Water movements in frozen soils

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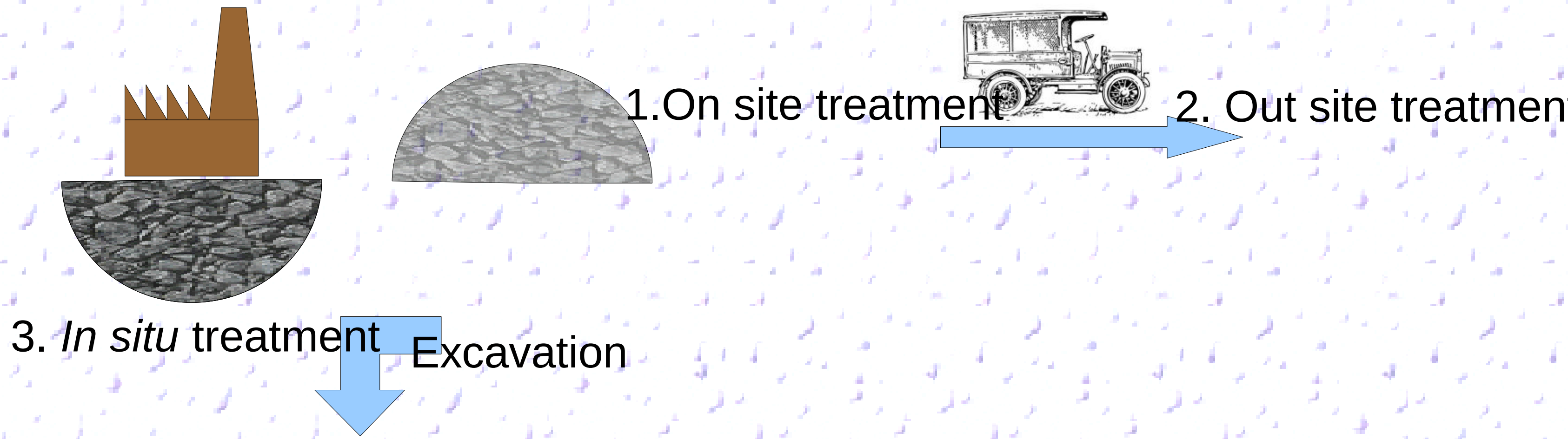

- Physical
- Chemical
- Biological
- ...

- Ventilation
- Biological treatment
- Thermal desorption
- ...

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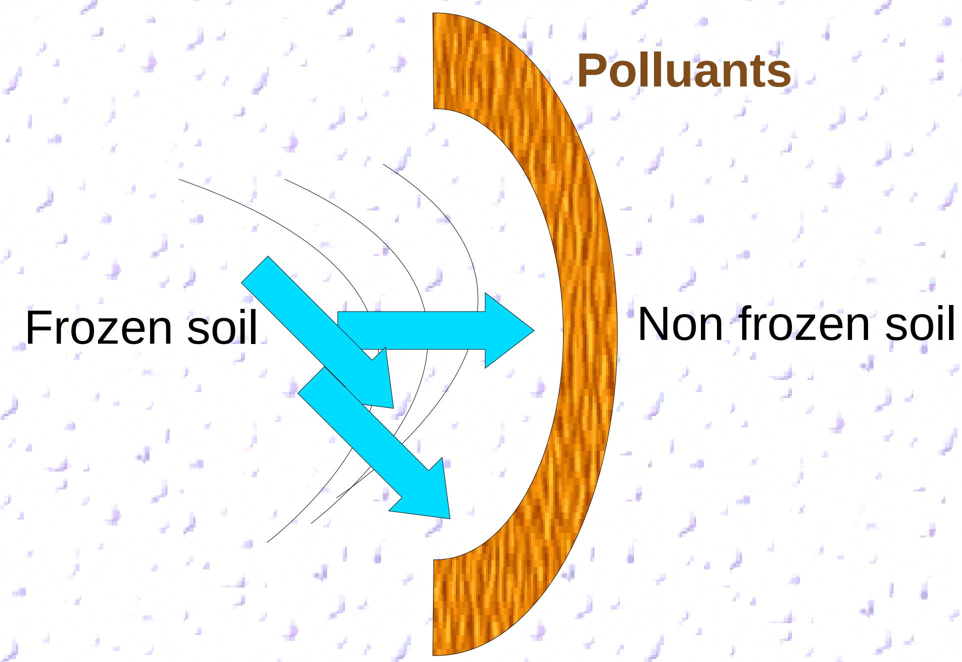
- Slow freezing
- Moving freezing front
- Displacement of impurities, polluants
- Concentration of polluants, impurities in reduced soil volumes



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Heat and mass transfer : a complex problem

- Coupling between heat, dry air, vapor, water and ice
- Non linear equations
  - Conservation
  - Transport
- Huge number of state variables and equations (pde!)
- There is liquid water at temperature lower than 0°C
- Bad knowledge of the microscopical phenomena
- Many parameters value required (direct measurement not always possible or easy)

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Hypothesis

- Local thermal, physical and chemical species and phases equilibrium
- Pores are spherical and are homogeneously filled by the ice
  - The behaviour of the frozen porous media is the one of a usual porous media whose porosity and permeabilities depend on the ice content
- Air and water vapor are perfect gas
- Transport is diffusive (Darcy, Fick)
- Non deformable porous dry soil

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Model structure : three fluids and two solids model

- 5 species:
  - Liquid water
  - Water vapor
  - Ice
  - Solid dry soil
  - Dry air
- State variables
  - Liquid and gases: pressure, density, temperature
  - Ratio of frozen water
  - ...

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Mass conservation for each specie i

$$\frac{\partial r_i}{\partial t} + div(w_i) = a_i$$

Water conservation

$$a_{el} + a_{es} + a_{eg} = 0$$

Energy conservation

$$\frac{\partial U}{\partial t} + div\left(h_a w_a + h_{eg} w_{eg} + h_{el} w_{el} + q\right) = 0$$

Energy balance

$$U = r_a u_a + r_{el} u_{el} + r_{eg} u_{eg} + r_{es} u_{es} + r_m u_m$$

Liquid water flow (Darcy)

$$v_{el} = \frac{w_{el}}{\rho_{el}} = -k_l grad(p_{el})$$

Water vapor and air flows (Darcy+Fick)

$$v_i = \frac{w_i}{\rho_i} = -k_g grad(p_g) - \frac{p_g}{p_i} Df\, grad\left(\frac{p_i}{p_g}\right)$$

Conductive heat flux (Fourier)

$$q = -\lambda grad T$$

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Air and water vapor are perfect gases

$$p_i = \frac{\rho_i R T}{M_i}$$

Thermodynamical gas-liquid equilibrium (Clapeyron)

$$p_{el} = p_{atm} + \rho_{el}\frac{RT}{M_e}\ln\left(\frac{p_{eg}}{p_{eg}^{sat}(T)}\right)$$

Mechanical gas-liquid equilibrium (Kelvin-Laplace + empirical)

$$S_l' = exp^{(-\alpha\chi^{\beta})}$$

$$p_c = p_g - p_{e'} = 2\sigma(T)\chi$$

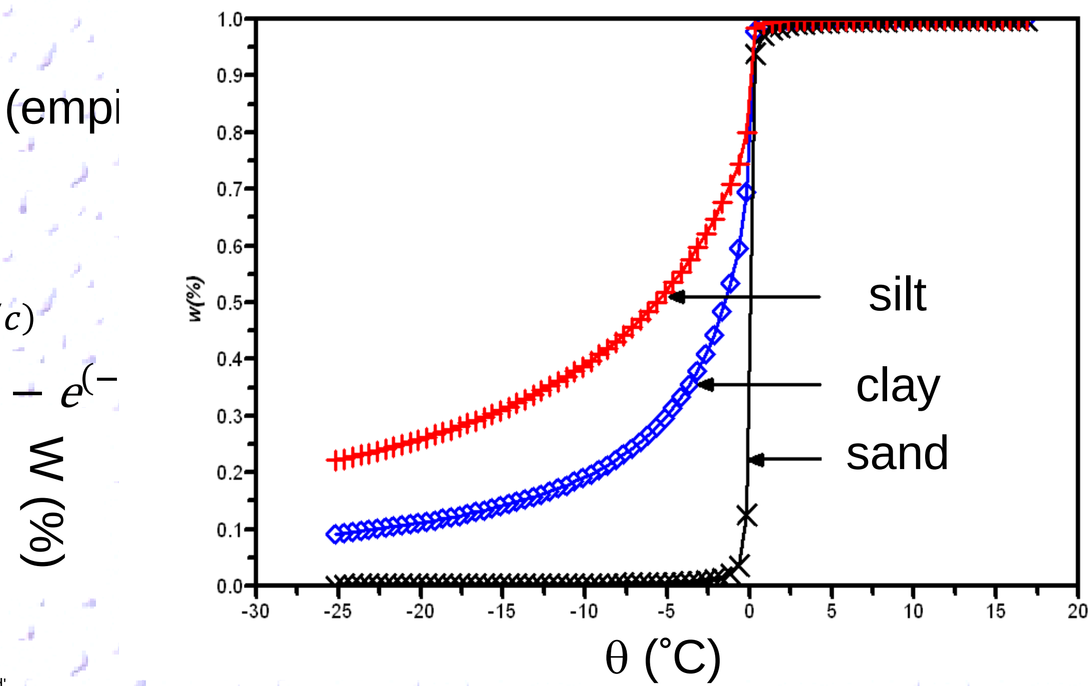
Ice content versus temperature (empi

$$\text{si}\,\theta < 0\, alors\, \omega' = a\, e^{(\theta/c)}$$

$$si\,\theta > 0\, alors\, \omega' = b + (1-b)\big(1 - e^{(-}$$

$$où\,\theta = T - 273{,}15$$

Liquid water concentration in soils



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Water superficial stress

$$\sigma = 0{,}2358(1-T^*)^{1{,}256}\left(1-0{,}625(1-T^*)\right) \quad T^* = T/T_c \quad T_c = 647{,}096K$$

Liquid and gas permeabilities

$$k_l = \frac{k k_{rl}}{\mu_l} \qquad k_{rl} = \sqrt{S_l'}\left(1-\left(1-S_l'^{1/m}\right)^m\right)^2$$

$$k_g = \frac{k k_{rg}}{\mu_g} \qquad k_{rg} = \sqrt{S_l'}\left(1-S_l'^{1/m}\right)^{2m}$$

Water vapor partial pressure

$$\ln p_{eg}^{sat}(T) = 68{,}148 - \frac{7214{,}64}{T} - 6{,}2973\,lnT$$

Equivalent conductivity

$$\lambda = \lambda_m^{1-\Phi}\lambda_{es}^{\Phi'-\Phi}\lambda_{el}^{\Phi' S_l'}\lambda_g^{\Phi' S_g'}$$

+ closing equation

Control volume method
Scilab implementation

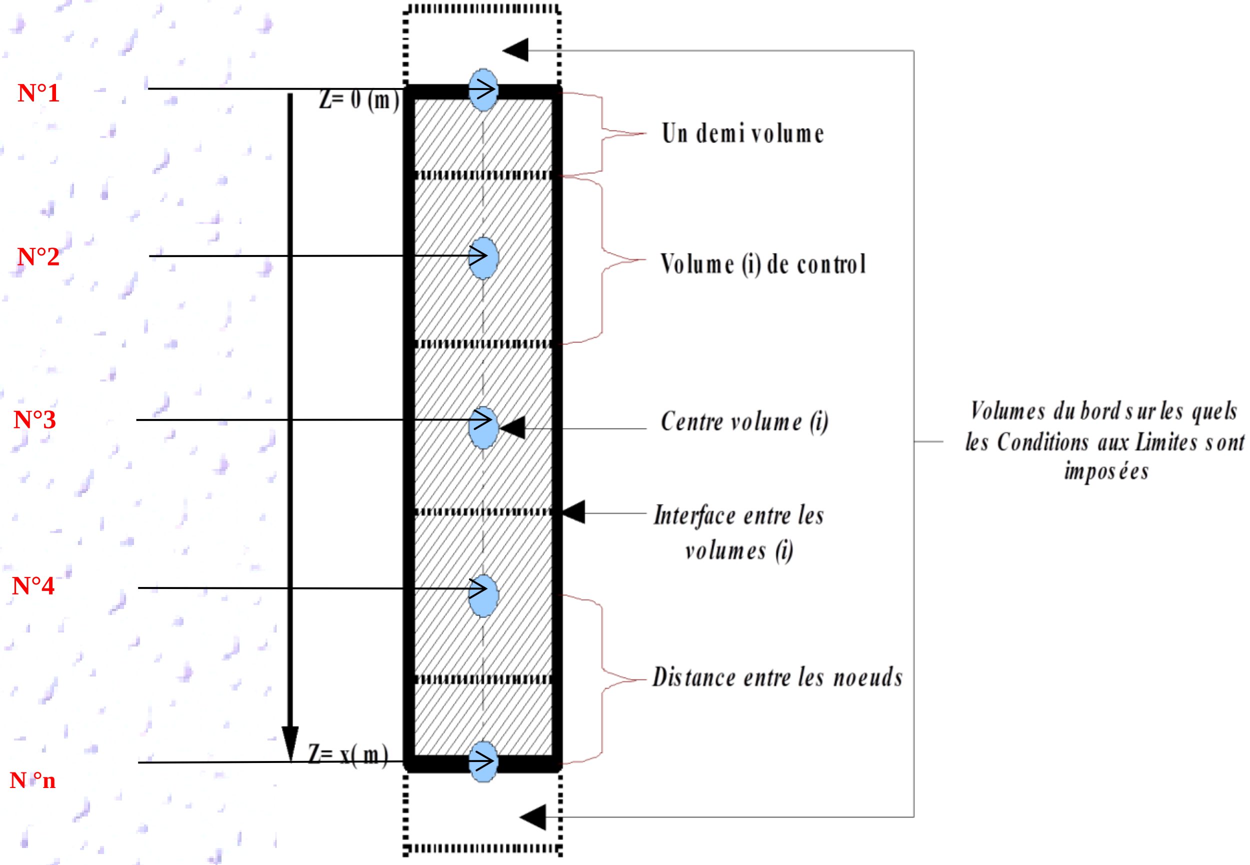

Figure (2) maillage uniforme

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Homogeneous soil : clay

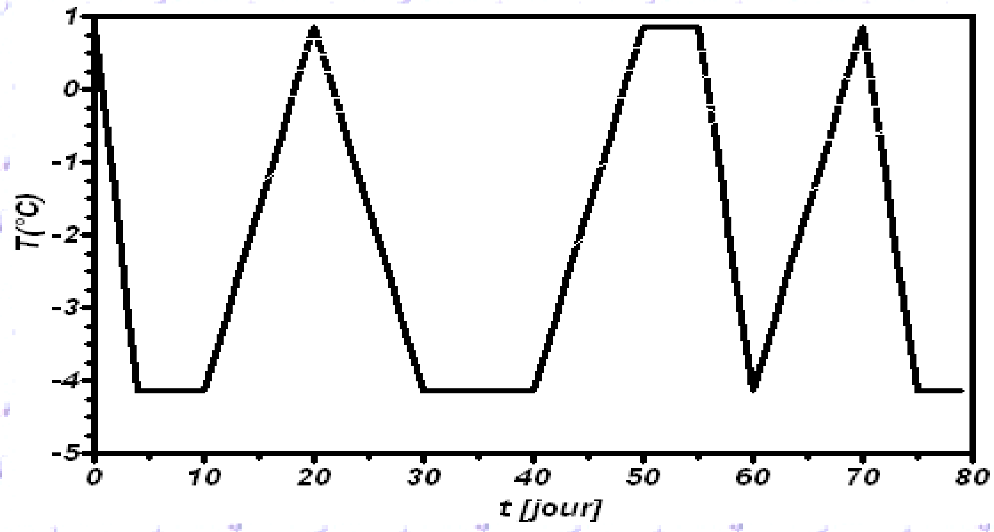

Figure (3) Evolution de la température imposée en surface du sol

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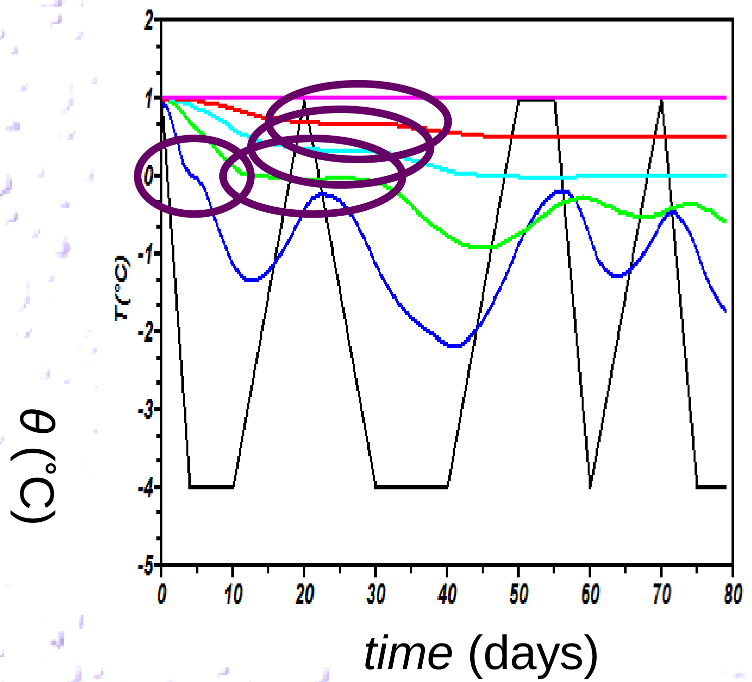
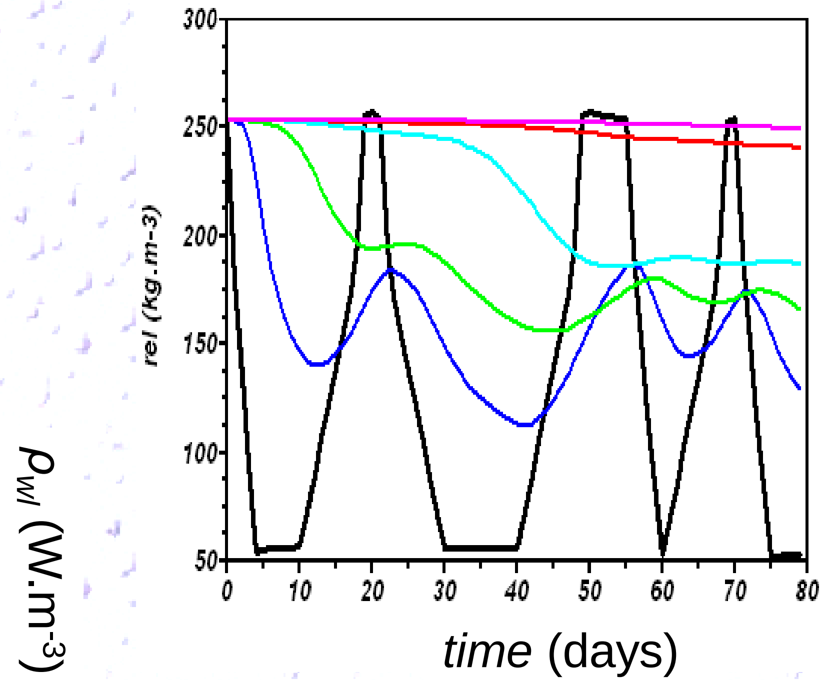
Top (node 1)
0.2m (node 3)
0.4m (node 5)
0.6m (node 7)
0.8m (node 9)
1 m (node 11)

Soil temperature evolution



Liquid water apparent density ev



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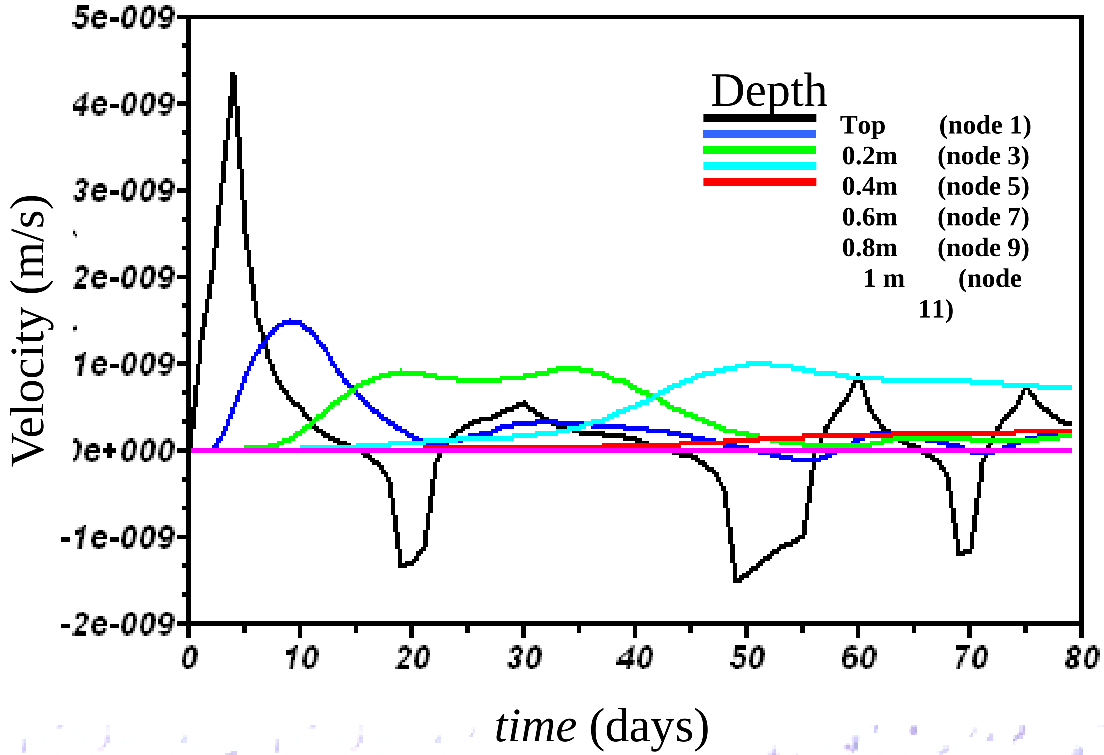
Apparent liquid water velocity evolution



Bottom-up velocity 4.6 10^{-9} m/s
Water flow 4.6 10^{-9} (
Every day 0.4 10^{-3} (
Every 5 days 2 10^{-3} (

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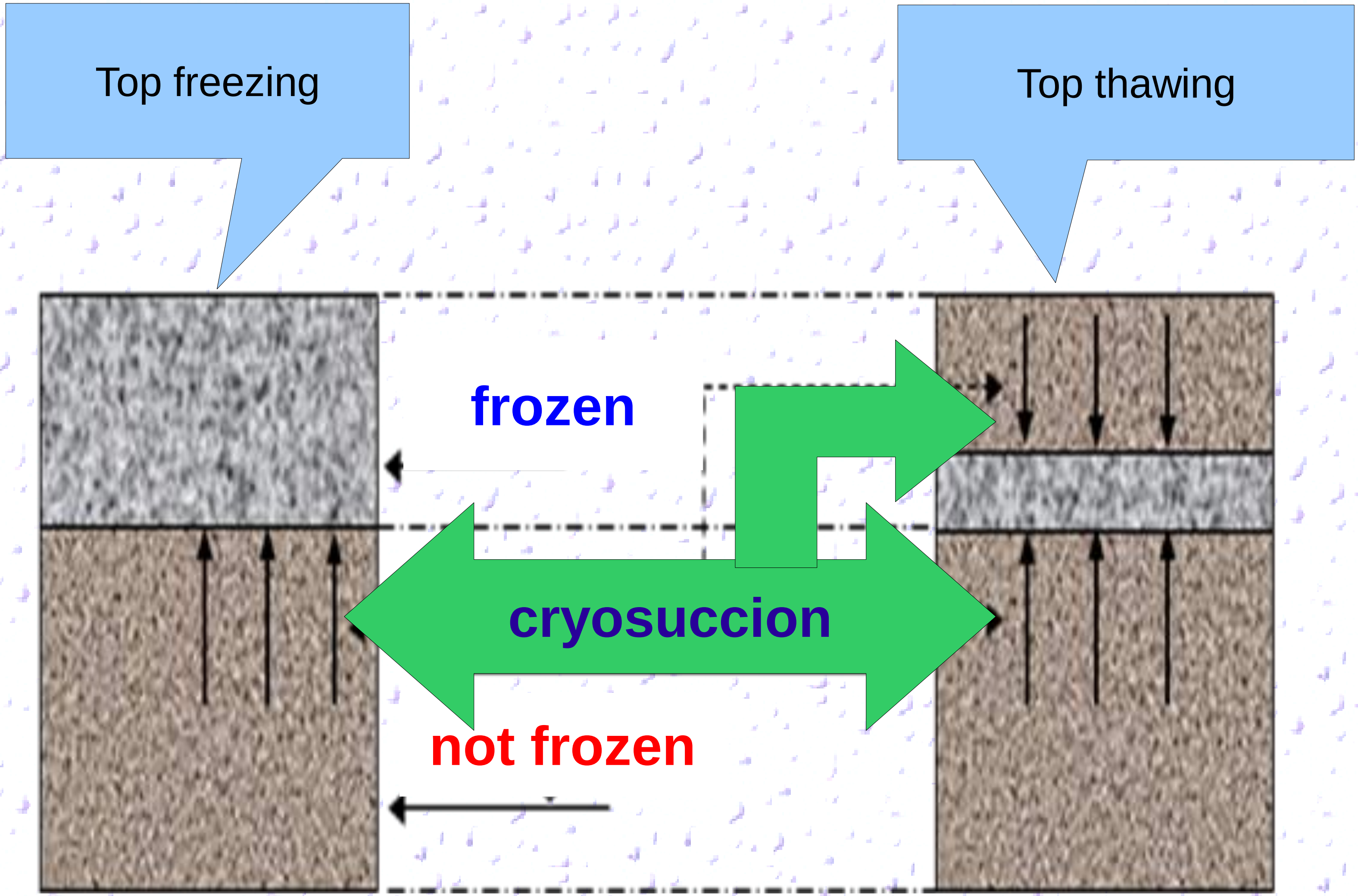
Top freezing
Top thawing
frozen
cryosuccion
not frozen