WELL TEST ANALYSIS

Nomenclature

k	mD	permeability
B	vol/vol	Formation volume factor
μ	cp	viscosity
$\mathbf{S_o, S_g, S_w}$	fraction	oil, gas, water saturation $S_o+S_g+S_w=1$
c	1/psi	compressibility
$\mathbf{c_t}$	1/psi	Total compressibility $c_t=S_o c_o+S_g c_g+S_w c_w+c_f$

WELL TEST ANALYSIS

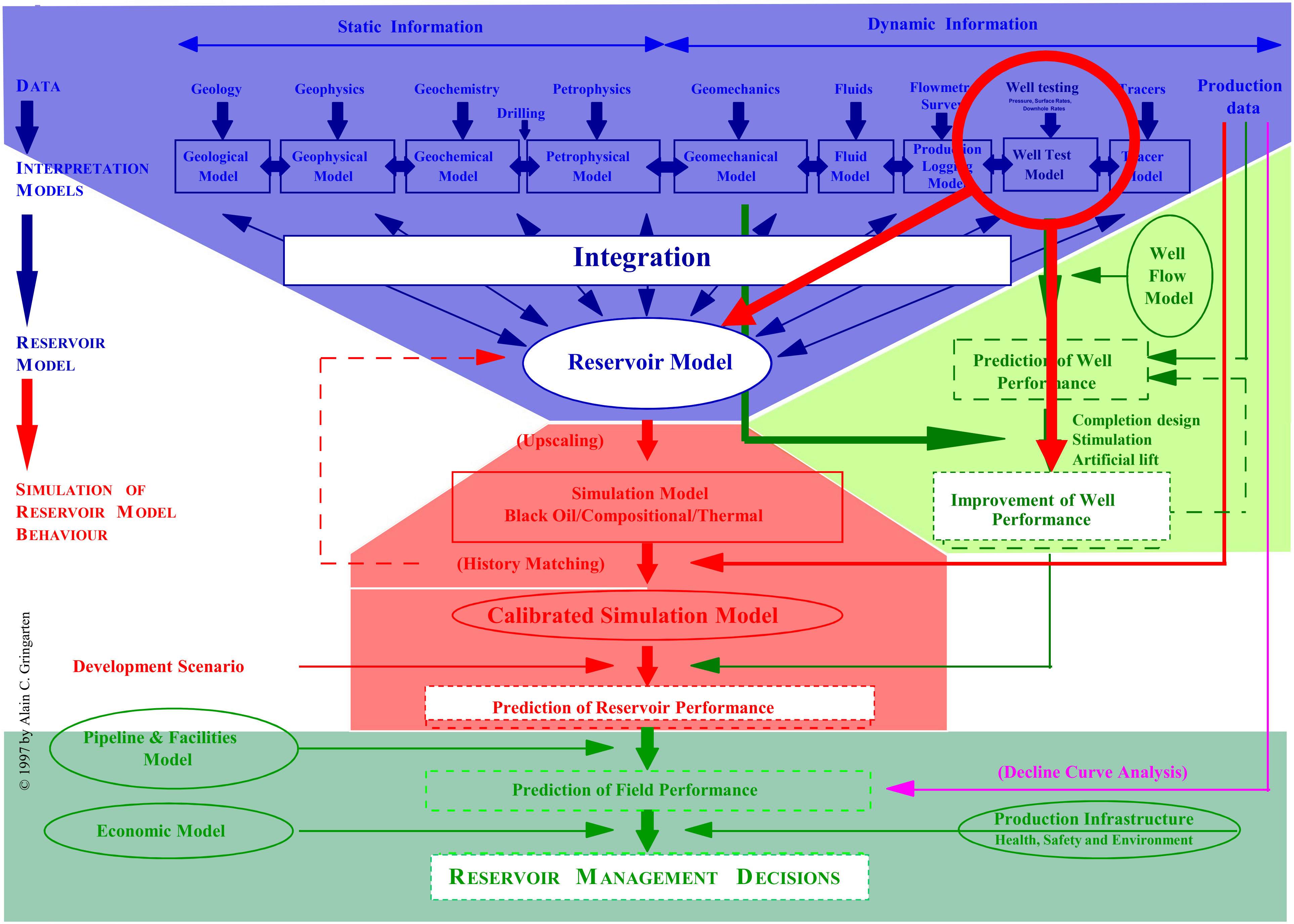
PART OF THE RESERVOIR MANAGEMENT PROCESS

FOR

1- RESERVOIR CHARACTERISATION

2- WELL PERFORMANCE

RESERVOIR MANAGEMENT PROCESS



Gringarten *et al.*, SPE 64311 ATCE Dallas(Oct. 2000)

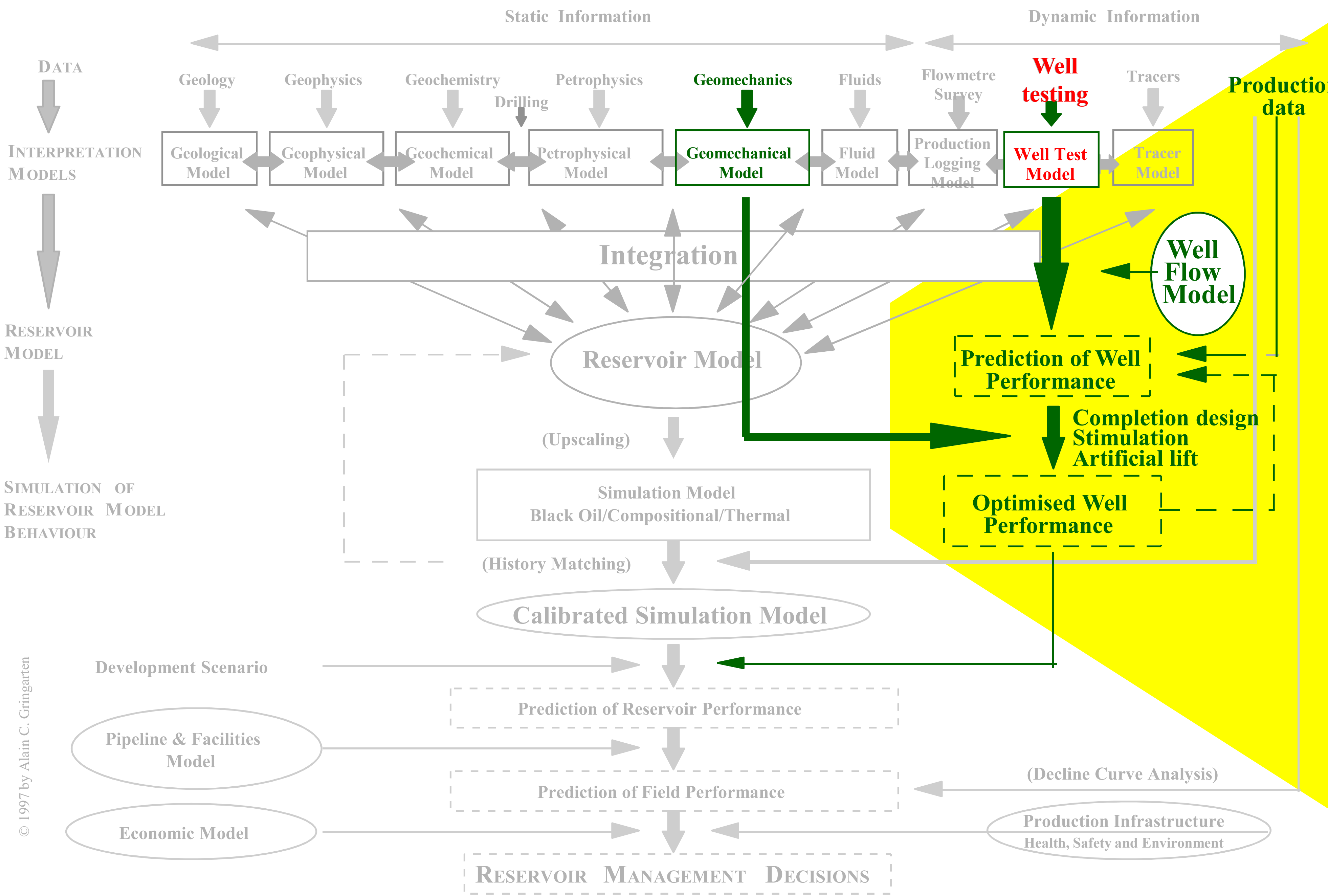
Why do we test wells?

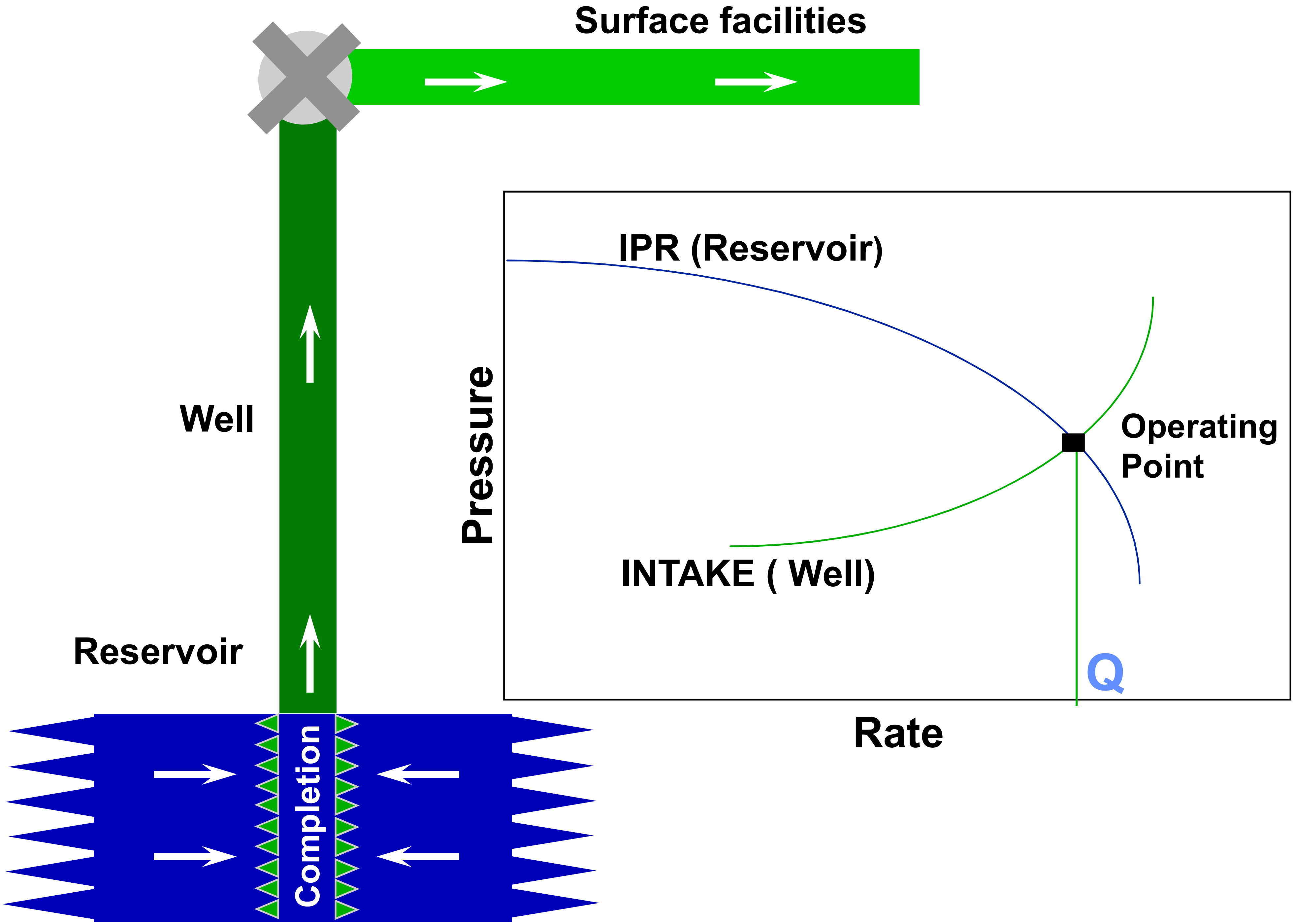
Well performance

- Fluid samples
- Permeability
- Well damage or stimulation (skin effect)
- Average reservoir pressure
- Reservoir heterogeneities
- Reservoir hydraulic connectivity
- Distance to boundaries

Reservoir performance

WELL PERFORMANCE




Surface facilities
Well
Reservoir
Completion
IPR (Reservoir)
Pressure
Operating Point
INTAKE (Well)
Q
Rate

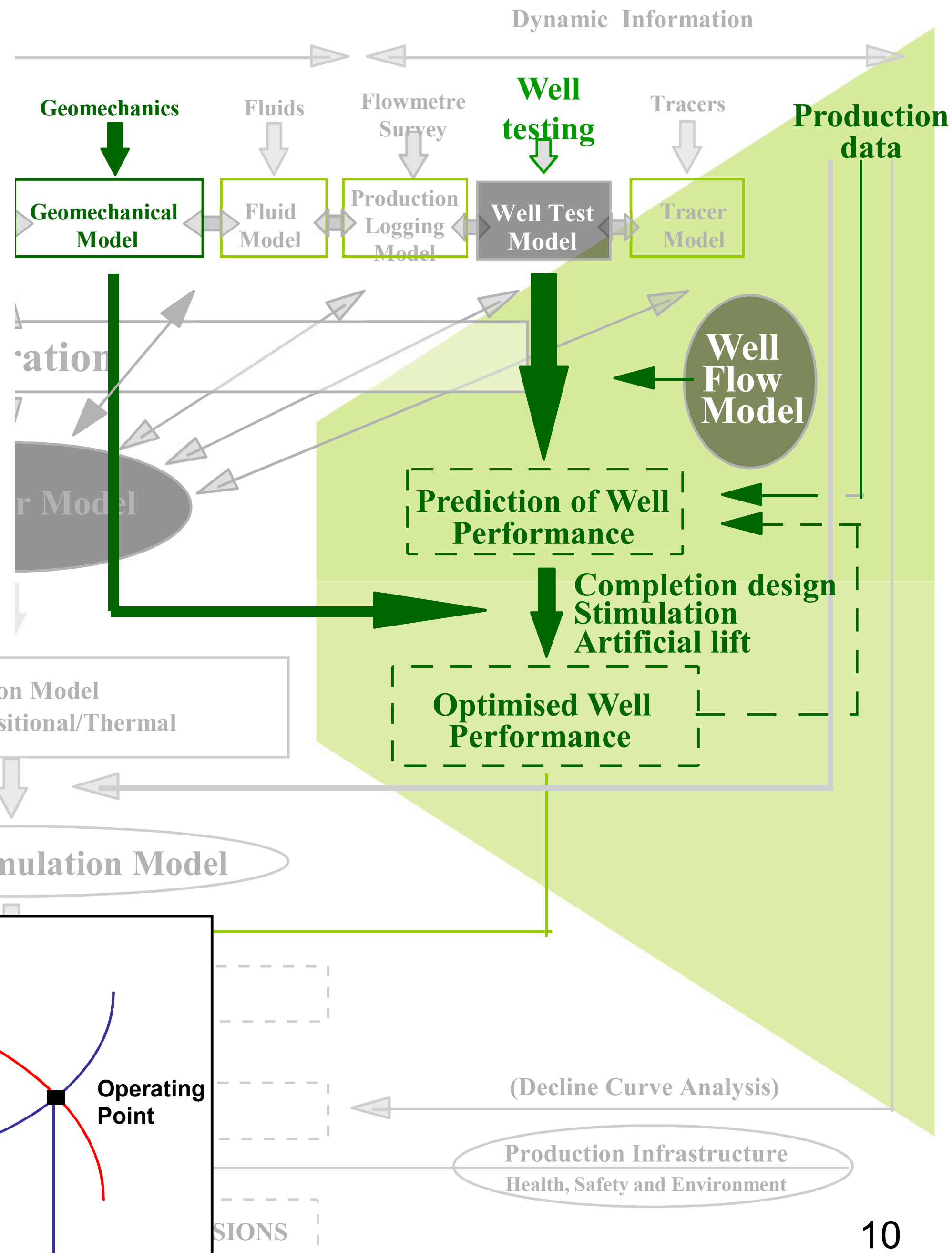
WELL PERFORMANCE

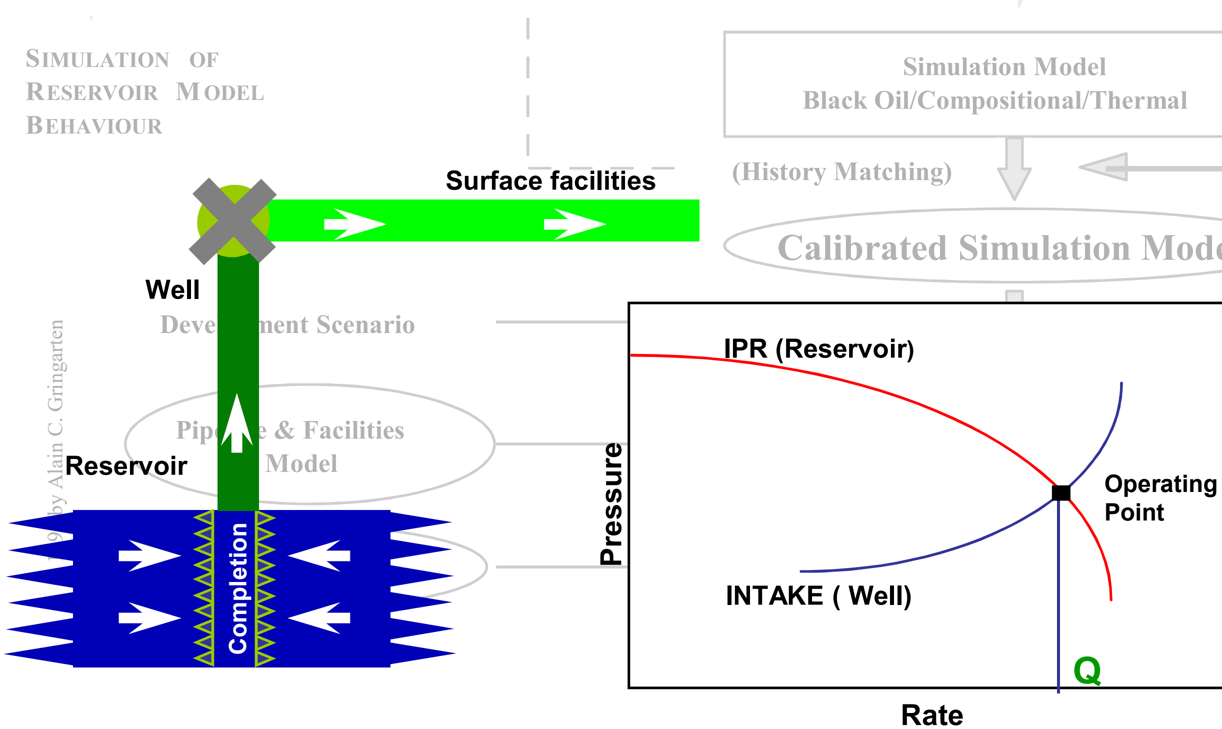
The purpose of well performance analysis (production system analysis, or Nodal analysis) is to:

(1) Assess the current production Q from the reservoir (IPR) and well (Intake) (and possibly surface facilities) together

(2) Evaluate all possible solutions for increasing this production

(3) Determine the optimal solution, both from a technical and economic point of view

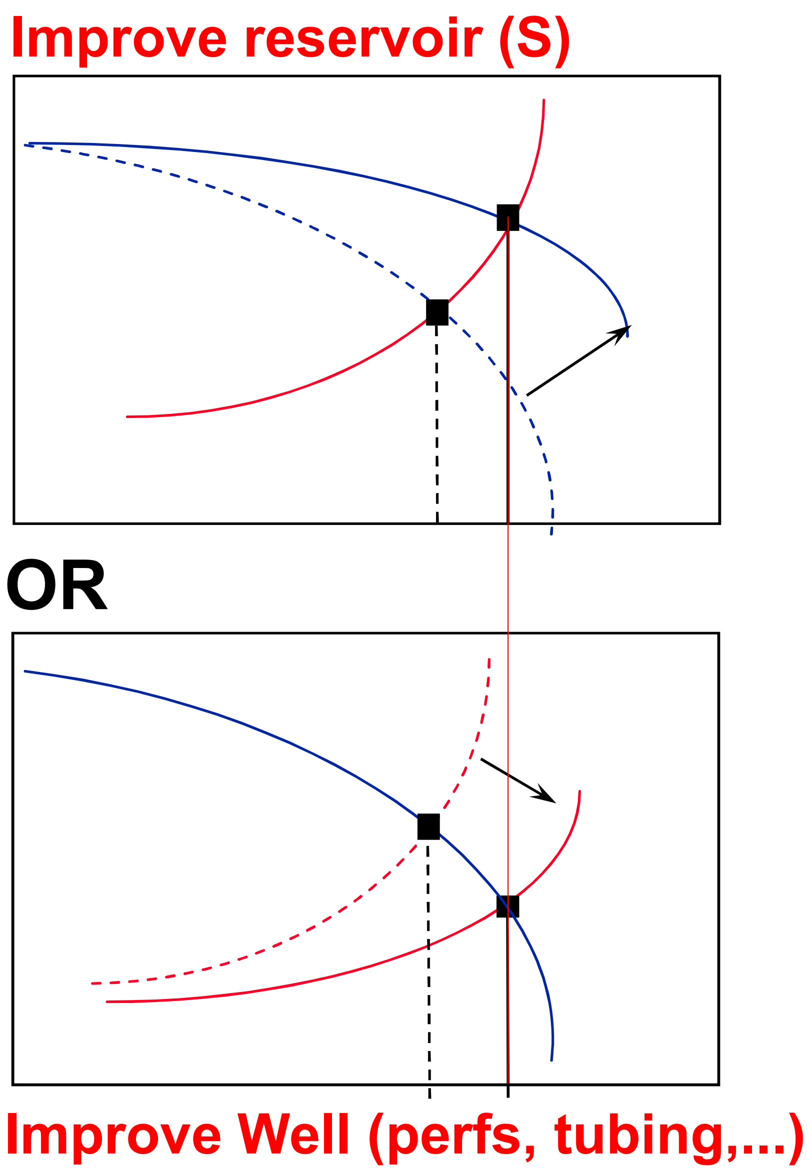


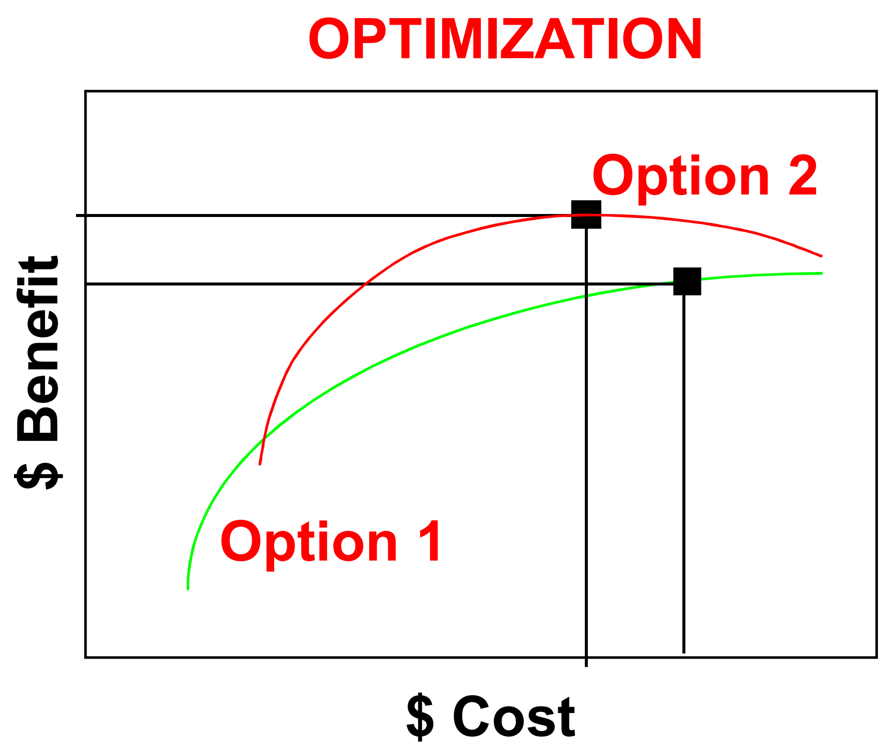


NODAL ANALYSIS™

PRODUCTION OPTIMISATION

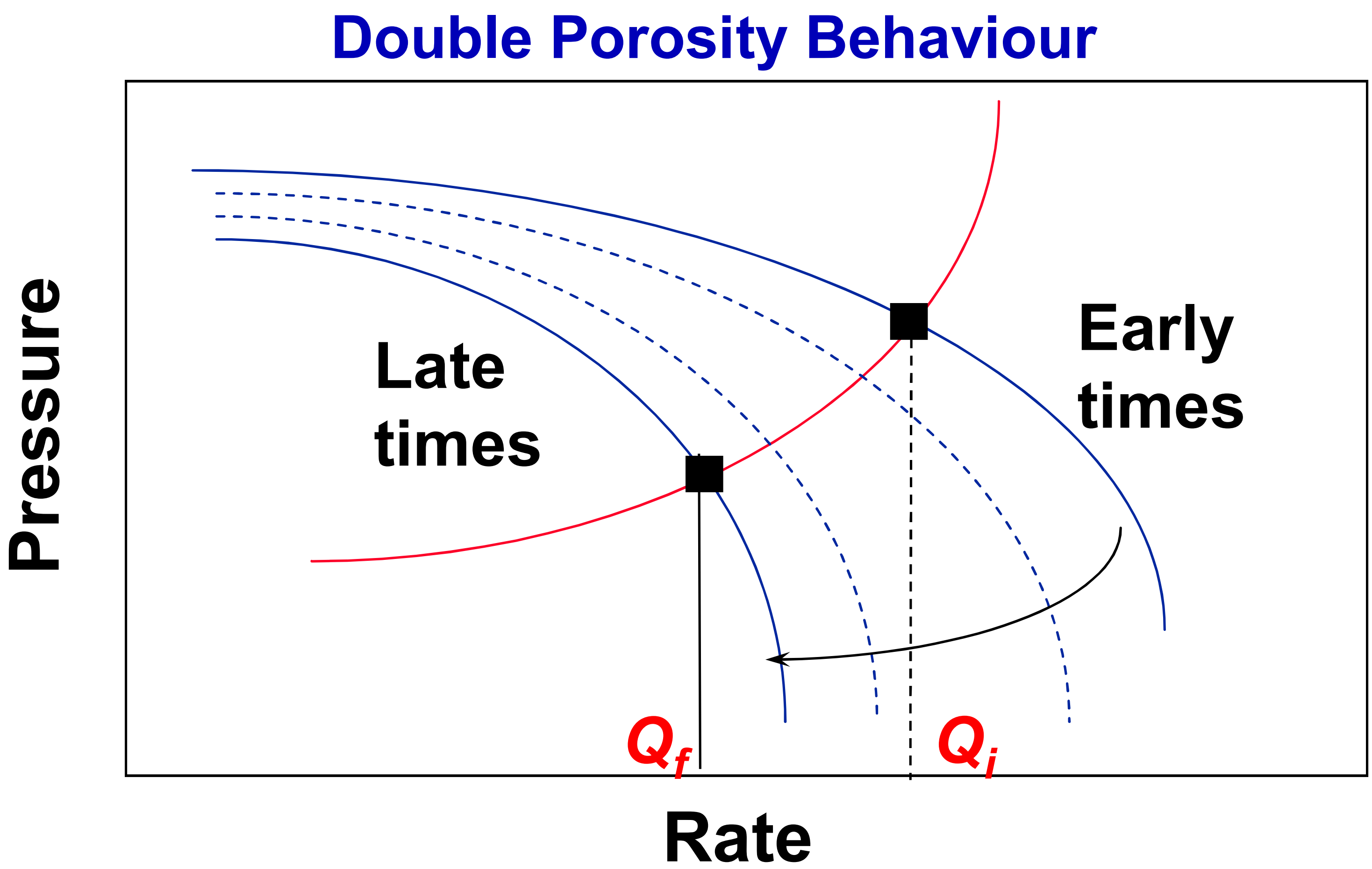
Mach, Proano, and Brown:"A Nodal Approach for Applying Sytems Analysis to the Flowing and Artificial Lift of Oil or Gas Well," *SPE 8025* (March 1979)



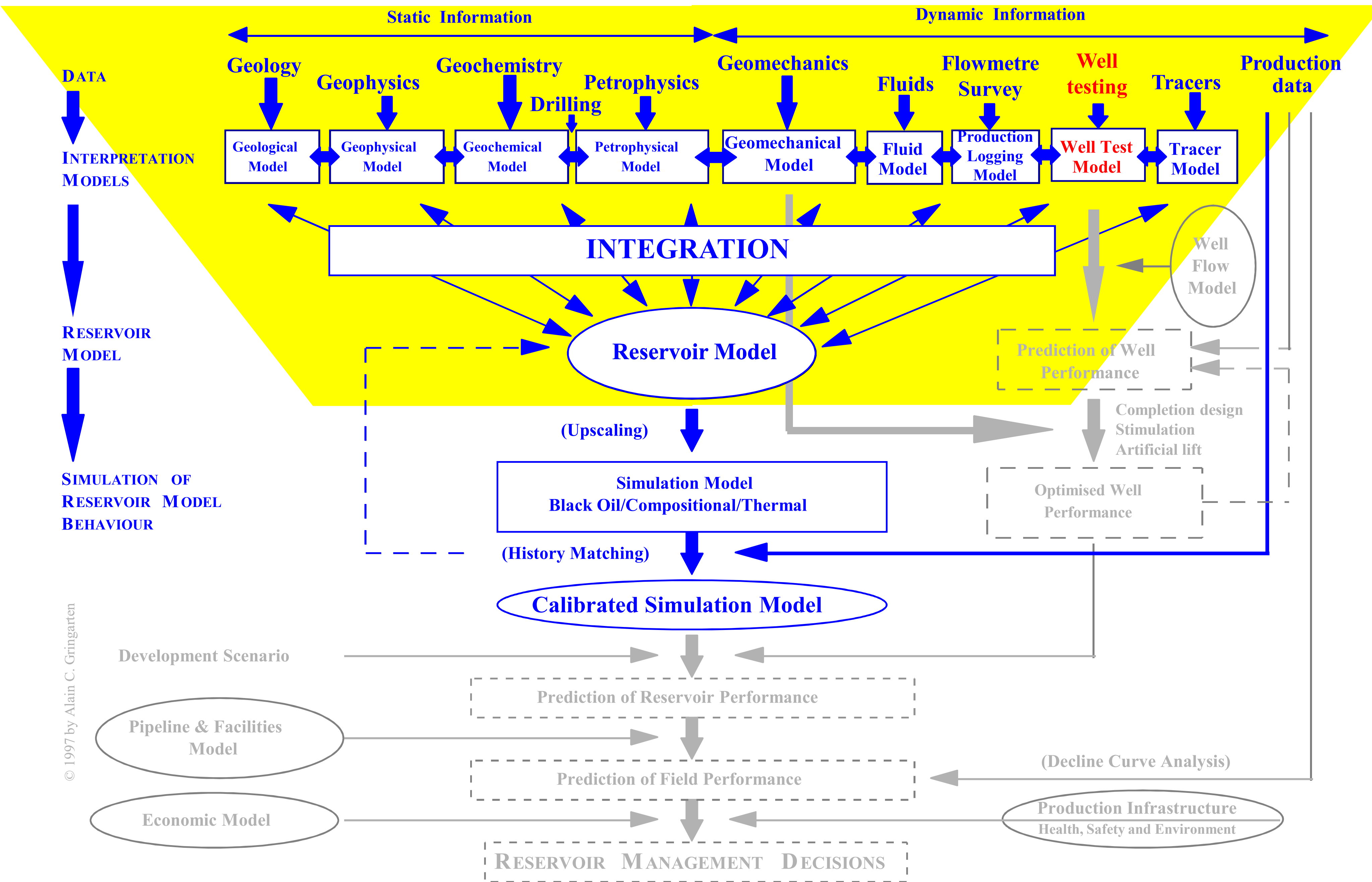


NODAL ANALYSIS™

IPR function of Interpretation Model



RESERVOIR CHARACTERISATION



RESERVOIR CHARACTERISATION

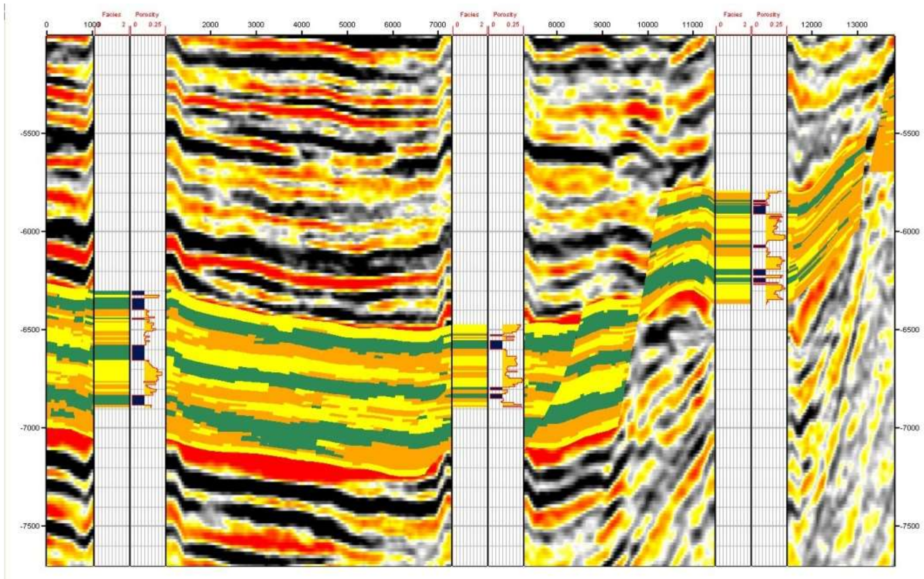
- The purpose of reservoir characterisation is to define a reservoir model that honours both static and dynamic knowledge about the reservoir.

3D Reservoir Modelling

1. Structural Model

2. Grid Model

3. Property Model

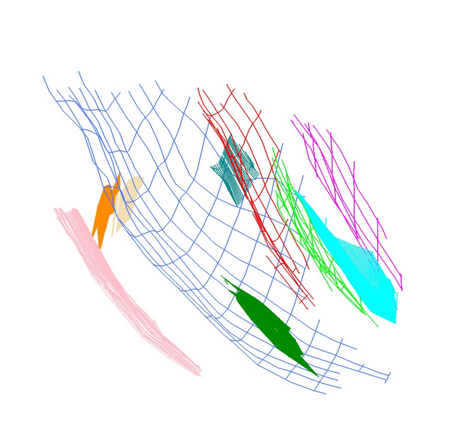


Courtesy of Paradigm

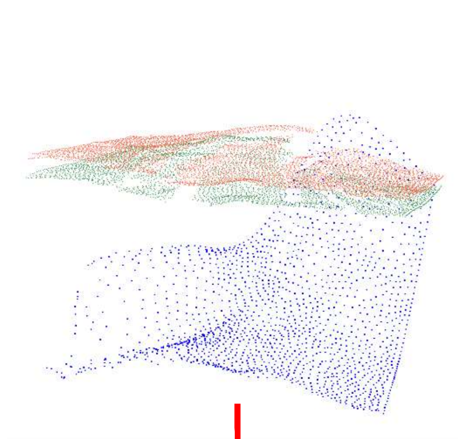
RESERVOIR MODEL

1. Structural Model

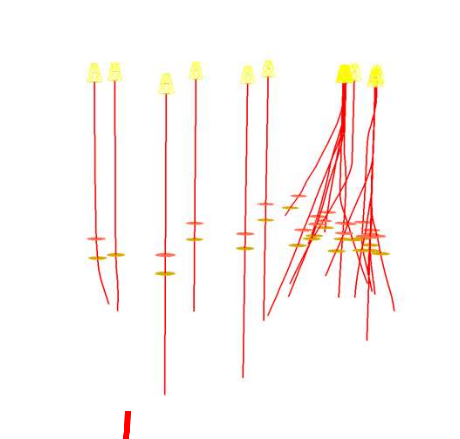
Fault Interpretations
Seismic, Well tests

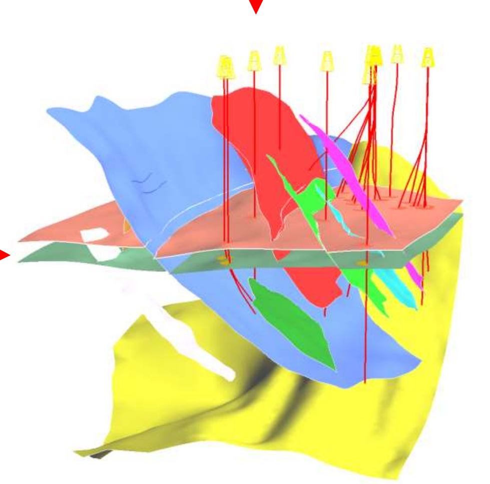


Horizon Interpretations
Geology



Well Picks
Logs



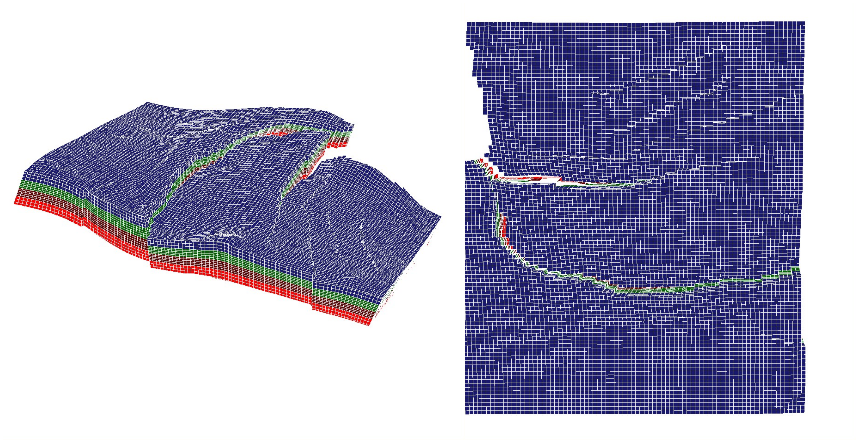


Courtesy of Paradigm

2. Grid Model

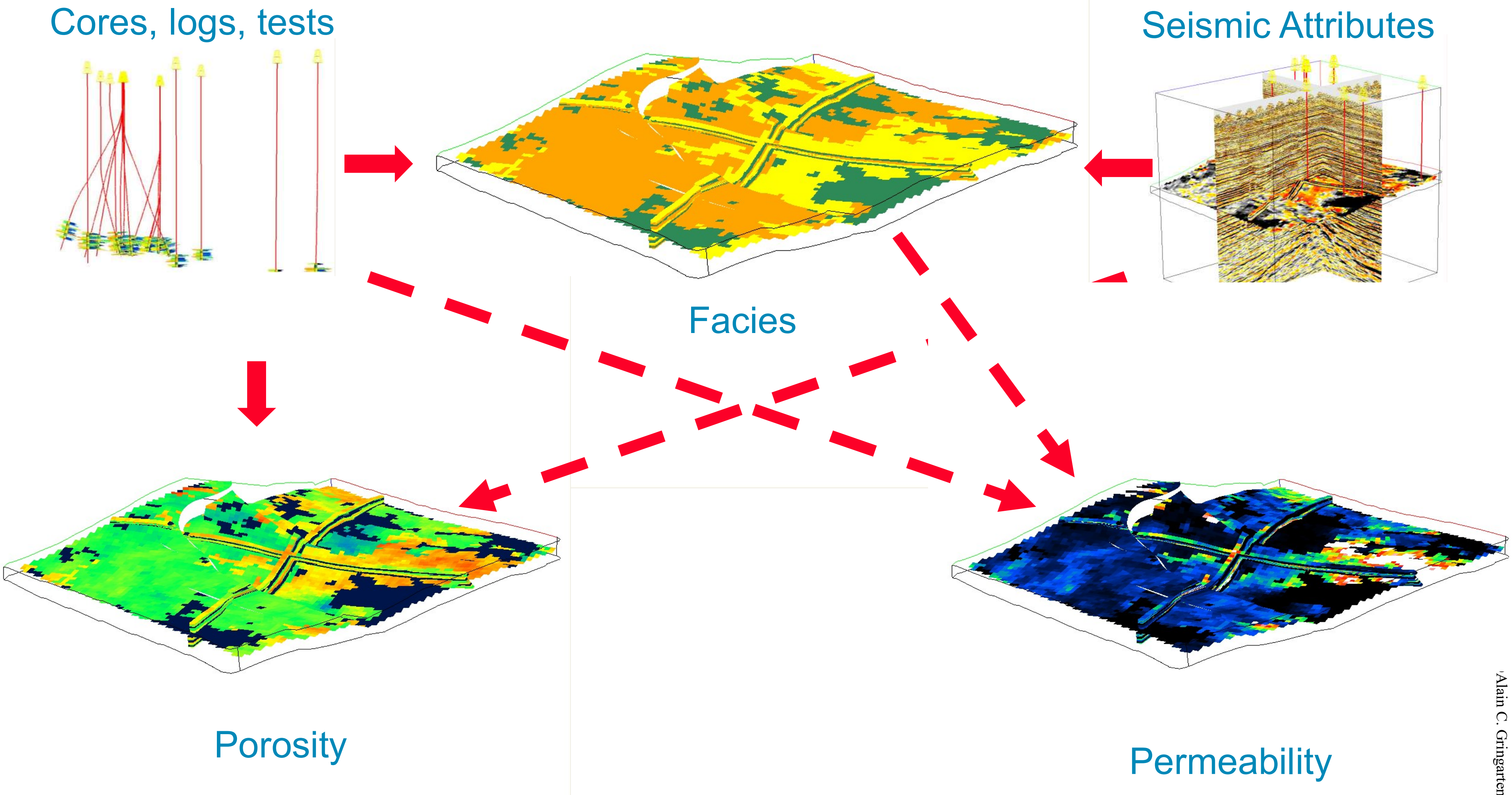
Property Modelling

- aligned with stratigraphy and deposition; must be as regular as possible



Courtesy of Paradigm

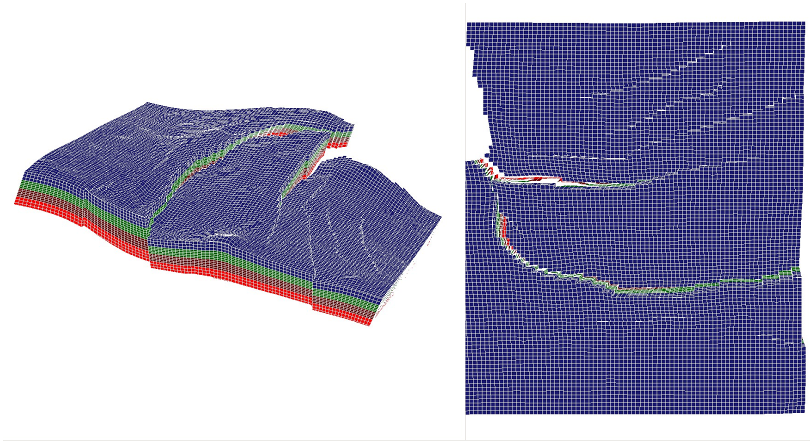
3. Property Model



Courtesy of Paradigm

4. Upscaling

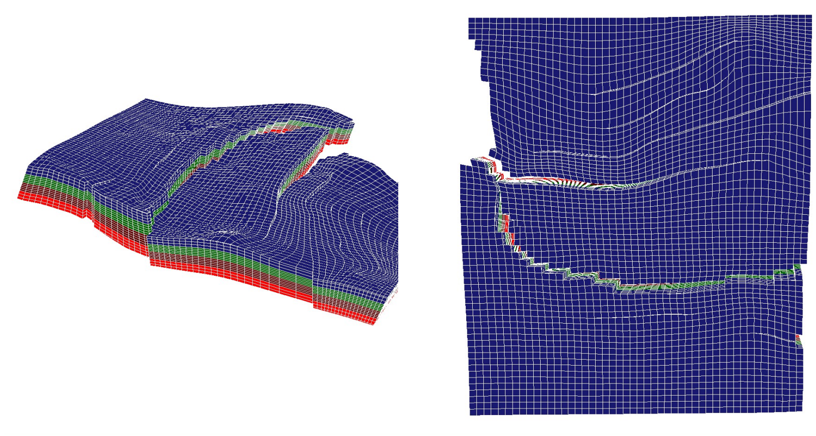
Grid for Property Modeling



UPSCALING ↓

Grid for Flow Simulation

- aligned with major flow direction, faults; can be irregular (tartan, Local Grid Refinement)

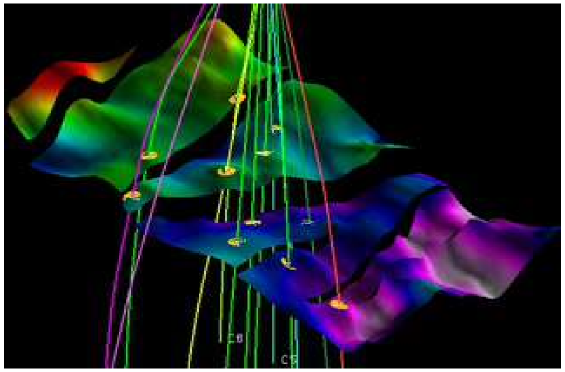


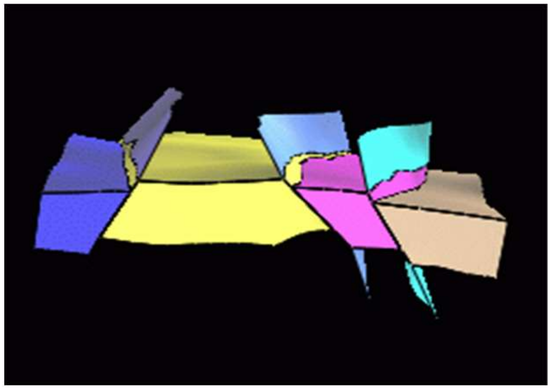
Courtesy of Paradigm

3D Reservoir Modelling Uncertainty

- "Uncertainty is Everywhere"
  - Geometry
  - Facies
  - Petrophysical Properties
  - Fluid Contacts
  - Fluid Properties
  - Well Data
  - Modelling Parameters

Example:Structural Uncertainty





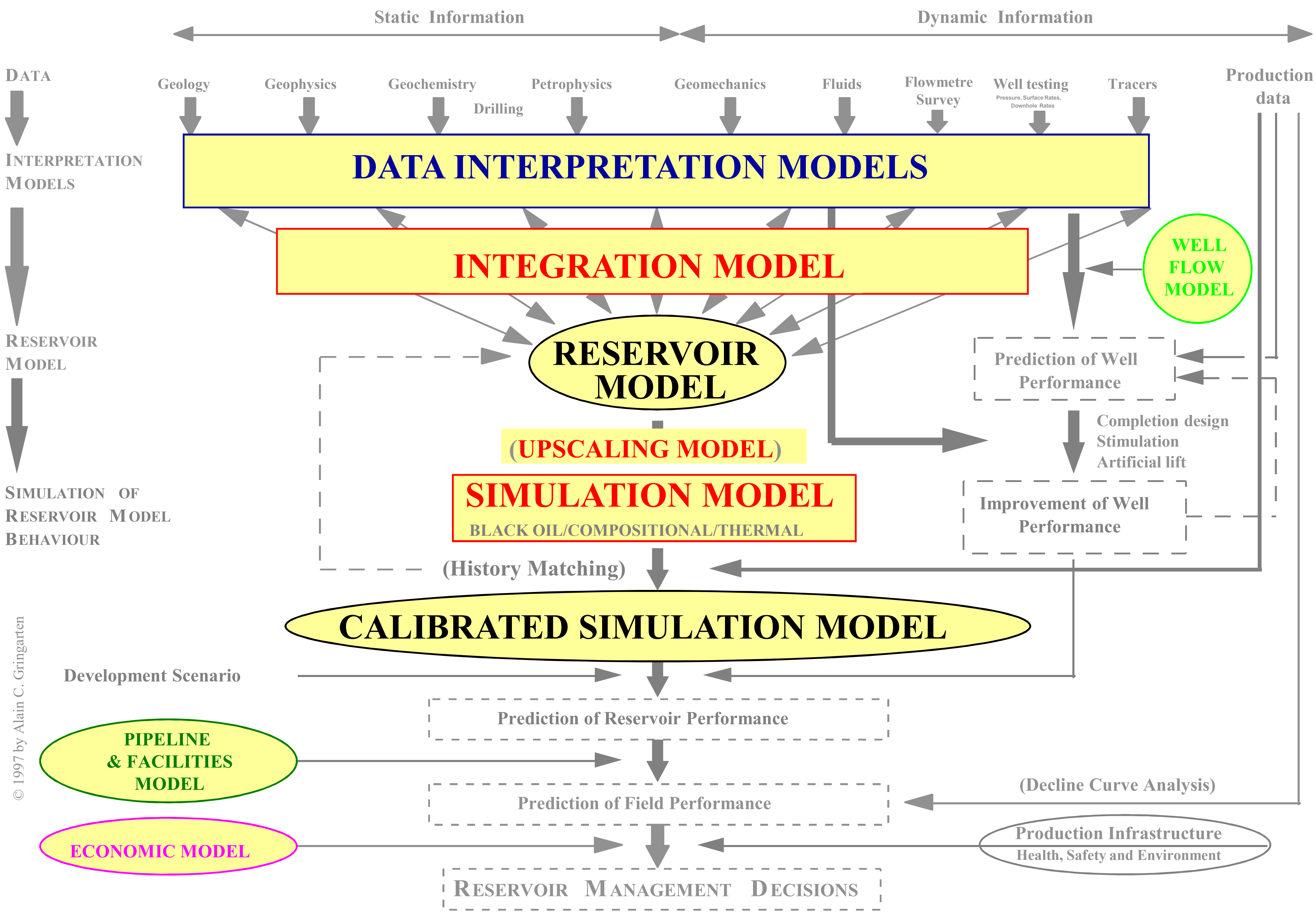
- Interpretation (picking)
- Time-to-Depth
- Migration
- Well picks

Courtesy of Paradigm

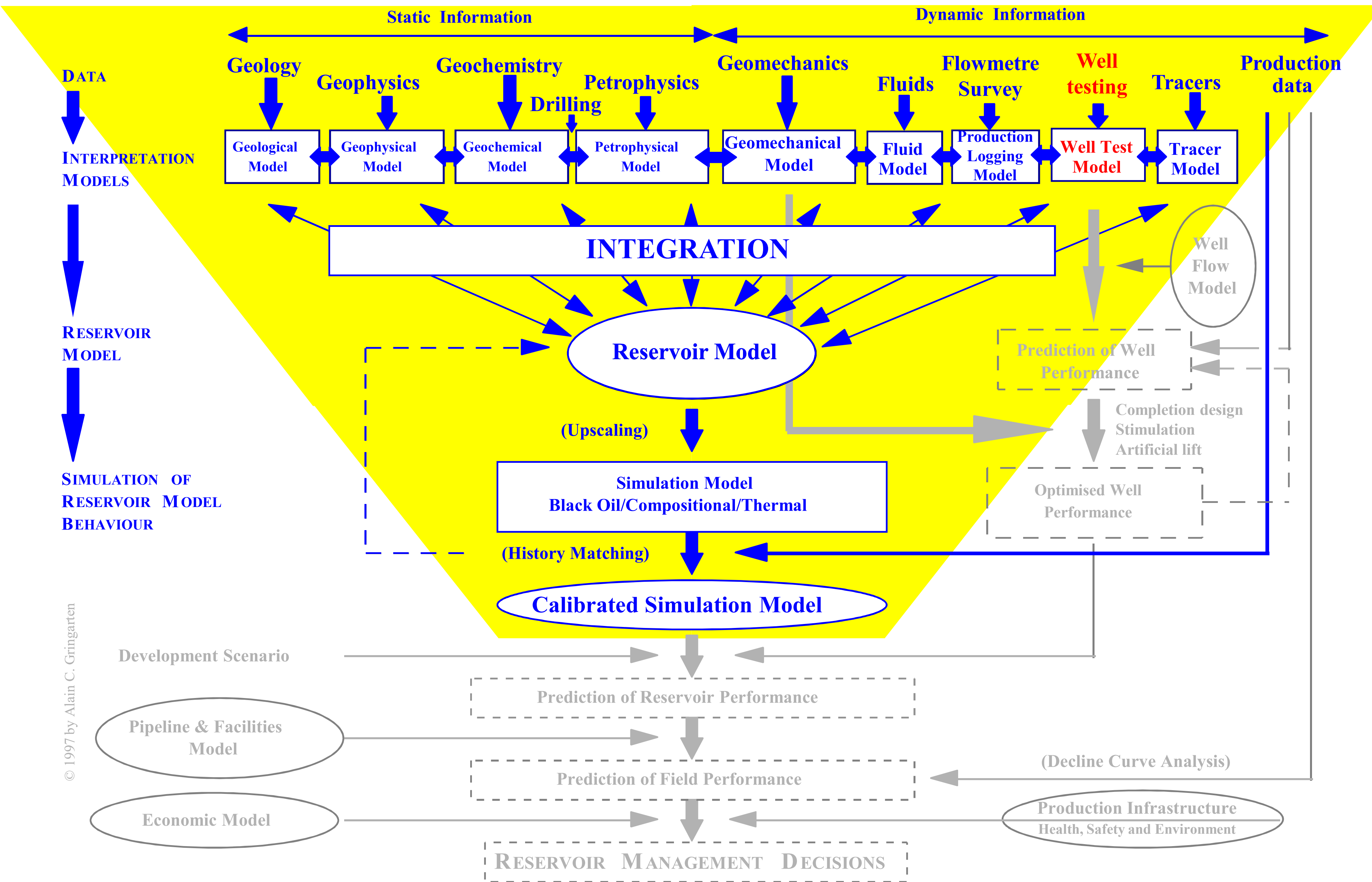
Leads to errors in Volume Estimation and Target Picking.

Importance is reduced in later part of reservoir development.

UNCERTAINTY IN RESERVOIR MANAGEMENT



RESERVOIR CHARACTERISATION

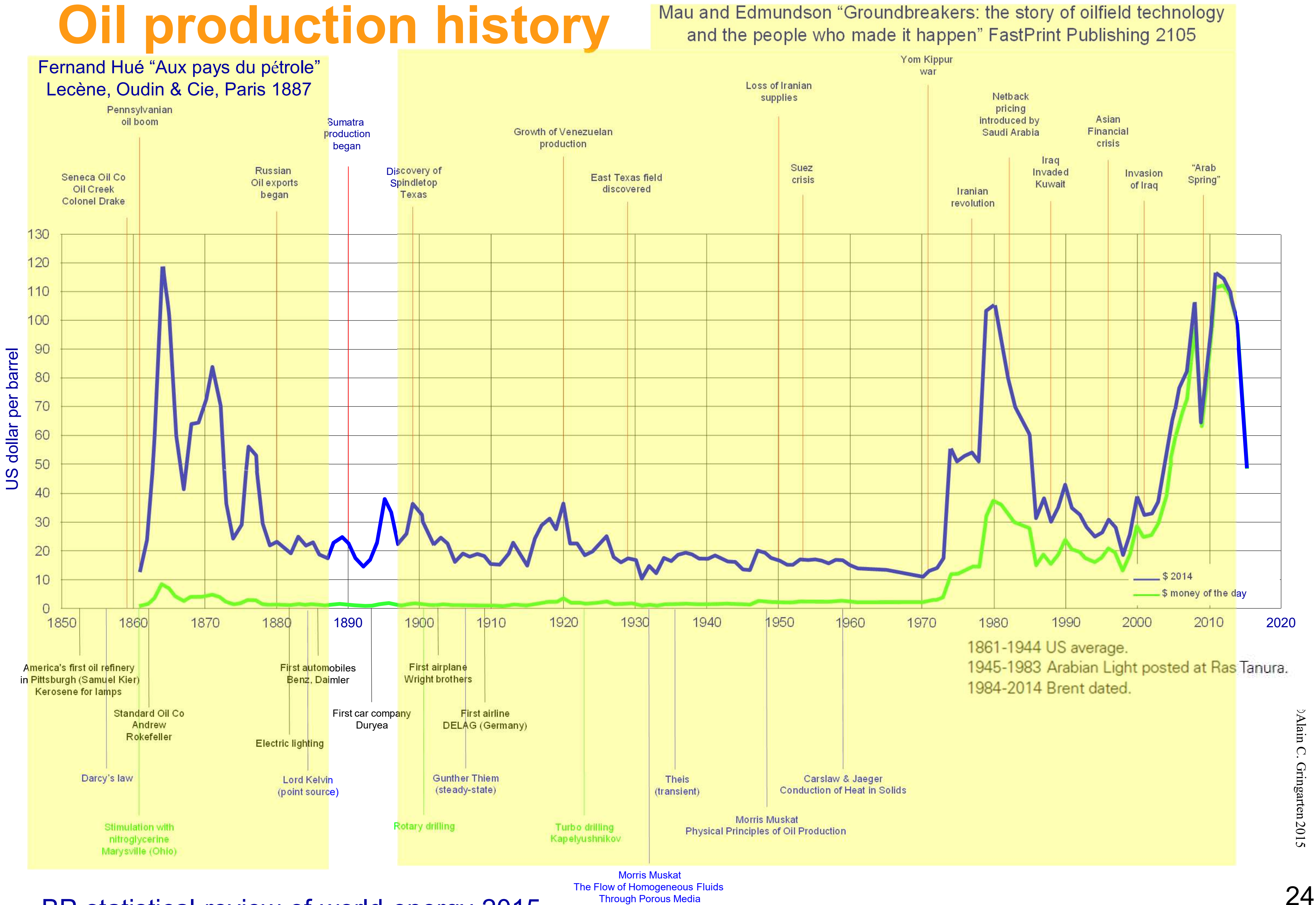


RESERVOIR CHARACTERISATION

- **The purpose of reservoir characterisation is to define a reservoir model that honours both static and dynamic knowledge about the reservoir.**

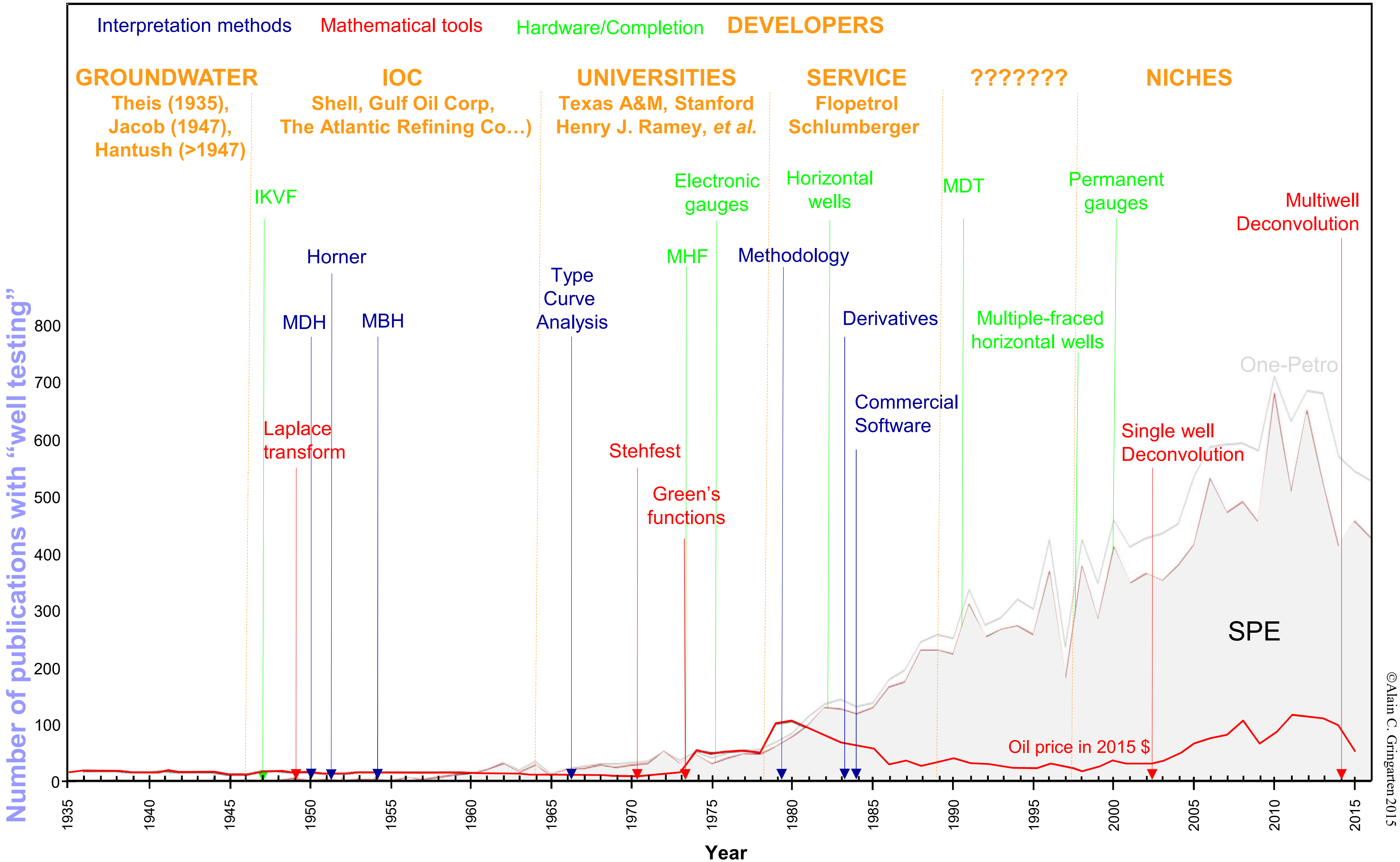
- **Well testing belongs to the dynamic part of the characterisation process. The contribution of well testing to that process is the well test interpretation model.**

Oil production history



BP-statistical-review-of-world-energy-2015

Well Interpretation history



http://www.spe.org/industry/history/oral_archives.php

WELL TEST ANALYSIS MILESTONES

50's	Straight lines	Laplace Transform	Homogeneous Reservoir Behaviour (Radial Flow)
Late 60's Early 70's	Pressure Type Curve Analysis	Green's Functions	Near Wellbore Effects
Late 70's	Type Curves with Independent Variables	Integrated Methodology Stehfest Algorithm	Double Porosity Behaviour
Early 80's	Derivatives	Computerised Analysis	Heterogeneous Reservoir Behaviour and Boundaries
90's		Computer Aided Analysis Downhole Rate Measurements Integration with Interpretation Models from other Data	Multilayered Reservoir
Early 00's		Deconvolution	Enhanced Radius of Investigation Boundaries

WELL TEST ANALYSIS NAMES

Water	Theis	Type curve analysis	mid 1930's
		"Horner" analysis	
	Jacob	"MDH" analysis	mid 1940's
Oil Co's	Muskat	Theory, equations	late 1930's
	Van Everdingen, Hurst	Laplace transforms; Wellbore storage; Skin	early 1950's
	Miller, Dyes, Hutchinson	"MDH" analysis: p vs. log Δt	early 1950's
	Horner	"Horner" analysis: p vs. log $(tp+\Delta t)/\Delta t$	early 1950's
	Matthews, Brons, Hazebroek	"MBH" analysis: average reservoir pressure	mid 1950's
Universities	H. J. Ramey, Jr	Well test analysis solutions, early time analysis, average reservoir pressure	mid 1960's - early 1990's
	Ramey's Texas A&M students:		
	Al-Hussainy	Gas pseudo-pressure	mid 1960's
	Agarwal, Al-Hussainy	Wellbore storage and skin type curves	late 1960's
	Ramey's Stanford students:		
	Gringarten	Green's functions; high conductivity fractures	mid 1970's
	Cinco-Ley	Low conductivity fractures	late 1970's
Service Co's	Flopetrol-Schlumberger	Wellbore storage and skin type curve	late 1970's
	Gringarten, Bourdet, Whittle	Double porosity type curves	late 1970's
		Interpretation methodology and software	late 1970's
		Derivative analysis and type curves	early 1980's
	Schlumberger		late 1980's
	Eligh-Economides, Kuchuk, Stewart	Multilayer analysis, deconvolution (attempts)	mid 1980's
	Elf: Daviau	Horizontal well	mid 1980's
	Others Earlougher (1977), Hantush, Horne Kamal, Kumar, Larsen, McKinley, Raghavan, Reynolds, Russell & Truitt (1966)		

ENVIRONMENTAL CHANGES

Before 1970	Mechanical Pressure Gauges
1975	Electronic Pressure Gauges
1980	Surface Pressure Read-out
1980	Horizontal Wells
1983	Off-the-Shelf Well Test Analysis Software
1986	Powerful Personal Computers
Late1990's	Permanent downhole pressure gauges

Time lag between theory and practice: 5-10 years

1980's BREAKTHROUGH

FROM

UNCONNECTED METHODS
GIVING DIFFERENT RESULTS

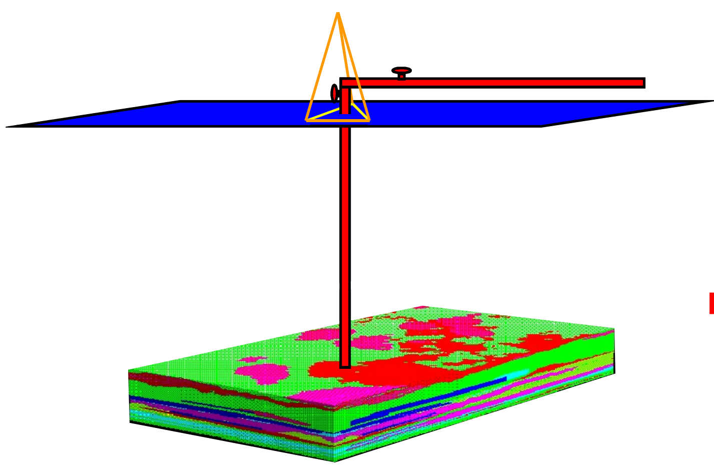
TO

AN INTEGRATED METHODOLOGY
BASED ON SIGNAL THEORY

WELL TEST ANALYSIS

Study of WELL - RESERVOIR BEHAVIOUR

Input Signal | **Unknown Reservoir** | **Output Signal**

I →  → **O**

Gringarten, Bourdet, Landel and Kniazeff 54th ATCE Las Vegas(Sept., 1979)

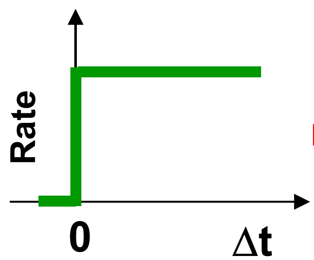
WELL TEST ANALYSIS

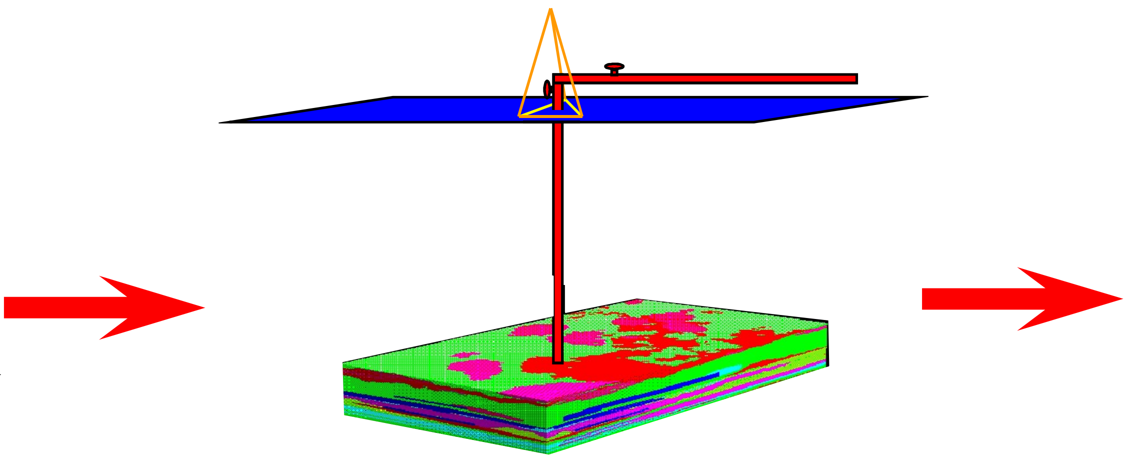
Study of WELL - RESERVOIR BEHAVIOUR

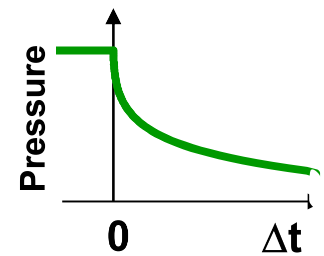
Step function of Rate

Unknown Reservoir

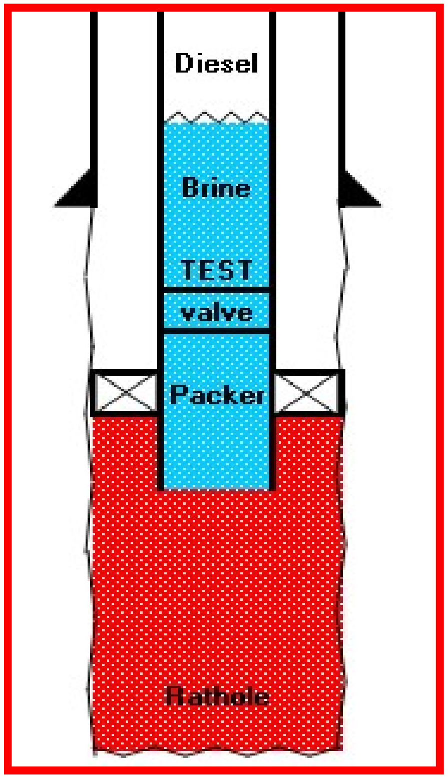
Measured Pressure Response



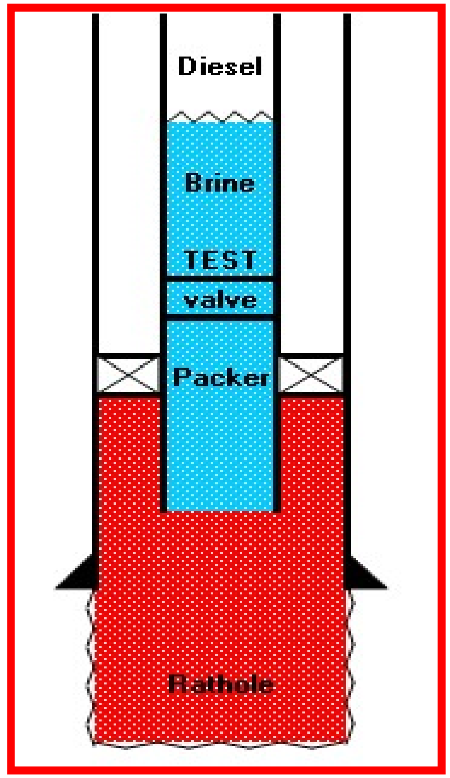




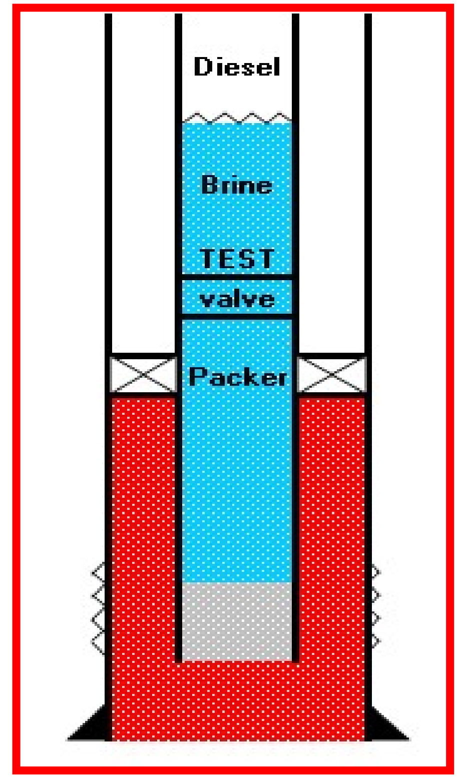
Summary of Test Types



Open Hole Test



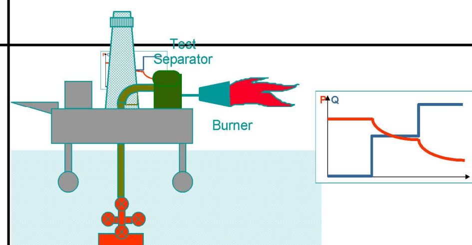
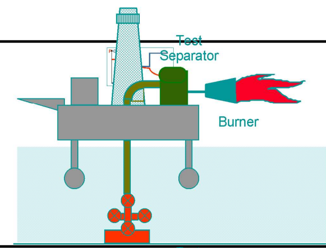
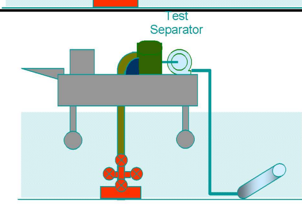
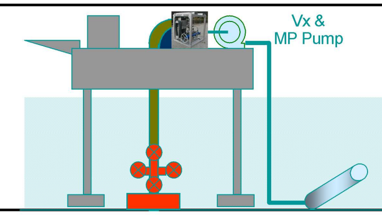
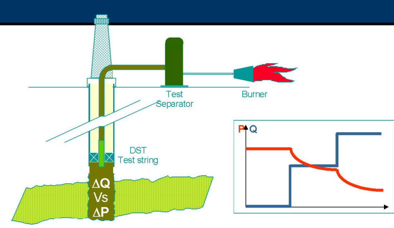
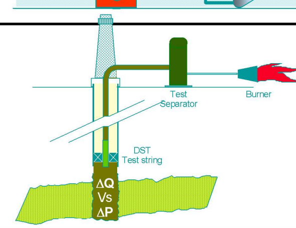
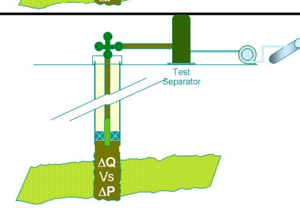
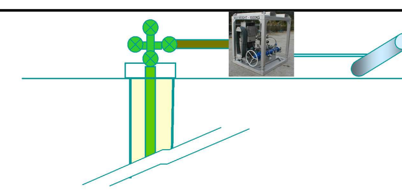
Barefoot Test



Cased Hole Test

Courtesy of Schlumberger

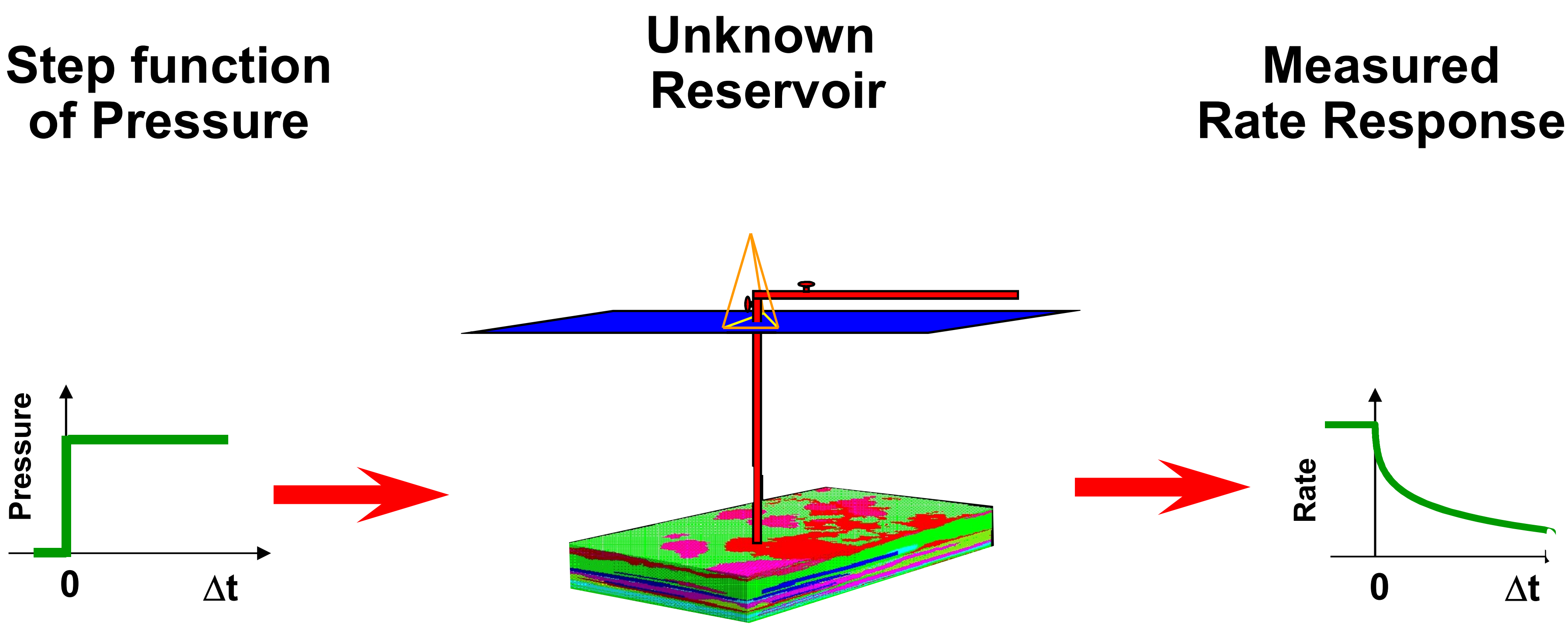
Operation Segmentation & Drivers

	E & A	Dev & Cl-Up	Prod
Offshore (Flow back to rig)			
Offshore (Flow back to host)			
Onshore (Flow back to rig)			
Onshore (Flow back to host)			

Courtesy of Schlumberger

WELL TEST ANALYSIS

Study of WELL - RESERVOIR BEHAVIOUR



I → S → O

- I AND O ARE KNOWN: FIND S

  IDENTIFICATION — INVERSE PROBLEM, NON UNIQUE SOLUTION

  Model diagnostic — I = (1, 2, 3), O =6, S = + or *

- I AND S ARE KNOWN: FIND O

  CONVOLUTION — DIRECT PROBLEM, UNIQUE SOLUTION

  Model verification — I = (1, 2, 3), S = +, O = 6

  Design

- S AND O ARE KNOWN: FIND I

  DECONVOLUTION — INVERSE PROBLEM, NON UNIQUE SOLUTION

  Constant rate conversion — O =6, S = +, I = (1, 5) or (4,2) or (3,3)

INTERPRETATION PROCESS

STEP 1: MODEL IDENTIFICATION

Find a MODEL S' which behaves in the same way as S

I ➔ S' ➔ O'   O' has the same shape as O

INVERSE PROBLEM   Non-unique solution

☞ To reduce the non uniqueness:

- more test data: pressure and rate
- checking procedure on model
- consistency with geophysics, geology, petrophysics, etc.

MODEL IDENTIFICATION IS A PATTERN RECOGNITION, INVERSE PROBLEM:

- **given the data (well test and others),**
- **knowing characteristic shapes created by well defined flow regimes,**
- **identify which flow regimes could create this type of test data**

INTERPRETATION PROCESS

STEP 2: MODEL PARAMETER CALCULATION

Adjust the parameters of the MODEL S' so that

O' ≡ O **O' become identical to O**

DIRECT PROBLEM **Unique solution**

☞ **Calculated parameters independent of the method used:**

- **straight line techniques**
- **type curve matching, pressure and/or derivative**
- **non-linear regression**

INTERPRETATION PROCESS

STEP 3: MODEL VERIFICATION

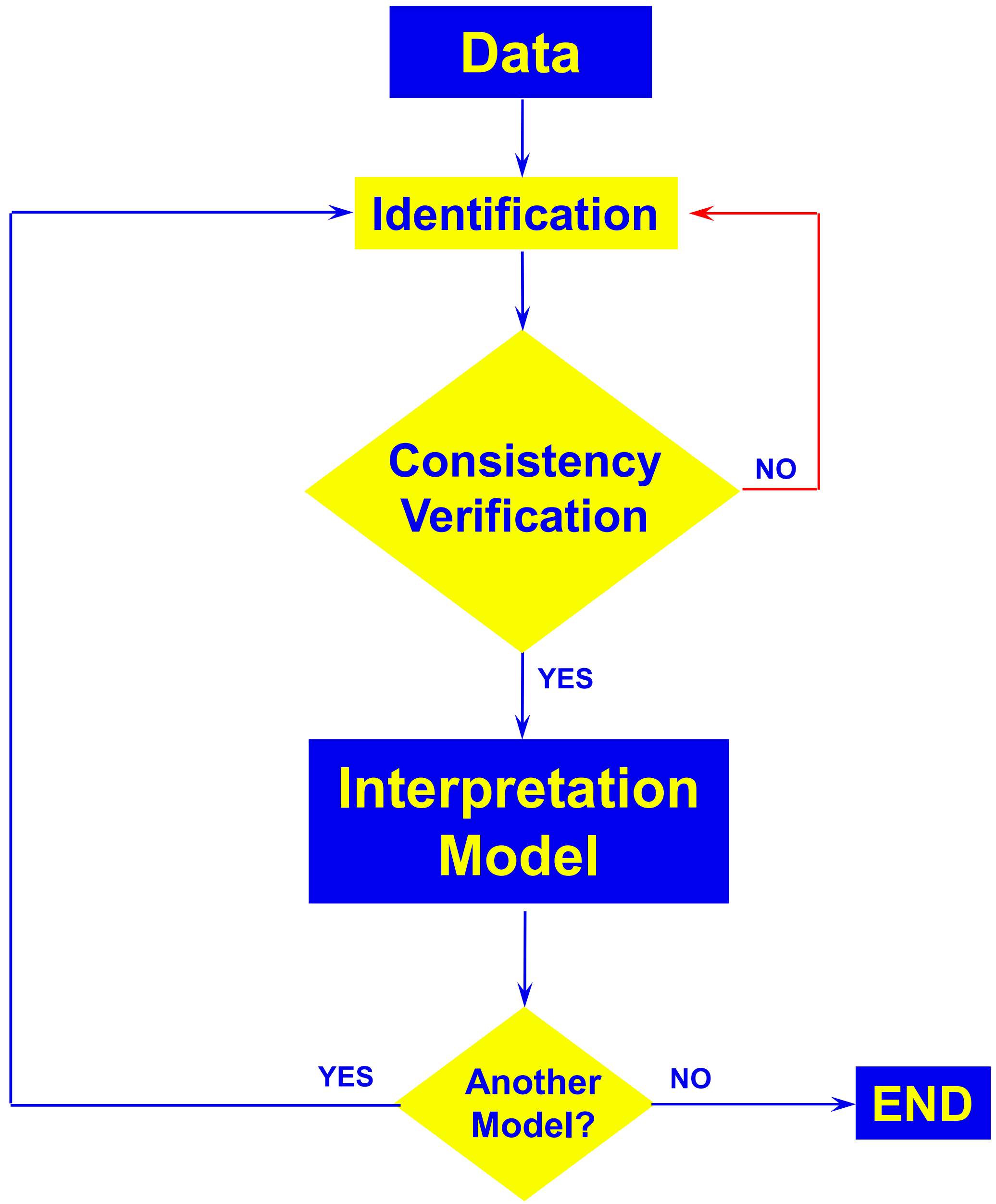
Verify the consistency of the interpretation model:

- **matching with test observed data (log-log, Horner, simulation)**
- **matching with results from other well tests**
- **matching with other knowledge (geology, petrophysics, cores, fluid, completion,...)**
- **common sense (range of parameter values)**

MODEL VERIFICATION IS A DIRECT PROBLEM

- given the data (well test and others),
- given a well test interpretation model,
- verify that the well test interpretation model is consistent with the data

INTERPRETATION PROCESS



COMPONENTS OF THE WELL TEST INTERPRETATION MODEL

NEAR WELLBORE EFFECTS	RESERVOIR BEHAVIOUR	BOUNDARY EFFECTS

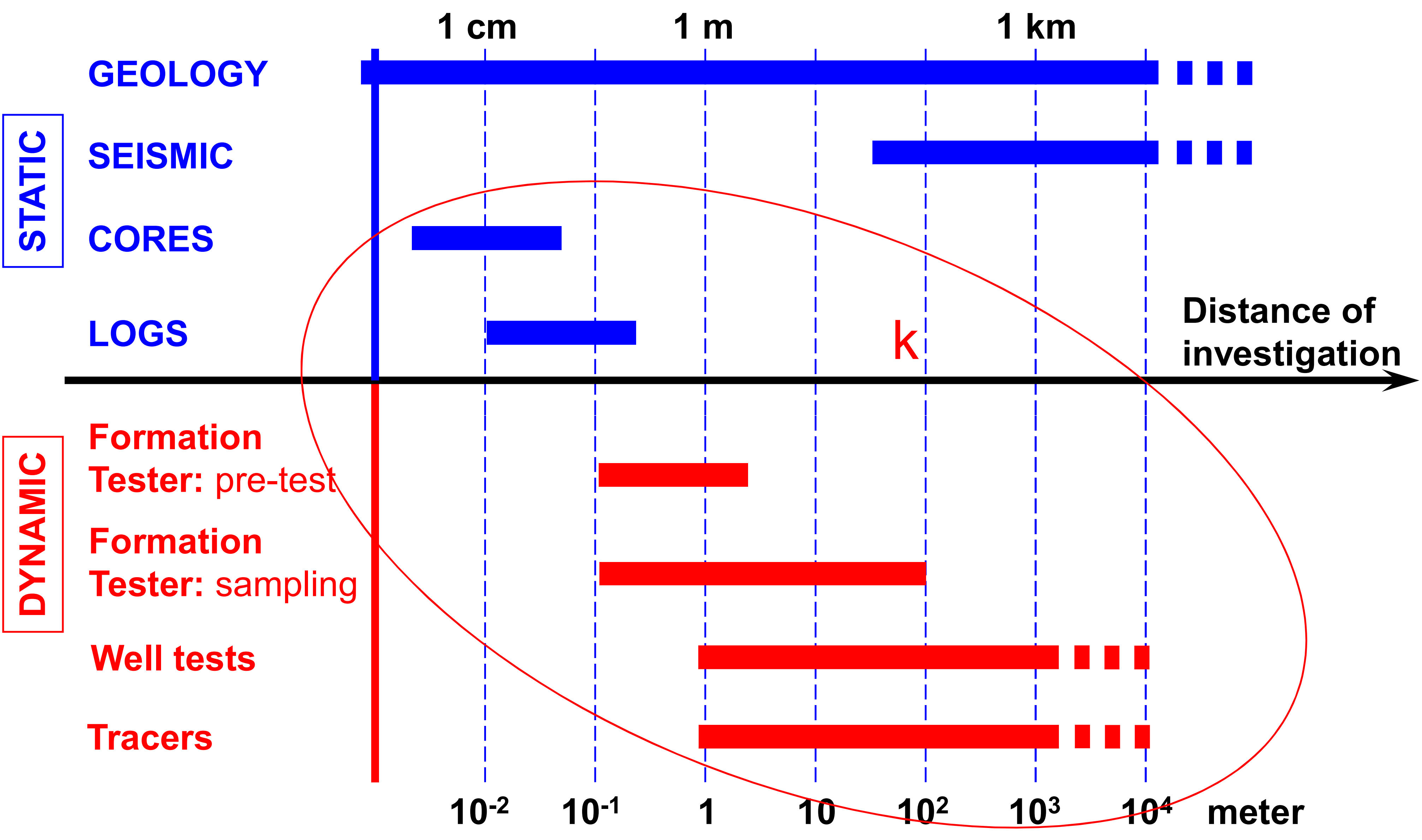
DATA INTERPRETATION MODELS
DESCRIBE DIFFERENT ASPECTS OF RESERVOIR

WELL TEST MODEL → **MOBILITY CONTRASTS**
STORATIVITY CONTRASTS

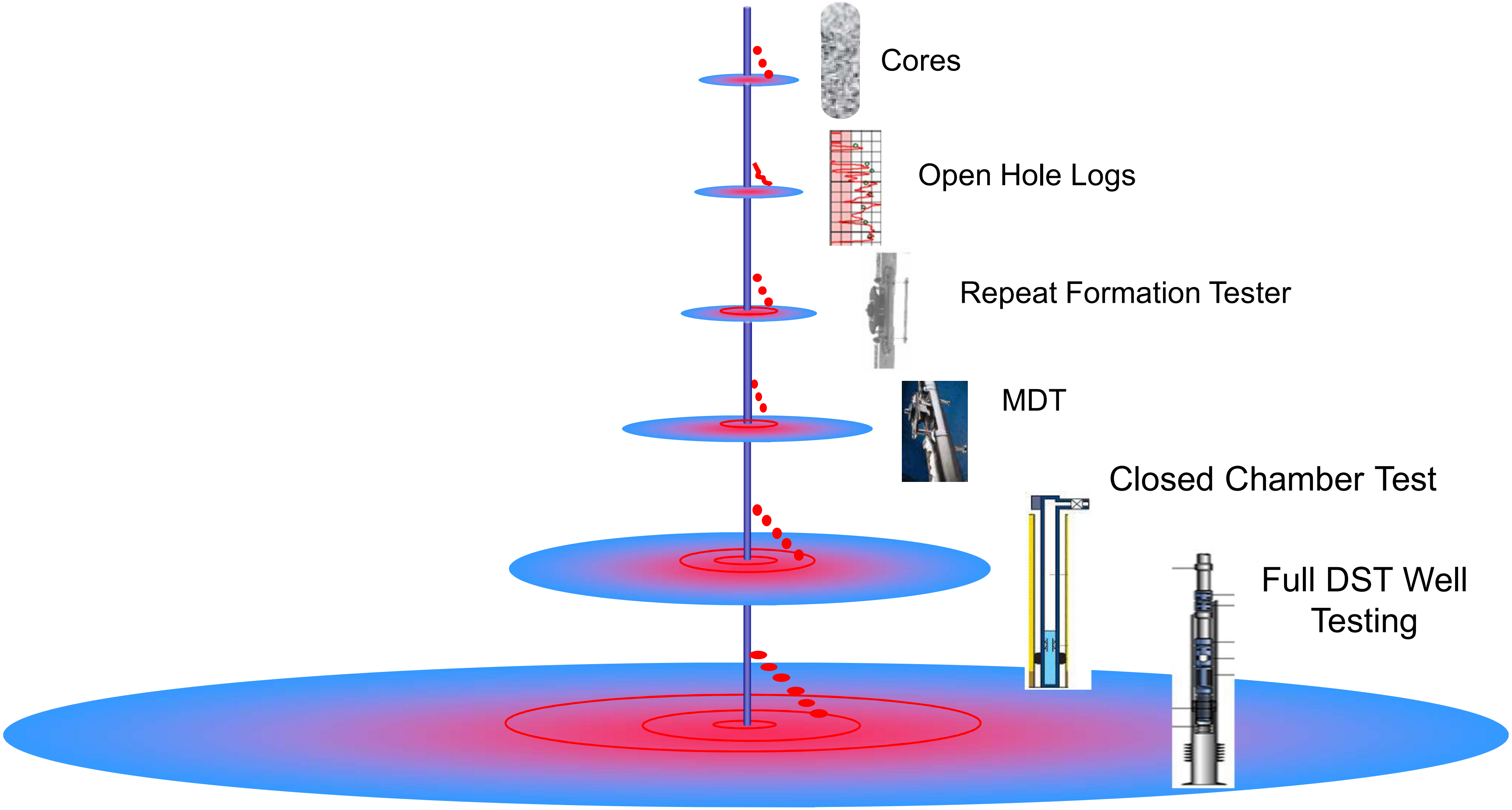
GEOPHYSICAL MODEL → **IMPEDANCE CONTRASTS**

Understanding the cause of these contrasts require the knowledge of interpretation models from other types of data

DIFFERENT DATA SEE DIFFERENT SCALES

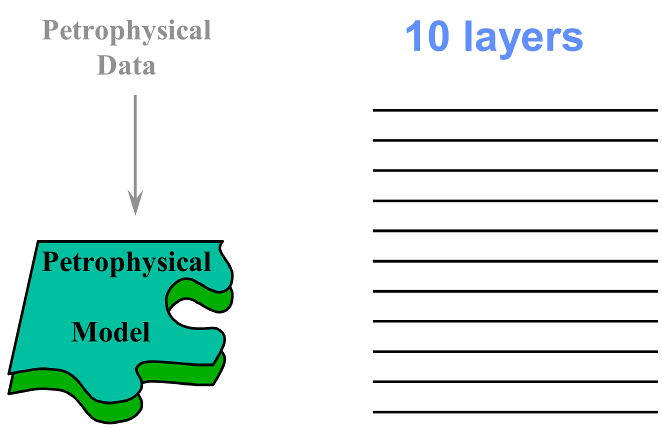


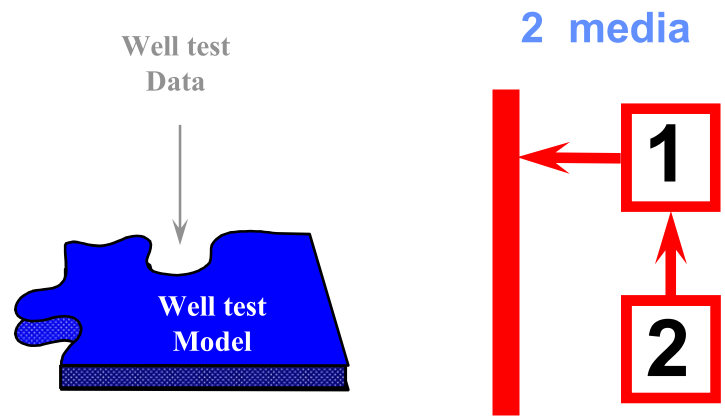
Relative Scale of Permeability Measurements

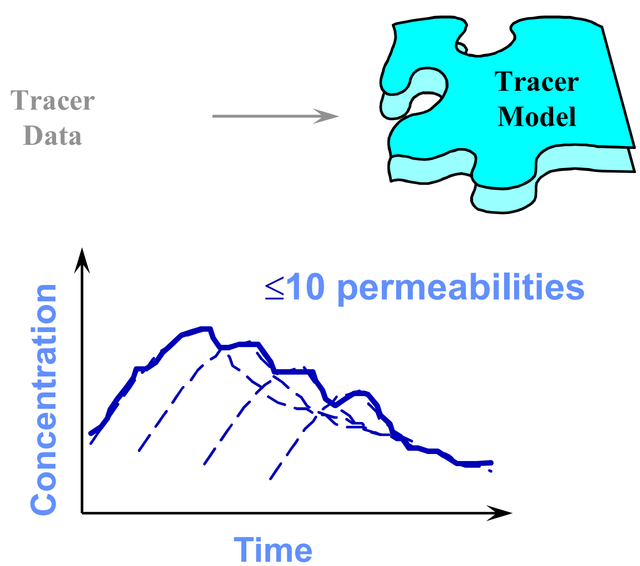


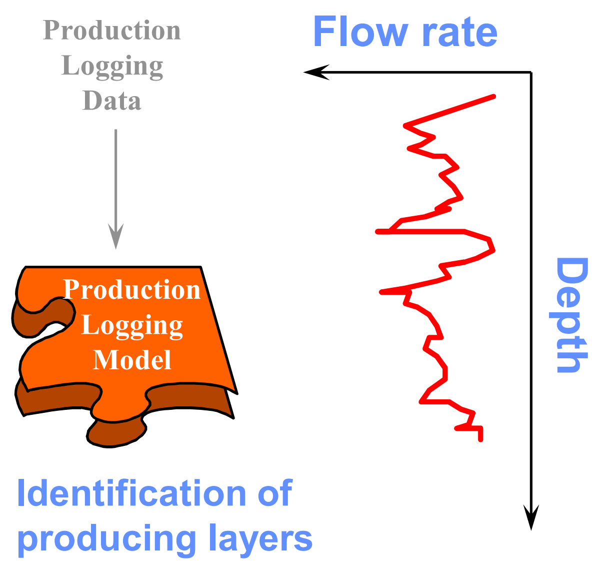
Courtesy of Schlumberger

DIFFERENT INTERPRETATION MODELS YIELD DIFFERENT INFORMATION ON THE RESERVOIR MODEL

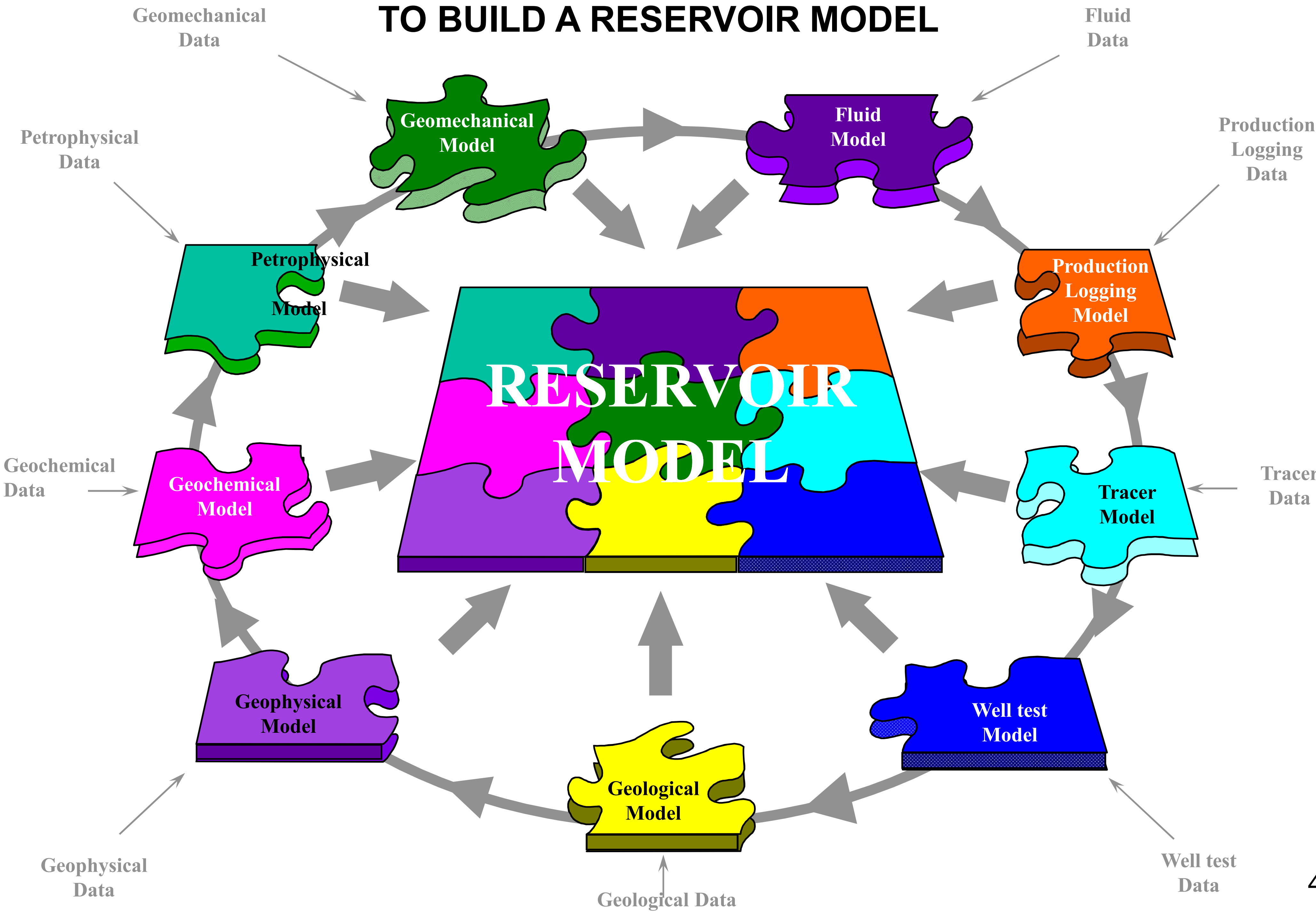








IT TAKES ALL THE INTERPRETATION MODELS TO BUILD A RESERVOIR MODEL



COMPONENTS OF THE WELL TEST INTERPRETATION MODEL

NEAR WELLBORE EFFECTS	RESERVOIR BEHAVIOUR	BOUNDARY EFFECTS

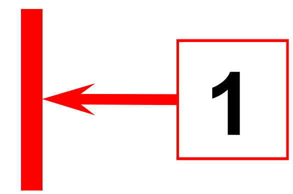
WELL TEST INTERPRETATION MODEL

BASIC RESERVOIR BEHAVIOURS

1- HOMOGENEOUS BEHAVIOUR

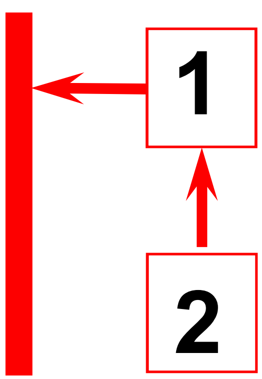
One mobility kh/μ

One storativity $\phi c_t h$



2- HETEROGENEOUS BEHAVIOUR

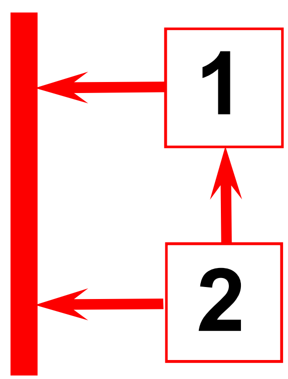
More than one mobility, storativity



2-Porosity

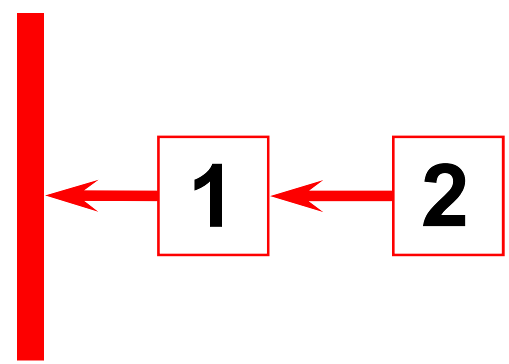
Fissured

Multilayered



2-Permeability

Multilayered



Composite

Geology

Multiphase Fluid

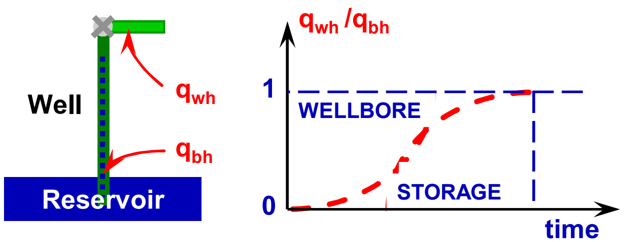
COMPONENTS OF THE WELL TEST INTERPRETATION MODEL

NEAR WELLBORE EFFECTS	RESERVOIR BEHAVIOUR	BOUNDARY EFFECTS

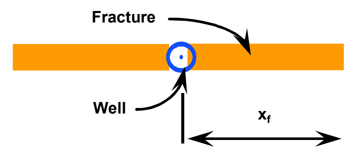
WELL TEST INTERPRETATION MODEL

NEAR WELLBORE EFFECTS

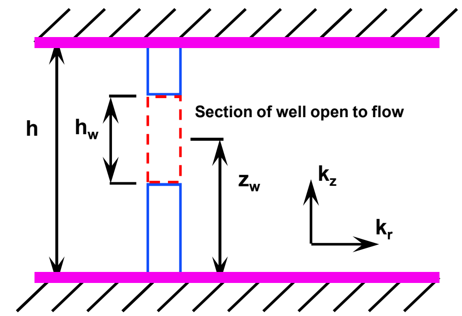
Wellbore storage



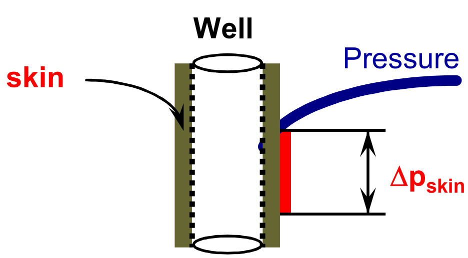
High conductivity fracture



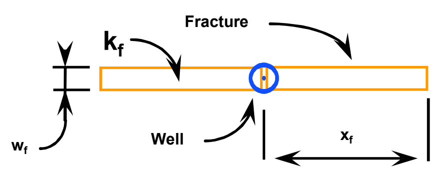
Limited entry



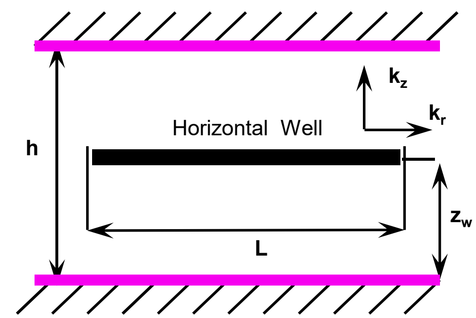
Skin



Low conductivity fracture

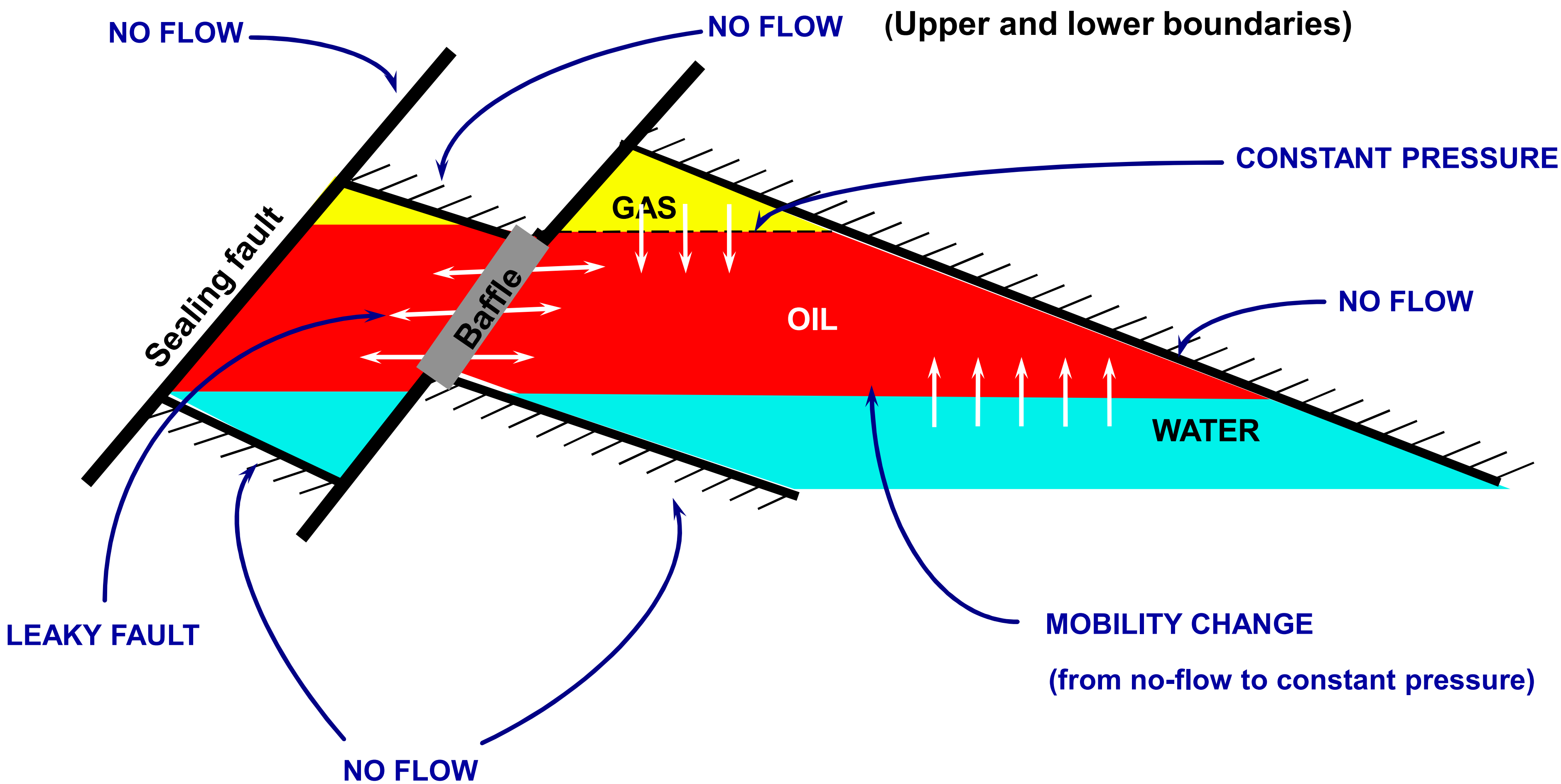


Horizontal well



WELL TEST INTERPRETATION MODEL

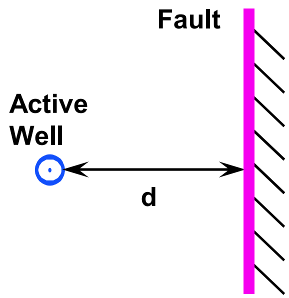
BOUNDARIES (Cross Section)



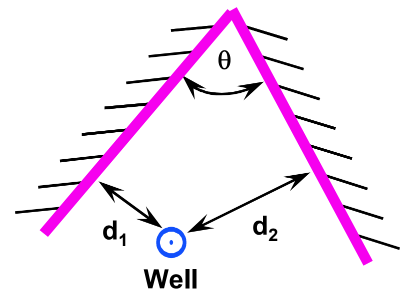
WELL TEST INTERPRETATION MODEL

BOUNDARIES (Top view)

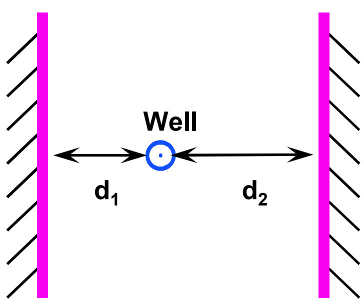
Fault



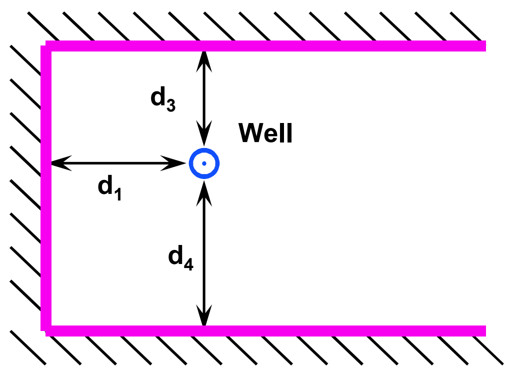
Wedge



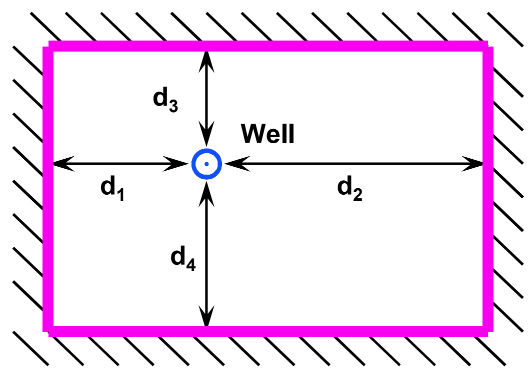
Channel



Open Rectangle



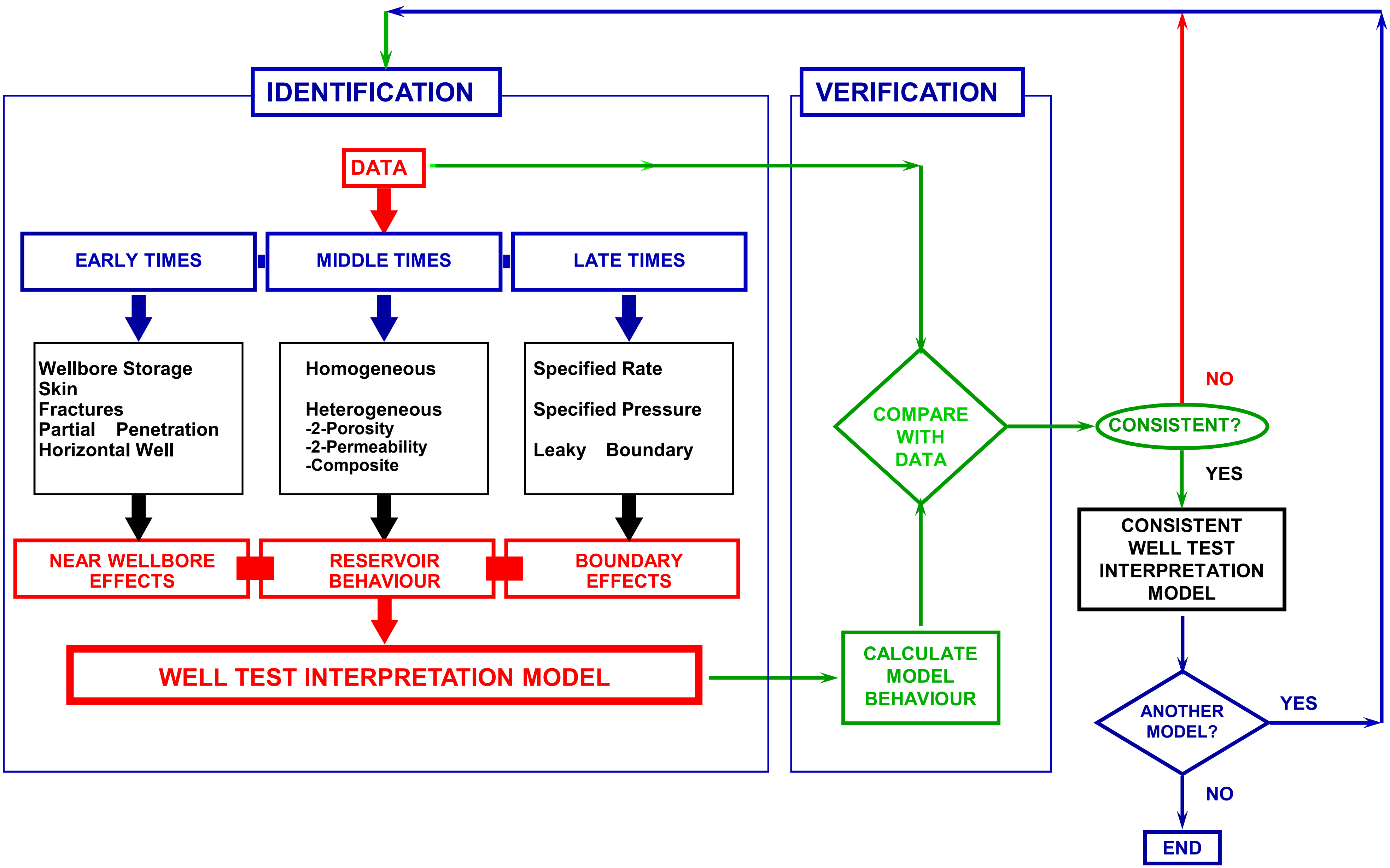
Rectangular reservoir



WELL TEST INTERPRETATION MODEL

NEAR WELLBORE EFFECTS	RESERVOIR BEHAVIOUR	BOUNDARY EFFECTS
Wellbore Storage Skin Fractures Partial Penetration Horizontal Well	Homogeneous Heterogeneous -2-Porosity -2-Permeability -Composite	Specified Rates Specified pressure Leaky boundary
EARLY TIMES	MIDDLE TIMES	LATE TIMES

WELL TEST INTERPRETATION PROCESS



ANALYSIS TECHNIQUES

Value tied to power in Identification and Verification

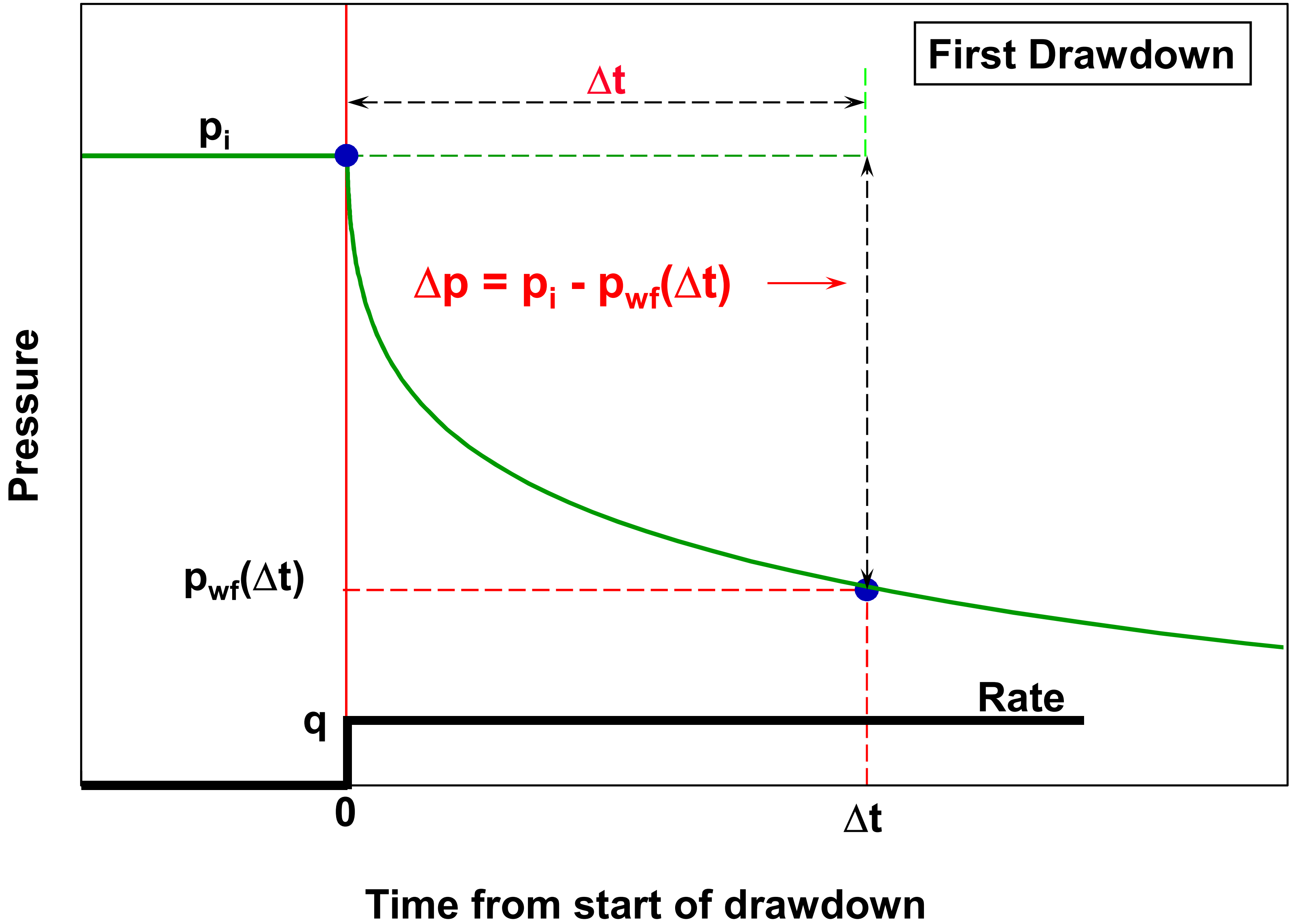
	ANALYSIS METHOD	IDENTIFICATION	VERIFICATION
50's	Straight lines	Poor	None
70's	Pressure Type Curves	Fair (limited)	Fair to Good
80's	Pressure Derivative	Very Good	Very Good
00's	Deconvolution	Much better	Same as derivative
	Multiwell Deconvolution	Much, much better	Same as derivative
Next	?	>>>	>>>

RESERVOIR PARAMETERS

Interpretation Model controls number and meaning of parameters

Homogeneous Behaviour	Double Porosity Behaviour	Double Permeability Behaviour
kh permeability-thickness **S** skin **(<0, 0, >0)** $(p_{av})_i$ initial pressure	**kh** most permeable medium **S** **(<-3.5, -3.5, >-3.5)** $(p_{av})_i$	**kh** total system **S** **(<-3.5, -3.5, >-3.5)** $(p_{av})_i$
C wellbore storage **Surface : 10^{-2} Bbl/psi** **Downhole: 10^{-4} Bbl/psi**	**C** ω storativity ratio λ interporosity flow coefficient	**C** ω λ $(kh)_i/(kh)_t$

MODEL RESPONSE, FIRST DRAWDOWN
after stabilisation



MODEL RESPONSE IN THE FIRST DRAWDOWN

Signal in drawdown: $(\Delta p)_{wf} = [p_i - p_{wf}(\Delta t)]$

$$(\Delta p)_{wf} = f[\Delta t,(kh,S,C,..),\Delta q,(r_w,\phi,\mu,c_t,B,..)]$$

Dimensionless parameters:

$[(\Delta p)_{wf}]_D$ = PM $(kh,\Delta q,B,\mu,...)$ Δp

$[(\Delta t)]_D$ = TM $(kh,\phi,\mu,c_t,r_w,...)$ Δt

$$[(\Delta p)_{wf}]_D = f_D(\Delta t_D,S,C_D,...) \text{ or } p_D = p_D(t_D)$$

$[(\Delta p)_{wf}]_D = p_D(t_D)$ is called a **Drawdown Type Curve**

☞ Usually plotted as: $\log [(\Delta p)_{wf}]_D$ vs $\log t_D$

DRAWDOWN TYPE CURVES

Examples of Dimensionless Variables

(all parameters are expressed in Engineering Oil Field (EOF) units.)

Dimensionless Pressure

(Same for most models)

PM

$$p_D = \frac{k(mD)\,h(ft)}{141.2\,\Delta q(bbl/D)\,B(vol/vol)\,\mu(cp)}\,\Delta p(psi)$$

Dimensionless Time

(Depends on model)

TM

Based on ***well radius:***

$$t_D = \frac{0.000264\;k(mD)}{\varphi(fraction)\,\mu(cp)\,c_t(1/psi)\,r_w^2(ft)}\,\Delta t(hour)$$

Based on ***fracture half-length:***

$$t_{Df} = \frac{0.000264\,k}{\phi\mu\,c_t x_f^2}\,\Delta t$$

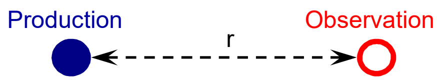
Based on ***effective well radius*** $r_{we} = r_w e^{-S}$ **:**

$$t_{De} = \frac{0.000264\;k}{\phi\mu\,c_t r_{we}^2}\,\Delta t$$

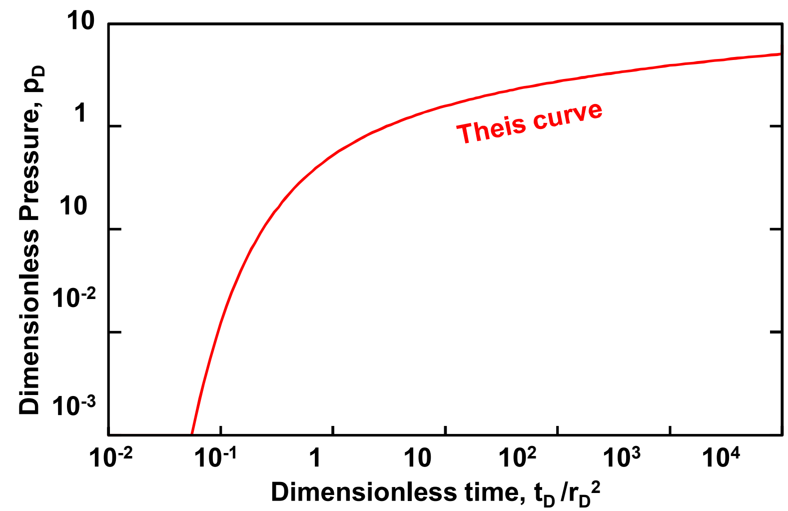
DRAWDOWN TYPE CURVES

Example of $p_D(t_D)$ function

INTERFERENCE TEST IN AN INFINITE RESERVOIR WITH HOMOGENEOUS BEHAVIOUR:



$$p_D = -\frac{1}{2} Ei\left(\frac{-r_D^2}{4t_D}\right)$$



Ei represents the Exponential Integral:

$$Ei(-x) = -\int_x^\infty \frac{e^{-u}}{u} du$$

Data measured in an observation well at a distance ***r*** from the production well

$$p_D = \frac{kh}{141.2\,\Delta q\,B\,\mu}\Delta p \qquad t_D = \frac{0.000264\ k}{\phi\mu\,c_t r_w^2}\Delta t \qquad r_D = \frac{r}{r_w}$$

DRAWDOWN TYPE CURVES

Examples of Independent Variables

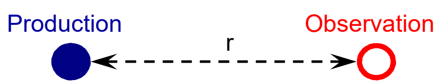
(all parameters are expressed in Engineering Oil Field (EOF) units.)

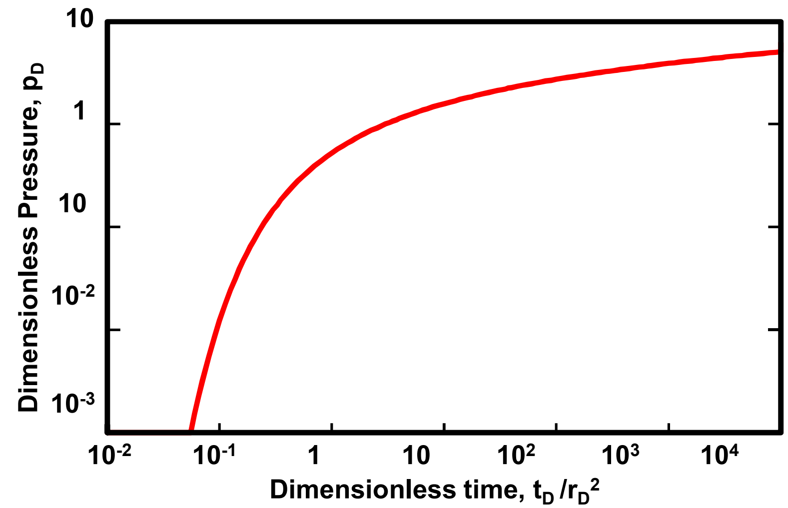
INTERFERENCE TEST IN AN INFINITE RESERVOIR WITH HOMOGENEOUS BEHAVIOUR:

Independent variables, unique match

$$p_D = \frac{kh}{141.2\,\Delta q\, B\, \mu}\Delta p$$

$$t_D / r_D^2 = \frac{0.000264\, k}{\phi \mu c_t r^2}\Delta t$$



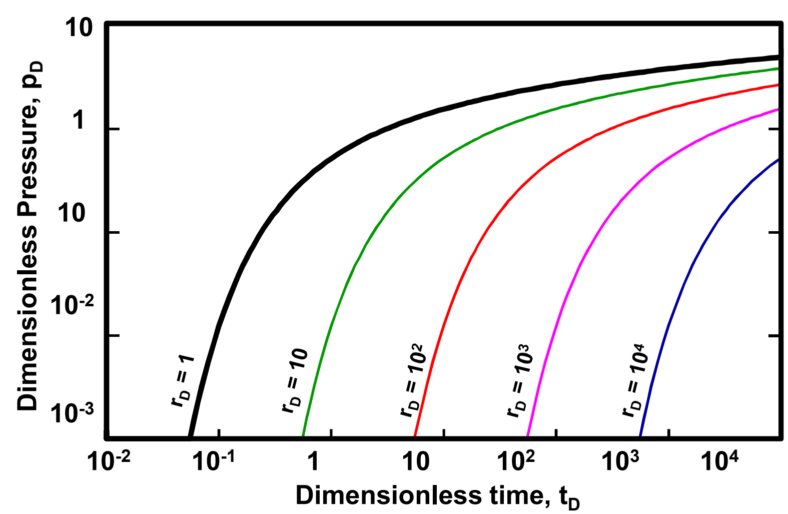


Dimensionless parameters, non-unique match

$$p_D = \frac{kh}{141.2\,\Delta q\, B\, \mu}\Delta p$$

$$t_D = \frac{0.000264\, k}{\phi \mu\, c_t r_w^2}\Delta t$$

$$r_D = \frac{r}{r_w}$$



DRAWDOWN TYPE CURVES

Examples of Independent Variables

(all parameters are expressed in Engineering Oil Field (EOF) units.)

WELL WITH WELLBORE STORAGE AND SKIN IN AN INFINITE RESERVOIR WITH HOMOGENEOUS BEHAVIOUR:

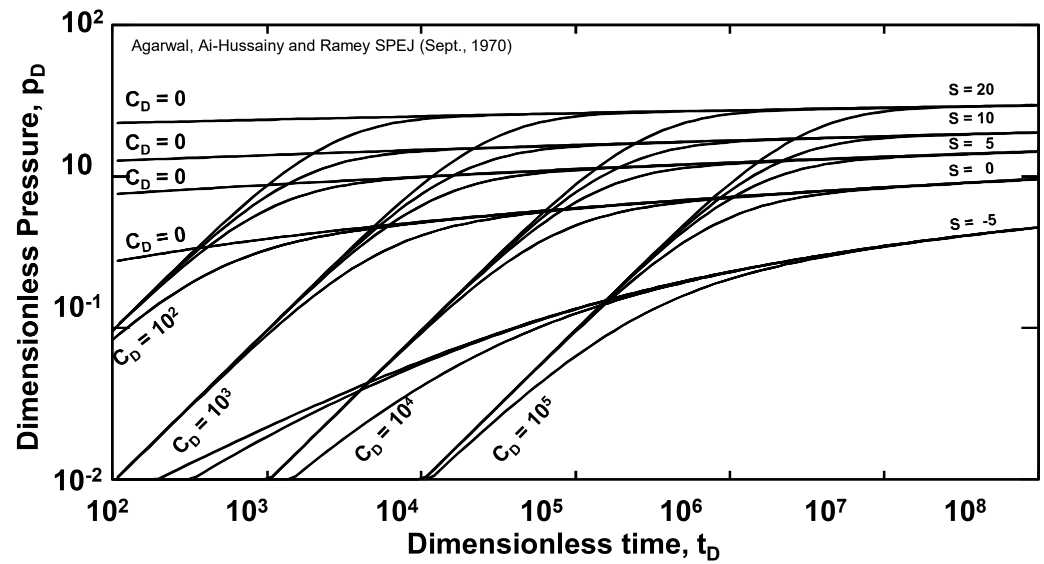
Dimensionless parameters, non-unique match

$$p_D = \frac{kh}{141.2\Delta q\, B\, \mu}\Delta p$$

$$t_D = \frac{0.000264\, k}{\phi \mu\, c_t r_w^2}\Delta t$$

$$C_D = \frac{0.8936\, C}{\phi\, c_t h r_w^2}$$

$$(S)$$

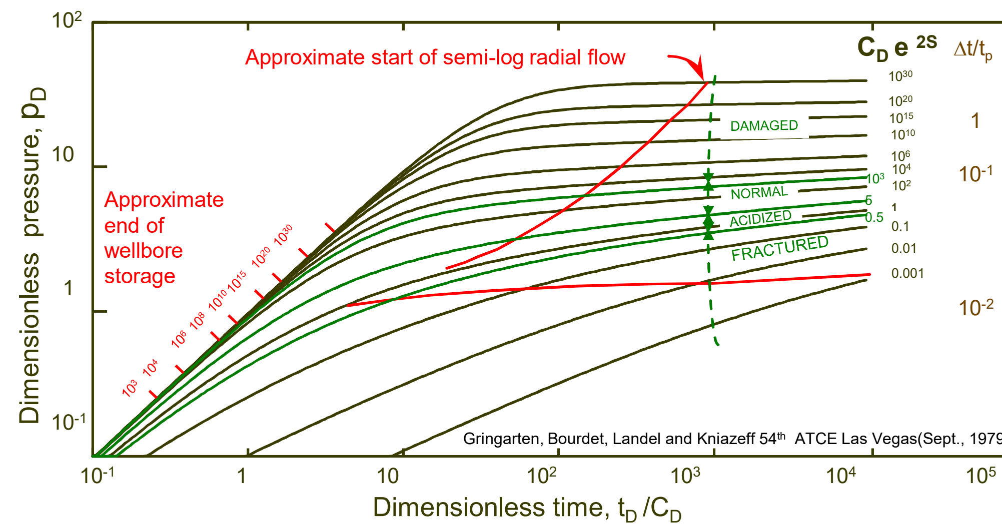


Independent variables, unique match

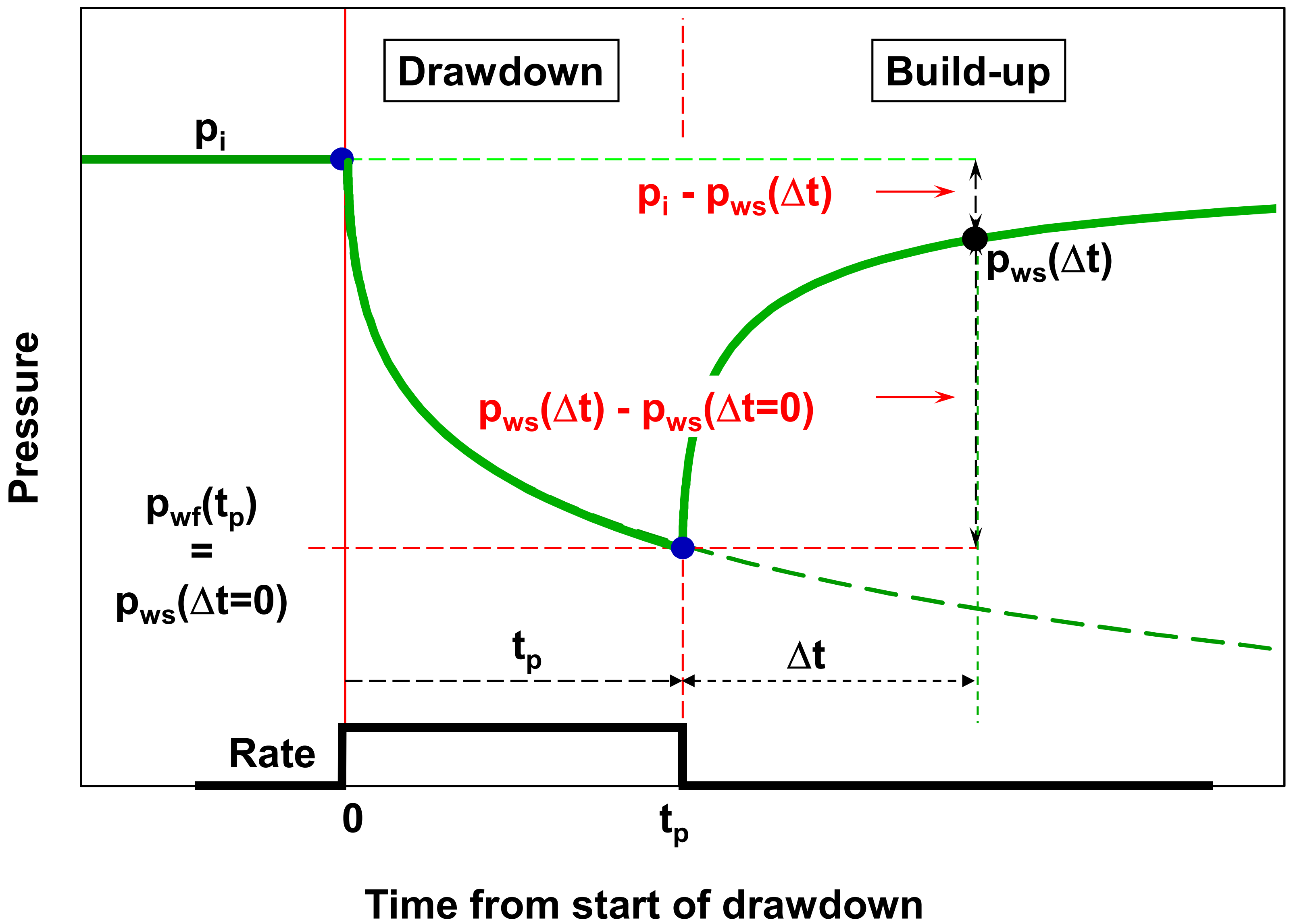
$$p_D = \frac{kh}{141.2\Delta q\, B\, \mu}\Delta p$$

$$\frac{t_D}{C_D} = 0.000295\frac{kh}{\mu\, C}\Delta t$$

$$C_D\, e^{2S} = \frac{0.8936}{\phi\, c_t h r_w^2} C\, e^{2S}$$

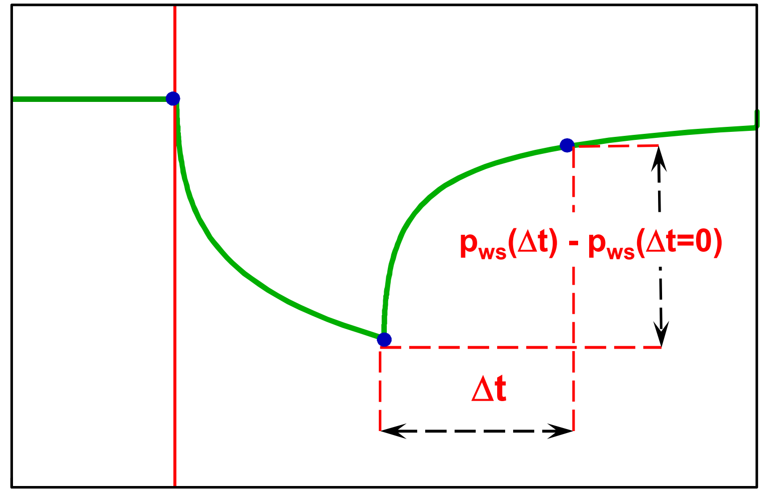


MODEL RESPONSE, BUILD-UP AFTER FIRST DRAWDOWN



MODEL RESPONSE, BUILD-UP AFTER FIRST DRAWDOWN

(1) Signal in build-up: $(\Delta p)_{ws} = [p_{ws}(\Delta t) - p_{ws}(\Delta t{=}0)]$



$$[(\Delta p)_{ws}]_D = PM\,[p_{ws}(\Delta t) - p_{ws}(\Delta t{=}0)]$$

$$[(\Delta p)_{ws}]_D = PM\,[p_{ws}(\Delta t) - p_i + p_i - p_{ws}(\Delta t{=}0)]$$

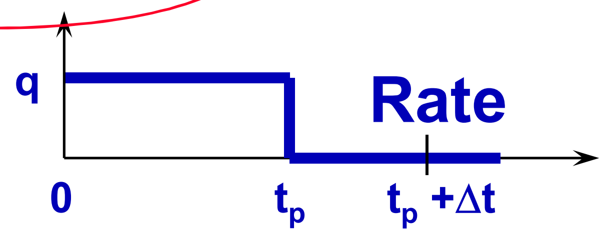
$$[(\Delta p)_{ws}]_D = PM\,[p_i - p_{ws}(\Delta t{=}0)] - PM\,[p_i - p_{ws}(\Delta t)]$$

$$[(\Delta p)_{ws}]_D = PM\,[p_i - p_{wf}(t_p)] - PM\,[p_i - p_{ws}(\Delta t)]$$

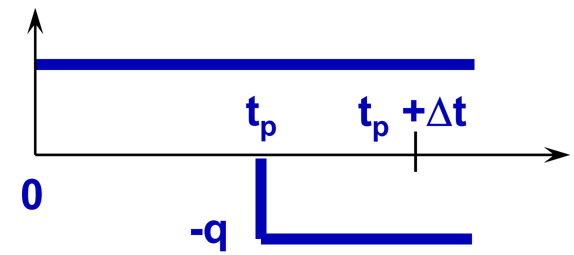
$$[(\Delta p)_{ws}]_D = p_D(t_p)_D - PM\,[p_i - p_{ws}(\Delta t)]$$

Superposition in time:

$PM\,[p_i - p_{ws}(\Delta t)] =$
$p_D(t_p + \Delta t)_D - p_D(t_p + \Delta t - t_p)_D$



$\equiv$



$$[(\Delta p)_{ws}]_D = p_D(t_p)_D - [p_D(t_p + \Delta t)_D - p_D(\Delta t)_D]$$

$$[(\Delta p)_{ws}]_D = p_D(\Delta t)_D + p_D(t_p)_D - p_D(t_p + \Delta t)_D$$ **Build-up Type Curve**

☞ **Usually plotted as:** $\log [(\Delta p)_{ws}]_D$ vs $\log t_D$

Agarwal, Al-Hussainy and Ramey SPE 2466 44th ATCE Denver (Sept. 1969; SPEJ(Sept. 1970)

BUILD-UP TYPE CURVE BEHAVIOUR

$$[(\Delta p)_{ws}]_D = p_D(\Delta t)_D + [p_D(t_p)_D - p_D(t_p + \Delta t)_D]$$

- Δt small compared with t_p

$[p_D(t_p + \Delta t)_D - p_D(t_p)_D] \longrightarrow 0$

$[(\Delta p)_{ws}]_D = p_D(\Delta t)_D$

- Δt large compared with t_p

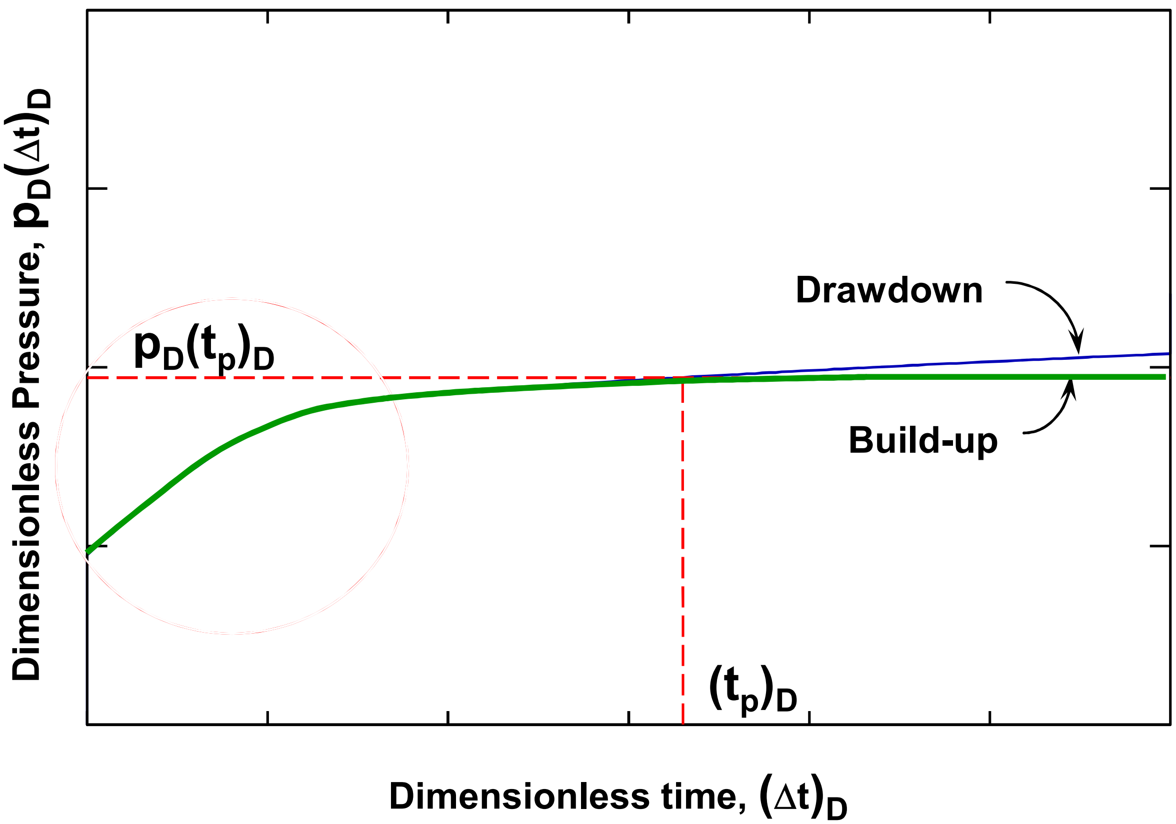
$p_D(t_p + \Delta t)_D \longrightarrow p_D(\Delta t)_D]$

$[(\Delta p)_{ws}]_D \longrightarrow p_D(t_p)_D$

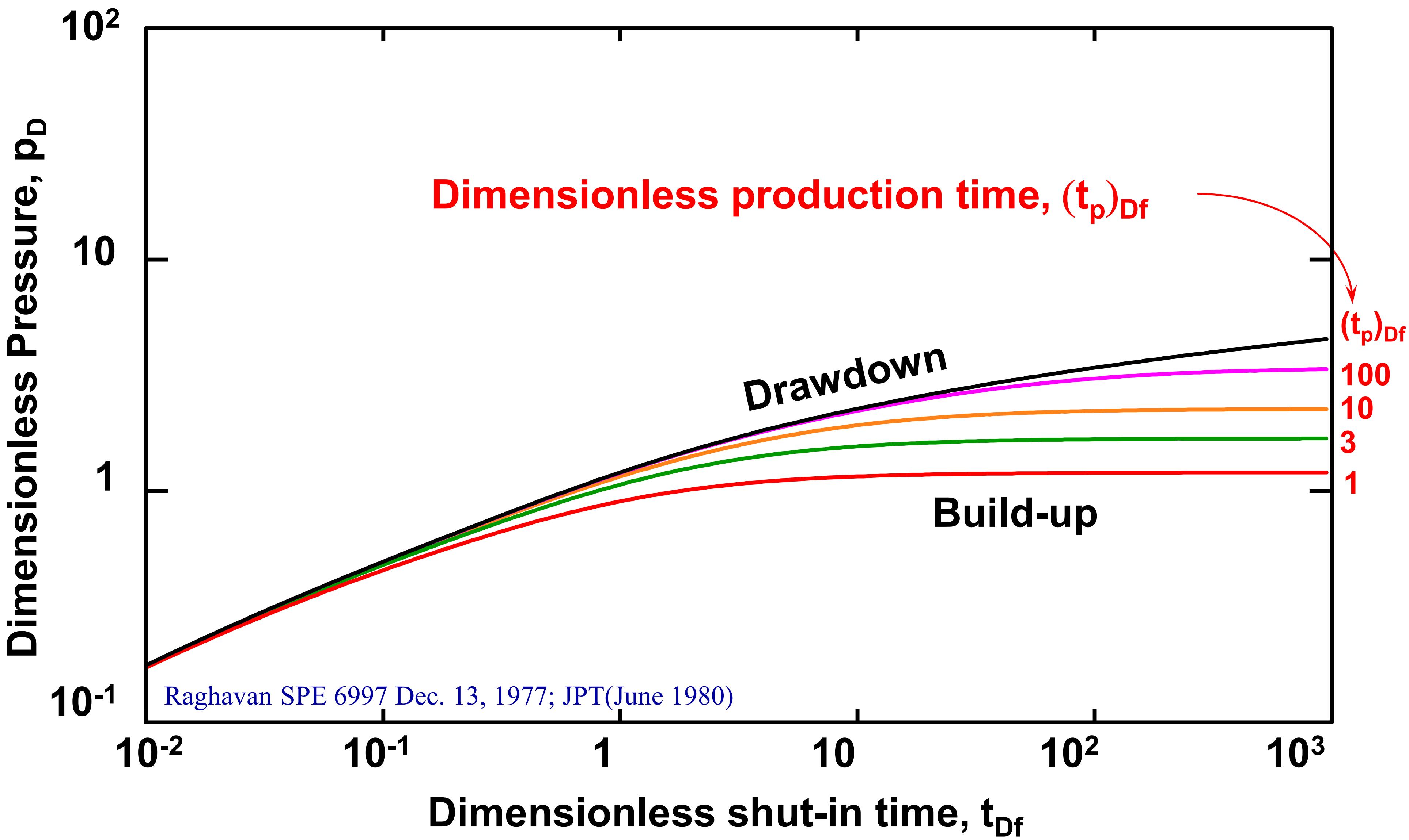
- in between

$[p_D(t_p)_D - p_D(t_p + \Delta t] < 0$

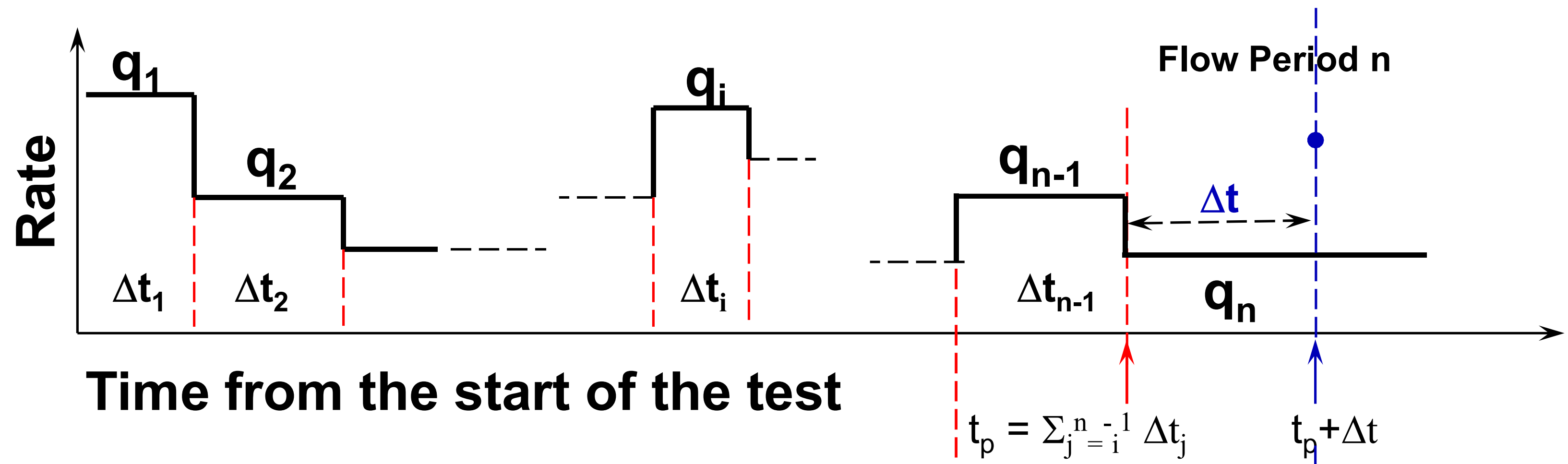
$[(\Delta p)_{ws}]_D < p_D(\Delta t)_D$



DRAWDOWN AND BUILD-UP TYPE CURVES
for a well with an infinite conductivity fracture in an infinite reservoir with homogeneous behaviour



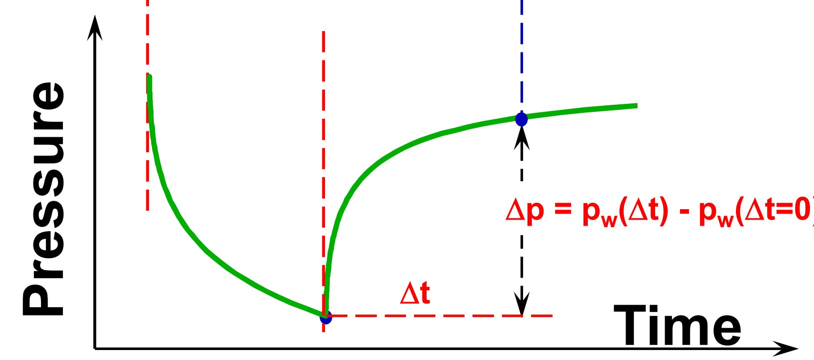
MODEL RESPONSE, SUBSEQUENT FLOW PERIOD



(1) Multirate Signal:

$\Delta p = |p(\Delta t) - p(\Delta t=0)|$

$(\Delta p)_D = PM\ |p(\Delta t) - p(\Delta t=0)|$



$(\Delta p)_D = p_D(\Delta t)_D$

$+ \Sigma_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\ [p_D(\Sigma_{j=i}^{n-1} \Delta t_j)_D - p_D(\Sigma_{j=i}^{n-1} \Delta t_j + \Delta t)_D]$

Multirate Type Curve usually plotted as: $\log [(\Delta p)]_D$ vs $\log t_D$

MULTIRATE TYPE CURVE BEHAVIOUR

$(\Delta p)_D = p_D(\Delta t)_D$

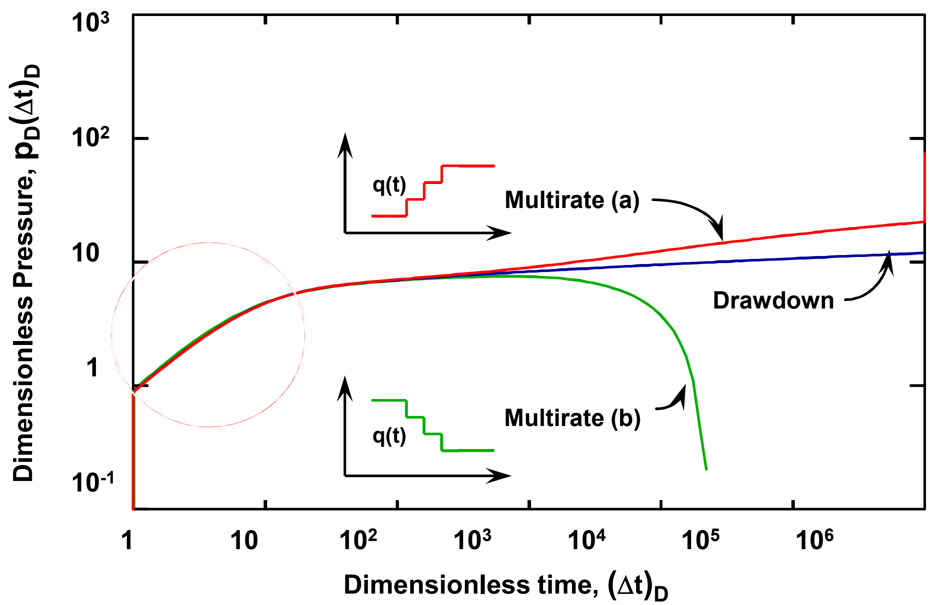
$+ \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)] [p_D(\sum_{j=i}^{n-1} \Delta t_j)_D - p_D(\sum_{j=i}^{n-1} \Delta t_j + \Delta t)_D]$

- ❑ Δt small compared with t_p

[bracket term] → 0

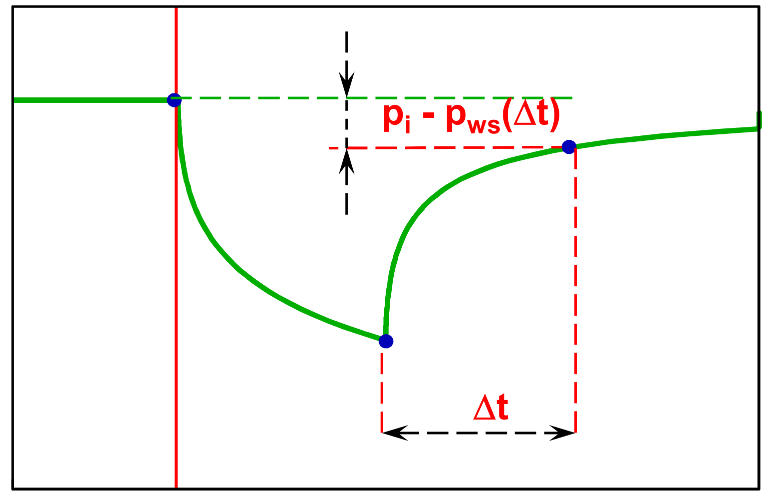
$[(\Delta p)_{ws}]_D = p_D(\Delta t)_D$

- ❑ [bracket term] >0 or <0



MODEL RESPONSE, BUILD-UP AFTER FIRST DRAWDOWN

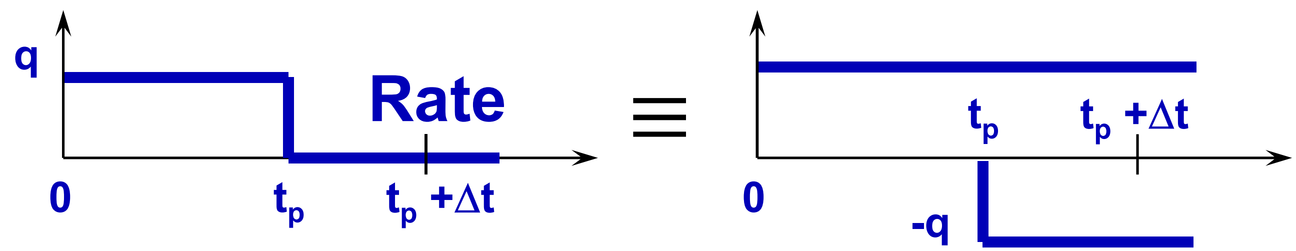
(2) Signal in build-up: $(\Delta p)_H = [p_i - p_{ws}(\Delta t)]$



$[(\Delta p)_H]_D = PM\ [p_i - p_{ws}(\Delta t)]$

Superposition in time:

$PM\ [p_i - p_{ws}(\Delta t)] =$
$p_D(t_p + \Delta t)_D - p_D(t_p + \Delta t - t_p)_D$



$[(\Delta p)_H]_D = p_D(t_p + \Delta t)_D - p_D(\Delta t)_D$

$[(\Delta p)_H]_D = p_D(t_p + \Delta t)_D - p_D(\Delta t)_D$ **Horner Type Curve**

☞ **Usually plotted as:** $[(\Delta p)_H]_D$ **vs Horner time** $f(t_p + \Delta t)_D - f(\Delta t)_D$

Radial Flow HORNER Time

$$p(\Delta t) = p_i - \frac{1}{\mathrm{PM}}\left\{p_D\left[\mathrm{TM}\left(t_p + \Delta t\right)\right] - p_D\left(\mathrm{TM}\,\Delta t\right)\right\}$$

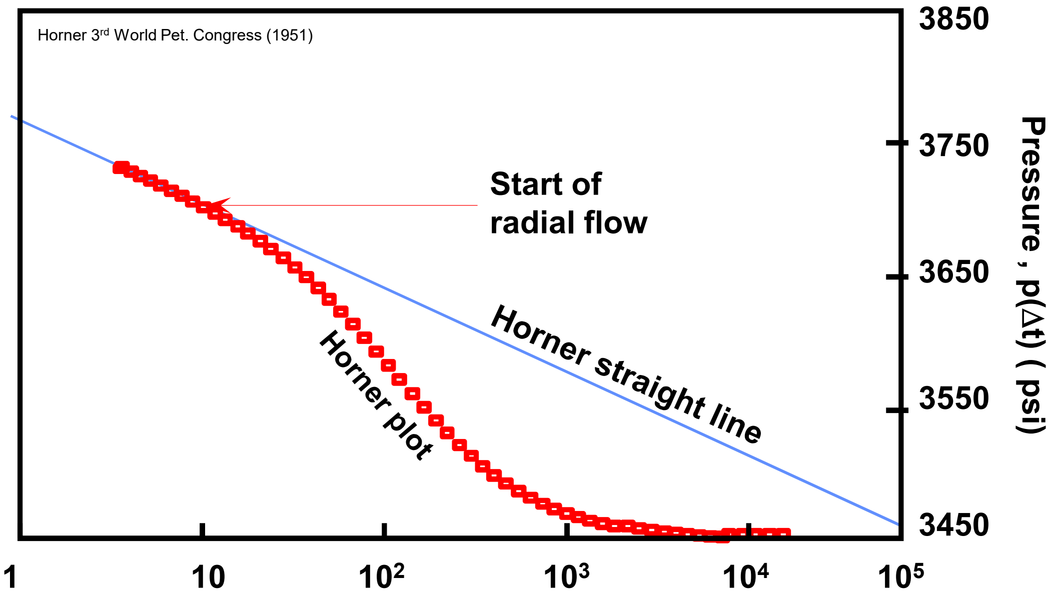
If $p_D(\mathrm{TM}\,\Delta t)$ can be approximated by a log (Radial flow):

$$p_D\left(TM\ \Delta t\right) = \frac{1}{2}\left(\ln TM\ \Delta t + 0.80907\right) = 1.151\left(\log TM\ \Delta t + 0.35\right)$$

$p_D\left[\mathrm{TM}\left(t_p + \Delta t\right)\right]$ **can also be approximated by a log:** $p_D\left[TM\left(t_p + \Delta t\right)\right] = 1.151\left[\log TM\left(t_p + \Delta t\right) + 0.35\right]$

$$p(\Delta t) = p_i - \frac{1.151}{PM}\log\frac{t_p + \Delta t}{\Delta t}$$

$\frac{t_p + \Delta t}{\Delta t}$ **= Horner time**

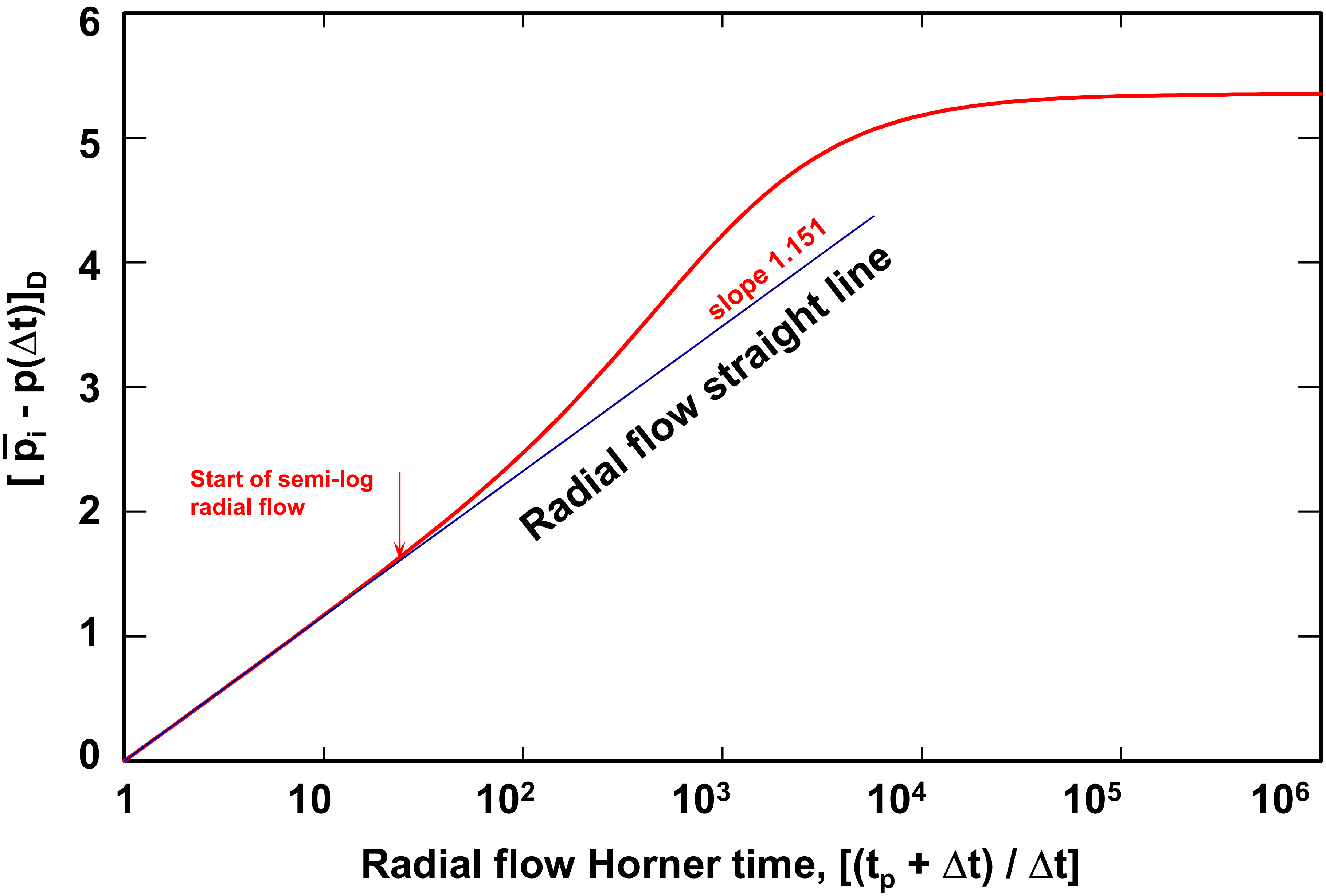


$$\frac{t_p + \Delta t}{\Delta t}$$

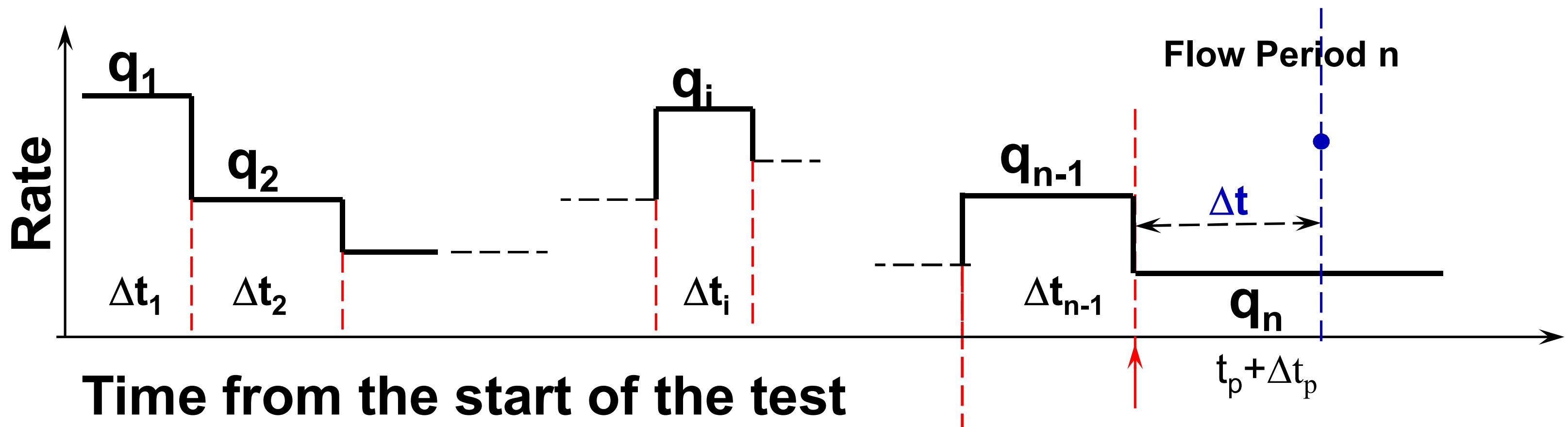
$Linear\ \ flow = \left(t_p + \Delta t\right)^{1/2} - \left(\Delta t\right)^{1/2}$

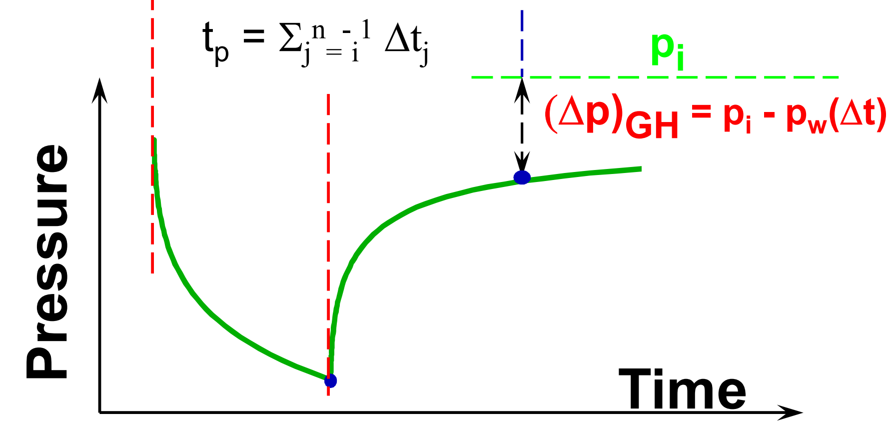
$Spherical\ \ flow = \left(\Delta t\right)^{-1/2} - \left(t_p + \Delta t\right)^{-1/2}$

HORNER TYPE CURVE
BUILD-UP AFTER FIRST DRAWDOWN



MODEL RESPONSE, SUBSEQUENT FLOW PERIOD





(2) Multirate Signal:

$\Delta p = (p_i - p(\Delta t))$

$(\Delta p)_{GH} = PM\ |p_i - p(\Delta t)|$

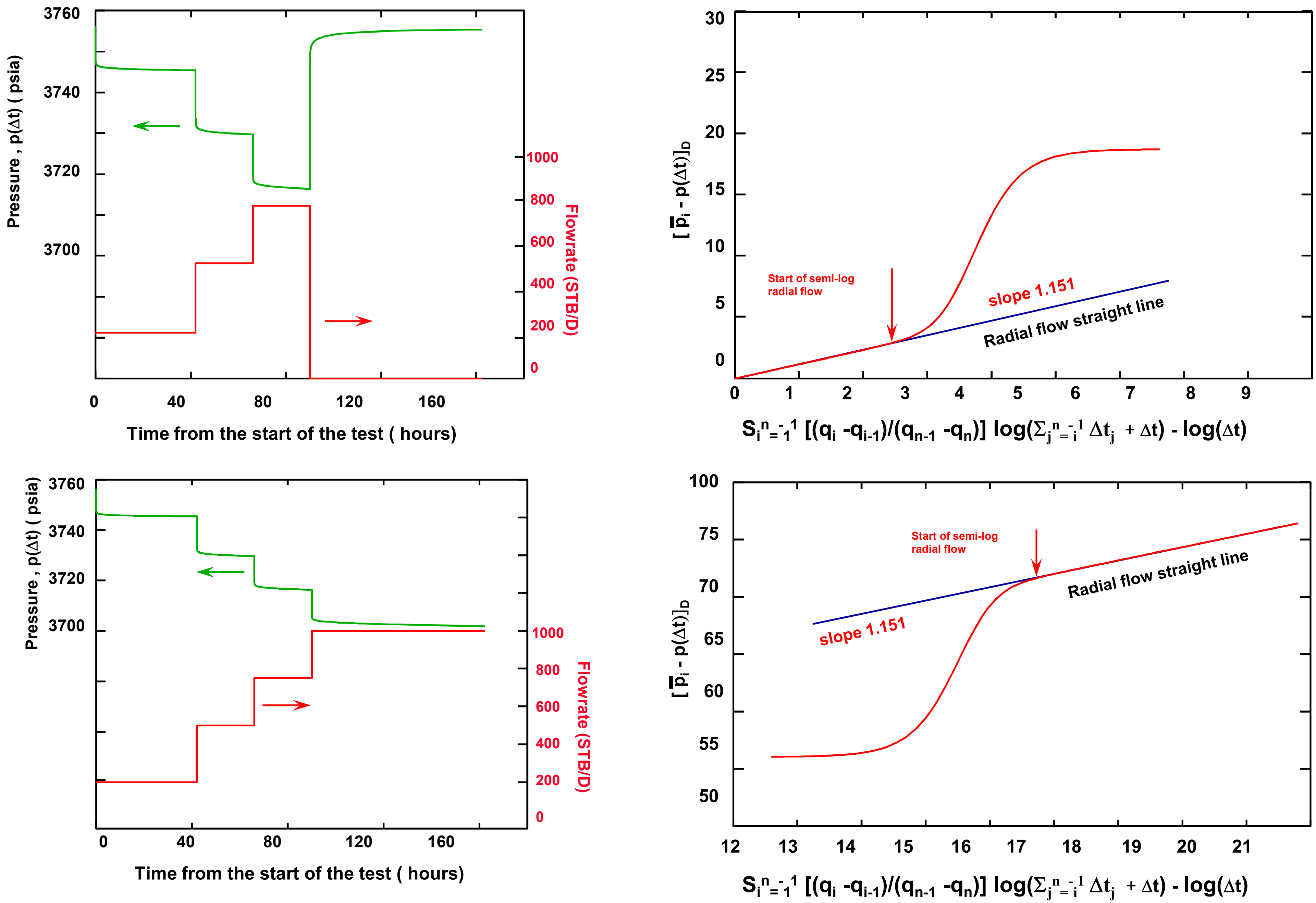
$$(\Delta p)_{GH} = \Sigma_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\ p_D(\Sigma_{j=i}^{n-1} \Delta t_j + \Delta t)_D - p_D(\Delta t)_D$$

Generalised Horner Type Curve usually plotted as:

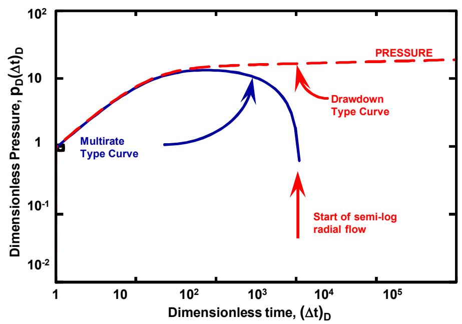
$$(\Delta p_{\ GH})_D \text{ vs } \Sigma_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\ f(\Sigma_{j=i}^{n-1} \Delta t_j + \Delta t) - f(\Delta t)$$

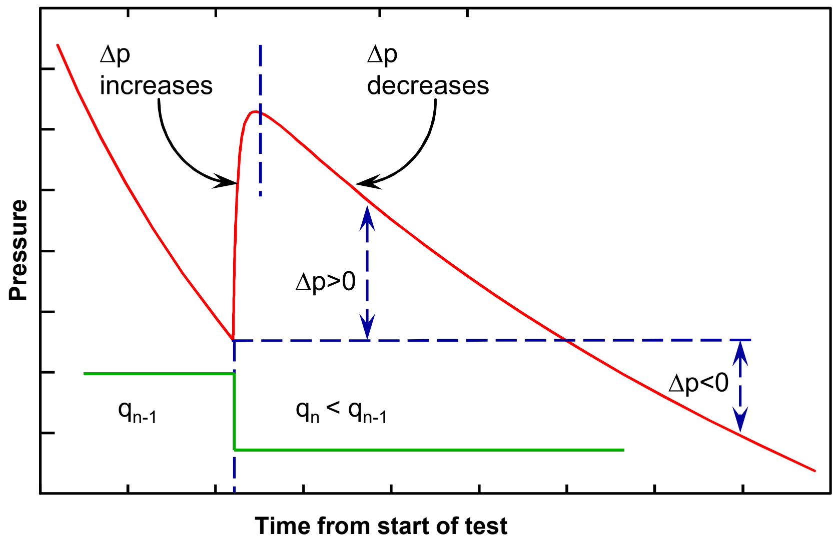
(Superposition time)

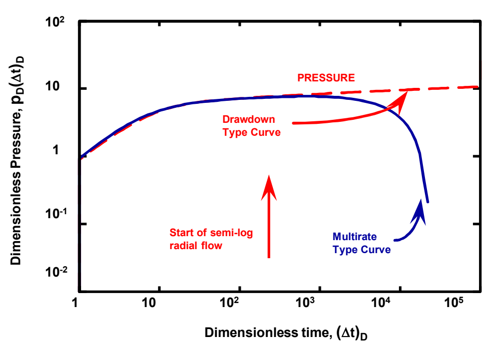
GENERALISED HORNER TYPE CURVE

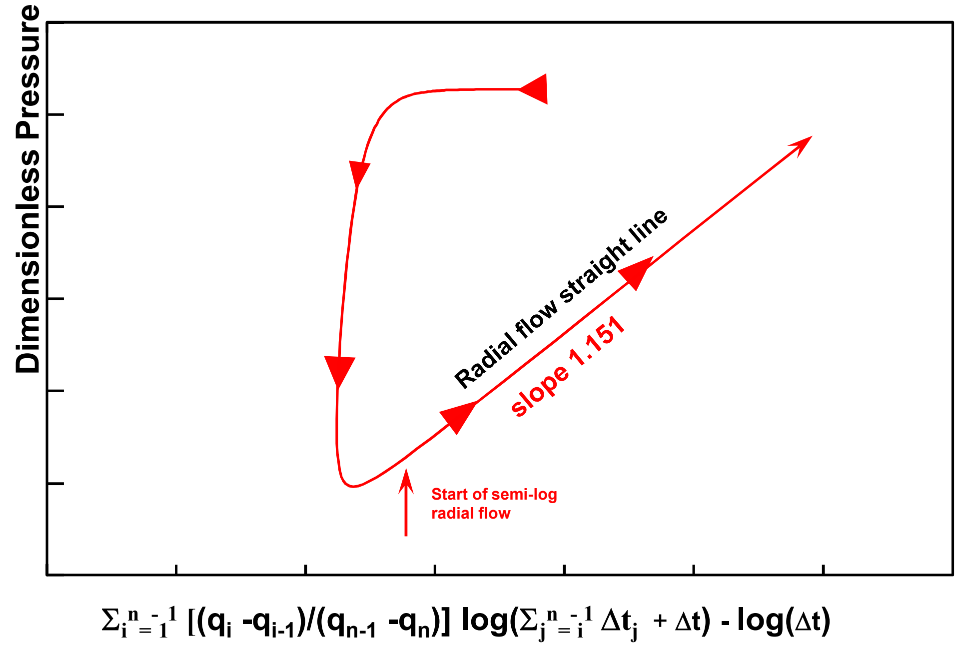


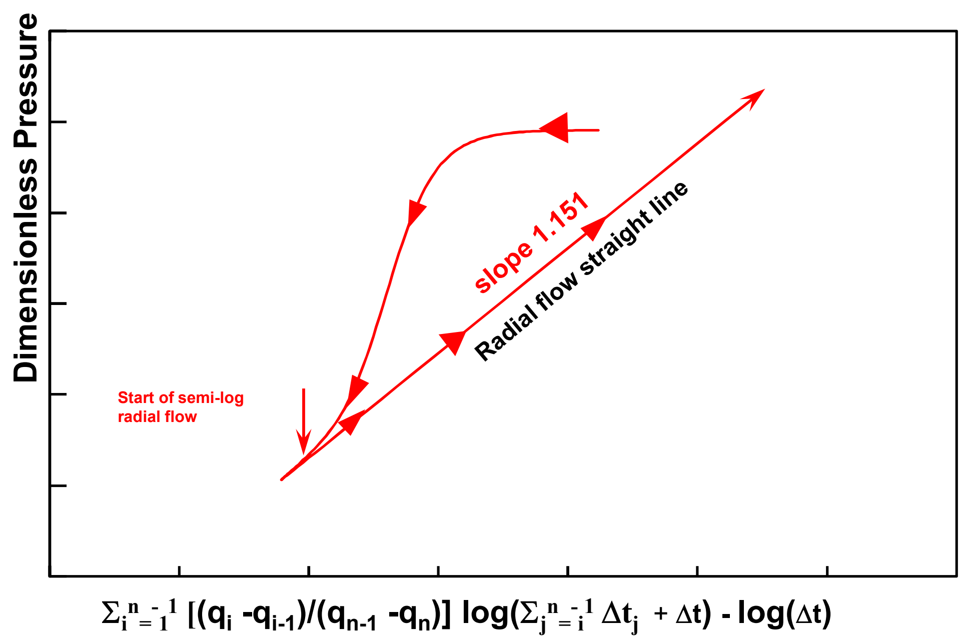
GENERALISED HORNER TYPE CURVE











ANALYSIS TECHNIQUES

Once a MODEL has been identified:

- **The Model response equations:**
  provide relationships between data and model
- **They apply to:**
  - **entire <u>test</u>**
  - **individual <u>flow periods</u> in the test**
  - **individual <u>flow regimes</u> within a flow period**
- **They are used to calculate model parameters**
  (manual or computer “fit” or “match”)
- **They are used to check analysis results**
  (verification)

CALCULATION OF RESERVOIR PARAMETERS

(1.a) From Drawdown Type Curve:

$$[(\Delta p)_{wf}]_D = p_D(\Delta t_D)$$

Data

$$PM\,[p_i - p_{wf}(\Delta t)] \equiv p_D\,(TM\,\Delta t)$$

Selected Model

Unknown model parameters

If p_D represents the equation for the entire model:

☞ ***LOG-LOG ANALYSIS*** **of data from first drawdown with** ***drawdown type curves***

If p_D represents the equation of a specific flow regime only:

☞ ***SPECIALISED ANALYSES*** **of data from first drawdown**

CALCULATION OF RESERVOIR PARAMETERS

(1.b) From Build-up Type Curve: $[(\Delta p)_{ws}]_D = p_D(\Delta t_D) + [p_D(t_p)_D - p_D(t_p + \Delta t)_D]$

Data

$PM\ [p_{ws}(\Delta t) - p_{ws}(\Delta t=0)] \equiv p_D(TM\ \Delta t) + \{p_D\ (TM\ \ t_p) - p_D[TM\ (t_p + \Delta t)]\}$

Selected Model

Unknown model parameters

If p_D represents the equation for the entire model:

☞ ***LOG-LOG ANALYSIS*** **of data from the build-up following the first drawdown with** ***build-up type curves***

☛ **IF** $\{p_D\ (TM\ \ t_p) - p_D[TM\ (t_p + \Delta t)]\}$ **can be neglected,**

$PM\ [\ p_{ws}(\Delta t) - p_{ws}(\Delta t=0)] \equiv p_D(TM\ \Delta t)$ **Drawdown type curve**

☞ ***Log-log analysis*** **of first build-up data with drawdown type curves**
(if p_D represents the equation for the entire model)

☞ ***Specialised analyses*** **of first build-up data**
(if p_D represents the equation of a specific flow regime only)

CALCULATION OF RESERVOIR PARAMETERS

(1.c) From Multirate Type Curve:

$$(\Delta p)_D = p_D(\Delta t)_D + \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\, [p_D(\sum_{j=i}^{n-1} \Delta t_j)_D - p_D(\sum_{j=i}^{n-1} \Delta t_j + \Delta t)_D]$$

Data

$$PM\, |p_w(\Delta t) - p_w(\Delta t{=}0)| \equiv p_D(TM\, \Delta t) + \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\, \{p_D(TM \sum_{j=i}^{n-1} \Delta t_j) - p_D[TM(\sum_{j=i}^{n-1} \Delta t_j + \Delta t)]\}$$

Selected Model

Unknown model parameters

If p_D represents the equation for the <u>entire</u> model:

☞ ***LOG-LOG ANALYSIS*** **of data from a subsequent flow period with** ***multirate type curves***

☛ **<u>IF</u>** $\sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\, \{p_D(TM \sum_{j=i}^{n-1} \Delta t_j) - p_D[TM(\sum_{j=i}^{n-1} \Delta t_j + \Delta t)]\}$ **can be neglected,**

$PM\, |\, p_w(\Delta t) - p_w(\Delta t{=}0)| \equiv p_D(TM\, \Delta t)$ **Drawdown type curve**

☞ ***Log-log analysis*** **of subsequent data with drawdown type curves**
(if p_D represents the equation for the <u>entire</u> model)

☞ ***Specialised analyses*** **of subsequent flow period data**
(if p_D represents the equation of a <u>specific flow regime</u> only)

CALCULATION OF RESERVOIR PARAMETERS

(2.a) From Horner Type Curve:

$$[(\Delta p)_H]_D = p_D(t_p + \Delta t)_D - p_D(\Delta t)_D$$

Data

$$PM\,[(p_{av})_i - p_{ws}(\Delta t)] \equiv p_D\,[TM\,(t_p + \Delta t)] - p_D\,[TM\,(\Delta t)]$$

Unknown model parameters

Selected Model

If p_D represents the equation of a <u>specific flow regime</u> only:

☞ *Horner analysis* of data from the build-up following the first drawdown

CALCULATION OF RESERVOIR PARAMETERS

(2.b) From Generalised Horner Type Curve:

$$(\Delta p)_{GH} = \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\; p_D\left(\sum_{j=i}^{n-1} \Delta t_j + \Delta t\right)_D - p_D(\Delta t)_D$$

Data

$$PM\,[(p_{av})_i - p_w(\Delta t)] \equiv \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\; p_D\left[TM\left(\sum_{j=i}^{n-1} \Delta t_j + \Delta t\right)\right] - p_D(TM\,\Delta t)$$

Unknown model parameters

Selected Model

If p_D represents the equation of a <u>specific flow regime</u> only:

☞ ***Generalised Horner analysis (Superposition analysis)*** **of data from a subsequent flow period**

LOG-LOG ANALYSIS

(1) Analysis by "hand"

$$PM\ [p_w(\Delta t) - p_w(\Delta t=0)] \equiv p_D(TM\ \Delta t)$$

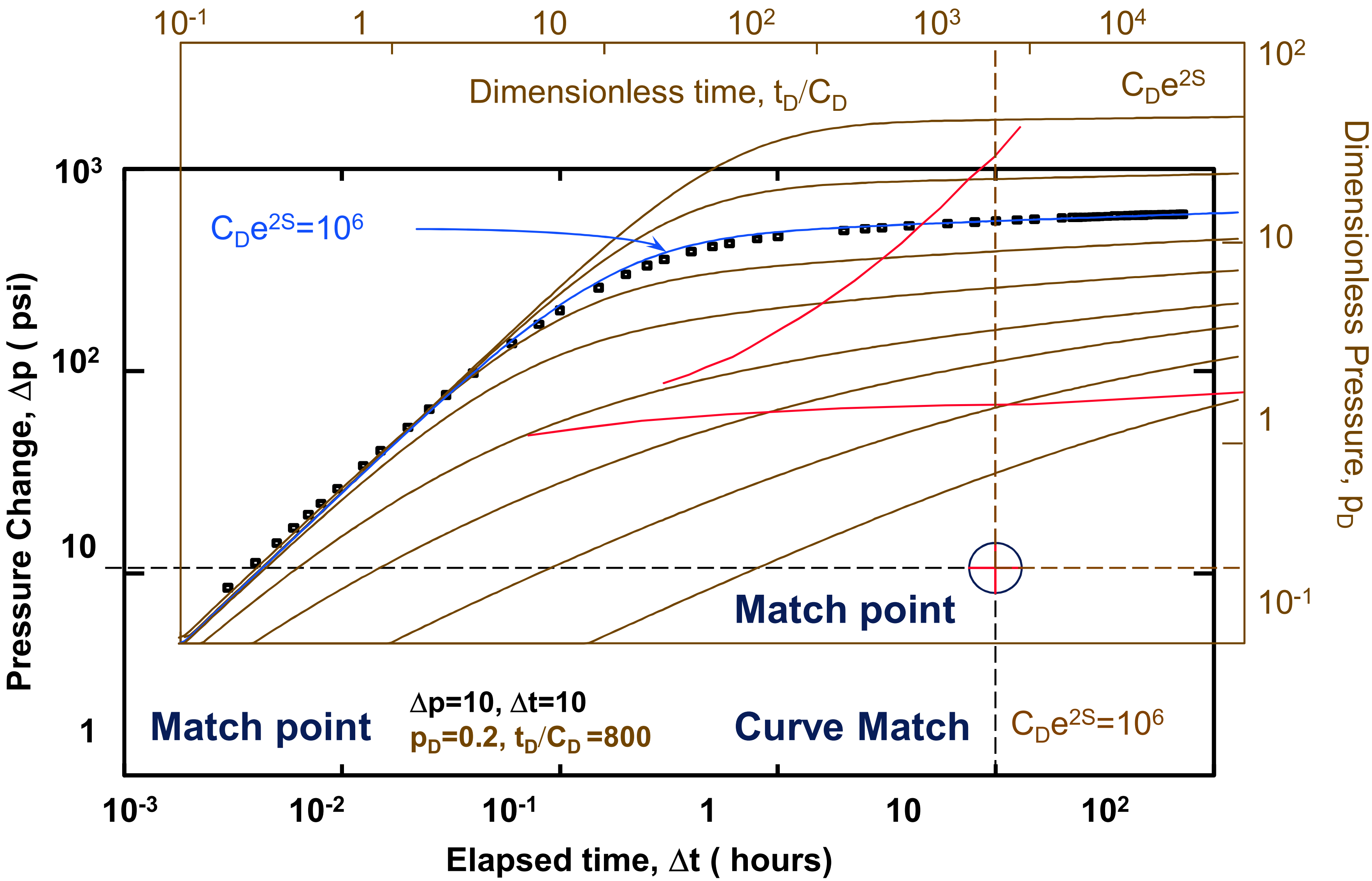
- Data, $[p(\Delta t) - p(\Delta t=0)]$ vs Δt , are "matched" with:

  a Drawdown Type Curve
  for the entire applicable interpretation model, $p_D(\Delta t)_D$ vs $(\Delta t)_D$,
  over an entire flow period

- Yields all the interpretation model parameters
  (i.e., ALL analysis results)

☞ Applies to build-up or multirate data
as long as $\{p_D(TM\ \ t_p) - p_D[TM\ (t_p + \Delta t)]\}$ can be neglected

Type Curve Match for a Well with Wellbore Storage and Skin in a Reservoir of Infinite Extent with Homogeneous Behaviour



LOG-LOG ANALYSIS

(2) Analysis by computer

$$PM\,[p_{ws}(\Delta t) - p_{ws}(\Delta t=0)] \equiv p_D(TM\,\Delta t) + \{p_D(TM\,t_p) - p_D[TM\,(t_p + \Delta t)]\}$$

$$PM\,|p_w(\Delta t) - p_w(\Delta t=0)| \equiv p_D(TM\,\Delta t) + \Sigma_{i=1}^{n-1}\,[(q_i - q_{i-1})/(q_{n-1} - q_n)]\,\{p_D(TM\,\Sigma_{j=i}^{n-1}\,\Delta t_j) - p_D[TM(\Sigma_{j=i}^{n-1}\,\Delta t_j + \Delta t)]\}$$

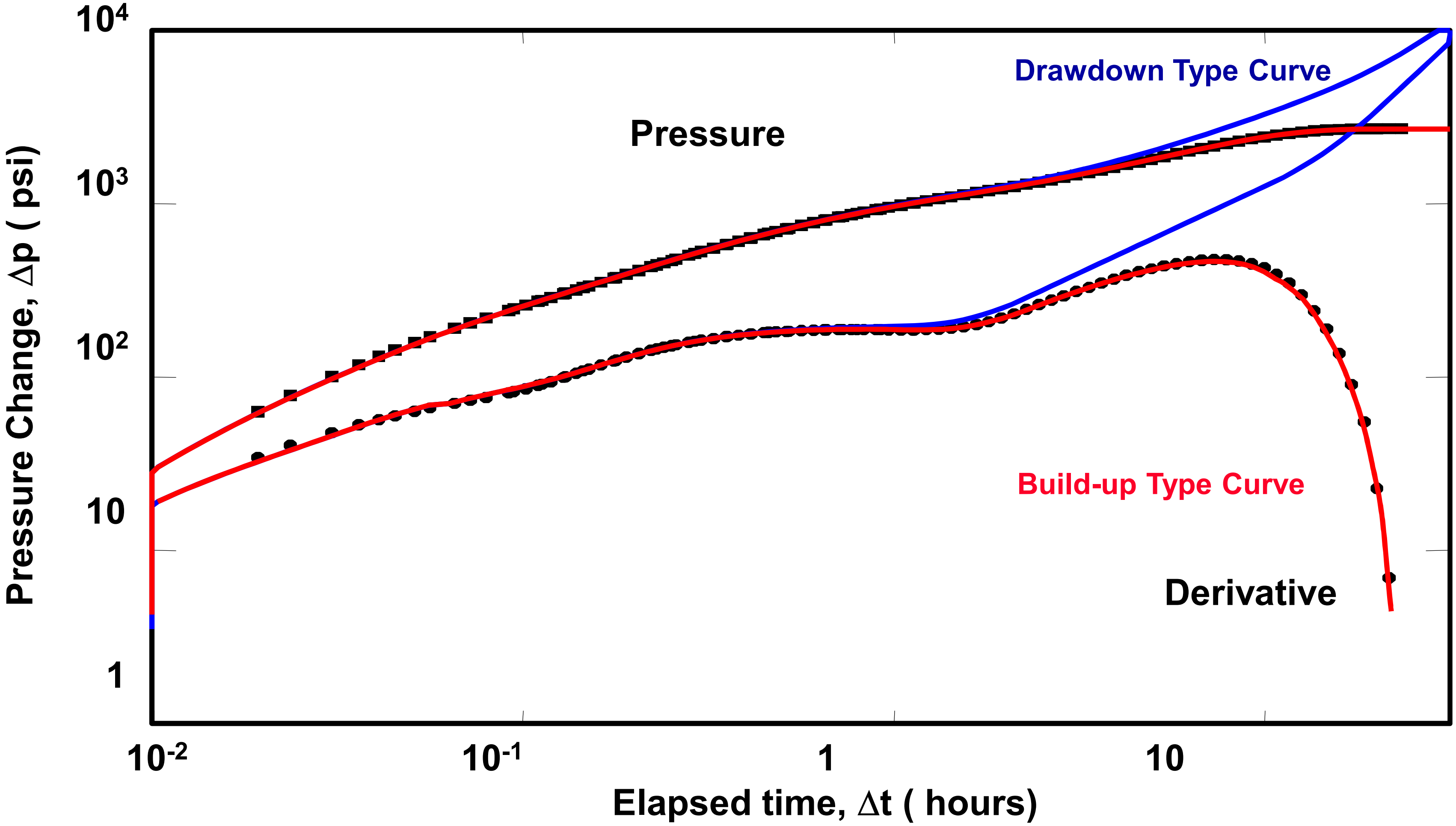
- Data , $|p(\Delta t) - p(\Delta t=0)|$ vs Δt, are "matched" with

  a Build-up (or Multirate) Type Curve
  for the entire applicable interpretation model ,
  $p_D(\Delta t)_D + p_D(t_p)_D - p_D(t_p+\Delta t)_D$ (or multirate equivalent) vs $(\Delta t)_D$,
  over an entire flow period

- Yields all the interpretation model parameters
  (i.e., ALL analysis results)

- Applies to build-up (or multirate) data

Match for a Well with Wellbore Storage and Skin in a Closed Rectangular Reservoir with Homogeneous Behaviour



STRAIGHT LINE ANALYSES

(1) Specialised analyses

PM [$p_w(\Delta t) - p_w(\Delta t=0)$] $\equiv$ p_D(TM Δt)

where $p_D(\Delta t)_D$ corresponds to a specific flow regime:

Wellbore storage: $p_D = \frac{t_D}{C_D}$

Linear flow: $p_D = \left(\pi \; t_{Df}\right)^{1/2}$

Finite conductivity fracture bilinear flow: $p_D = 2.45\left(k_{fD}\, w_D\right)^{-1/2}\left(t_{Df}\right)^{1/4}$

Spherical flow: $p_{\mathrm{SPH}\;D} = \frac{1}{2}\left[1 - \left(\pi \; t_{\mathrm{SPH}\;D}\right)^{-1/2}\right]$

Radial flow: $p_D = 1.151\left(\log t_{De} + 0.35\right)$

Pseudo-steady state flow: $p_D = 2\pi \frac{r_{wa}^2}{A} t_{De} + 1.151\left[\log \frac{A}{r_{wa}^2} - \log C_A + 0.786\right]$

- **Data in a flow period, [$p(\Delta t) - p(\Delta t=0)$], are plotted vs the corresponding time function $f(\Delta t)$ (resp., Δt, $\Delta t^{1/2}$, $\Delta t^{1/4}$, $\Delta t^{-1/2}$, log Δt and Δt)**

- **A straight line is obtained where the specific flow regime dominates. Slope and intercept yield flow regime-specific model parameters**

- **Applies to build-up or multirate data if, and only if {p_D(TM t_p) - p_D[TM (t_p +Δt)]} can be neglected (i.e. [$p(\Delta t) - p(\Delta t=0)$] match a drawdown type curve)**

STRAIGHT LINE ANALYSES

(2) Horner (superposition) analyses

$$PM\,[(p_{av})_i - p_{ws}(\Delta t)] \equiv p_D\,[TM\,(t_p + \Delta t)] - p_D\,[TM\,(\Delta t)]$$

$$PM\,[(p_{av})_i - p_w(\Delta t)] \equiv \Sigma_{i=1}^{n-1}\,[(q_i - q_{i-1})/(q_{n-1} - q_n)]\,p_D[TM(\Sigma_{j=i}^{n-1}\,\Delta t_j + \Delta t)] - p_D(TM\,\Delta t)$$

where $p_D(\Delta t)_D$ corresponds to a specific flow regime:

Linear flow: $p_D = (\pi\, t_{Df})^{1/2}$

Finite conductivity fracture bilinear flow: $p_D = 2.45\,(k_{fD}\,w_D)^{-1/2}\,(t_{Df})^{1/4}$

Spherical flow: $p_{SPH\,D} = \frac{1}{2}\left[1 - (\pi\, t_{SPH\,D})^{-1/2}\right]$

Radial flow: $p_D = 1.151\,(\log t_{De} + 0.35)$

- Data in a flow period, $p(\Delta t)$, are plotted vs $f(t_p + \Delta t) - f(\Delta t)$ where $f(\Delta t)$ is the corresponding time function (resp., $\Delta t^{1/2}$, $\Delta t^{1/4}$, $\Delta t^{-1/2}$ and $\log \Delta t$)
- A straight line is obtained where the specific flow regime dominates. Slope and intercept yield flow regime-specific model parameters and $(p_{av})_i$
- Applies to build-up or multirate data

VERIFICATION

(1) Log-log Match

$PM\,[p_{ws}(\Delta t) - p_{ws}(\Delta t=0)]$ vs $(TM\,\Delta t)$

is compared with

$p_D(t_D)$ vs t_D

for the flow period being analysed.

Dimensionless data

Selected type curve

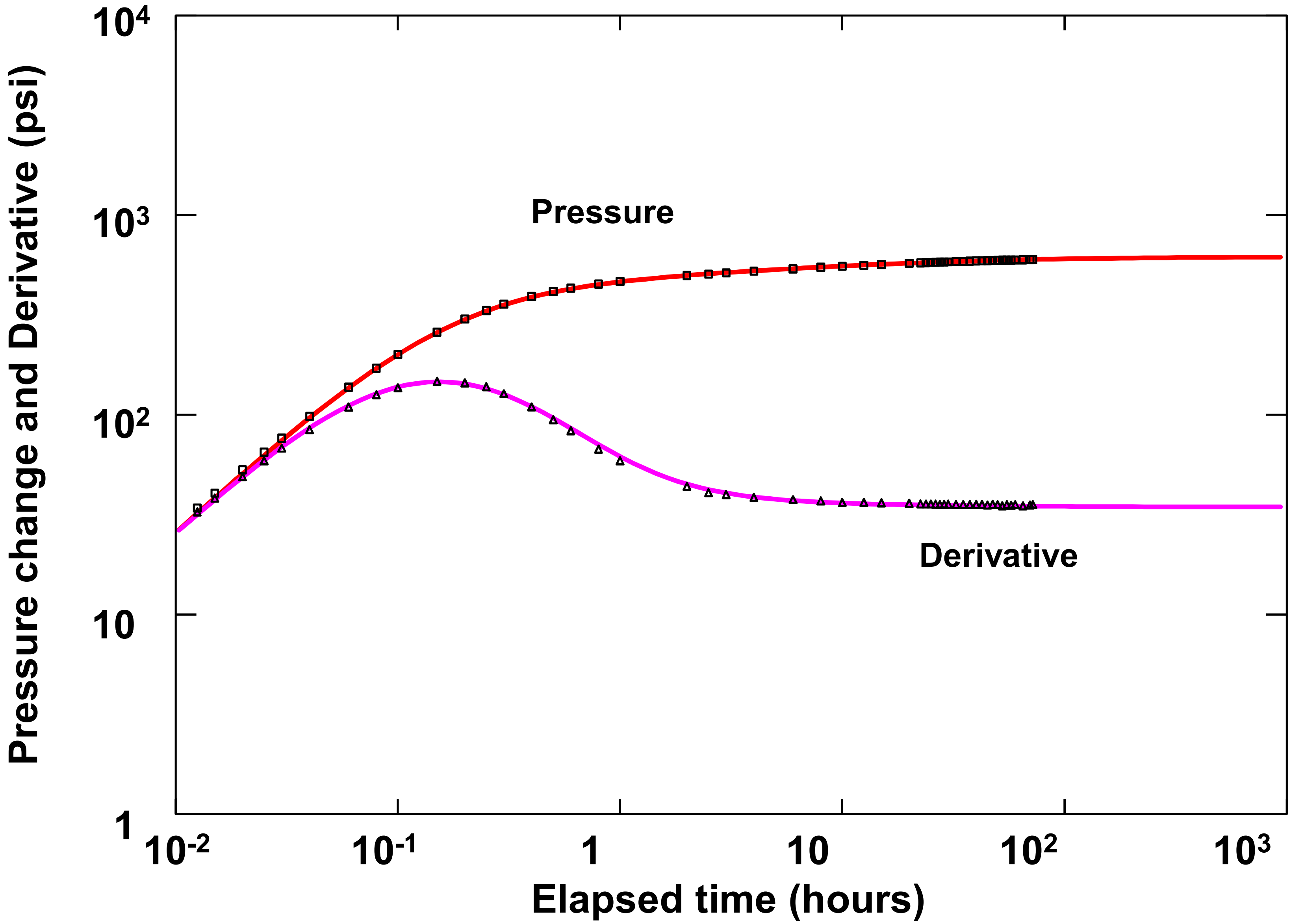
$$PM\,[p_{ws}(\Delta t) - p_{ws}(\Delta t=0)] \text{ vs. } TM\,\Delta t \overset{?}{\equiv} p_D(\Delta t)_D + \{p_D(TM\,t_p) - p_D[TM\,t_p + (\Delta t)_D]\} \text{ vs. } (\Delta t)_D$$

Calculated parameters

Data

$$PM\,|p_w(\Delta t) - p_w(\Delta t=0)| \overset{?}{\equiv} p_D(\Delta t)_D + \sum_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\, \{p_D(TM \sum_{j=i}^{n-1} \Delta t_j)_D - p_D[TM \sum_{j=i}^{n-1} \Delta t_j + (\Delta t)_D]\}$$

Log-log match verification plot



VERIFICATION

(2.1) Horner Match (build-up following the first drawdown)

PM $[(p_{av})_i - p_{ws}(\Delta t)]$ vs $\log (t_p + \Delta t)/\Delta t$
is compared with
$p_D[(t_p + \Delta t)_D] - p_D[(\Delta t)_D]$ vs $\log (t_p + \Delta t)_D / (\Delta t)_D$

Dimensionless Horner data — Selected Horner type curve

$$PM\ [(p_{av})_i - p_{ws}(\Delta t)] \text{ vs. } \log[\Delta t/(t_p + \Delta t)] \overset{?}{\equiv} p_D[(t_p + \Delta t)_D] - p_D[(\Delta t)_D] \text{ vs. } \log[\Delta t/(t_p+\Delta t)]_D$$

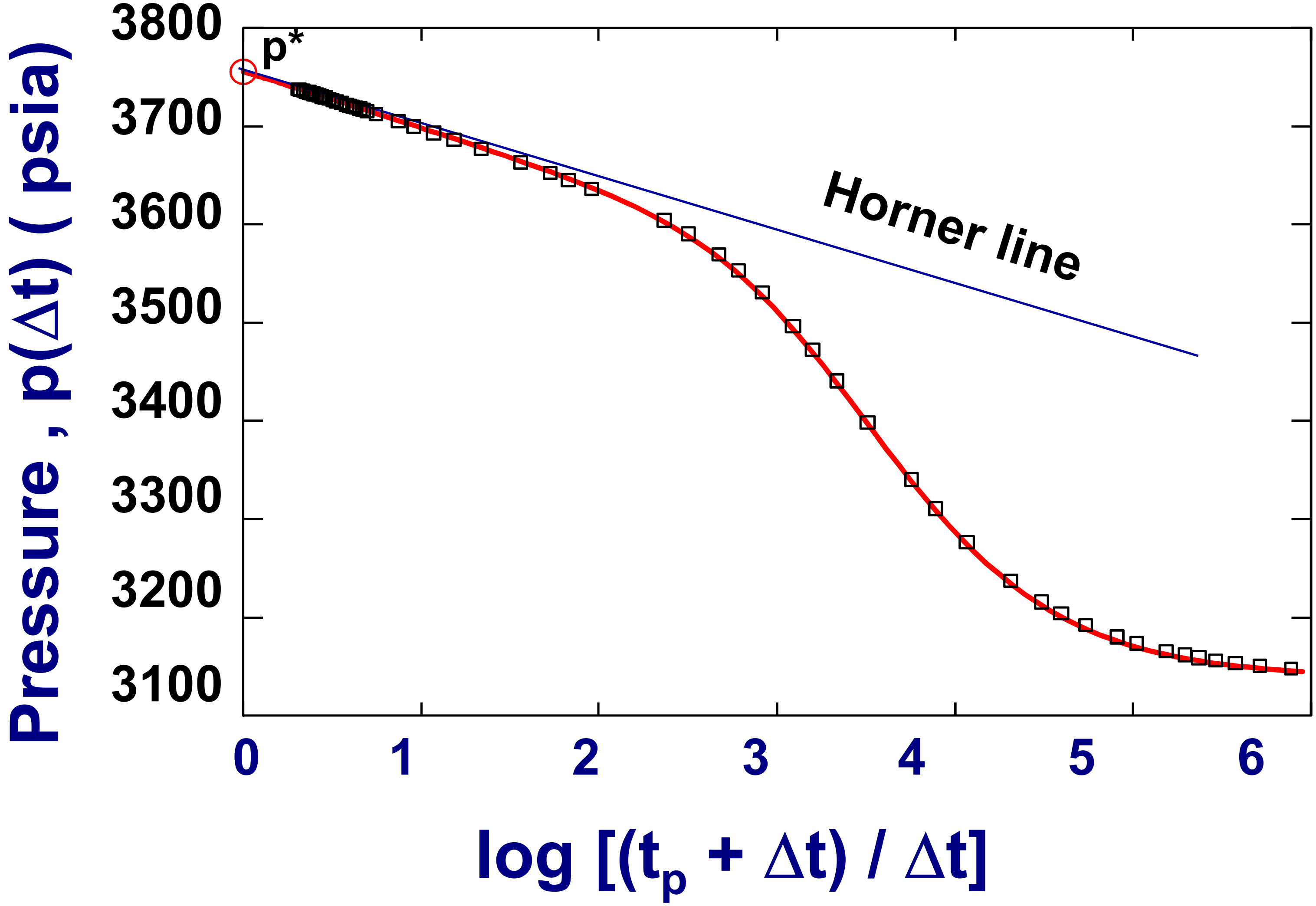
Data: $p_{ws}(\Delta t)$, Δt, t_p

Calculated parameters: PM, $(p_{av})_i$

(2.2) Superposition Match (subsequent flow period)

$$PM\ [(p_{av})_i - p_w(\Delta t)] \overset{?}{\equiv} \Sigma_{i=1}^{n-1} [(q_i - q_{i-1})/(q_{n-1} - q_n)]\ p_D[(\Sigma_{j=i}^{n-1} \Delta t_j + \Delta t)_D] - p_D(\Delta t)_D$$

Horner match verification plot, build-up



VERIFICATION

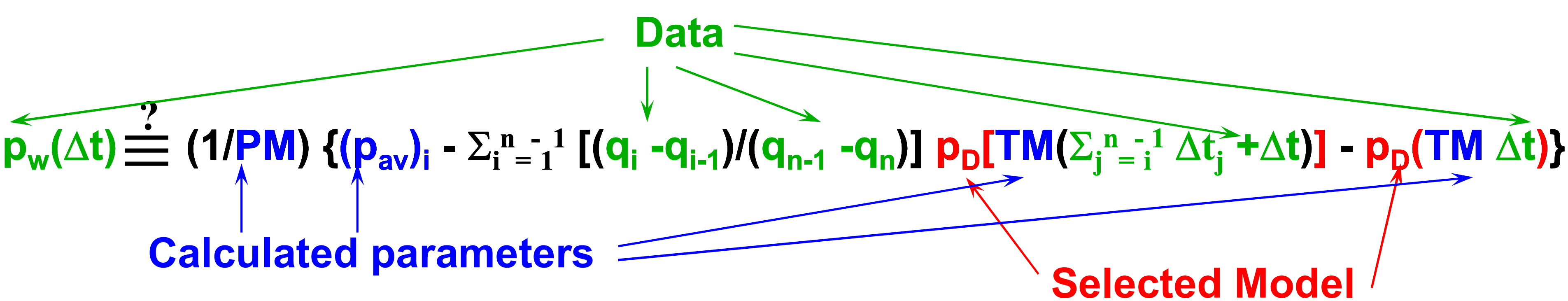
(3) Simulation

$p_w(\Delta t)$ vs Δt

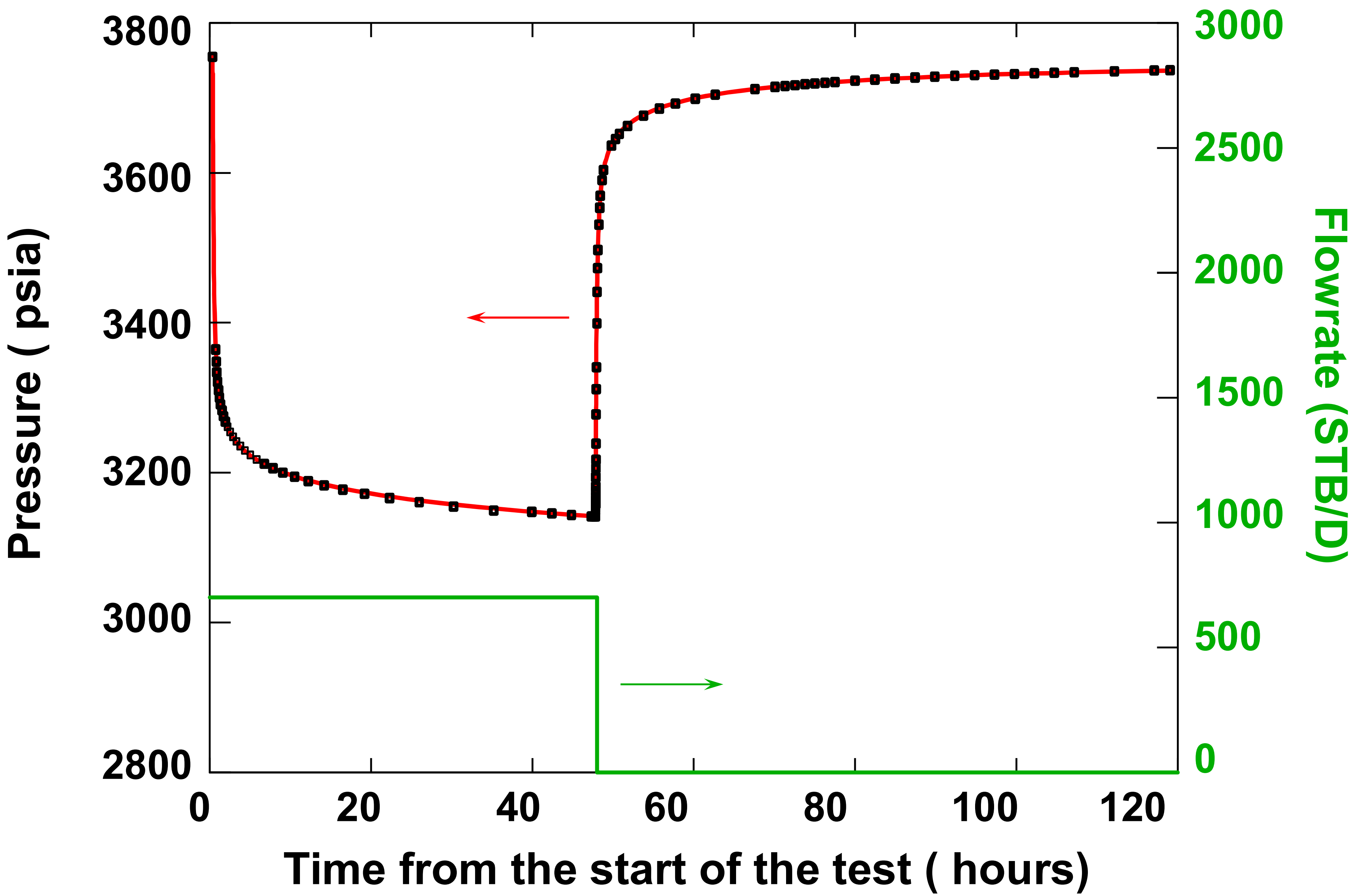
is compared with

$$(1/PM)\ \{(p_{av})_i - \Sigma_{i=1}^{n-1}\ [(q_i - q_{i-1})/(q_{n-1} - q_n)]\ p_D[TM(\Sigma_{j=i}^{n-1}\ \Delta t_j + \Delta t)] - p_D(TM\ \Delta t)\}\ \text{vs}\ t$$

over the entire rate history



Simulation match verification plot



ANALYSIS PROCESS:
Model identification, Parameter calculation and model verification

(1) Analysis by "hand"

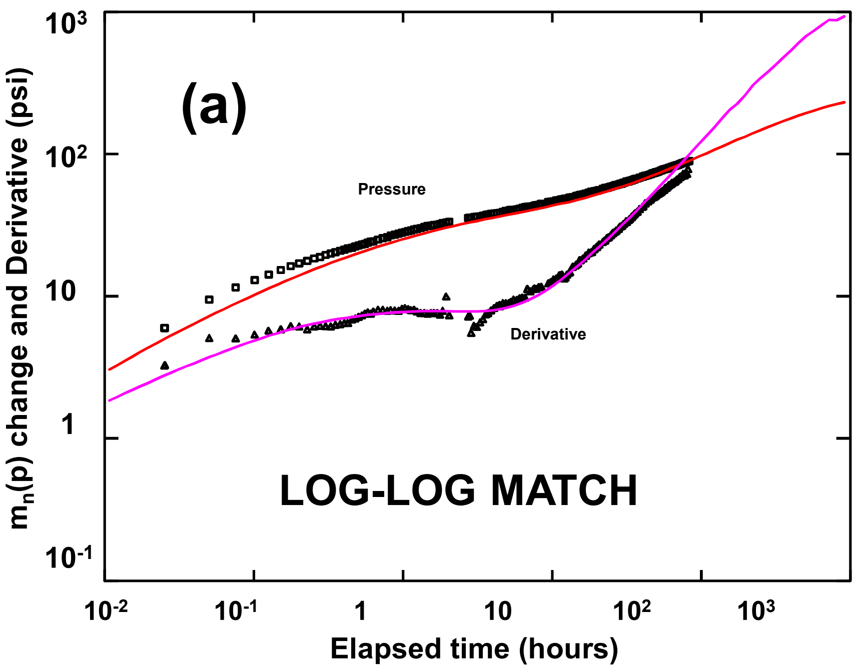
- Identify the interpretation model from its flow regime components
- Select a "published drawdown type curve" representing the model behaviour
- Calculate all the interpretation model parameters by matching data, $[p(\Delta t) - p(\Delta t{=}0)]$ vs Δt , with the selected published drawdown type curve (log-log analysis)
- Calculate flow regime-specific model parameters with applicable specialised and Horner plots
- Verify consistency between log-log, specialised and Horner analyses
- Verify by matching with Horner type curve

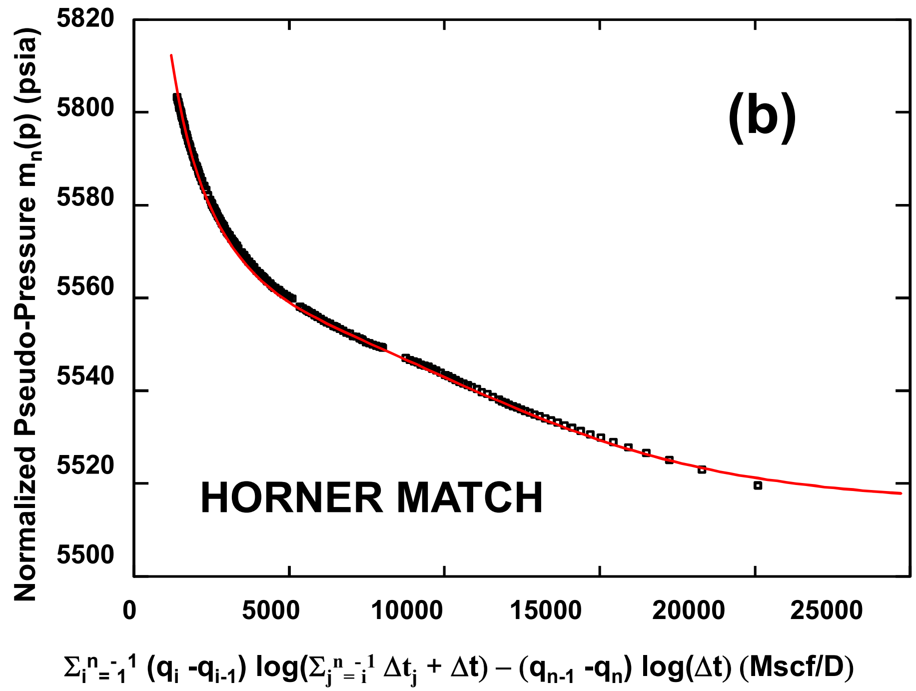
ANALYSIS PROCESS:
Model identification, Parameter calculation and model verification

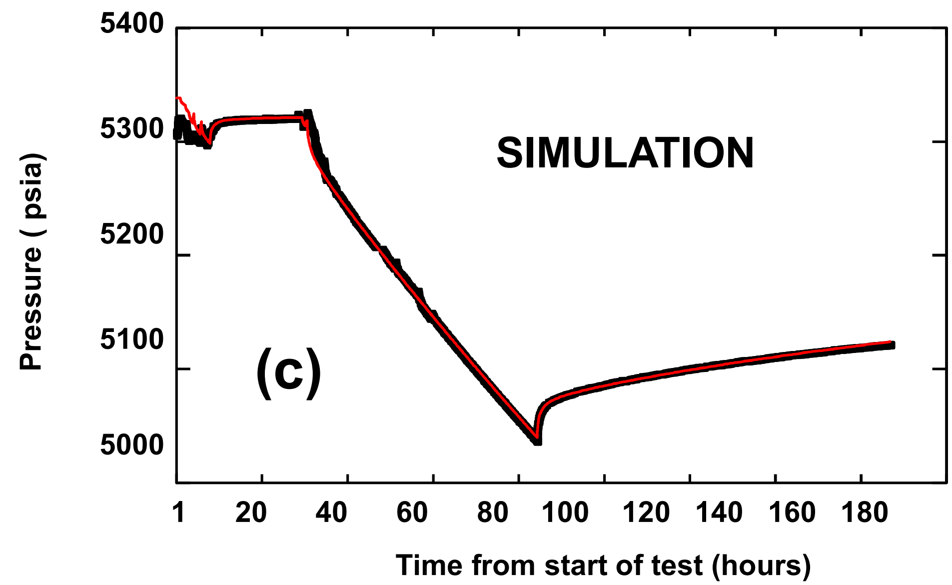
(2) Analysis by computer

- Identify the interpretation model from its flow regime components
- Calculate flow regime-specific model parameters with applicable specialised plots
- Verify quality of match on multirate type curve and (generalised) Horner type curve
- Verify quality of match by simulating the entire test

Example of consistent analysis (build-up)





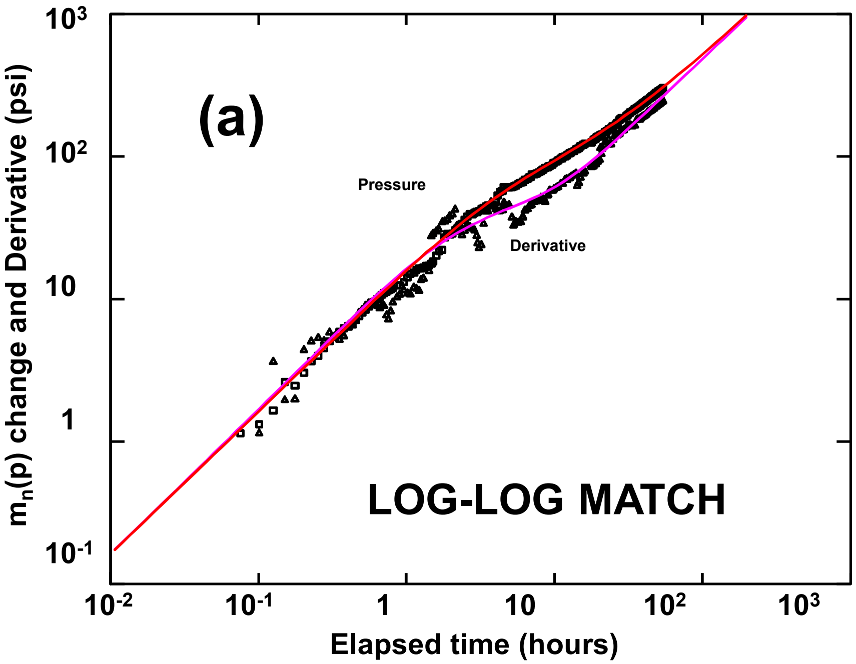


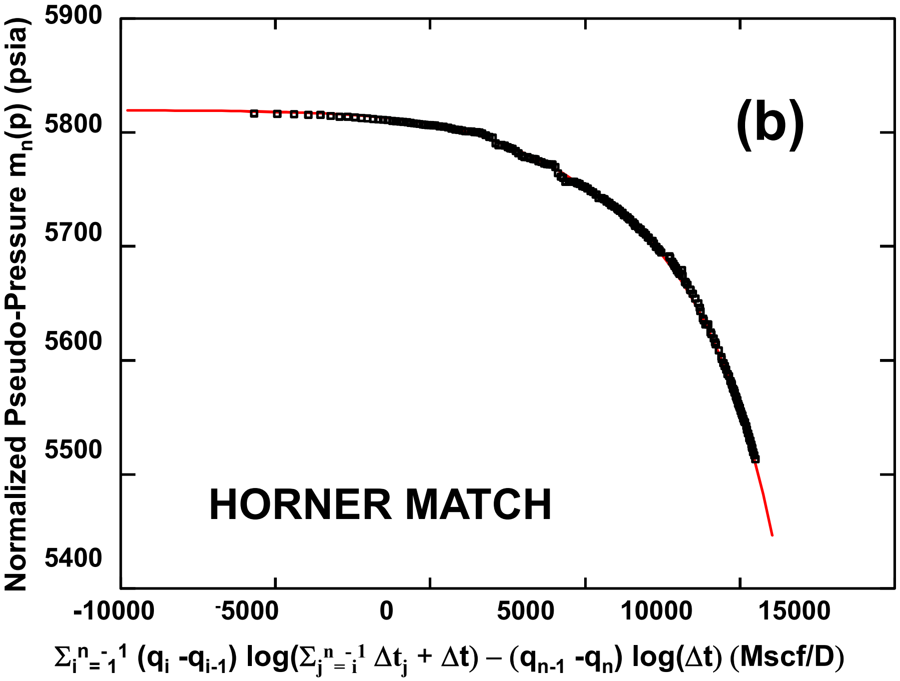
Type Curve

Data

Gas well offshore Louisiana

Example of inconsistent analysis (drawdown)

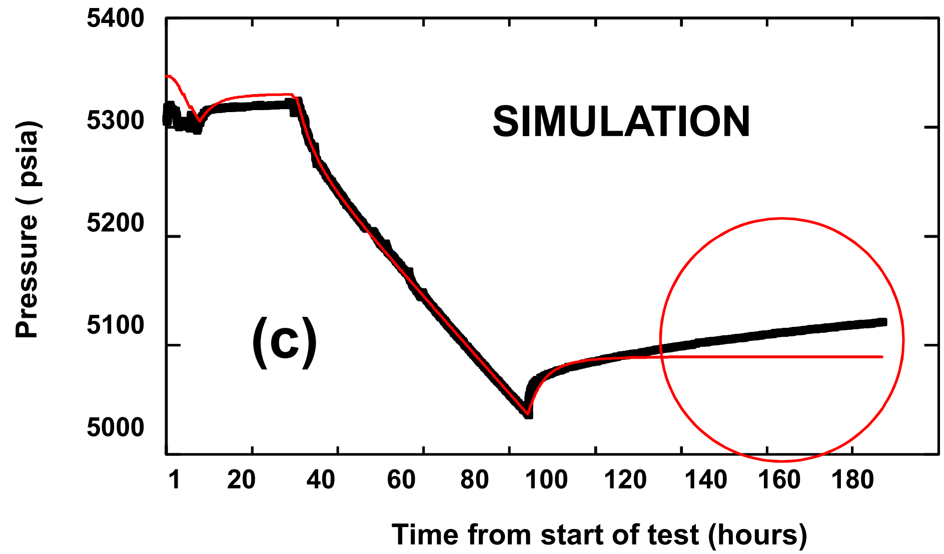




Type Curve

Data

Gas well offshore Louisiana



Example of non-unique analysis