Bandung, May 2016

Well Testing for Geothermal Reservoirs

TTT Workshop on Geothermal Reservoir and Production Engineering Knowledge and Skills

Peter A. Fokker; Sutopo;

Public

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

Well Testing

Books

- M.A. Grant & P.F. Bixley (2011) Geothermal Reservoir Engineering
- D. Bourdet (2002) Well test analysis: the use of advanced interpretation models
- R. Horne (2001) Cumputer aided well test analysis SPE monograph
- Gringarten (2008) From Straight Lines to Deconvolution: The Evolution of the State of the Art in Well Test Analysis

Outline

- I Introduction
- II Well testing basics
- III Geothermal Well testing

I Introduction

- Principle of Well Testing
- Objectives
- Types
- Interpretation

Principle of well testing

Analyze the OUTPUT of a well on which a known INPUT signal has been applied

- INPUT:
  Production and Injection Flow Rates

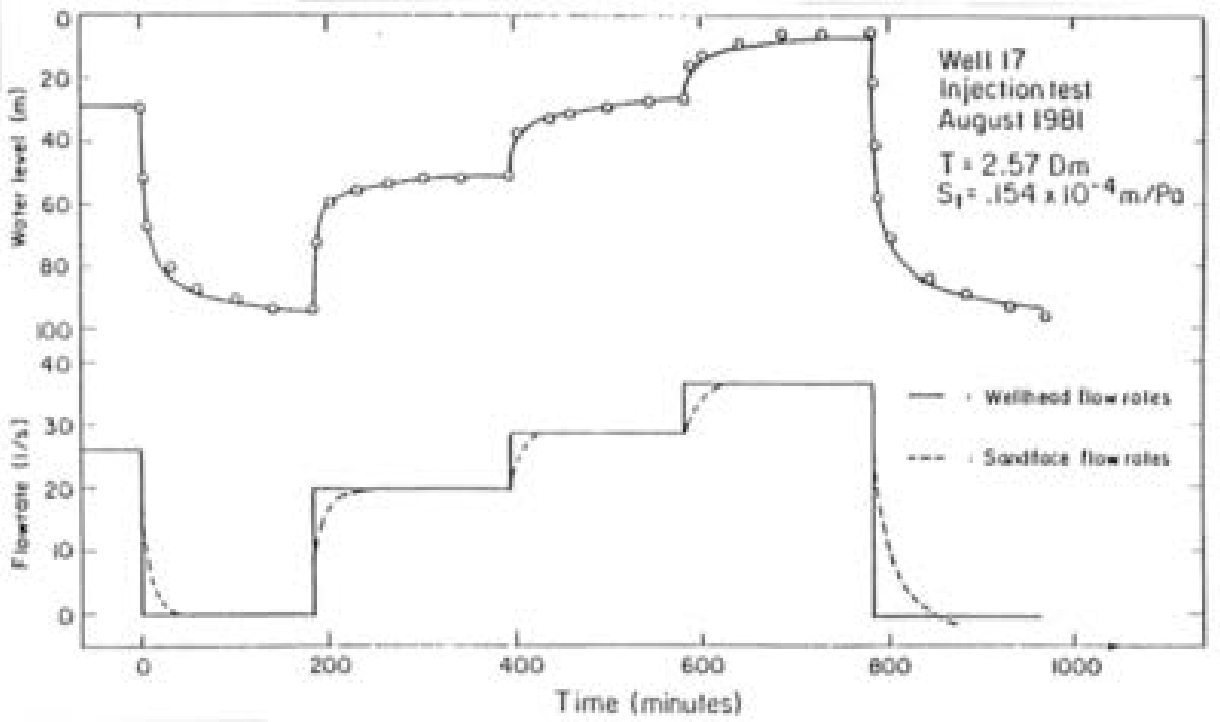
- OUTPUT
  Bottom Hole Pressures and Temperatures

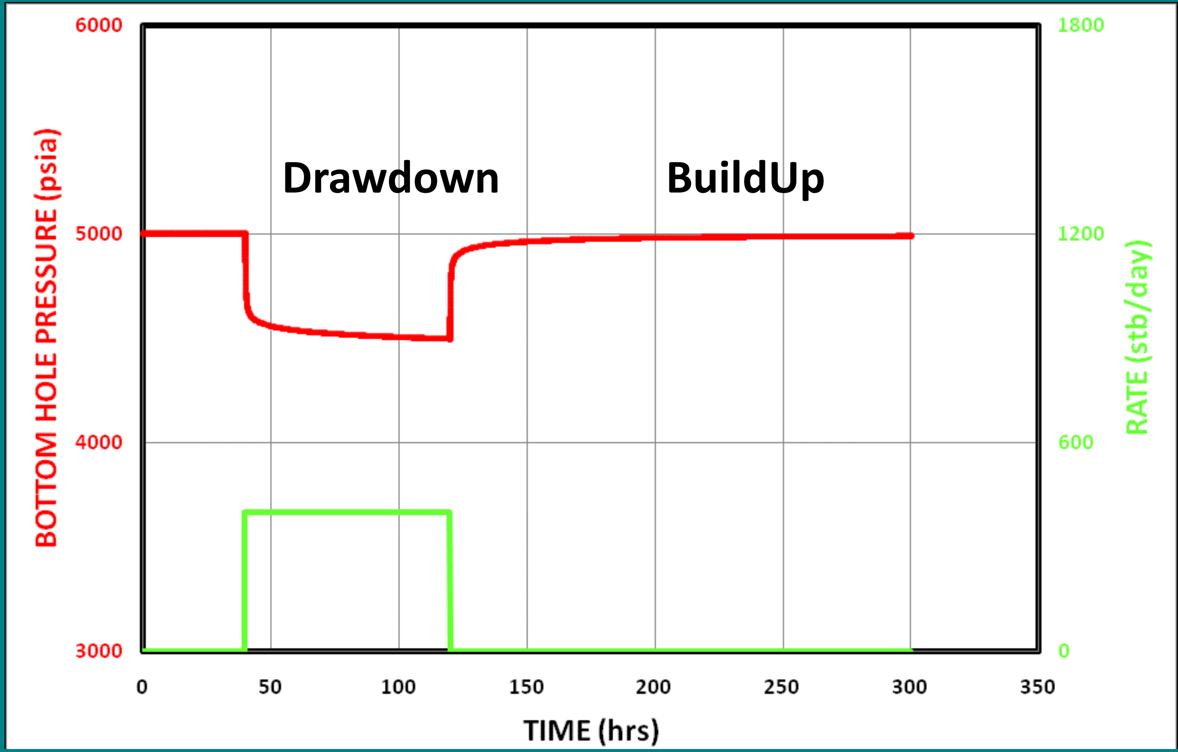
Standard Well Testing

Rate and

Bottom Hole Pressure

vs Time





Main Objectives of Well Testing: Reservoir and Well Description

- Temperature distribution
- Pressure distribution
- Permeability distribution (horizontal and vertical)
- Reservoir state (gas/liquid; one/two phase flow)
- Reservoir heterogeneities (fractures, layering, changes)
- Reservoir size
- Production potential
- Well damage (skin)
- Pressure changes
- Temperature changes
- Composition changes

Types of Tests

- Measurements while drilling
  - Temperature buildup tests
  - Pressure buildup tests
- Measurements on well completion
  - Feed zones
  - Overall permeability
- Heating
  - Formation temperatures and pressures
- Production / Injection tests: Well testing
  - Production potential at surface
  - Downhole response
  - Interference

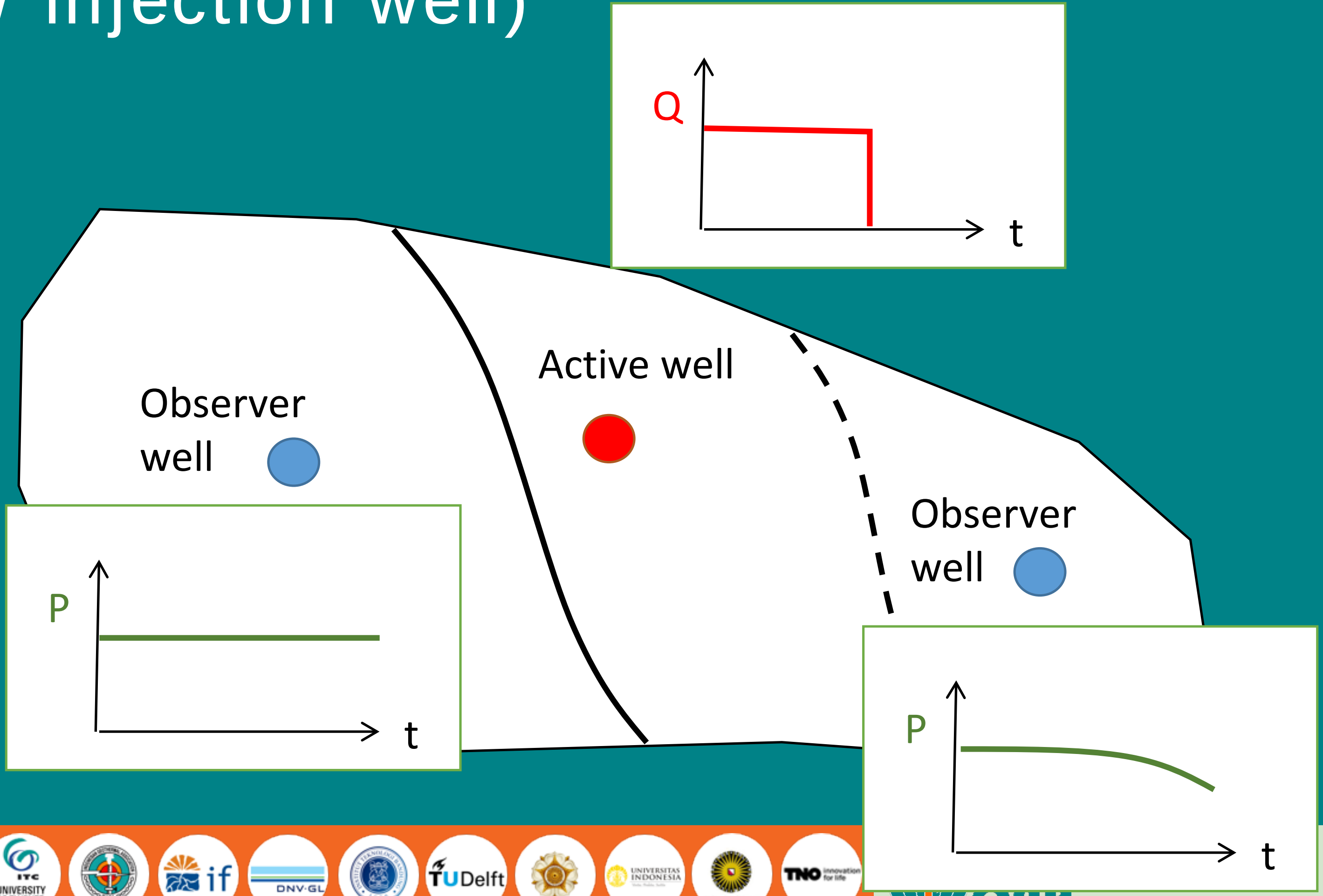
Standard production test

- Let well pressure stabilize
- Open to flow; measure pressure decline

  Problems:
  - Control of constant rate
  - Not static as a start
- Shutin and watch pressure Buildup
  - Easy achievable constant = zero rate
  - Loss of production time
- Long-term test:reservoir boundaries and reservoir size

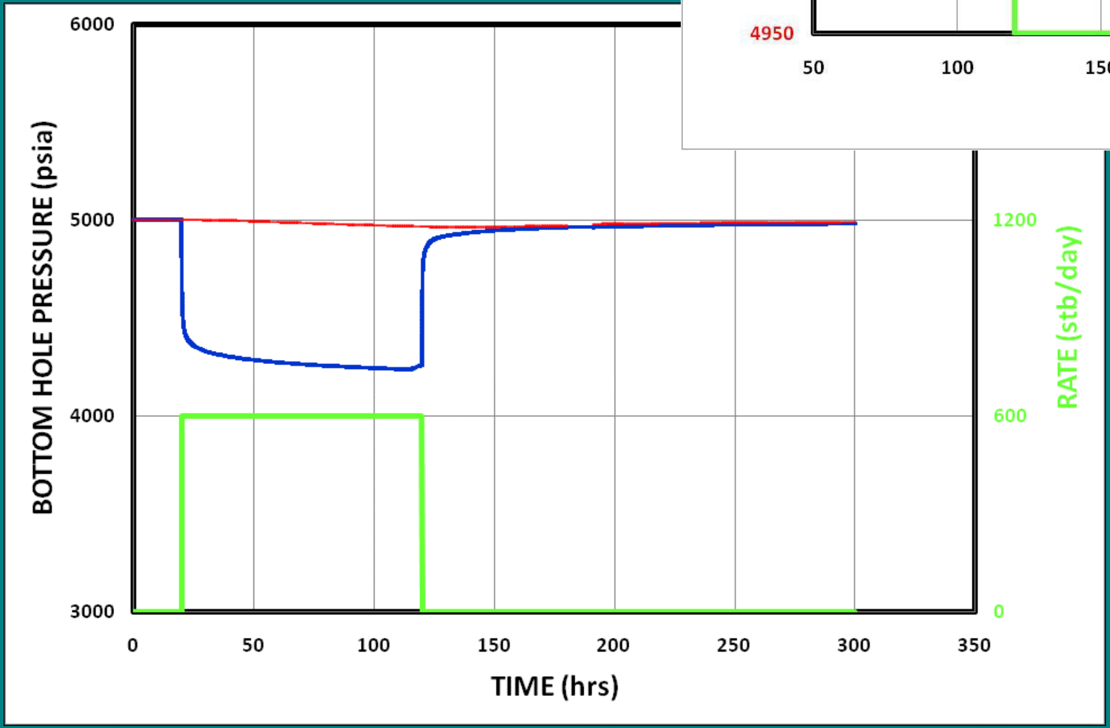
Interference testing

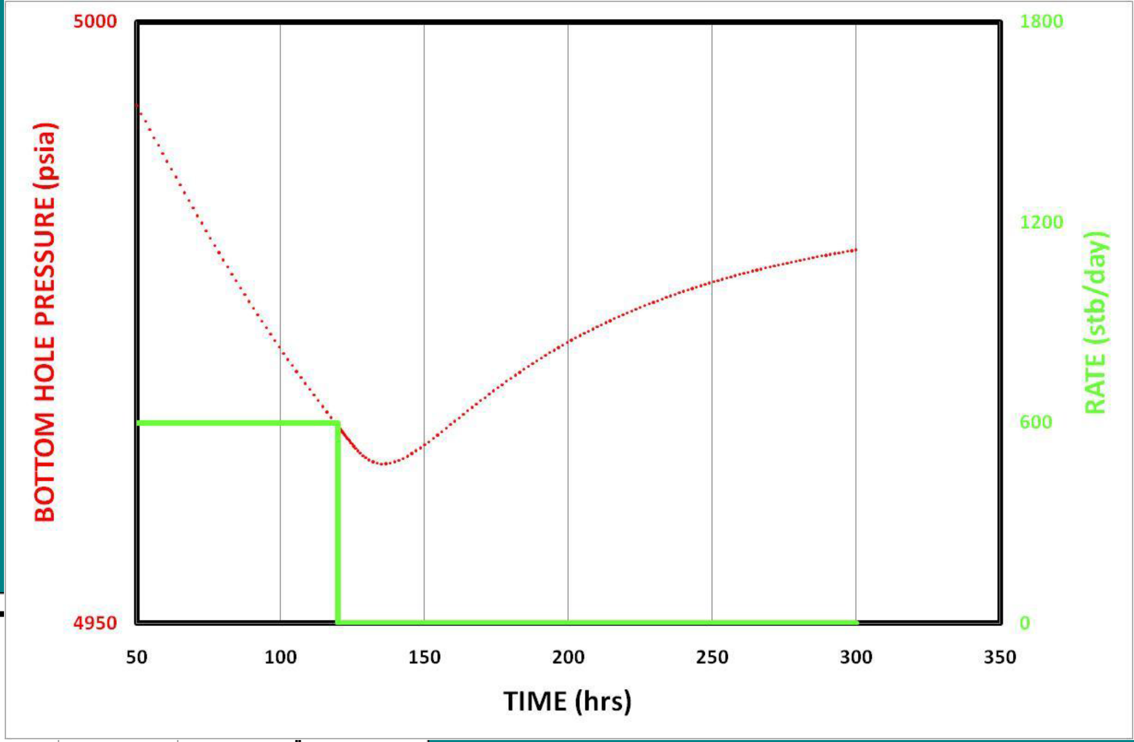
- Active well(production / injection well)
- Observation well



Interference testing

- Time lag in observation well response





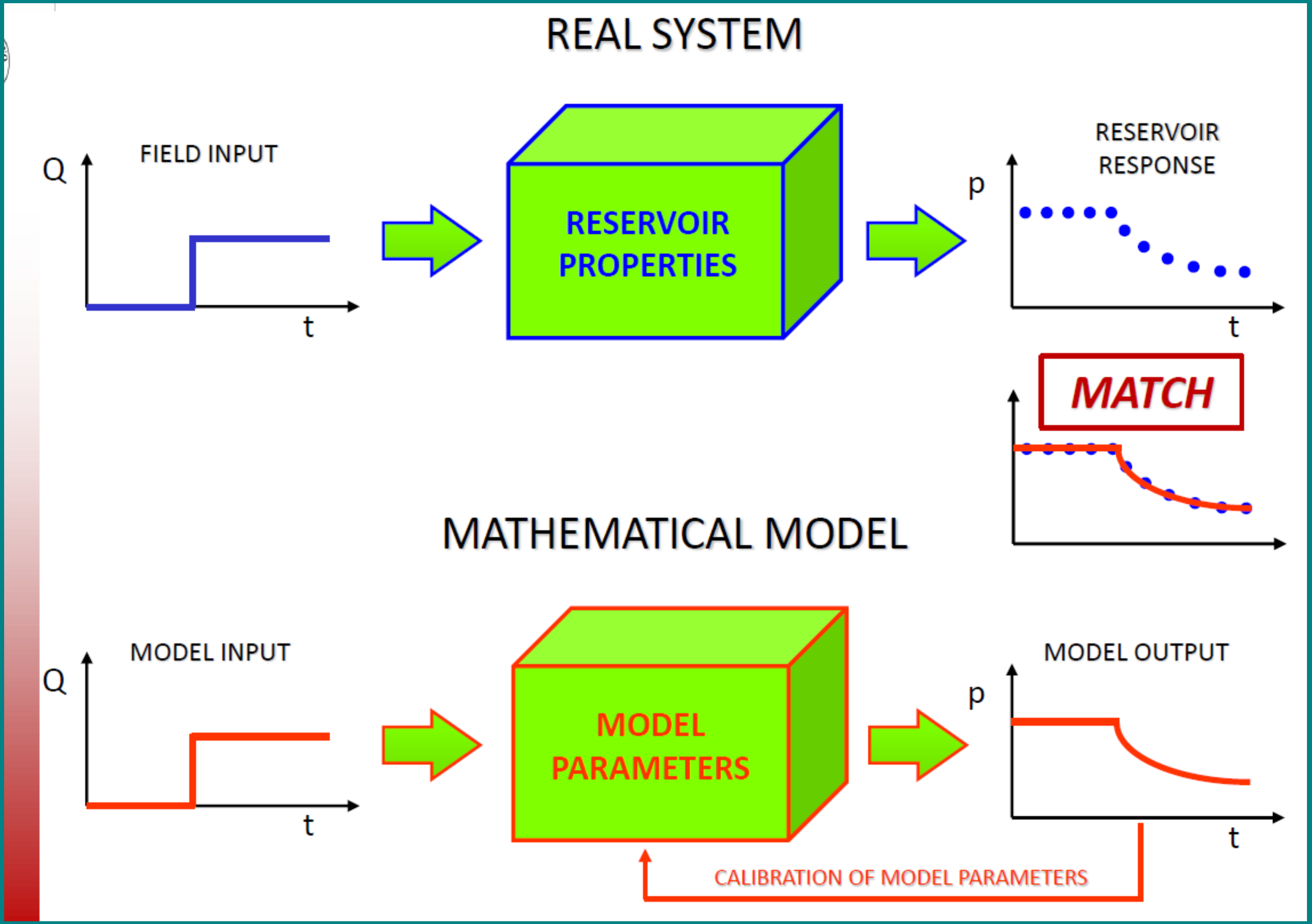
Quality control

- Check instrumental response (validation of gauges)
- Check gauge pressures vs wellhead pressures
- Check timings of pressures vs rates

Interpretation

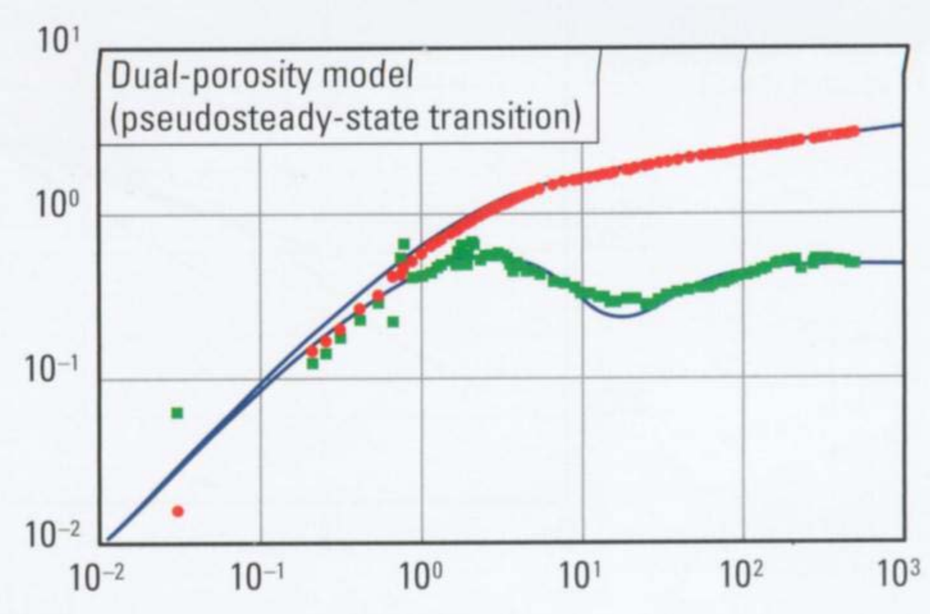
- Measure response of physical system
- Calculate model response
- Calibrate model parameters to obtain match

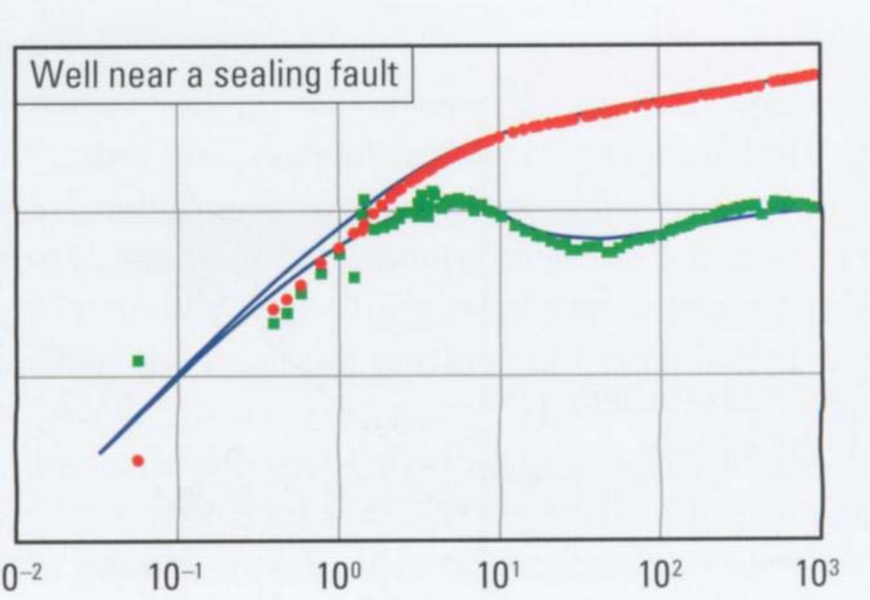
Inverse problem: Gm=d

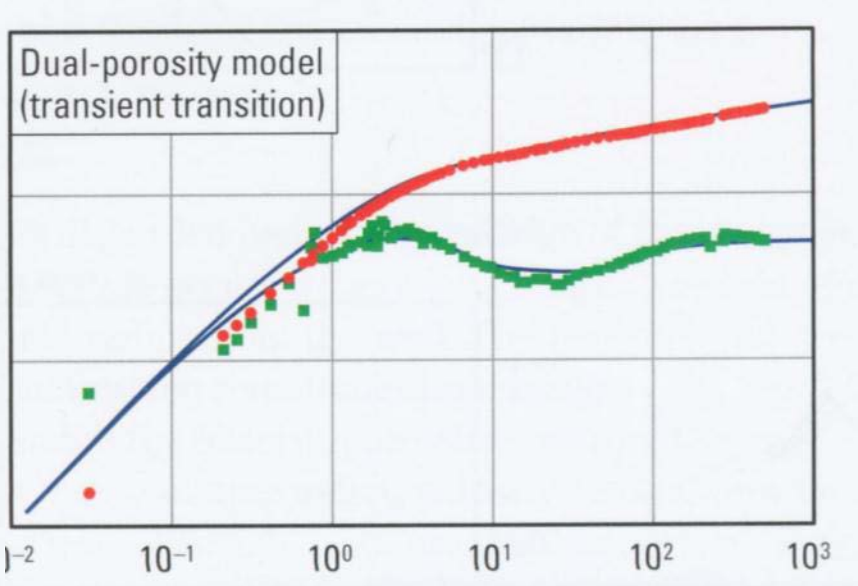


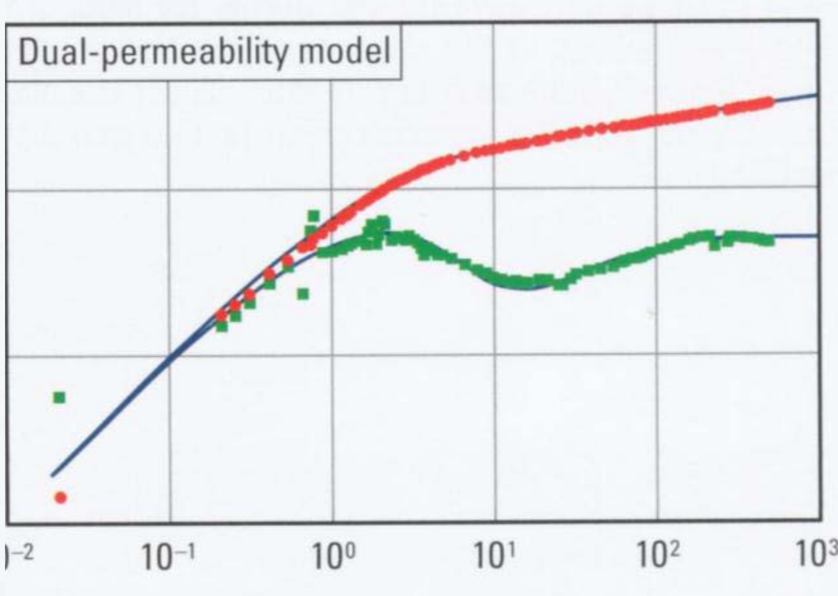
Example of non-uniqueness of solutions

Same data can be fitted with different models









II Well testing basics

- Models
- Wellbore storage, Skin
- Analysis methods
- Pressure derivative analysis

Model

- A schematic description or representation of something, especially a system or phenomenon, that accounts for its properties and is used to study its characteristics
- Mathematical model:
  A model in terms of equations
  - Mass balance
  - Flow
  - Energy
  - Initial and boundary conditions

Analytical vs Numerical models

- Analytical
  - Mathematical solution to the equations
  - Usually obtainable for simple geometries only
  - Fast to calculate
  - Conceptually tractable

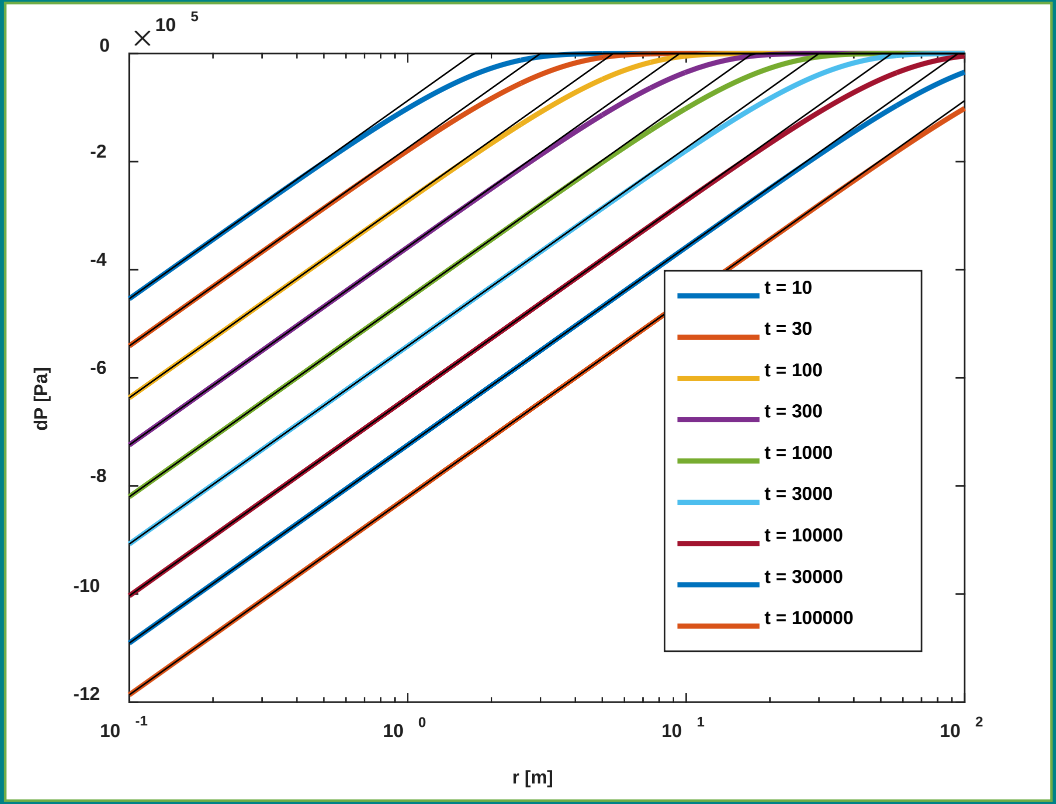
- Numerical
  - Non-linear equations (e.g. two-phase flow)
  - Complicated boundary conditions
  - Heterogeneity
  - Usually in the form of "discrete analogues"
    - Finite differences
    - Finite elements
    - Discrete elements

Model ingredients

- Phases
  - Single phase
  - Two-phase
- Nature of fluids
  - Compressibility
  - Viscosity
  - Specific enthalpy
- Geometry
  - Radial
  - 3D
  - Heterogeneous
- Hydraulic regime
  - Steady-state
  - Pseudo-steady-state
  - Transient

Demonstration of hydraulic flow regime

- Steady-state: No changes with time
- Pseudo-steady-state: Changes with time independent of position
- Transient: Full temporal-spatial solution



Basic Equations

- Darcy

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

- Radially symmetric

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

- Continuity

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

- Radially symmetric

$$\frac{\partial}{\partial t}(\varphi\rho) = -\frac{1}{r}\frac{\partial}{\partial r}(r \cdot \rho v)$$

- Diffusivity equation

$$\varphi c\rho\frac{\partial P}{\partial t} = \nabla \cdot \left(\frac{\rho k}{\mu}(\nabla P - g\nabla z)\right)$$

- Radially symmetric

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

Steady-State Solution

- Applicable for constant-pressure boundary condition (open reservoir)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\rho k}{\mu} r \frac{\partial P}{\partial r}\right) = 0$$

$$p = p_e - \frac{q\mu}{2\pi k h}\ln\frac{r_e}{r} = p_e - \frac{1}{T}\frac{q}{2\pi}\ln\frac{r_e}{r}$$

Constant Terminal Rate Solution

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

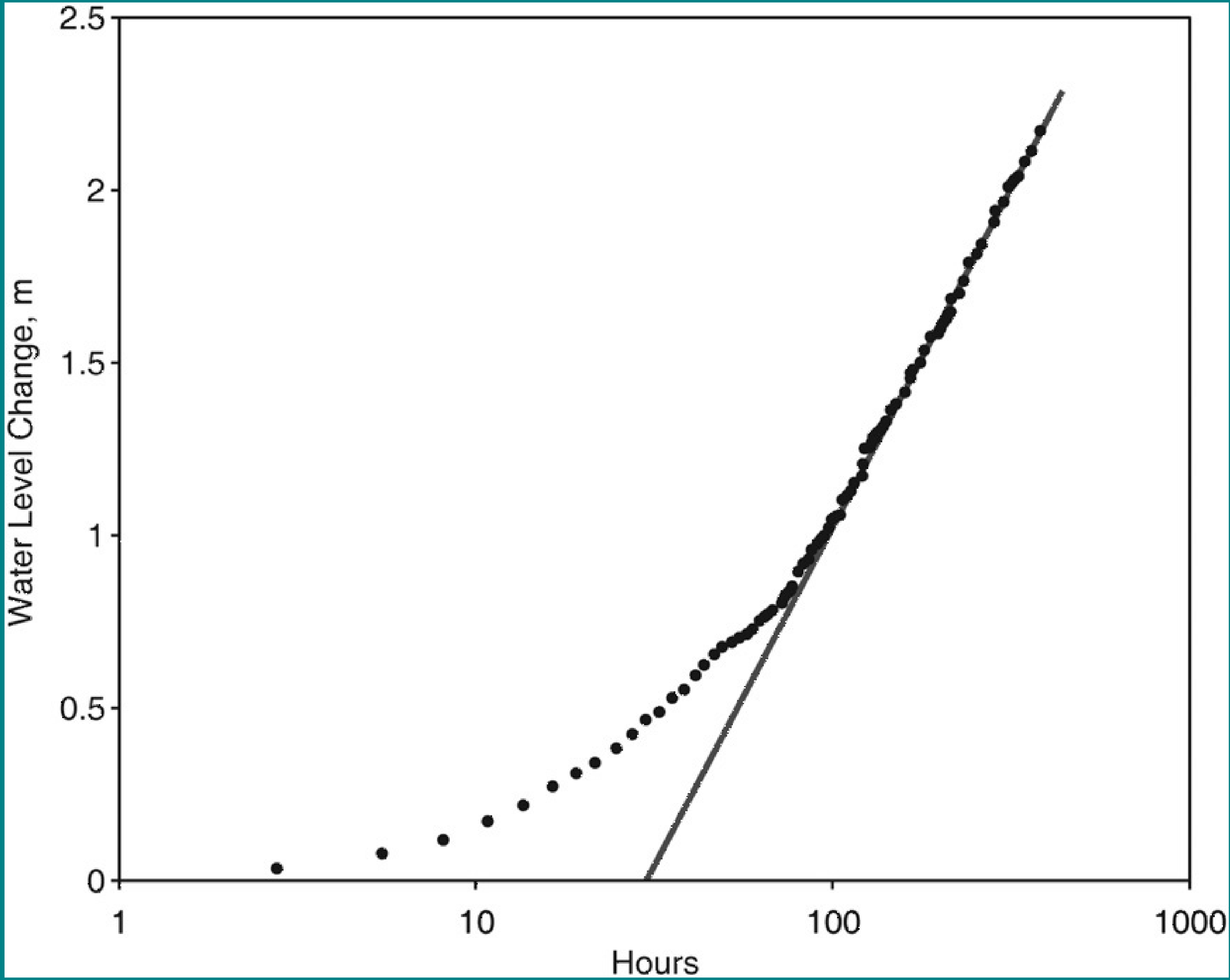
Character of curve determined by

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

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

Exercise

- Determine
  $T = kh/\mu$
  $S = \varphi ch$
- T = 275°C
- Viscosity 0.1 mPa.s
- Flow rate 0.084m^3/s
- 1 bar corresponding to 9.8 m water level

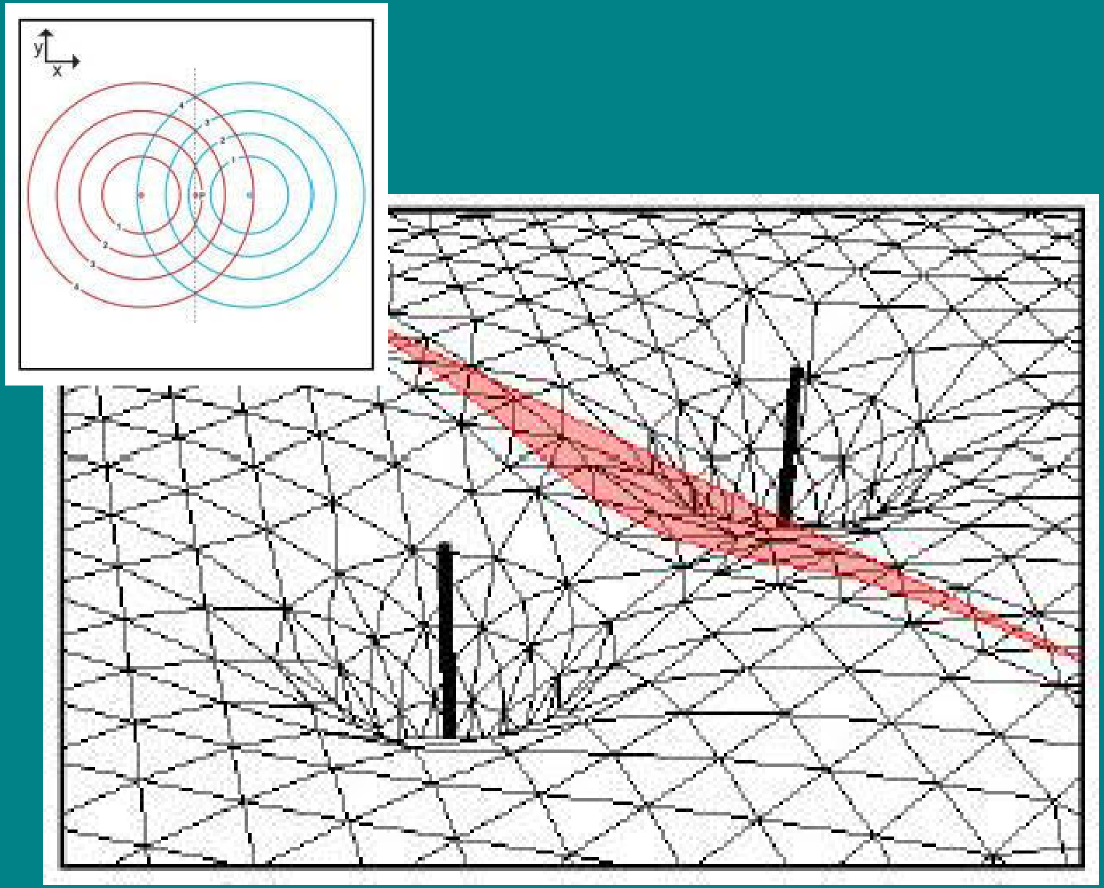


Superposition

- Linear equation allow superposition of solutions

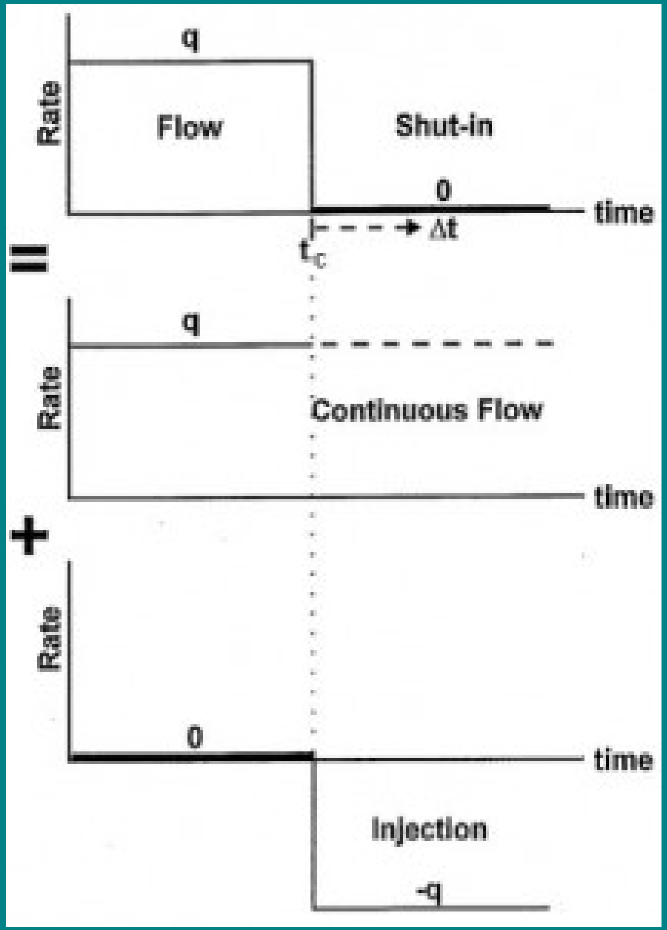
$$\varphi c\rho \frac{\partial (P_1 + P_2)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\rho k}{\mu} r \frac{\partial (P_1 + P_2)}{\partial r}\right)$$

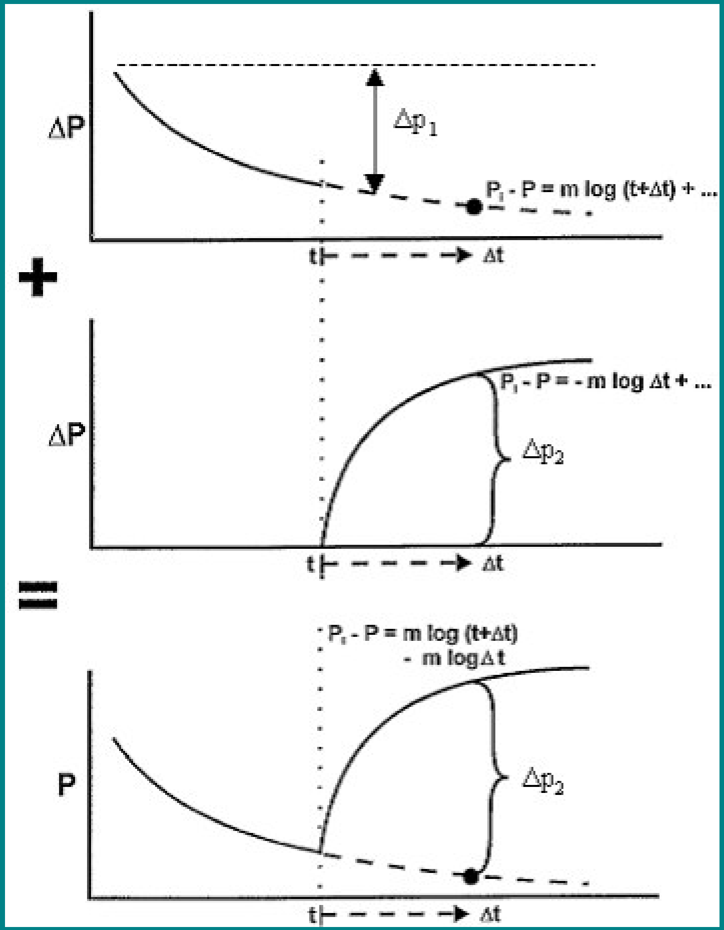
- Sealing fault: Employ "Image well" to address boundary condition



For finite production/injection time

- Two periods
  - Opposite sign (production / injection)
  - Delayed start
- Superposition of partial solutions
- After shutin:
- $\Delta P = m(\log_{10}(t + \Delta t) -$





Closed reservoir

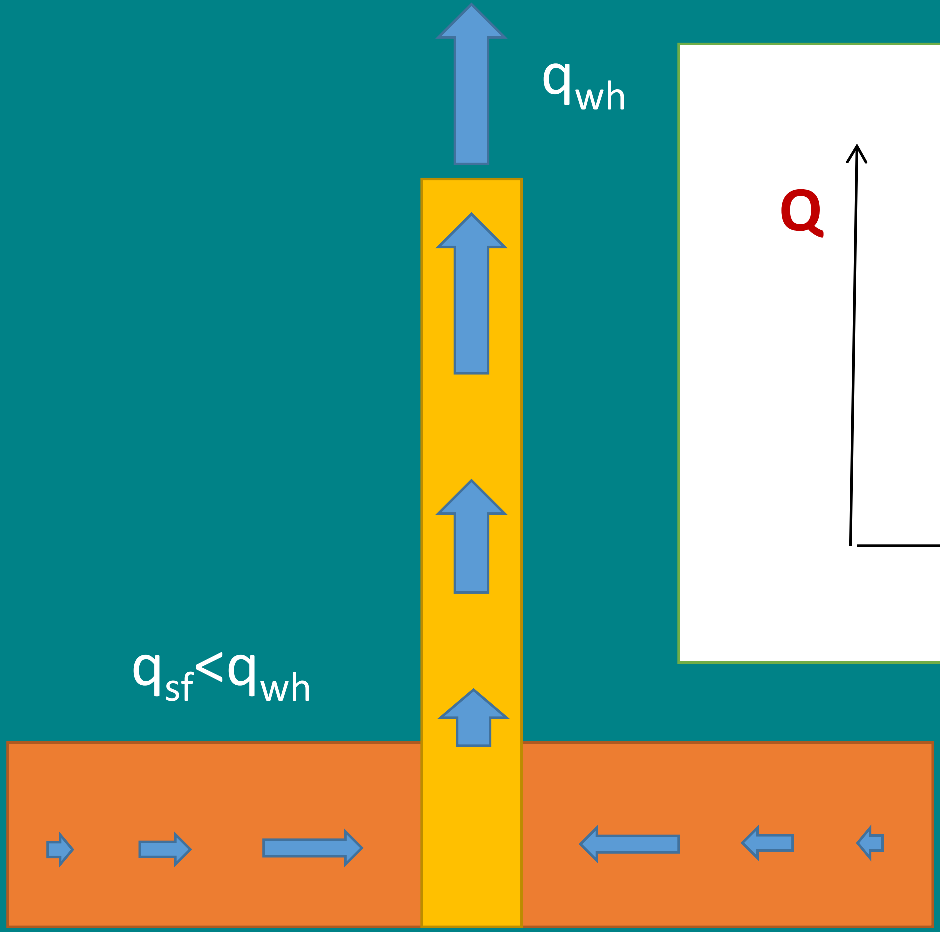
- Late time for a closed reservoir: Semi-steady state solution – pressure time derivative constant and homogeneous:

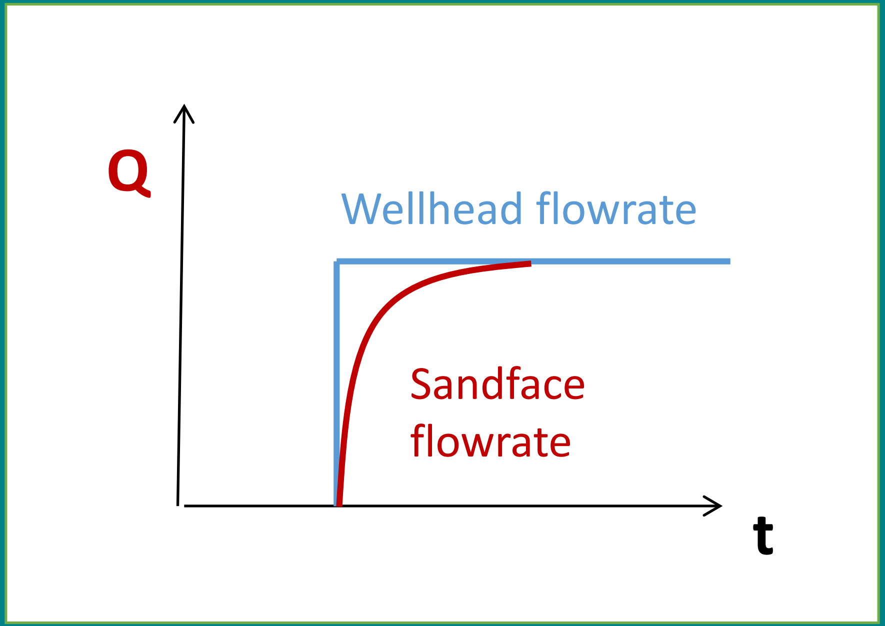
$$\frac{\partial p}{\partial t} = -\frac{q}{c\pi r_e^2 h\phi}$$

$$p_e - p_{wf} = \frac{q\mu}{2\pi kh}\left(\ln\frac{r_e}{r_w} - \frac{1}{2}\right)$$

- But the global increase in pressure starts after pressure disturbance has reached the reservoir boundaries

Wellbore Storage





- Drawdown test
- Effect of fluid expansion in the wellbore
- In geothermal: Additional effect of flashing and condensation

Wellbore Storage

- Wellbore storage coefficient containing fluid compressibility and wellbore volume:

$$C = \frac{\Delta V}{\Delta P} = cV_w$$

- With dimensionless wellbore storage coefficient:

$$q_D^{sf} = 1 - C_D \frac{\partial p_D}{\partial t_D}$$

$$C_D = \frac{C}{2\pi c\phi h r_w^2}$$

Skin

- Damaged zone in vicinity of wellbore

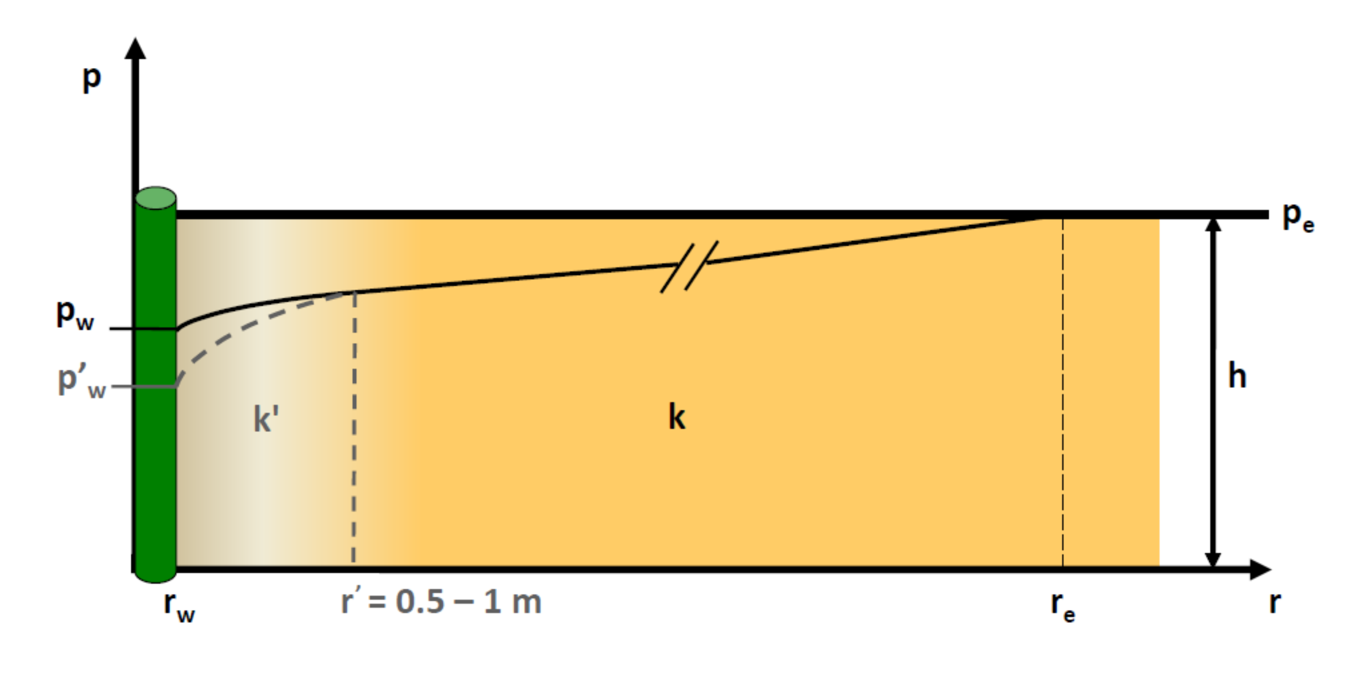
$$p_w = p_e - \frac{q\mu}{2\pi kh}\ln\frac{r_e}{r_w}$$

$$p'_w = p_w - \Delta p_S$$

$$= p_e - \frac{q\mu}{2\pi kh}\left(\ln\frac{r_e}{r_w} + S\right)$$

$$\Delta p_S = \frac{q\mu}{2\pi kh}\left(\frac{k}{k'} - 1\right)\ln\frac{r'}{r_w}$$

$$= \frac{q\mu}{2\pi kh}S$$



$$S = \left(\frac{k}{k'} - 1\right)\ln\frac{r'}{r_w}$$

$S > 0$: Permeability reduction (damage)

$S < 0$: Permeability increase (stimulation)

Skin

- Essentially an additional pressure drop

- Can be mimicked by an “effective wellbore radius”

$$\ln\frac{r_e}{r_w'} = \ln\frac{r_e}{r_w} + S$$

$$r_w' = r_w e^{-S}$$

Wellbore conditions

Often not fully penetrating vertical well in homogeneous reservoir...

- Intersecting fracture
- Partial penetration
- Horizontal well
- Slanted well

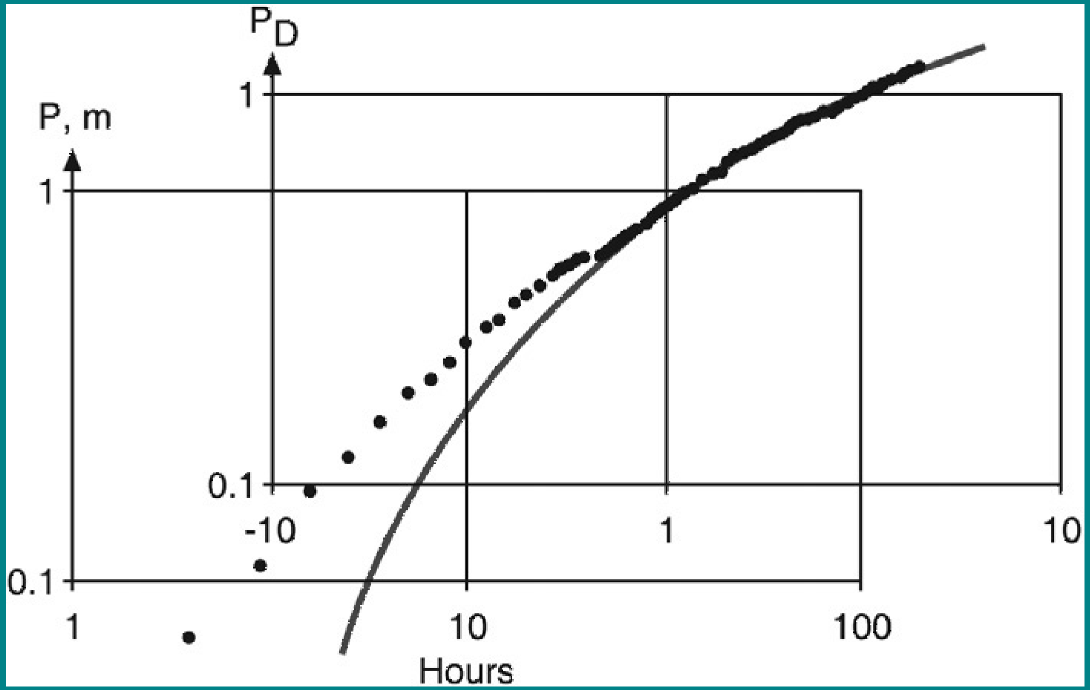
Classical well test analysis

- Formulate solution for dimensionless variables – log-log type curves

$$P_D = \frac{2\pi kh}{q\mu}\Delta P$$

$$t_D = \frac{kt}{\phi\mu c r^2}$$

- Fit type curves to measurement by shifting
- Calculate T and S from shifts



Exercise

- Type curve matching exercise (##Sutopo##)
- Can this be done with Sapphire?
- Is it possible to obtain storage???

Semi-log analysis

For long times

$$\Delta P = -\frac{q}{4\pi T} E_1$$

$$\approx -m\left(\log_{10}\frac{4kt}{\phi\mu c r^2} - 0.251\right)$$

$$m = \frac{2.303 q\mu}{4\pi k h}$$

Straight line on semi-log plot

Slope m

$$\frac{kh}{\mu} = \frac{2.303q}{4\pi m} = \frac{2.303W}{4\pi m\rho}$$

Value ΔP at t

$$\phi c h = 2.25\frac{kht}{\mu r^2}10^{\frac{\Delta P}{m}}$$

Pressure derivative analysis

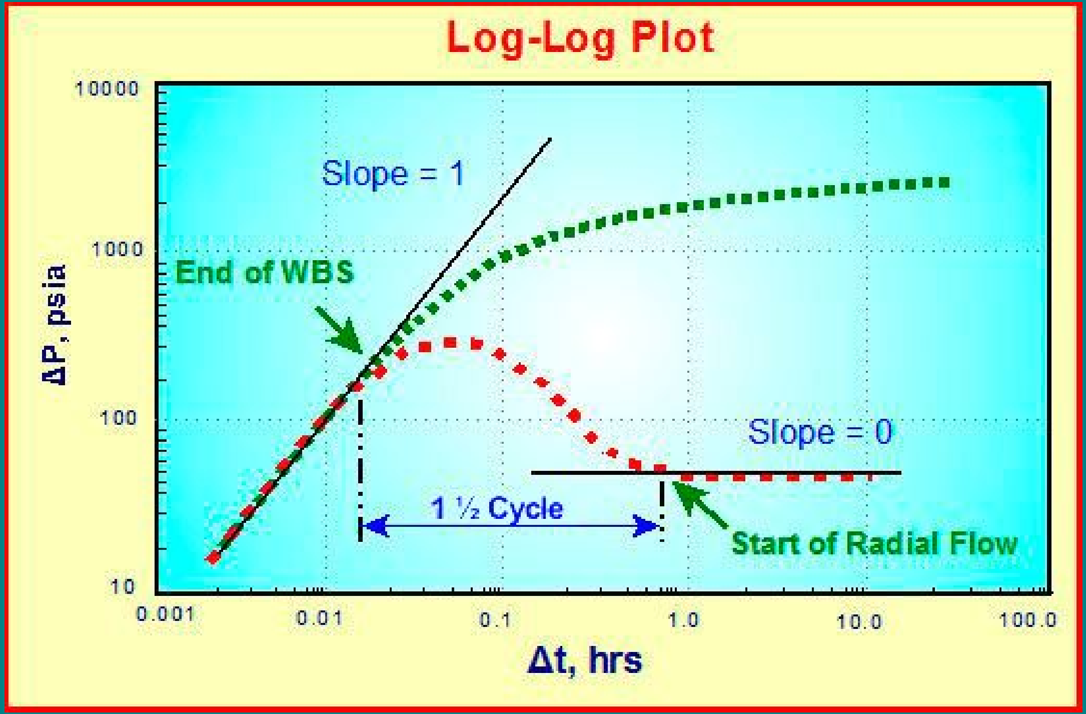
- Bourdet (1983) Observations:
  - Infinite acting reservoir with radial flow: $dP \propto \ln \Delta t$
  - Wellbore storage: $dP \propto \Delta t$
  - Late-time closed reservoir: $dP \propto \Delta t$
- Introduced

$$\Delta p' = \frac{dp}{d \ln \Delta t} = \Delta t \frac{dp}{dt}$$

- Possible thanks to precise pressure measurements

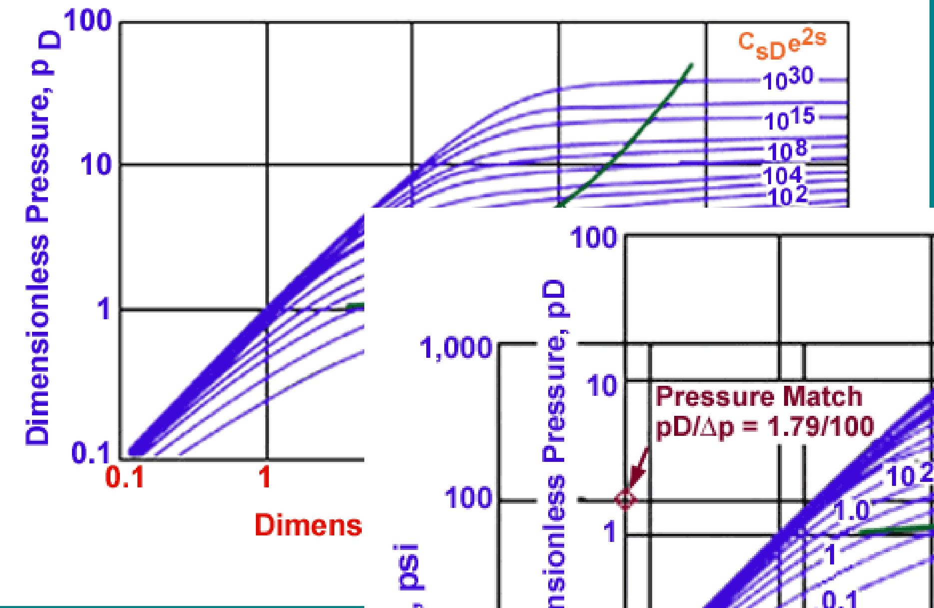
Type curves

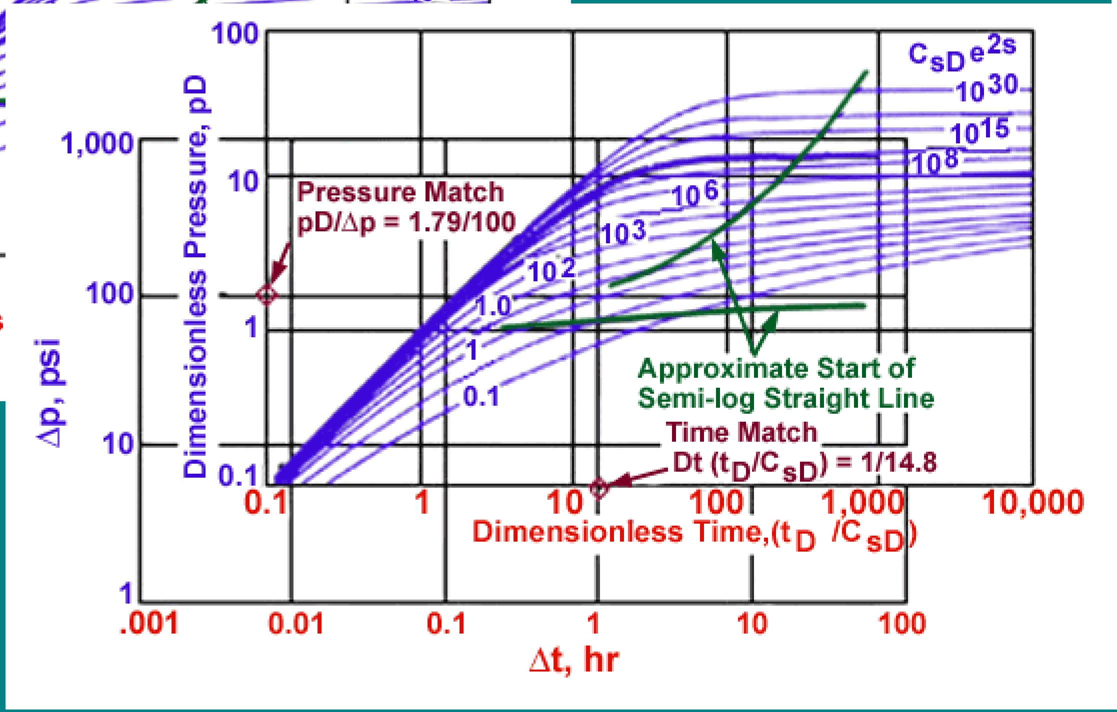
- Pressure response often difficult to interpret
- Slowly changing between flow regimes
- Pressure derivative gives typical response for different regimes

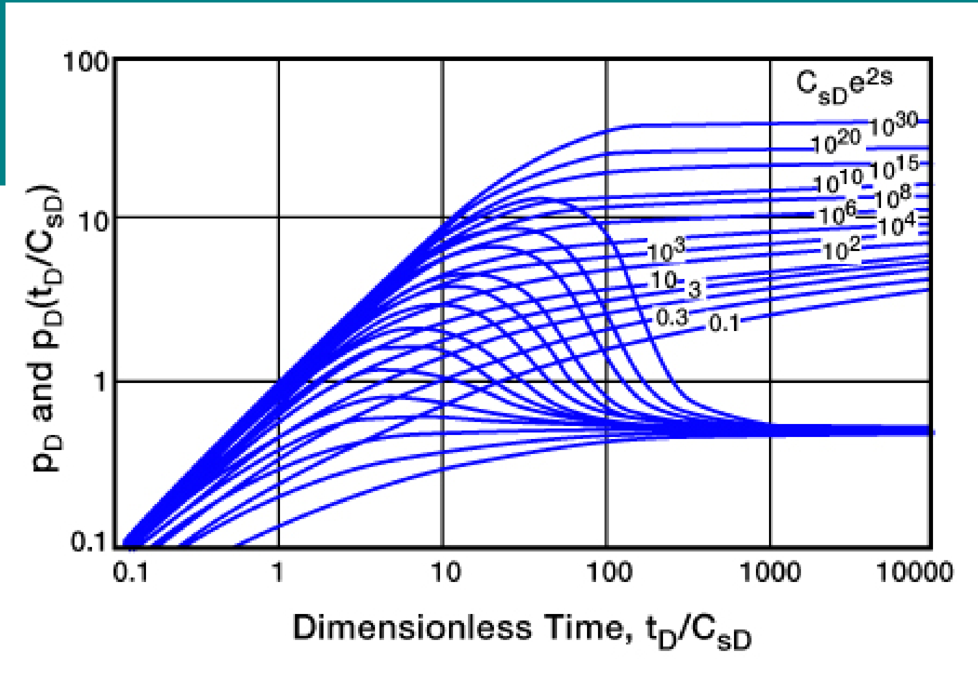


37

Type curves to identify Wellbore storage and Skin

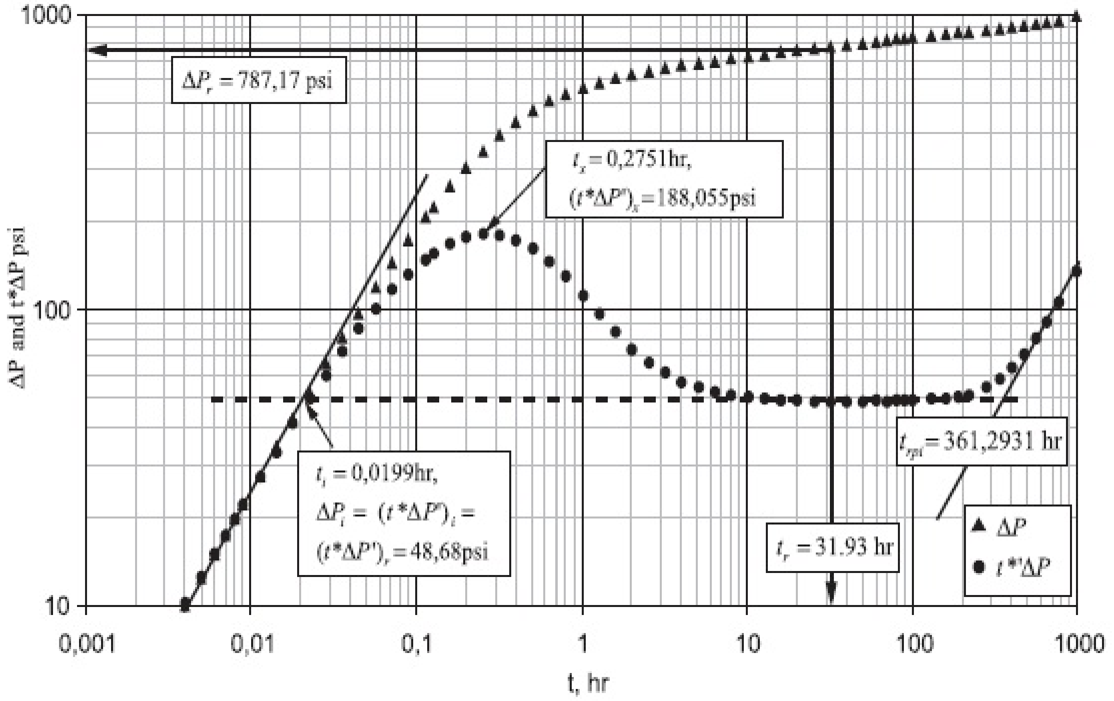


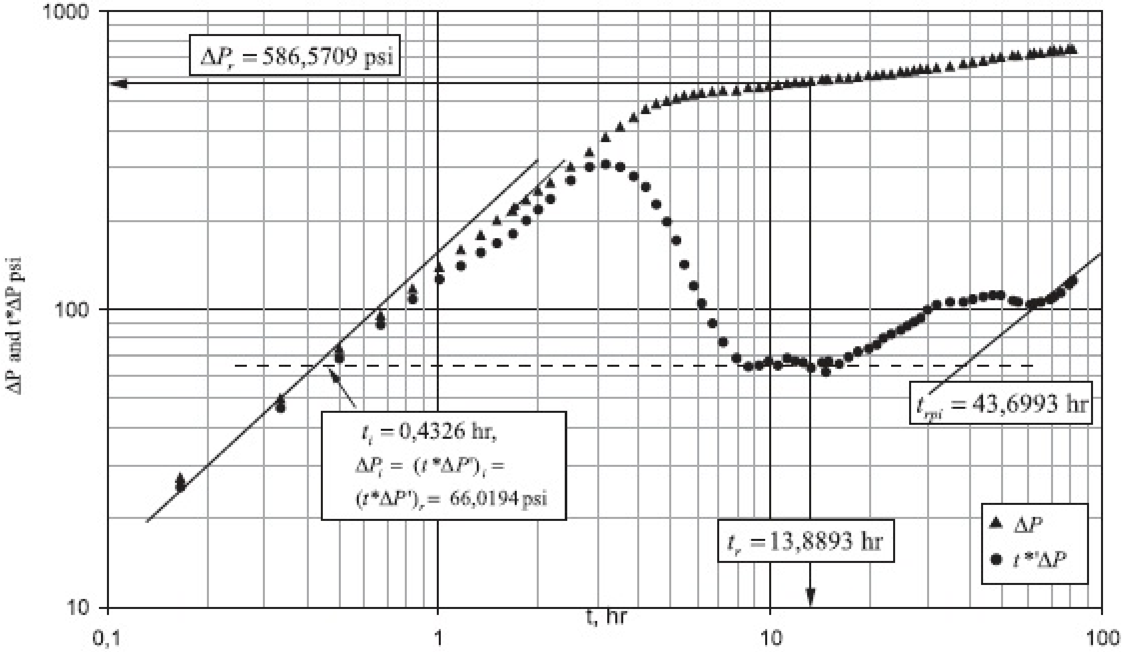




Demonstration

- Wellbore storage
- Skin
- Radial flow
- Reservoir boundary
- Bounding fault





Exercise

- Use Sapphire with a field test to identify permeability, skin, wellbore storage, reservoir size…

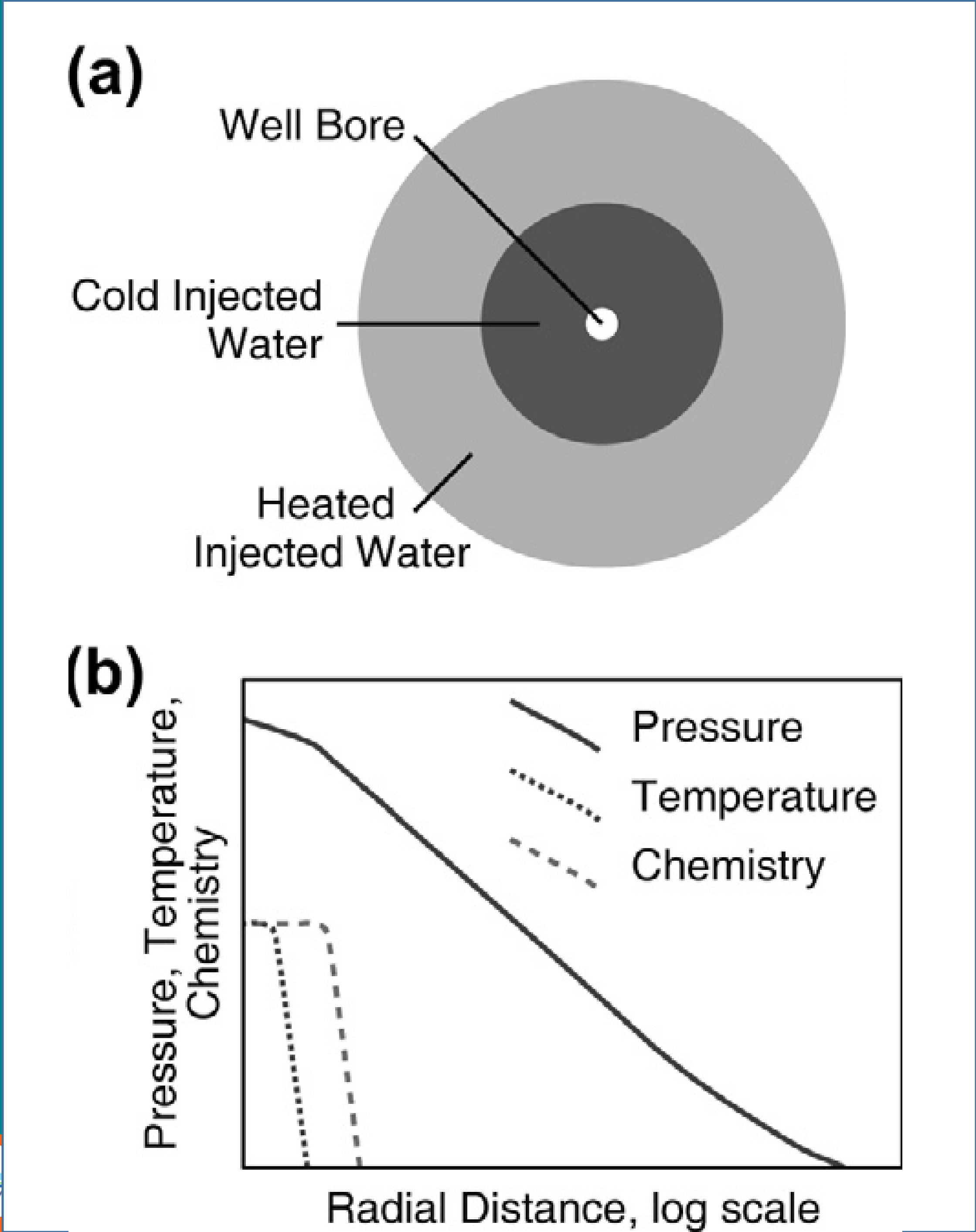
Injection

The reverse of production – but

- Possibly different fluid phases (chemistry)
- Cooled part of rock

Far-field response is that of reservoir fluid

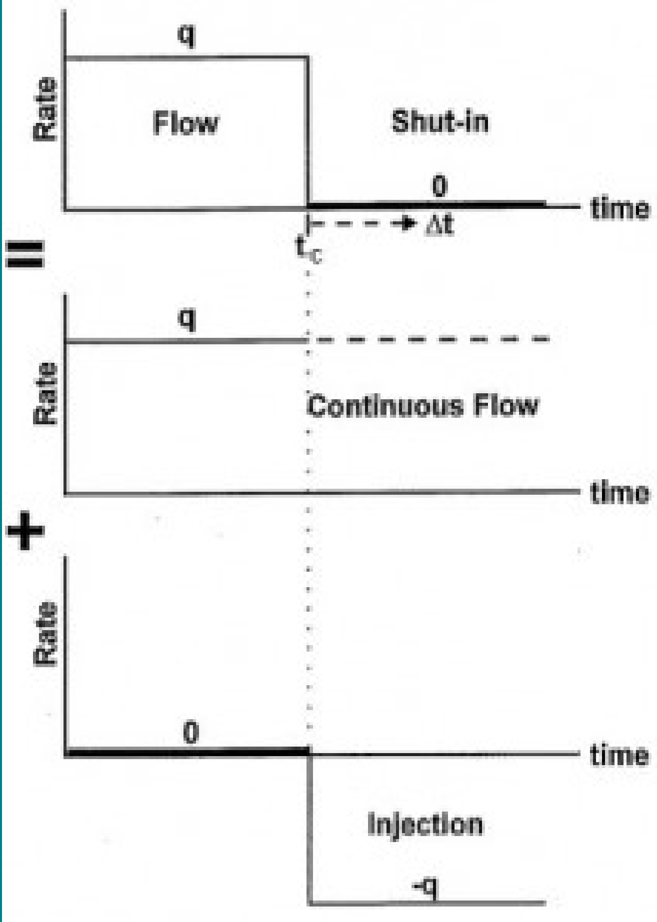
- Match near-well behaviour with effective skin
- Thermal stimulation

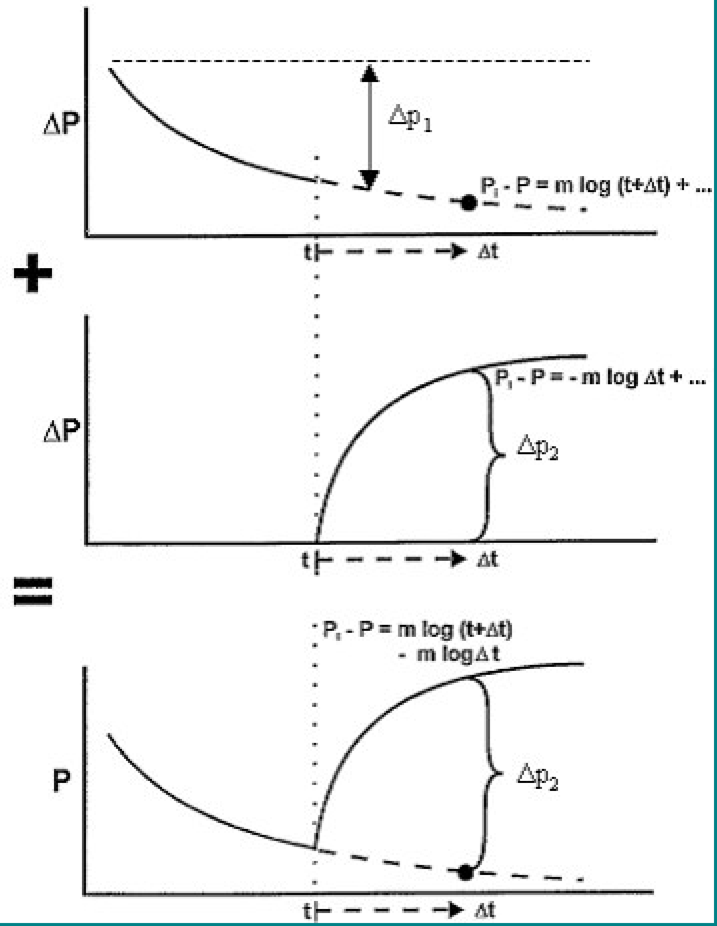


Pressure buildup – Horner

$$\Delta P = m\log_{10}(\mathrm{t} + \Delta t) - m\log_{10} t = m\log_{10}\frac{\mathrm{t} + \Delta t}{t}$$

- Plot against $\log_{10}\frac{\mathrm{t}+\Delta t}{t}$

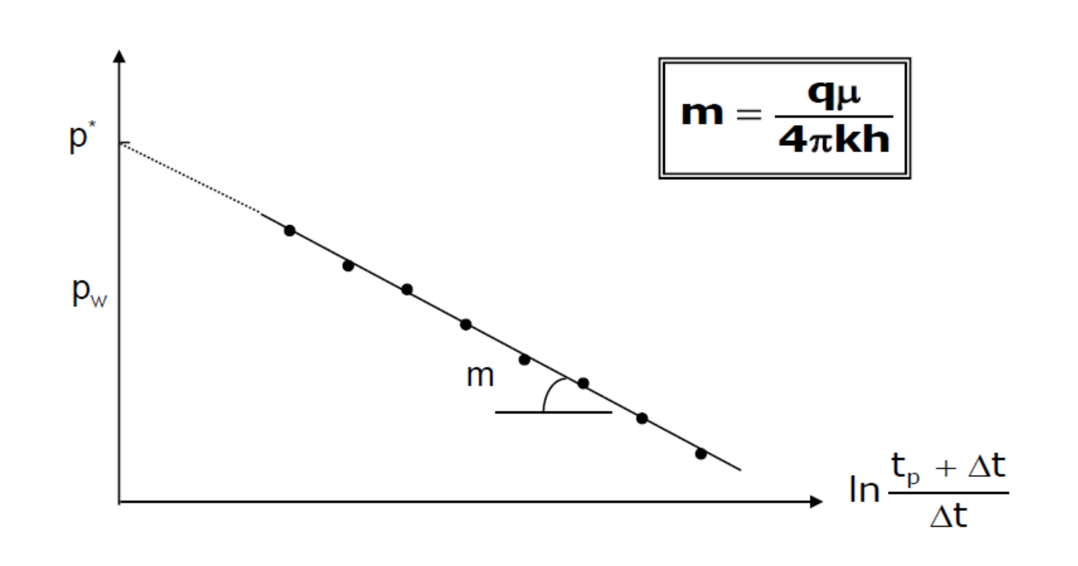




Horner plot

$$p = p^* - \frac{q\mu}{4\pi kh} \ln \frac{t_p + \Delta t}{\Delta t}$$

- Extrapolate to y-axis ($\Delta t = 0$) to obtain average reservoir pressure



III Geothermal Well Testing

- Fluid properties
- Temperature transients
- Heterogeneous reservoirs

Gas flow

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

Define pseudo pressure to address non-linearity

$$m(P) = \int_{P_{ref}}^{P} \frac{\rho dP}{\mu} = \frac{M}{RT} \int_{P_{ref}}^{P} \frac{P dP}{\mu Z}$$

$$\varphi \mu c \frac{\partial m}{\partial t} = k \nabla^2 m$$

Two-phase flow

- Standard procedure but
  - Compressibility – dependent on steam-water transition enthalpy
  - Density
  - Relative permeability
  - Viscosity

Temperature transients

- To determine the reservoir pressure after drilling-induced cooling
- For conduction only:

$$\rho_t C_t \frac{\partial T}{\partial t} = K \nabla^2 T$$

- Again: Horner plot

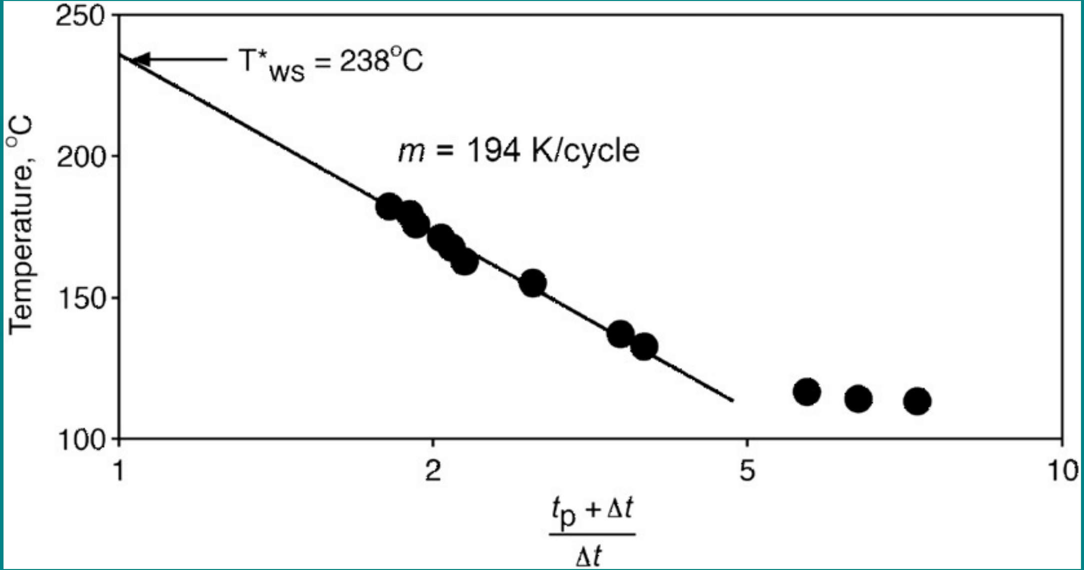
$$T = T^* - m \ln \frac{t_p + \Delta t}{\Delta t}$$

Temperature transients

- Cooling phase: Constant temperature; not constant heat flux
- Correction term:

$$T = T^*_{WS} + mT_{DB}(t_{PD})$$

$$t_{PD} = \left(\frac{K}{\rho_t C_T r_w^2}\right) t_p \approx 0.4 \cdot t_p(hr)$$



Reservoir heterogeneity

- Dual-porosity reservoir
- Dual-permeability reservoir
- Composite reservoir

Dual-porosity reservoir

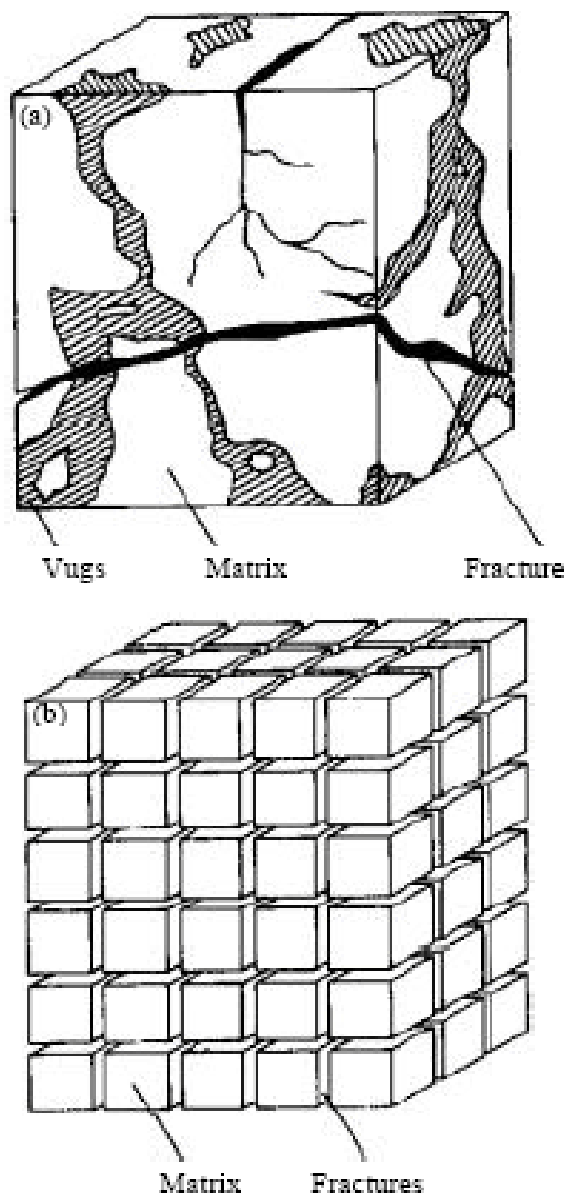
- Reservoir with fissures / fractures
- Flow mainly through fissures

$$kh = k_f h_f$$

- Storage in mainly in matrix

$$\phi = \phi_f V_f + \phi_m V_m \approx V_f + \phi_m$$

- Model assumption:
  Two communicating sub-models
  occupying the “same” volume



Assumptions

- Matrix blocks are small compared to reservoir volume
- Matrix blocks are not connected
- Matrix blocks are homogeneous
- Most storage in matrix blocks

Storativity ratio

$$\omega = \frac{(\phi V c_t)_f}{(\phi V c_t)_f + (\phi V c_t)_m}$$

$$= \frac{(\phi V c_t)_f}{(\phi V c_t)_{f+m}}$$

Assumptions

- Matrix block geometries dependent on number of fissure plane directions *n*:
  - n=3 Cubes / spheres
  - n=2 Cylinders
  - n=1 Slabs
- Flow between matrix blocks and fissures

Interporosity flow coefficient:

$$\lambda = \alpha r_w^2 \frac{k_m}{k}$$

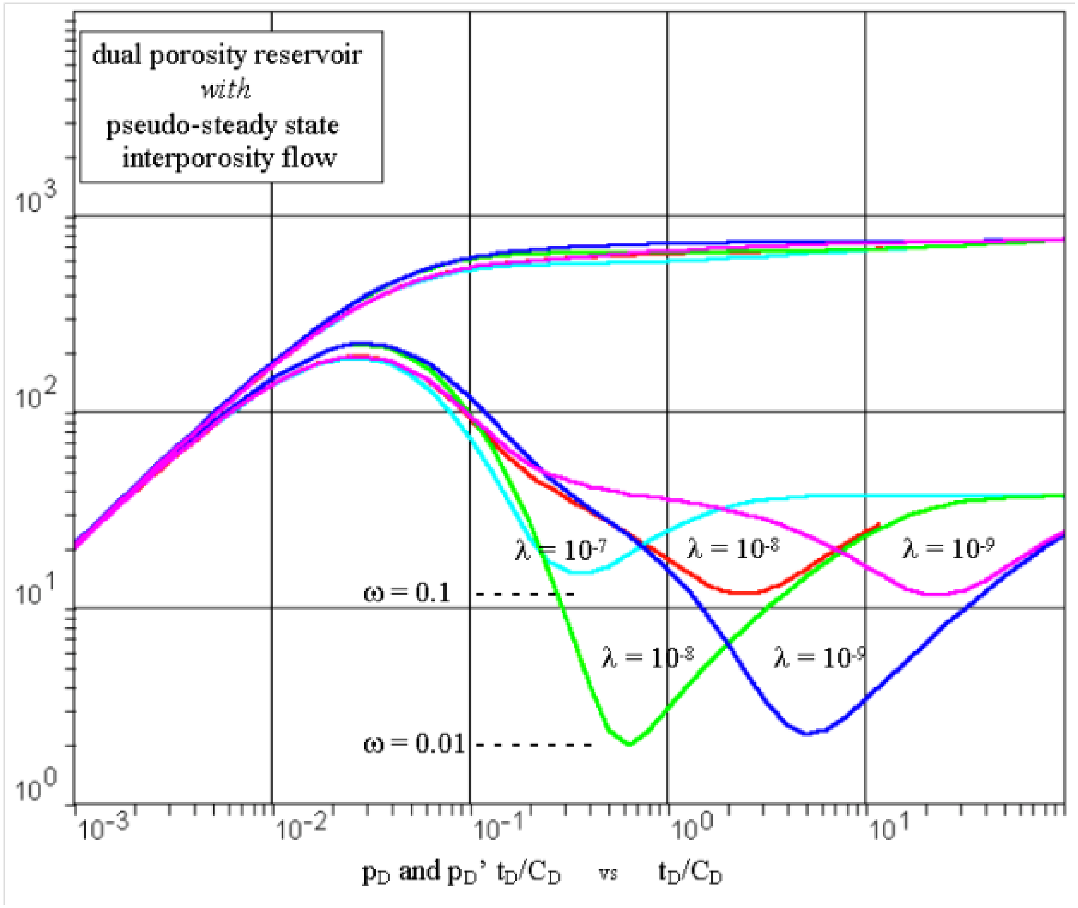
Geometry factor α dependent on characteristic size r_m of matrix blocks

$$\alpha = \frac{n(n+2)}{r_m^2}$$

Warren & Root model

- Matrix flow with skin
- Pseudo-steady state in matrix blocks
- Flow from fissures to well

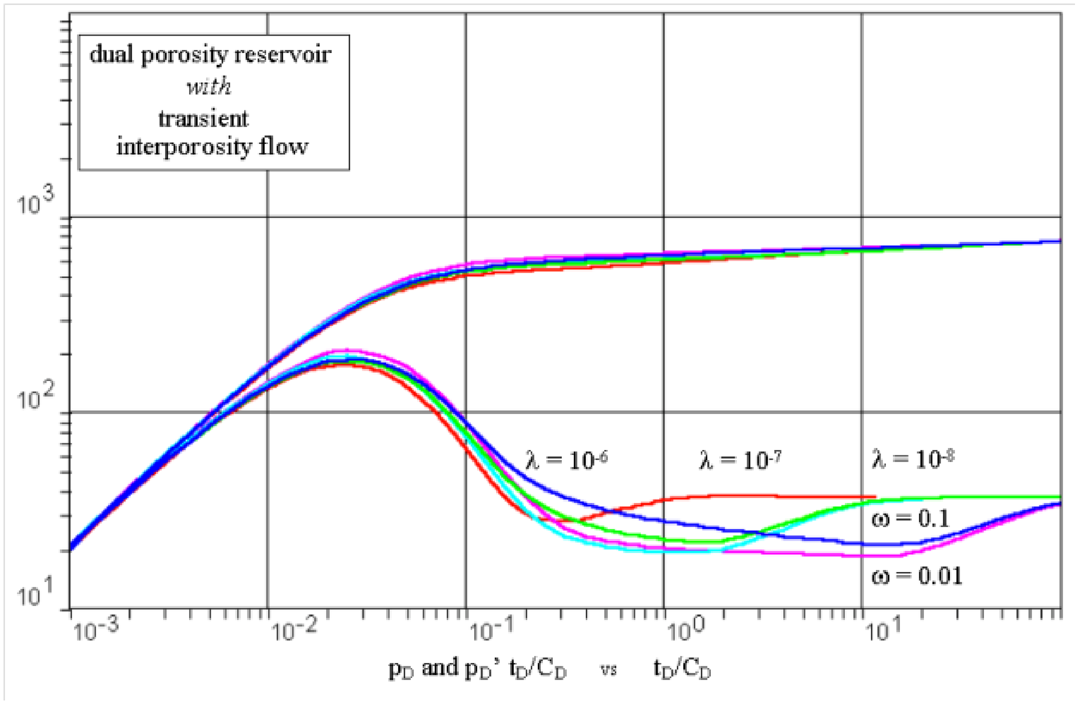
1. Starting with fissure flow
2. Transition
3. Matrix-dominated



Dual porosity, unrestricted interporosity flow

- Transient flow in matrix blocks
- Flow from fissures to well

1. Starting with transitional flow
2. Total-system



Dual-porosity reservoirs

Storativity ratio ω

- Contrast between fissure regime and matrix regime
- Usually no effect for unrestricted interporosity (short-lived fissure flow)

Interporosity flow coefficient λ

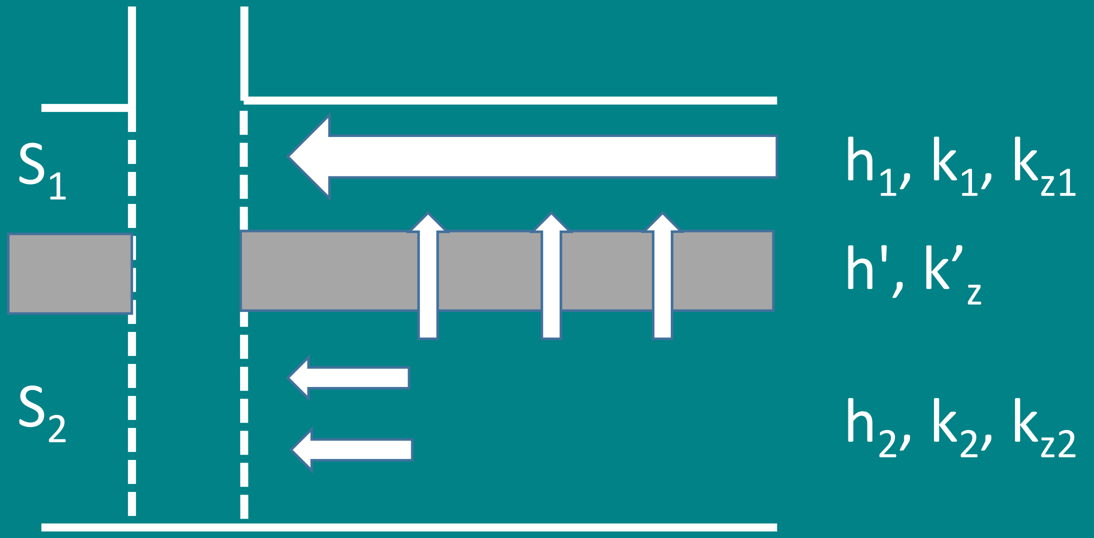
- Defining start of total system flow

Interpretation ambiguity

- Similar response from dual-porosity and sealing fault
- Choose based on geology; interpreted parameters; multiple well responses...
- High wellbore storage + negative skin – indication for possible dual-porosity reservoir

Dual-permeability reservoir

- Layered reservoir
  - With or without crossflow
  - Commingled production or not
- Flow through both layers
- Conceptual model with possible barrier



Conceptual model

- Mobility ratio

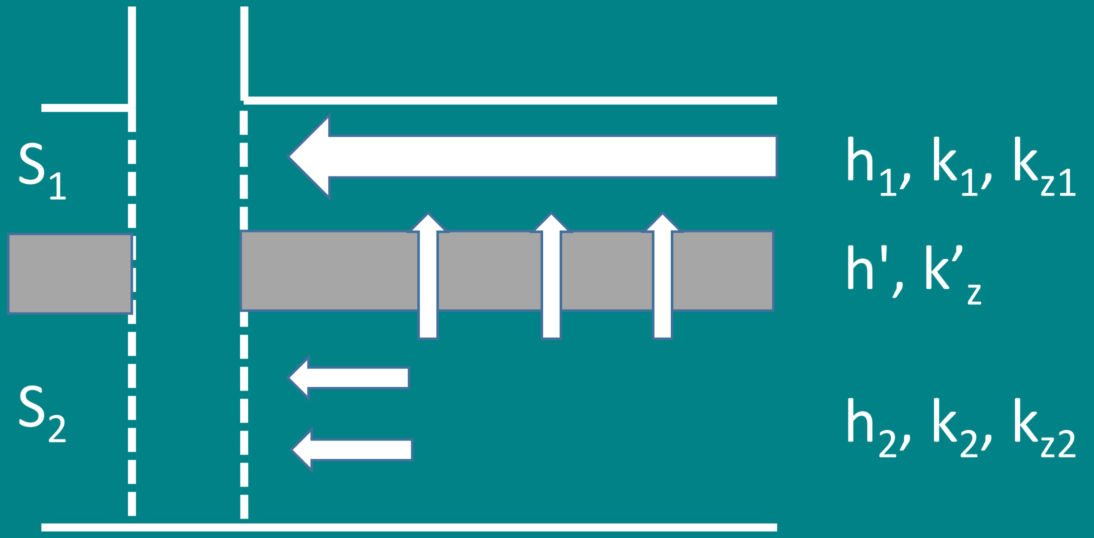
$$\kappa = \frac{k_1 h_1}{k_1 h_1 + k_2 h_2}$$

- Storativity ratio

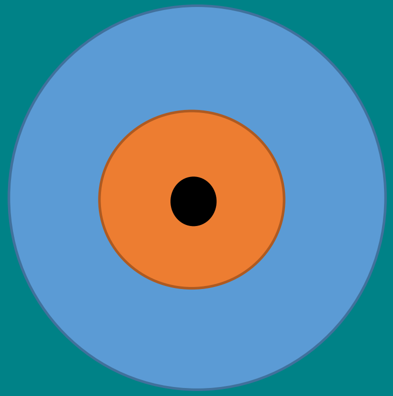
$$\omega = \frac{(\phi c_t h)_1}{(\phi c_t h)_1 + (\phi c_t h)_2}$$

- Interlayer crossflow coefficient

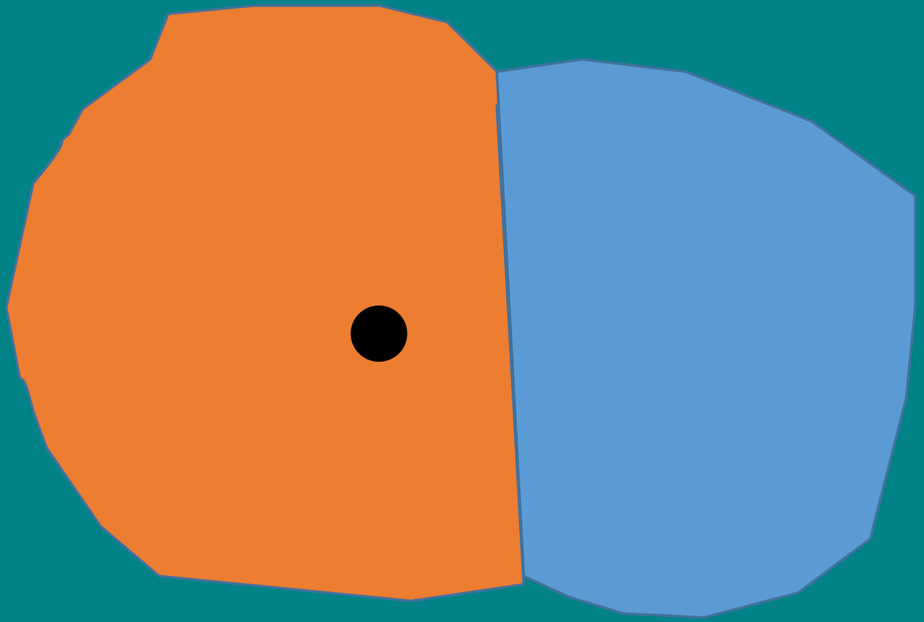
$$\lambda = \frac{r_w^2}{k_1 h_1 + k_2 h_2} \frac{2}{\frac{2h'}{k'_z} + \frac{h_1}{k_{z1}} + \frac{h_2}{k_{z2}}}$$



Composite reservoirs



- Reservoir consisting of distinct media
  - Radially composite
    - Analytical solutions for parts
    - Connect through interface conditions
  - Linearly composite
    - Analytical solutions using images



Exercise

- Exercise dual-porosity well test (Sutopo)
- Exercise interference testing (Sutopo)