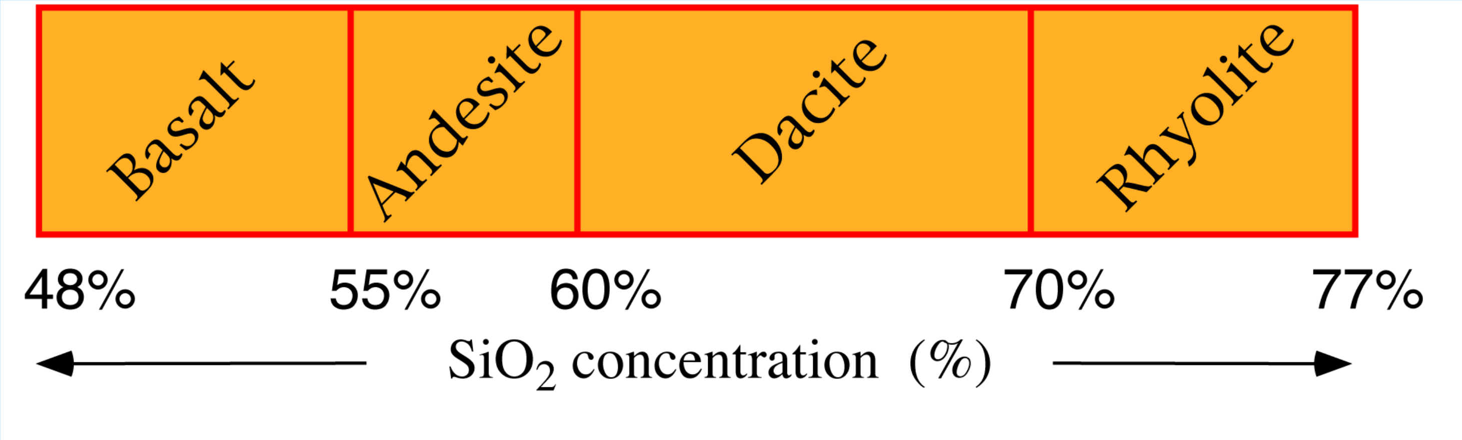
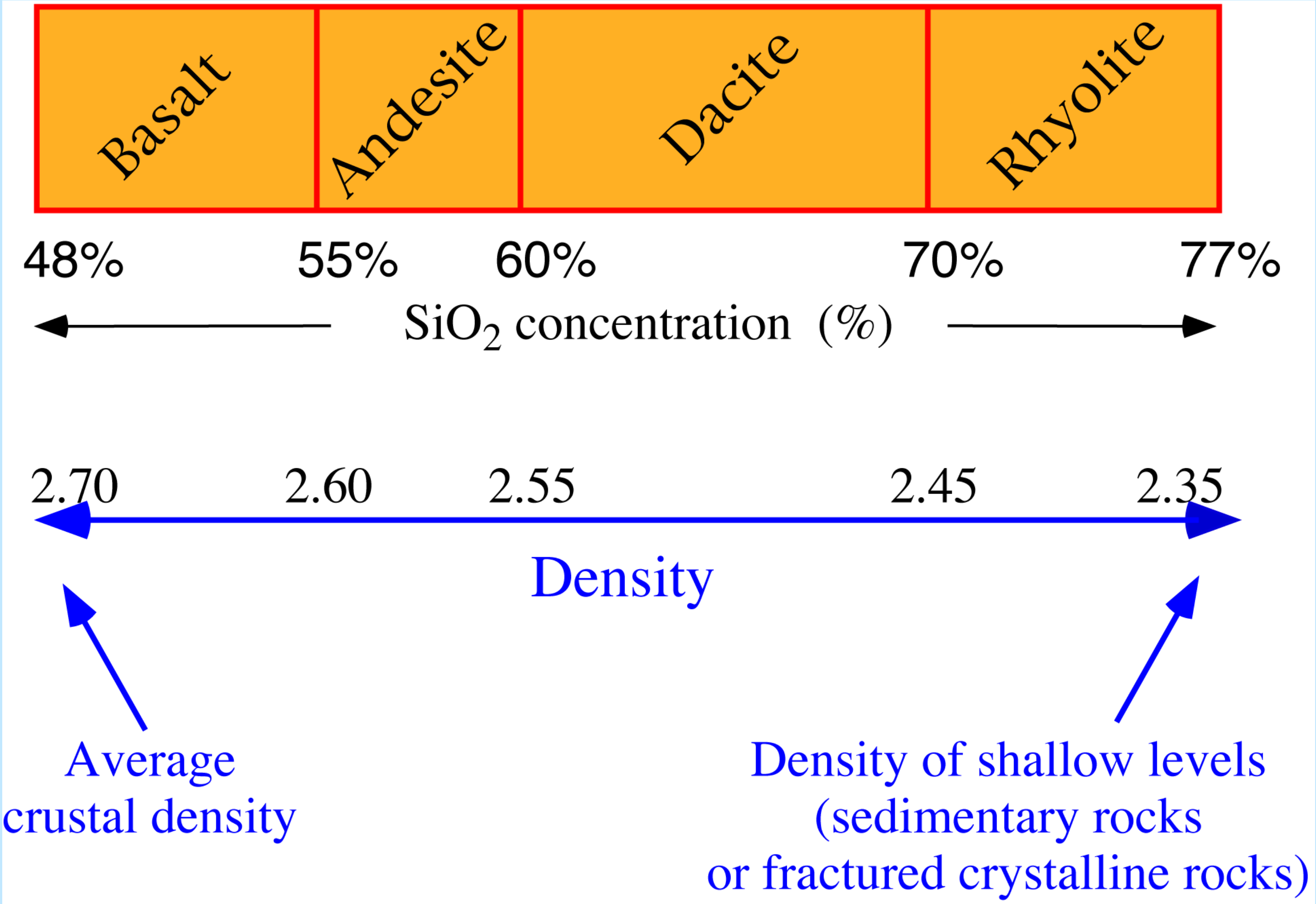
MAGMA RESERVOIRS:

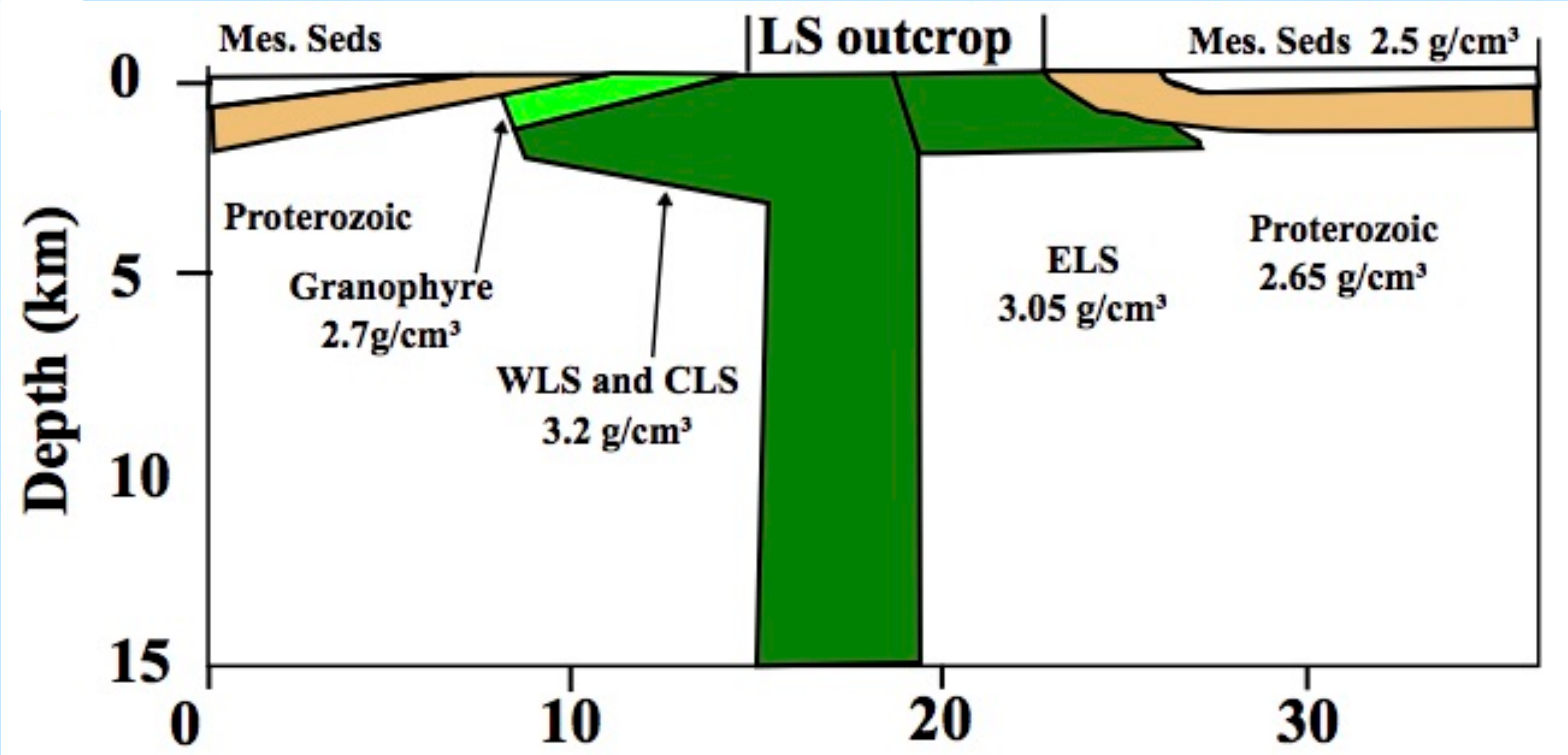
EMPLACEMENT
AND
POST-EMPLACEMENT DYNAMICS



Bulk composition of continental crust dictates that:
- mafic magmas differentiate (to produce evolved compositions),
- mafic cumulates founder or sink (out of the crust).

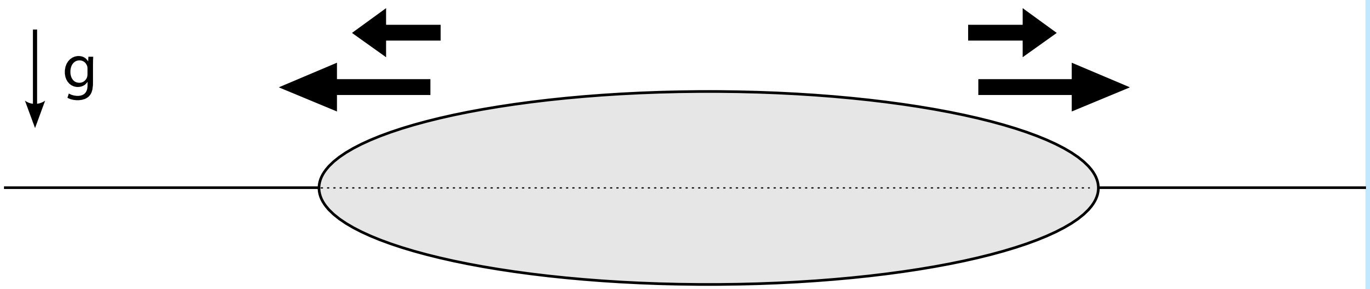


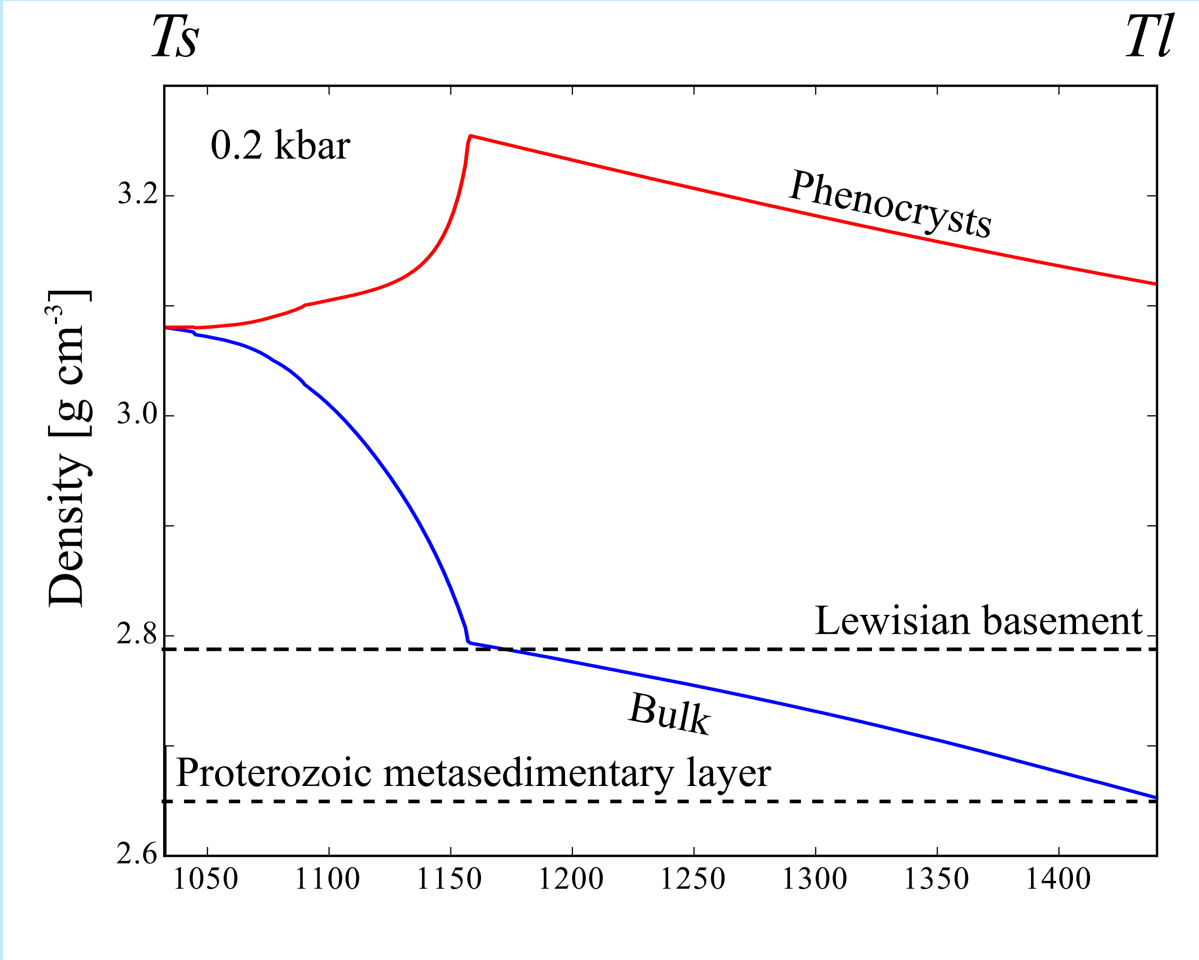
Magma ascent is buoyancy driven.



Rum intrusion, Scotland

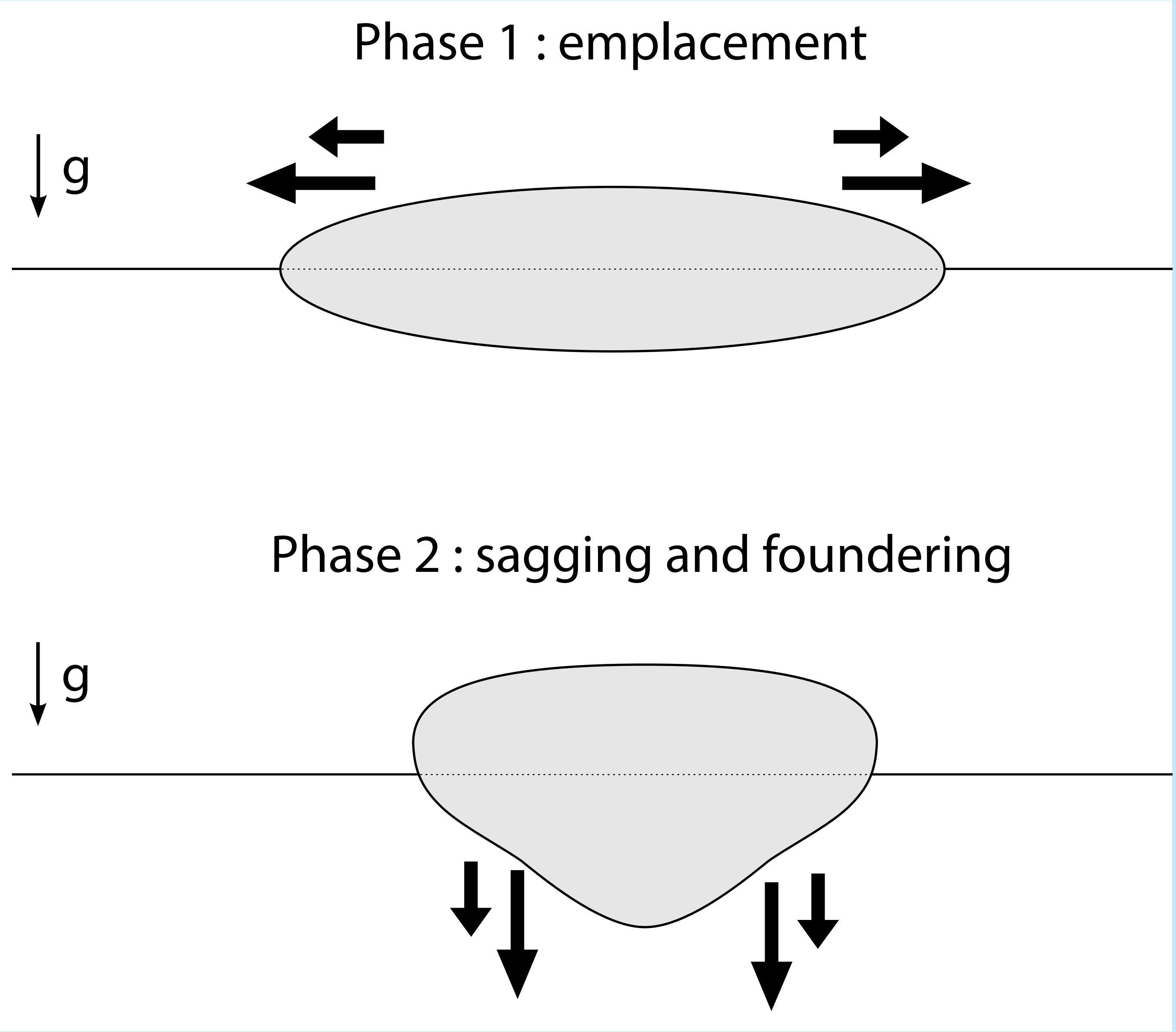
Phase 1 : emplacement

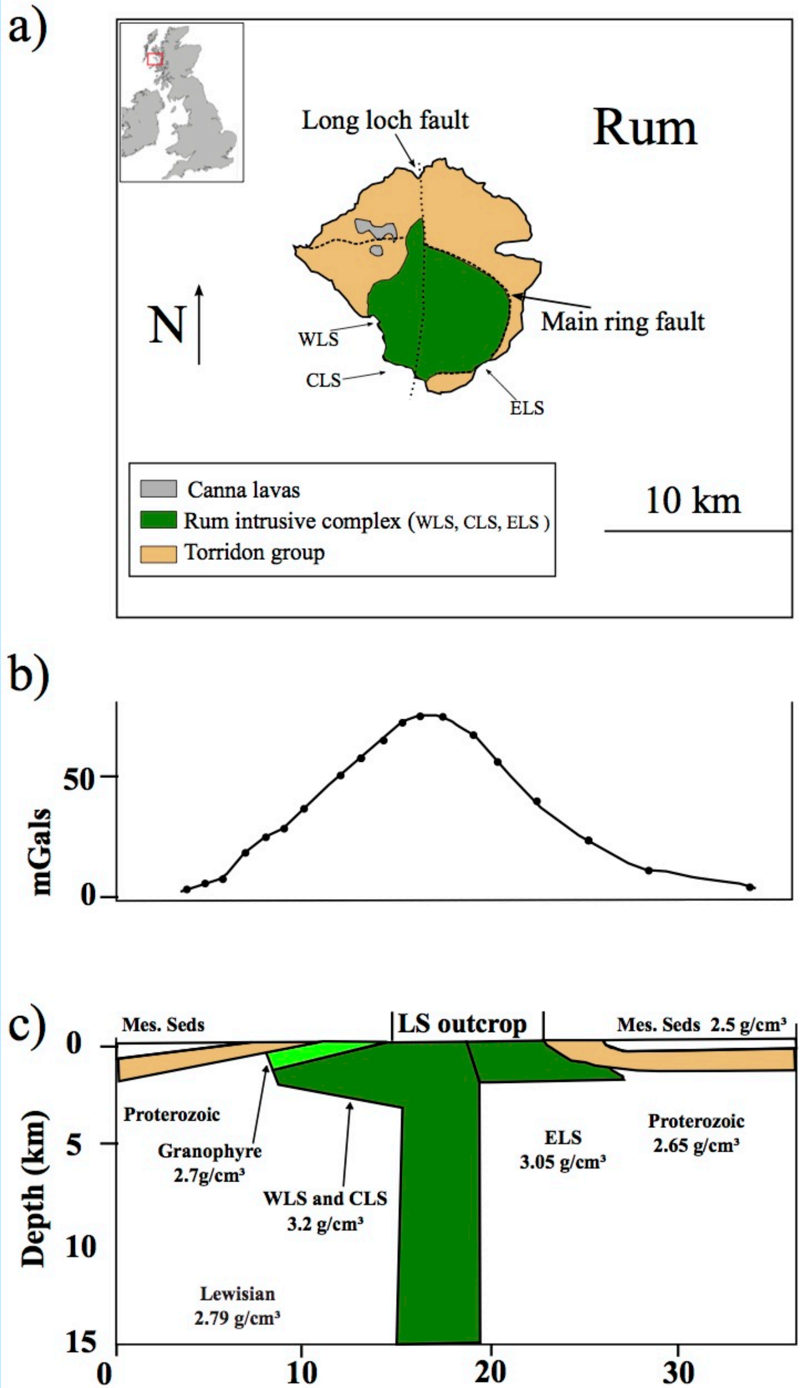




Rum intrusion, Scotland

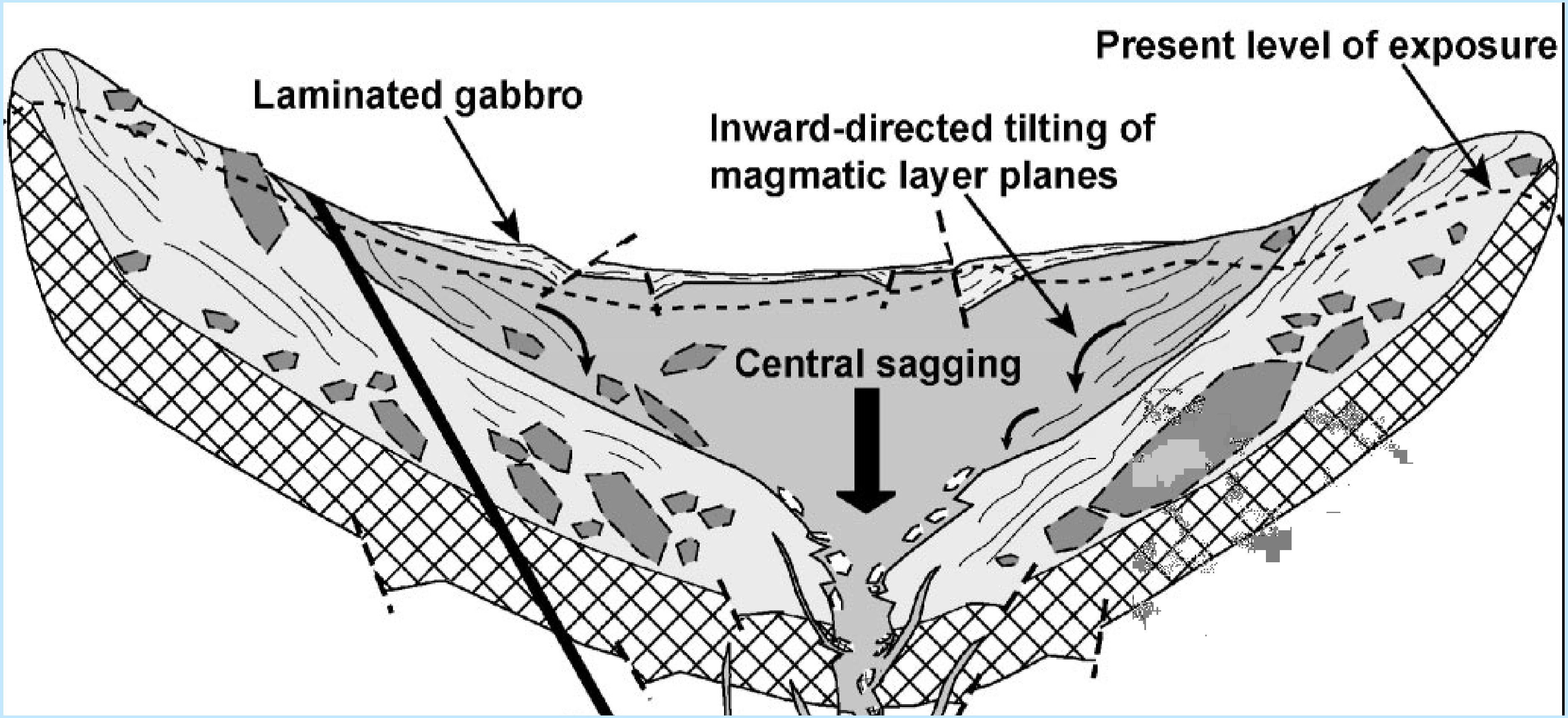
Intrusion	ρ Mafics ($kg\ m^{-3}$)	ρ Host Rocks ($kg\ m^{-3}$)	ρ Magma ($kg\ m^{-3}$)
Ardnamurchan			
Rum	3100-3200	2500-2650	2640
Sept-Iles	3000-3200	2760-2820	2680
Bushveld	3000-3200	2700-2870	2780


Phase 1 : emplacement
g
Phase 2 : sagging and foundering
g



a)
Long loch fault
Rum
N
WLS
CLS
ELS
Main ring fault
Canna lavas
Rum intrusive complex (WLS, CLS, ELS)
Torridon group
10 km
b)
mGals
50
0
c)
Mes. Seds
LS outcrop
Mes. Seds 2.5 g/cm³
Proterozoic
Granophyre
2.7g/cm³
WLS and CLS
3.2 g/cm³
ELS
3.05 g/cm³
Proterozoic
2.65 g/cm³
Lewisian
2.79 g/cm³
Depth (km)
0
5
10
15
0
10
20
30

Ardnamurchan, Scotland

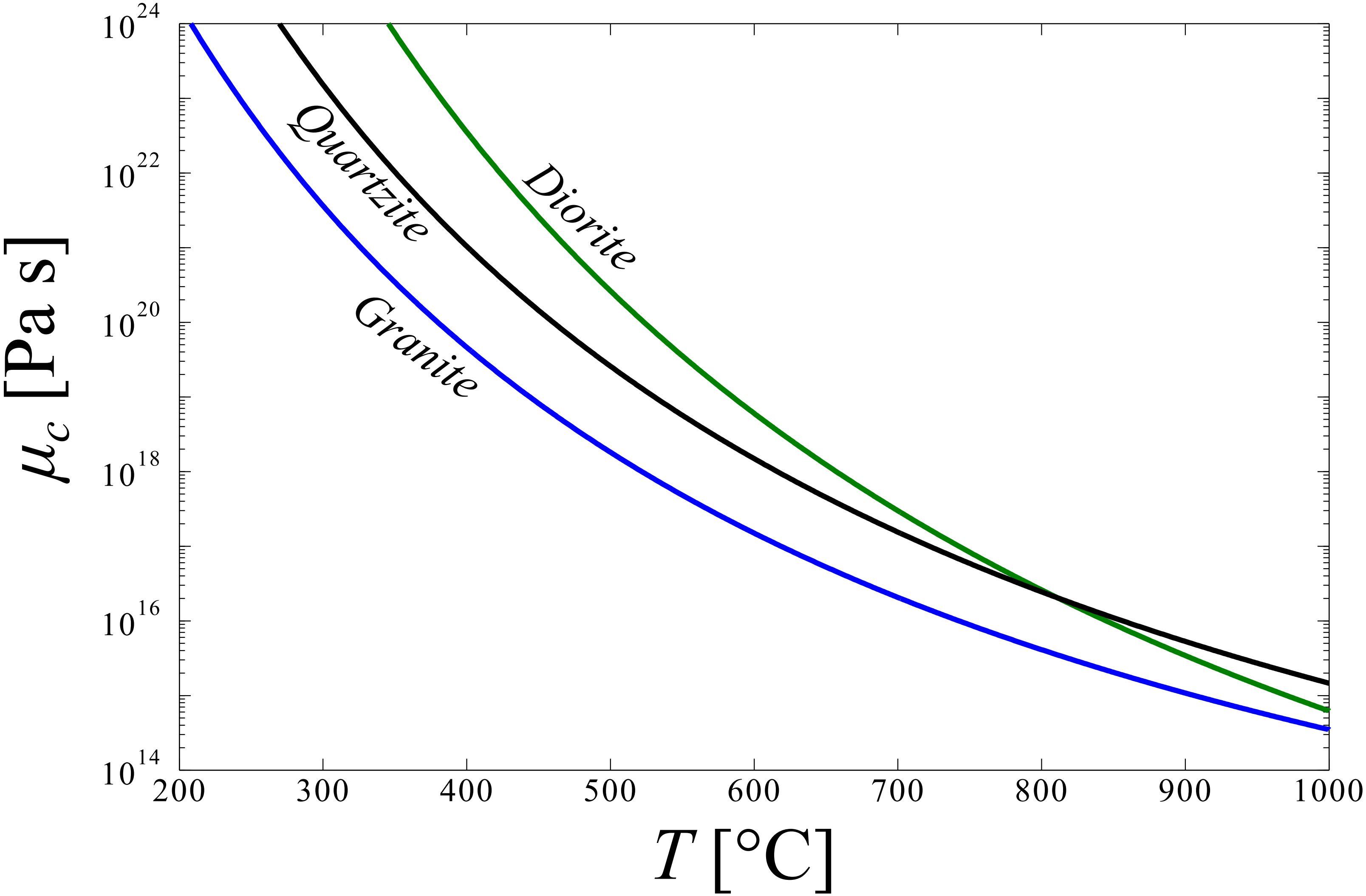


Sagging : evidence for dense material in the intrusion
(not the initial magma)

Rheological behaviour of crustal rocks: brittle and power-law creep.
Stresses in post-crystallization phase: imposed by mafic cumulates.

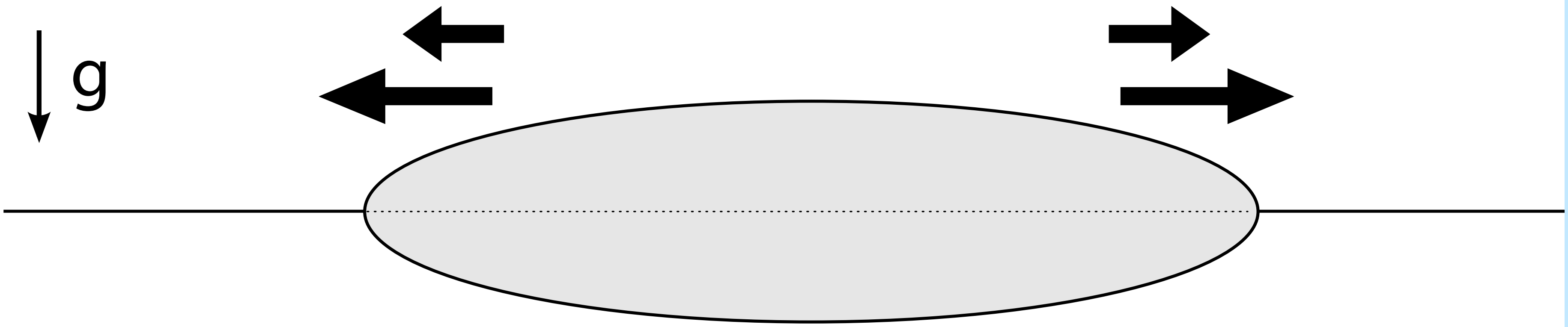
$$\sigma \approx \Delta\rho g h$$

$\Delta\rho$ = density contrast between intrusion and host rocks 300-400 kg m^{-3}.
h = intrusion thickness 3-8 km.
Effective viscosity $10^{15} - 10^{20}$ Pa s (strain rates $> 10^{-13}$ s^{-1}).

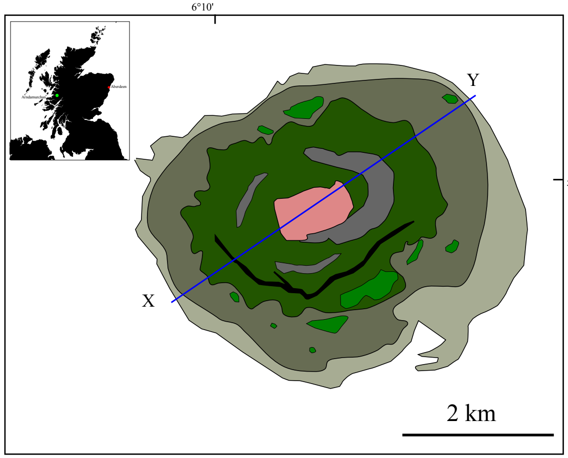


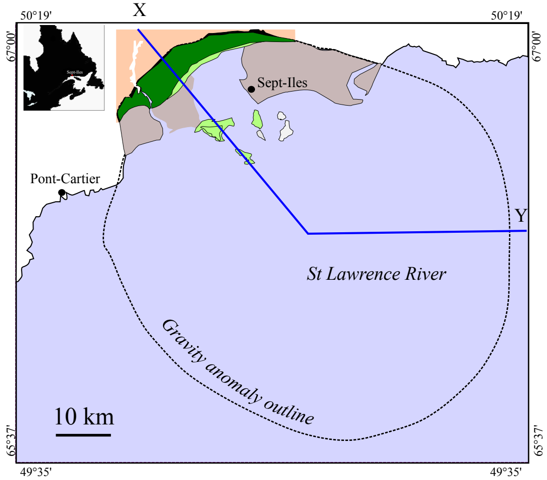
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
200
300
400
500
600
700
800
900
1000
μ_c [Pa s]
T [°C]
Quartzite
Diorite
Granite

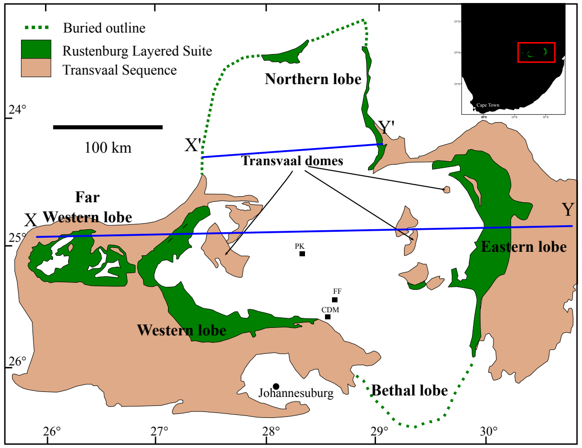
Phase 1 : emplacement

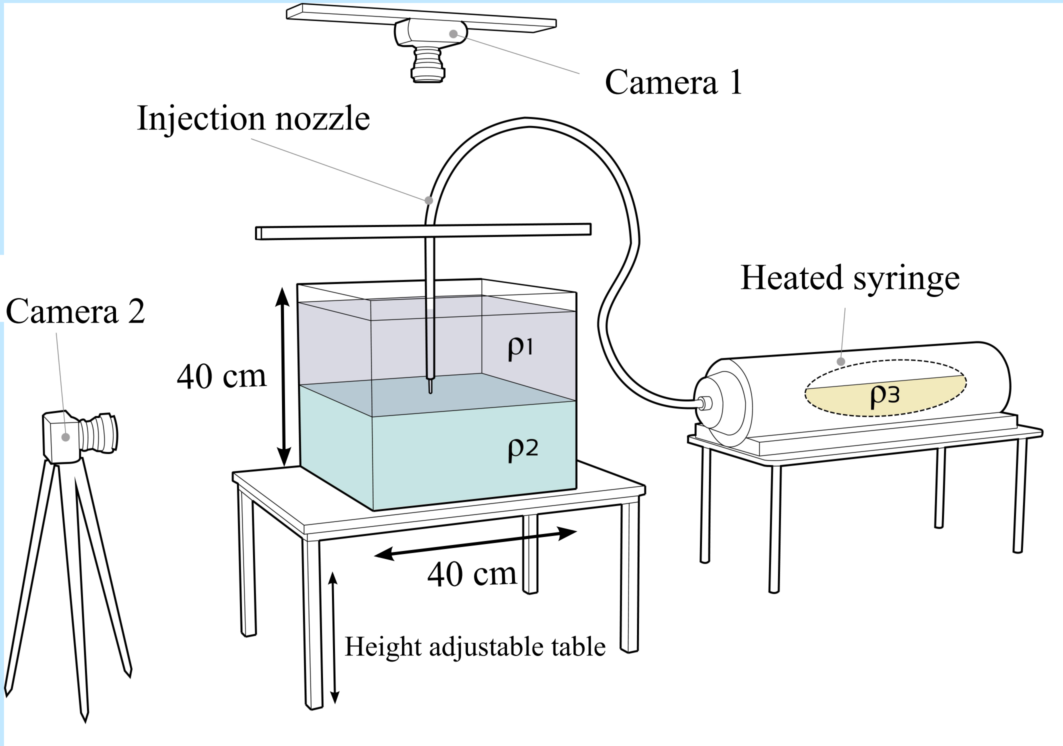


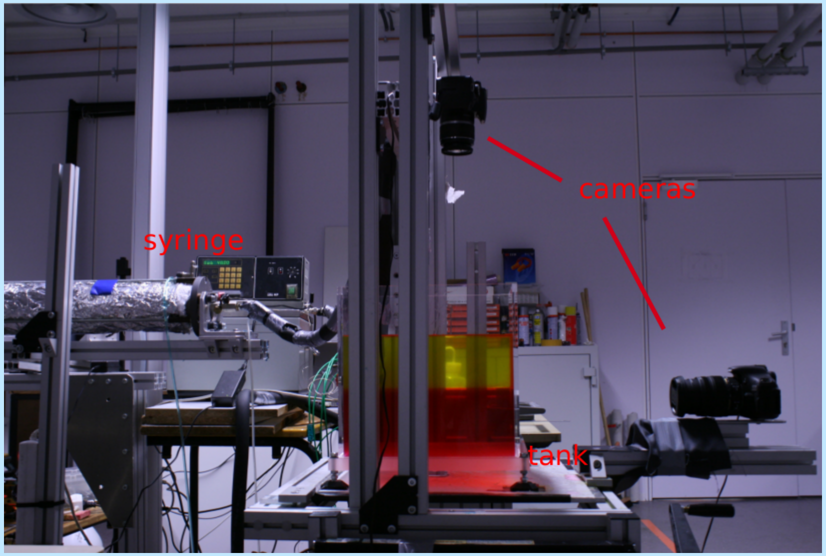
Intrusion	Volume (km^3)	Aspect ratio
Ardnamurchan	30	1
Rum	$5.4\ 10^2$	0.5
Sept-Iles	$2.8\ 10^4$	0.2
Bushveld	10^6	0.04

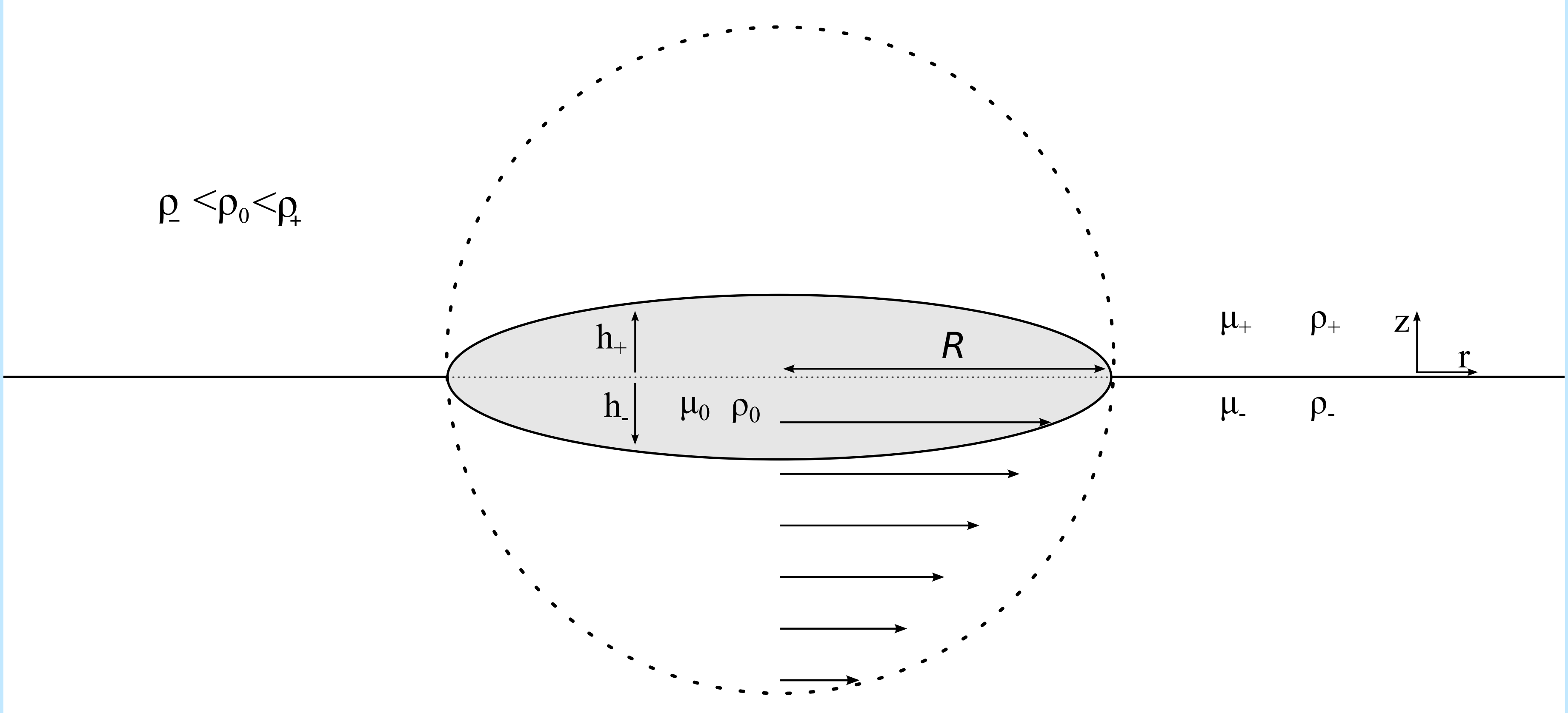




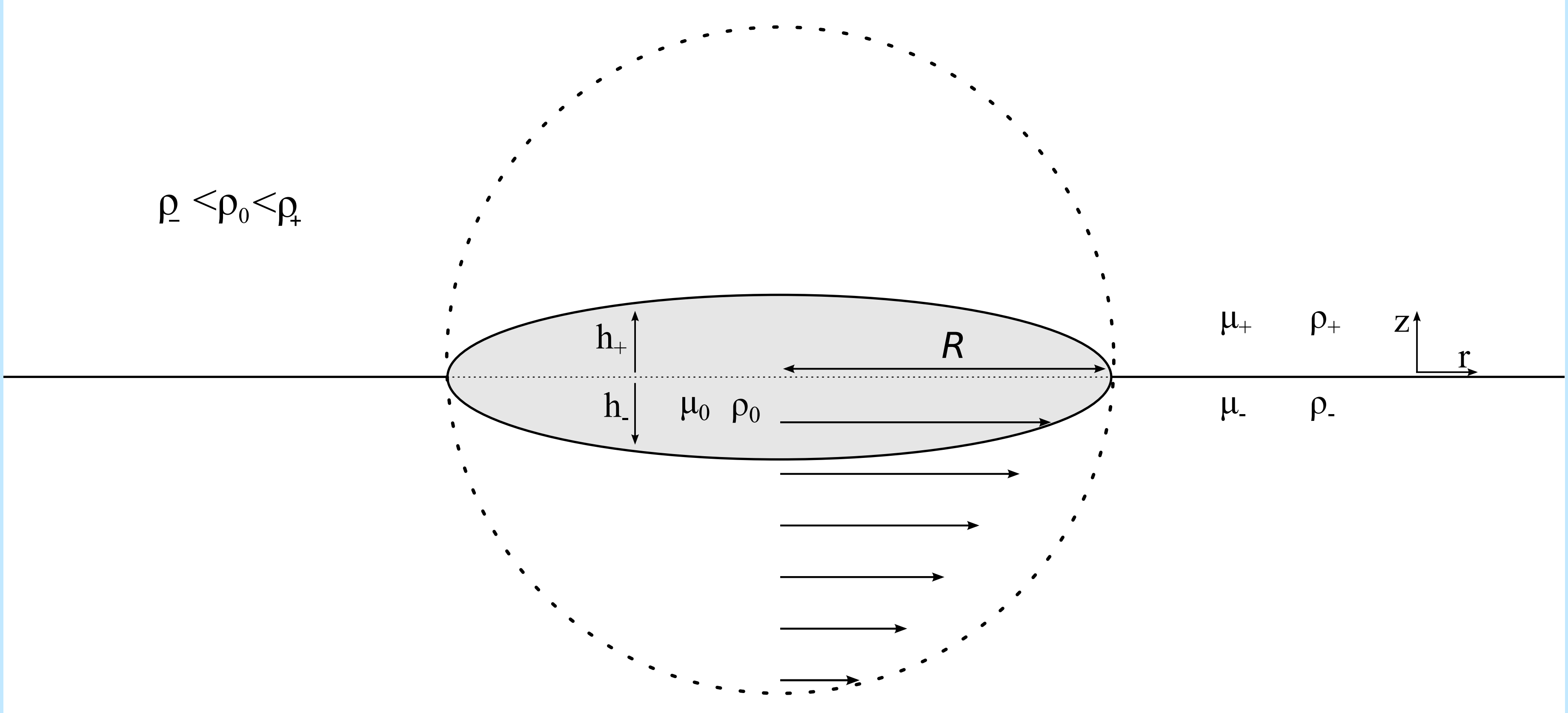



Camera 1
Injection nozzle
Heated syringe
Camera 2
40 cm
ρ1
ρ2
ρ3
40 cm
Height adjustable table


cameras
syringe
tank



Driving = buoyancy.
Resisting = viscous shear at top and bottom of intrusion.
Flow of radius R^*, thickness H^*.
For flow over radial distance R^*, kinematic boundary layer extends to distance $\sim R^*$.
Characteristic velocity (spreading rate) U_S.
Strain rate $\sim U_S/R^*$.



Bulk horizontal momentum balance:

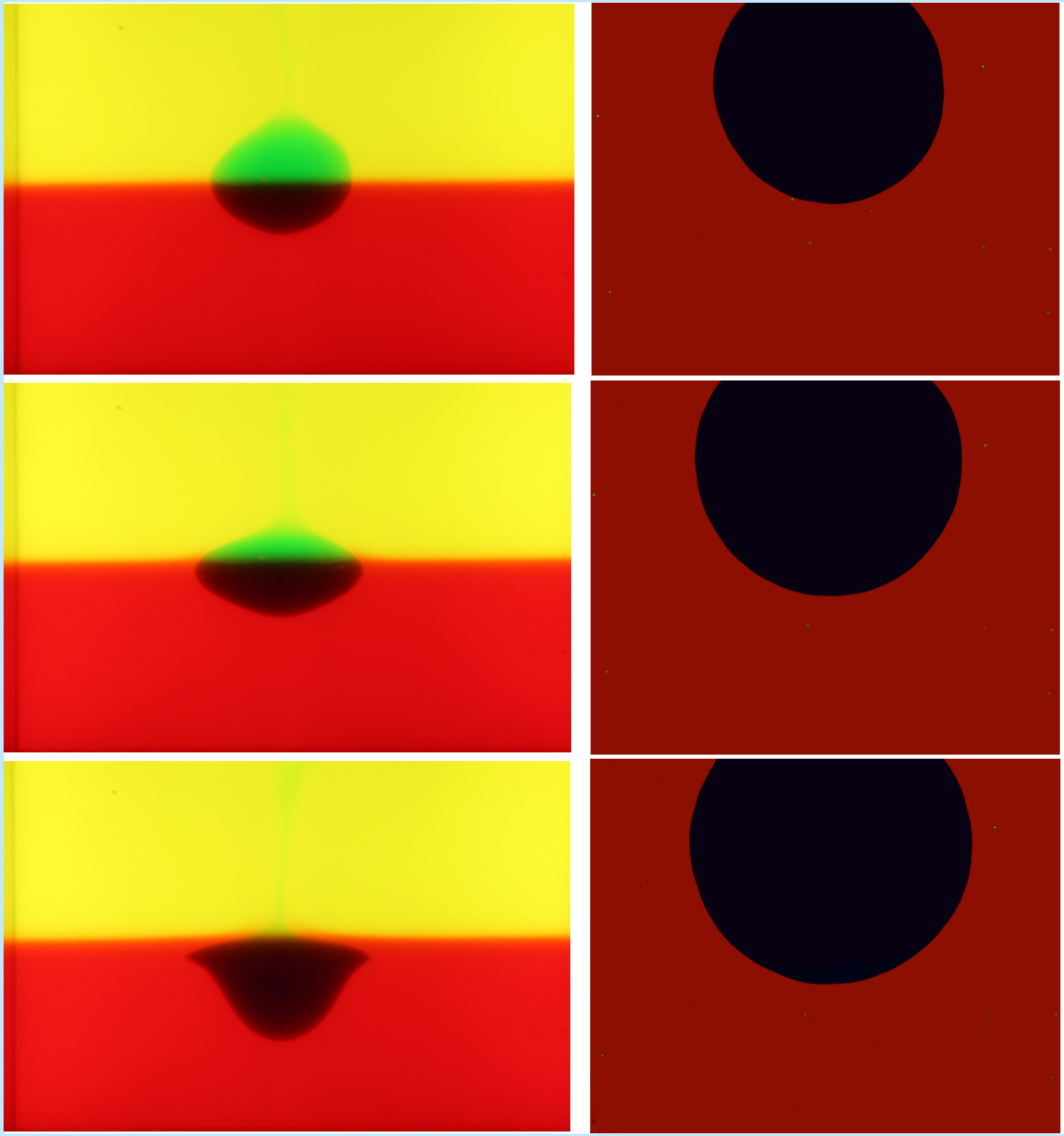
$$\left(\rho_T g' H^*\right) H^* R^* \sim \left[(\mu_- + \mu_+) \frac{U_s}{R^*} \right] R^{*2}$$

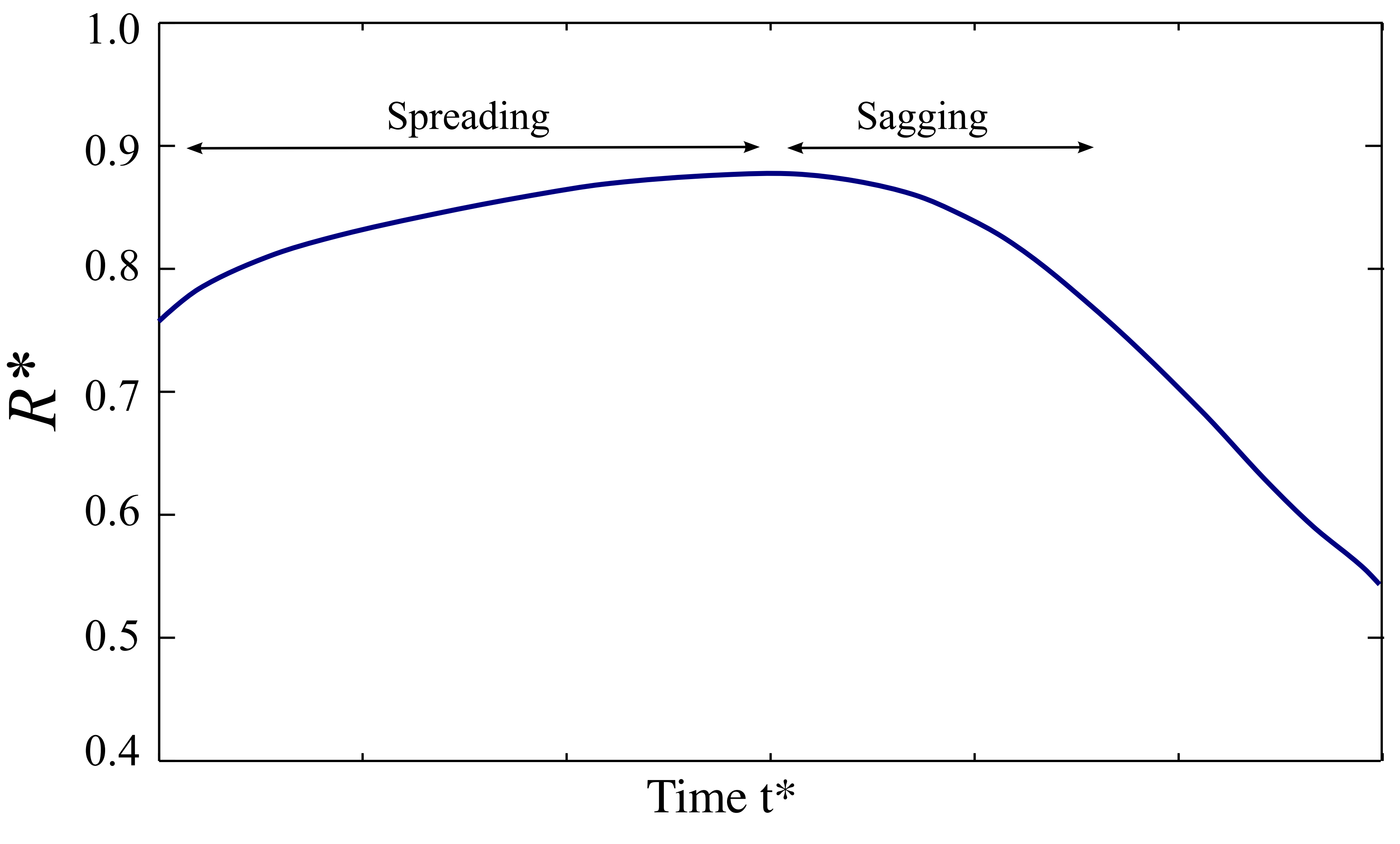
Add volume conservation.

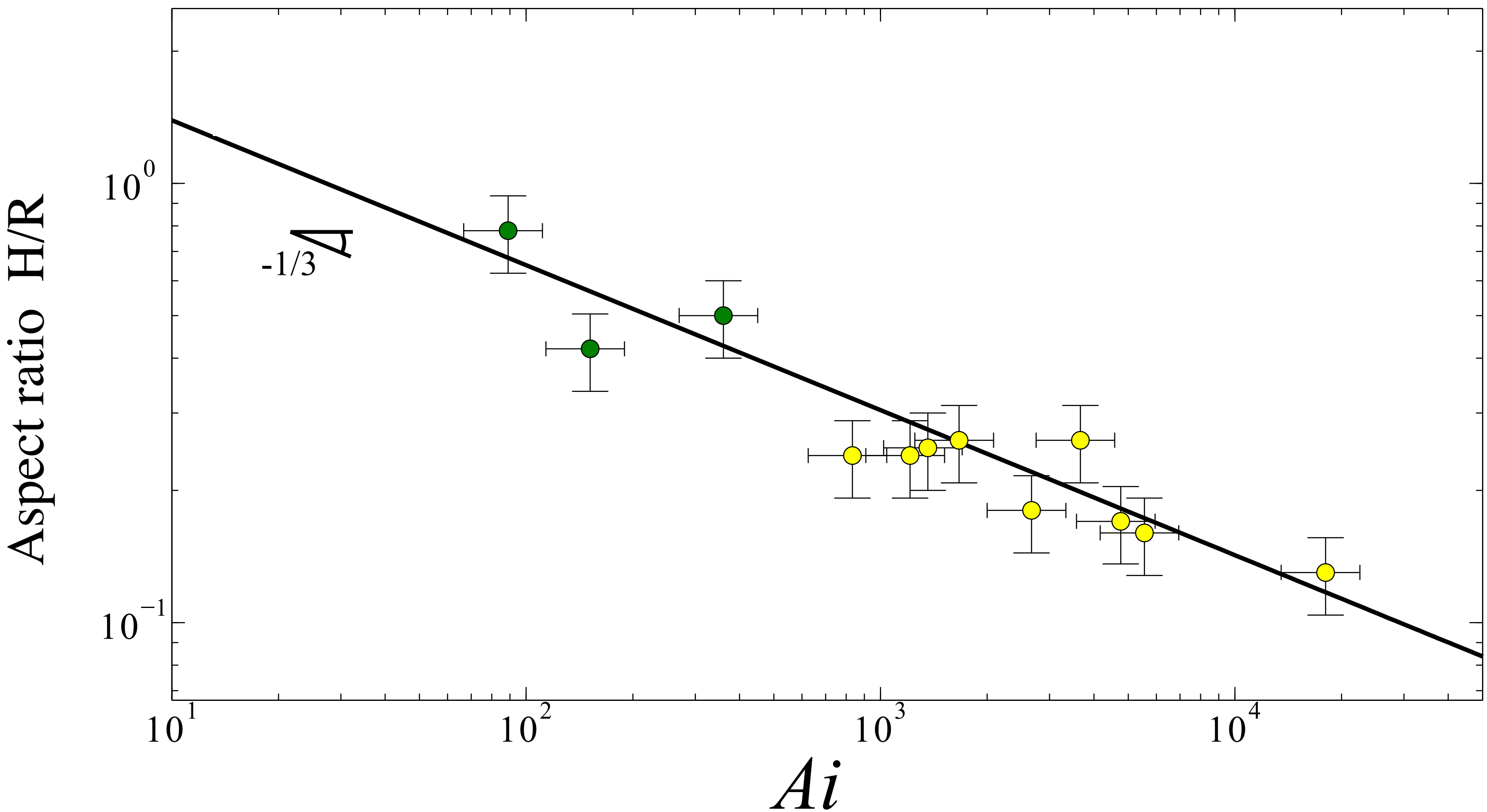
$$U_s \sim \frac{\rho_T g' H^{*2}}{\mu_- + \mu_+}$$

$$\begin{aligned} R(t) &\sim \left(\frac{\rho_T g' V^2}{\mu_+ + \mu_-}\right)^{1/5} t^{1/5} \\ h(t) &\sim \left(\frac{(\mu_- + \mu_+) V^{1/2}}{\rho_T g'}\right)^{2/5} t^{-2/5} \end{aligned}$$

Side view View from above




1.0
0.9
0.8
0.7
0.6
0.5
0.4
R*
Spreading
Sagging
Time t*



Aspect ratio H/R
10^0
10^{-1}
-1/3
10^1
10^2
10^3
10^4
Ai

End of the spreading phase such that cooling proceeds faster than spreading.

$$\text{Cooling rate} \sim \kappa/H.$$

$$\text{Spreading rate} \sim \frac{dR}{dt} \sim \left(\frac{\rho_T g' V^2}{\mu_+ + \mu_-}\right)^{1/5} t^{-4/5}$$

Thus, critical time for buoyancy reversal:

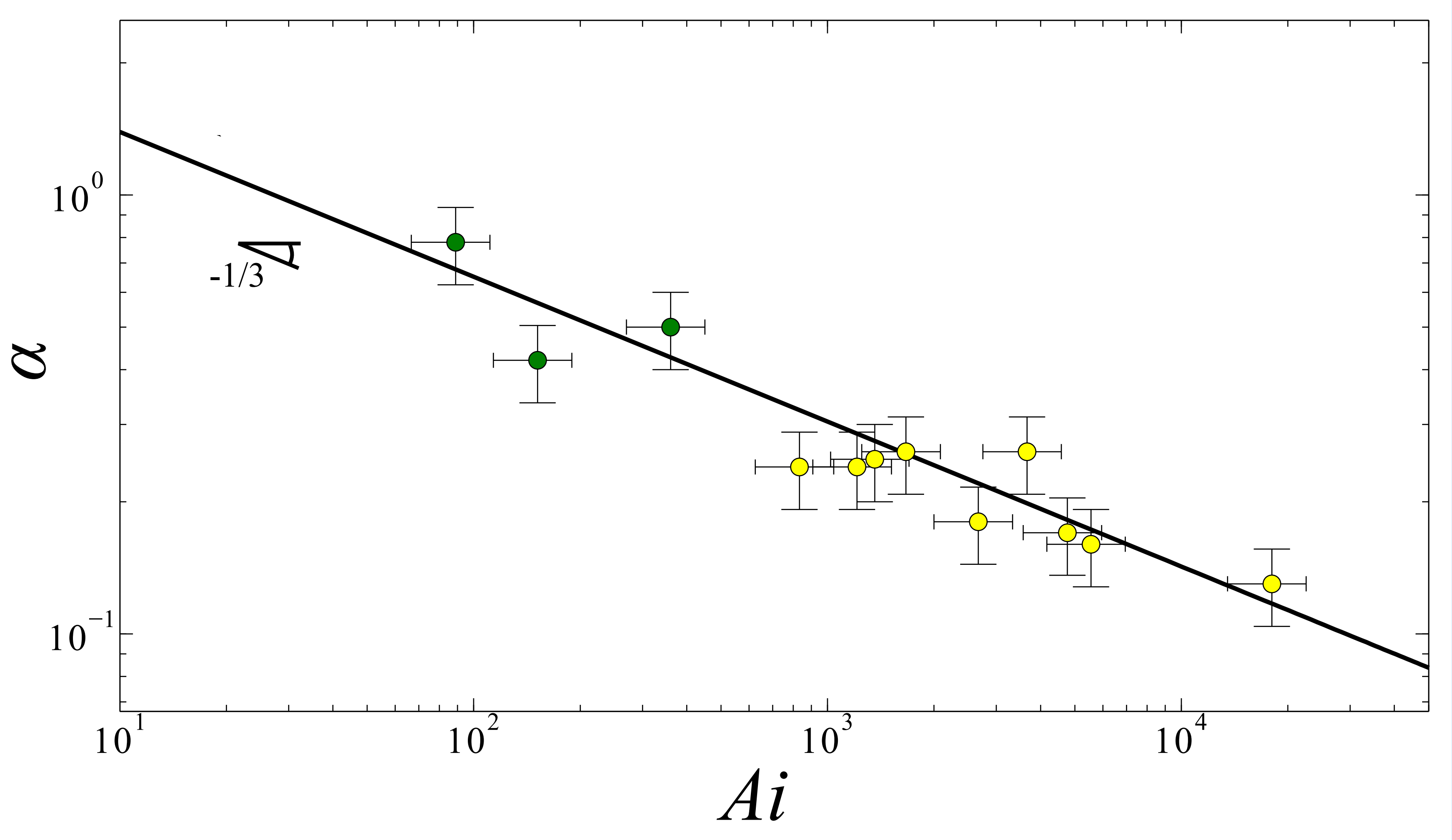
$$t_c \sim \left(\frac{(\mu_- + \mu_+)V^{1/2}}{\rho_T g' \kappa^{5/4}}\right)^{4/9}$$

At $t = t_c$, $H = H_c$ and $R = R_c$, corresponding to critical aspect ratio $\alpha_c = H_c/R_C$:

$$\alpha_c \sim \frac{H_c}{R_c} \sim \left(\frac{(\mu_- + \mu_+)\kappa}{\rho_T g' V}\right)^{1/3} = Ai^{-1/3}$$

Dimensionless number Ai:

$$Ai = \frac{\rho_T g' V}{(\mu_- + \mu_+)\kappa}.$$



$$\alpha_c = (2.8 \pm 0.10) Ai^{-1/3}.$$

α_c decreases with increasing volume $V*$.

Dimensionless number Ai = ratio between two velocity scales.
Spreading rate versus and cooling rate (diffusion controlled).
Cooling rate.

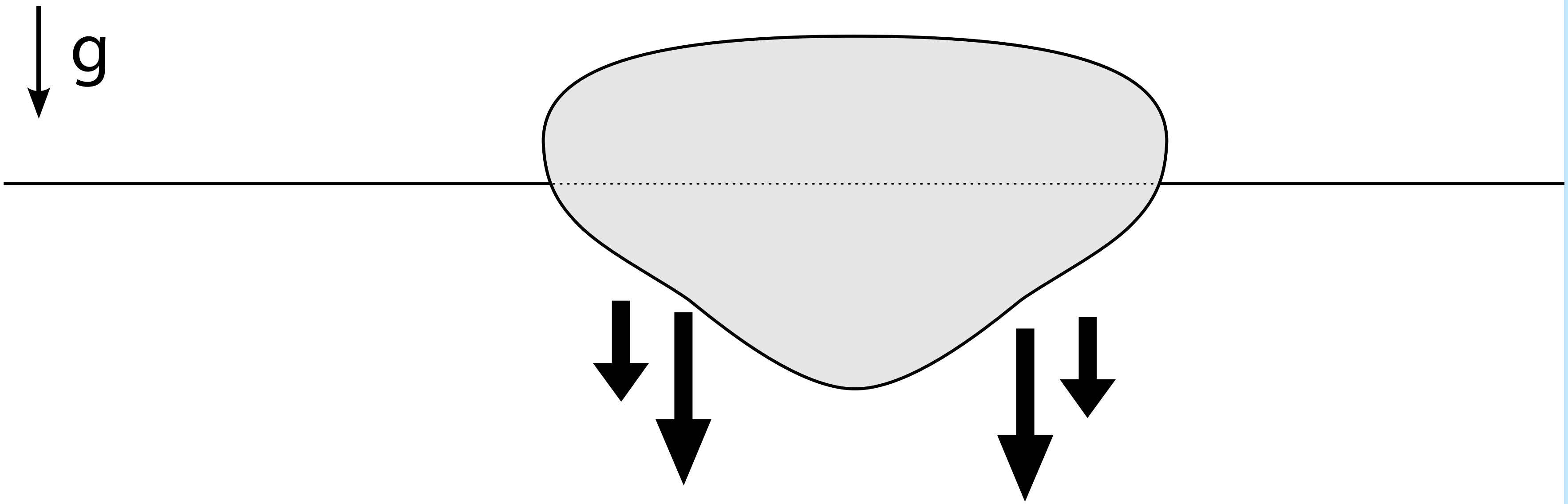
$$U_d = \frac{\kappa}{H^*}$$

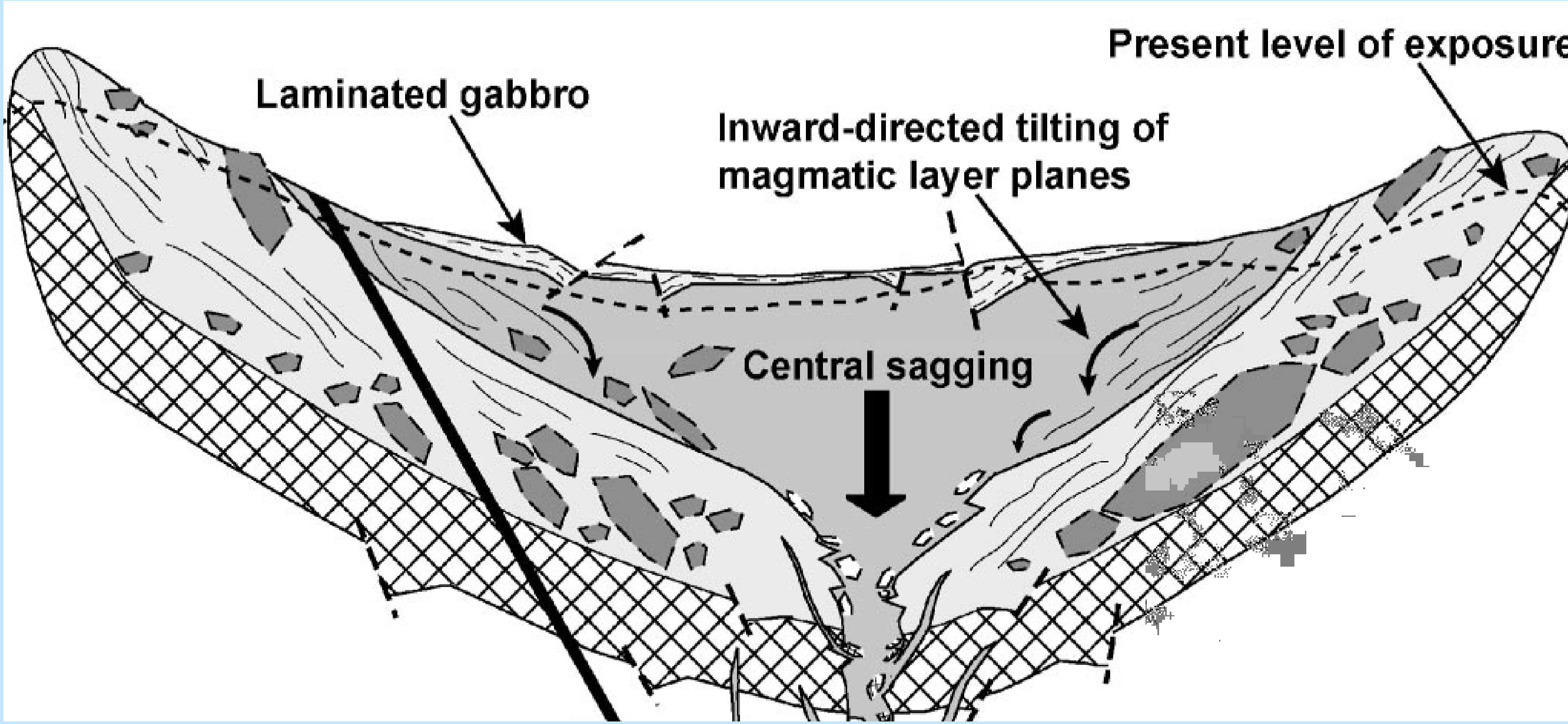
Set $H^* \sim V^{1/3}$ and $R^* \sim V^{1/3}$:

$$\frac{U_s}{U_d} = \frac{\rho_T g' V}{(\mu_- + \mu_+)\kappa} = Ai$$

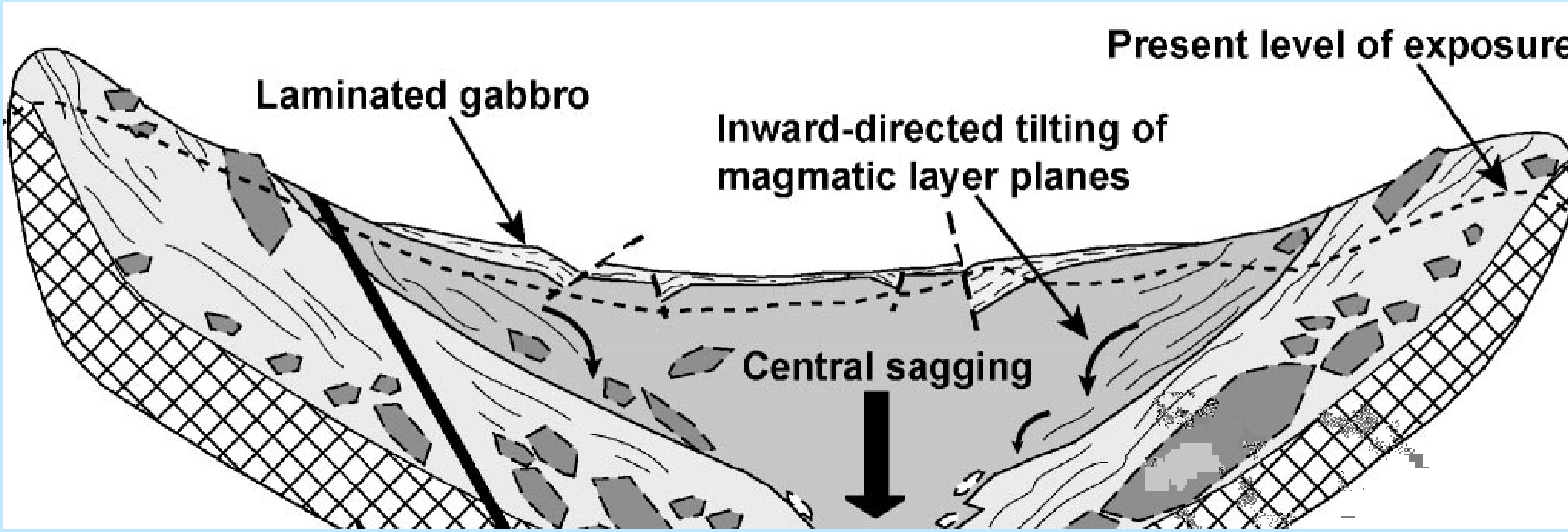
Large Ai : spreading faster than cooling = intrusion extends to large distances.
Small Ai : cooling faster than spreading = intrusion does not spread.

Phase 2 : sagging and foundering

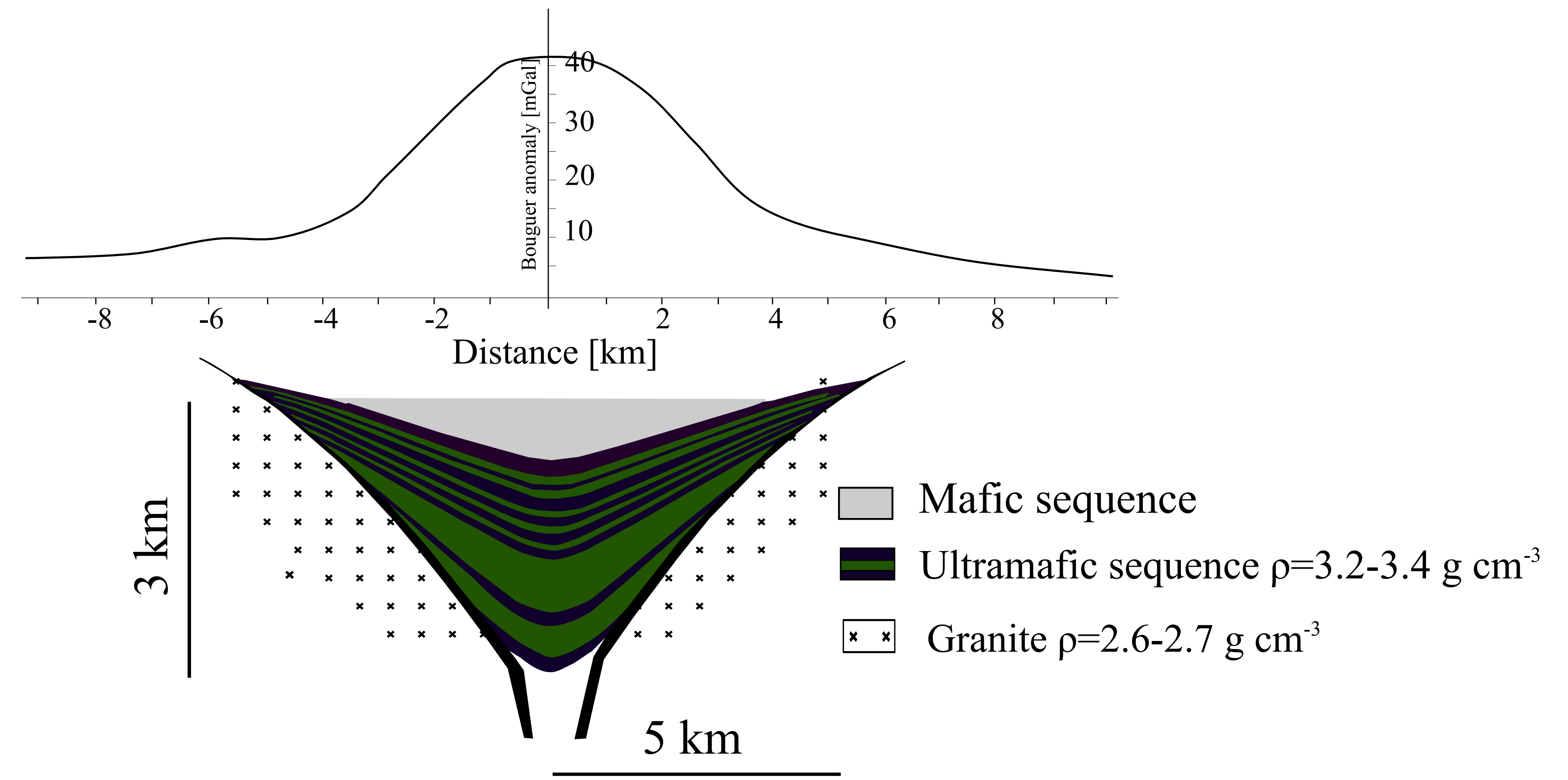




Present level of exposure
Laminated gabbro
Inward-directed tilting of
magmatic layer planes
Central sagging

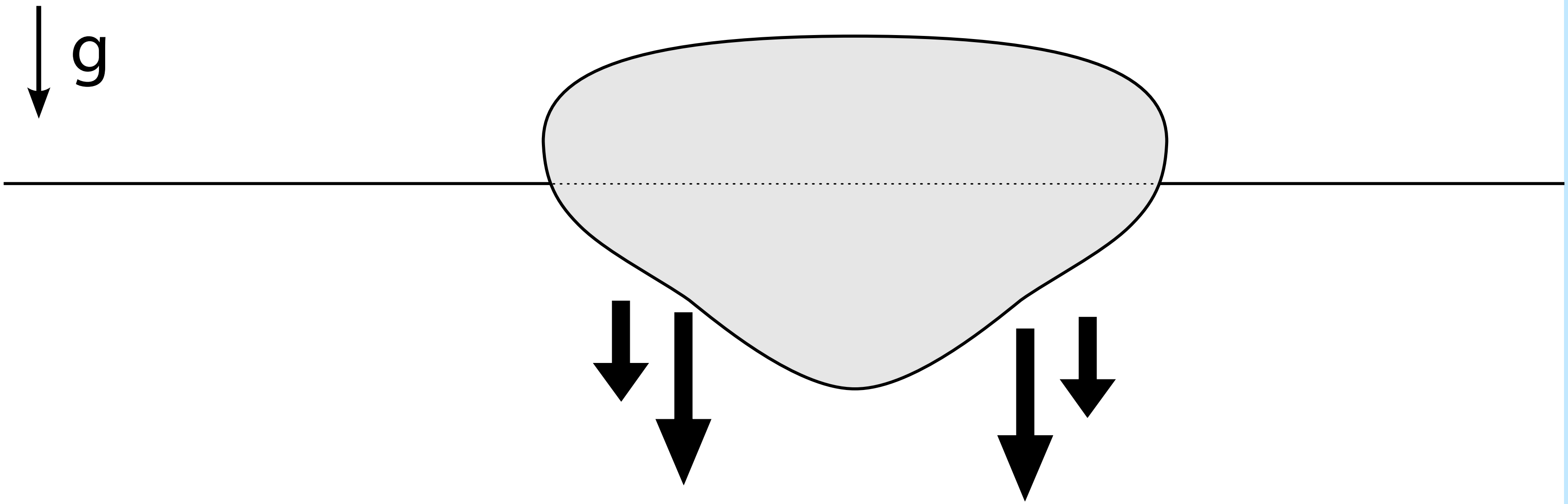


Sagging ?
inward dips increase towards axial zone:
not consistent with sagging (flexural behaviour)
suggests incipient foundering

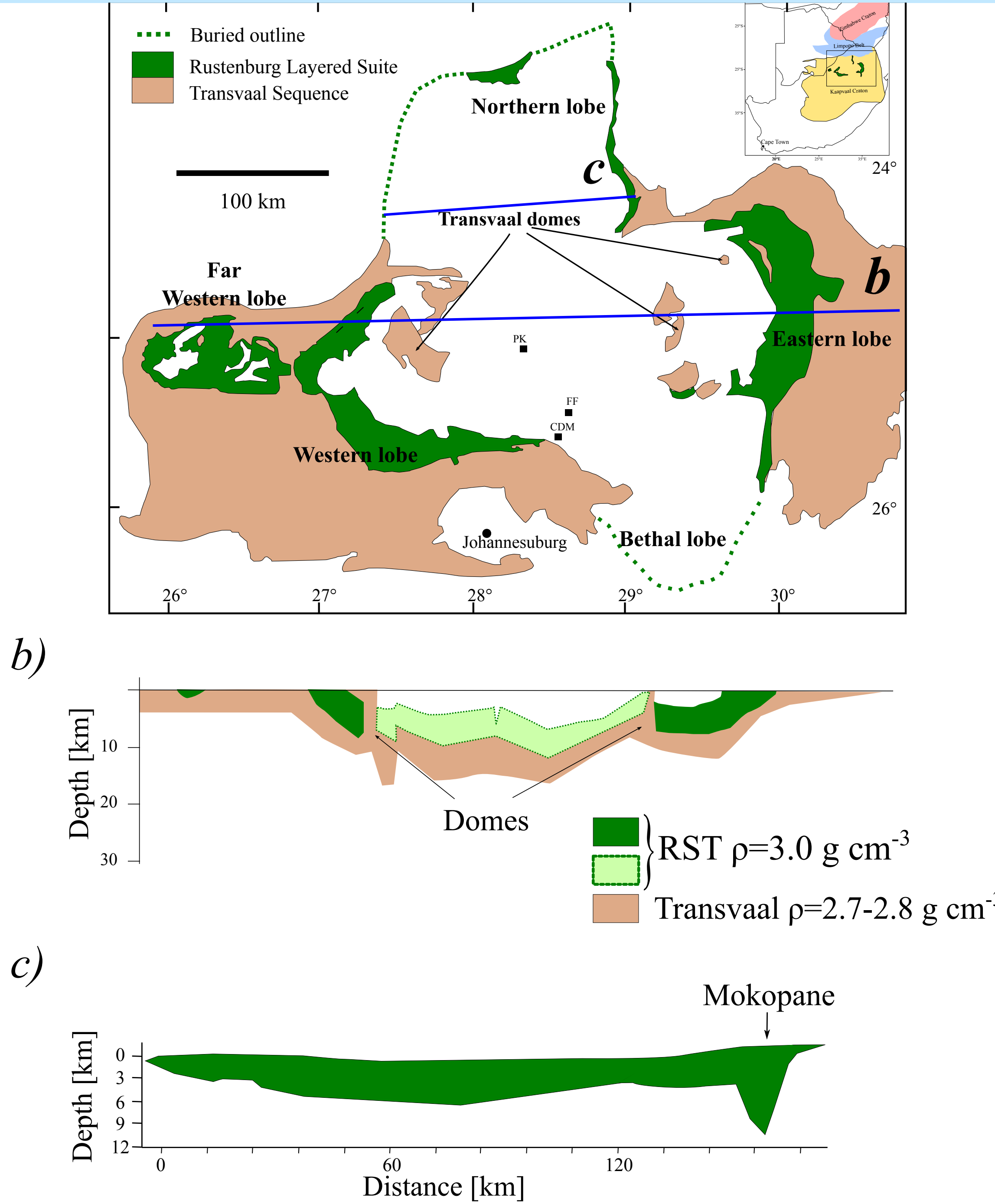


Bouguer anomaly [mGal]
40
30
20
10
-8
-6
-4
-2
2
4
6
8
Distance [km]
3 km
5 km
Mafic sequence
Ultramafic sequence ρ=3.2-3.4 g cm-3
Granite ρ=2.6-2.7 g cm-3

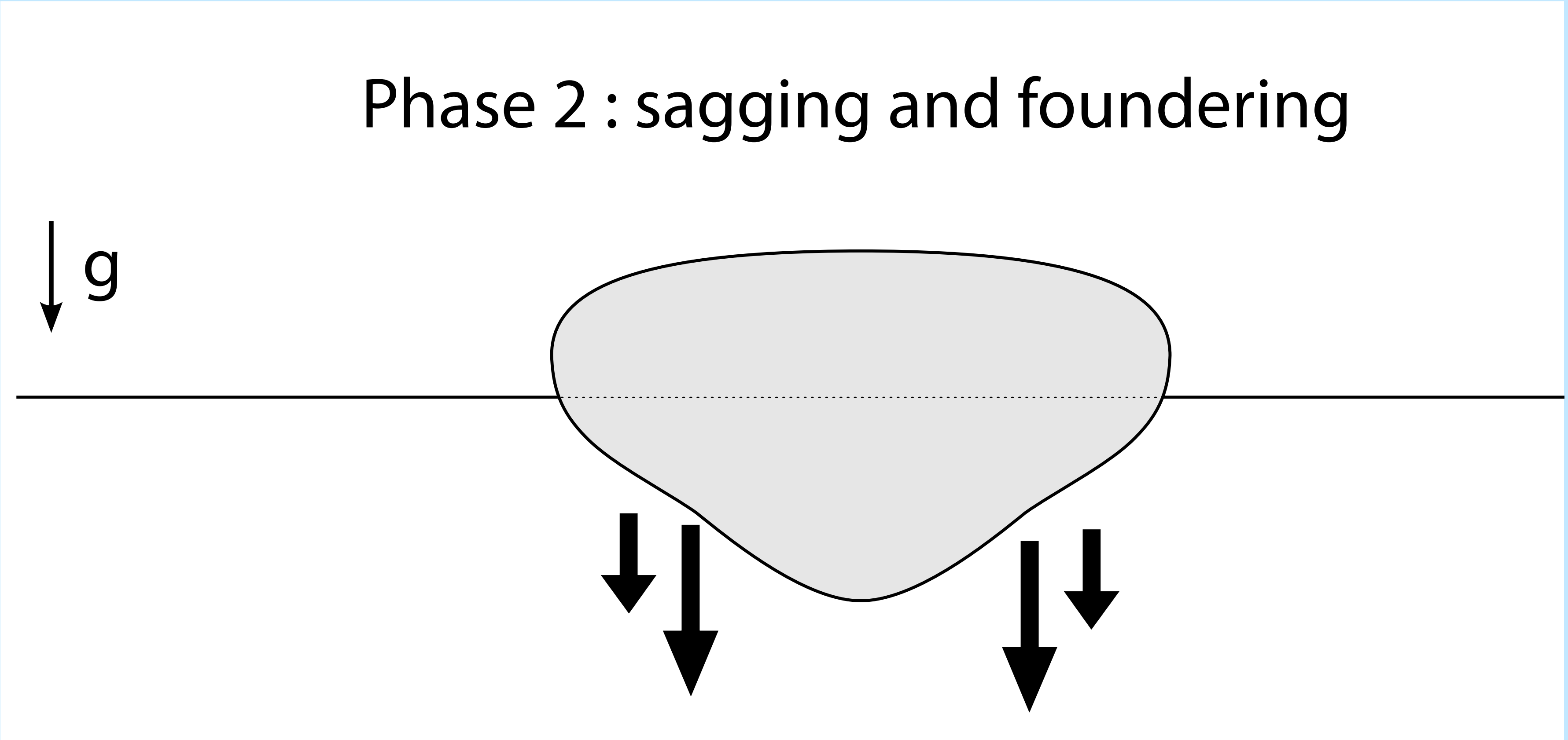
Phase 2 : sagging and foundering



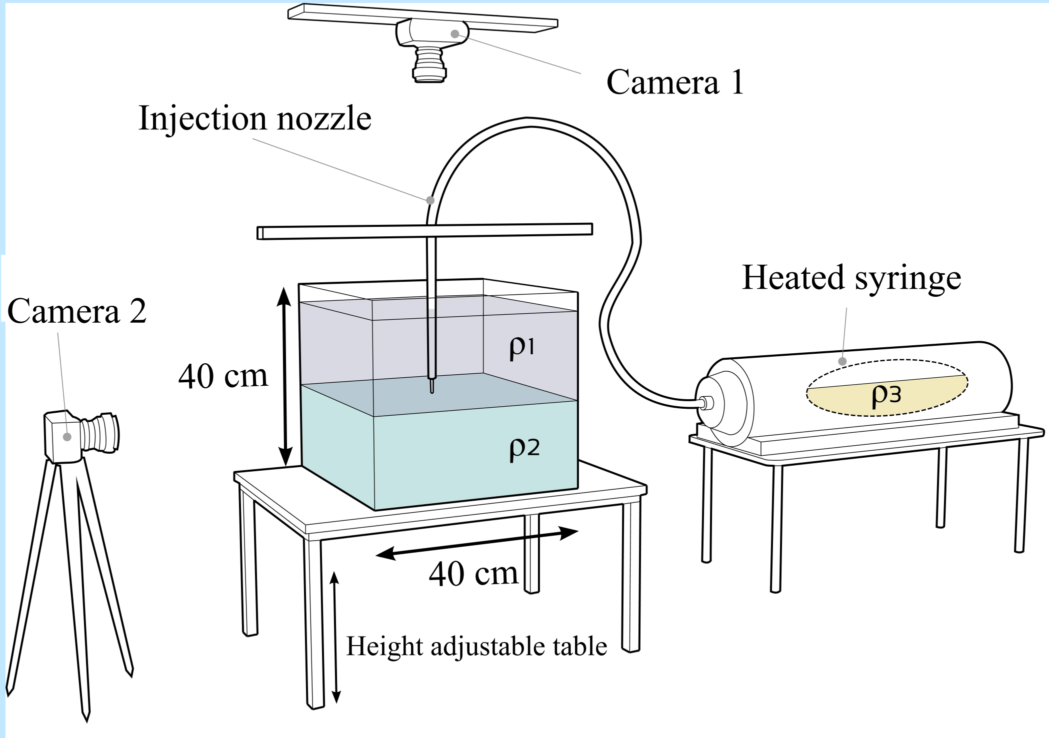
Sequence of increasing deformation with increasing volume.
Sagging – funnel structure – sinking (?)

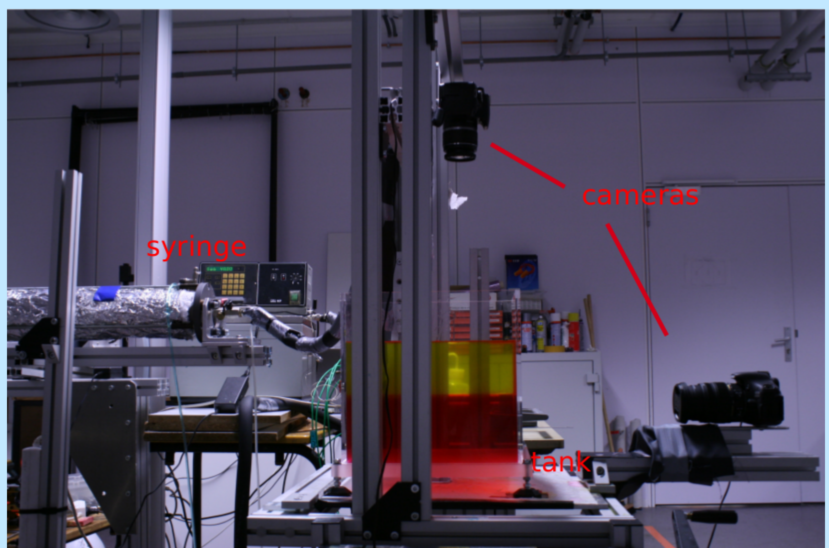


Buried outline
Rustenburg Layered Suite
Transvaal Sequence
100 km
Northern lobe
c
Transvaal domes
Far
Western lobe
b
Eastern lobe
PK
FF
CDM
Western lobe
Johannesburg
Bethal lobe
24°
26°
26°
27°
28°
29°
30°
b)
Depth [km]
10
20
30
Domes
RST ρ=3.0 g cm-3
Transvaal ρ=2.7-2.8 g cm-3
c)
Mokopane
Depth [km]
0
3
6
9
12
0
60
120
Distance [km]

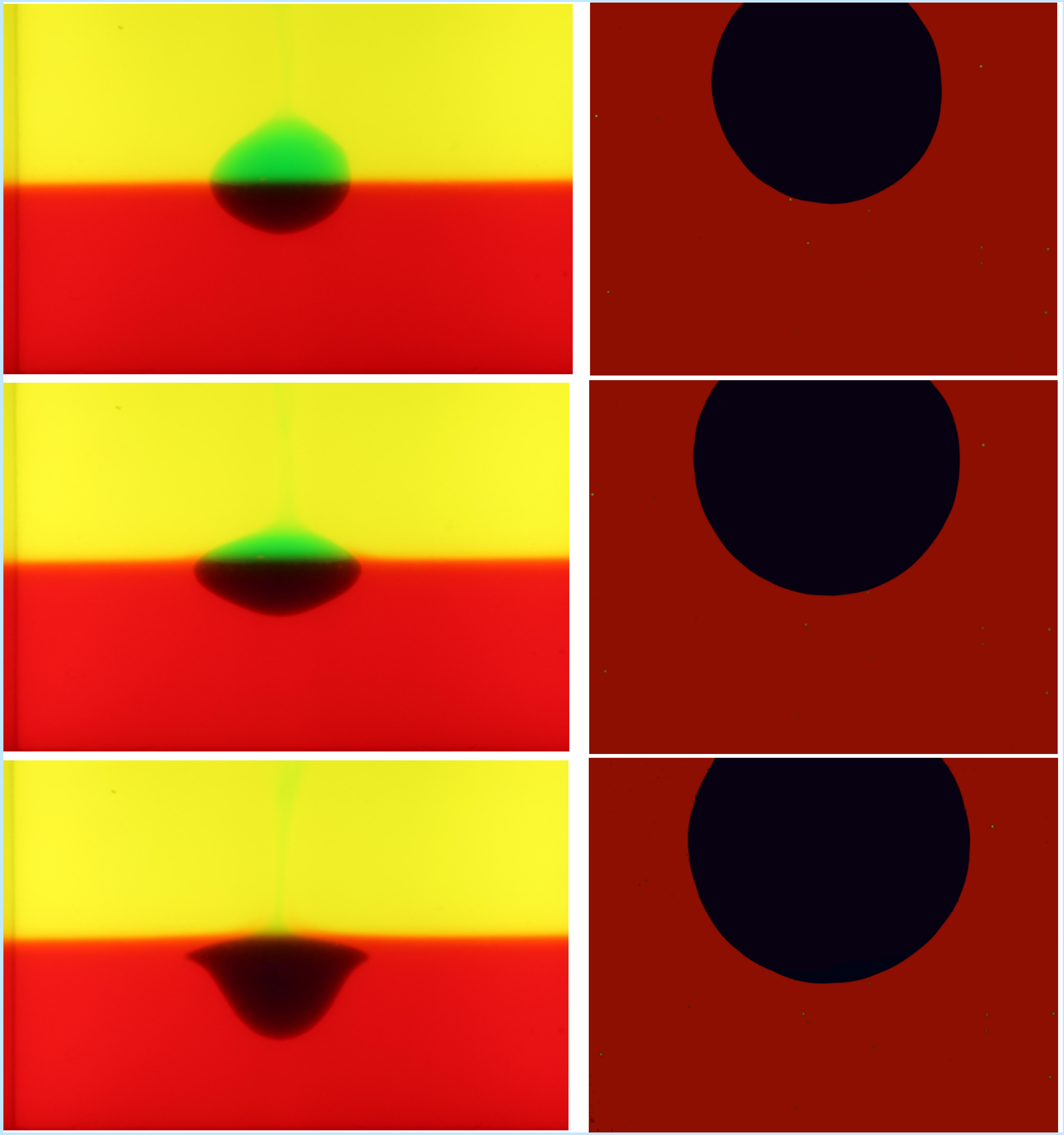


Sequence of increasing deformation with increasing volume.
Complex shapes for small aspect-ratio intrusions.


Camera 1
Injection nozzle
Camera 2
40 cm
ρ1
ρ2
Heated syringe
ρ3
40 cm
Height adjustable table

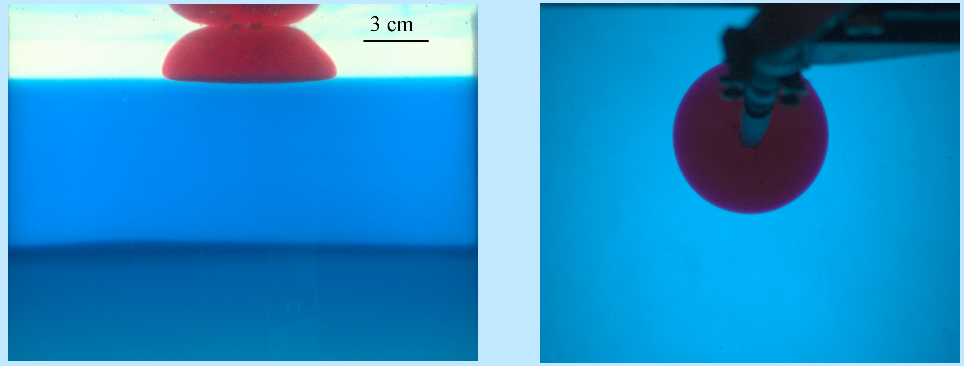

cameras
syringe
tank

Teardrop regime



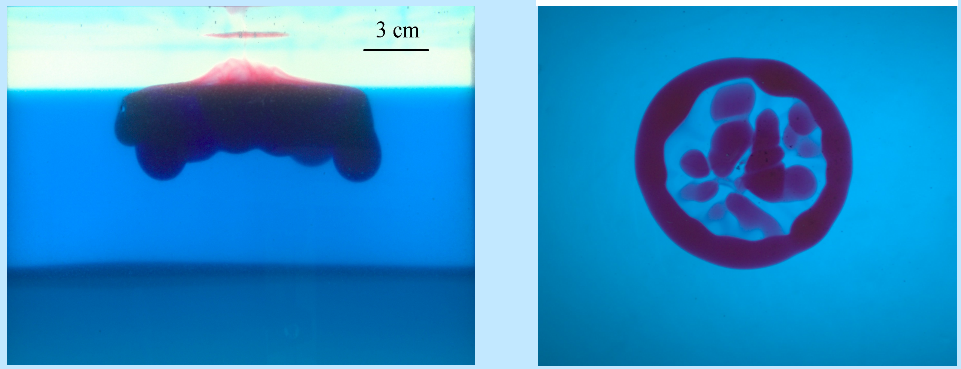
“Jellyfish” regime

a)



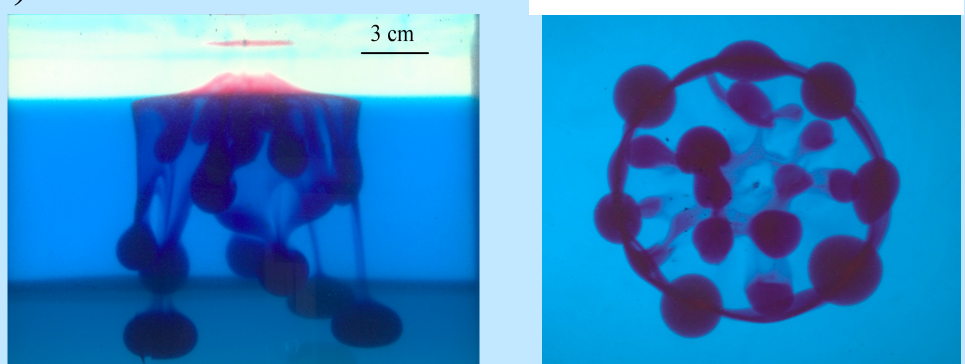
t=10 s

b)

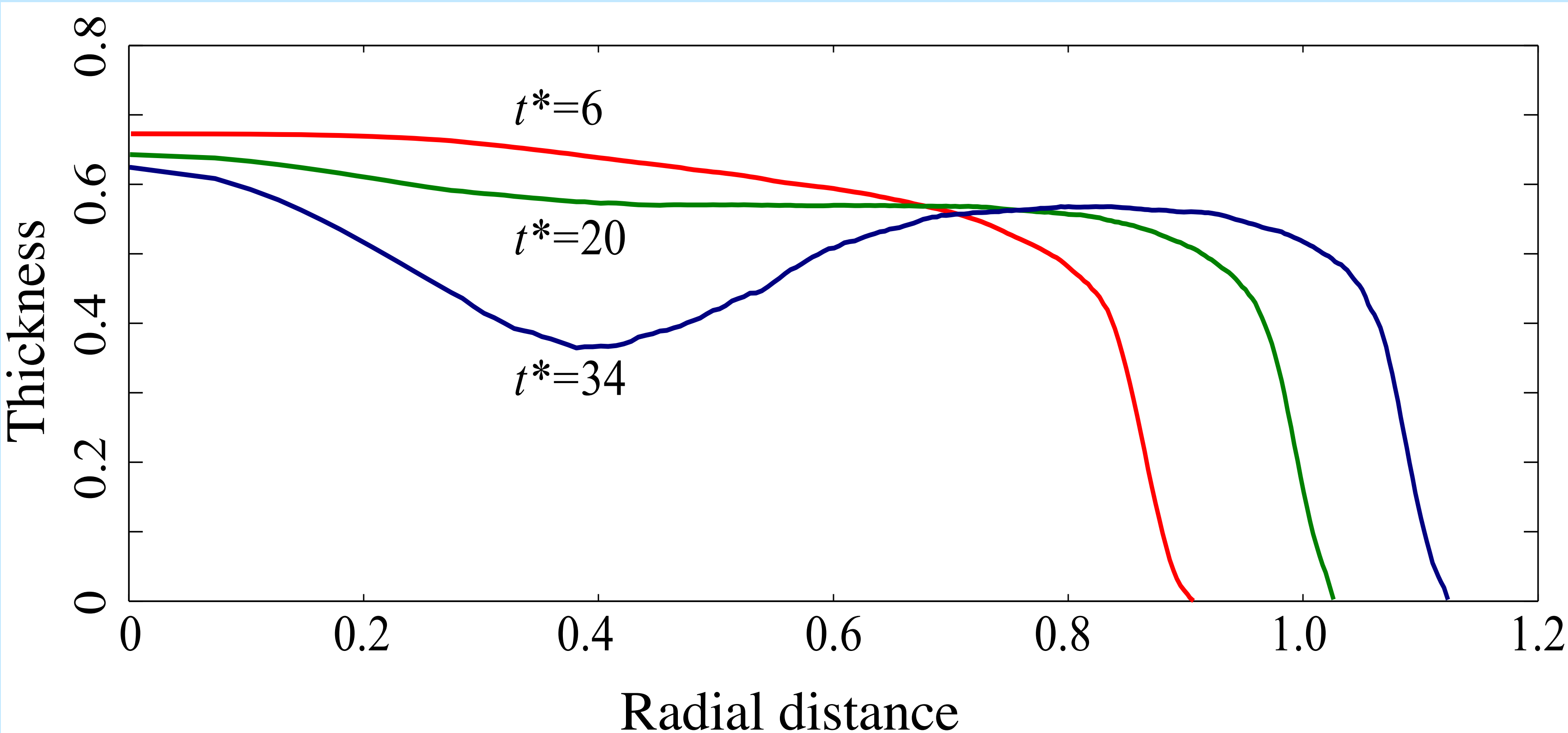


t=480s

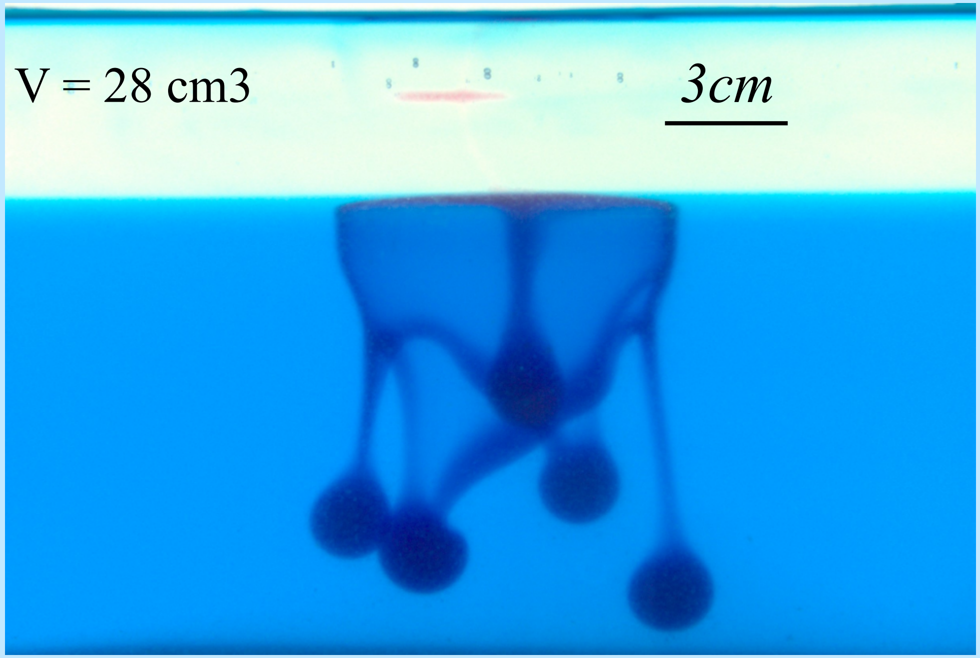
c)

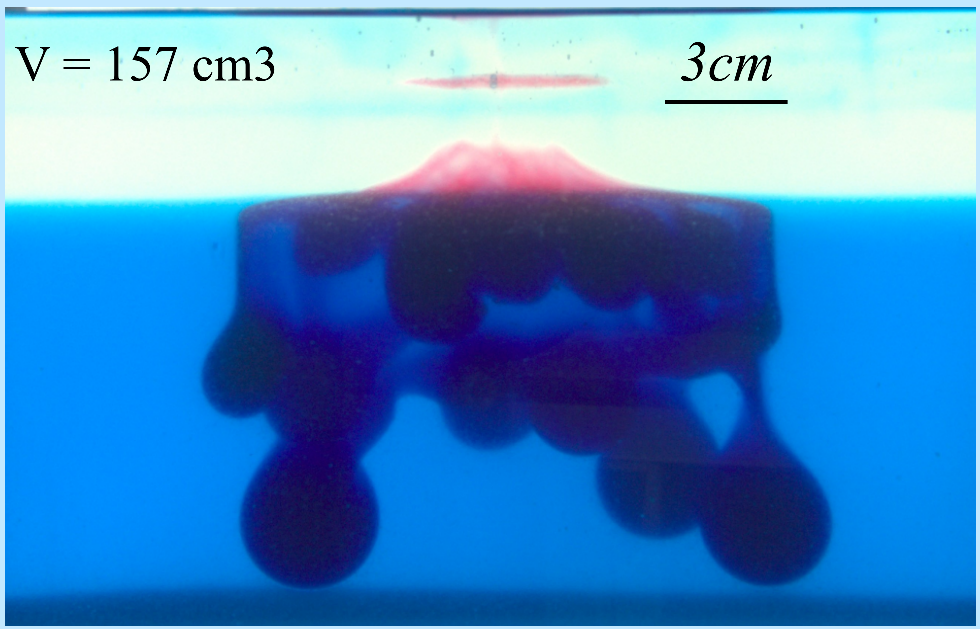


t=710s

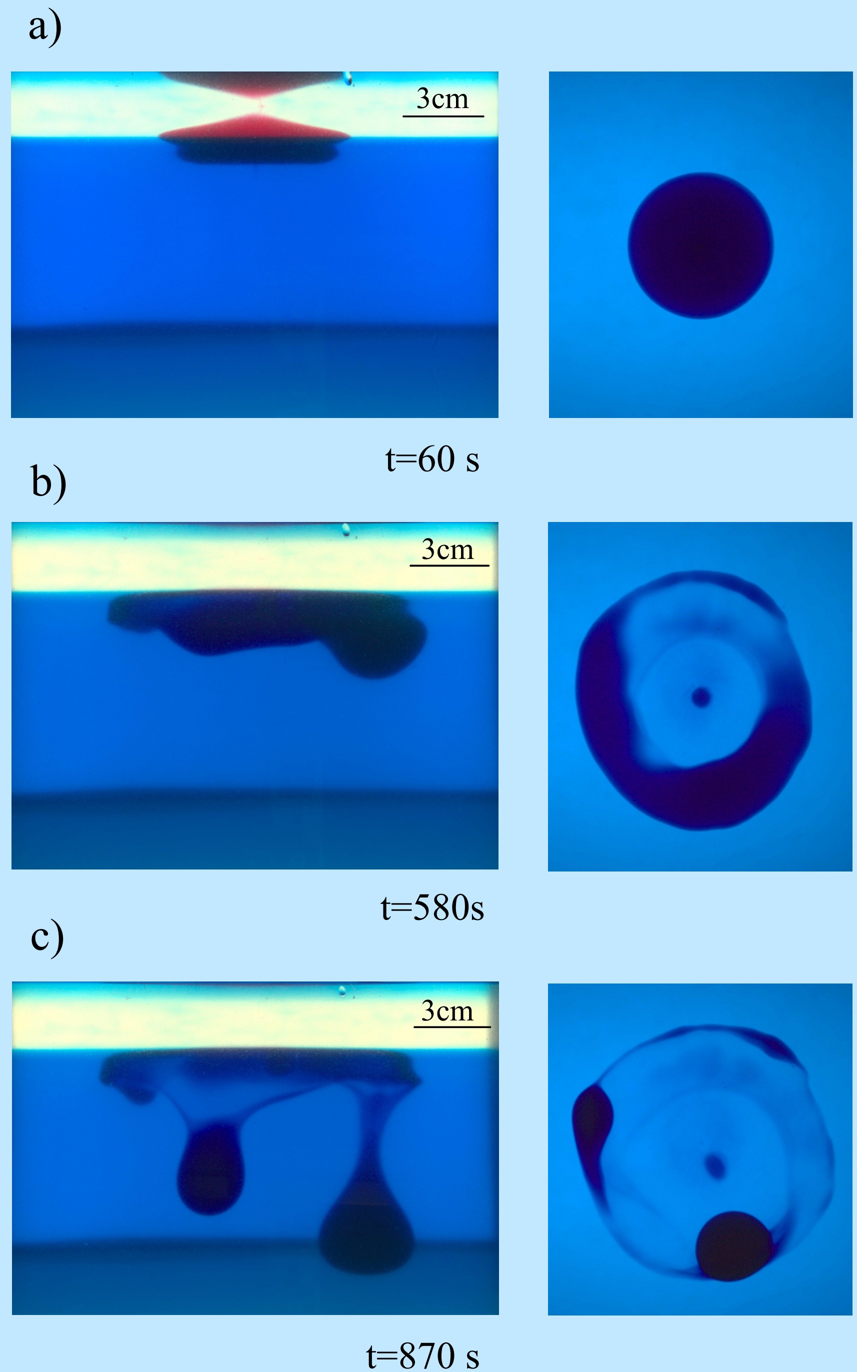


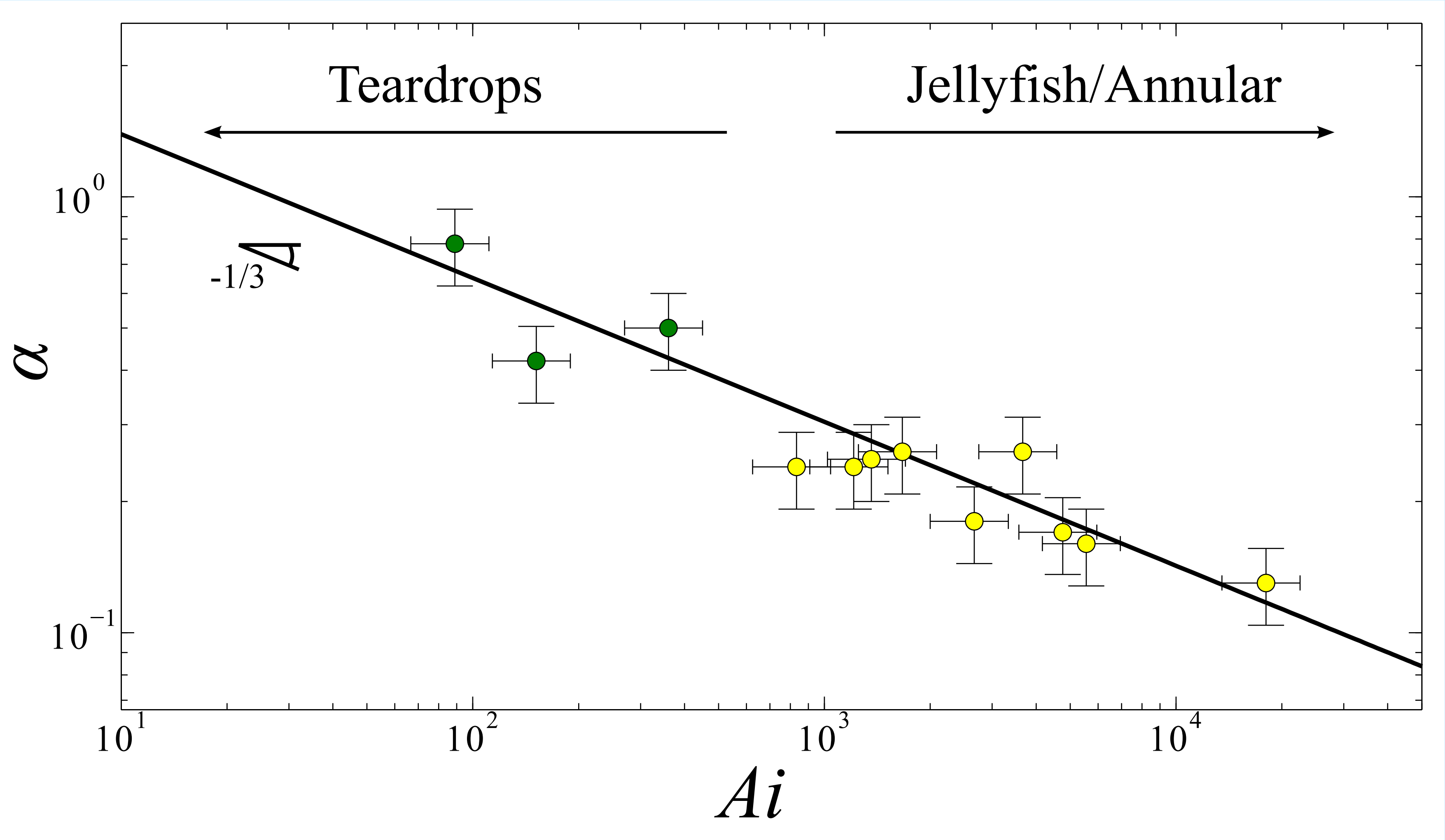
Thickness
0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
0.8
1.0
1.2
Radial distance
t*=6
t*=20
t*=34

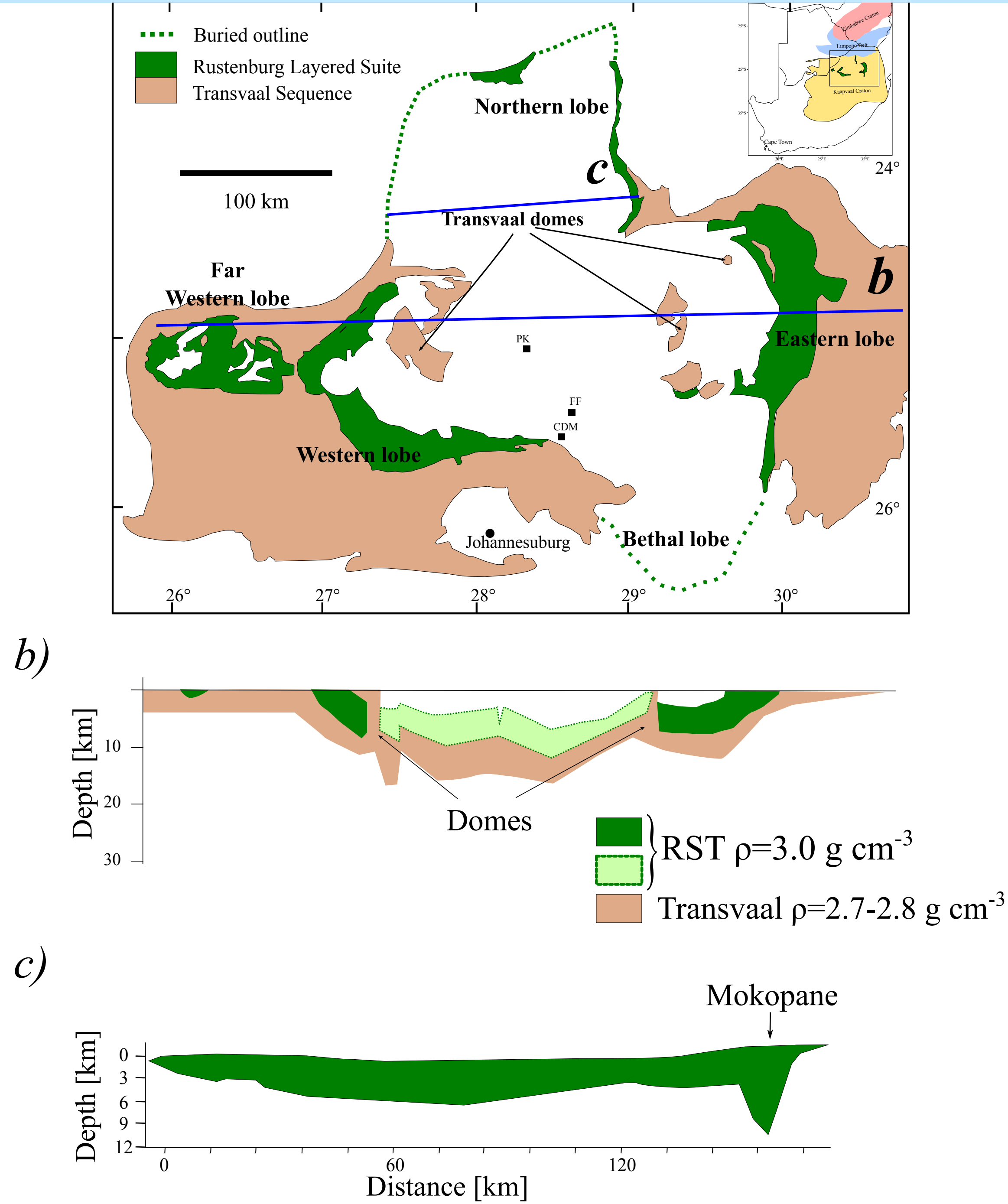

V = 28 cm3
3cm


V = 157 cm3
3cm

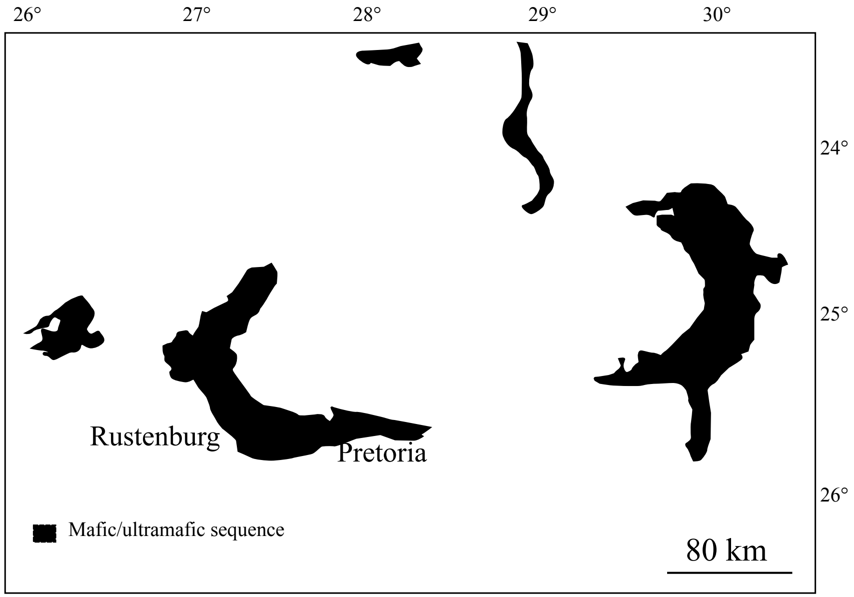
Annular regime

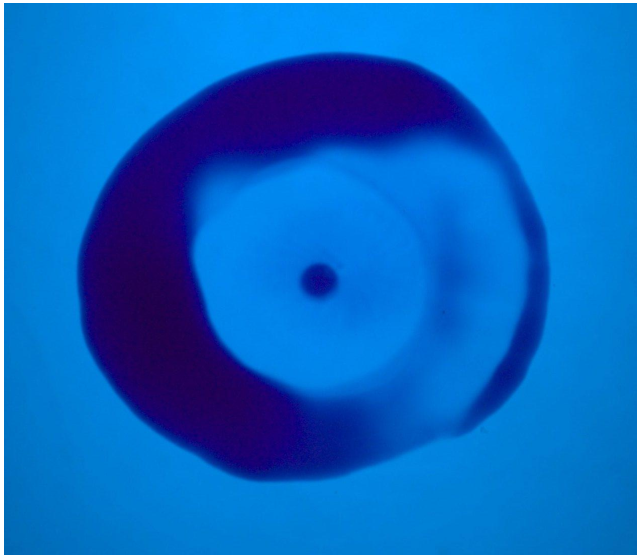



Teardrops
Jellyfish/Annular
-1/3
10^0
10^{-1}
α
10^1
10^2
10^3
10^4
Ai

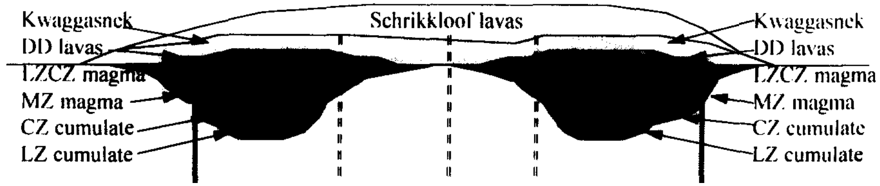


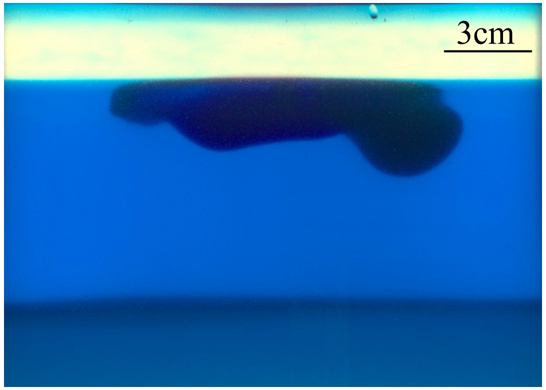
Buried outline
Rustenburg Layered Suite
Transvaal Sequence
100 km
Northern lobe
c
Transvaal domes
Far Western lobe
b
Eastern lobe
PK
FF
CDM
Western lobe
Johannesuburg
Bethal lobe
24°
26°
26°
27°
28°
29°
30°
b)
Depth [km]
10
20
30
Domes
RST ρ=3.0 g cm-3
Transvaal ρ=2.7-2.8 g cm-3
c)
Mokopane
Depth [km]
0
3
6
9
12
0
60
120
Distance [km]

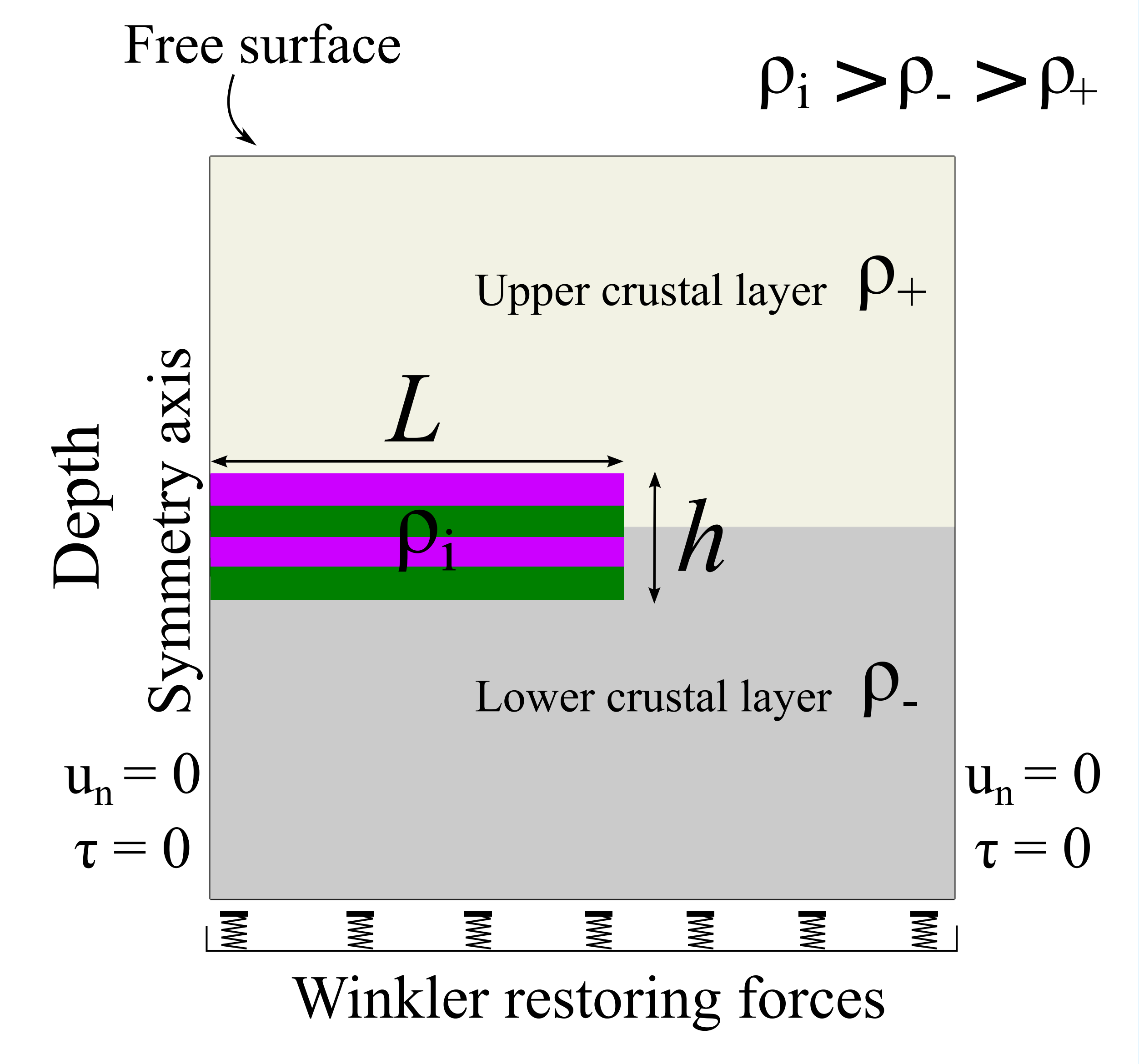




Idealized cross-section



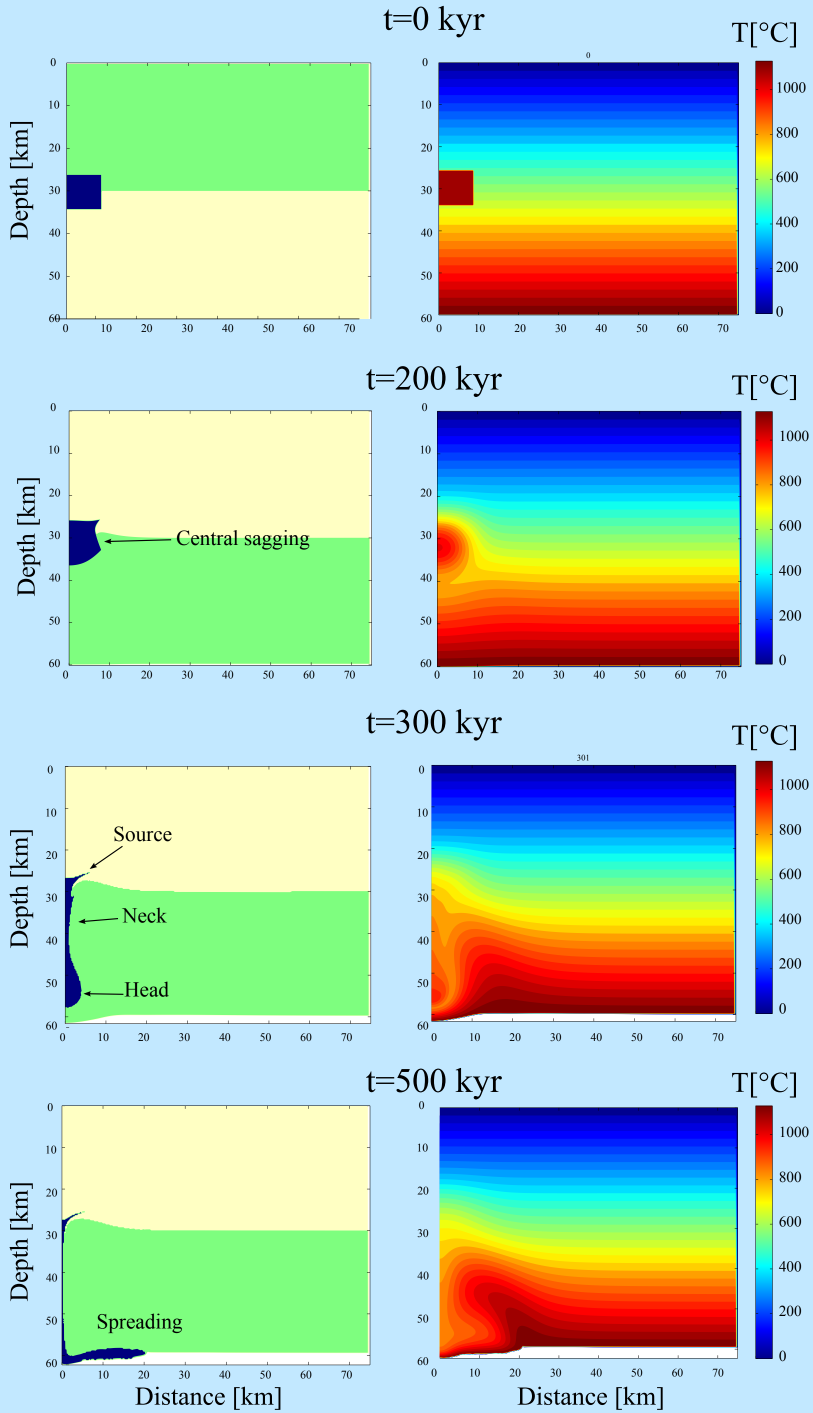




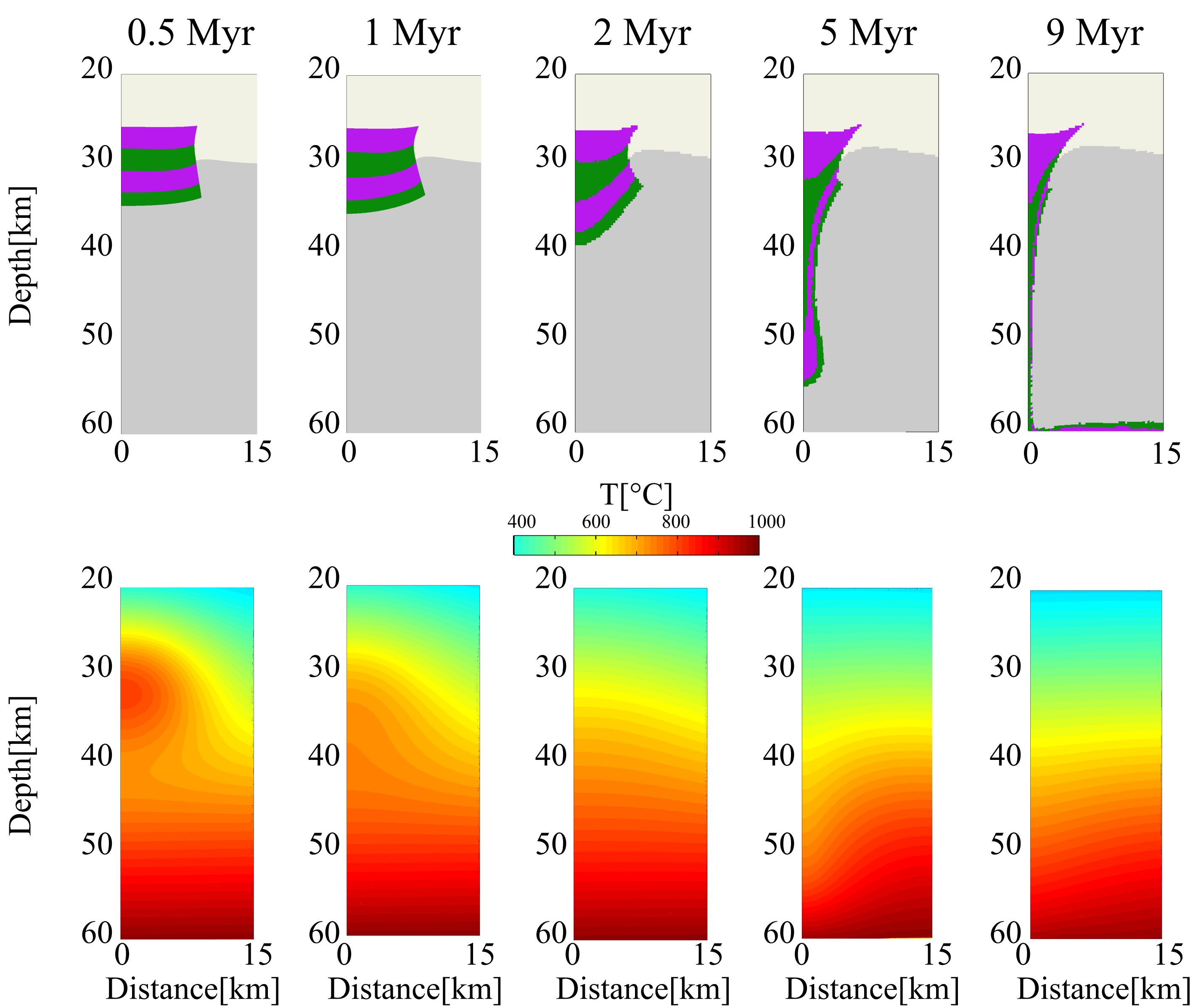
Free surface
ρi > ρ- > ρ+
Upper crustal layer ρ+
L
ρi
h
Depth
Symmetry axis
Lower crustal layer ρ-
un = 0
τ = 0
un = 0
τ = 0
Winkler restoring forces

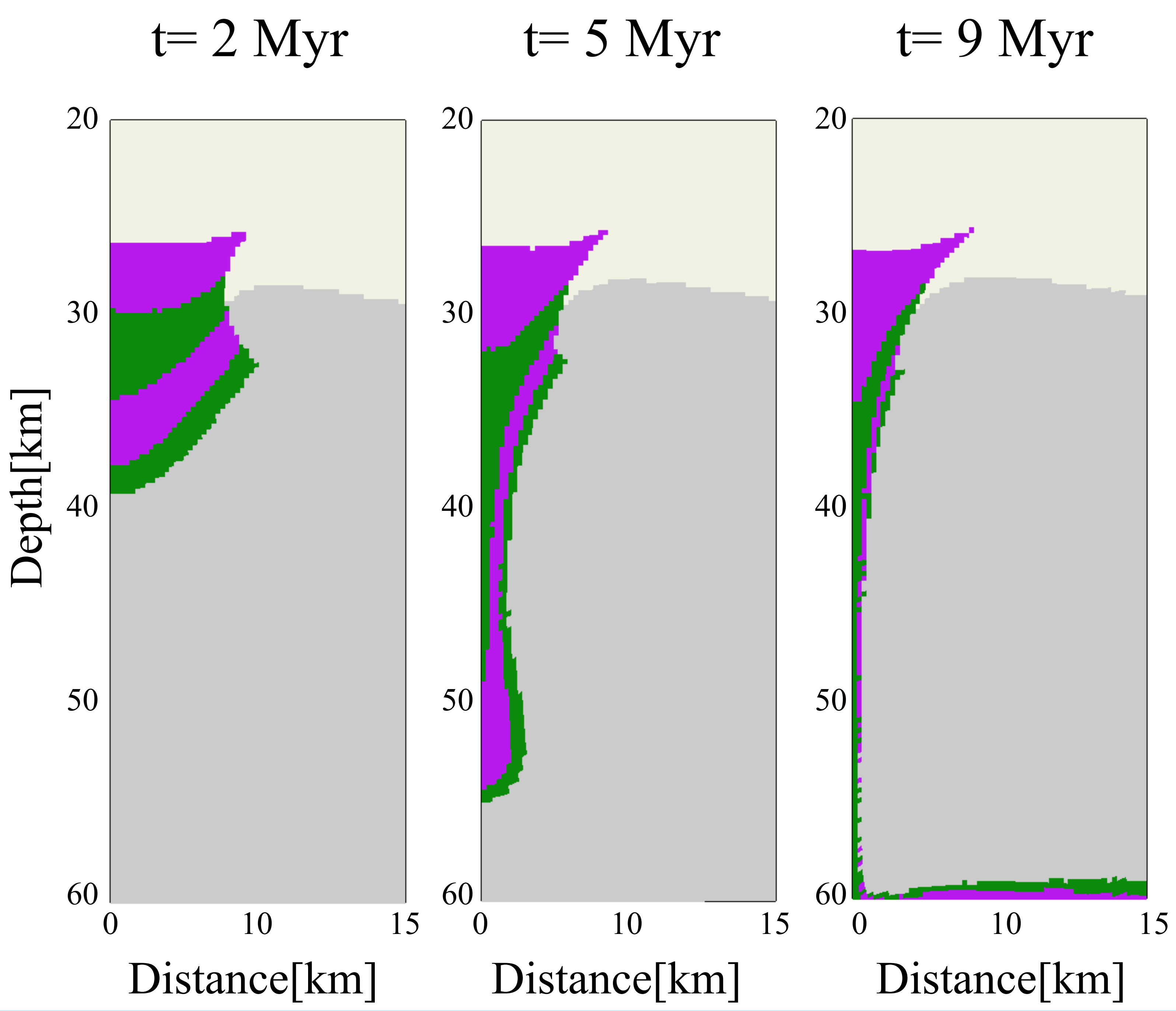
Sinking regime:

very small residual volume at original emplacement depth

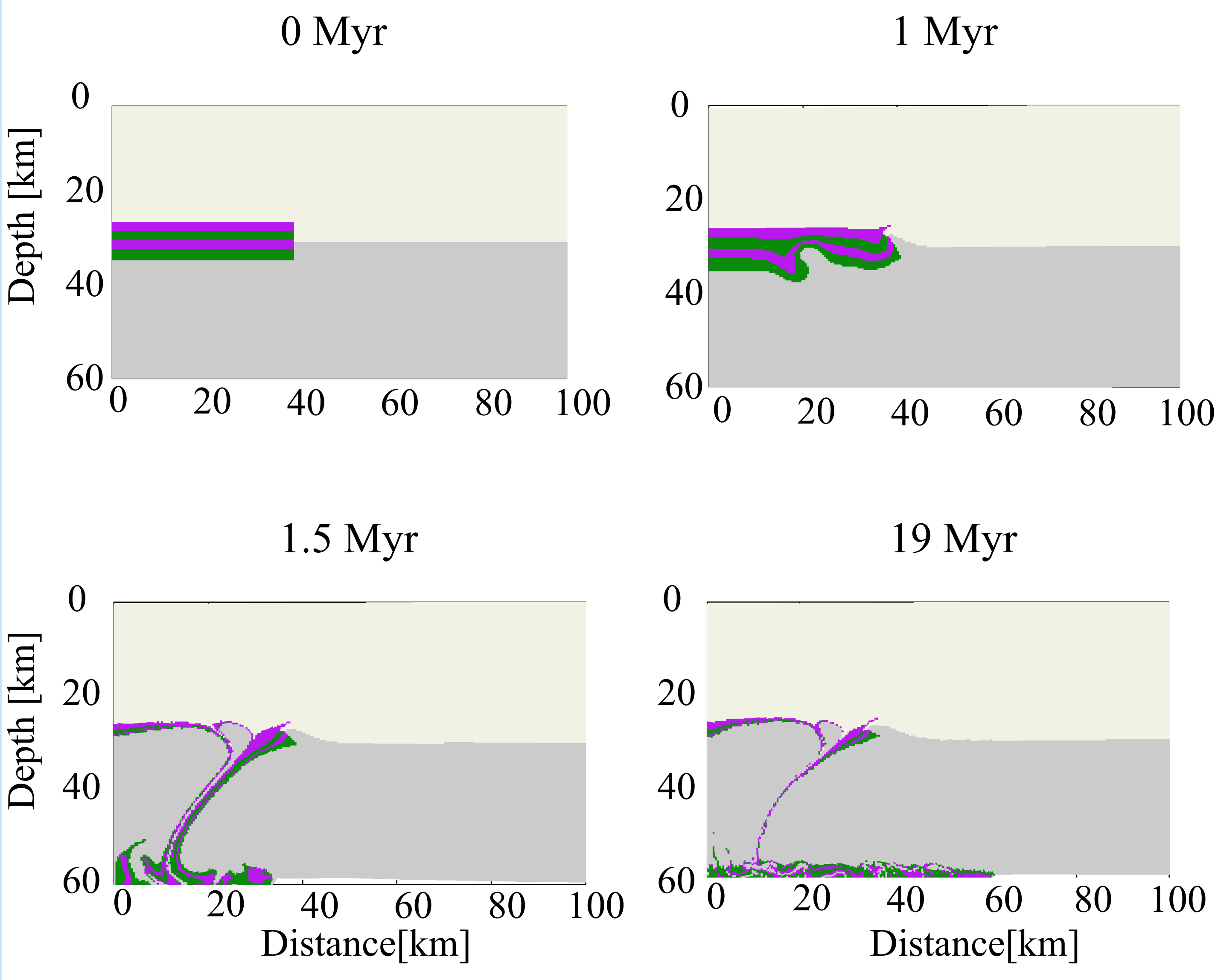


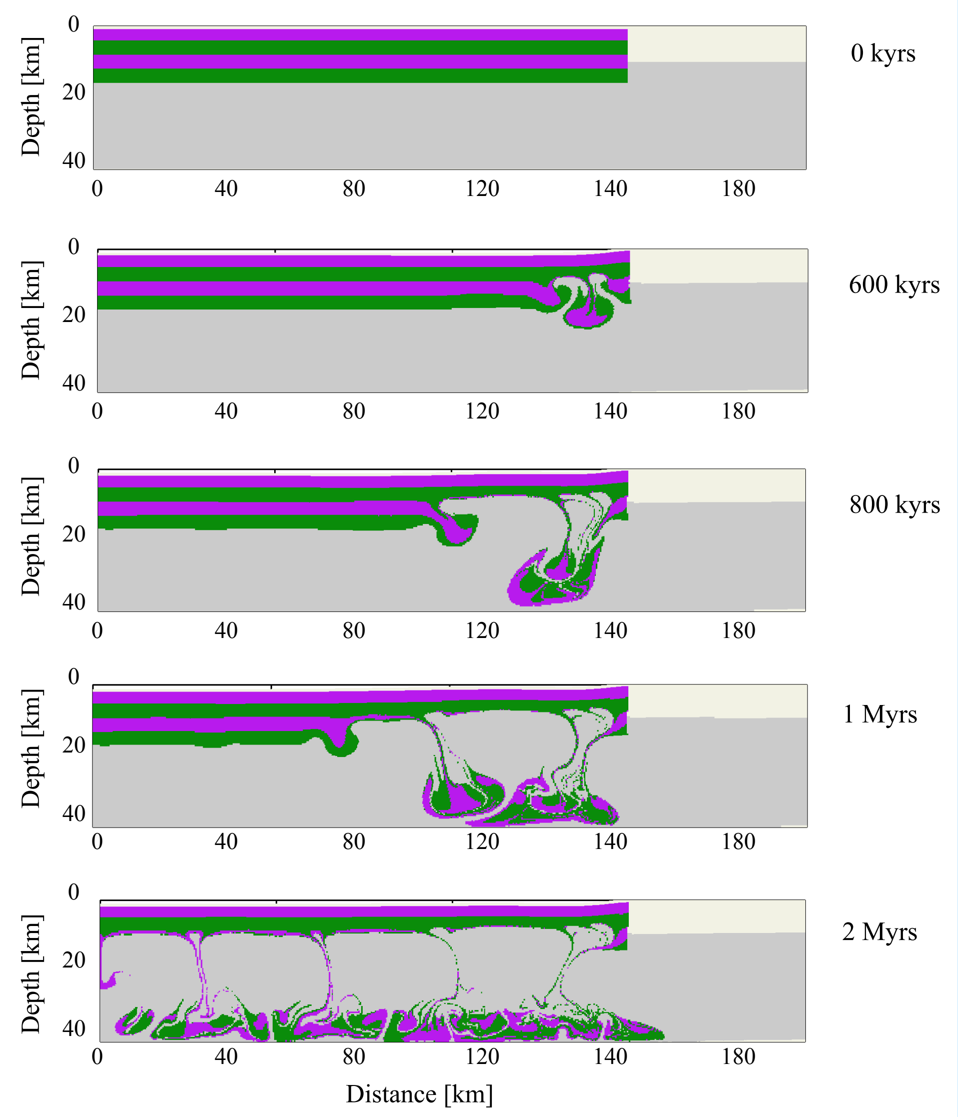
Residual intrusion regime:
large volume left at original emplacement level BUT intrusion strongly deformed



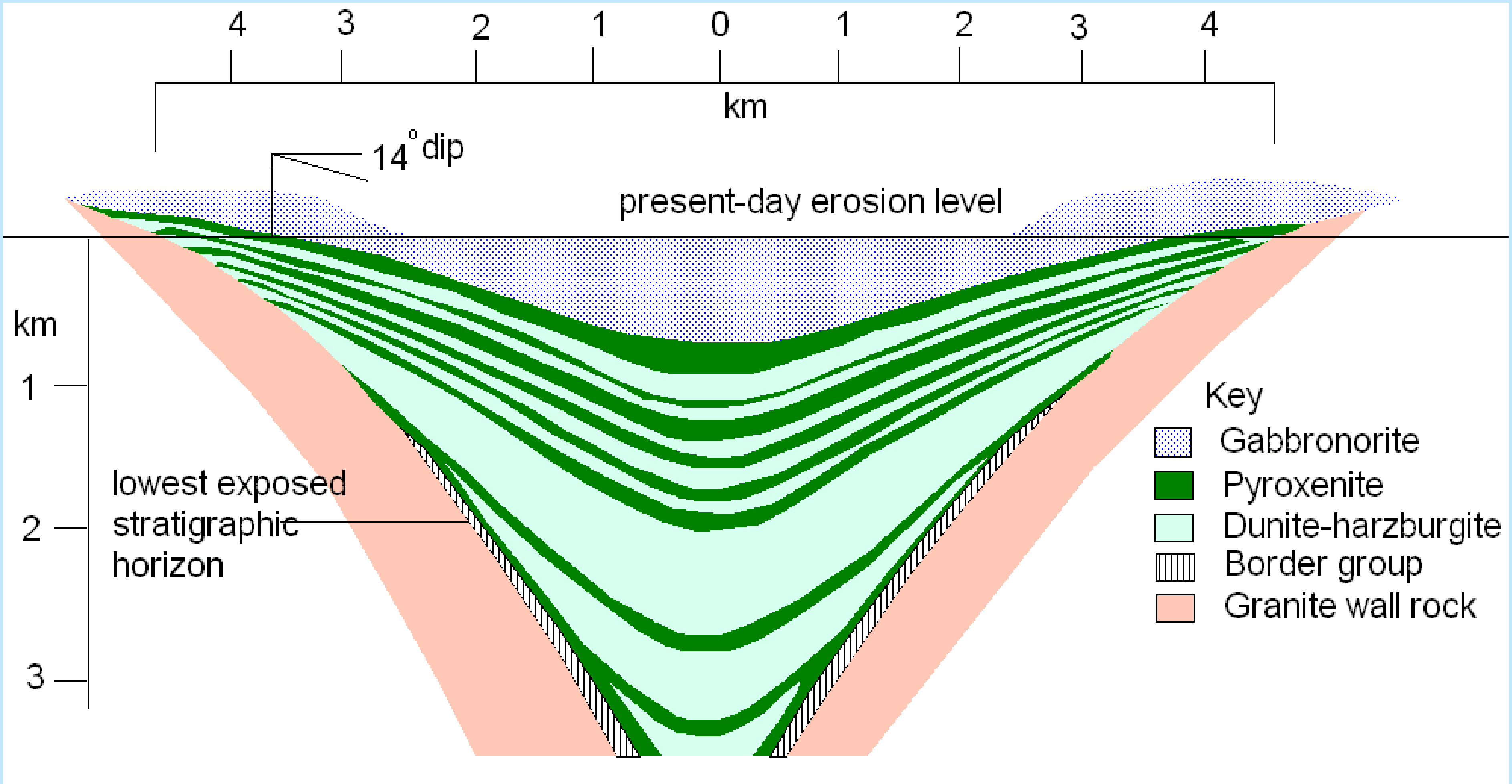

t= 2 Myr
t= 5 Myr
t= 9 Myr
Depth[km]
20
30
40
50
60
0
10
15
Distance[km]

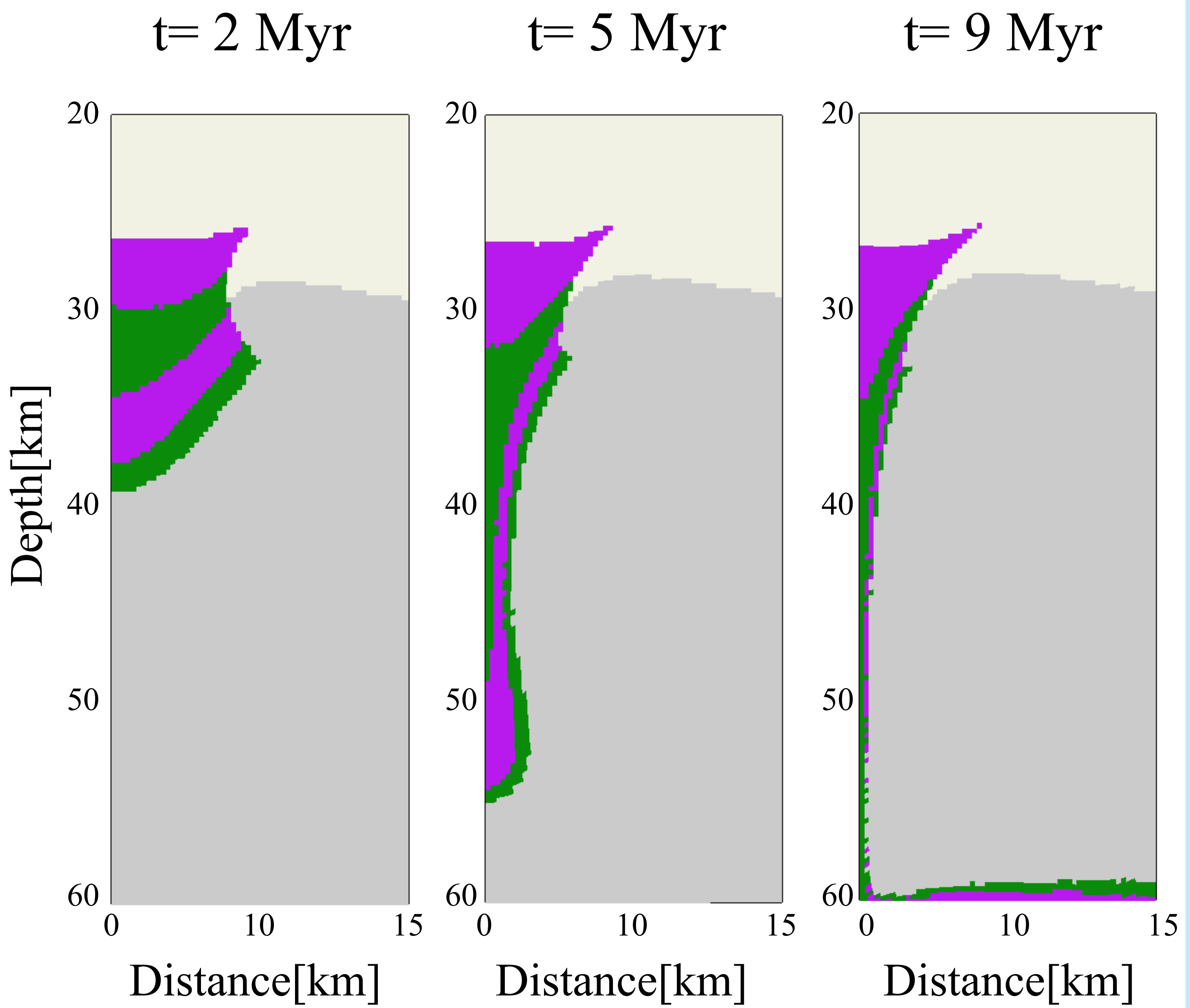
Foundering proceeds differently depending on intrusion aspect ratio



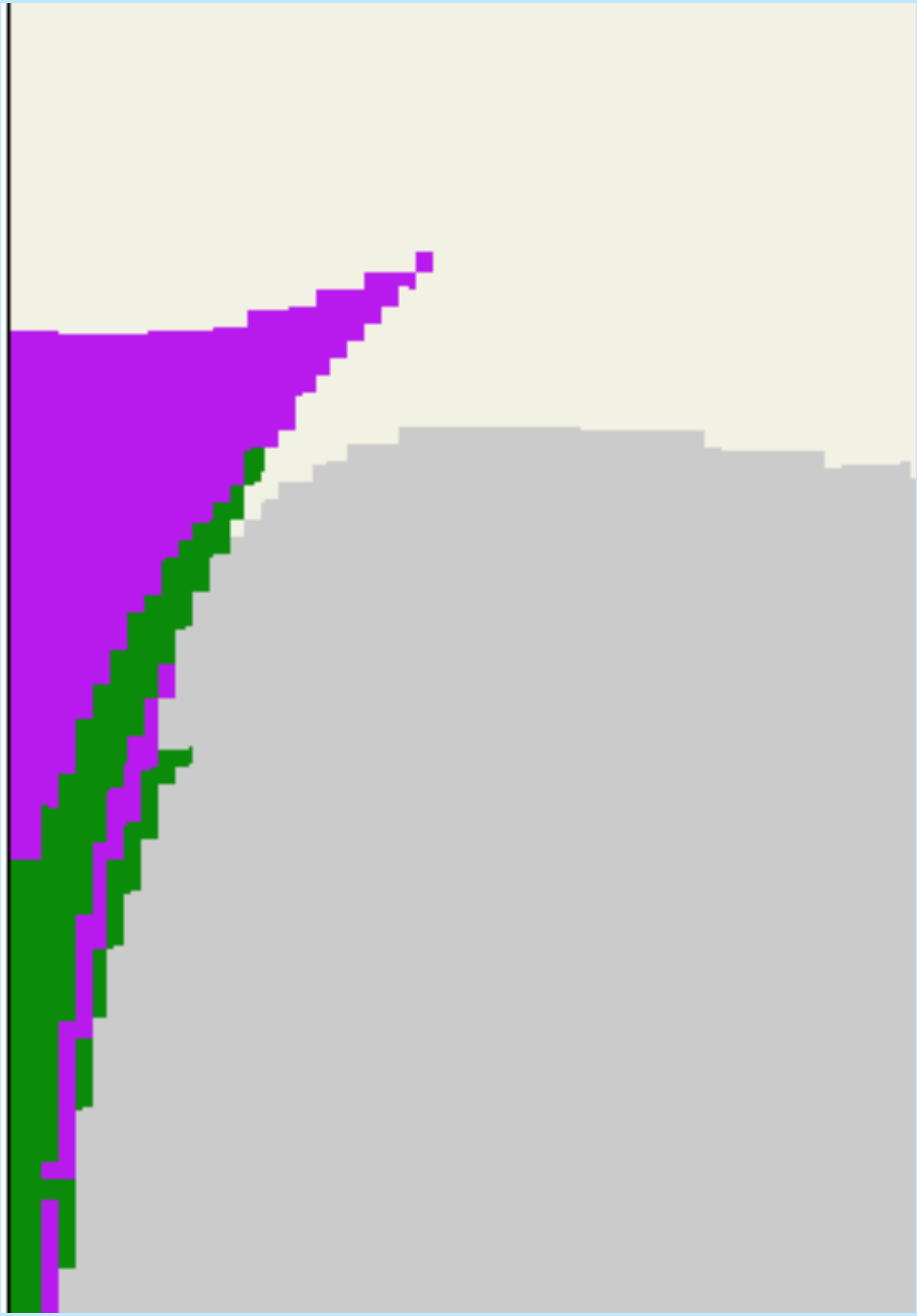


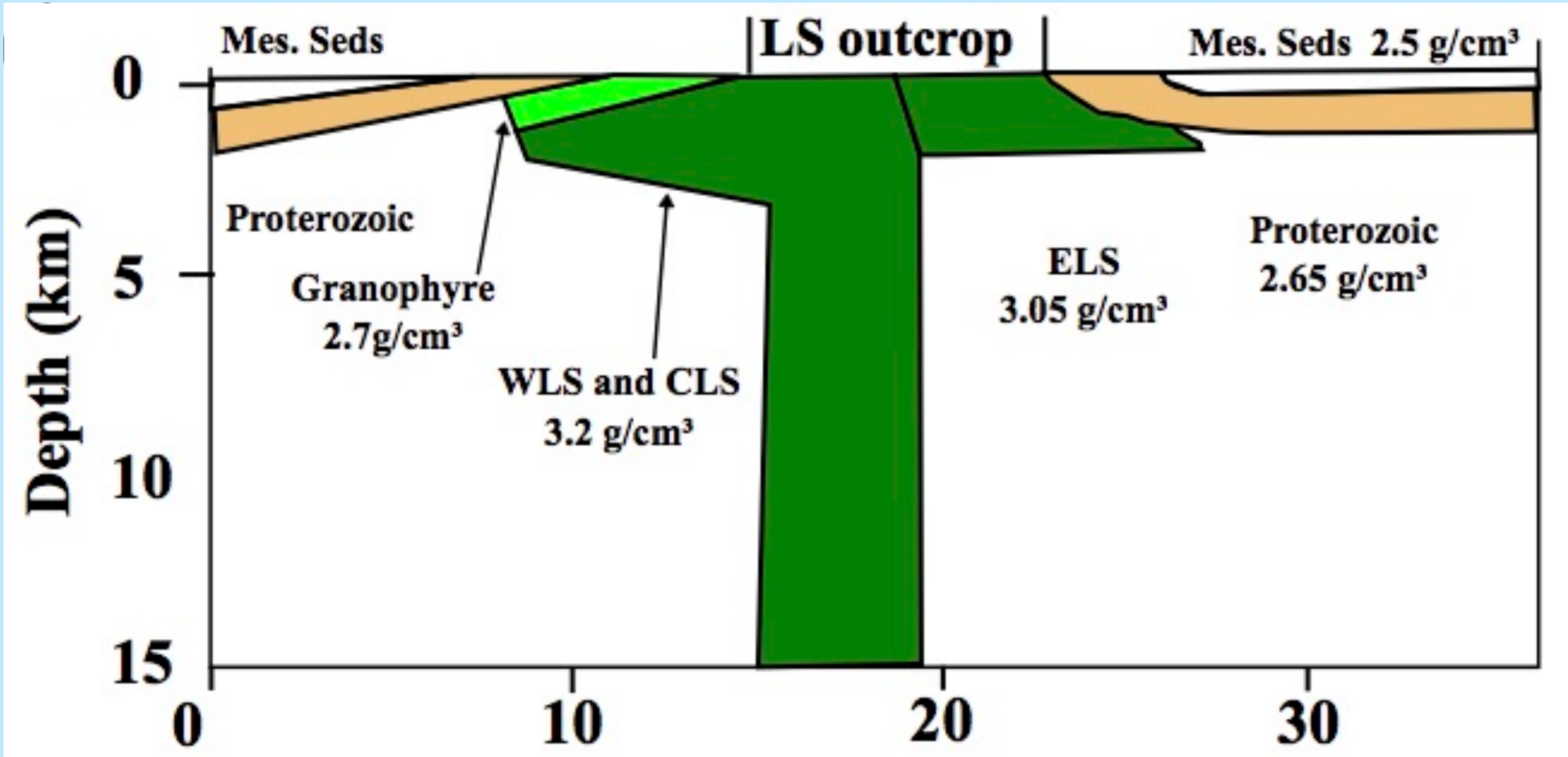
0 kyrs
600 kyrs
800 kyrs
1 Myrs
2 Myrs
Depth [km]
0
20
40
0
40
80
120
140
180
Distance [km]

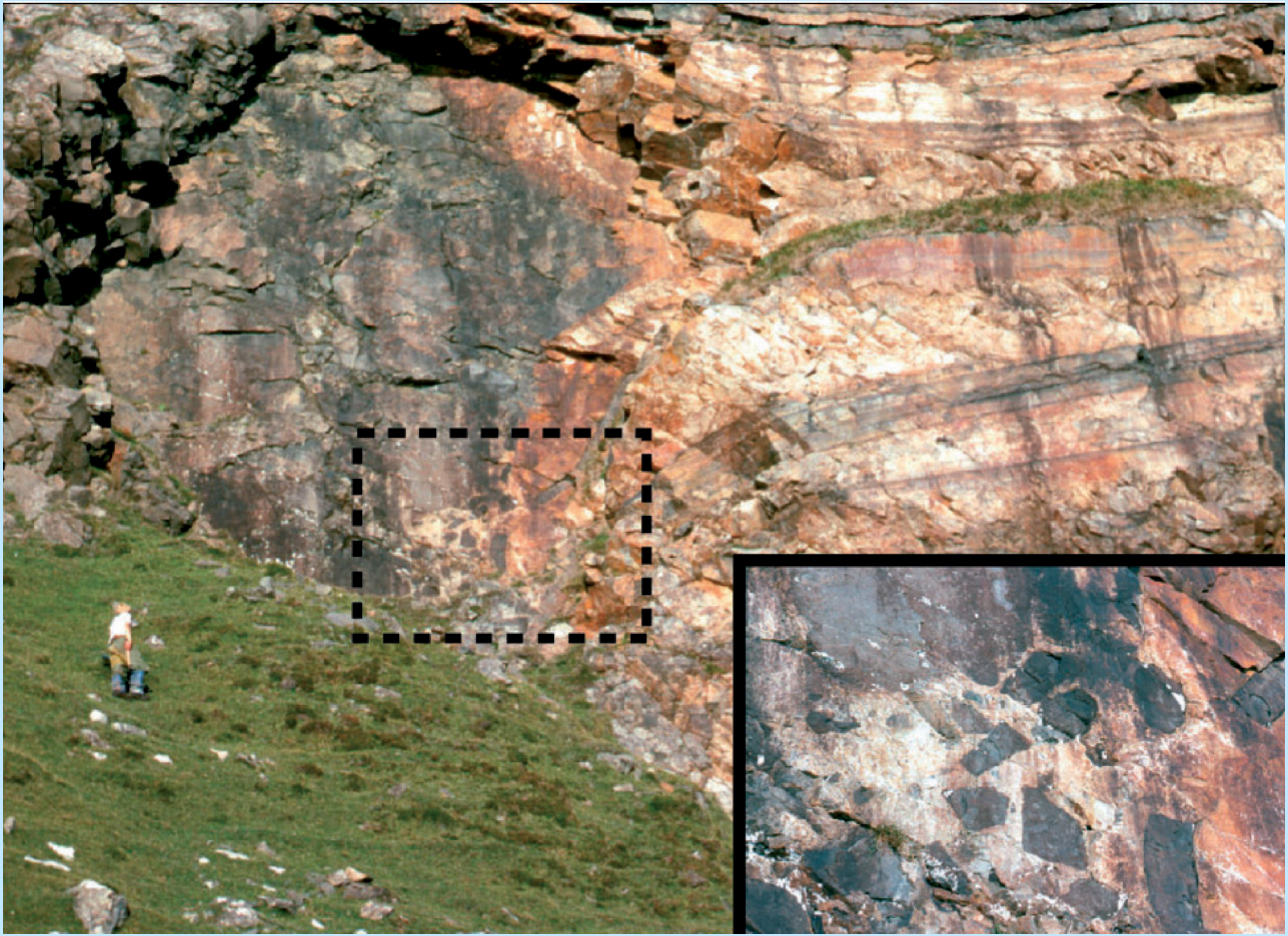

4 3 2 1 0 1 2 3 4
km
14° dip
present-day erosion level
km
1
2
3
lowest exposed stratigraphic horizon
Key
Gabbronorite
Pyroxenite
Dunite-harzburgite
Border group
Granite wall rock

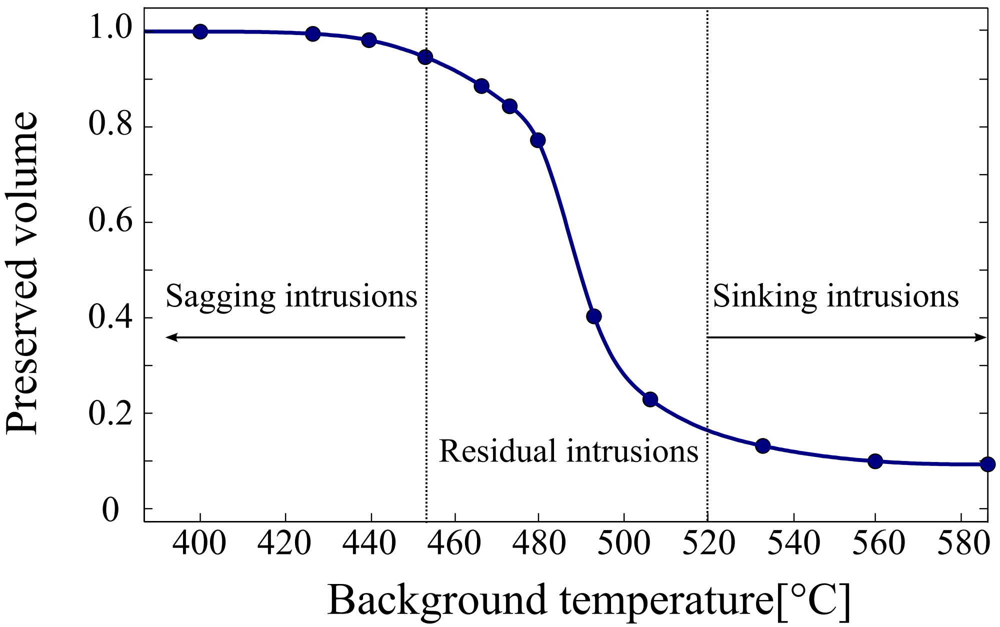


t= 2 Myr
t= 5 Myr
t= 9 Myr
Depth[km]
20
30
40
50
60
0
10
15
Distance[km]



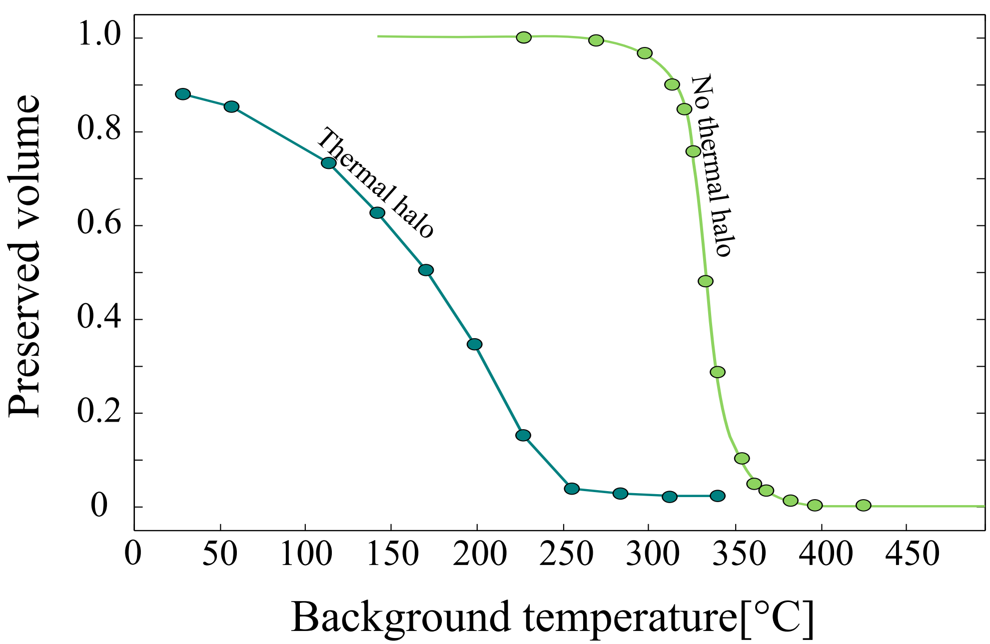

Mes. Seds
LS outcrop
Mes. Seds 2.5 g/cm³
0
5
10
15
Depth (km)
Proterozoic
Granophyre
2.7g/cm³
WLS and CLS
3.2 g/cm³
ELS
3.05 g/cm³
Proterozoic
2.65 g/cm³
0
10
20
30





Preserved volume
Background temperature[°C]
Sagging intrusions
Residual intrusions
Sinking intrusions
0
0.2
0.4
0.6
0.8
1.0
400
420
440
460
480
500
520
540
560
580

b)



Preserved volume
Background temperature[°C]
Thermal halo
No thermal halo
0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
400
450