GEOCAP
Geothermal Capacity Building Program Indonesia - Netherlands

Bandung May 2016

Fundamentals of Dynamic Reservoir Engineering

TTT Workshop on Geothermal Reservoir and Production Engineering Knowledge and Skills

Peter A. Fokker

Cooperating companies and Universities

INAGA

IF Technology

DNVGL

Institute Teknologi Bandung

Delft University of Technology

Department of Geo-Technology

University of Twente

Faculty of ITC

Universitas Gadjah Mada

Universitas Indonesia

University of Utrecht

Faculty of Geosciences – Department of Earth Sciences

Netherlands Organisation for Applied Scientific Research

IND coordinator:

INAGA

NL coordinator:

ITC

Advisory board:

BAPPENAS (chair)

MEMR

RISTEK DIKTI

Min. Foreign Affairs NL

Rector ITB

Rector UGM

Rector UI

INAGA

Funded by

Ministry of Foreign Affairs of the Netherlands

GEO CAP

Geothermal Reservoirs

First examples worldwide

- Lardarello (Italy)
- Wairakei (New Zealand)
- The Geysers (California, USA)

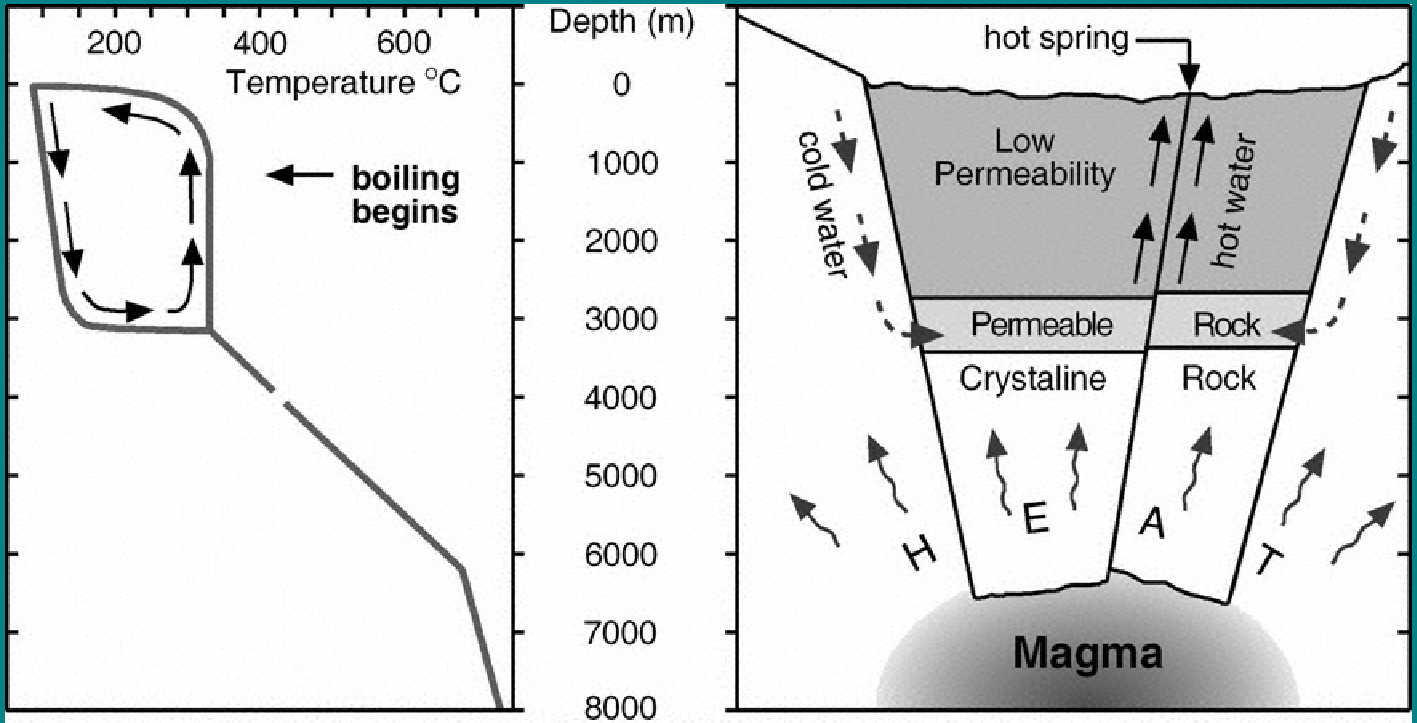
What represents a typical geothermal reservoir?

- Permeability through fracture network
- Large vertical extent
- Horizontal and vertical extents are often unclear
- Caprock? Communication with surroundings?

In all cases: FLOW of FLUIDS (water, steam, gas, mixtures) and CONVECTION of heat

- Natural convective flow
- Induced flow to and from wells

A geyser: Large-scale circulation of hot fluid



Fundamentals of Geothermal Reservoir Engineering

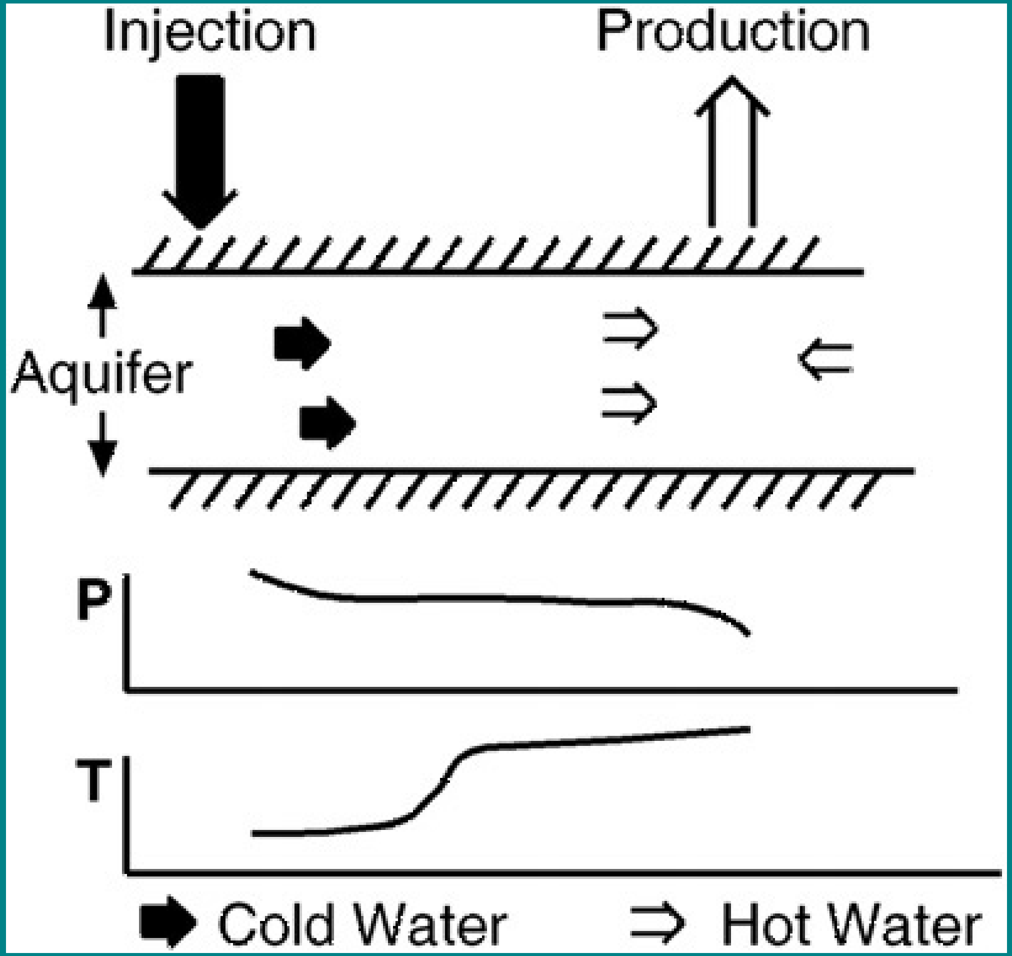
- Gain conceptual understanding
- Gain quantitative understanding
  - Flow of mass and heat
  - Development vs time
  - Response to operations (production and injection)
- Support decision making
- Approaches:
  - Material balance models, Lumped parameter models
  - Pressure transient models
  - Numerical simulation

OUTLINE

I. Simple Quantitative Models
   a. Storage concepts
   b. Lumped-parameter models
   c. Dual-porosity models

II. Pressure Transient Models
   a. Darcy’s law
   b. Mass balance
   c. Constant terminal rate solution

I. Concept of a material balance approach



Concepts of storage
1. Closed box with liquid

- Conservation of mass and energy

$$V\frac{d}{dt}(\varphi\rho) = -W$$

$$V\frac{d}{dt}[(1-\varphi)\rho_m U_m + \varphi\rho U] = -WH$$

- Small temperature changes yield

$$V\varphi\left(\frac{\partial\rho}{\partial P}\right)_T\frac{dP}{dt} = -W; \quad \frac{dP}{dt} = -\frac{q}{S_V} = -\frac{W}{S_M}$$

$$S_V = V\varphi c; S_M = V\varphi\rho c$$

Concepts of storage
2. Closed box with gas

- For gas: Use mass change rather than volume change

- Imperfect gas law $pV = ZnRT$

$$\varphi V \frac{p}{Z} = \varphi \rho V \frac{RT}{M}$$

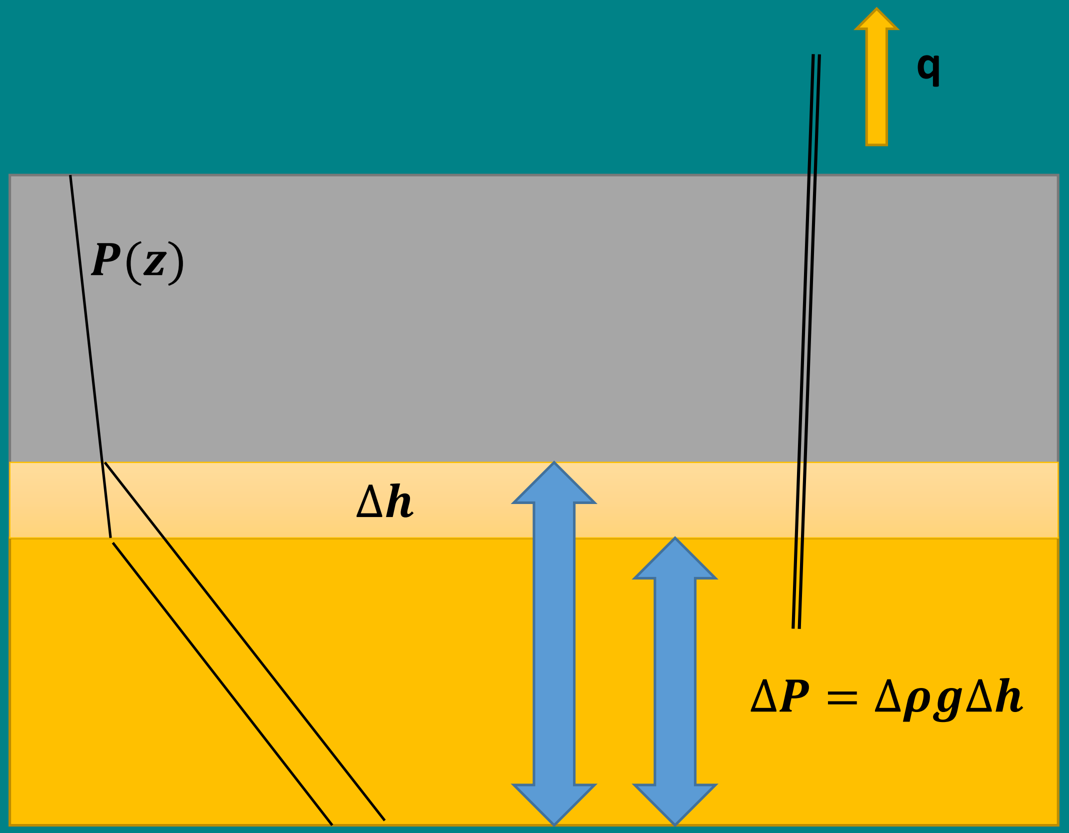
- So: linear change of p/Z with mass $\varphi \rho V$ in the reservoir

$$\frac{d}{dt}\left(\frac{p}{Z}\right) = -W \frac{RT}{M \varphi V}$$

Concepts of storage
3. Closed box with water level

- Constant pressure in gas zone

$$\frac{dP}{dt} = -\Delta\rho g \frac{dh}{dt} = -\Delta\rho g \frac{q}{A\varphi\Delta S}$$



Concepts of storage
4. Closed box with two-phase fluid

- Water and steam in contact
- Cooling of the total system (rock and pore content)
  - Production causes pressure drop
  - Part of the water evaporites
  - $\frac{dP_s}{dT}$ evaluated on saturation line

$$\Delta T = \Delta P / \left[\frac{dP_s}{dT} \right]$$

- Heat released from matrix and liquid (depending on total heat capacity $\rho_t C_t$):

$$Q = V \rho_t C_t \Delta T ; \qquad \rho_t C_t = (1 - \varphi) \rho_m C_m + \varphi S_w \rho_w C_w$$

- Increase in volume must contain the heat extracted

$$\Delta V = \frac{Q}{H_{sw}}\left(\frac{1}{\rho_s} - \frac{1}{\rho_w}\right) = \frac{V\rho_t C_t \Delta T}{H_{sw}}\left(\frac{1}{\rho_s} - \frac{1}{\rho_w}\right)$$

- Total compressibility follows

$$\varphi c_t = \frac{dV}{dP} = \frac{\rho_t C_t}{H_{sw}} \frac{\rho_w - \rho_s}{\rho_w \rho_s} \frac{dT_{sat}}{dP}$$

Exercise: Compare compressibilities

- 500-m thick aquifer
- 240°C
- 15% porosity
- Volumetric heat capacity $\rho_t C_t = 2.5$ MJ/m^{3}K

- What is the compressibility for the 4 systems?

Lumped-parameter models

- Volume balance of withdrawal and recharge ($S_M = V \cdot S = V \cdot \phi ch$):

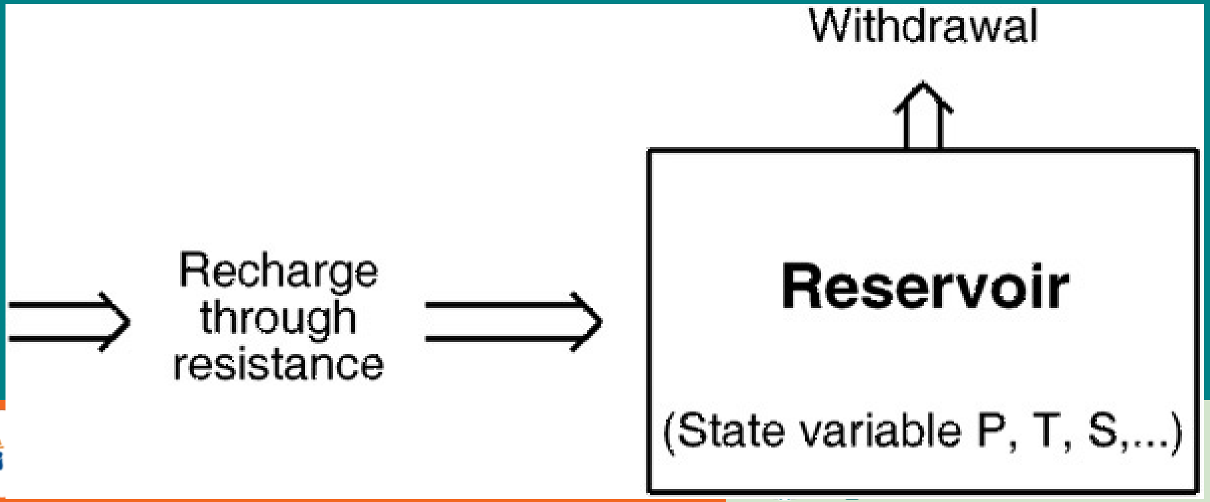
$$S_M \frac{dp}{dt} + W - W_r = 0$$

- Recharge rate proportional to pressure difference

$$W_r = \alpha(P_0 - P)$$

- Gives exponential approach to equilibrium

$$P_0 - P = \frac{W}{\alpha}\left(1 - \exp\left[-\frac{\alpha t}{S_M}\right]\right)$$



Lumped-parameter models

Withdrawal W and recharge α:

$$P_0 - P = \frac{W}{\alpha} \cdot \left(1 - \exp\left[-\frac{\alpha t}{S_M}\right]\right)$$

- Pressure decrease for short times linear; $P_0 - P \approx W/S_M \cdot t$
- Influence of recharge after $\tau = \frac{S_M}{\alpha}$
- Equilibrium pressure $P_0 - P \approx W/\alpha$

Lumped-parameter models

- Decrease in pressure
  - Free water level
  - Development of steam / two-phase flow
    - Changes in compressibility (S_M)

- Cold water recharge
  - Increasing the mass content
  - Both increase and decrease of pressure possible
    Depending on heat balance (condensation of steam!)

Steam reservoir with immobile water

- Production of steam will decrease pressure
- Evaporating water
- Until the reservoir is "superheated"

Most of the energy is stored in the rock and in the immobile water

- Possibility to raise the pressure by injecting cold water

Reserves

- Volume
- Temperature
- Recovery factor (3 – 17%)
- Conversion efficiency
  - Thermodynamic perfect engine ($\Delta T/T_{res}$)
  - Technological limit

- Consider uncertainties!

Production

- In-situ boiling / intergranular vaporization
  - Produce steam by reducing pressure

- Cold sweep
  - Inject cold water to extract all heat in liquid water
  - Use of heat still requires steam

Exercise

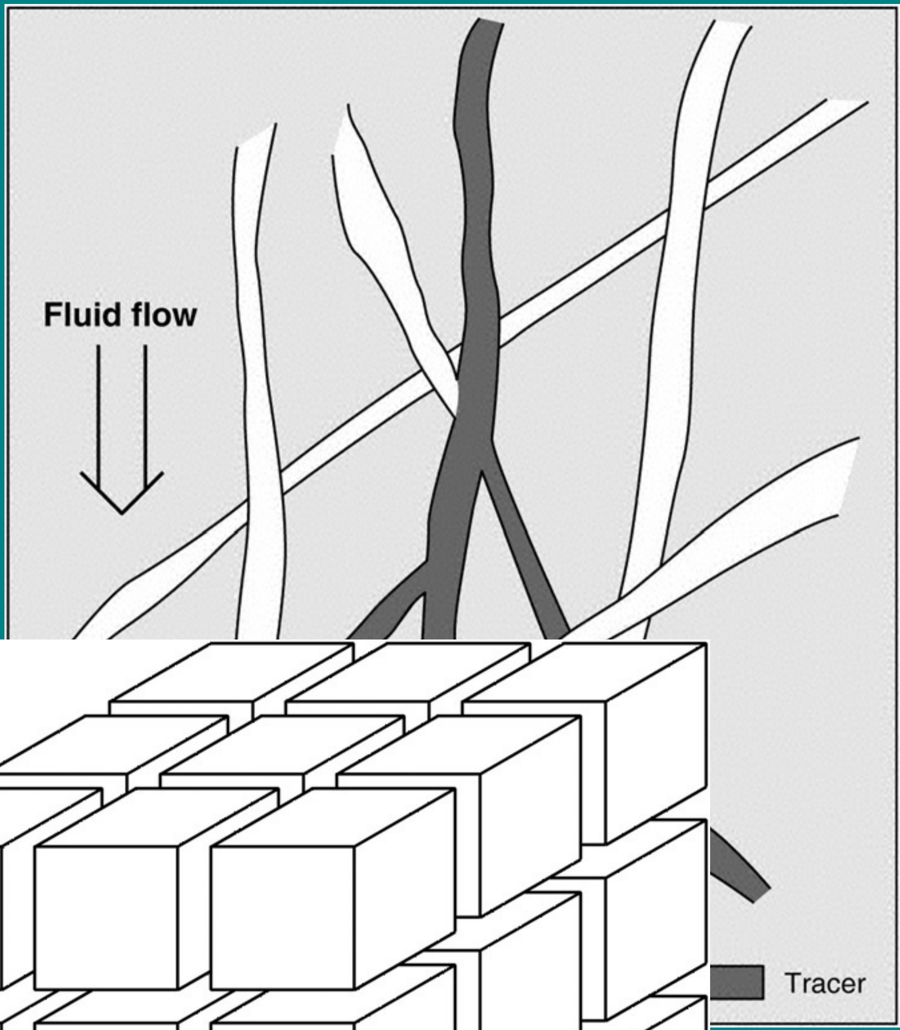
Estimate the energy of a reservoir

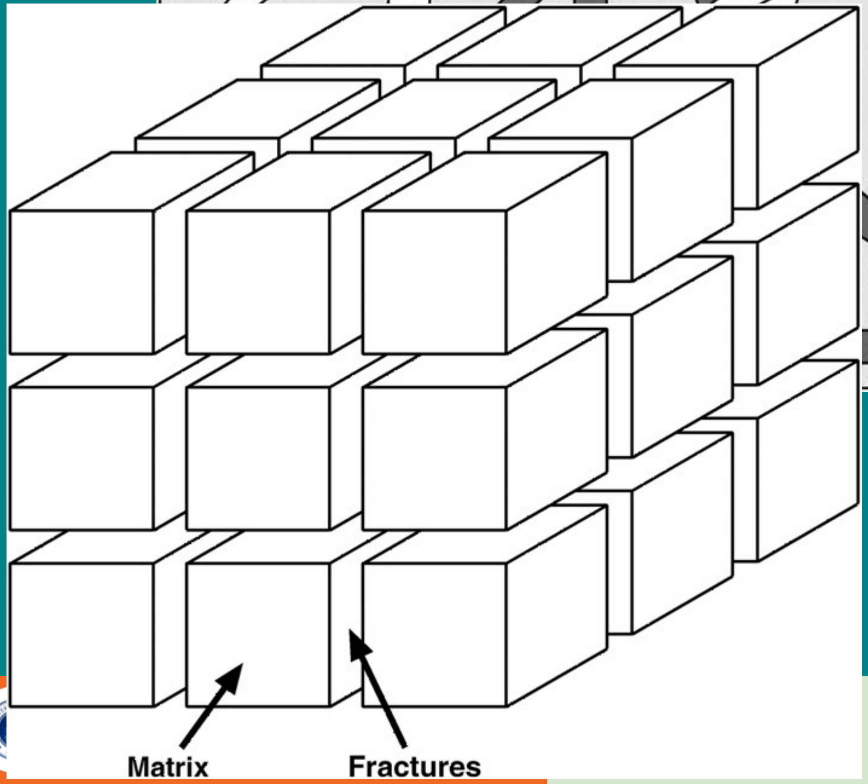
- Produce steam by decreasing pressure and temperature down to 10 bar / 180°C
- Cold sweep (extract all heat and use flash steam at 150°C)
  ## not enough info??

- 70% water saturated;
- V_{res} = 2 km x 2 km x 250 m
- T_{res} = 240°C
- T_0 = 15°C
- $\phi = 0.15$
- $\rho_t C_t = 2.5$ MJ/m^{3}K
  (rock specific heat capacity)
- $\rho_w C_w = 3.6$ MJ/m^{3}K
  (water specific heat capacity)
- $\rho_s C_s = 0.21$ MJ/m^{3}K
  (steam specific heat capacity)

Fractured reservoirs

- Modelled by dual-porosity systems
  - Flow through fracture system
  - Porosity in matrix system
  - Heat extracted from matrix blocks
  - Equations in two systems coupled through exchange term
- Slower cooling of matrix blocks
- Dispersion due to variability of speeds





II. Pressure transient models

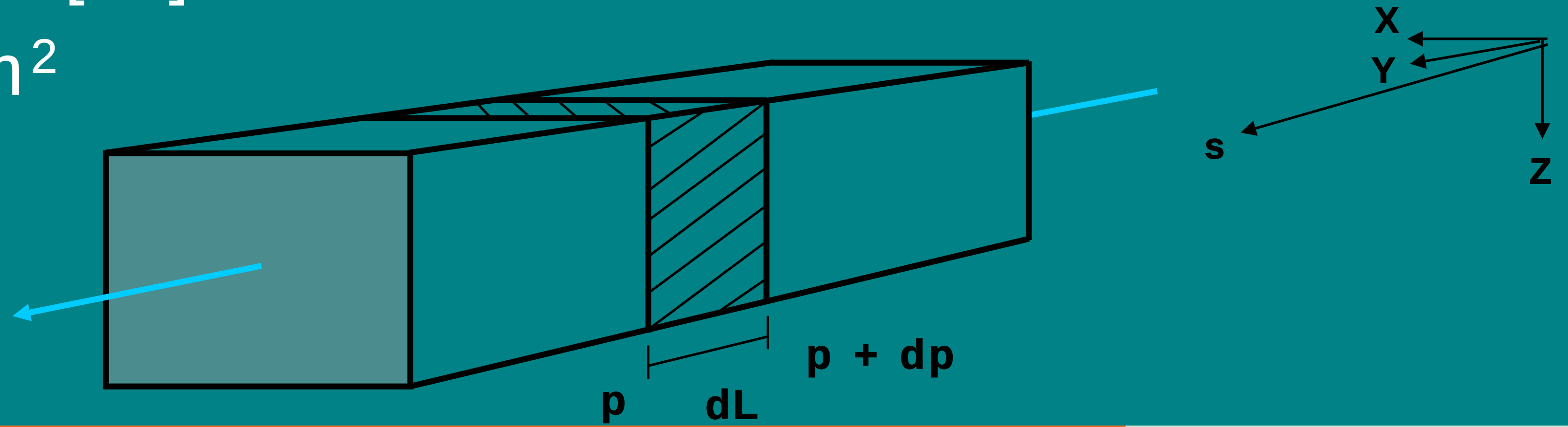
- Reservoir dynamics: Development of pressure in space and time
- Start with homogeneous model
- Start with single-phase fluid – liquid or gas
- Ingredients
  - Darcy’s law
  - Local mass balance

Darcy's law

- Linear relationship between pressure gradient and flow velocity

$$v = -\frac{k}{\mu}\left(\frac{dP}{dL} - g\frac{dz}{dL}\right); \ \mathbf{v} = -\frac{k}{\mu}(\nabla P - g\nabla z)$$

- Permeability k: measure of "ease of flow" – measurement unit [L^2]
- 1 Darcy ≈ 10^{-12} m^2

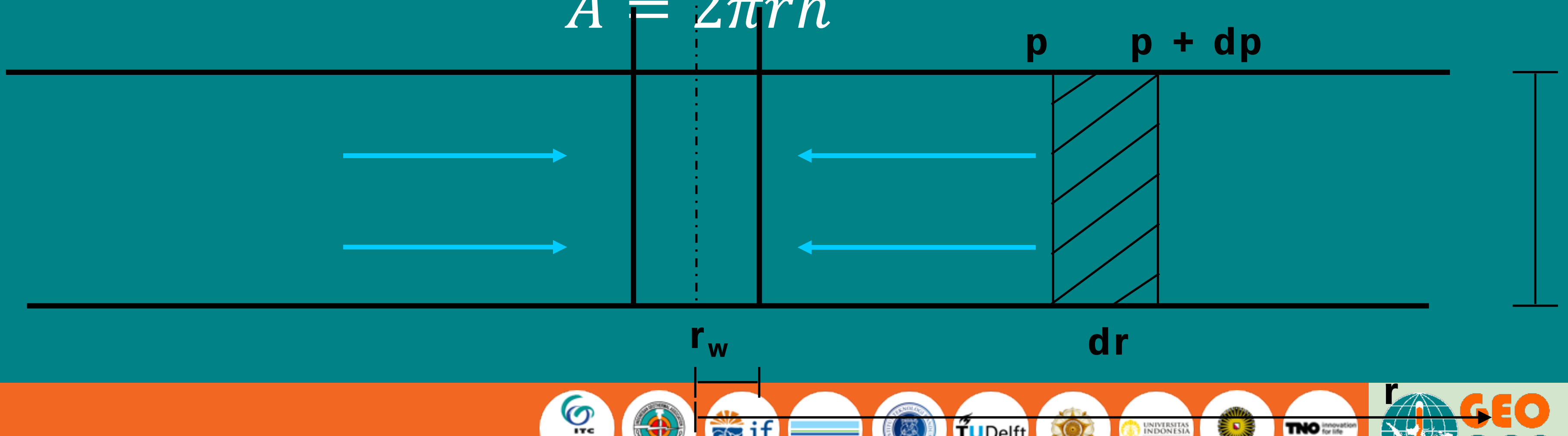


Radial geometry

- Horizontal flow – negligible gravitational forces
- Constant thickness
- Layer fully penetrated by well

$$v = -\frac{q}{A} = -\frac{k}{\mu}\frac{dP}{dr}$$

$$A = 2\pi r h$$



Homogeneity and Isotropy

- Heterogeneity:
  Spatially varying permeability
- Anisotropy:
  Permeability dependent on direction, i.e. a matrix

$$\mathbf{v} = -\frac{\mathbf{k}}{\mu}(\nabla P - g\nabla z);$$

$$\mathbf{k} = \begin{pmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{pmatrix}$$

- On principal axes:
  k_x; k_y; k_z

Homogeneity and Isotropy

Kx= 100 mD Kz=100 mD	Kx= 100 mD Kz=100 mD

homogeneous and **isotropic**

Kx= 200 mD Kz=200 mD	Kx= 100 mD Kz=100 mD

heterogeneous and **isotropic**

Kx= 100 mD Kz=200 mD	Kx= 100 mD Kz=200 mD

homogeneous and **anisotropic**

Kx= 100 mD Kz=200 mD	Kx= 50 mD Kz=100 mD

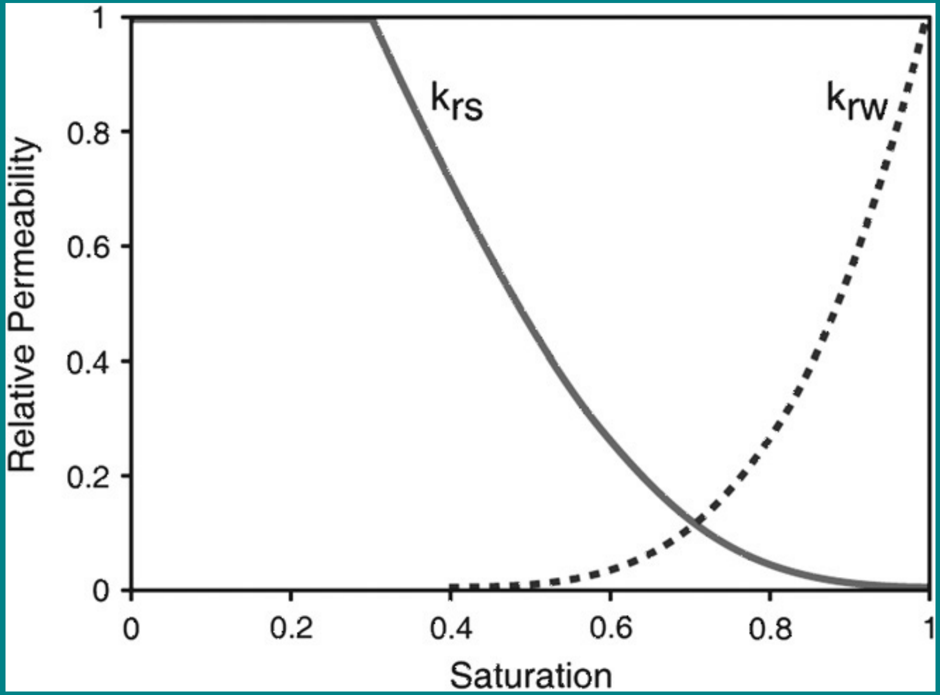
heterogeneous and **anisotropic**

Two-phase flow

- Co-existing water and steam, both flowing

- Relative permeability for water and for steam

$$u_t = u_w + u_s = -k\left\{\frac{k_{rw}}{\mu_w} + \frac{k_{rs}}{\mu_s}\right\}\nabla P$$



Local mass balance

- In a volume element, the accumulation of mass and the outflow cancel out

$$\frac{\partial}{\partial t}\left(\varphi\frac{m}{V}\right) = -\nabla\cdot\left(\frac{m}{V}\mathbf{v}\right)$$

$$\frac{\partial}{\partial t}(\varphi\rho) = -\nabla\cdot(\rho\mathbf{v})$$

- In a radially symmetric system

$$\nabla\cdot(\rho\mathbf{v}) = \frac{1}{r}\frac{\partial}{\partial r}(r\cdot\rho v)$$

Combining mass balance and Darcy's law

$$\varphi c \rho \frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\rho \frac{k}{\mu} r \frac{\partial P}{\partial r}\right)$$

- Assuming small, constant compressibility and constant viscosity facilitates linearization

$$\frac{\varphi c \mu}{k}\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial P}{\partial r}\right)$$

- Diffusivity equation (heat equation) with diffusivity $\kappa = \varphi c \mu / k$ – many solutions available

Constant Terminal Rate Solution

- Diffusivity equation

$$\frac{\varphi c\mu}{k}\frac{\partial P}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right)$$

- Start withdrawal at time 0 with a rate q or mass rate $W = \rho \cdot q$ gives solution in terms of exponential integral $E_1(x) = \int_x^\infty \frac{1}{y} e^{-y} dy$

$$\Delta P = P - P_0 = -\frac{q\mu}{4\pi kh} E_1\left(\frac{\varphi c\mu}{k}\frac{r^2}{4t}\right)$$

Constant Terminal Rate Solution

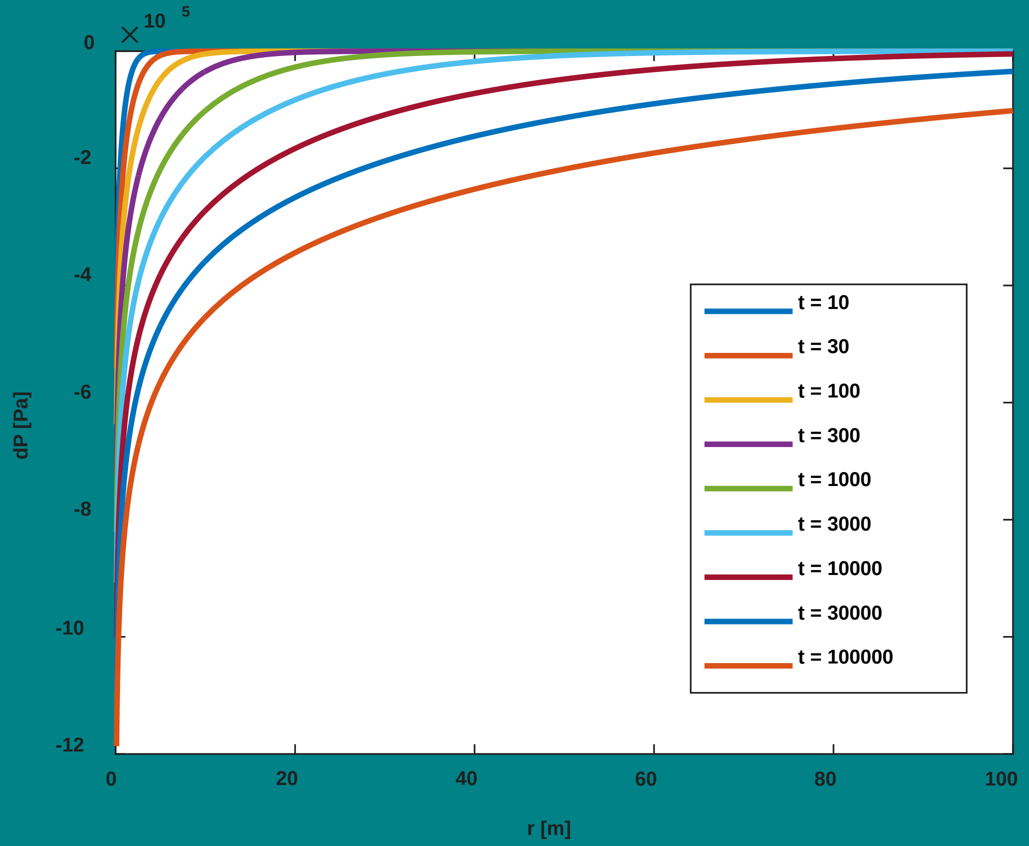
$$\Delta P = P - P_0 = -\frac{q\mu}{4\pi kh} E_1\left(\frac{\varphi c\mu}{k}\frac{r^2}{4t}\right) = -\frac{q}{4\pi T} E_1\left(\frac{S}{T}\frac{r^2}{4t}\right)$$

Character of curve determined by

- Transmissivity (Mobility-thickness) $T = kh/\mu$
- Storativity $S = \varphi ch$

Well testing: Determine *S* and *T* from observation of pressure development

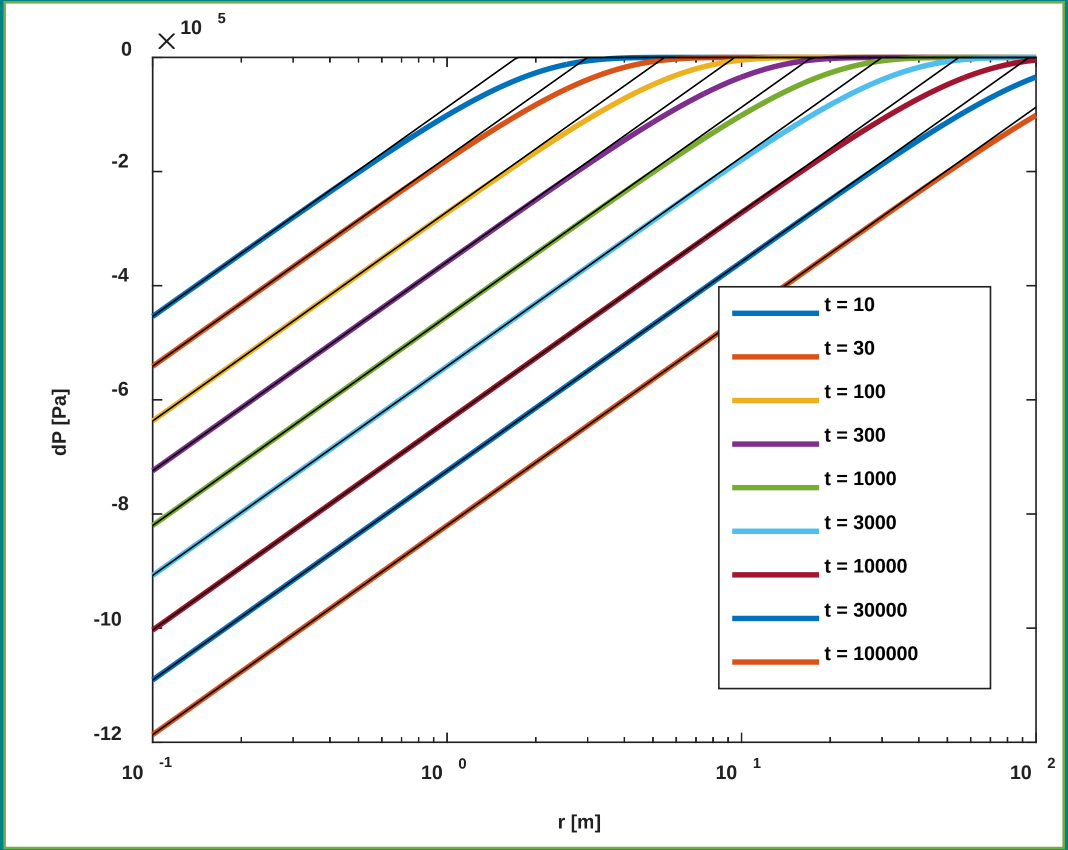
Constant Terminal Rate solution



Example pressure distribution with

- ϕ = 0.15
- k = 100 md
- c = 10^{-8} Pa^{-1}
- μ = 0.5 cP
- h = 50 m
- q = 0.01 m^3/s

Constant Terminal Rate solution



Semi-log plot

- Linear curves
- Pressure penetration depth

$$dP \approx \frac{q}{4\pi T}\left\{\ln\left(\frac{S}{T}\frac{r^2}{4t}\right)+\gamma\right\}$$

Exercise

- Typical reservoir
  - When are boundaries reached?
  - ...
  - ...