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The Importance of Anisotropy in Modeling Geothermal Reservoirs

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Introduction

The importance of anisotropy in modelling geothermal reservoirs is demonstrated by taking a theoretical example of a two phase flow situation with an immobile waterphase. An example from the Reykjanes geothermal field shows that pressure drawdown cannot be modelled both for a well in the middle of the production area as well as for an observation well further away without anisotropy. It is then shown that the TOUGH2 model code cannot take anisotropy into account except for two very limited cases. Finally a numerical scheme is introduced for implementing the anisotropy into the TOUGH2 code.

Simulation of two-phase reservoirs

General equations for two-phase reservoir :

$$\frac{\partial}{\partial t}\Big(\phi(\rho_w S_w + (1 - S_w)\rho_s) + \nabla \cdot (\rho_w V_w + \rho_s V_s)\Big) = 0$$

$$\frac{\partial}{\partial t}\Big((1-\phi)\rho_r h_r + \phi S_w \rho_w h_w + (1 - S_w)\rho_s h_s) + \nabla \cdot (\rho_w h_w V_w + \rho_s h_s V_s)\Big) = 0$$

Darcy's Law :

$$\begin{aligned} V_w &= -\frac{k k_w(S_w)}{\mu_w}\nabla p \\ V_s &= -\frac{k k_s(S_w)}{\mu_s}\nabla p \end{aligned}$$

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Simplification for immobile water phase:

$$\frac{\partial}{\partial x}\left(\frac{bk_x}{\nu_x}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{bk_y}{\nu_y}\frac{\partial p}{\partial y}\right) + M = b\rho_s\beta_s\phi\frac{\partial P}{\partial t}$$

$$\beta_s = \frac{\rho_w - \rho_s}{\rho_w\rho_s L}T\frac{(1-\phi)\rho_r C_r + \phi S_w\rho_w C_w}{\phi}$$

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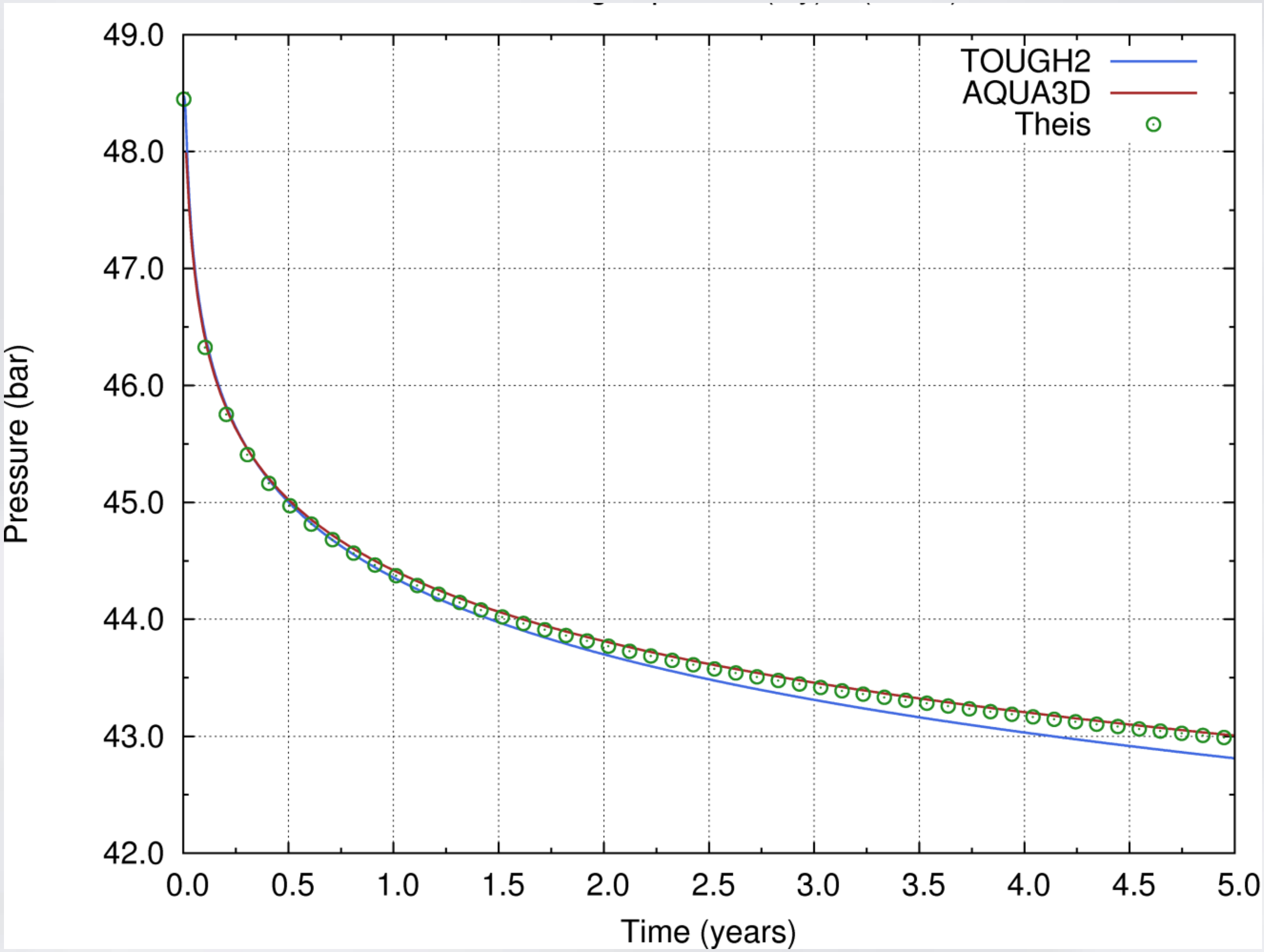
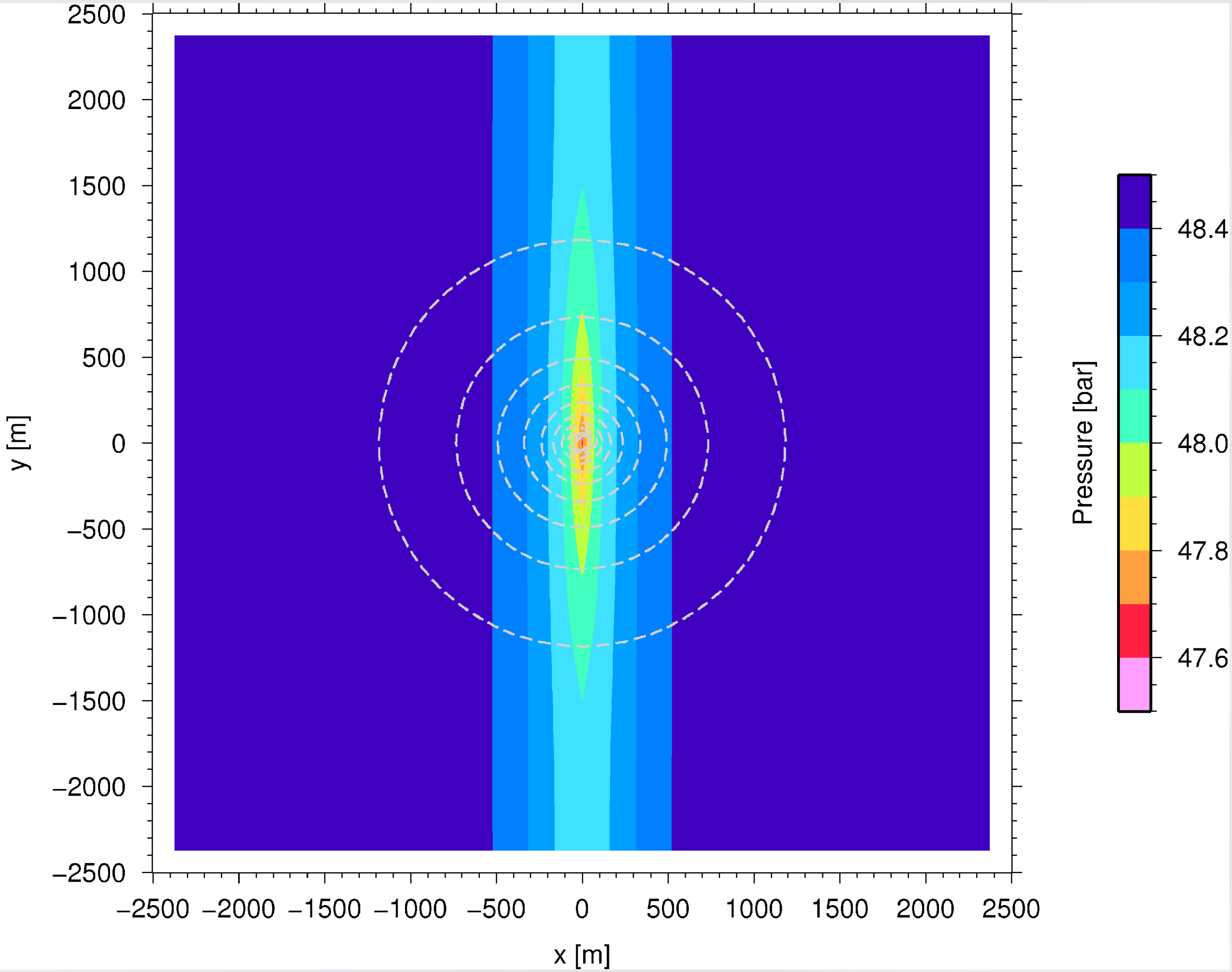
Comparison between full and simplified equations :



<u>Numerical example</u> : Fixed mass extraction from a closed aquifer

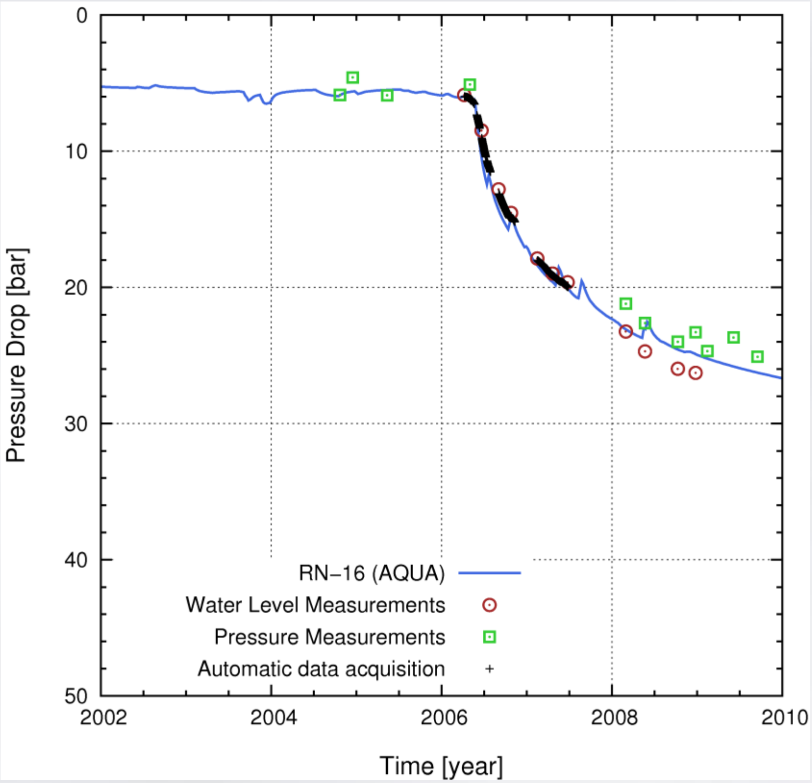
$k_x = 10^{-13}$ m^2
$k_y = 10^{-11}$ m^2

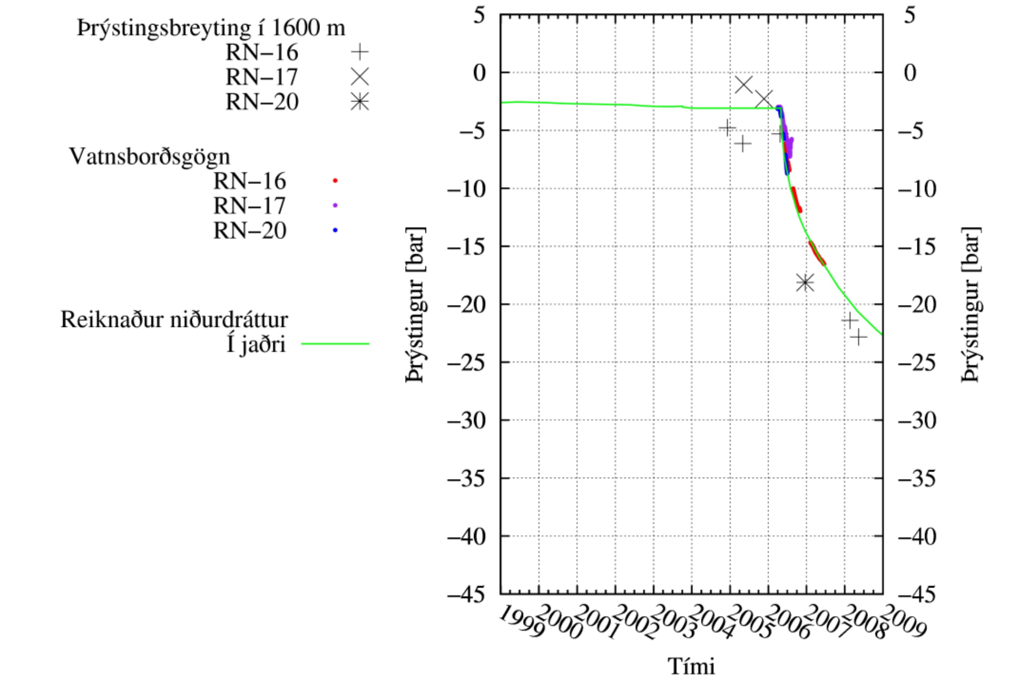
$kx = ky = 6.2\ 10^{-12}$ m^2



Practical example : Reykjanes Peninsula (SW-Iceland)

NW-edge of production zone





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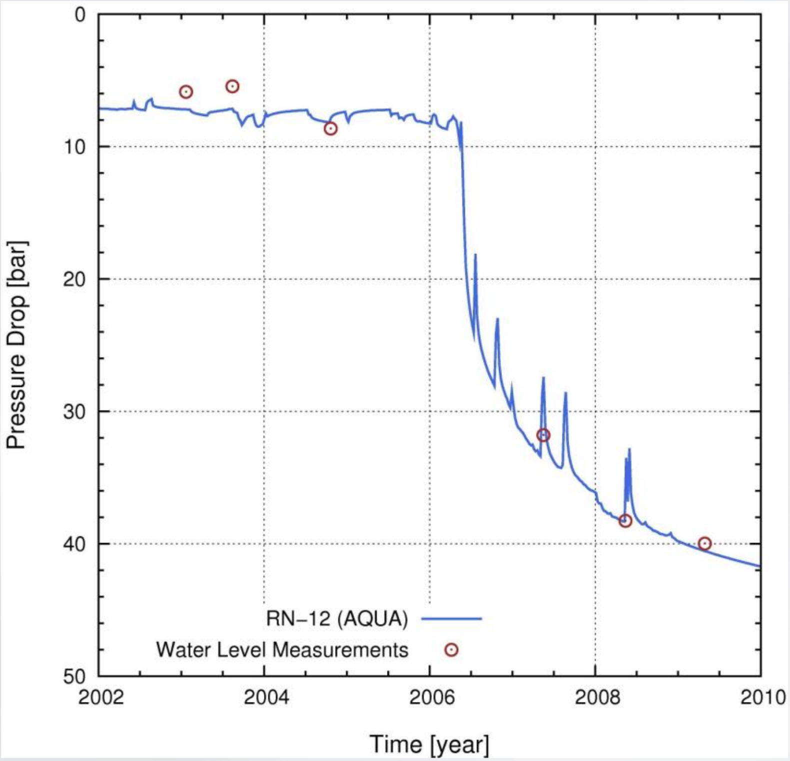
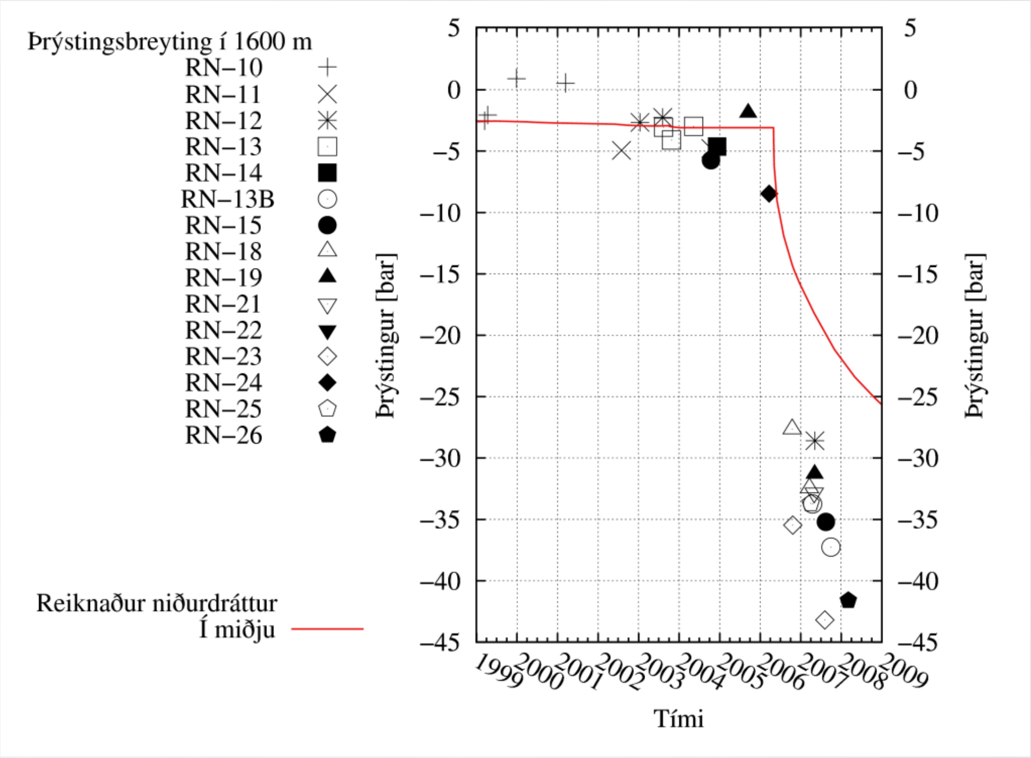
Center of production zone





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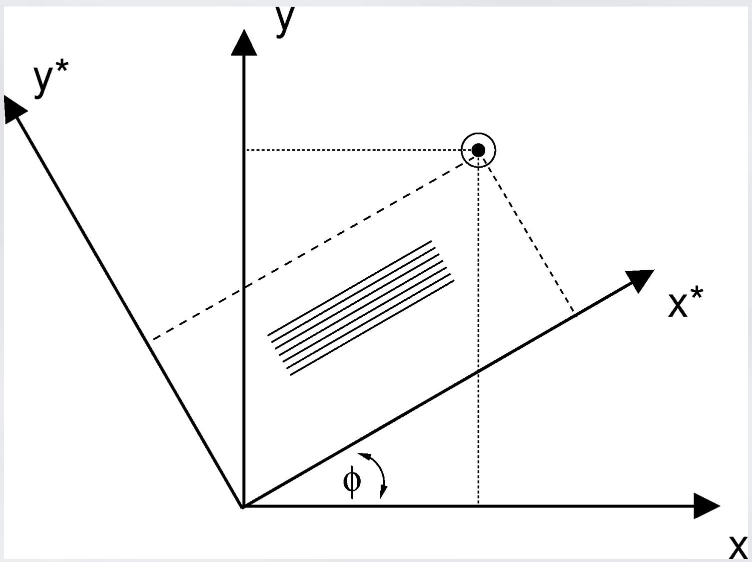
Anisotropy

Darcy's Law for anisotropic hydraulic conductivity :

$$q_x^* = -k_1 \frac{\partial \phi}{\partial x^*}$$

$$q_y^* = -k_2 \frac{\partial \phi}{\partial y^*}$$



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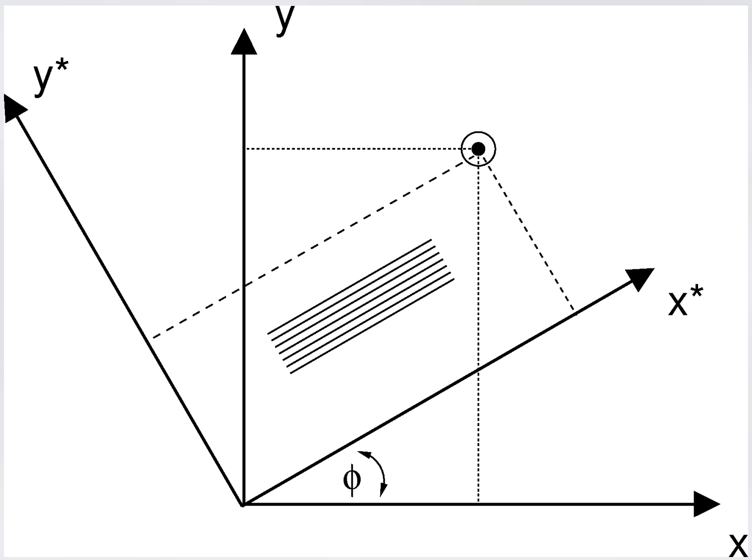
$$q_x = -k_{xx}\frac{\partial h}{\partial x} - k_{xy}\frac{\partial h}{\partial y}$$

$$q_y = -k_{yx}\frac{\partial h}{\partial x} - k_{yy}\frac{\partial h}{\partial y}$$

$$k_{xx} = k_1 \cos^2\phi + k_2 \sin^2\phi$$

$$k_{xy} = k_{yx} = (k_1 - k_2)\sin\phi\cos\phi$$

$$k_{yy} = k_1 \sin^2\phi + k_2 \cos^2\phi$$



Finite volume scheme

Flow in the principle direction :

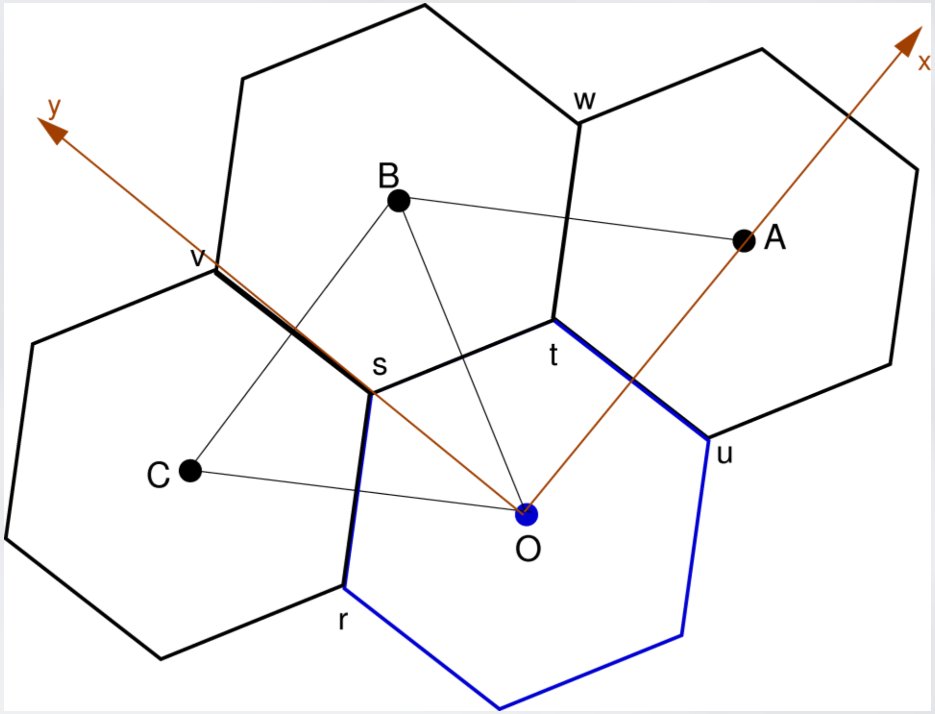
$$q_x = -k_1 \frac{\partial h}{\partial x}$$

Flow along a streamline :

$$q_x = -\left\{ \frac{k_1 k_2}{k_1 \sin^2\phi + k_2 \cos^2\phi} \right\} \frac{\partial h}{\partial x}$$

$$q_x = -k_1 \frac{\partial h}{\partial x'}$$

$$x' = \frac{x \cdot k_2}{k_1 \sin^2\phi + k_2 \cos^2\phi}$$



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Implementation into TOUGH2 :

Numerical scheme developed in collaboration with the University of Iceland (Sven Sigurðsson).

- Collaboration with LBNL (Karsten Pruess and Katie Boyle).
- Calculations triggered by ANISO block in TOUGH2 input file.
- New matrix elements into the matrix solver already present in TOUGH2.
- More input needed, anisotropy angle (element basis) and coordinates for element centers and vertices.

First steps

Validation :

1) Rectangular mesh in TOUGH2 with anisotropy via different k_x & k_y (PER(1) & PER(2)).
   Extract mass from center and compare with new scheme using a irregular mesh.

2) Radial mesh in TOUGH2, extract mass from center. Scale the permeability and compare with new scheme using a irregular grid.