# Influence of pore space reduction upon freezing on the electrical and seismic properties of permafrost

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ALPINE CRYOSPHERE AND GEOMORPHOLOGY

## MOTIVATION

We extended an existing model (4-phase model; Hauck et al. 2011, Pellet et al. 2016, Mewes et al. 2017), which calculates the ice-, water- and air content of the subsurface from electric and seismic data sets to its time-lapse variant and improved its electrical mixing rule formulation. In time-lapse formulation, the model is not anymore dependent on time-invariant properties such as porosity, pore water resistivity (if assumed constant), cementation exponent and P-wave velocity of the rock material. Temporal ground ice content changes can then be calculated from repeated electrical resistivity tomography (ERT) and refraction seismic tomography (RST) data sets. In addition, the electrical mixing rule for the frozen state was improved by taking into account the reduced pore space available for ionic conduction to take place.

The time-lapse and improved 4-phase model formulation should now be able to quantify more accurately the loss of ground ice in the context of ongoing climate change. A further application is the use of the model in joint inversion of ERT and RST measurements in permafrost context (Mollaret et al. 2018, EUCOP).

## NEW 4PM FORMULATION

**1** Modification of Archie's Law in the 4PM context

Archie: $\rho=\rho_w\Phi^{-m}S^{-n}$

NEW: $\boxed{\rho=\rho_w(\Phi-f_i)^{-m}\left(\frac{f_w}{\Phi-f_i}\right)^{-n}}$

**2** Time-lapse variant of the 4-phase model
(see also Hauck et al. 2017)

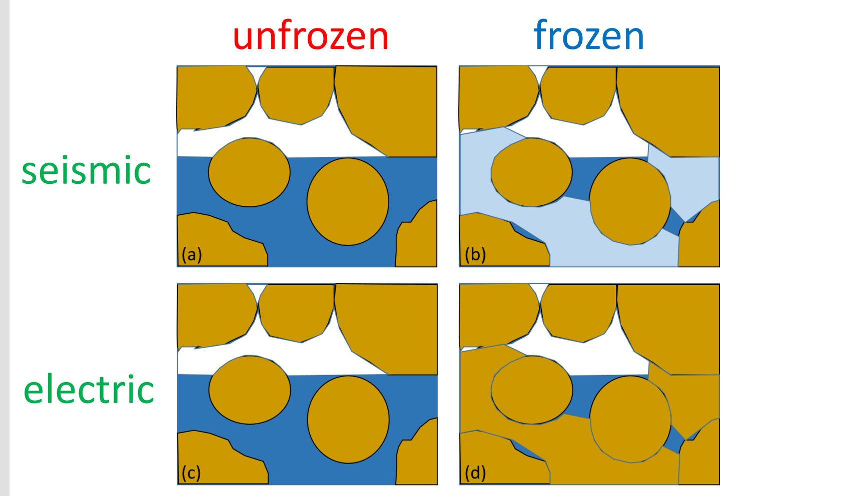
① $\rho_{1,2}=\rho_w\left(\Phi-f_{i;1,2}\right)^{-m}\left(\frac{f_{w;1,2}}{\Phi-f_{i;1,2}}\right)^{-n}$

② $\frac{1}{v_1}-\frac{1}{v_2}=\frac{f_{i1}-f_{i2}}{v_i}+\frac{f_{w1}-f_{w2}}{v_w}+\frac{f_{a1}-f_{a2}}{v_a}$

③ $\Delta f_i+\Delta f_w+\Delta f_a=0$

$$\boxed{\Delta f_i=\frac{v_a-v_i}{v_a v_i}\left(\frac{v_1-v_2}{v_1 v_2}-\Delta f_w\frac{v_a-v_w}{v_w v_a}\right)}$$

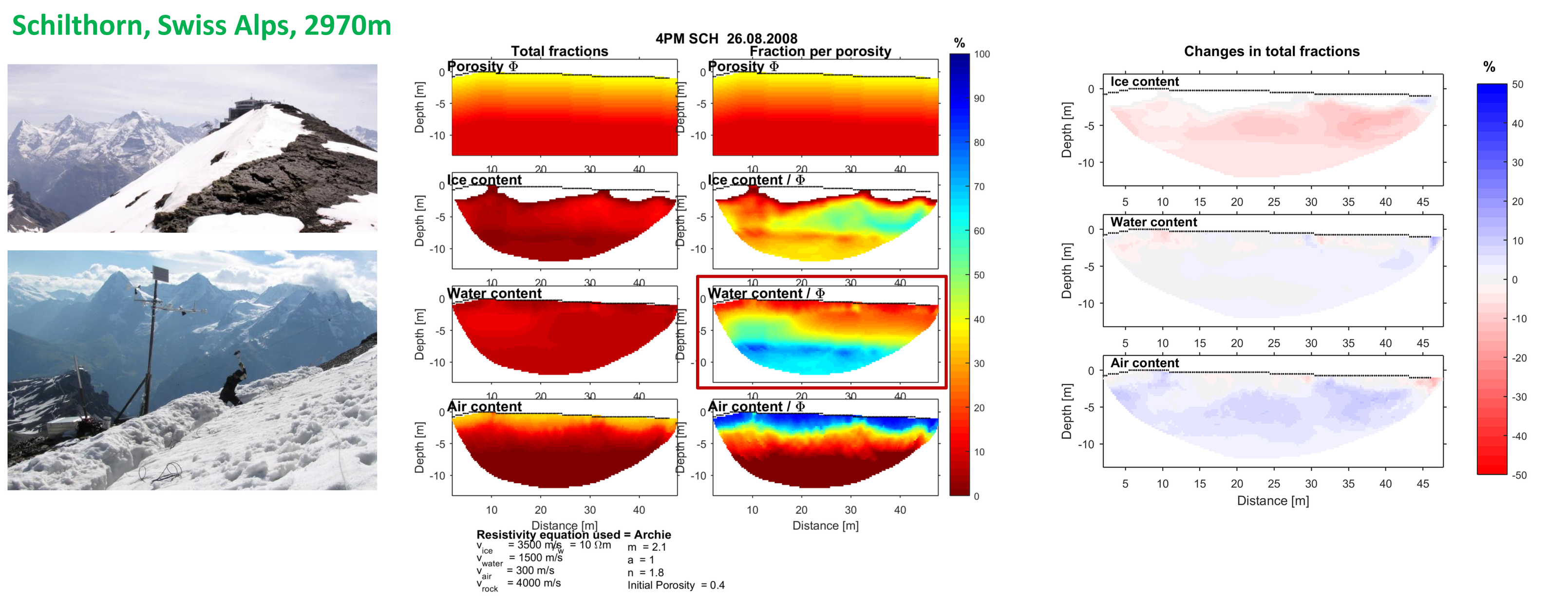
$\rho$ = inverted specific resistivity
$\rho_w$ = pore water resistivity
$\Phi$ = porosity
m, n = cementation/saturation exponent
$f_{i,w,a}$ = ice/water/air content
$_{1,2}$ = measurements at time $t_1$, $t_2$
$\Delta f_i$ = ice content change between $t_2$ and $t_1$



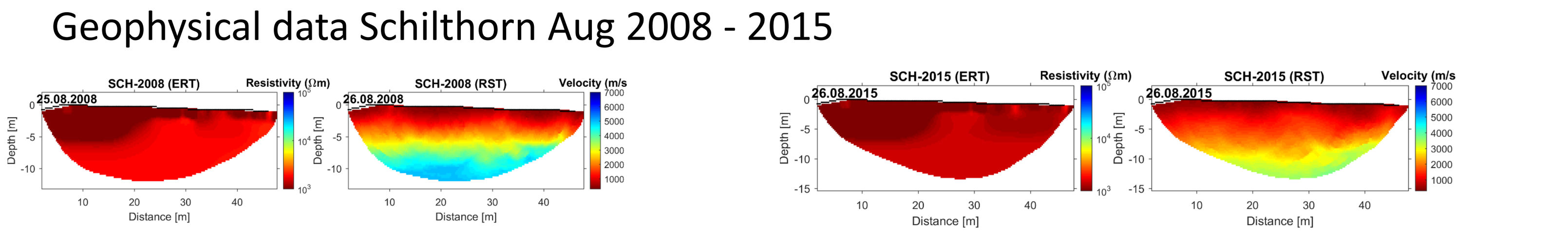

Conceptual model for (a) the seismic mixing rule in unfrozen state, (b) the seismic mixing rule in partly frozen state, (c) the electrical model in unfrozen state and (d) the Archie-type electrical model in partly frozen state.

The two modifications help to **(i)** better couple electrical and seismic mixing rules by including **fi in the electrical mixing rule** and **(ii)** reduce the importance of the (only weakly unknown) porosity by calculating ***ice/water content changes***

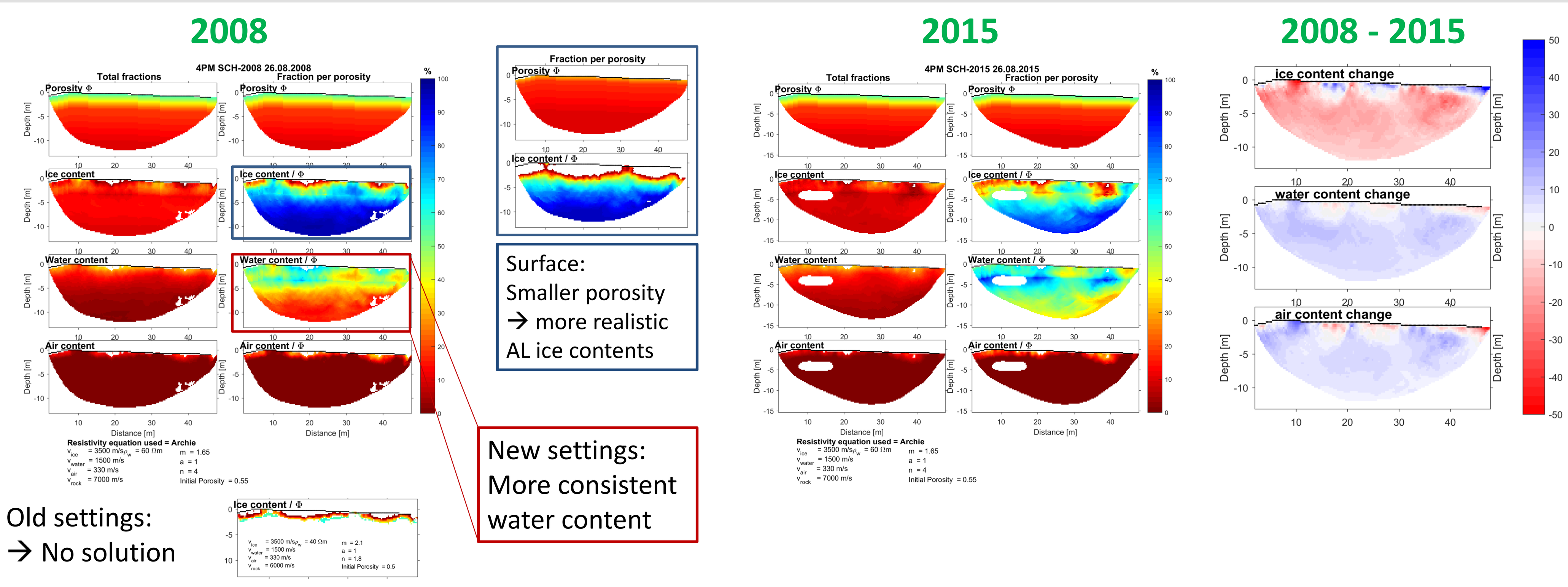
## 1. EXAMPLE SCHILTHORN OLD VERSION




Geophysical data Schilthorn Aug 2008 - 2015



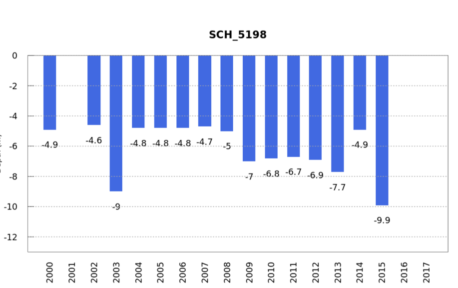

## 2. COMPARISON - NEW VERSION



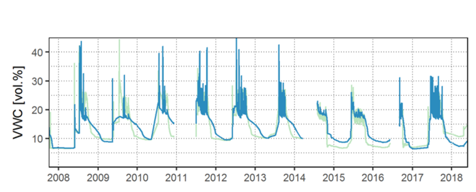

With the new formulation of the 4PM its parameters are less under-determined by the data → on the other hand, it becomes more difficult to find a physically consistent solution for a given data set.

## 3. GROUND TRUTH

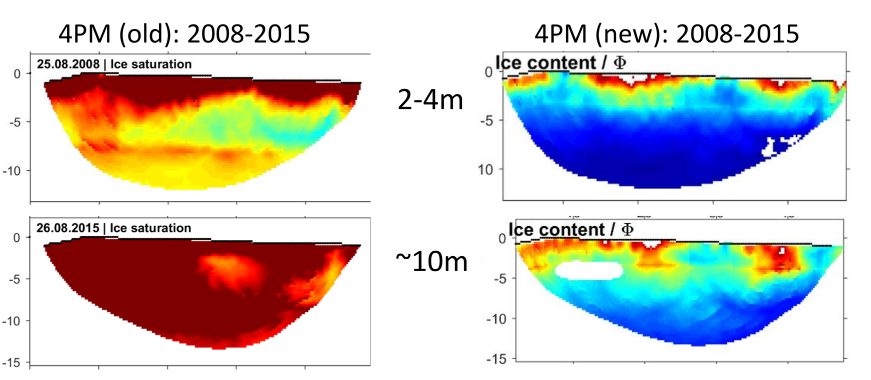
Active layer 2008-2015 | Ground temperature | Soil moisture



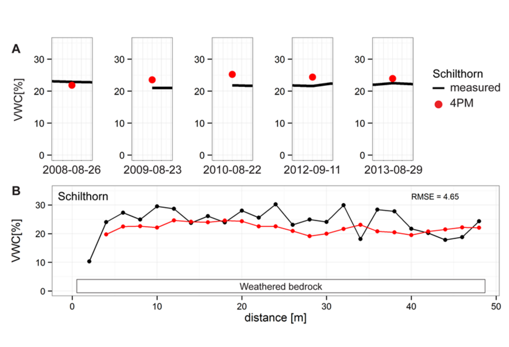

| Thaw depth | 25.08.2008 | 26.08.2015 |
|---|---|---|
| SCH-BH17 | 4-5 m | 5-7 m |



Measured soil moisture at 10 and 30 cm depth

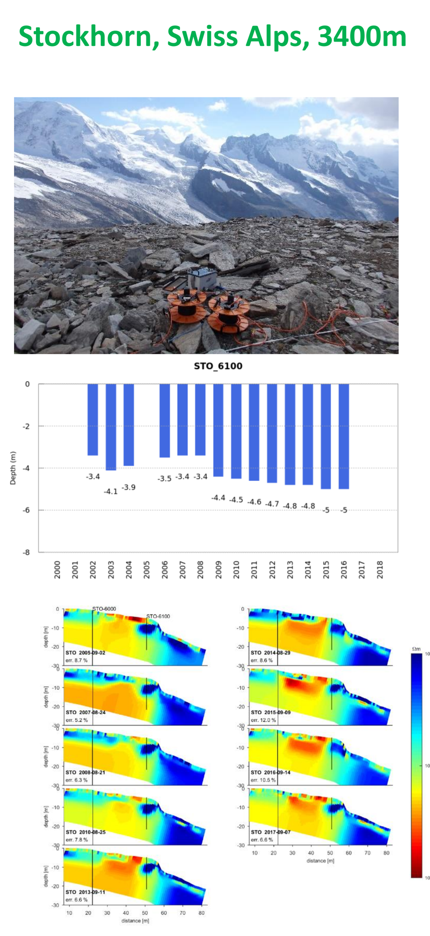


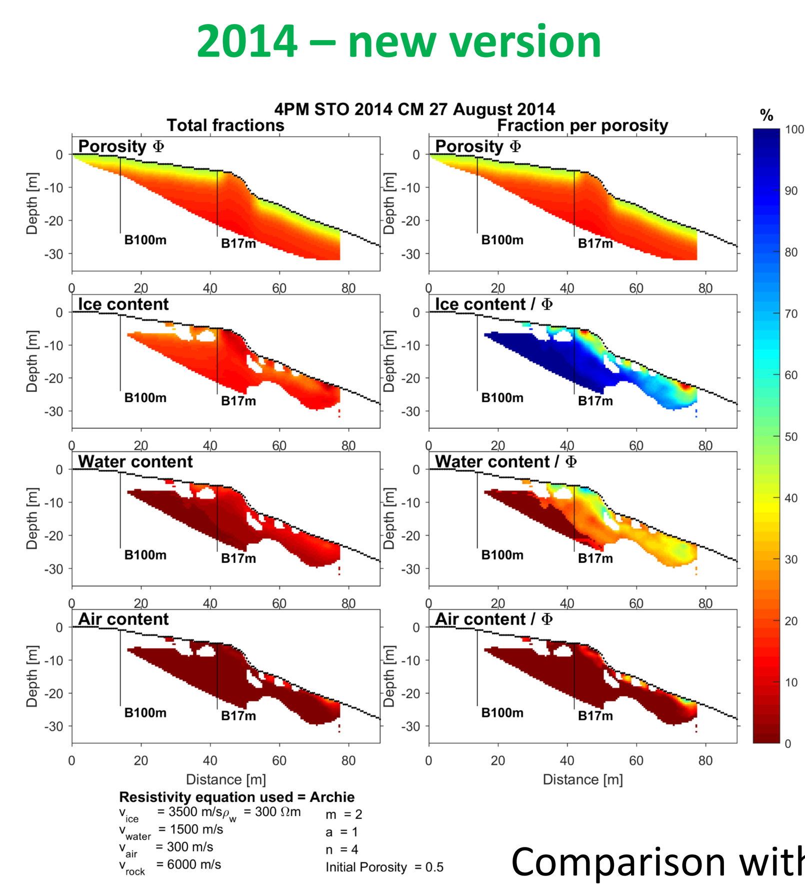

Clear over-estimation of ice saturation in the new version
However, ice saturation maximum is corresponding to ALT

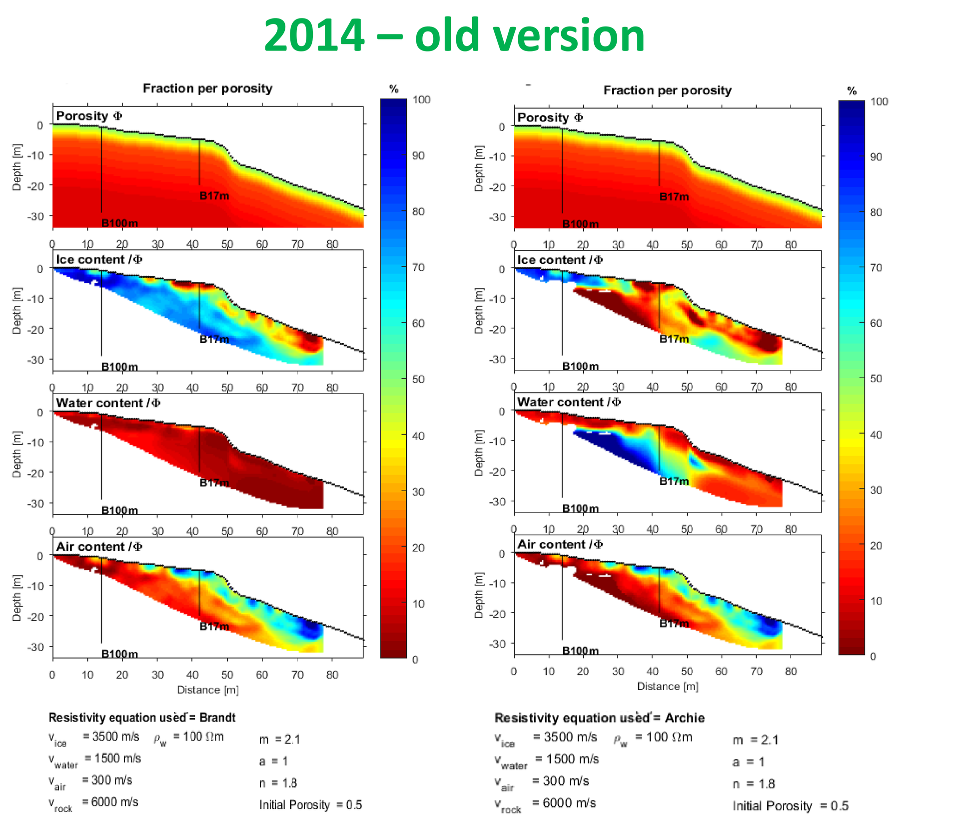


Comparison of measured and 4PM (old) soil moisture in a temporal (top) and spatial (bottom) context

## 4. SECOND EXAMPLE STOCKHORN



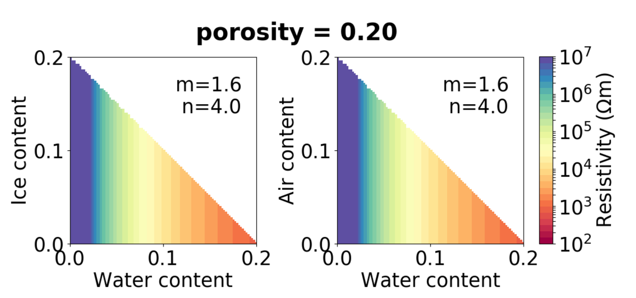




Comparison with old 4PM version: (left) with parameterization of surface conduction and (right) without surface conduction

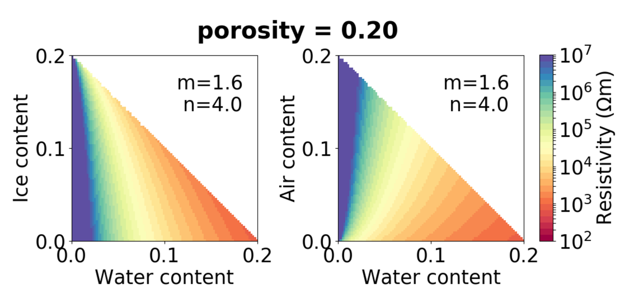
## DISCUSSION

Improvement of electrical mixing law:

- New formulation includes «non-trivial» dependence of resistivity on water content
- previous version/standard Archie's Law: ρ = f (water content)
- now: ρ = f (water content, ice content)




In the old formulation, electrical resistivity depends only on liquid water content




In the new formulation, electrical resistivity depends also on air and ice content (through the coupling with the seismic mixing rule)

Disadvantage:

- More difficult to find a physically-consistent solution
- Needs maybe spatially variable distributions of Archie parameters *n, m*
- Induces mathematical constraints for stable solution: e.g. *m* should not be equal to *n* for ice saturated conditions
- This raises questions of theoretical justification of the approach (see outlook)

## OUTLOOK

- Further tests with geophysical data from very different field sites in the Alps, Andes and Antarctica
- Focus on the connection between the different Archie parameters (saturation and cementation exponents *n, m*) and the link with connectivity and permeability (see e.g. Glover 2010)
- Improvement of the 4PM by including the complex resistivity (newly funded DACH project SIP-ice)
- Implementation in joint inversion approach (pyGIMLI, see Mollaret et al. EUCOP talk)

**References**

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