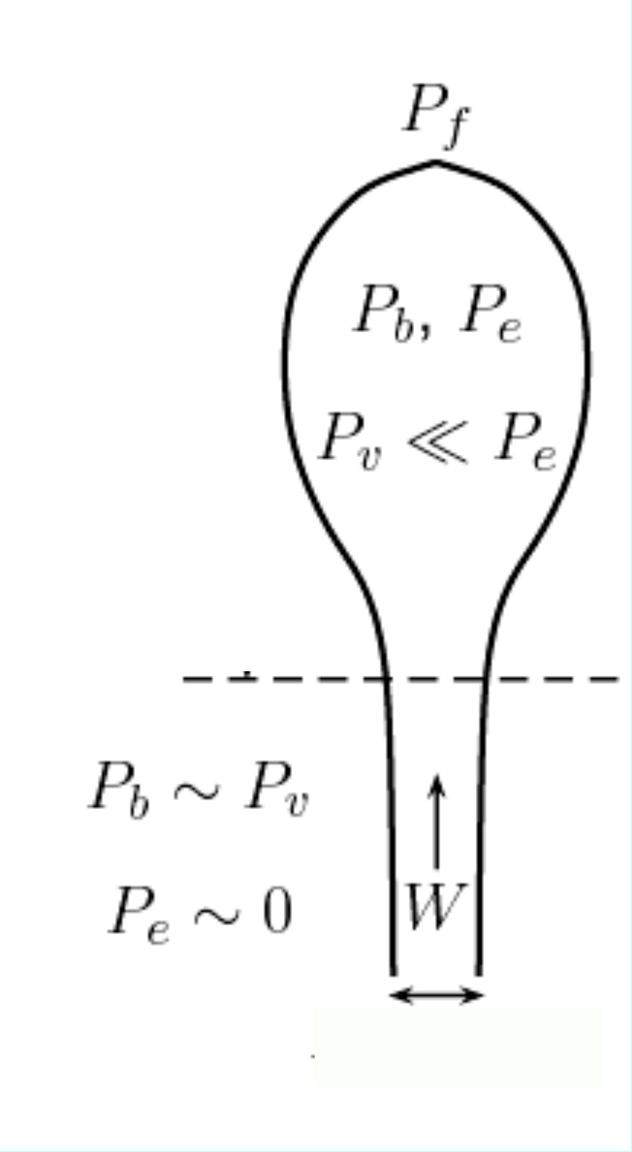


Nose

Tail

Structure of a dyke





Nose

Tail

Four types of pressure

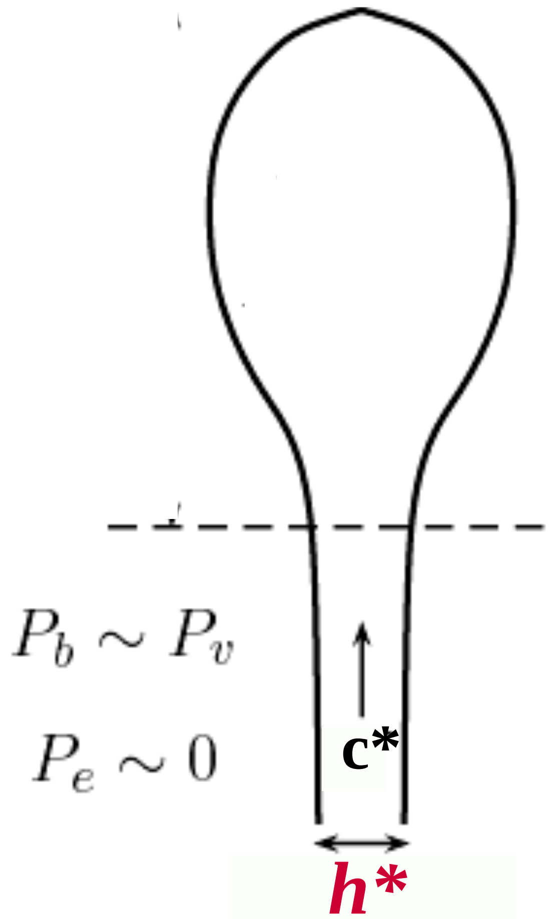
P_f : overpressure for fracturing at the tip

P_e : elastic normal stress

P_v : viscous head loss

P_b : hydrostatic pressure

Heimpel, 1994



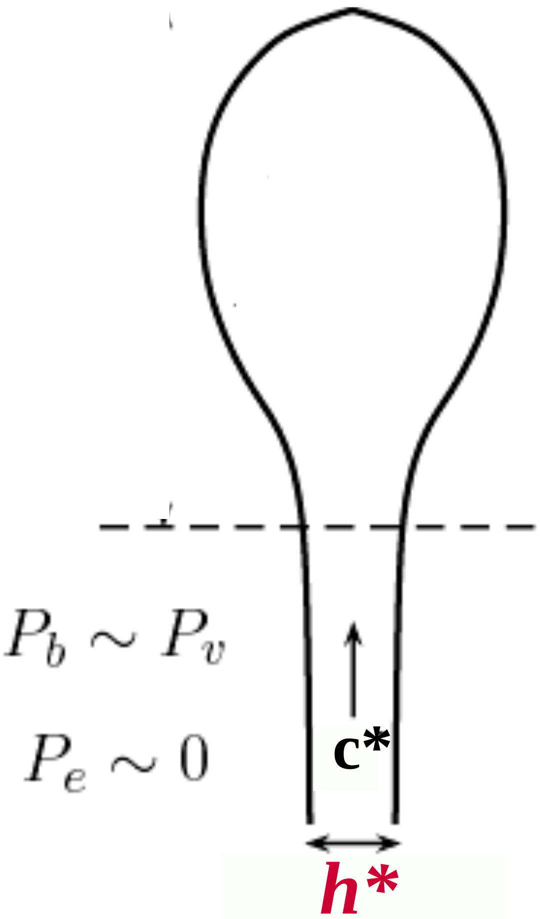
Tail

Elastic stress
to open the fracture
$h_e \approx \ell\, P_e/G$

$\ell >> 1 \;\rightarrow\; Pe << 1$

Buoyancy ≈ viscous head loss

Heimpel, 1994



Tail

Equilibrium between
buoyancy and viscous head loss

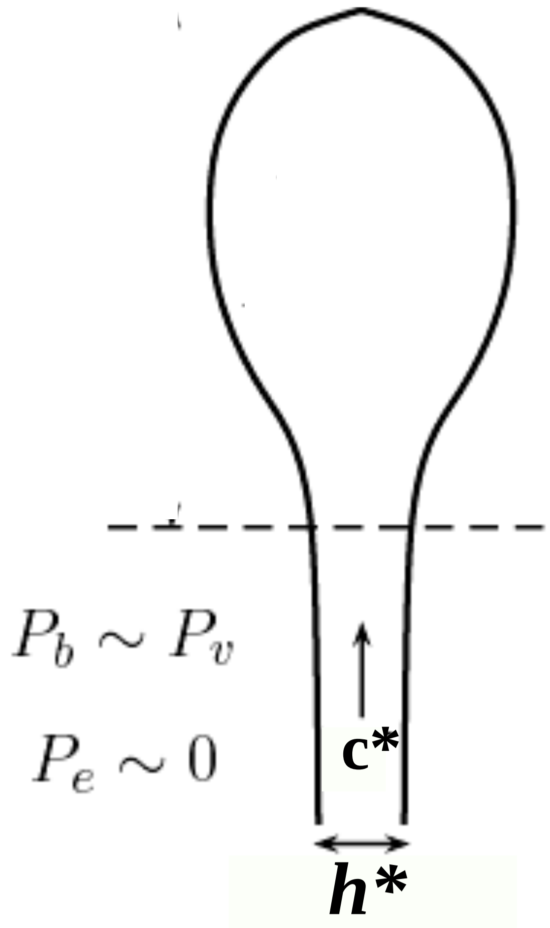
Width

$$h^* = h_\infty = \left[\frac{3\mu Q}{2(\rho_s - \rho_m)g}\right]^{1/3}$$

Velocity

$$c^* = \frac{Q}{2h^*}$$

Heimpel, 1994



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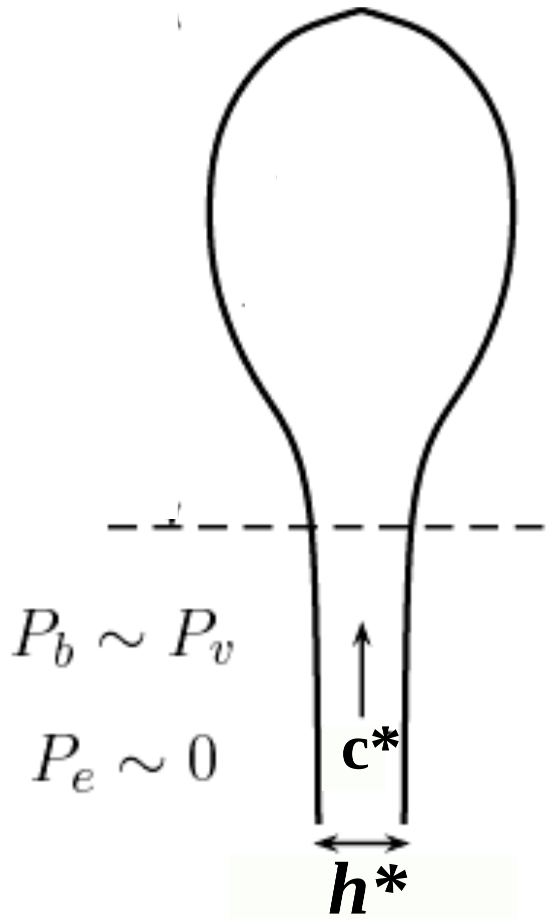
Velocity

$$c^* = \frac{Q}{2h^*}$$

$$\boxed{\mathbf{c^* \sim \mu^{-1/3}\, Q^{2/3}}}$$

Heimpel, 1994



Tail

Equilibrium between
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Width

$$h^* = h_\infty = \left[\frac{3\mu Q}{2(\rho_s - \rho_m)g}\right]^{1/3}$$

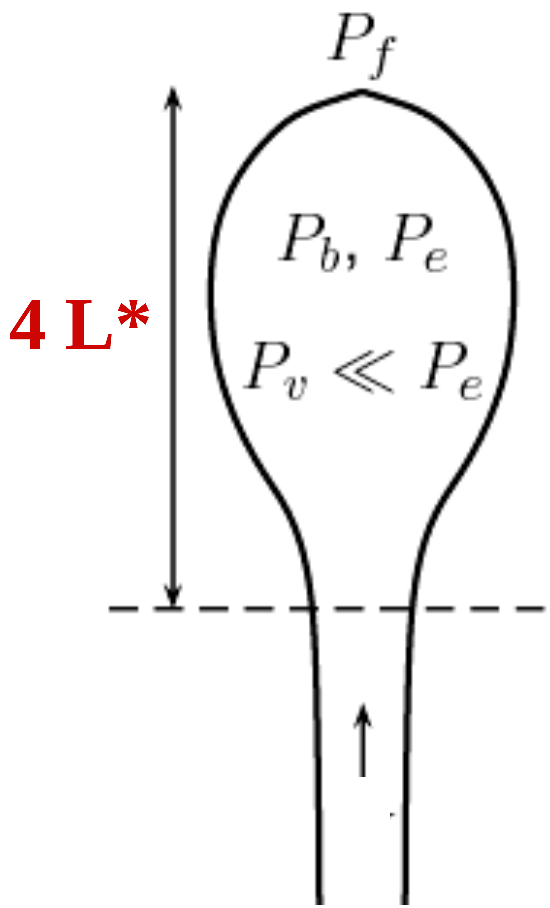
Velocity

$$c^* = \frac{Q}{2h^*}$$

$$\boxed{c^* \sim Q^{2/3}}$$

Not linear

Heimpel, 1994



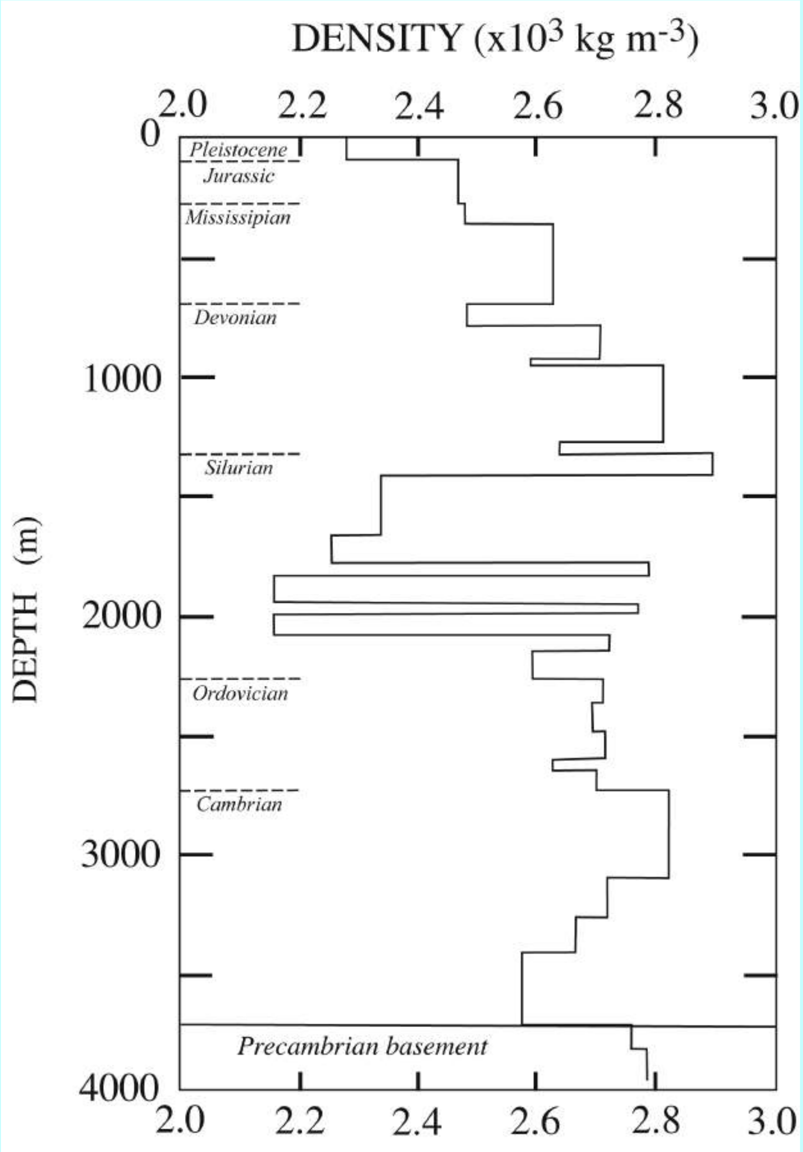
Nose

Equilibrium between buoyancy and elastic stresses

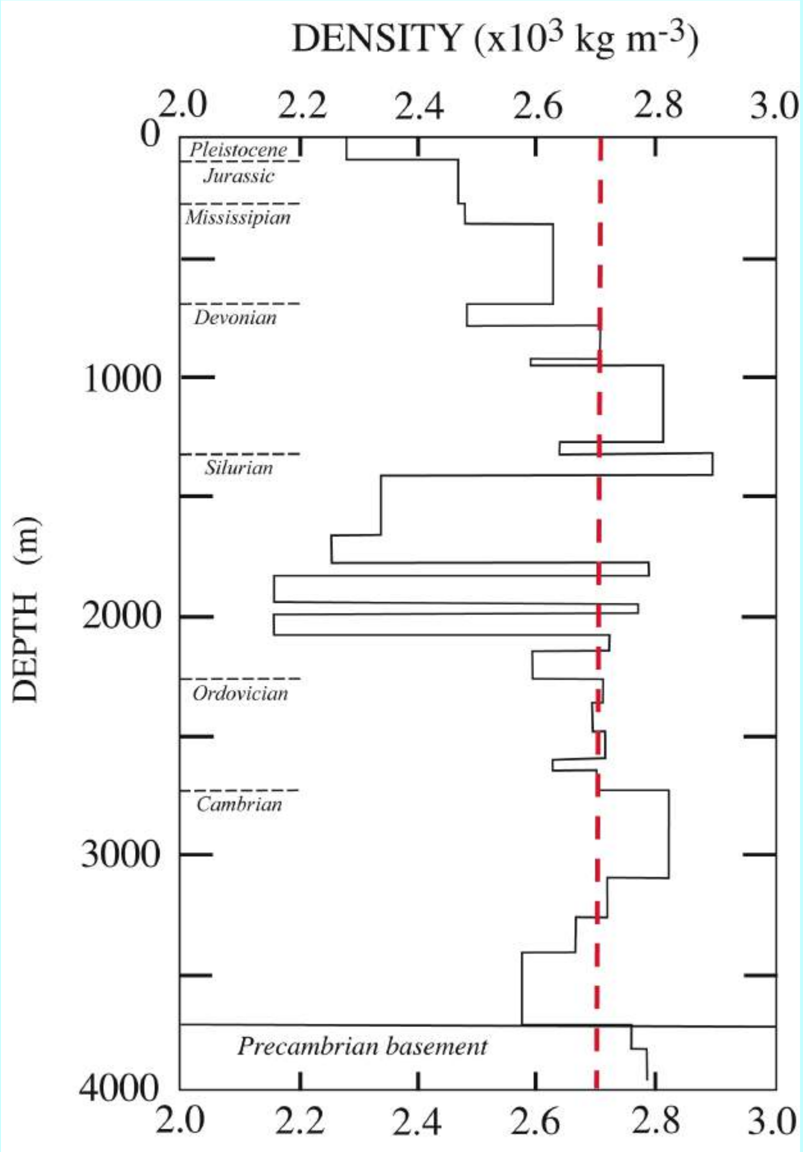
Length

$$(\rho_s - \rho_m) g L^* = \Delta P^* = \frac{G}{1-\nu}\frac{h^*}{L^*}$$

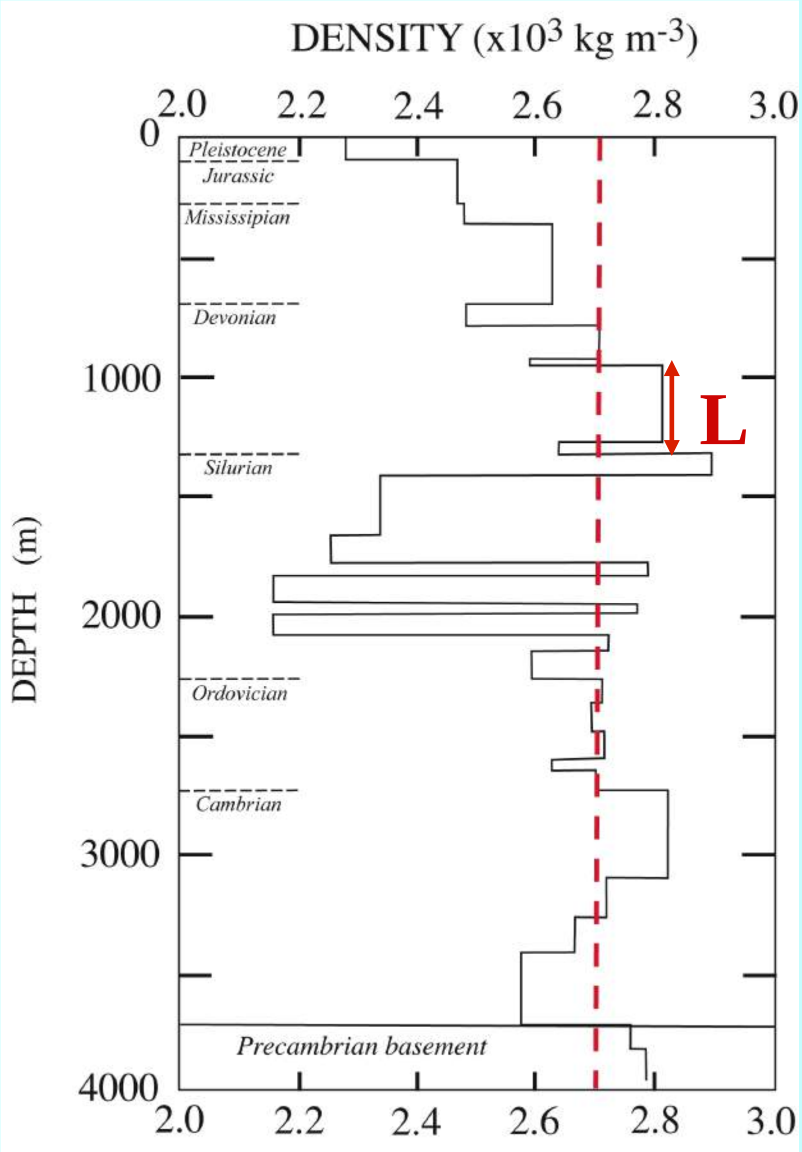
$$L^* = \left(\frac{3\mu Q}{2}\right)^{1/6} \left(\frac{G}{1-\nu}\right)^{1/2} (\Delta \rho g)^{-2/3}$$



Michigan basin strata



Michigan basin strata



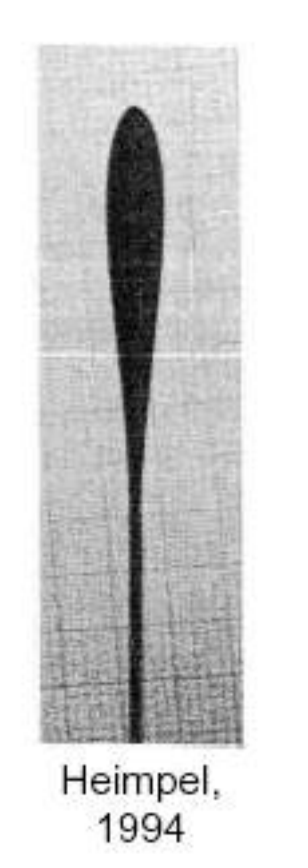
Importance of an individual layer depends on ratio

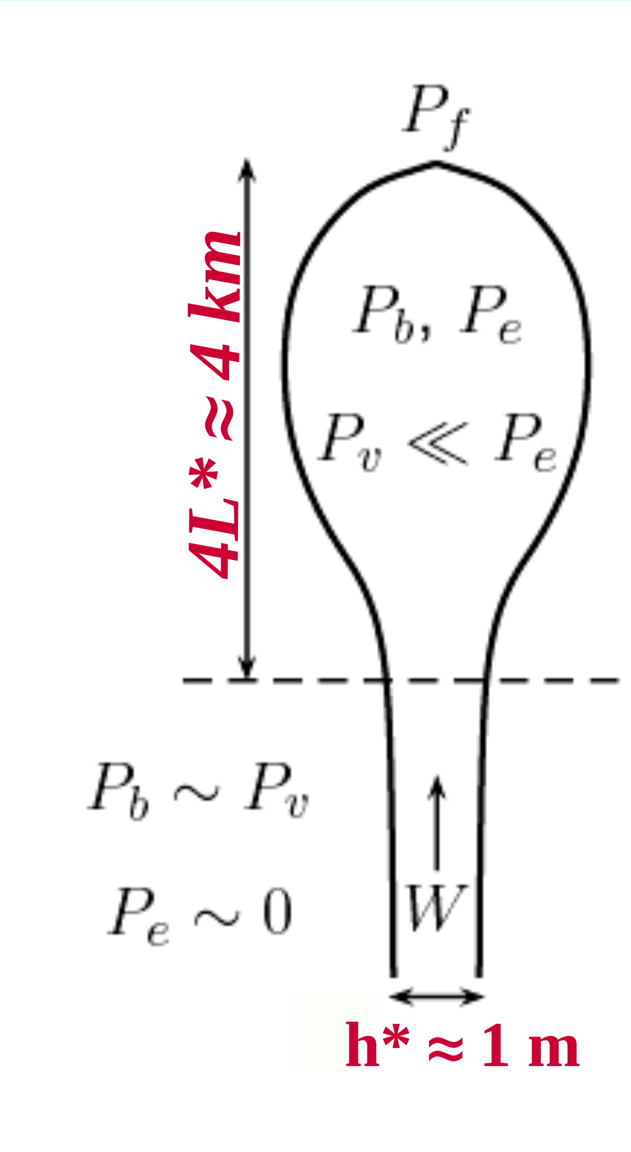
$$\frac{L}{L^*}$$

$\frac{L}{L^*}$ << **1** Layer has no effect

$\frac{L}{L^*}$ >> **1** Dyke behaves as in a semi- infinite medium

For a "typical" basaltic dyke





$$L^* \approx 1 \text{ km}$$

$$\frac{L}{L^*} \sim O(1)$$

Governing equations

Momentum equation + mass conservation

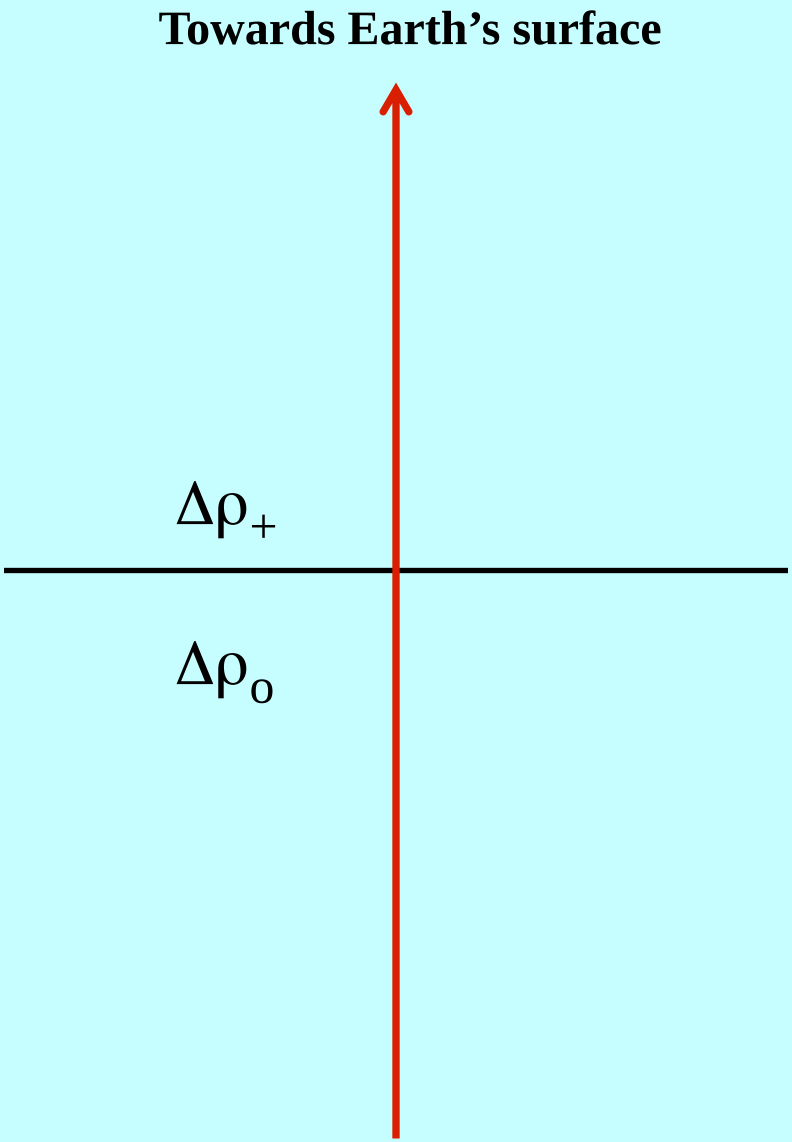
$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[\frac{1}{3\mu}h^3\left(\frac{\partial P_e}{\partial z} - \Delta\rho g\right)\right]$$

Elastic deformation

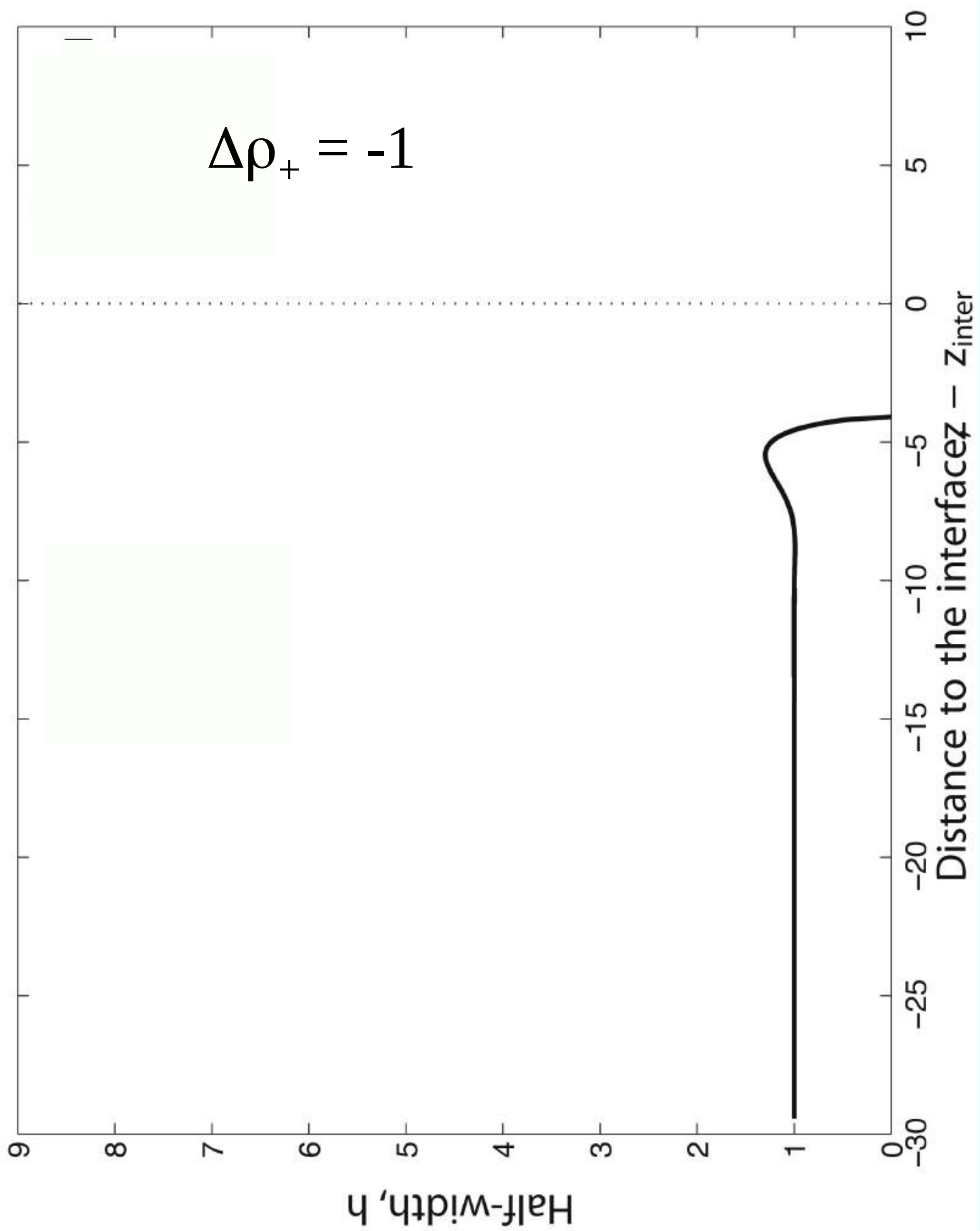
$$P_e(z) = -\frac{G}{1-\nu}\frac{1}{\pi}\int_{-\infty}^{z_f}\frac{\partial h}{\partial \xi}\frac{d\xi}{\xi - z}$$

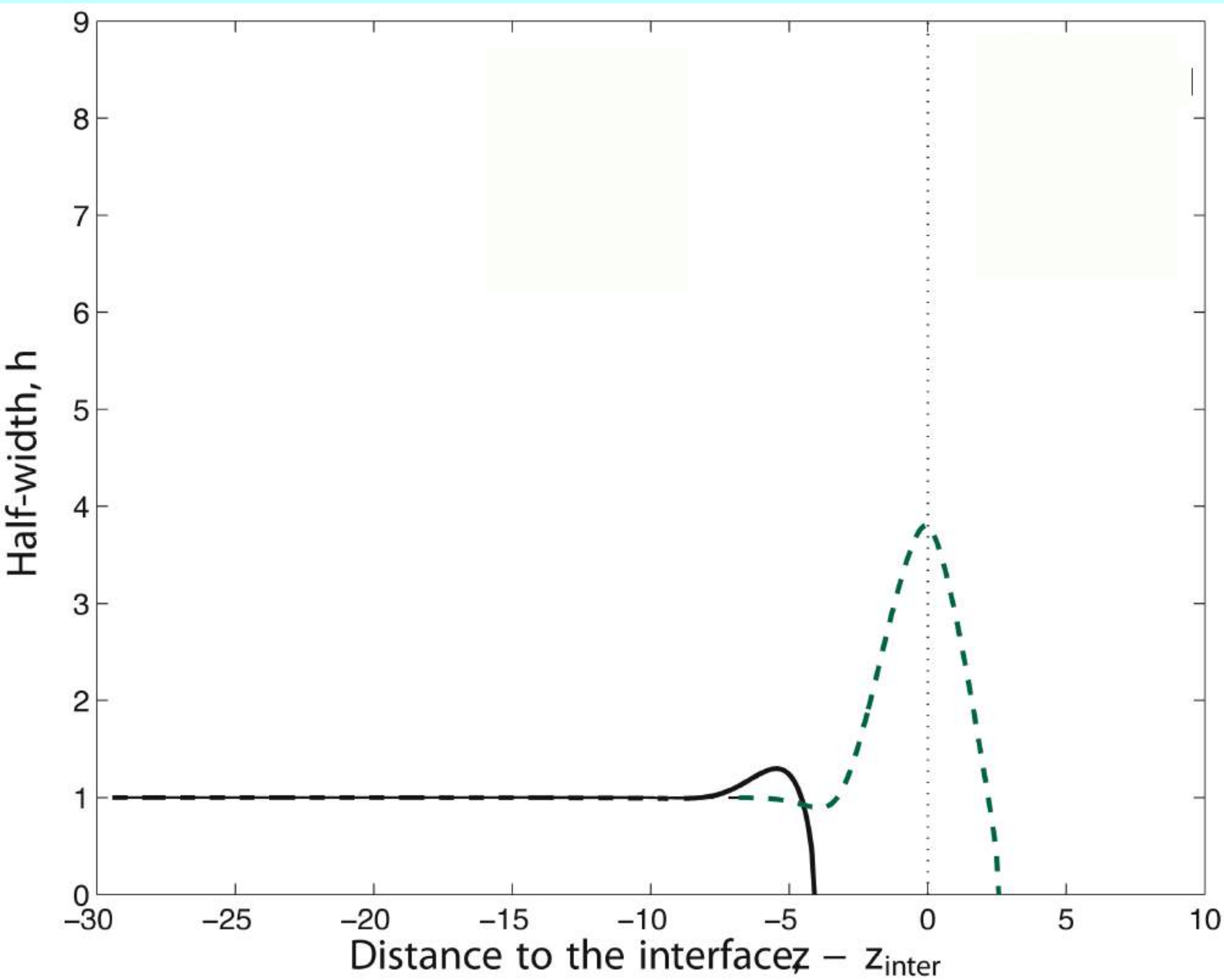
Stress intensity at dyke tip

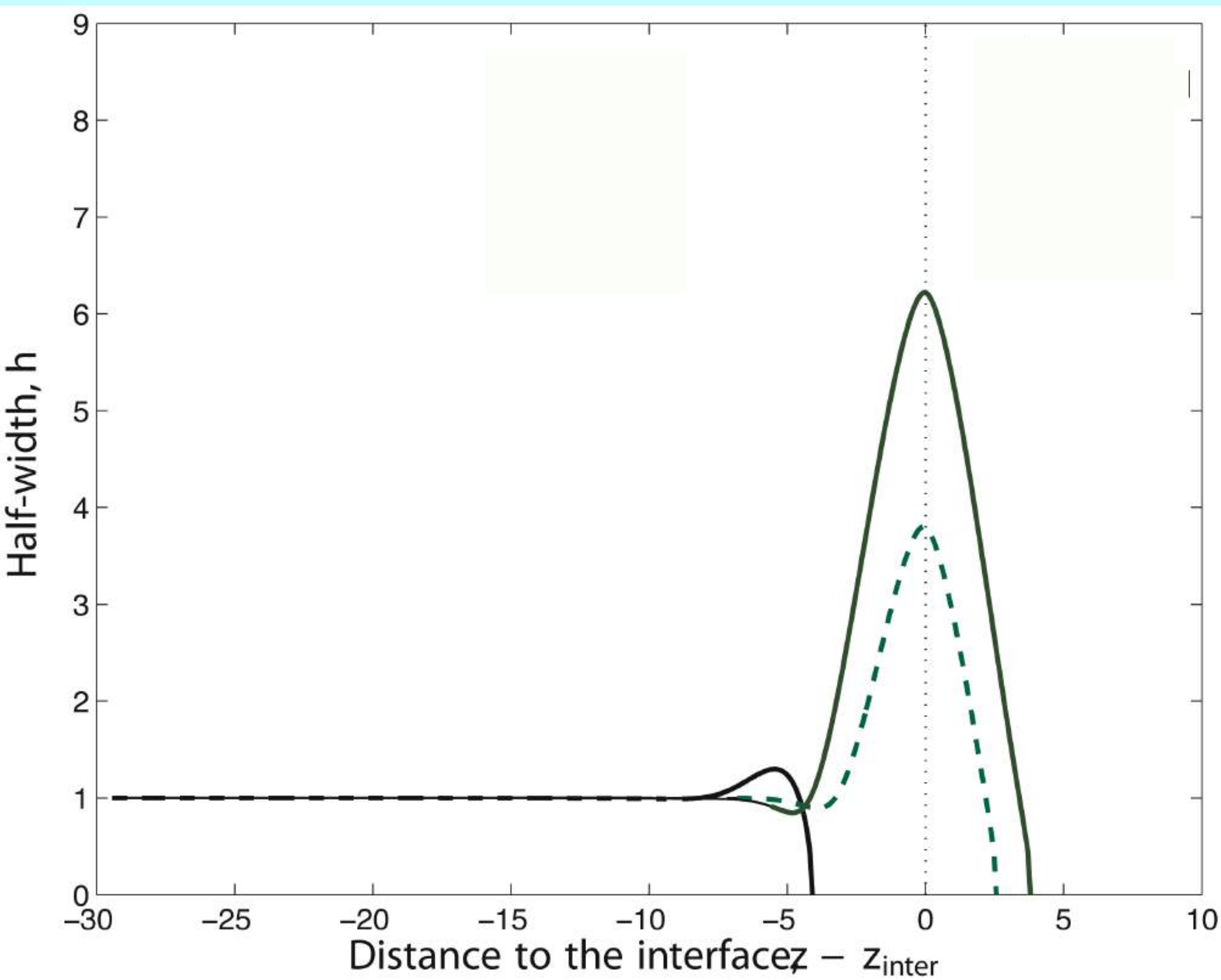
$$h(z \sim z_f) \sim \frac{1-\nu}{G}K_c\sqrt{2(z_f - z)}$$


Towards Earth's surface
Δρ+
Δρo

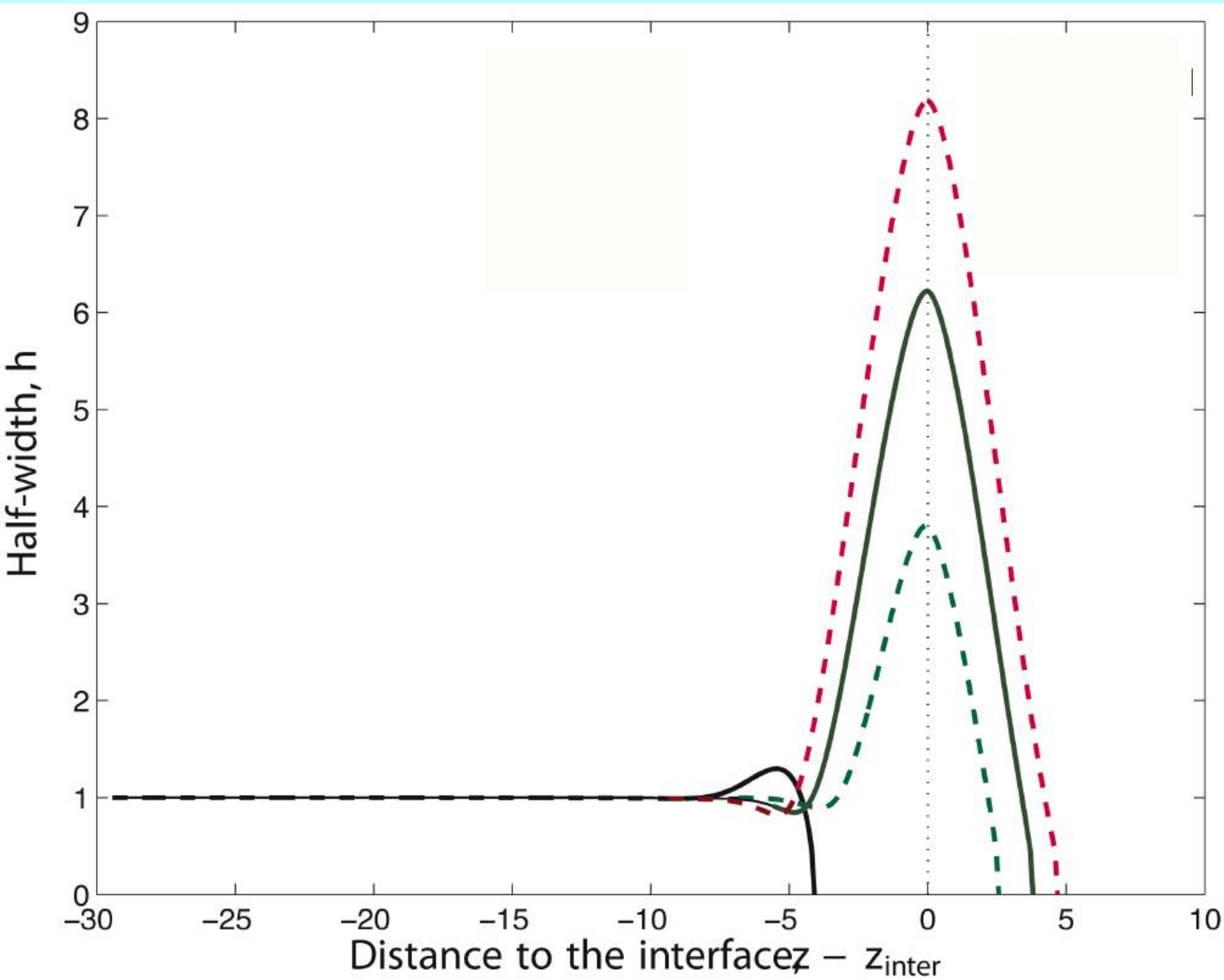
Penetration into less dense material




Half-width, h
Distance to the interface z − z_inter
0
1
2
3
4
5
6
7
8
9
−30
−25
−20
−15
−10
−5
0
5
10



Half-width, h
Distance to the interfacez − z_inter



Half-width, h
Distance to the interfacez − zinter
9
8
7
6
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4
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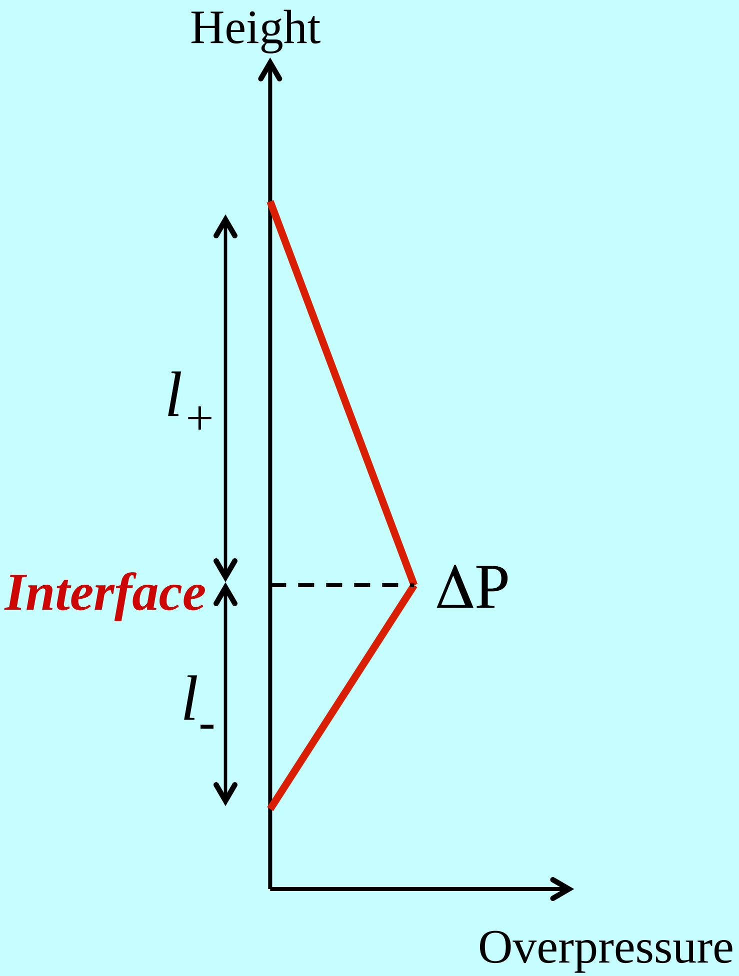
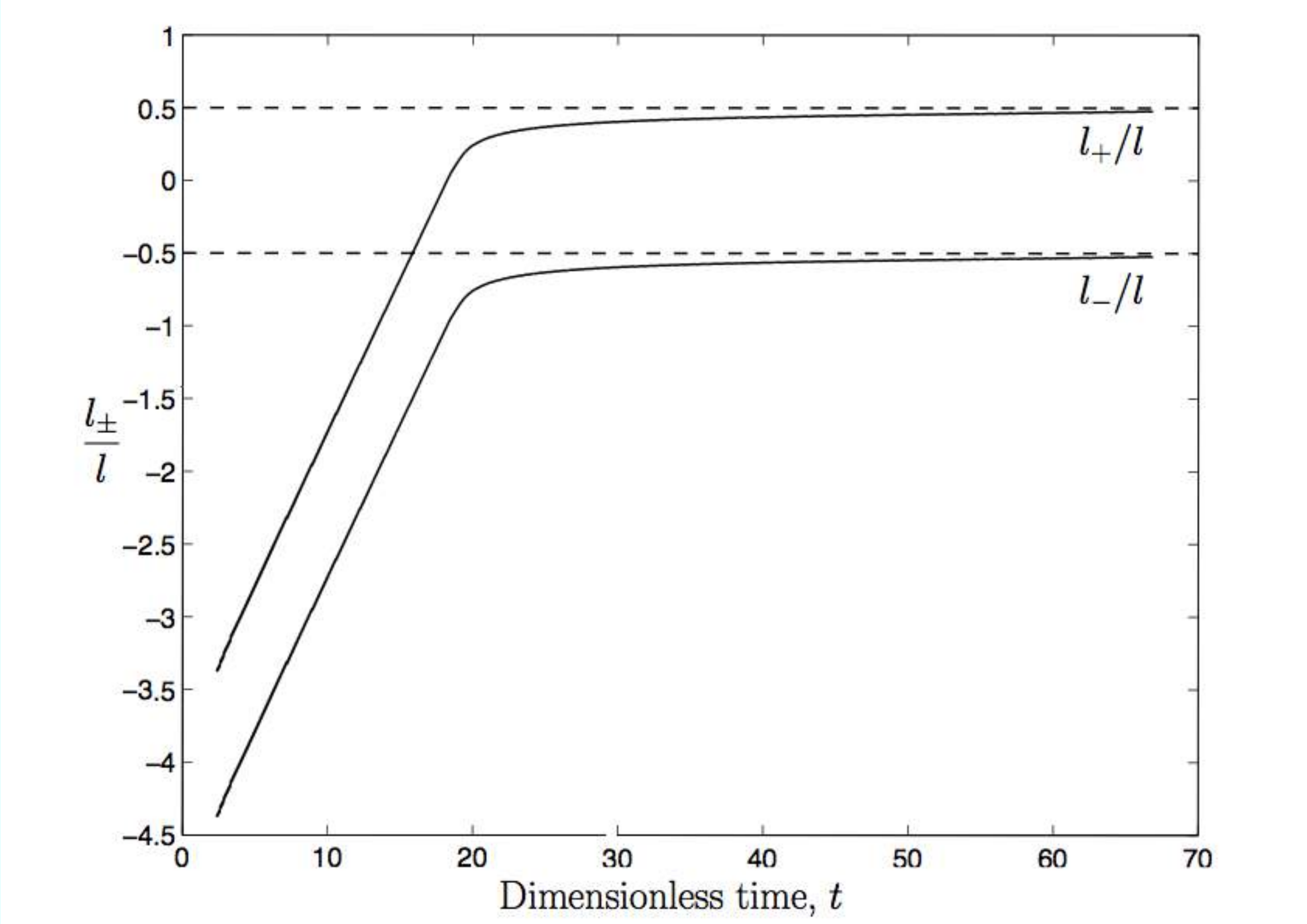
0
−30
−25
−20
−15
−10
−5
0
5
10

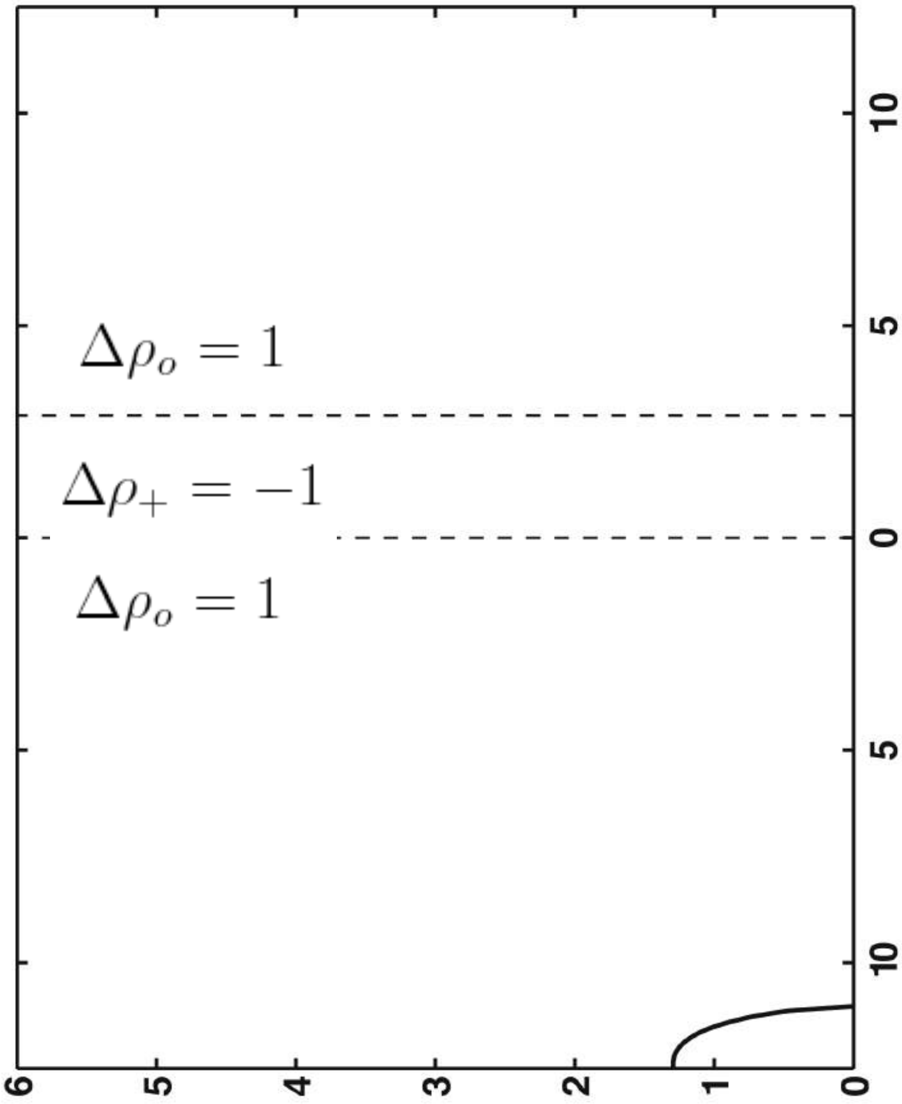
Hydrostatic balance in nose region

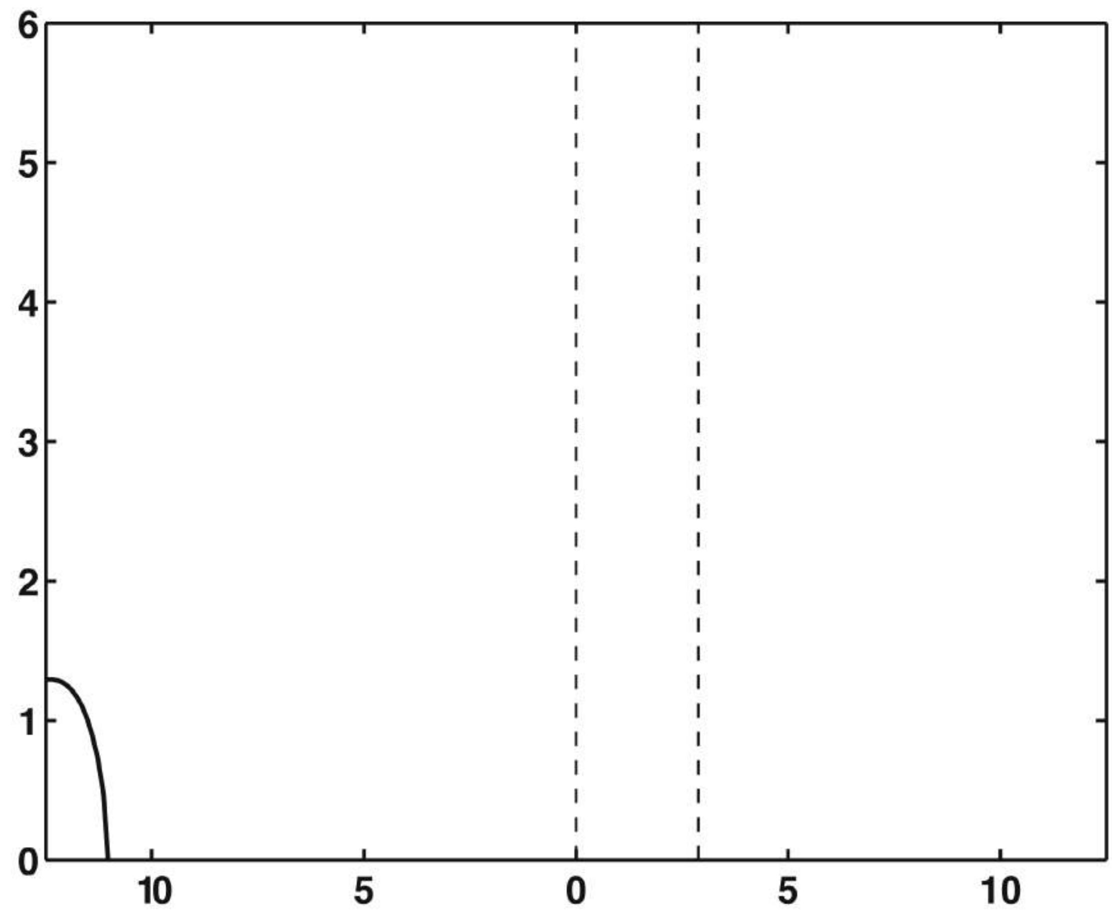




1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
−4
−4.5
$\frac{l_\pm}{l}$
l_+/l
l_-/l
0
10
20
30
40
50
60
70
Dimensionless time, t

Thin low density horizon





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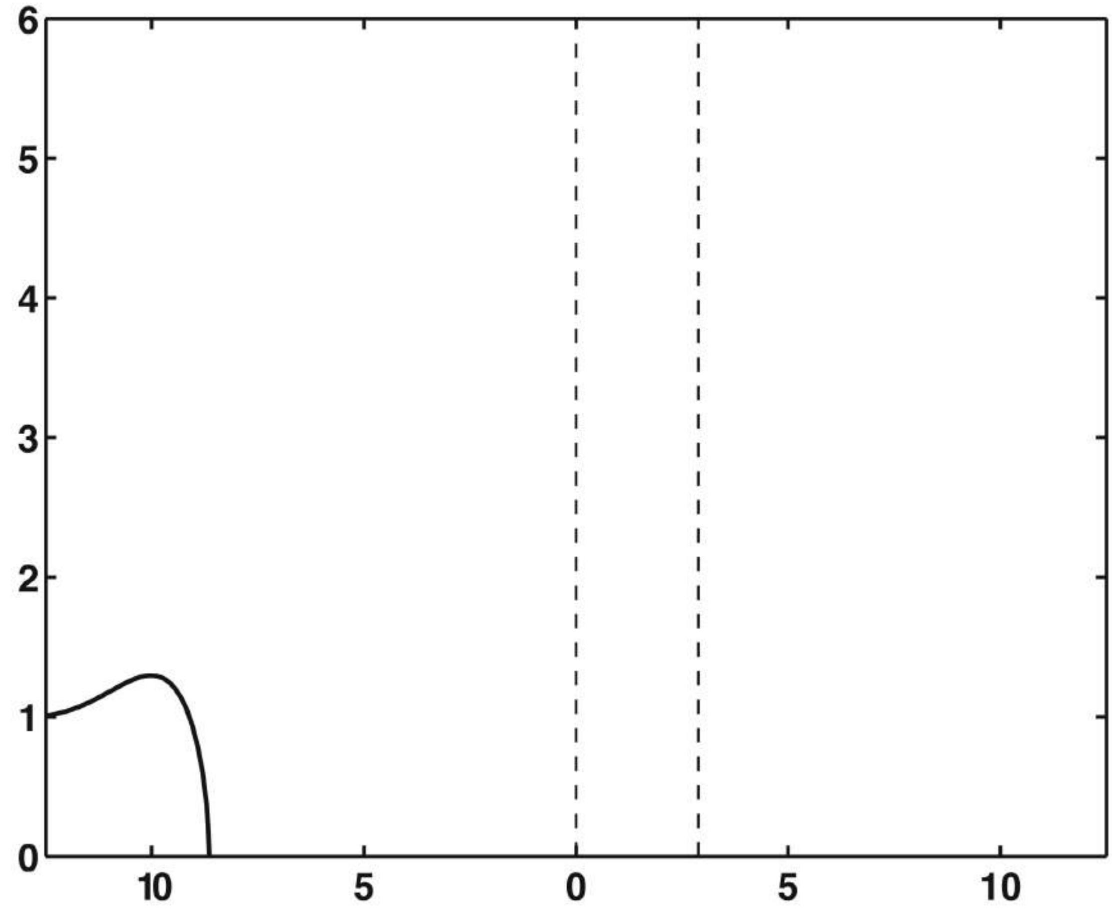
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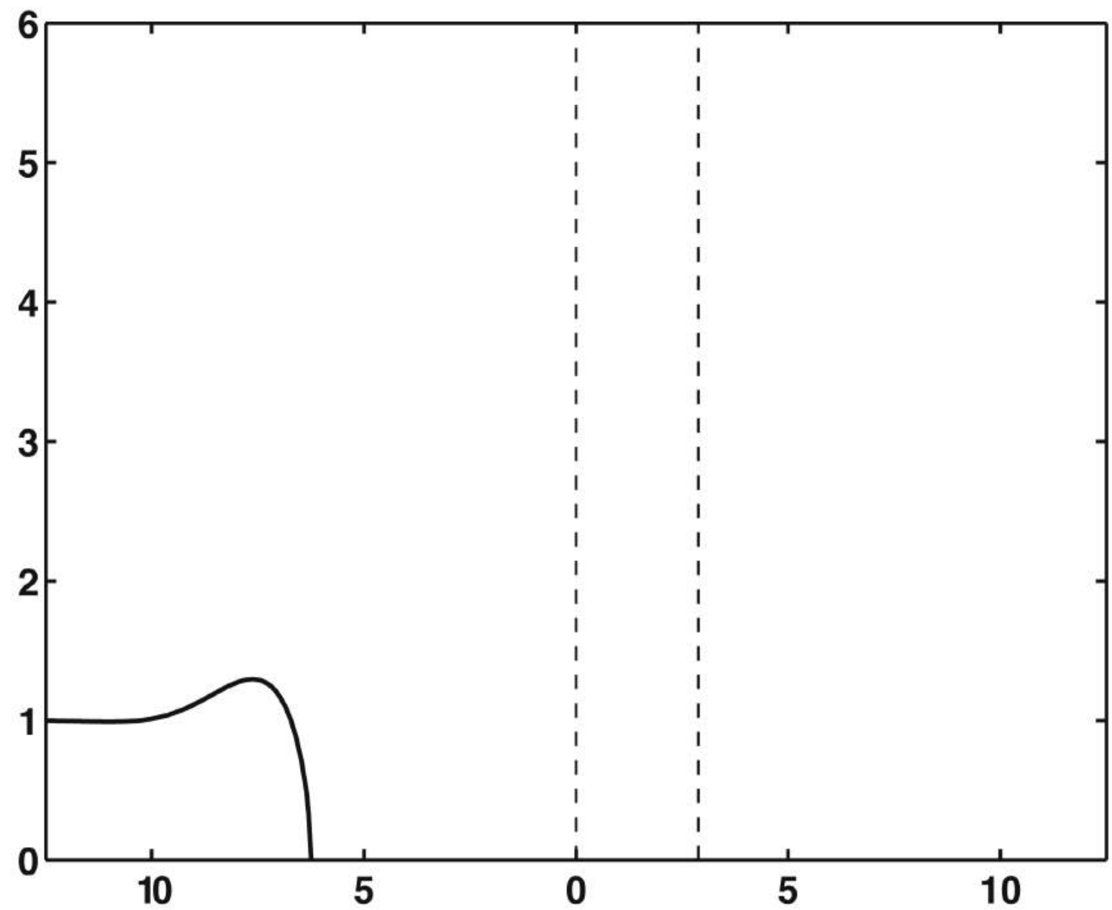

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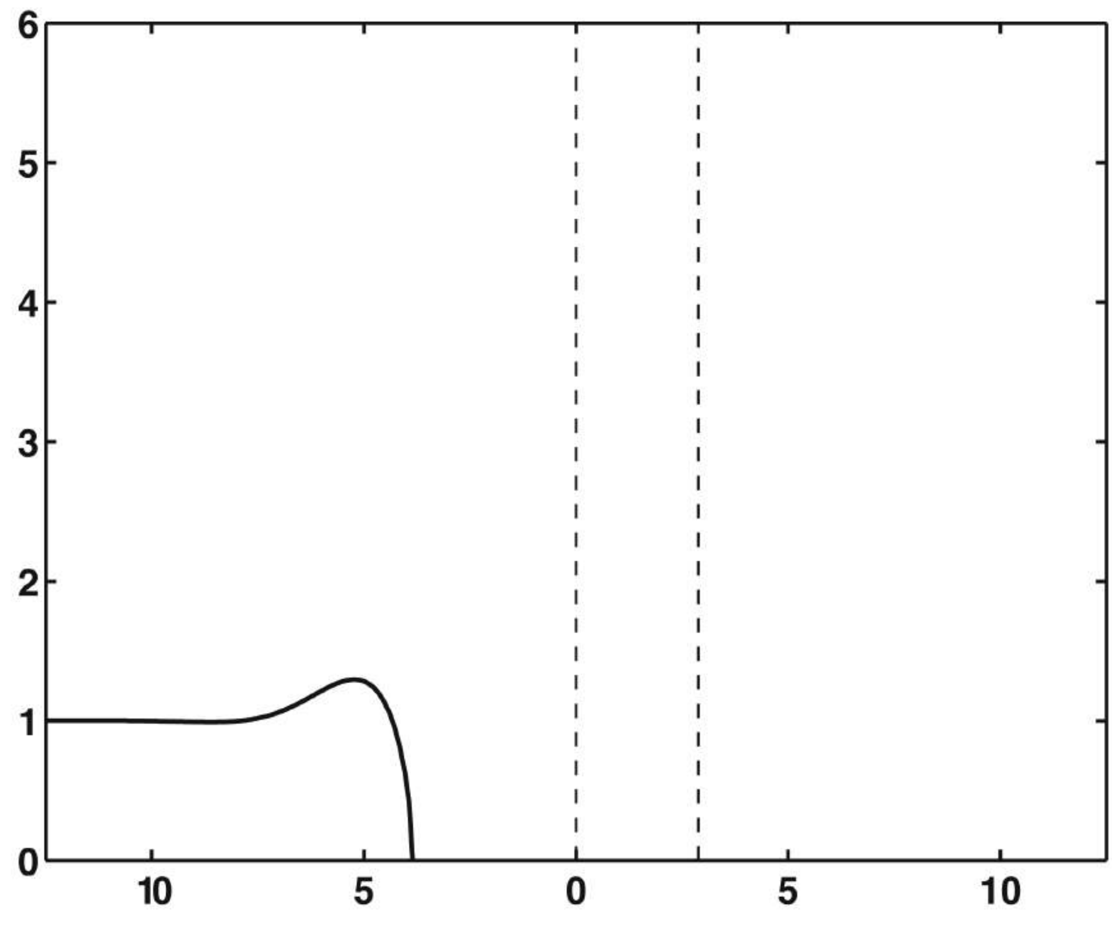

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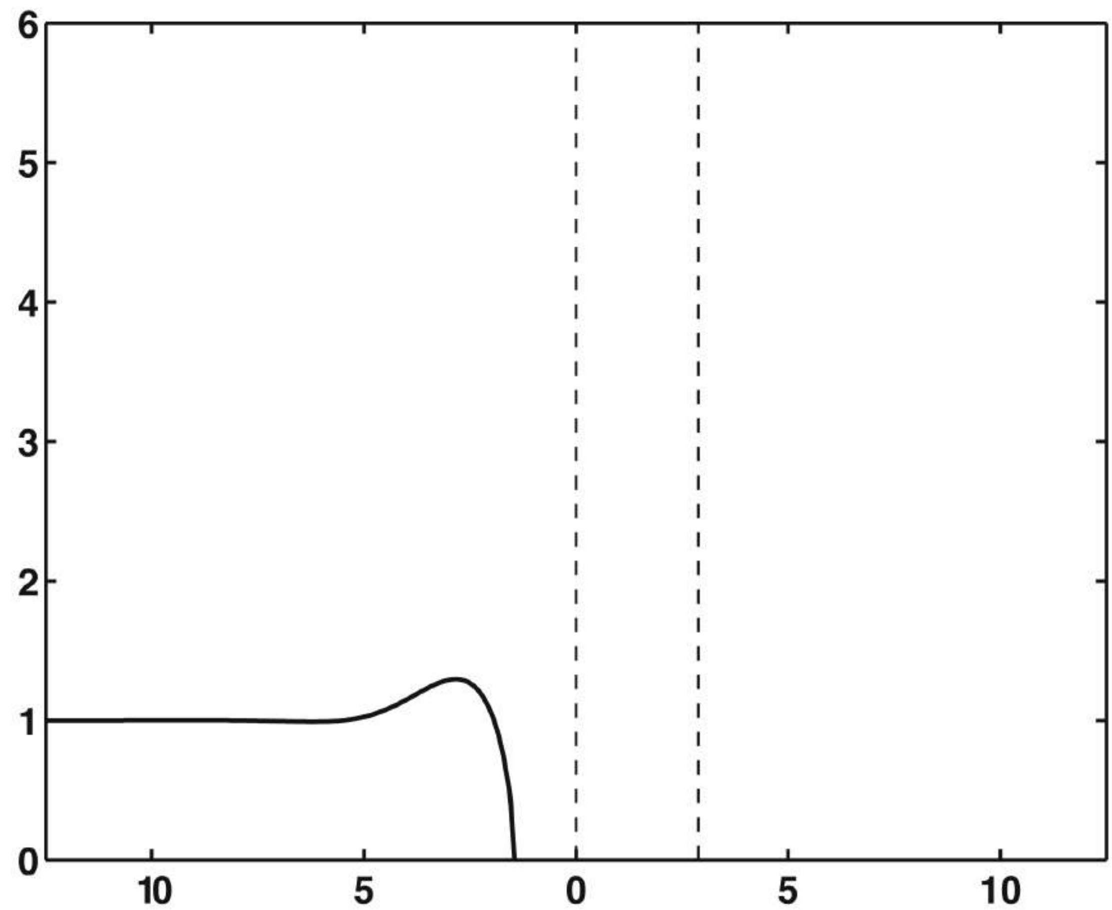

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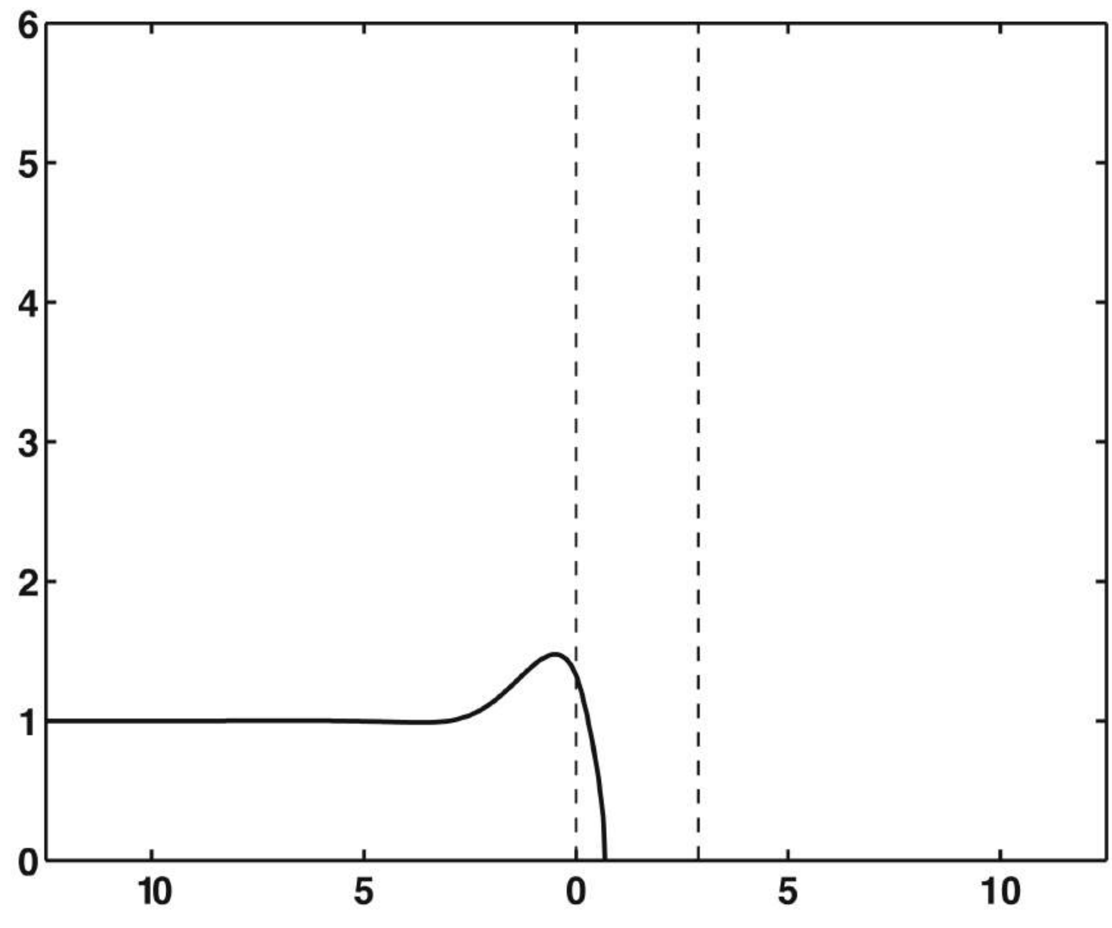

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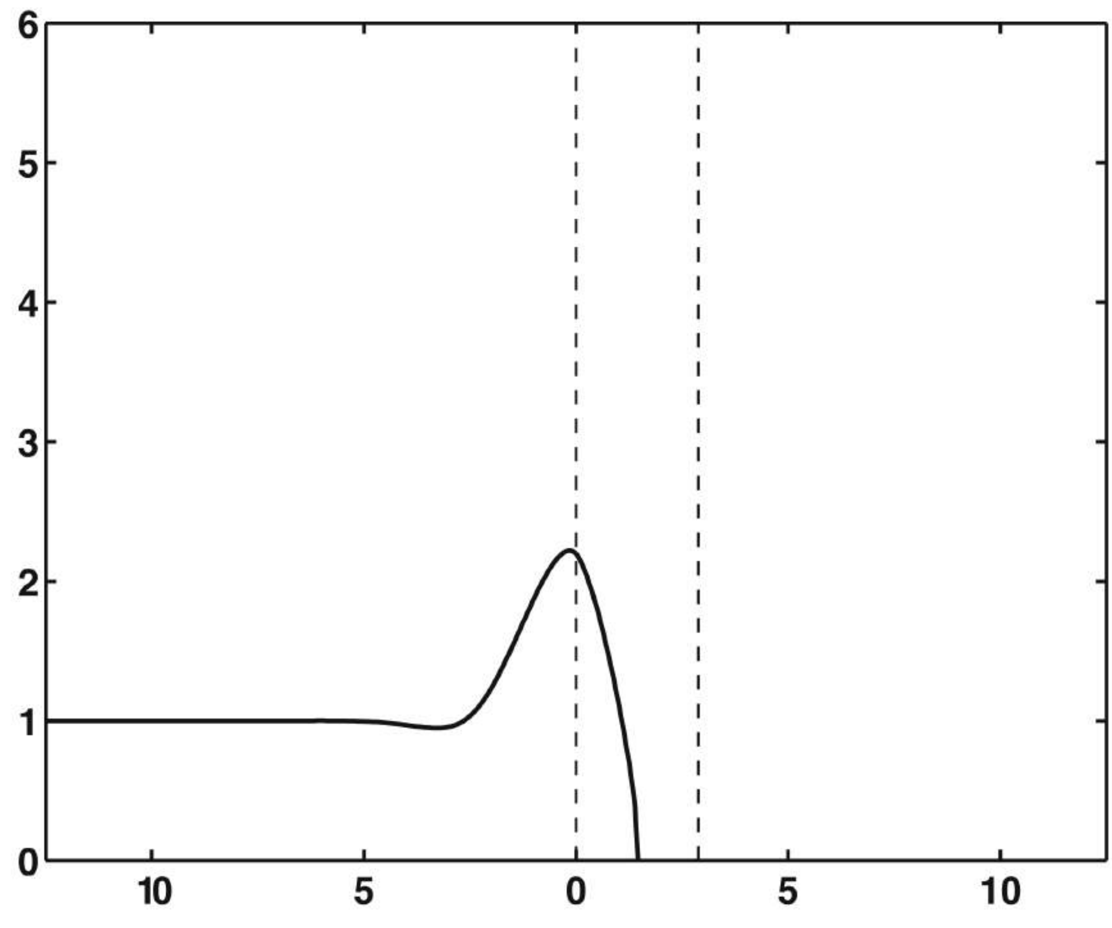

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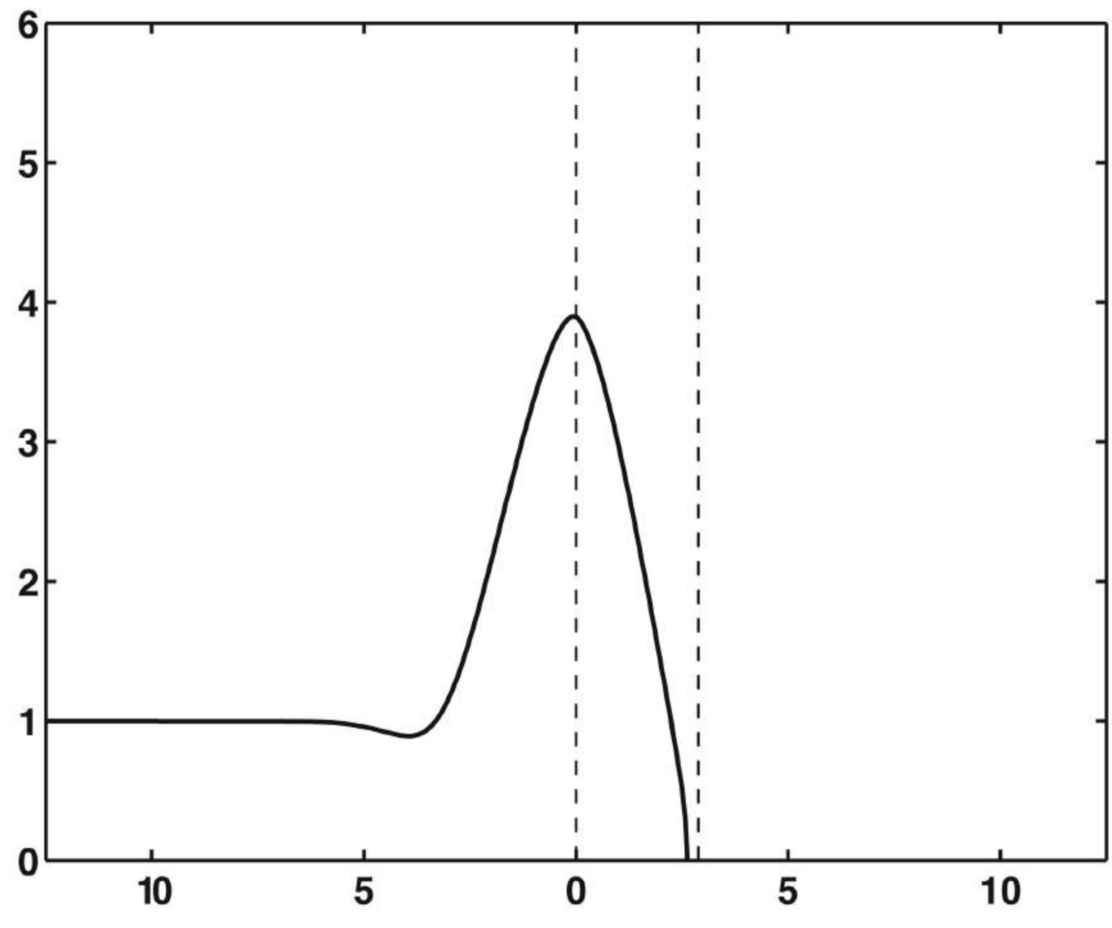
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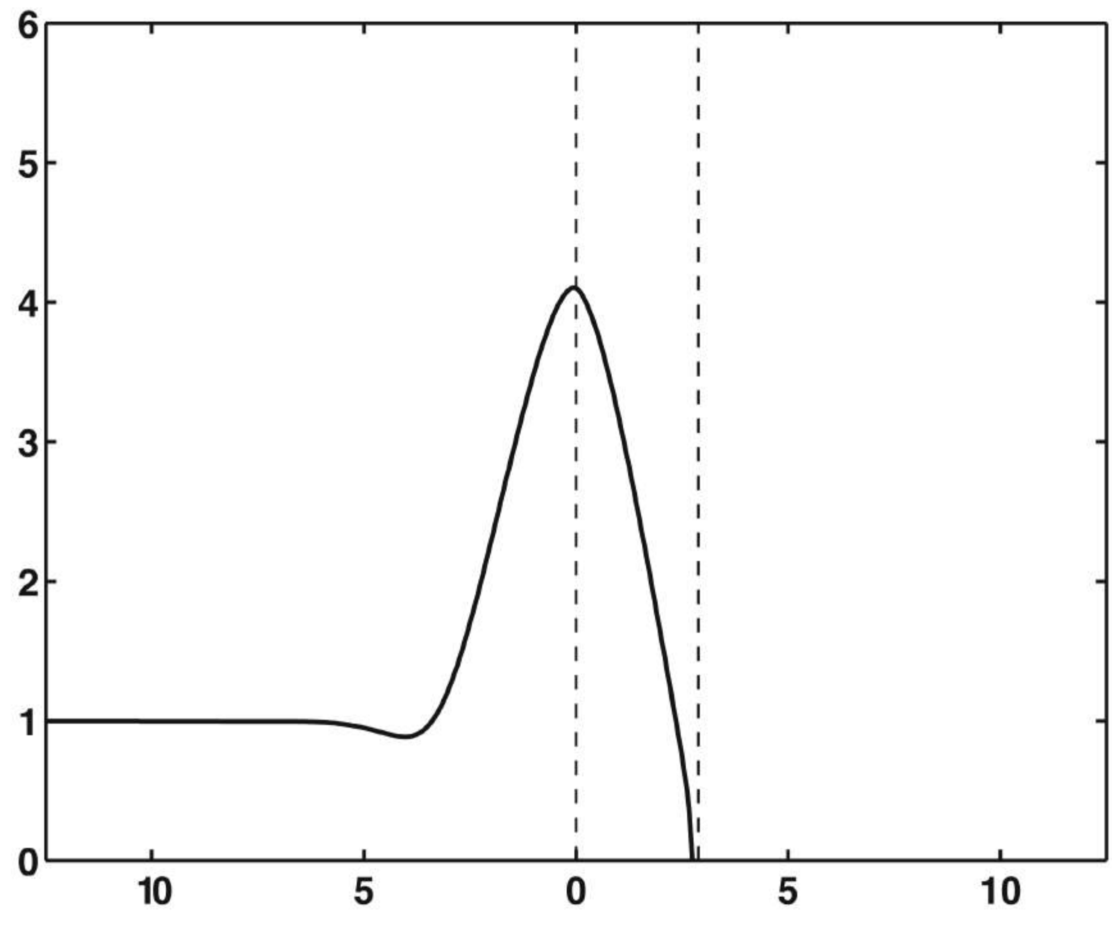
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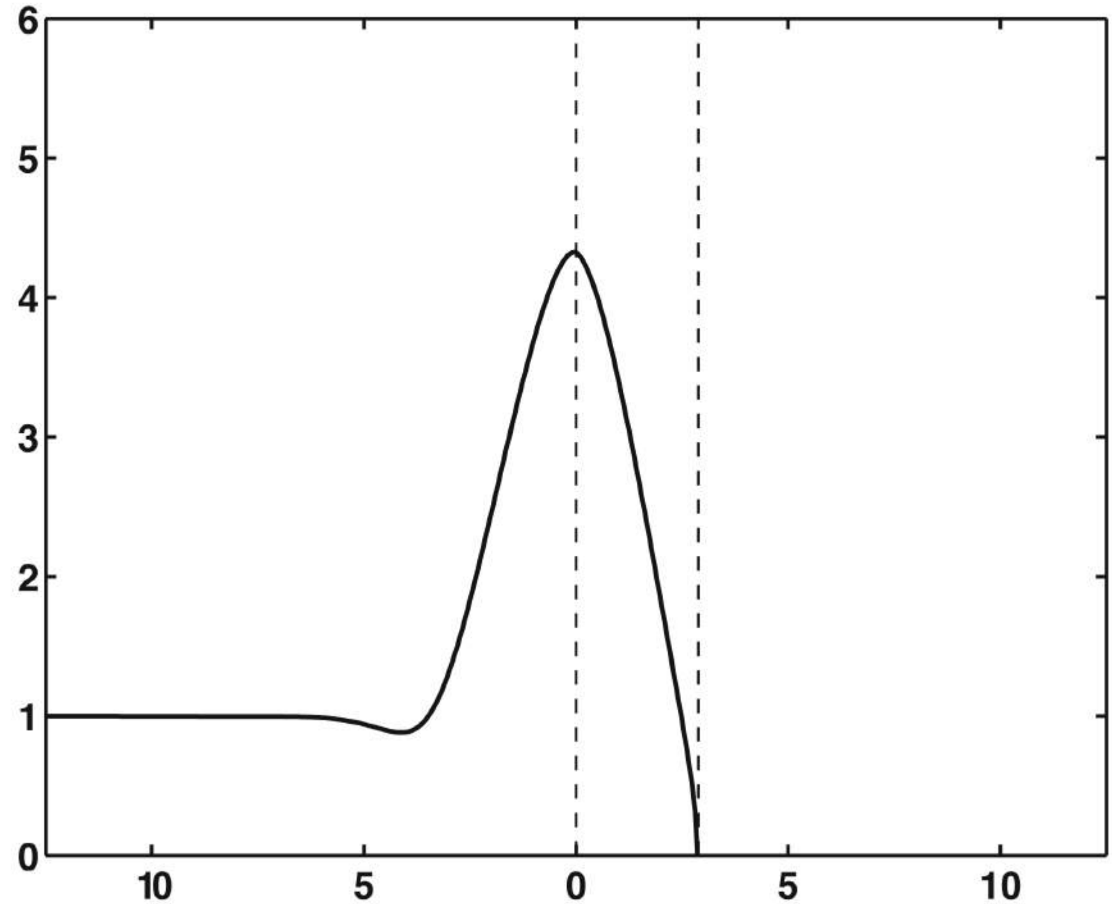

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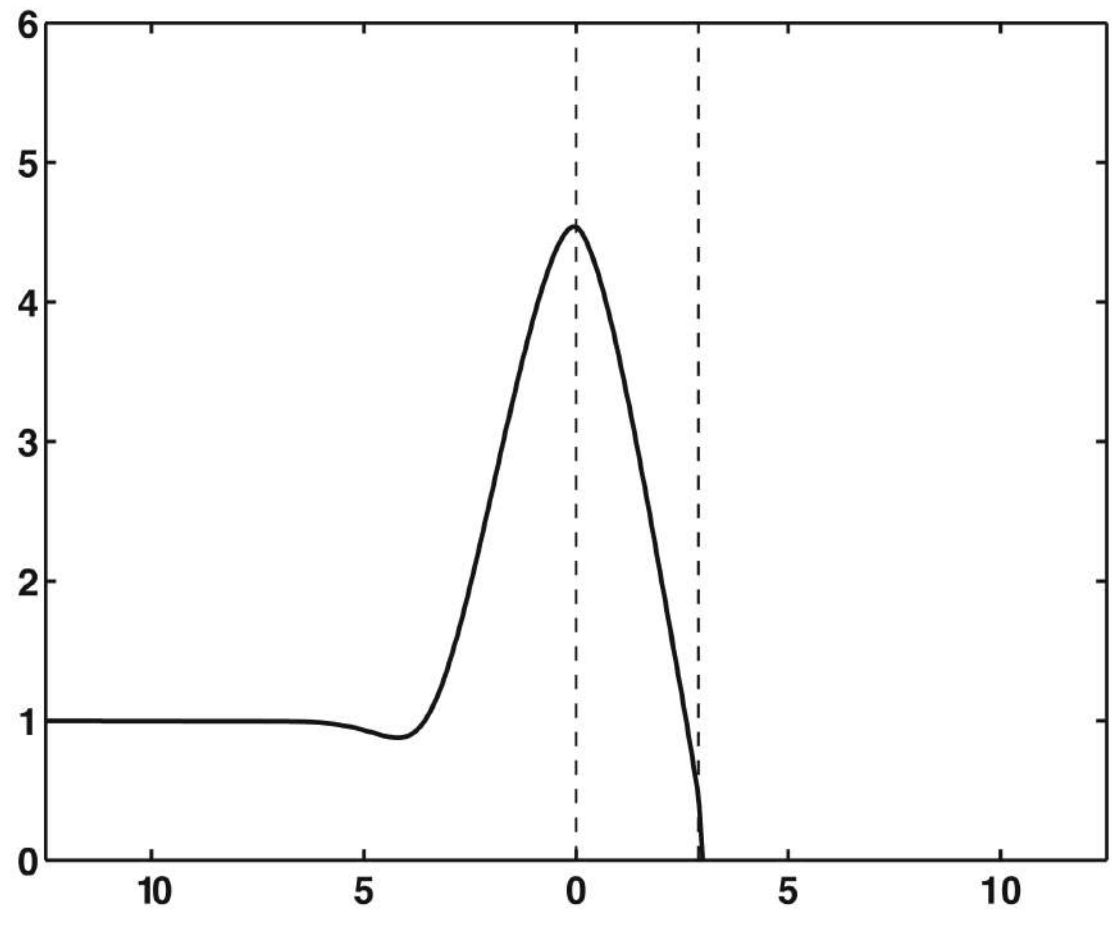
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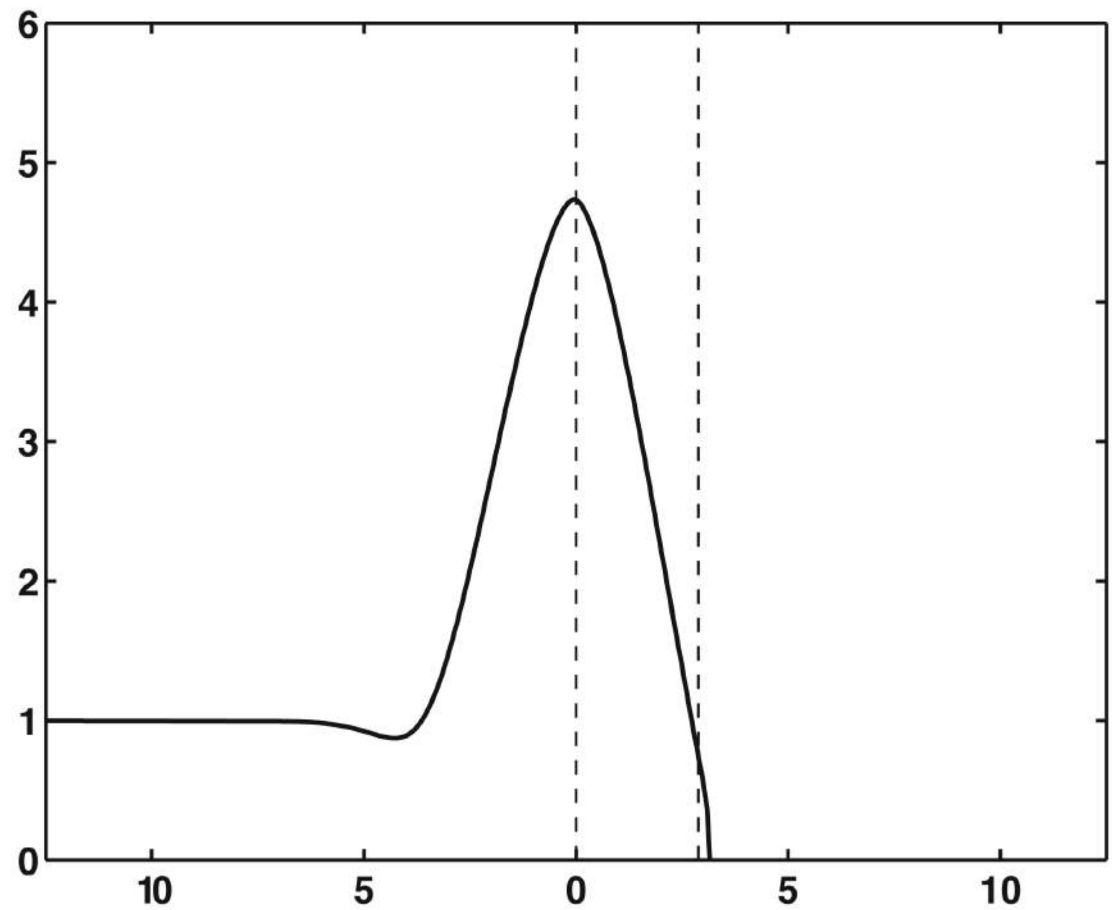

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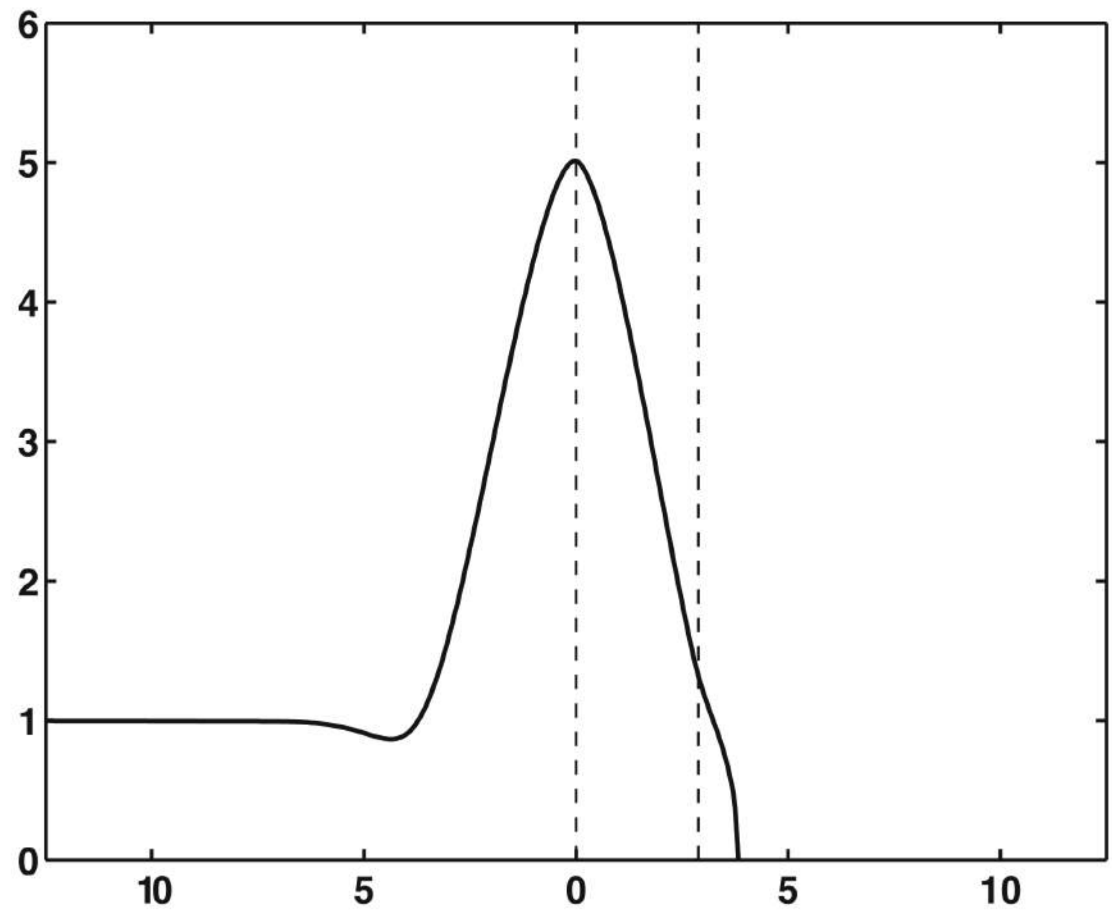
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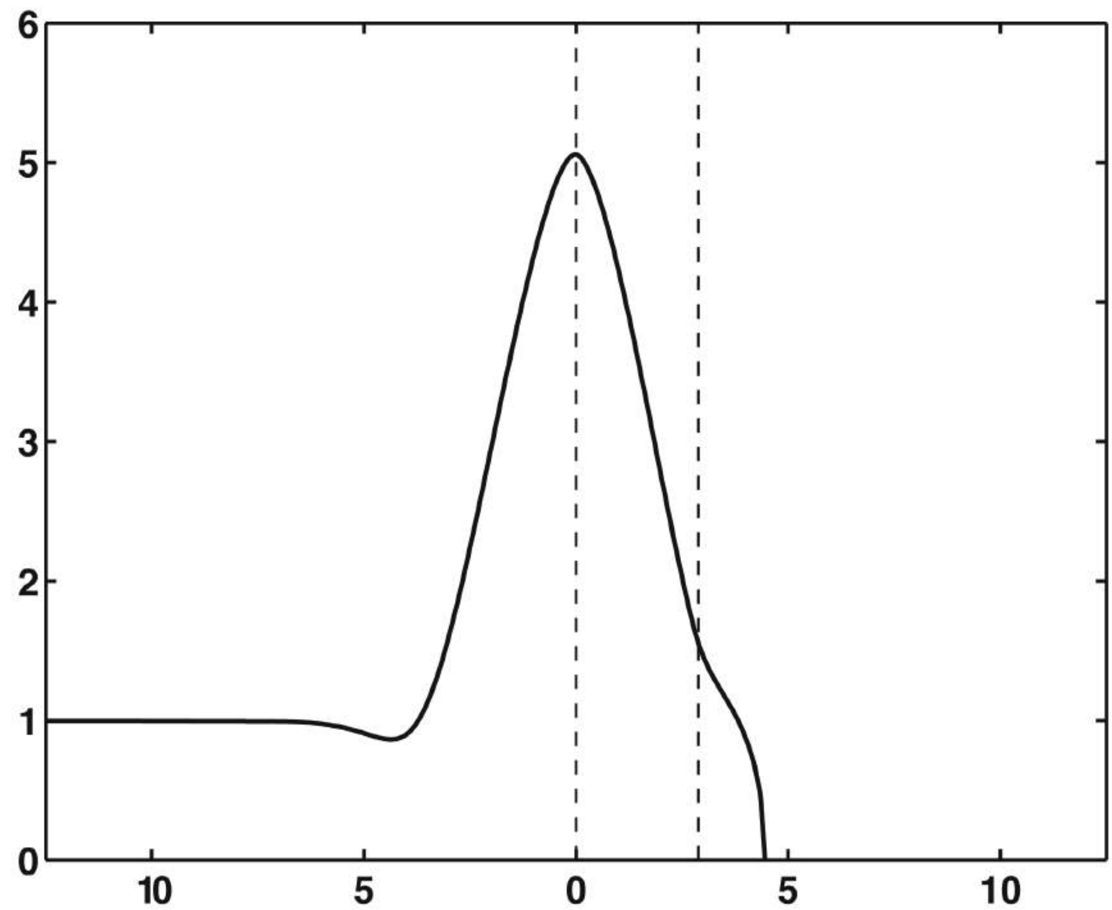

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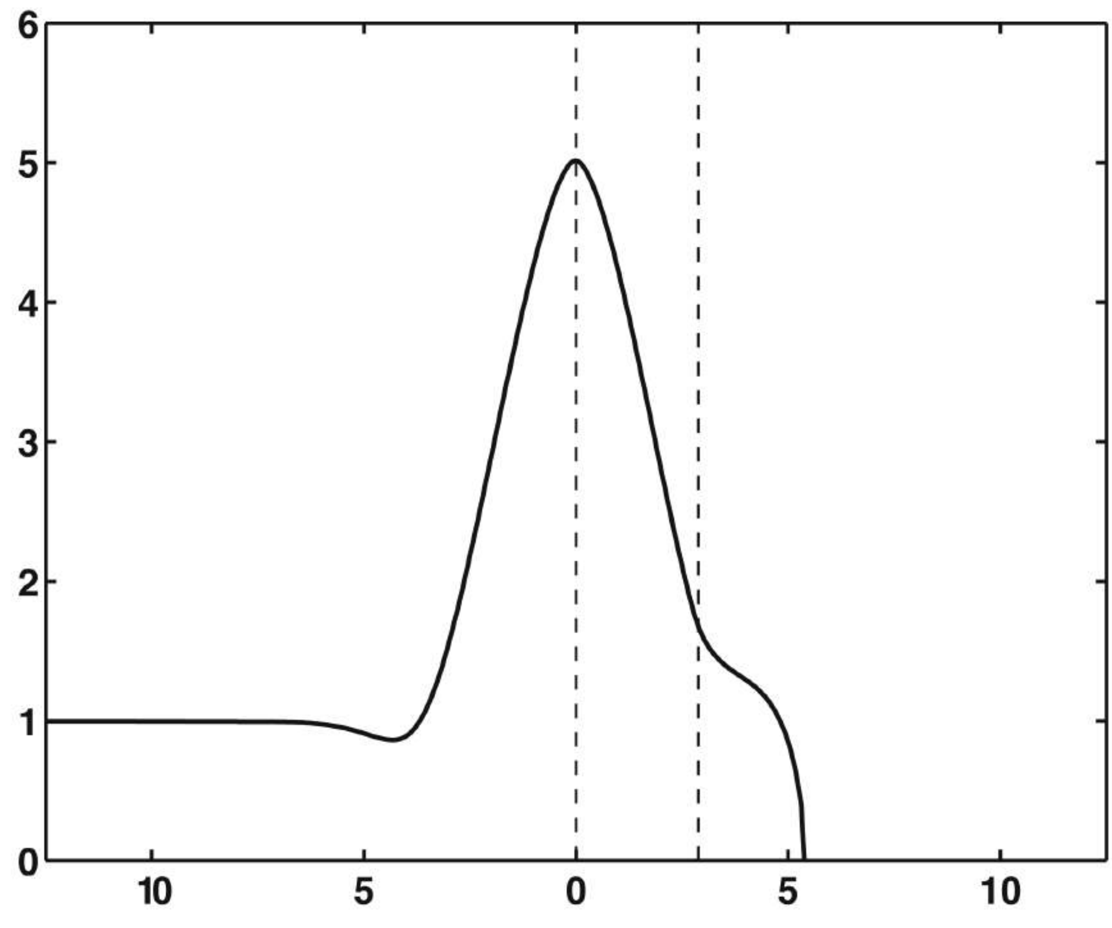

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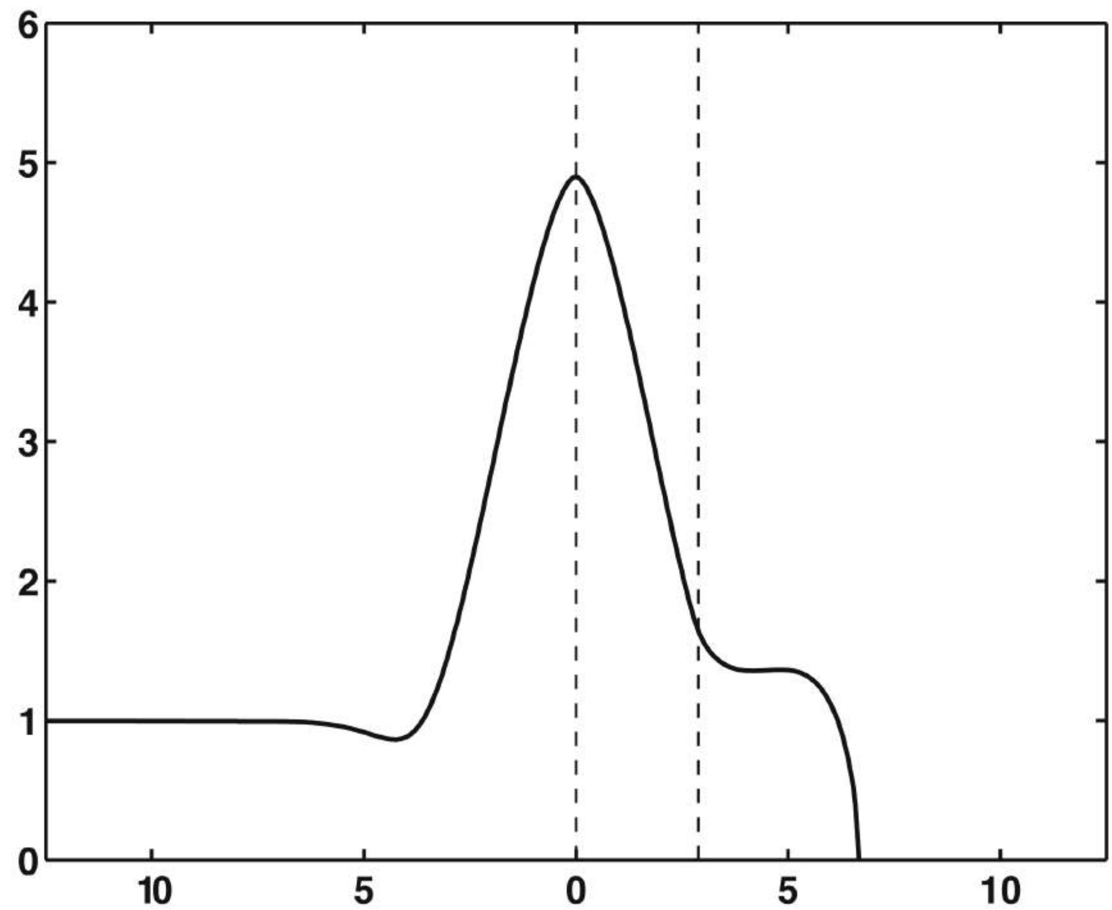

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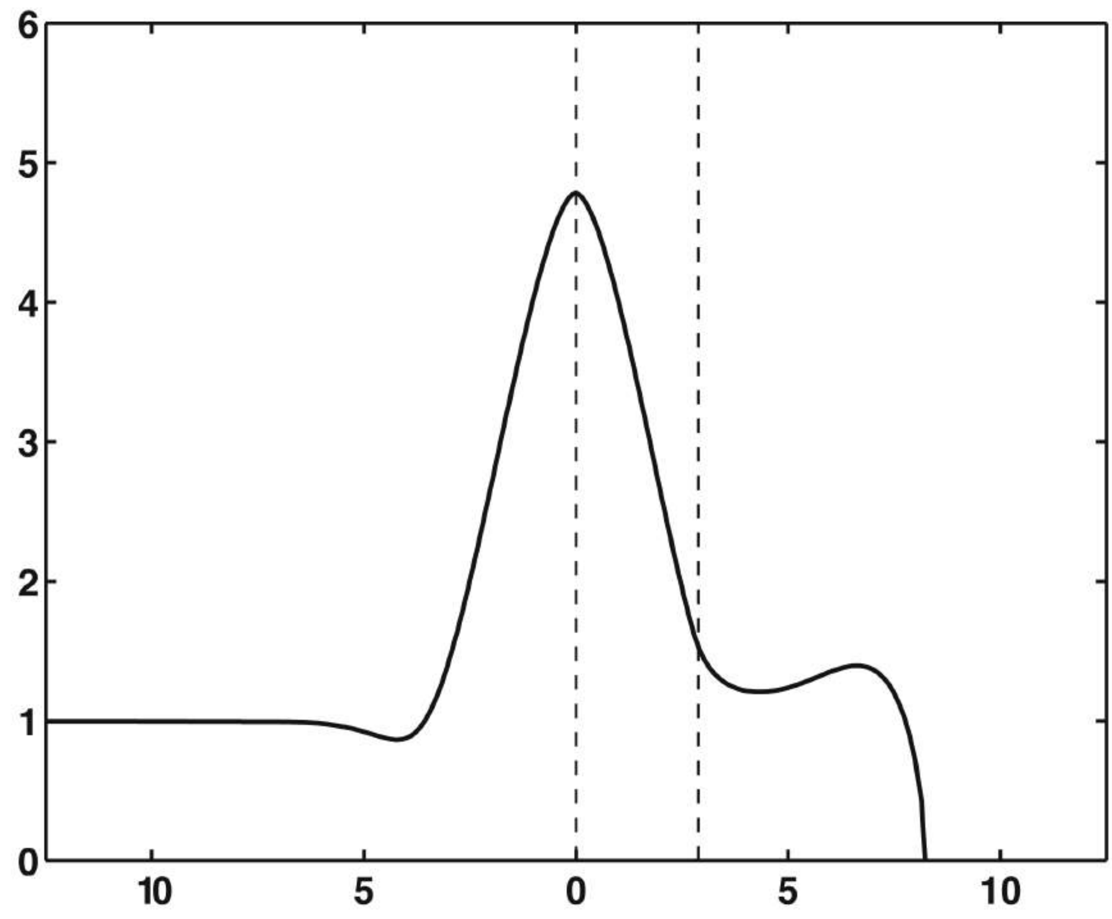
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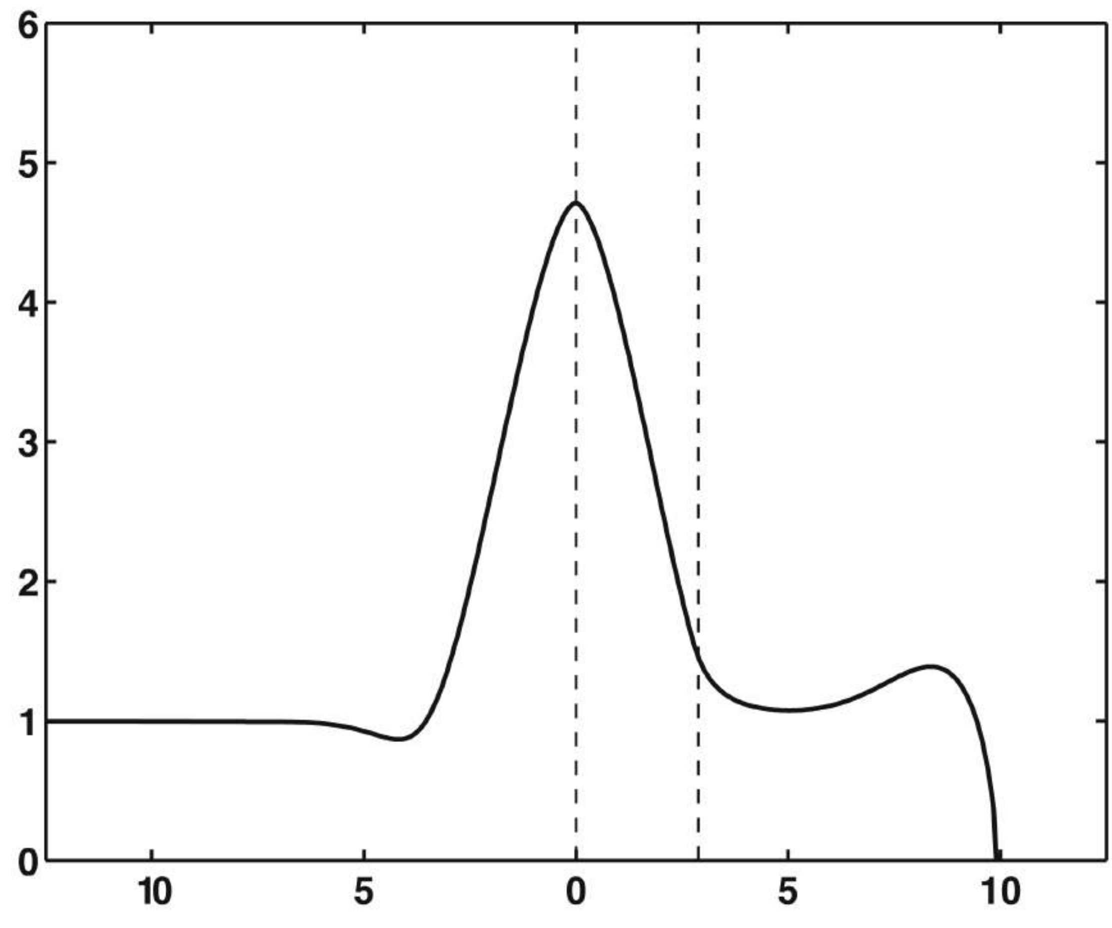
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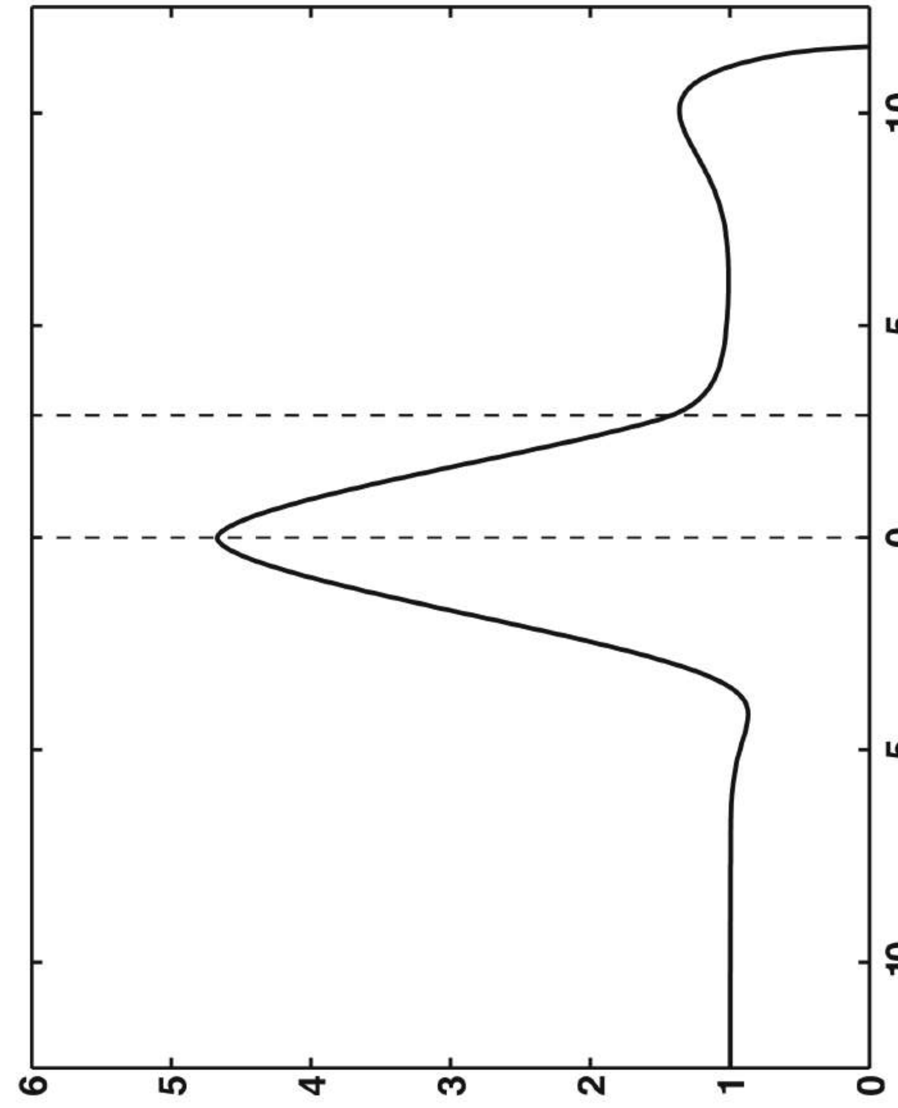

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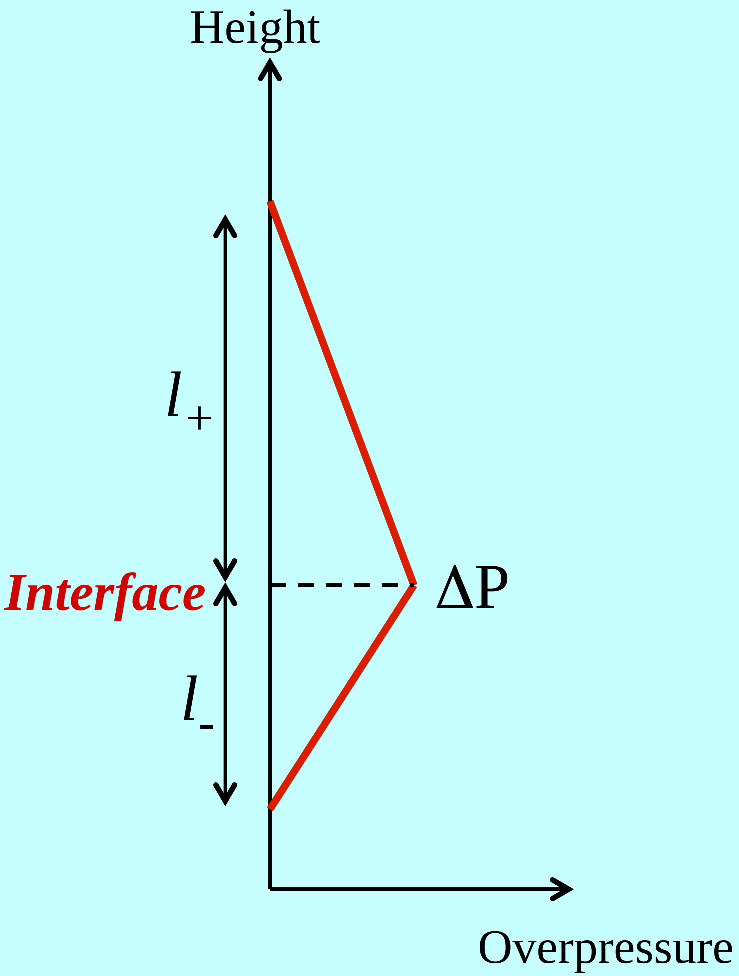
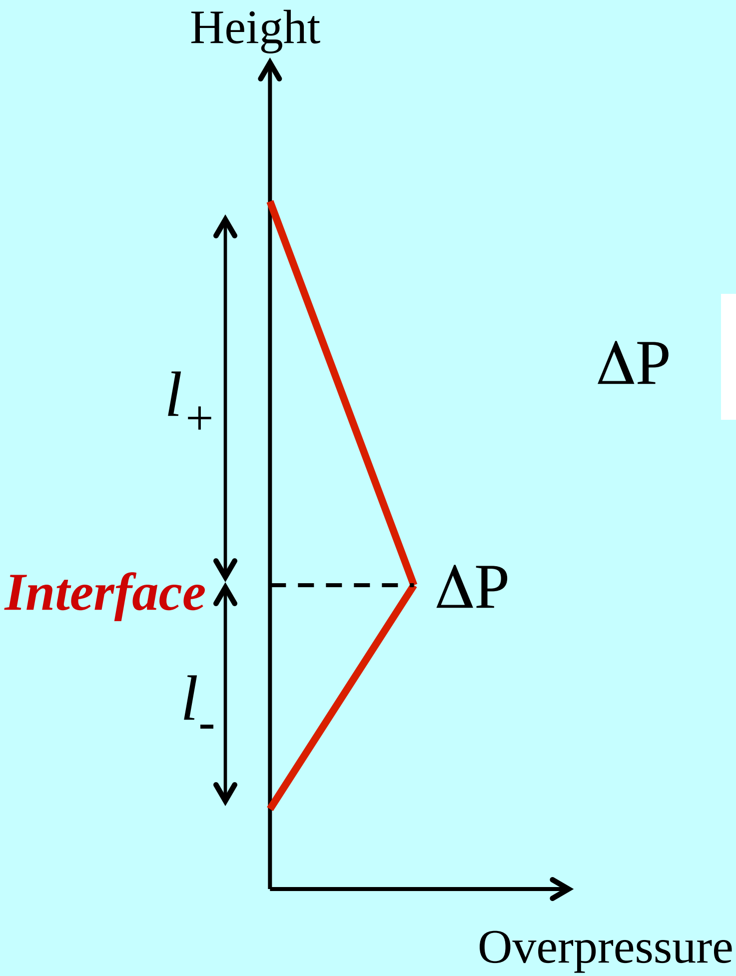
Hydrostatic balance in nose region



Hydrostatic balance in nose region

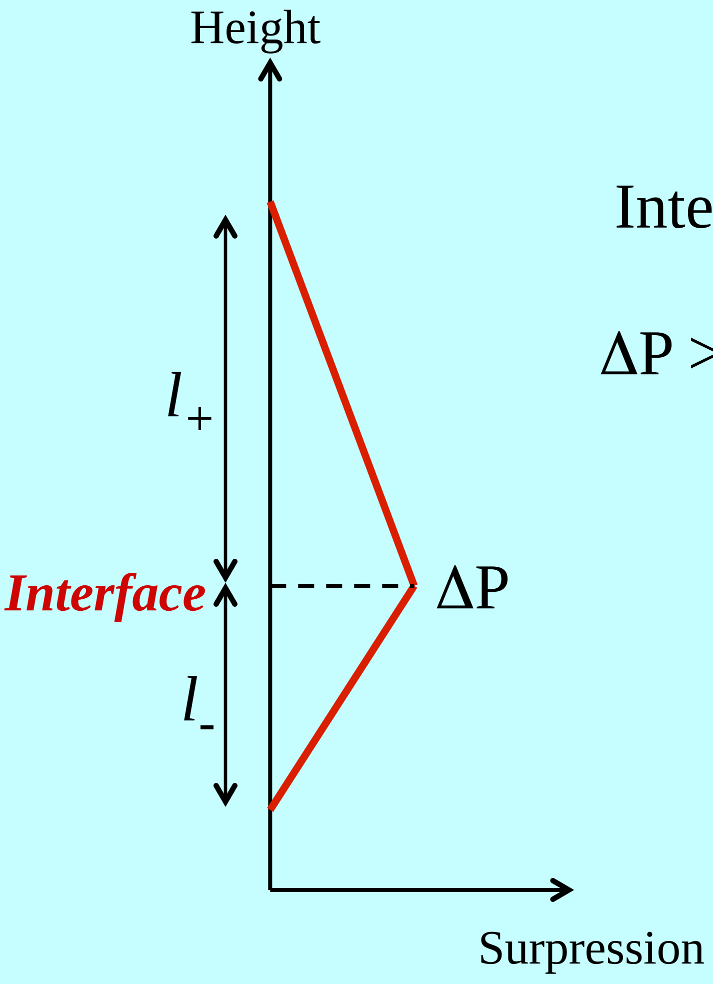


Pressure at the interface

ΔP $\quad |\Delta\rho_o g l_-| \sim |\Delta\rho_+ g l_+|$

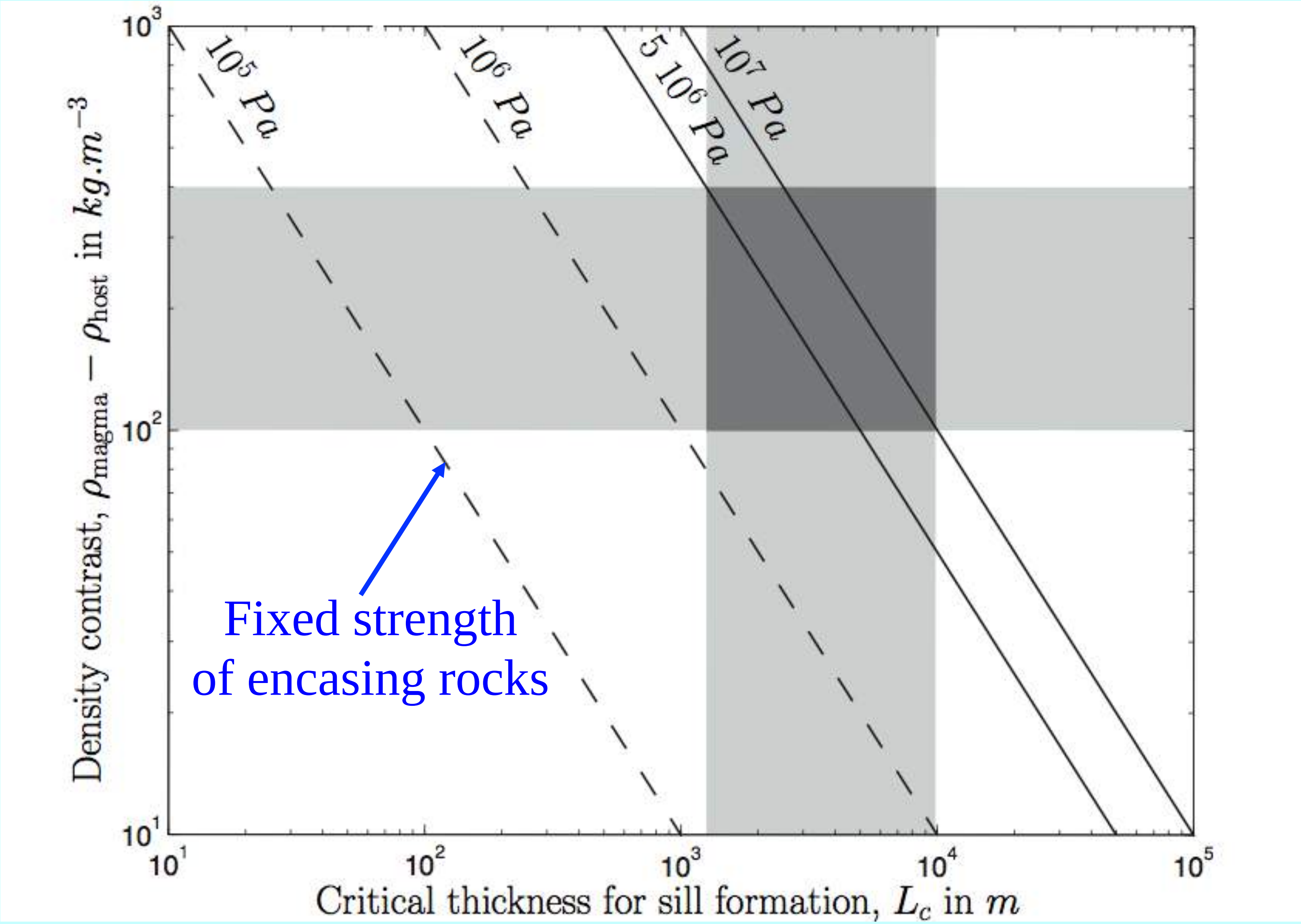
$$l_+ \sim l_- \left|\frac{\Delta\rho_o}{\Delta\rho_+}\right|$$

Hydrostatic balance in nose region



Internal pressure at the interface

$\Delta P > \tau$ (strength of encasing rocks)



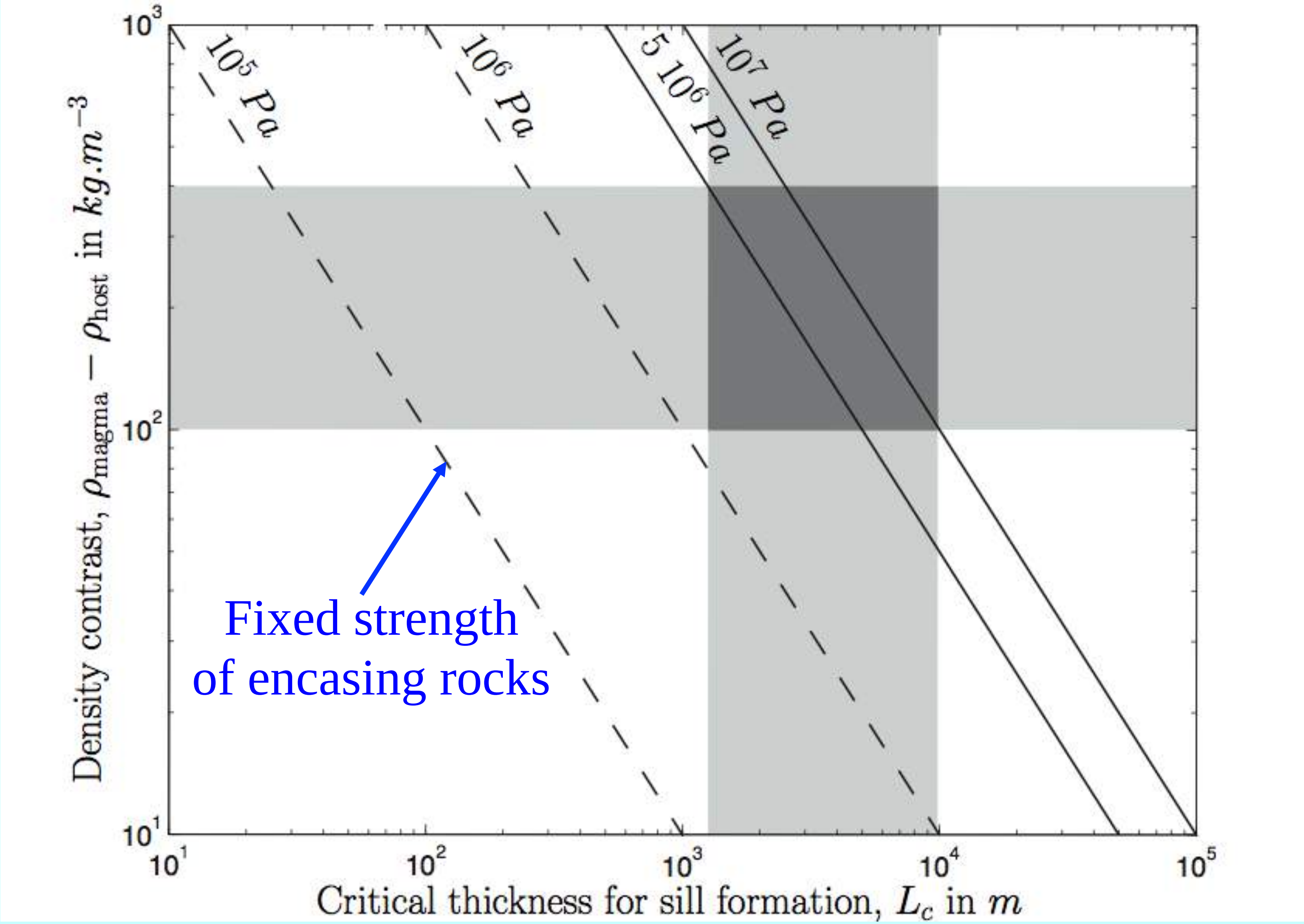
10^5 Pa
10^6 Pa
$5\ 10^6$ Pa
10^7 Pa
Fixed strength
of encasing rocks
Density contrast, $\rho_{\mathrm{magma}} - \rho_{\mathrm{host}}$ in $kg.m^{-3}$
Critical thickness for sill formation, L_c in m
10^1
10^2
10^3
10^4
10^5

Sill intrusion

Big Bend National Park, Texas

Intrusion along an interface !

Goat’s Creek, Utah

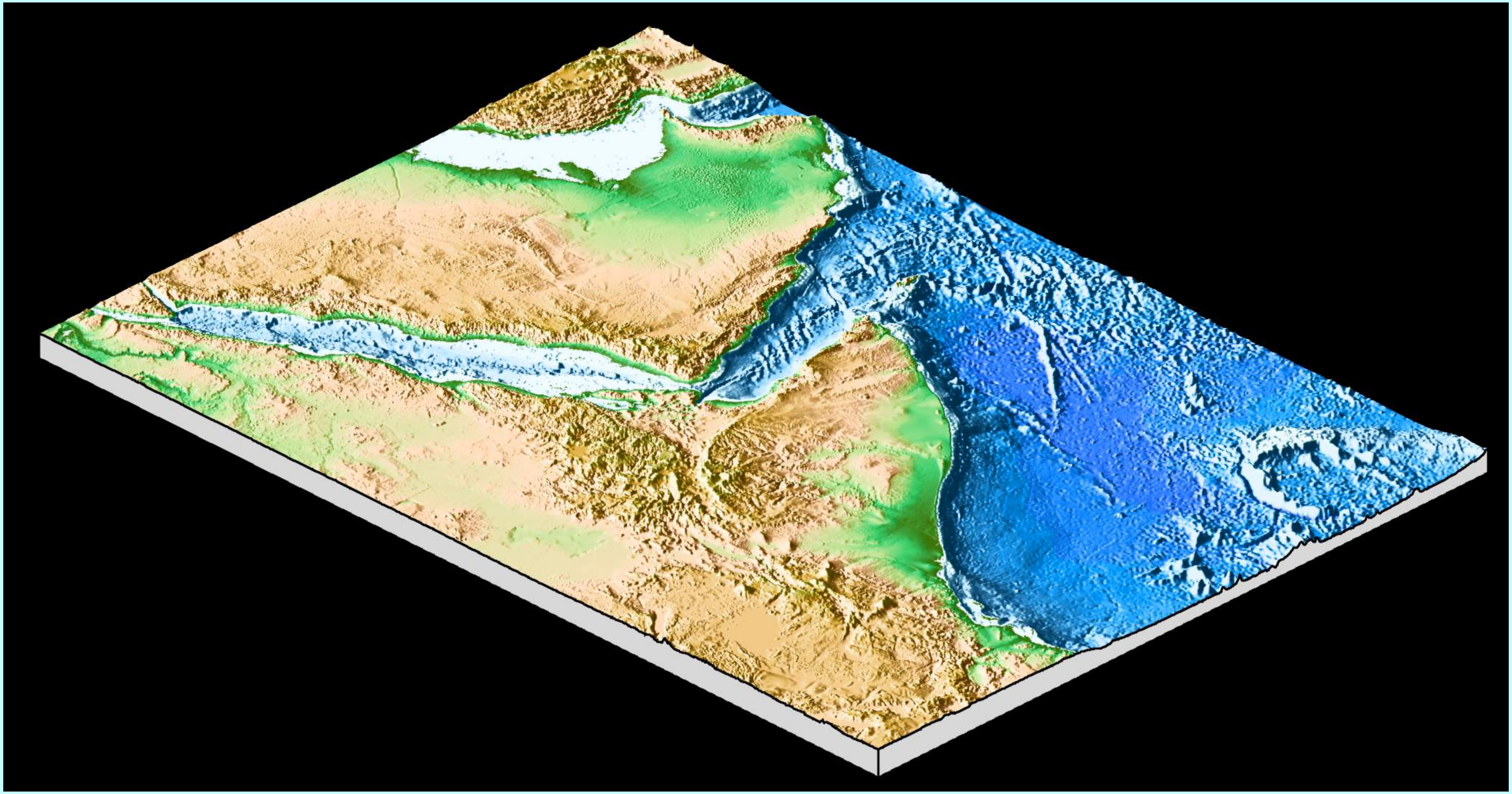


$10^5\ Pa$
$10^6\ Pa$
$5\ 10^6\ Pa$
$10^7\ Pa$
Fixed strength
of encasing rocks
Density contrast, $\rho_{\text{magma}} - \rho_{\text{host}}$ in $kg.m^{-3}$
Critical thickness for sill formation, L_c in m
10^1
10^2
10^3
10^4
10^5

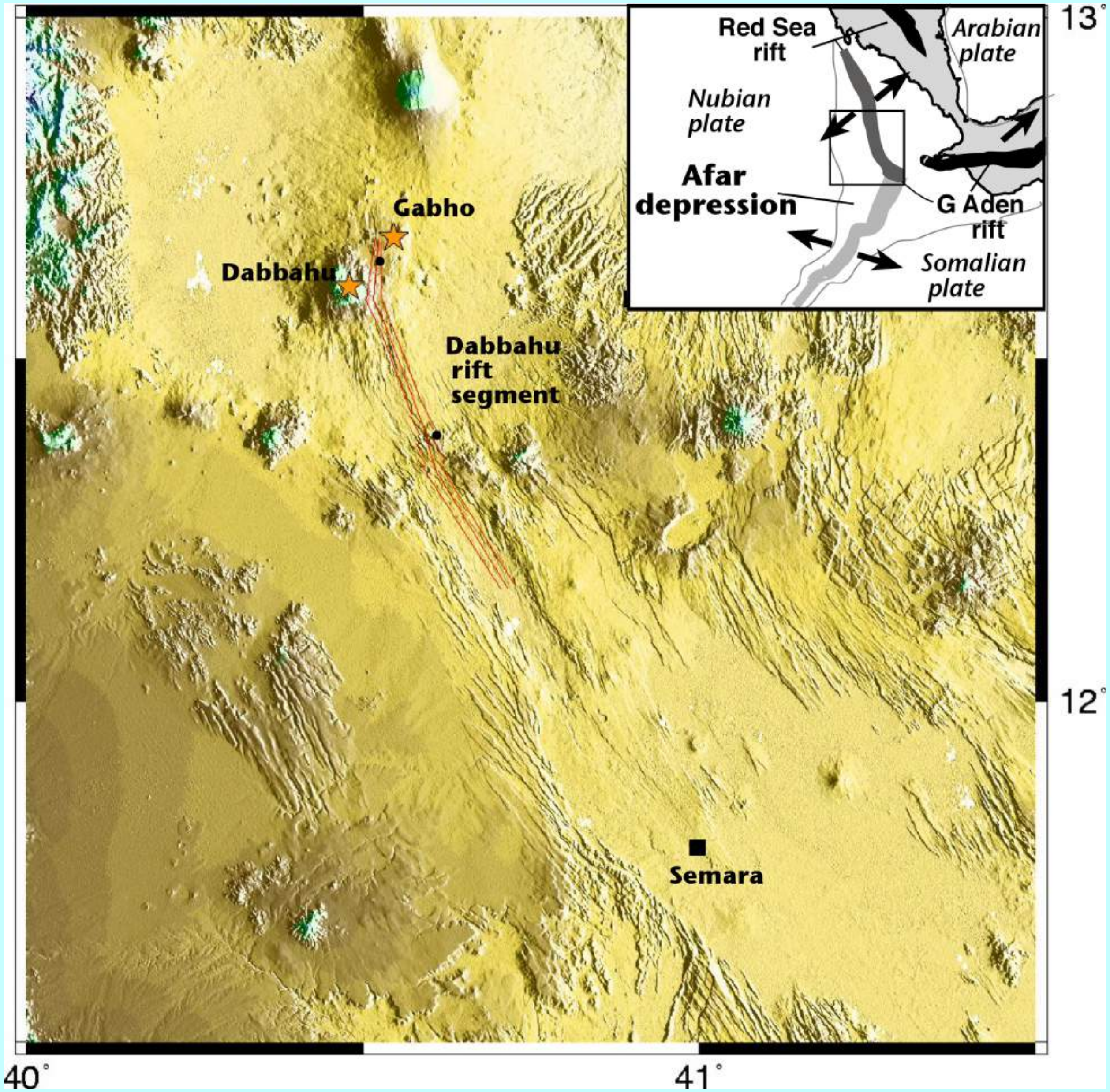
Nyiragongo

Nyiragongo

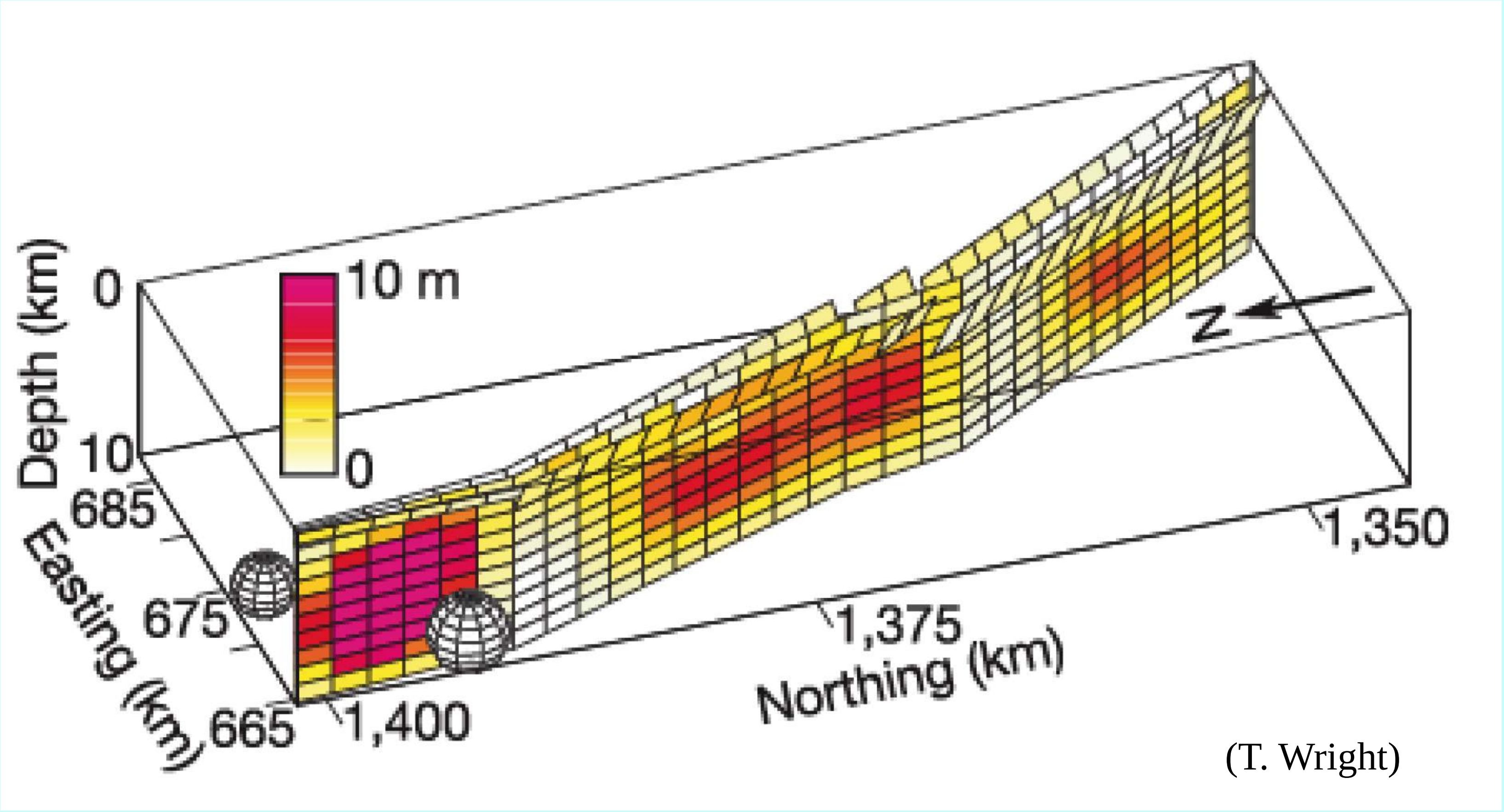
Rifting in Ethiopia



Rifting in Ethiopia



Dabbahu, sept.-oct. 2005



Width of ≈ 8 m and yet almost no eruption

CONCLUSIONS

1. Layering in the upper crust affects ascent of dykes

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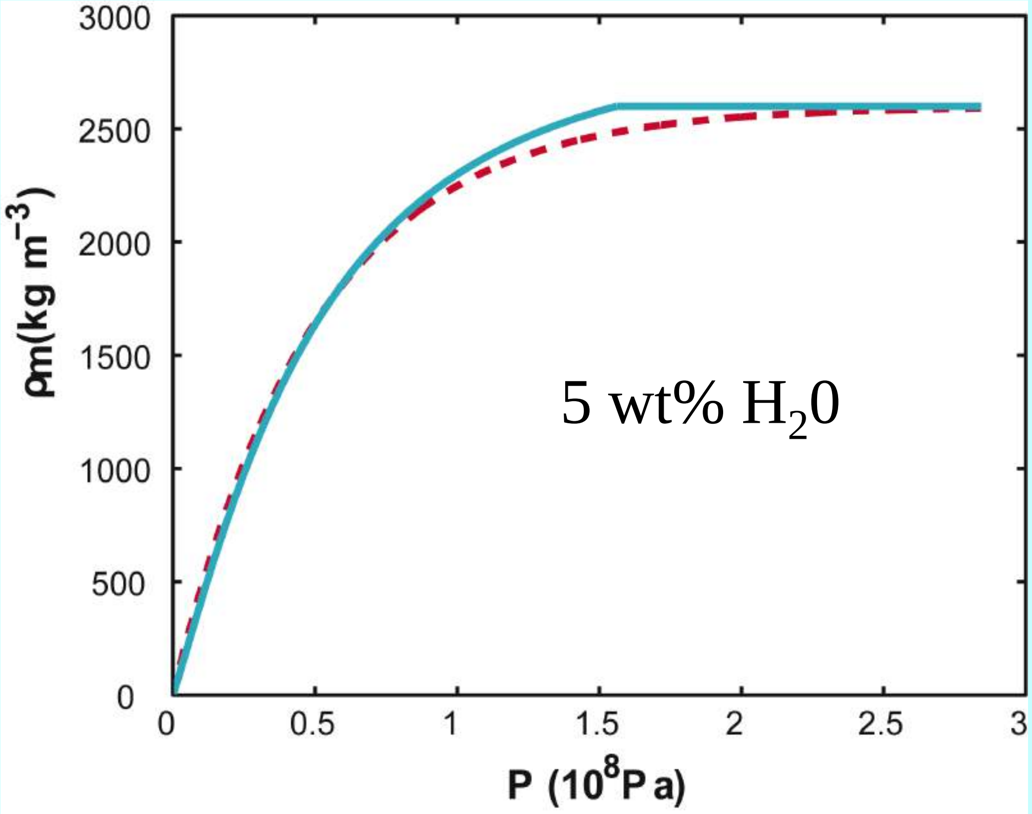
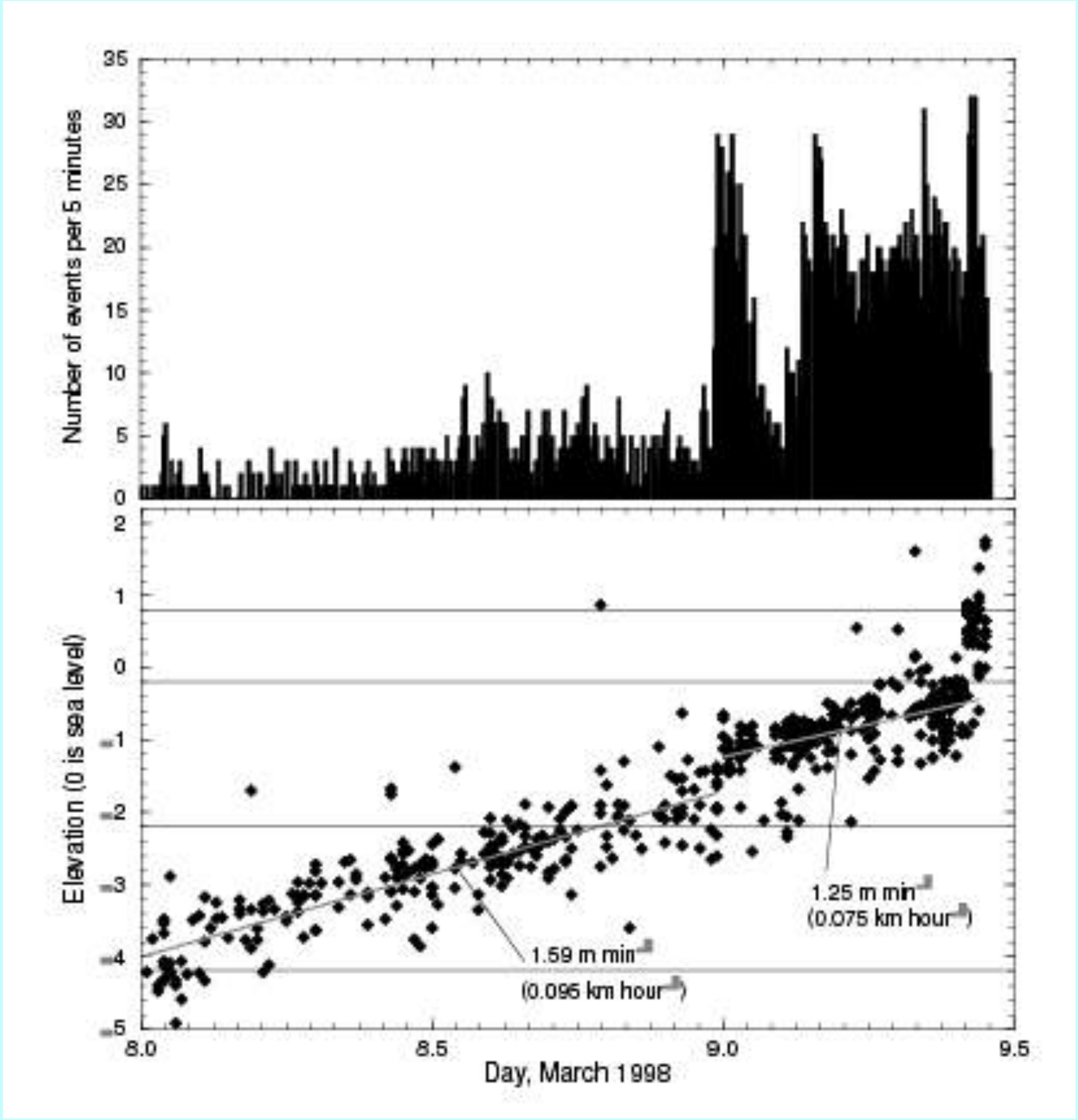
3. Large magma overpressures develop at the base of low density strata

4. Necessary condition for sill formation: low density strata must extend over a minimum thickness ($\approx$ 1 km)

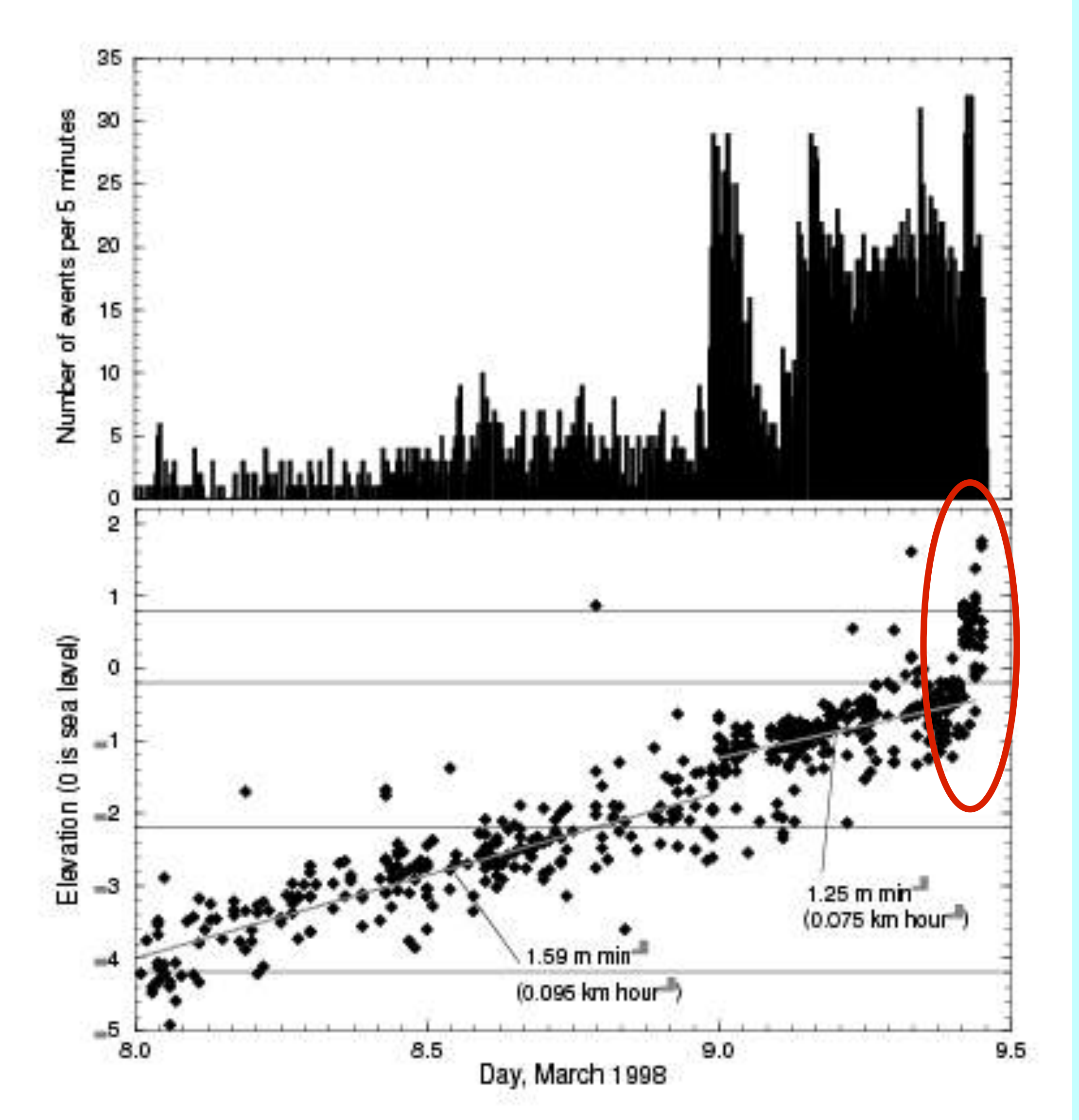
With volatile-rich magma



Small amounts of volatiles



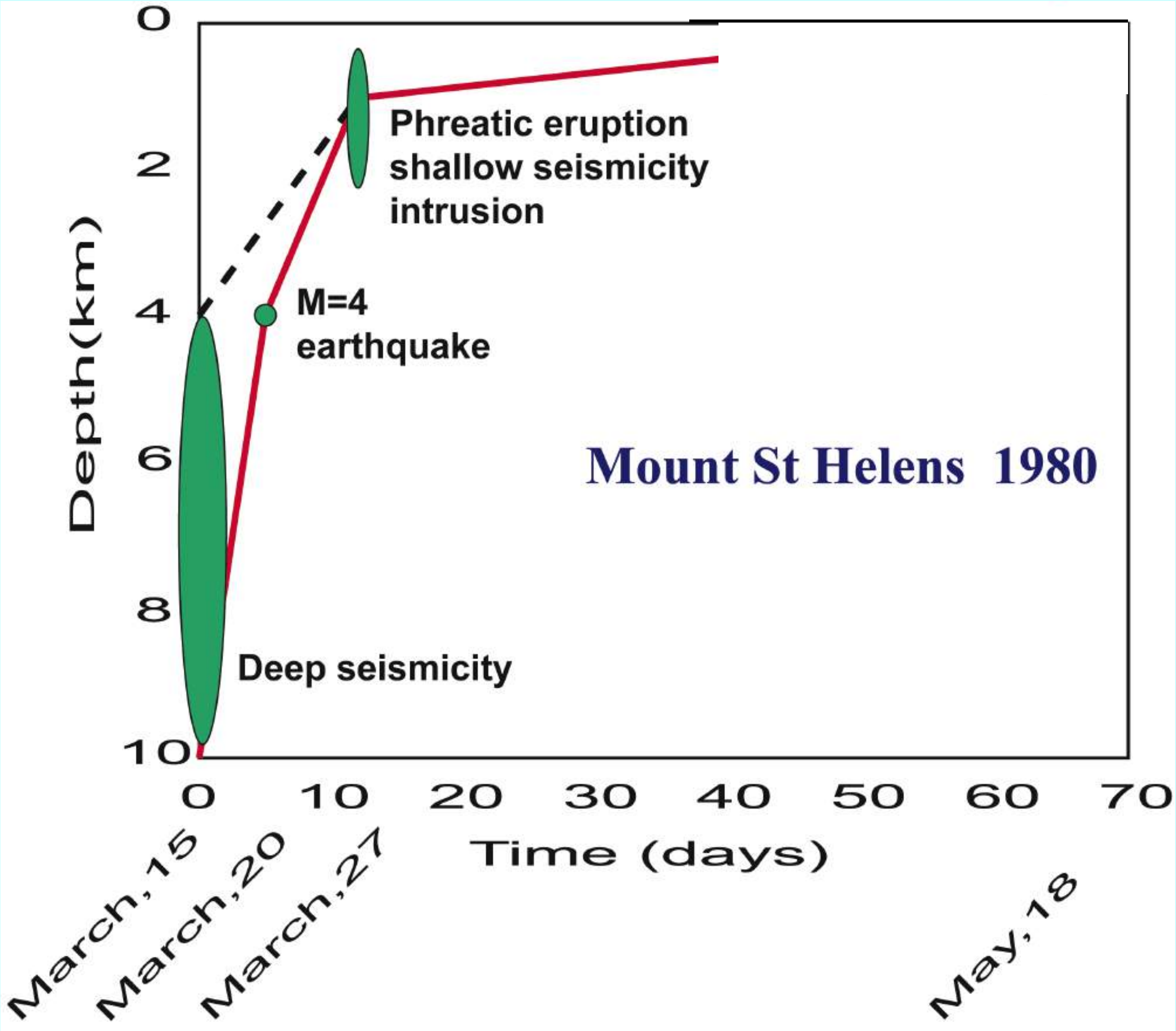
Piton de la Fournaise, 1998 (0.8 wt% H_2O)



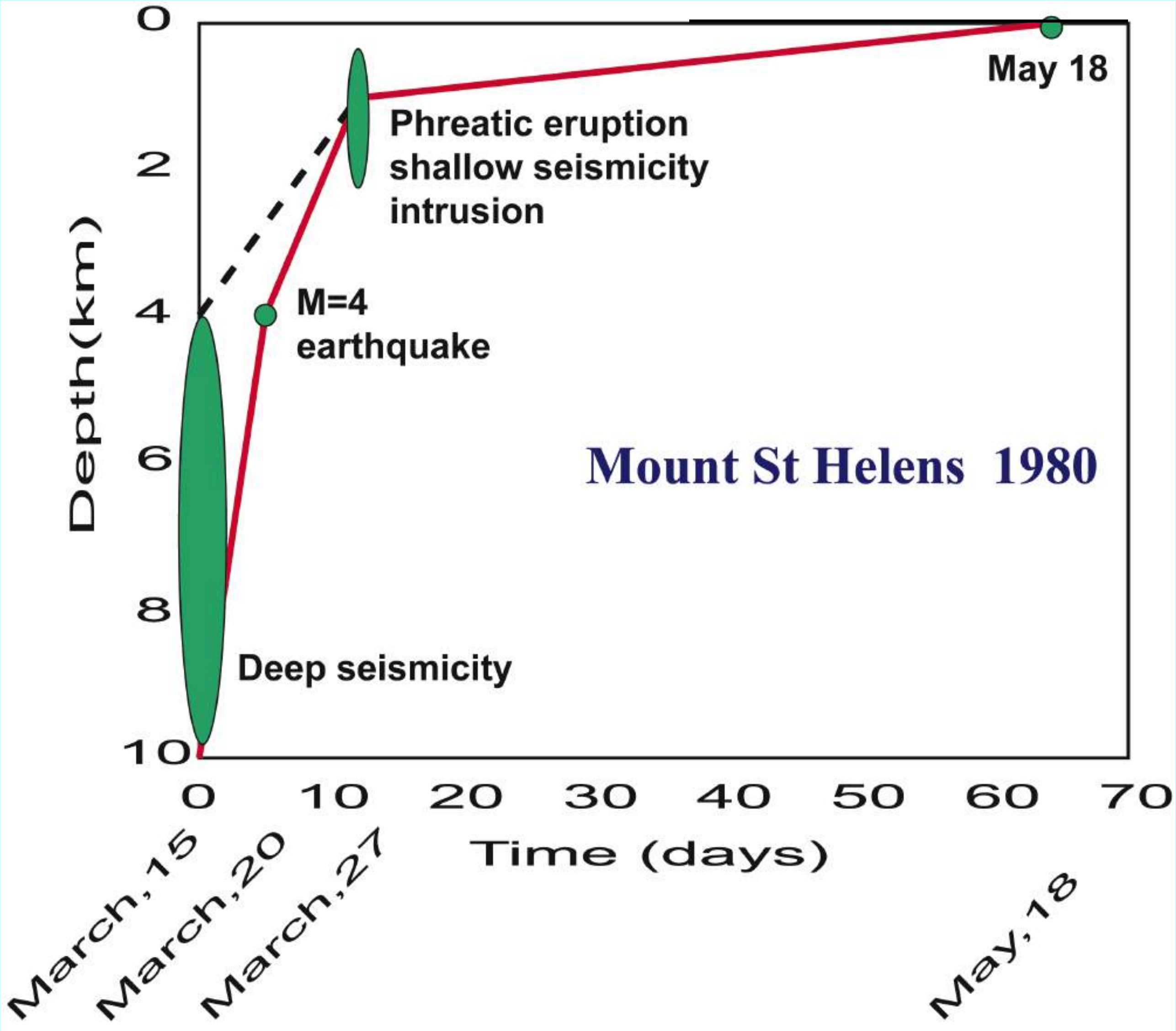
Near surface acceleration

Large amounts of volatiles

Mount St Helens, 1980 (5 wt% H_2O)



Phreatic eruption
shallow seismicity
intrusion
M=4
earthquake
Mount St Helens 1980
Deep seismicity
Depth(km)
0
2
4
6
8
10
0
10
20
30
40
50
60
70
Time (days)
March,15
March,20
March,27
May,18


0
2
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6
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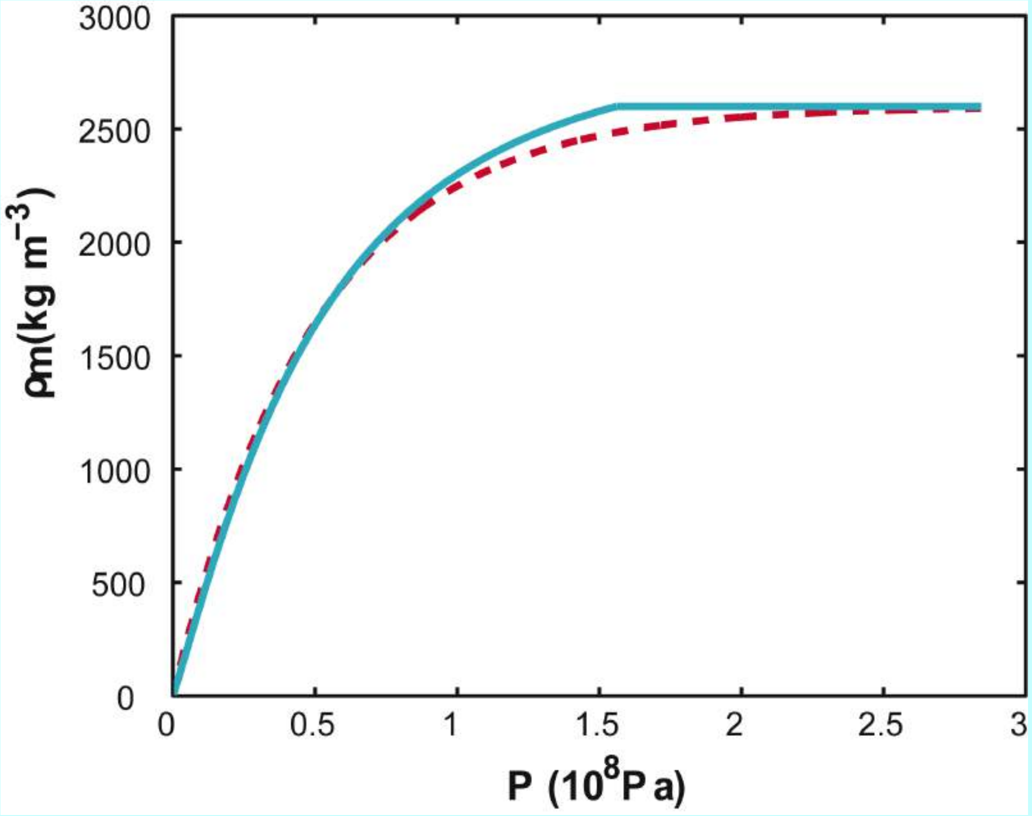
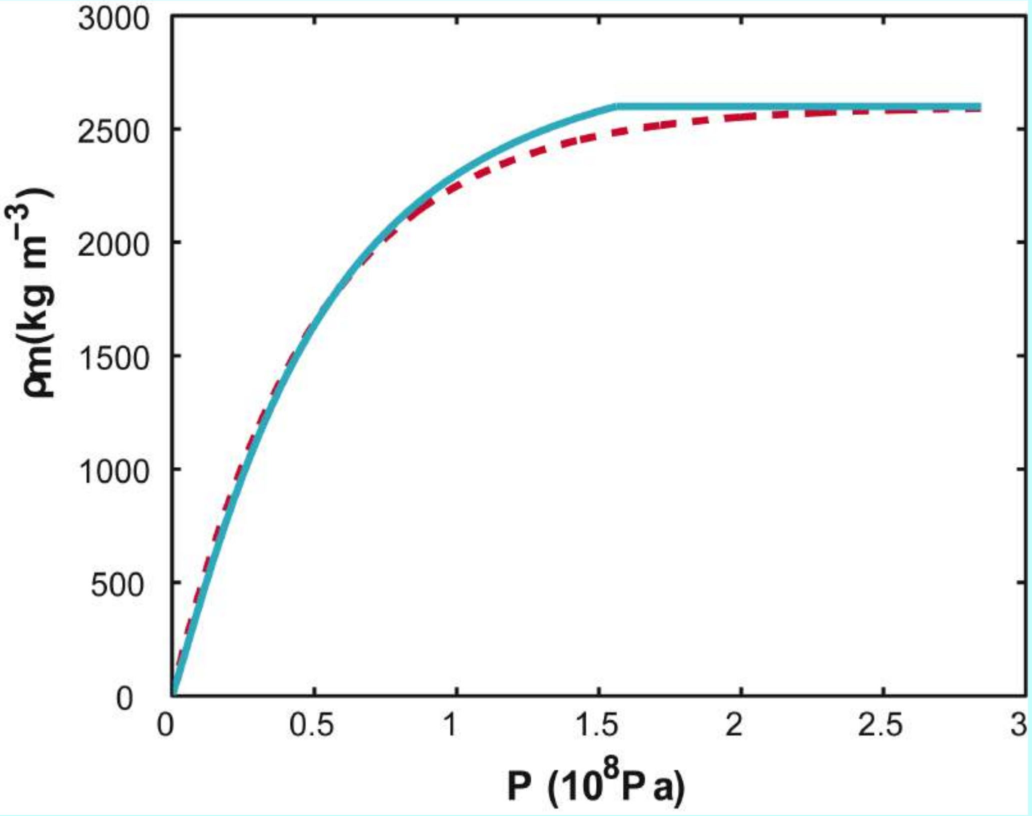
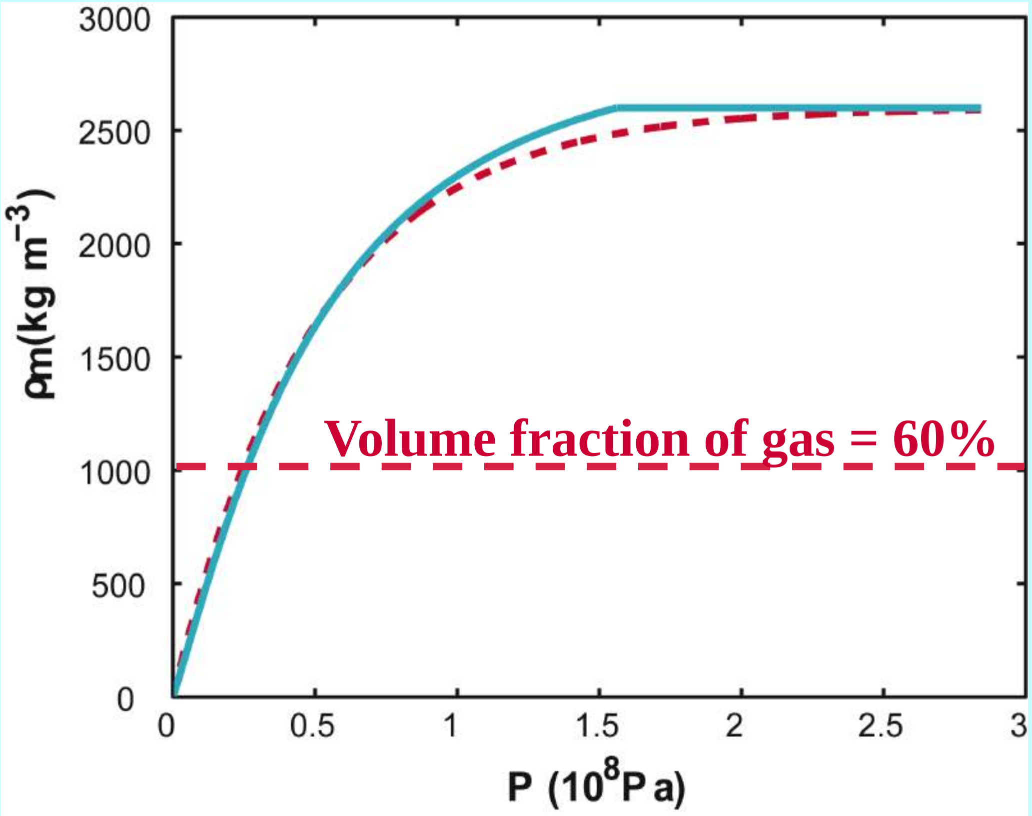
0
10
20
30
40
50
60
70
Time (days)
March,15
March,20
March,27
May,18

Volatile exsolution and expansion

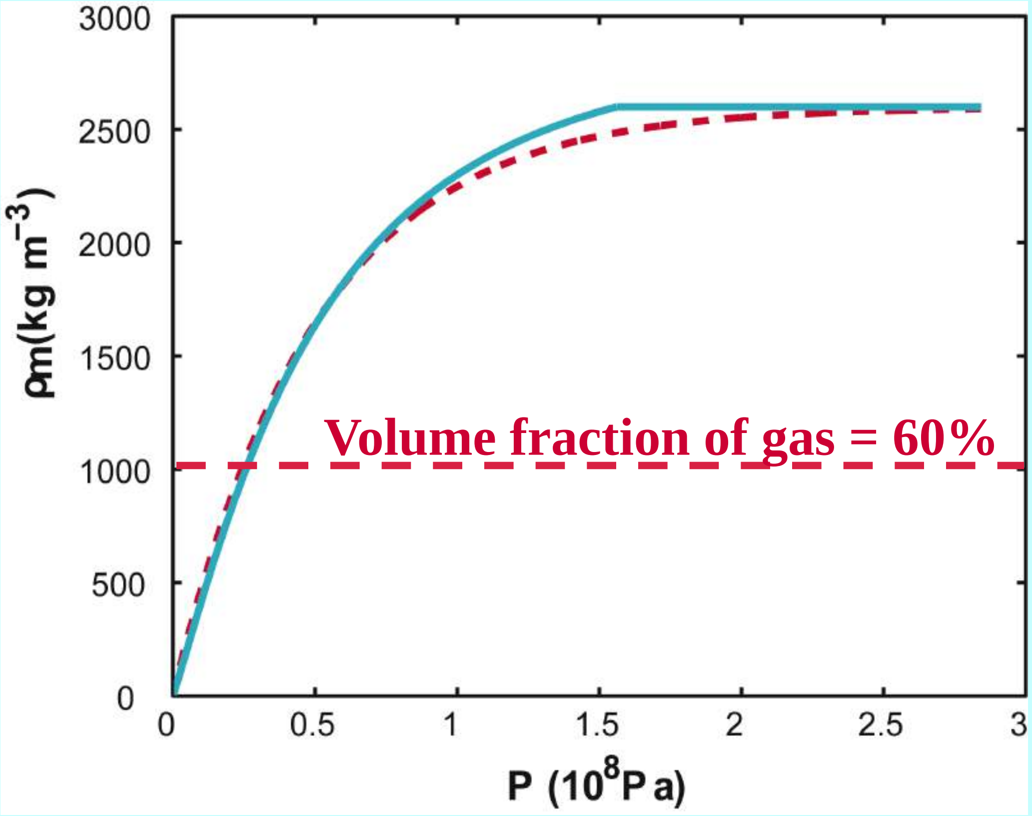




Constant mass flux Q = $\rho_m\,\phi$ **=>** volumetric flux ϕ increase



ρm(kg m^{-3})
3000
2500
2000
1500
1000
500
0
0
0.5
1
1.5
2
2.5
3
P (10^{8}Pa)
Volume fraction of gas = 60%



Fragmentation:

The mixture of magma and gas behaves as a “dusty” gas:

dense gas with low viscosity.

Equation for magma overpressure (stress at the walls)

$$\frac{\partial P_e}{\partial z} = -\frac{3\mu}{2h^3}\phi + (\rho_s - \rho_m)g$$

ϕ volumetric flux

Dyke width and ascent velocity

An increase of the volumetric flux of magma (due to gas exsolution and expansion) can be achieved by two different mechanisms

- **acceleration**
- **widening (swelling)**

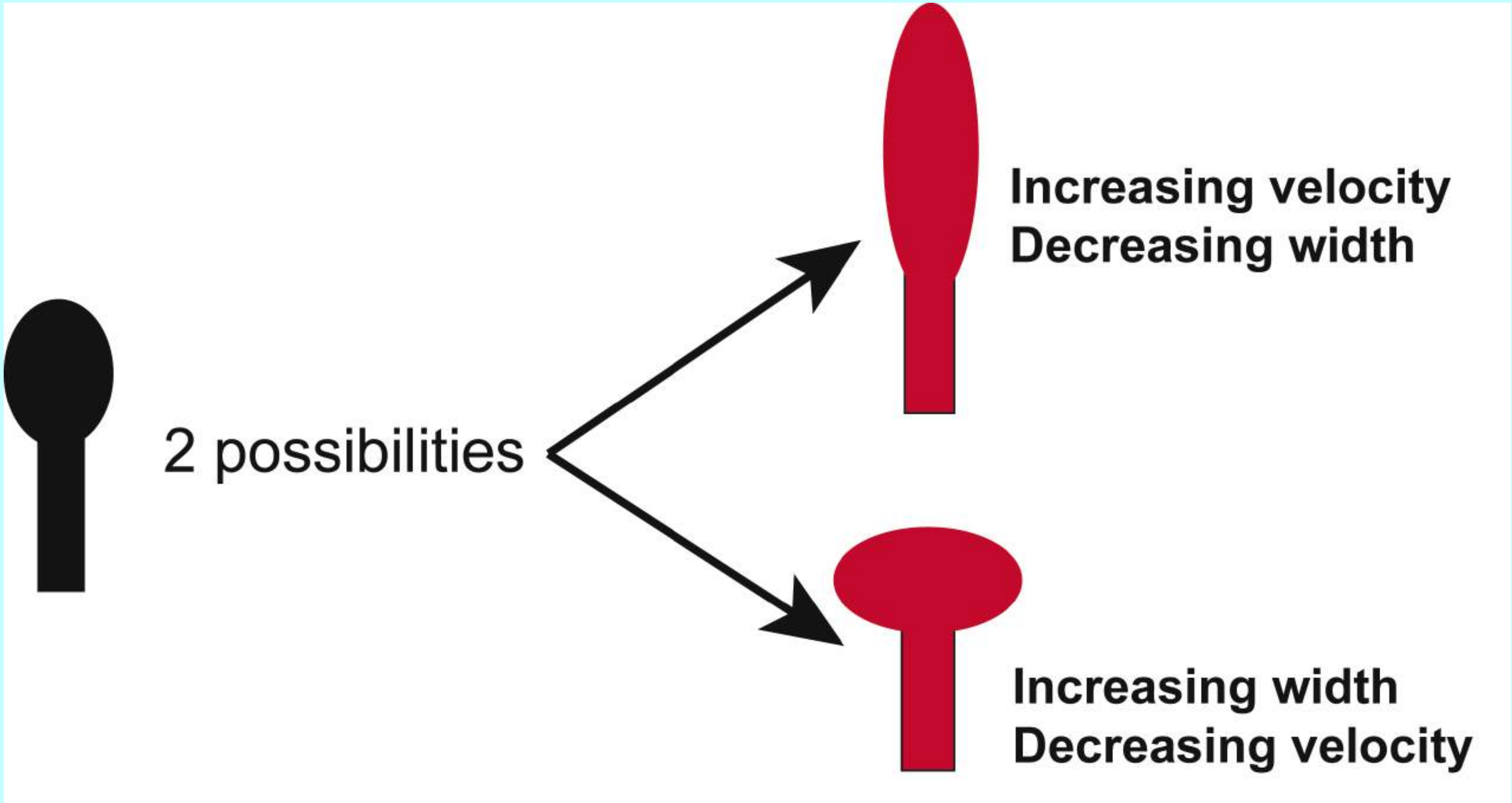
Dyke width and ascent velocity

An increase of the volumetric flux of magma (due to gas exsolution and expansion) can be achieved by two different mechanisms

- **acceleration**
- **widening (swelling)**

Magma pressure acts to

- **deform the dyke walls (widening)**
- **drive magma motion**


2 possibilities
Increasing velocity
Decreasing width
Increasing width
Decreasing velocity

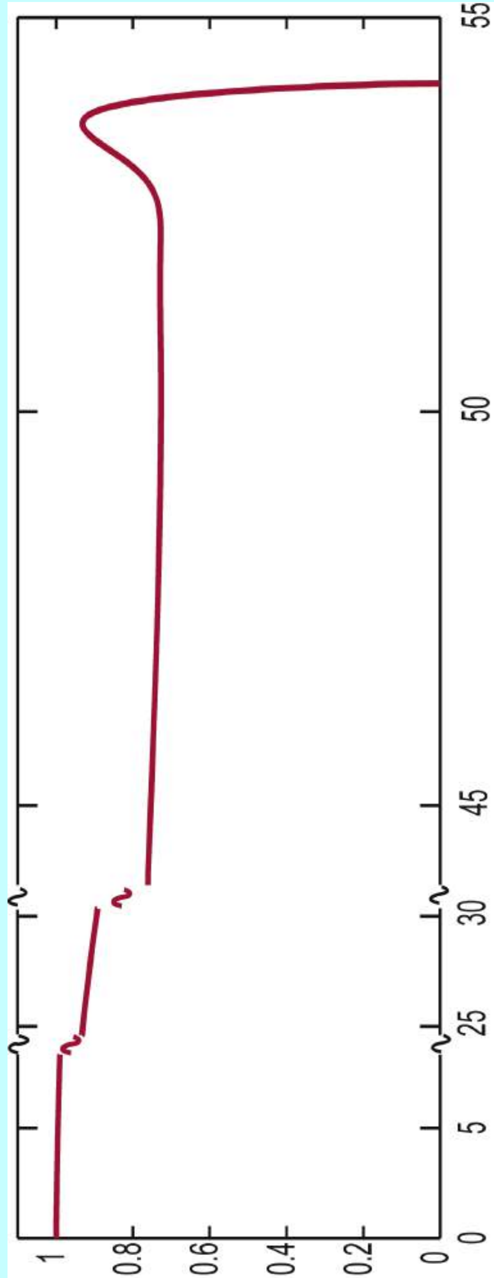
Small amounts of gas : no fragmentation = enhanced viscous head loss

Equation pour la contrainte aux parois

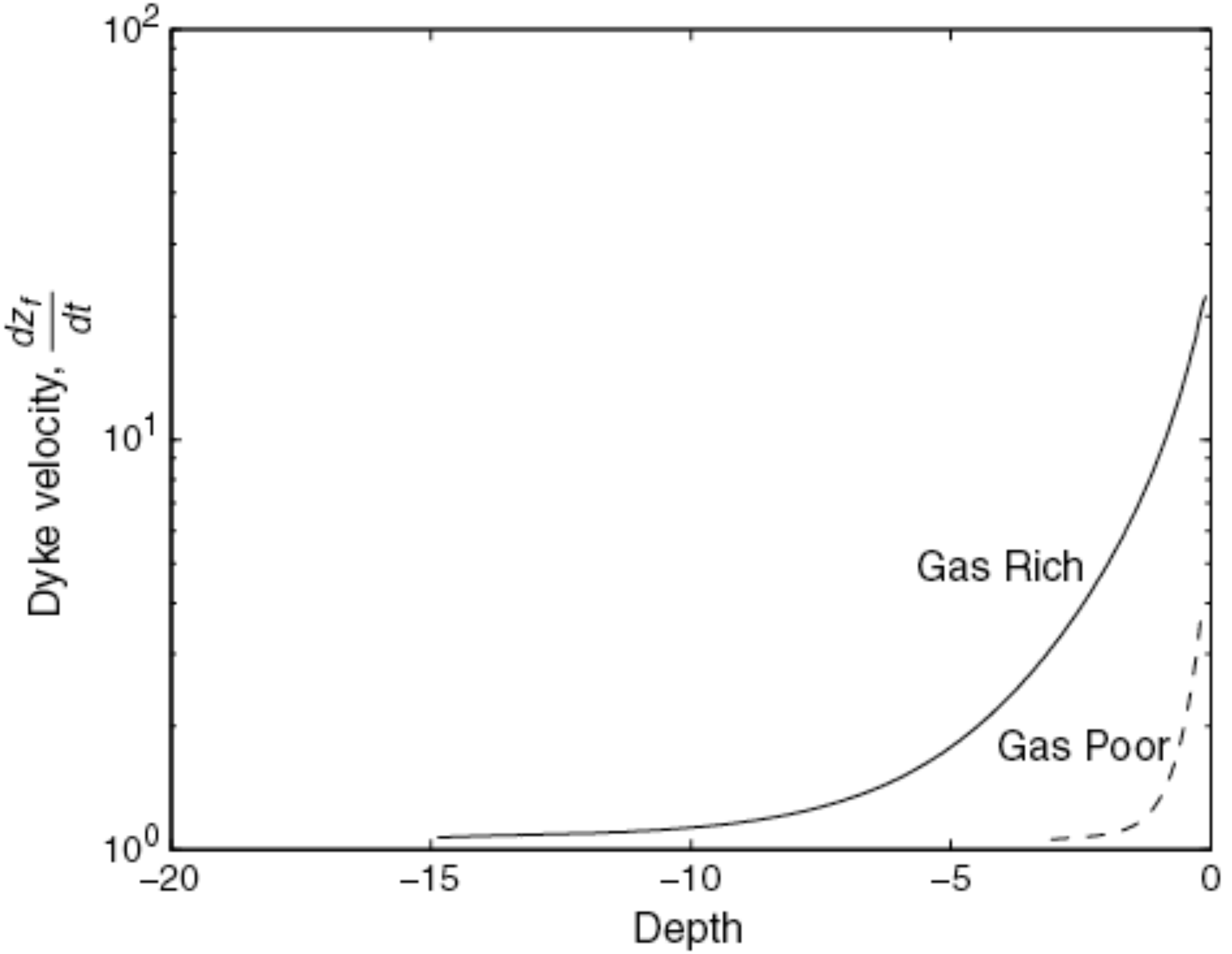
$$\frac{\partial P_e}{\partial z} = -\frac{3\mu}{2h^3}\phi + (\rho_s - \rho_m)g$$

ϕ volumetric flux

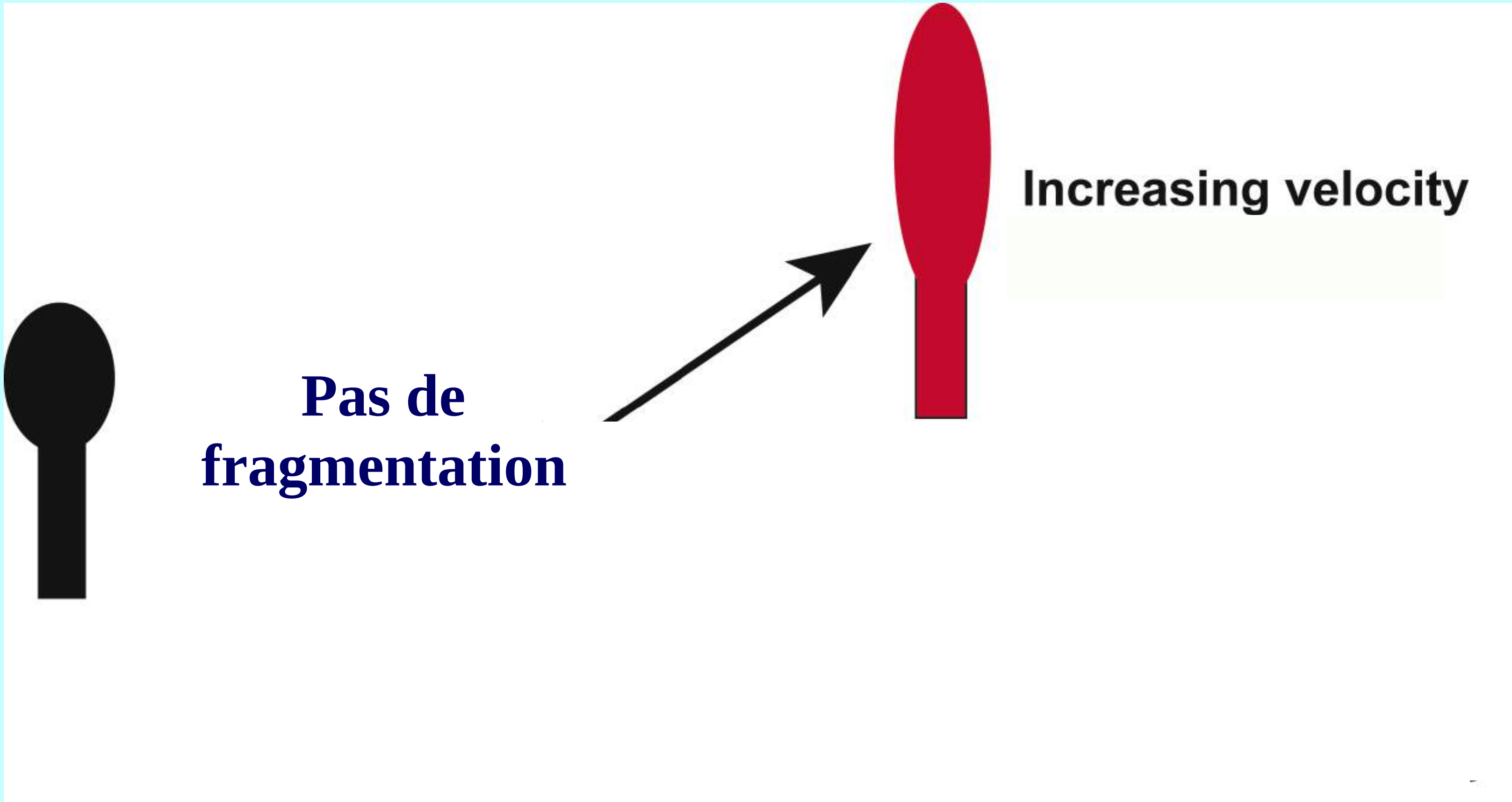
Height above source

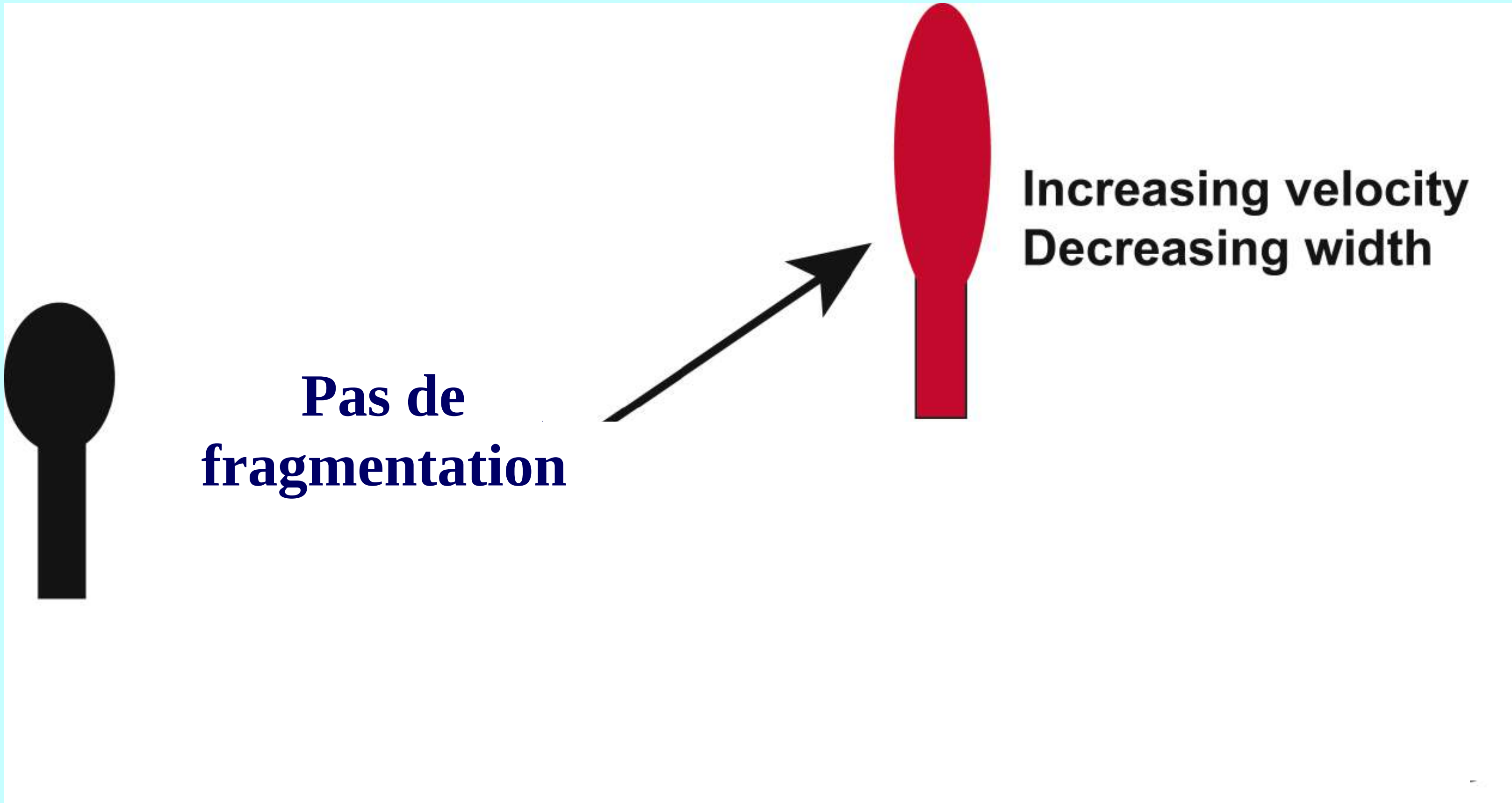


Dyke half-width



Dyke velocity, $\frac{dz_f}{dt}$
10^2
10^1
10^0
−20
−15
−10
−5
0
Depth
Gas Rich
Gas Poor


Increasing velocity
Pas de fragmentation

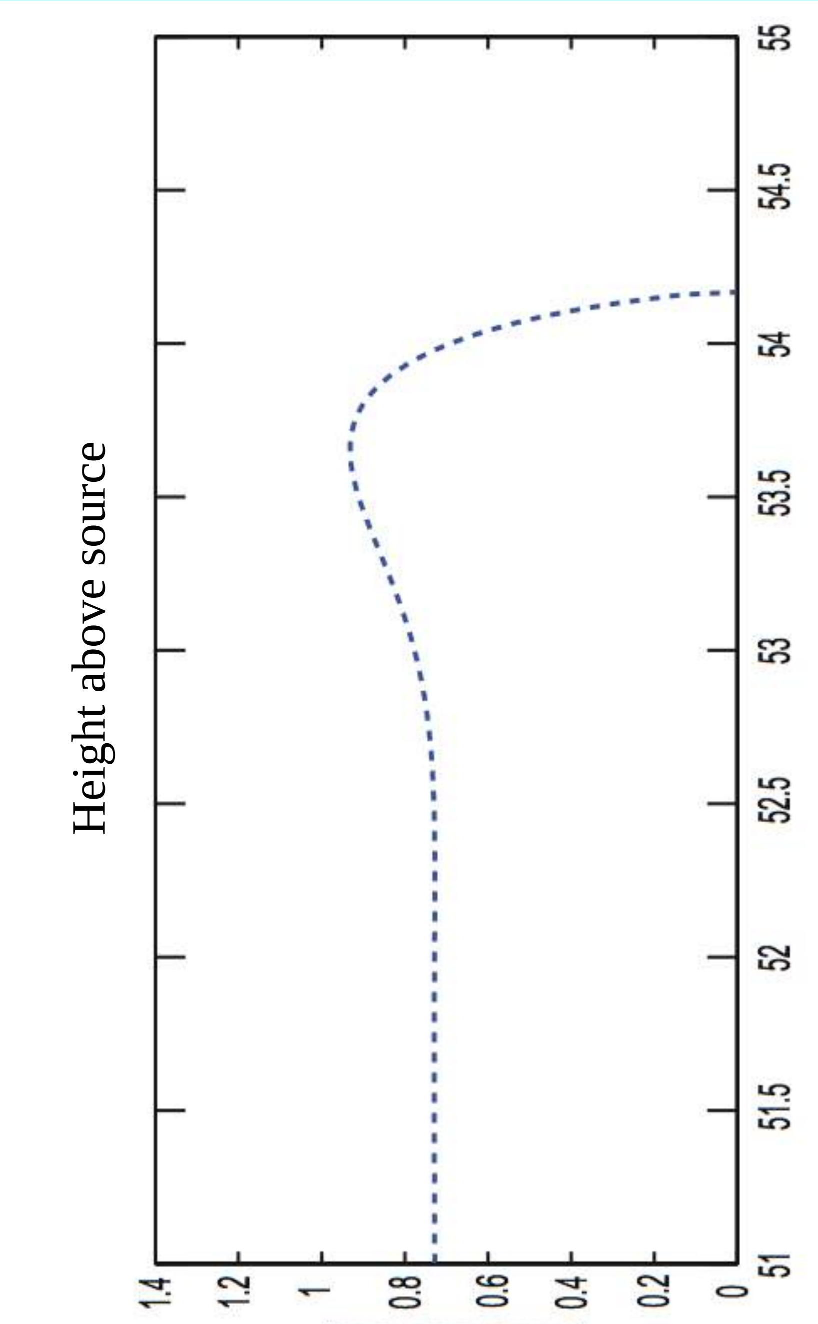

Increasing velocity
Decreasing width
Pas de
fragmentation

Fragmentation = reduced head loss

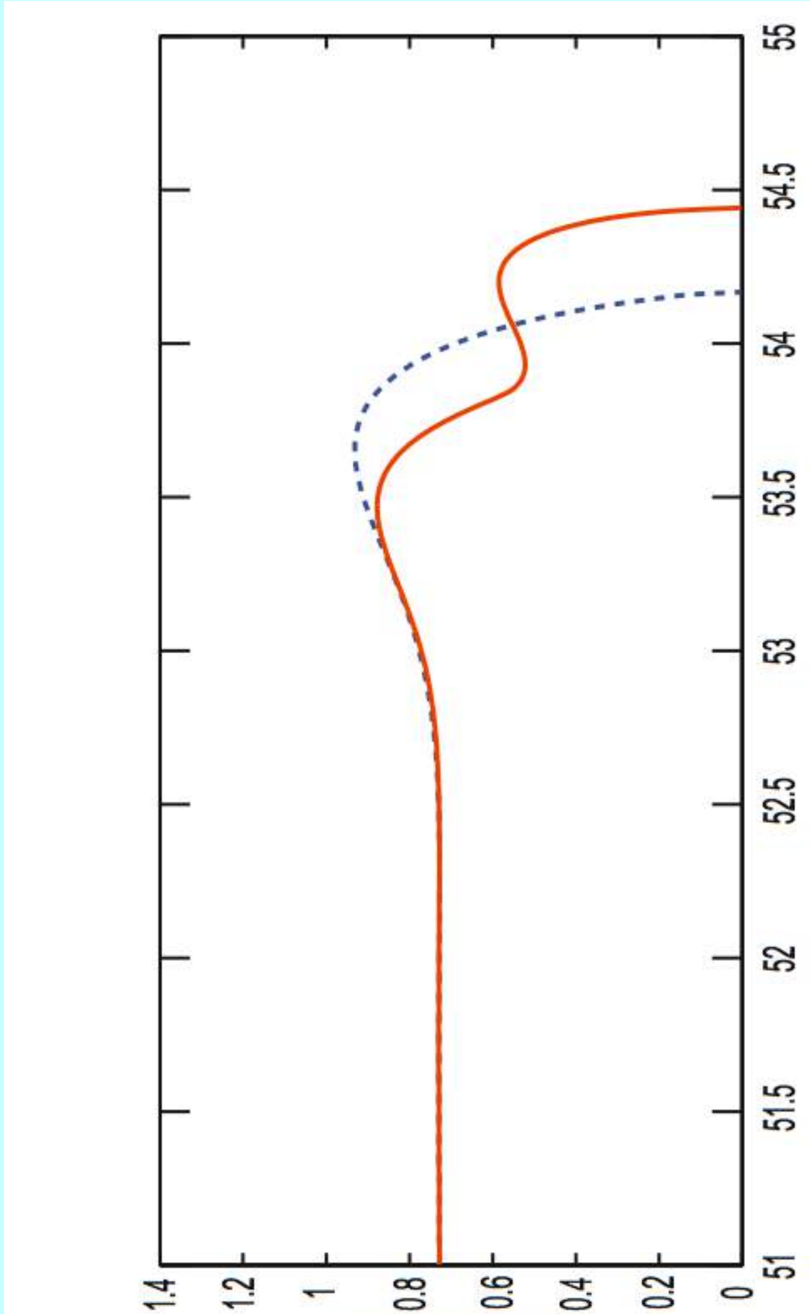
$$\frac{\partial P_e}{\partial z} = \cancel{-\frac{3\mu}{2h^3}}\phi + (\rho_s - \rho_m)g$$

Increase of internal overpressure =
increase of stress exerted on the dyke walls

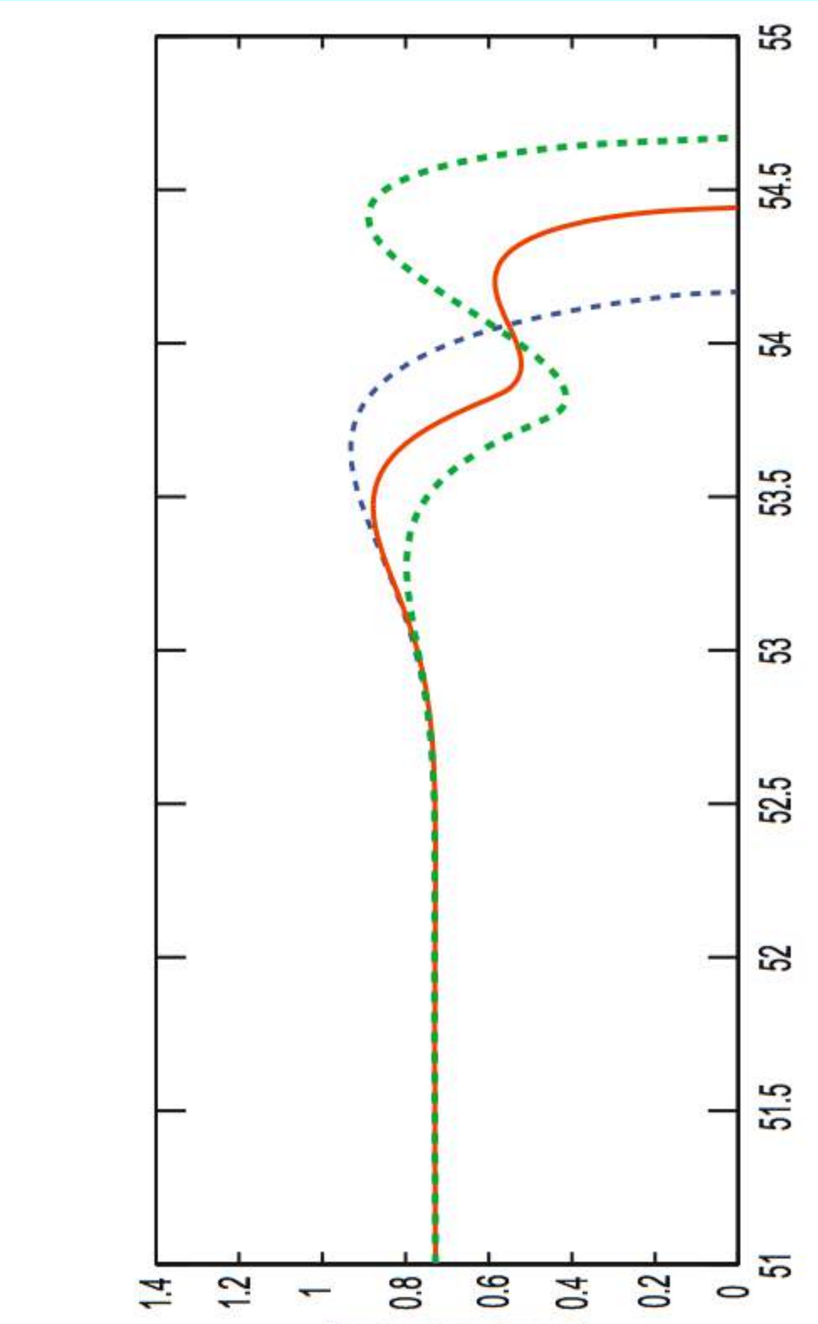
With fragmentation



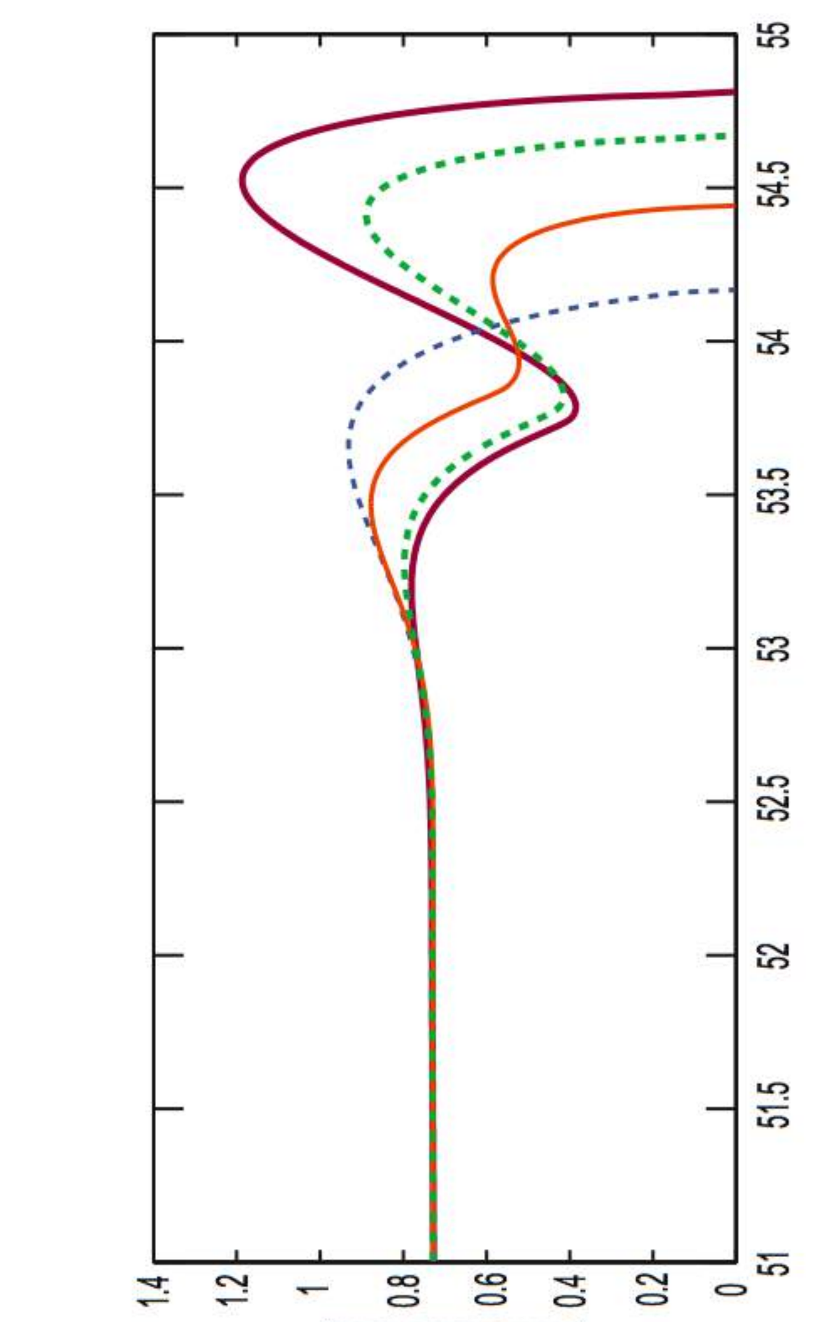
Dyke half-width



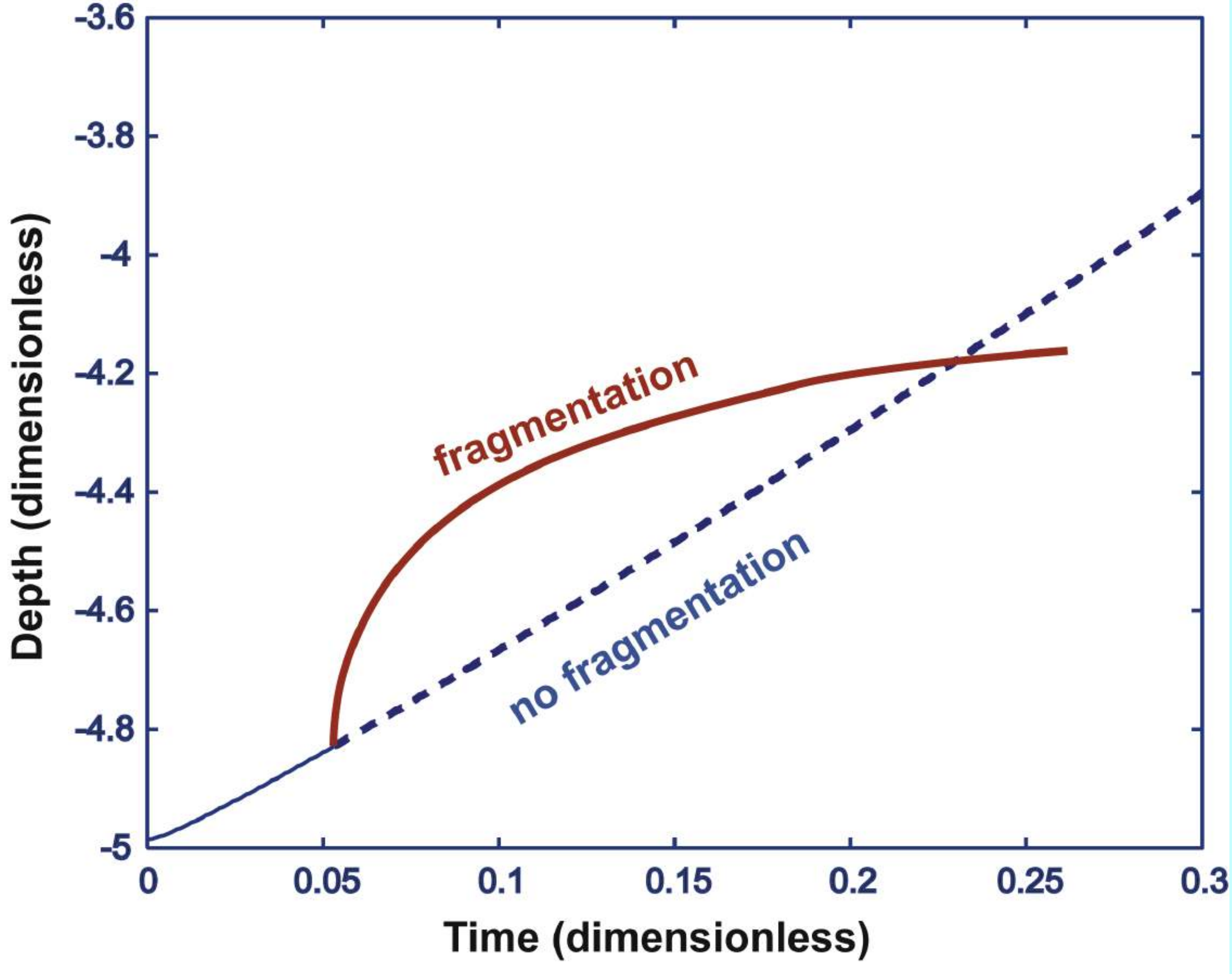
Dyke half-width

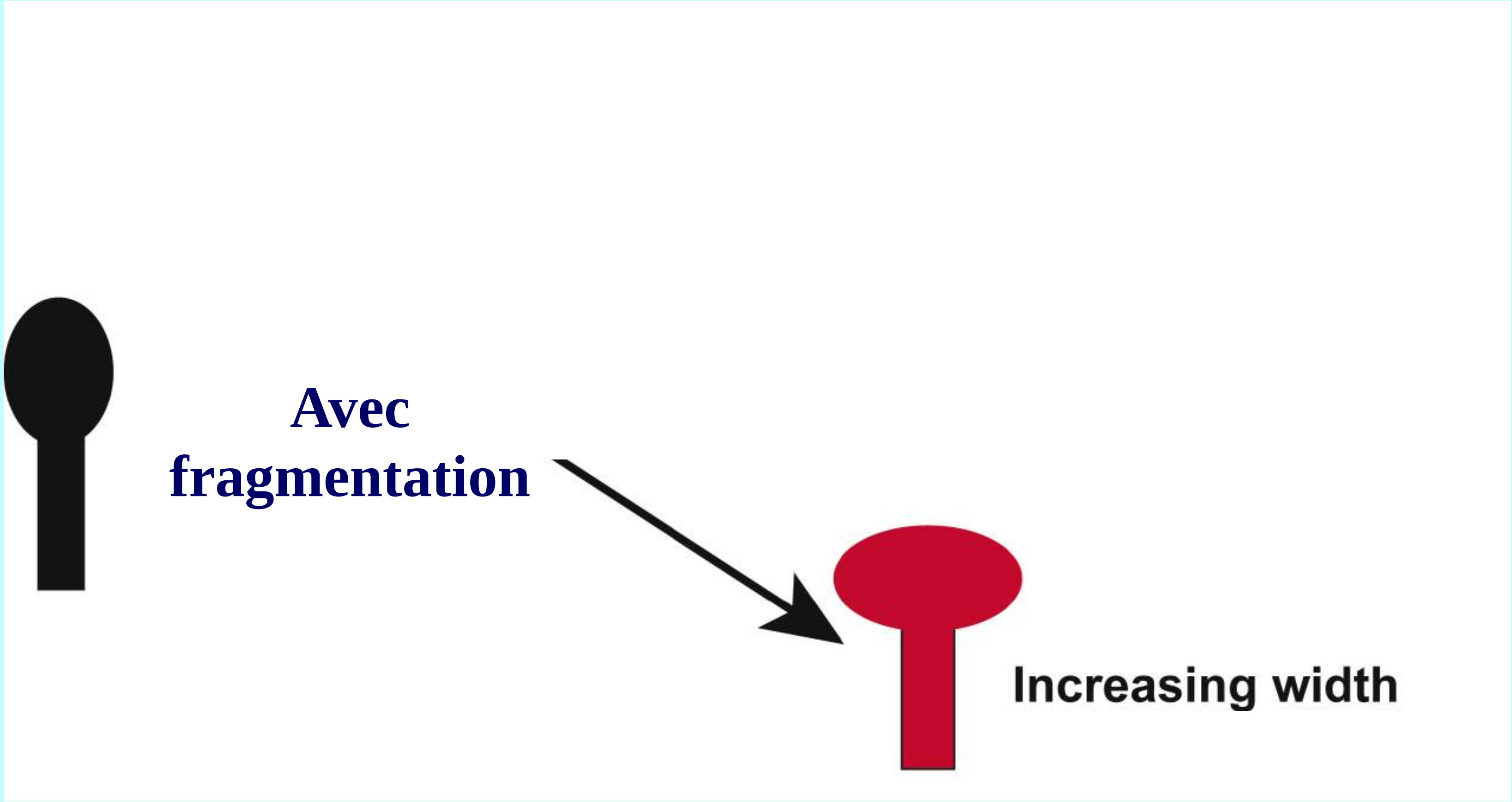


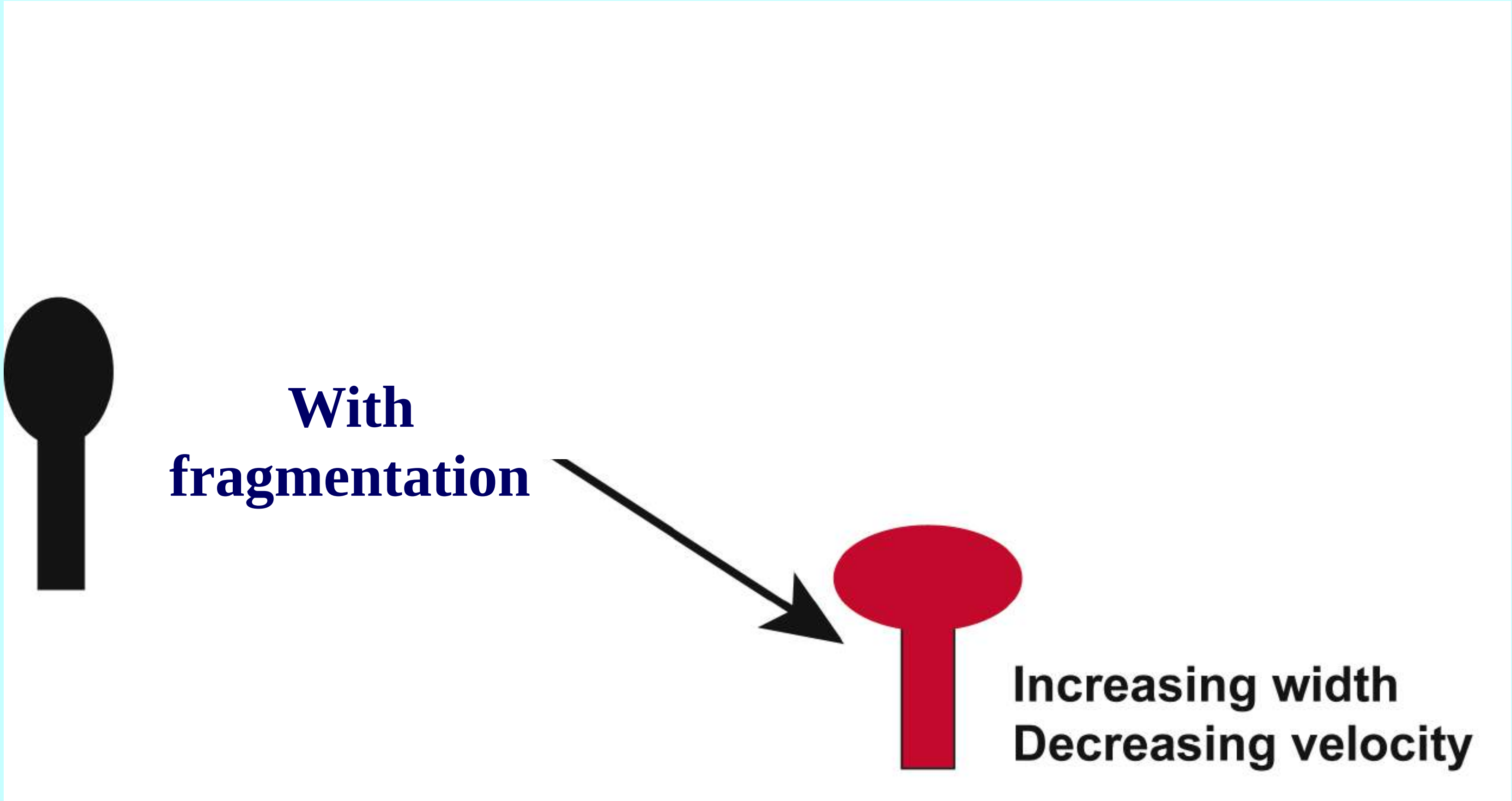
Dyke half-width



Dyke half-width


-3.6
-3.8
-4
-4.2
-4.4
-4.6
-4.8
-5
Depth (dimensionless)
0
0.05
0.1
0.15
0.2
0.25
0.3
Time (dimensionless)
fragmentation
no fragmentation


Avec
fragmentation
Increasing width


With
fragmentation
Increasing width
Decreasing velocity