University of Zagreb
FACULTY OF MINING, GEOLOGY AND PETROLEUM ENGINEERING

Lessons learned from the well test analysis applied to the unconventional reservoirs

Sonja Koščak Kolin, Vladislav Brkić
Department of Petroleum Engineering
Croatia

Workshop: Low and volatile oil price environment. Technical responses in the Pannonian basin.

Hungarian SPE Section, Szolnok, 17 November 2016.

Content

1. Introduction to the unconventional gas reservoirs....... 3-9
2. Production models of the stimulated wells………... 10-12
3. Methodology for the well test analysis……………... 13-24
4. Novel approach for the unconventional reservoirs... 25-27
5. Conclusions…………………………………….... 28

1. Introduction to the unconventional gas reservoirs

- global gas reserves;
- proved gas reserves;
- world gas production;
- largest gas producers;
- unconventional gas reservoirs in Croatia;
- unproved tight gas sand reserves in Europe.

1. Introduction – global gas resources

1000 TCM ≈
35 000 TCF

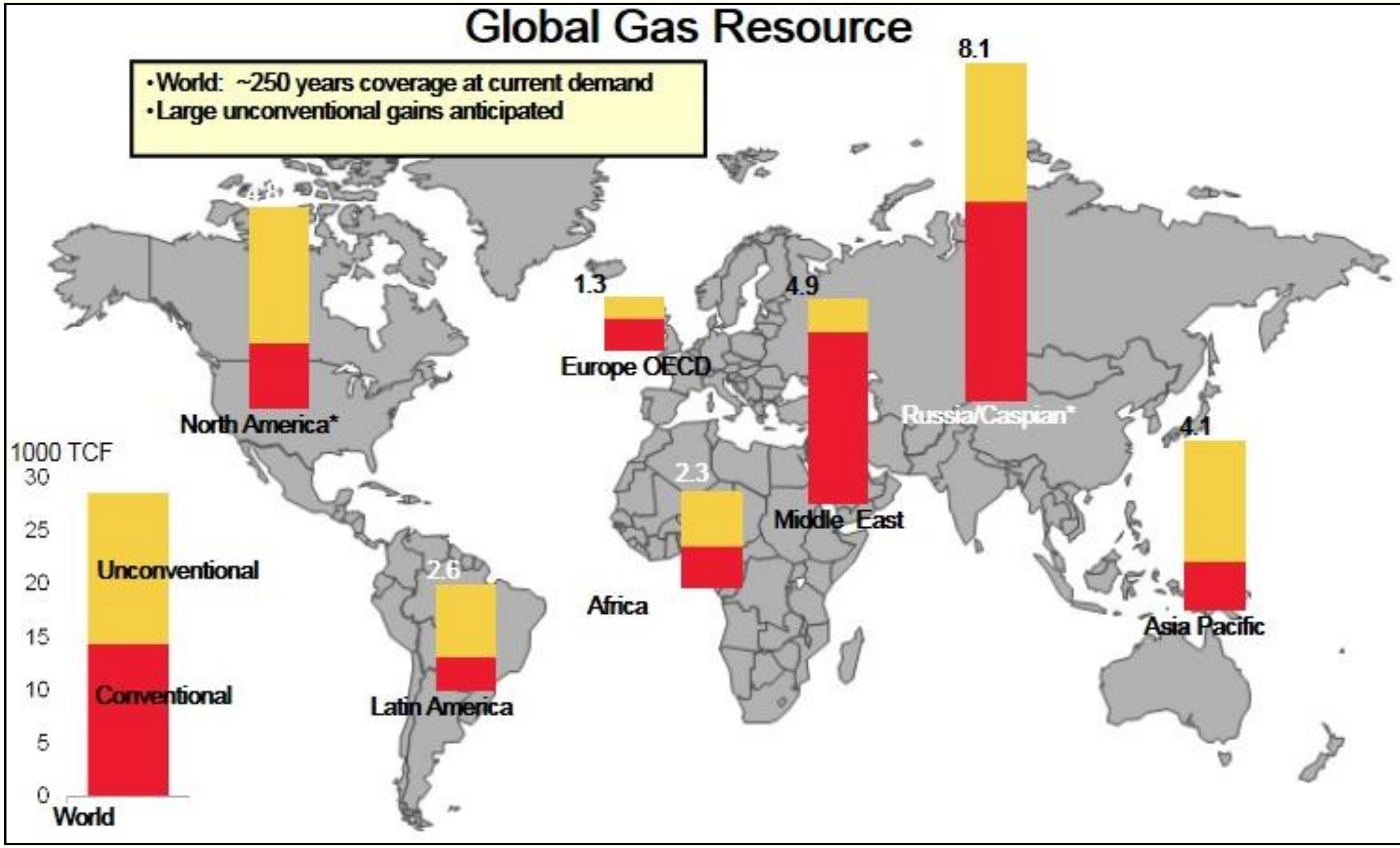


Figure 1: Total gas reserves (International Energy Agency 2013)

Total proved reserves

	At end 1994 Trillion cubic metres	At end 2004 Trillion cubic metres	At end 2013 Trillion cubic metres
US	4.6	5.5	9.6
Canada	1.9	1.6	2.0
Mexico	1.9	0.4	0.3
Total North America	8.5	7.5	12.0
Argentina	0.5	0.5	0.3
Bolivia	0.1	0.8	0.3
Brazil	0.1	0.3	0.5
Colombia	0.2	0.1	0.2
Peru	0.3	0.3	0.4
Trinidad & Tobago	0.3	0.5	0.3
Venezuela	4.0	4.3	5.6
Other S. & Cent. America	0.2	0.1	0.1
Total S. & Cent. America	5.7	7.0	7.7
Azerbaijan	n/a	0.9	0.9
Denmark	0.1	0.1	†
Germany	0.2	0.2	0.1
Italy	0.3	0.1	0.1
Kazakhstan	n/a	1.3	1.5
Netherlands	1.7	1.3	0.8
Norway	1.3	2.4	2.0
Poland	0.1	0.1	0.1
Romania	0.4	0.3	0.1
Russian Federation	n/a	31.1	32.3
Turkmenistan	n/a	2.3	17.5
Ukraine	n/a	0.7	0.6
United Kingdom	0.7	0.5	0.2
Uzbekistan	n/a	1.2	1.1
Other Europe & Eurasia	3.9	0.2	0.2
Total Europe & Eurasia	40.6	42.7	57.5
Bahrain	0.2	0.1	0.2
Iran	20.8	27.5	34.0
Iraq	3.1	3.2	3.6
Israel	†	†	0.2
Kuwait	1.5	1.6	1.8
Oman	0.3	1.0	0.7
Qatar	7.1	25.4	24.7
Saudi Arabia	5.3	6.8	8.2
Syria	0.2	0.3	0.3
United Arab Emirates	5.8	6.1	6.1
Yemen	0.3	0.3	0.3
Other Middle East	†	†	†
Total Middle East	45.5	72.2	80.0
Algeria	3.0	4.5	4.5
Egypt	0.6	1.9	1.8
Libya	1.3	1.5	1.5
Nigeria	3.5	5.2	5.1
Other Africa	0.8	1.1	1.2
Total Africa	9.1	14.2	14.2
Australia	1.3	2.3	3.7
Bangladesh	0.3	0.4	0.3
Brunei	0.4	0.3	0.3
China	1.7	1.5	3.5
India	0.7	0.9	1.4
Indonesia	1.8	2.8	2.9
Malaysia	1.9	2.5	1.1
Myanmar	0.3	0.5	0.3
Pakistan	0.6	0.8	0.6
Papua New Guinea	†	†	0.2
Thailand	0.2	0.4	0.2
Vietnam	0.1	0.2	0.6
Other Asia Pacific	0.3	0.4	0.3
Total Asia Pacific	9.7	13.0	15.2
Total World	**119.1**	**156.5**	**186.5**

1. Intro – proved gas reserves

Table 1: Total proved gas reserves (BP 2015)

186,5 x 10^{12} m^3 in 2014.

1. Introduction – world gas production

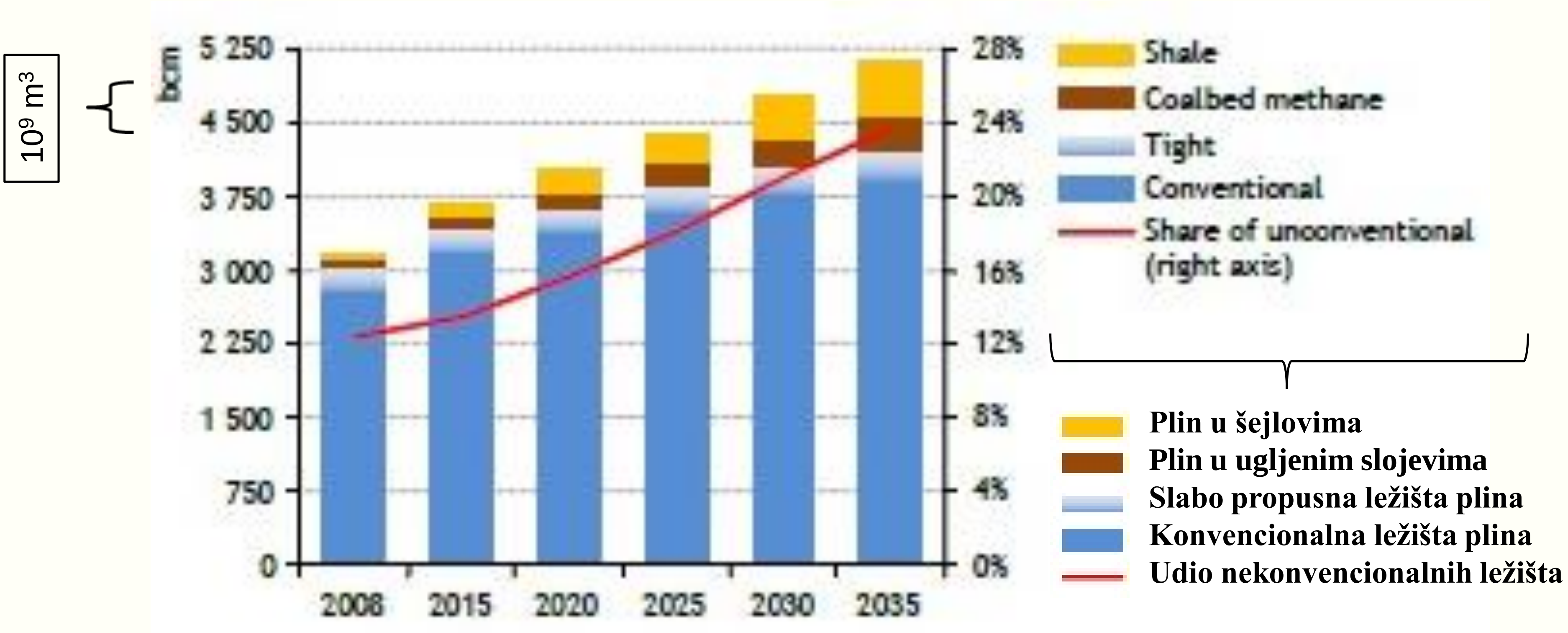


Figure 2: Natural gas production by type (OECD/IEA 2011)

1. Introduction – largest gas producers

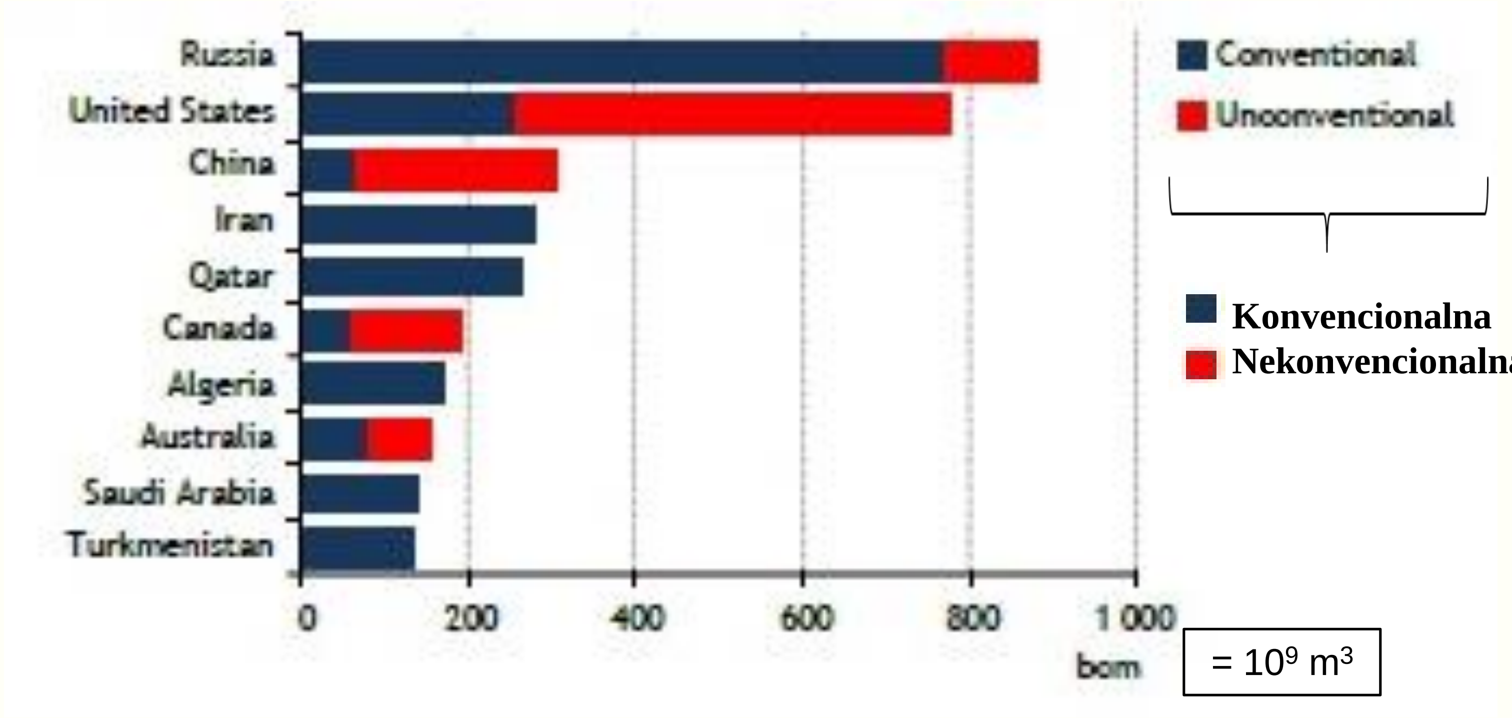


Figure 3: Largest gas producers by type (OECD/IEA 2011)

1. Introduction – unconventional gas reservoirs in Croatia

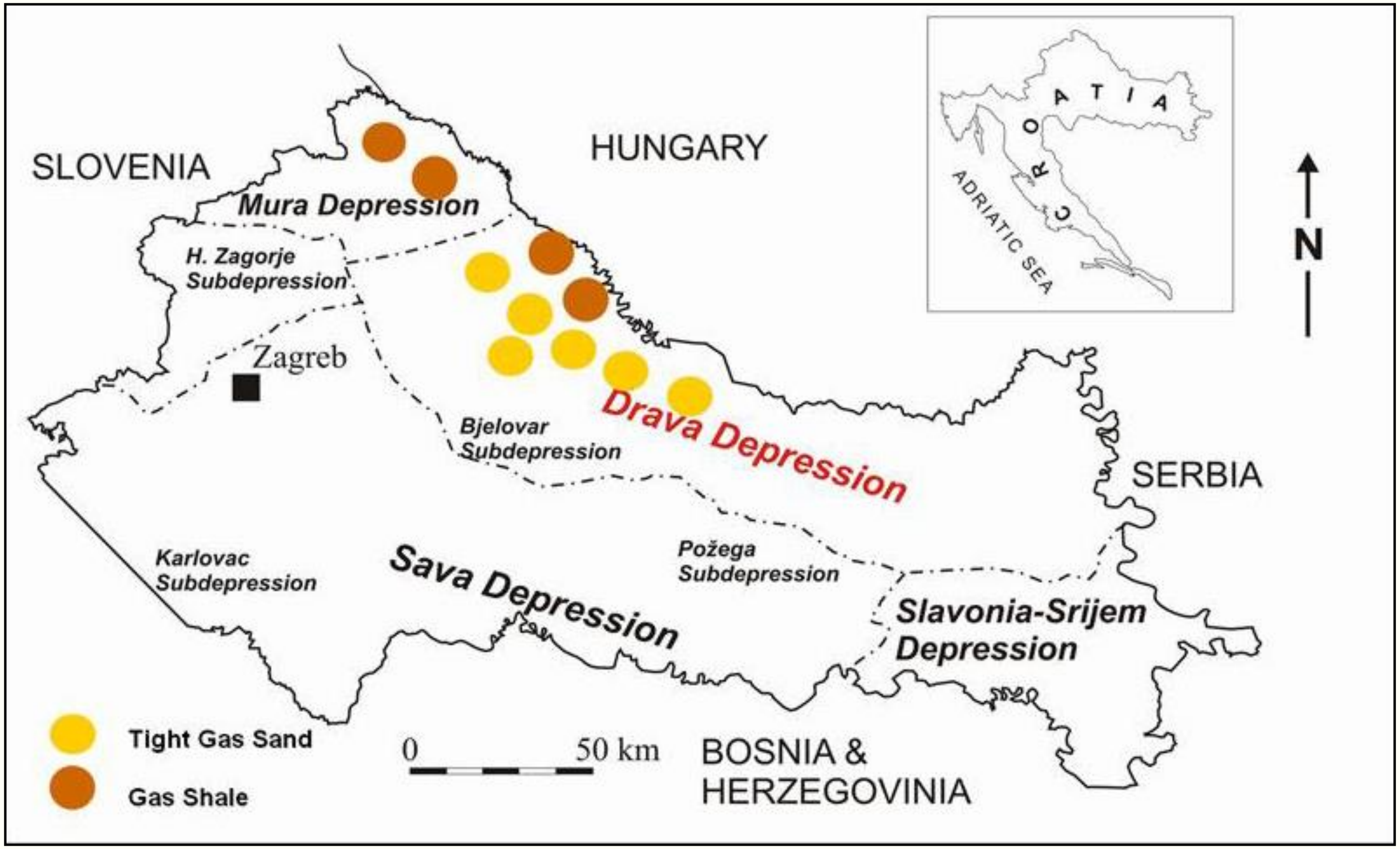


Figure 4: Unconventional gas reservoirs of Mura & Drava depression (Trogrlić et al. 2011)

1. Introduction – unproved tight gas sand reserves in Europe

Figure 5: European gas reserves in tight gas sands (Trogrlić et al. 2011, Jukić 2012)

2. Production model of the fractured well

- dimensionless time: $t_{Dx_f} = \frac{kt}{\phi \mu c_t x_f^2}$

- dimensionless conductivity: $C_{fD} = \frac{k_f w}{k x_f}$

- diffusivity equation for linear flow:

$$\frac{\partial^2 p_f}{\partial x^2} + \frac{2k}{w k_f}\frac{\partial p}{\partial y} = \frac{\phi_f \mu c_{ft}}{k_f}\frac{\partial p_f}{\partial t}$$

- solution for dimensionless flow:

$$q_D(t_{Dx_f}) = \frac{C_{fD}}{\sqrt{\pi^3 \eta_{fD}}} t_{Dx_f}^{-1/2}$$

2. Cumulative production of fractured and un-fractured well

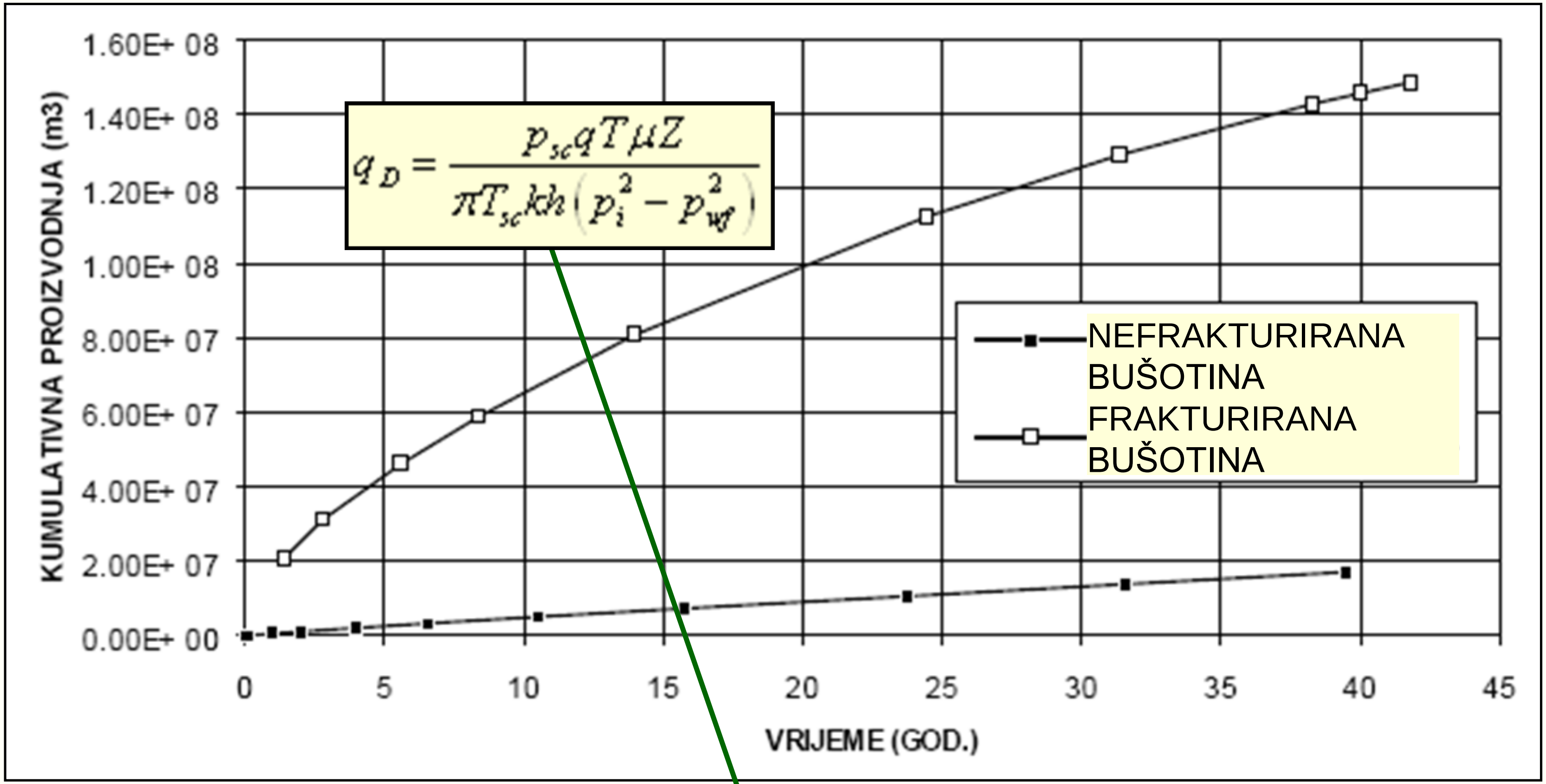


Figure 6: Cumulative gas production of the well in the very low permeability reservoir (k = 0,005 $\times 10^{-3}$ μm^2) – <u>RELIABLE GAS PRODUCTION ESTIMATION IS THE MAIN PURPOSE OF THE APPLICATION OF THE WELL TEST ANALYSIS RESULTS, SUCH AS THE ROCK PERMEABILITY, ***k***.</u>

2. Accuracy of the production models and the reliability of the well test analysis results

- The pressure build up test analysis of the gas wells in the low permeability reservoirs shows deviation of the measurement results for the rock permeability, k. The standard method of the infinite acting radial flow cannot be always applied, due to the wellbore storage effect, as the duration of the pressure build up test should be up to ten times longer than in conventional reservoirs.
- researches are aimed at determining the conditions under which the conventional methods in pressure build up test analysis can be applied to the stimulated gas wells, resulting in relatively acceptable deviations of the value of k. As the stimulation technologies like the hydraulic fracturing, horizontal or multi-stage horizontal fractured wells are necessary for the gas production at economical rate in the low permeability reservoirs, the accuracy of the future production model of a well is important as well, and the accuracy depends upon the estimated value of the permeability, k.

3. Methodology of the well test analysis

- methodology of the production test analysis;
- graphical interpretation of the flow regimes;
- methods for the pressure build up test and its duration;
- radial flow regimes in the pressure build up test analysis;
- linear flow regimes in the pressure build up tests analysis;
- result interpretation of the flow regimes identification in the pressure build up test analysis of the horizontal well;
- multi-stage horizontal fractured well.

3. Methodology of the production test analysis

- theory of the possible flow regimes in the oil and gas well production models
- analysis of the production test methodology applied to the conventional and unconventional reservoirs

flow regime identification in the pressure build up test analysis

3. Graphical interpretation of the flow regimes

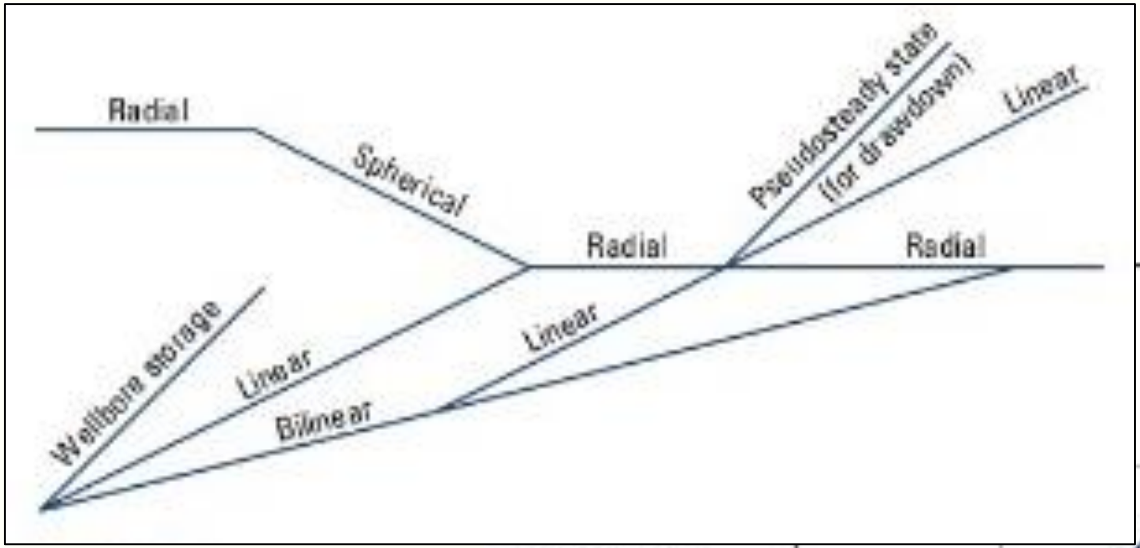


Figure 7: Flow regimes (Schlumberger 2008)

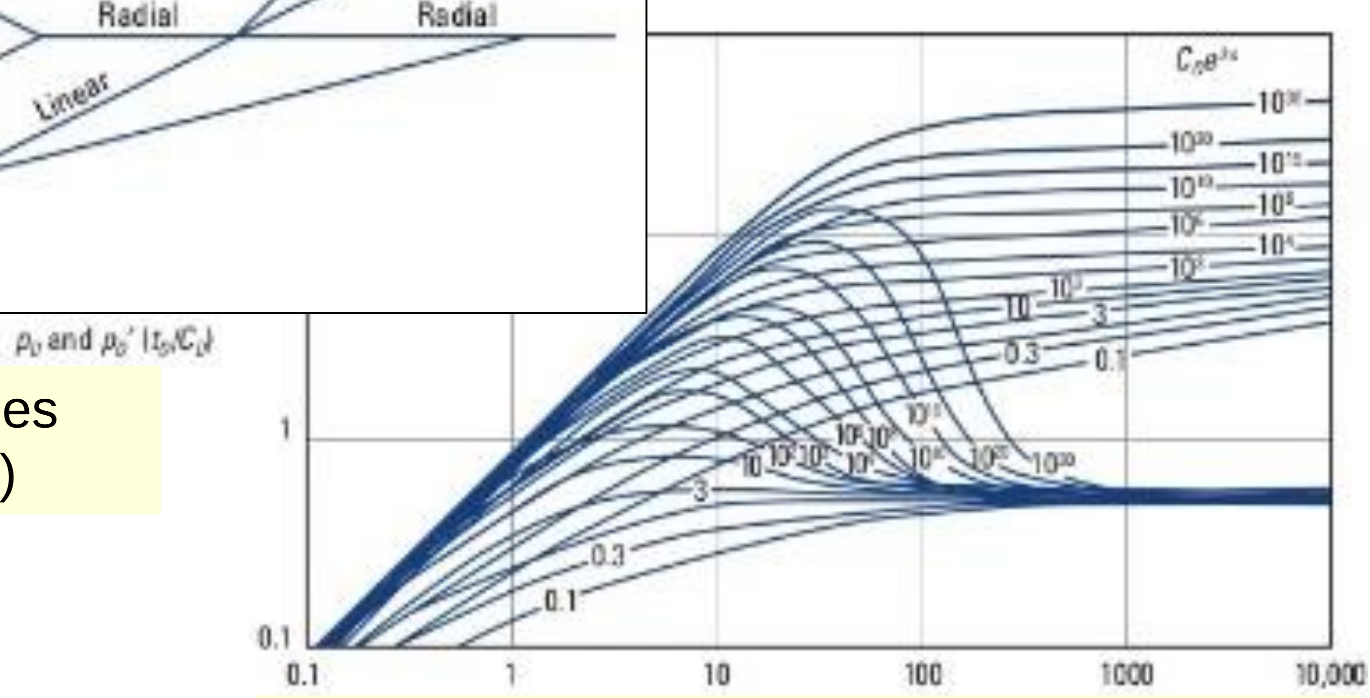
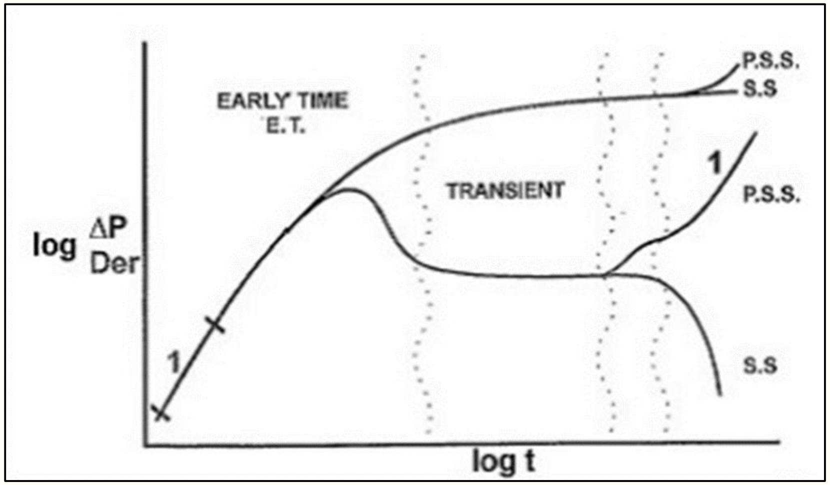
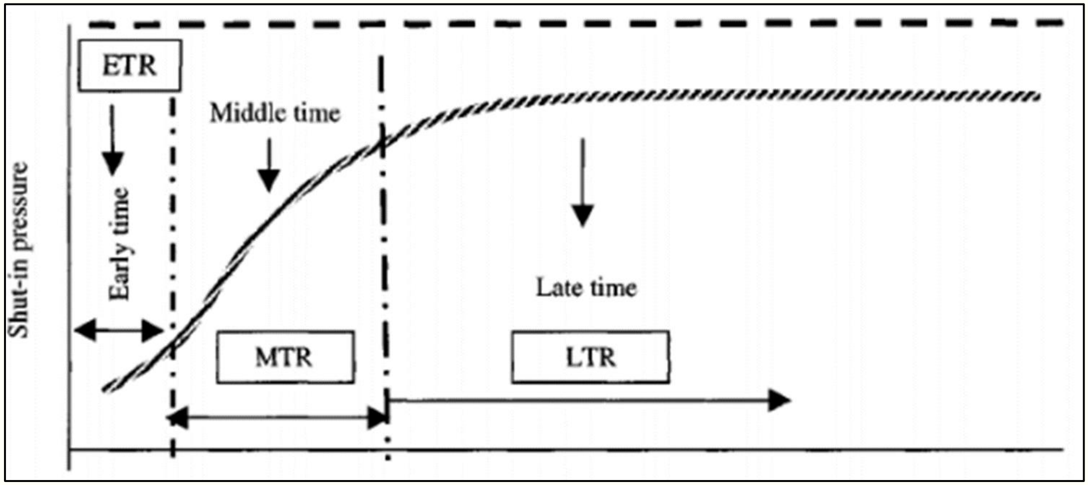
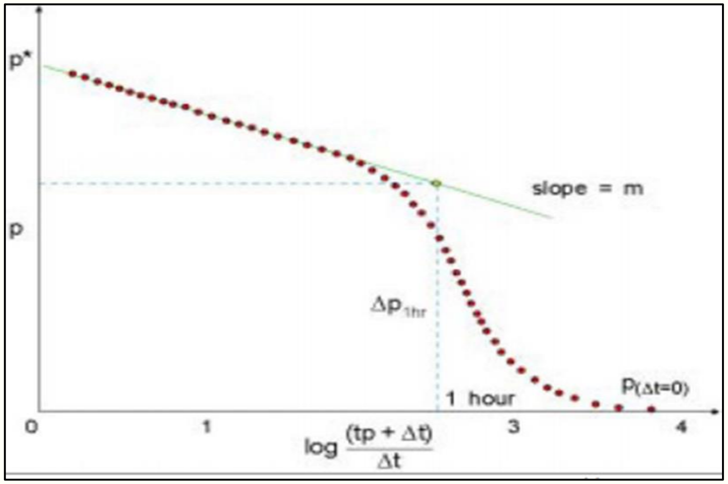


Figure 8: Type curve and pressure derviative (Schlumberger 2008)

3. Methods for the pressure build up test and its duration







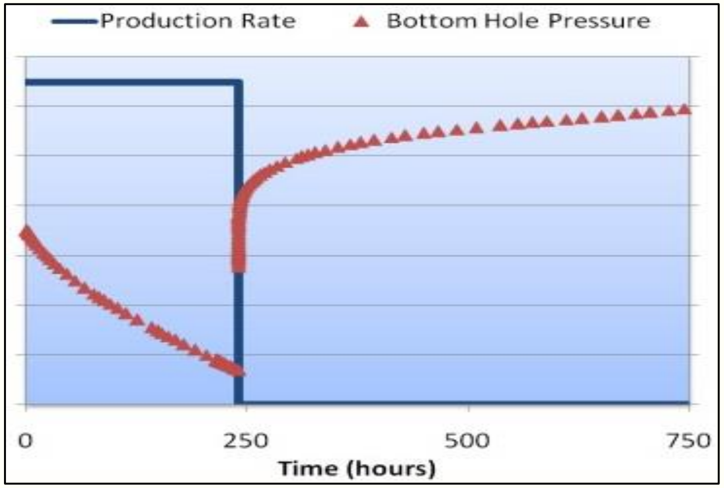


Figure 9 &10: Pressure derivative and Horner method (Yasin 2012)

Figure 11 & 12: Pressure build up test duration and its stabilization (Yasin 2012)

3. Radial flow regimes

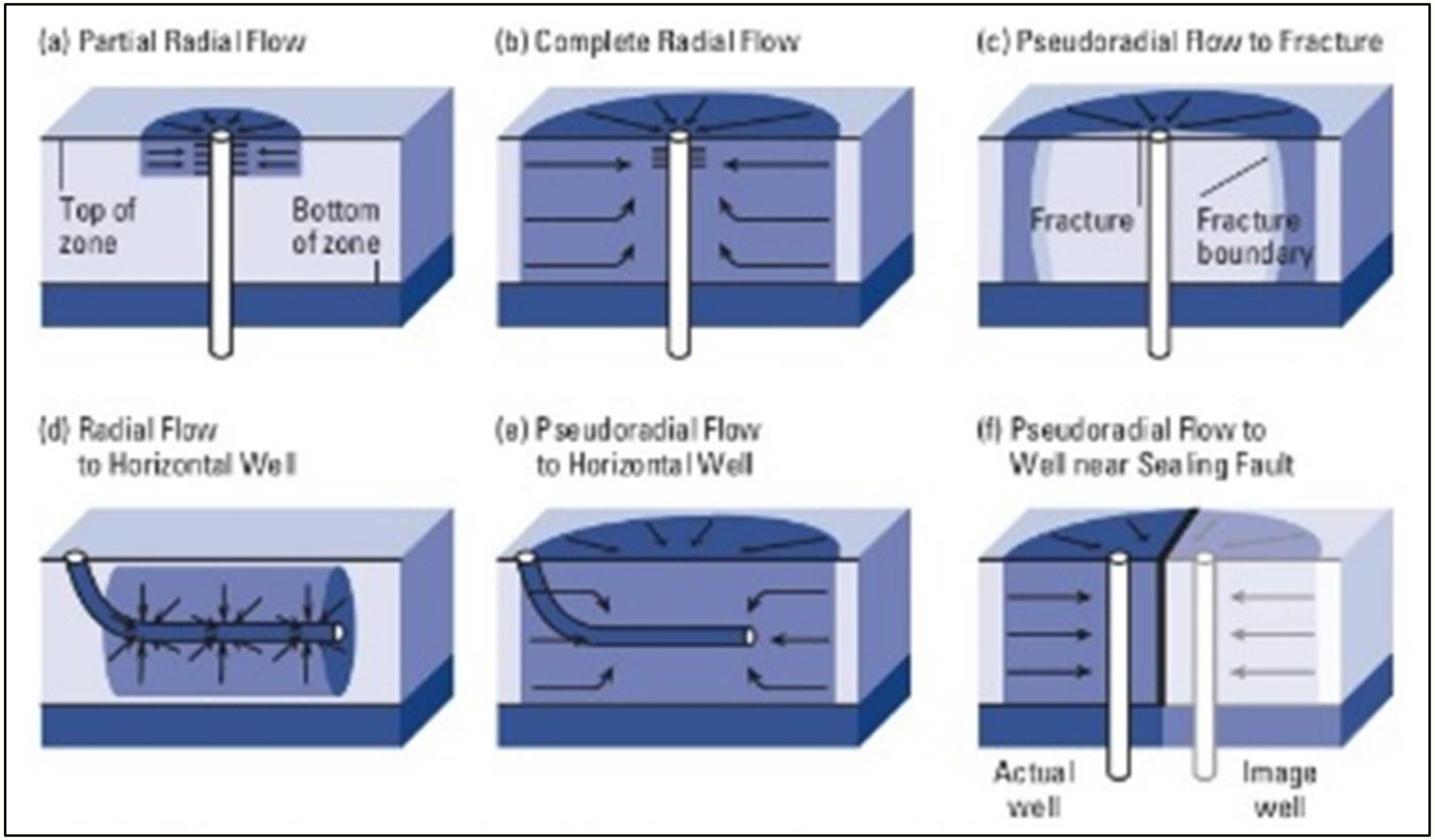


Figure 14: Radial flow regimes in the vertical, fractured and horizontal wells that can be identified by the specific slopes of the pressure derivative line (Economides 2000)

3. Radial flow regimes in the pressure build up test analysis

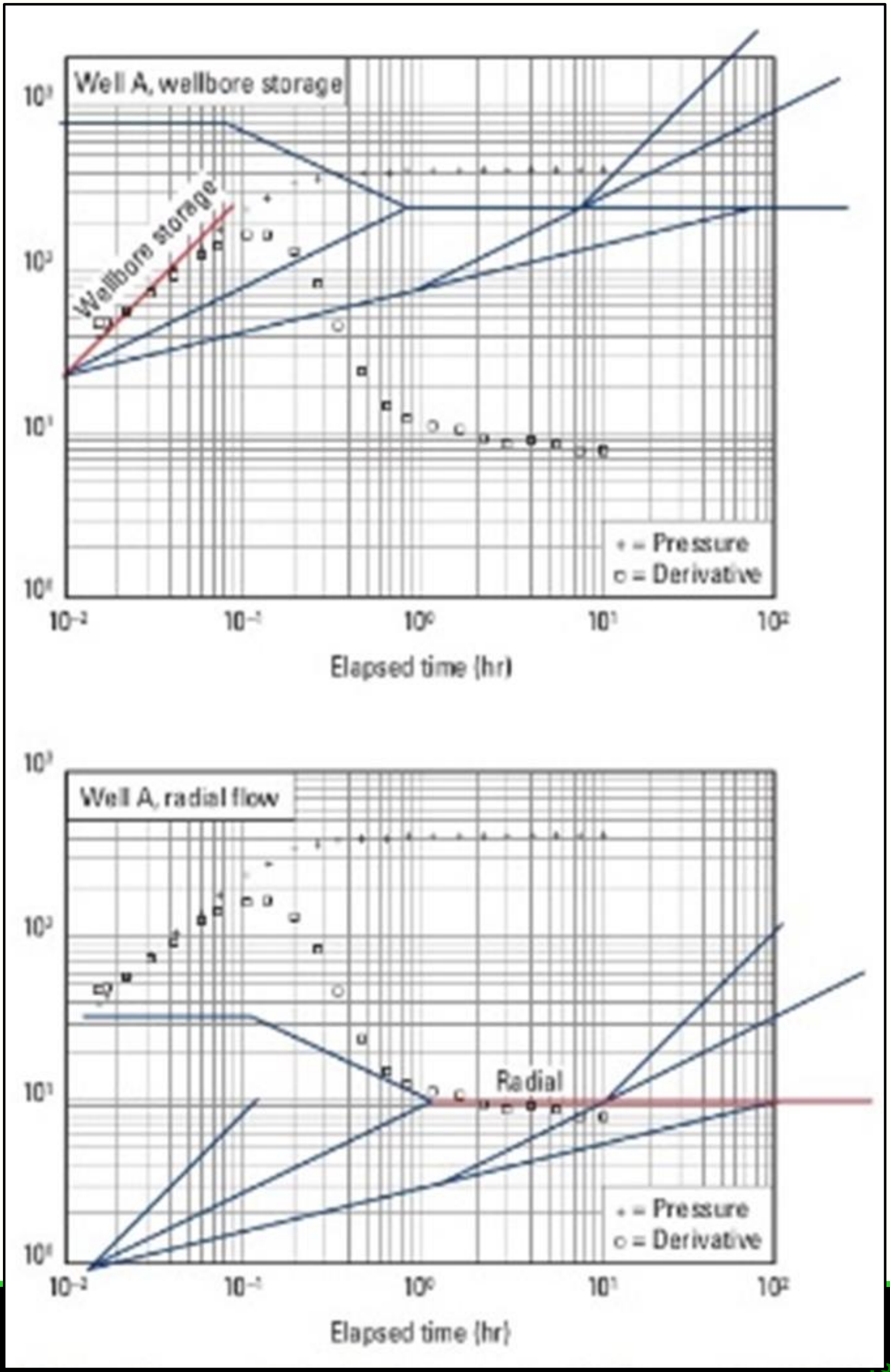


Figure 15 &16: Identification of the wellbore storage and of the radial flow in the same well during the pressure build up test (Economides 2000)

3. Linear flow regimes

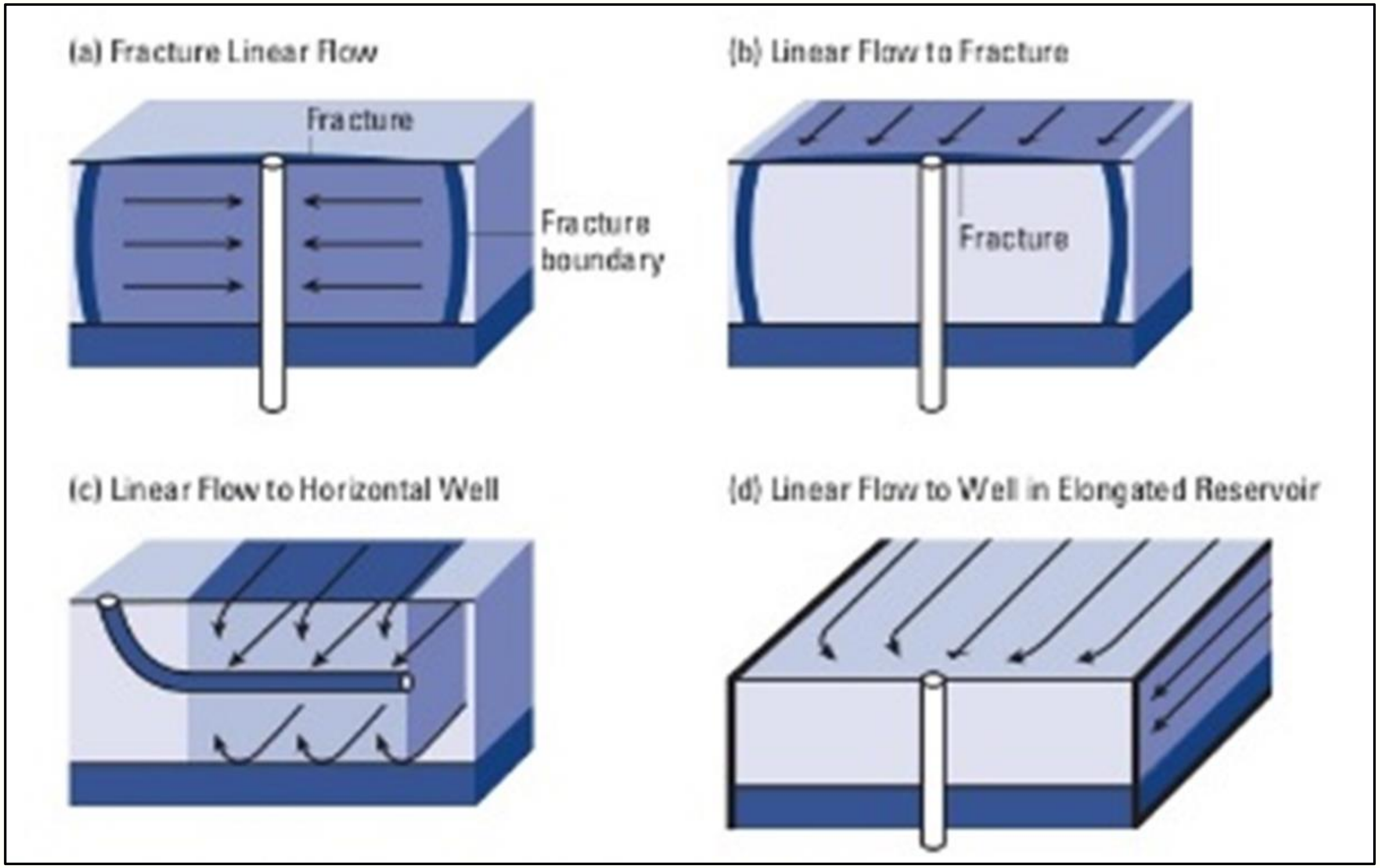


Figure 17: Linear flow regimes in fractured and horizontal wells (Economides et al. 1994, Economides 2000, Schlumberger 2008)

3. Linear flow regime in the pressure build up tests analysis

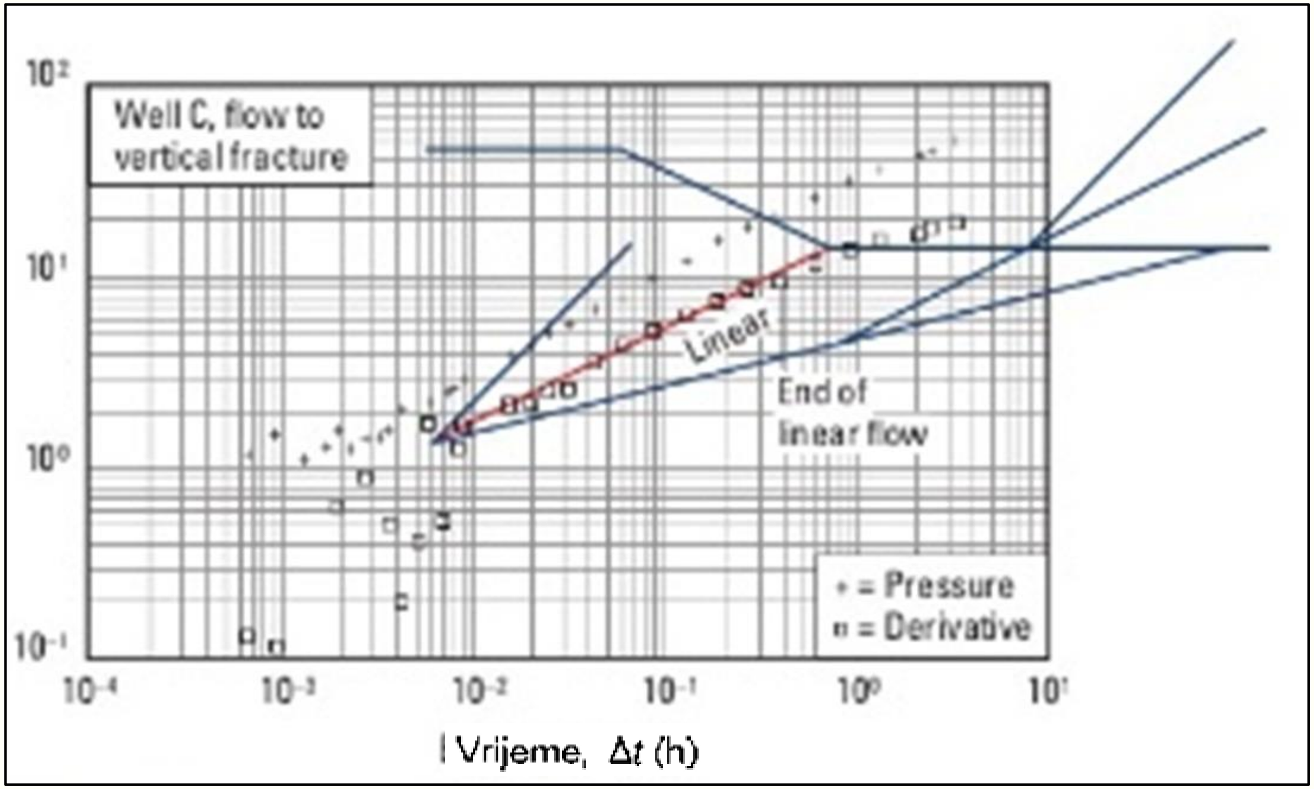


Figure 18: Identifcation of the linear flow regime by the derivative line slope of the od ½ (Economides 2000)

3. Result interpretation of the flow regimes identification in the pressure build up test analysis of the horizontal well

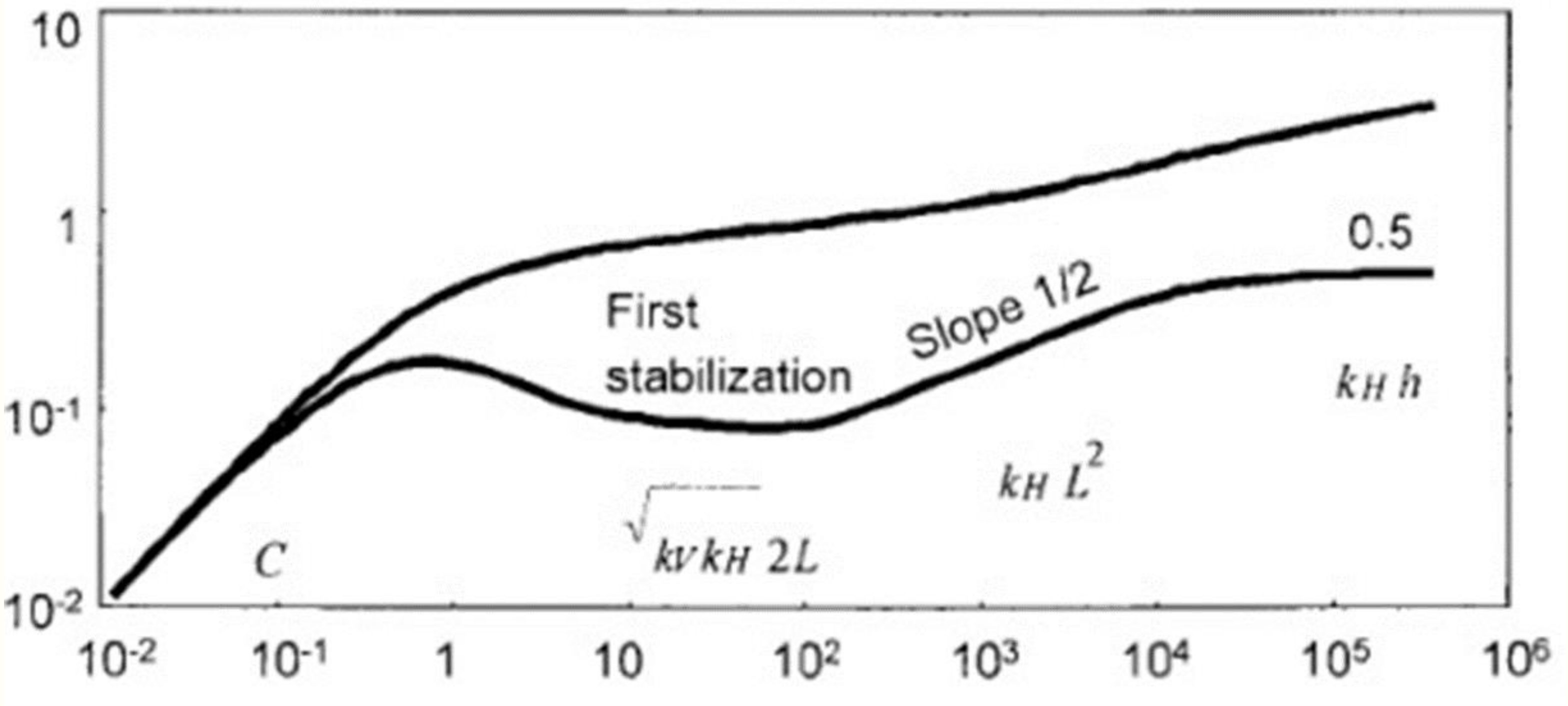


Figure 21: Example of the flow regimes interpretation for the pressure build up test of the horizontal well (Yasin 2012)

3. Multi-stage horizontal fractured well

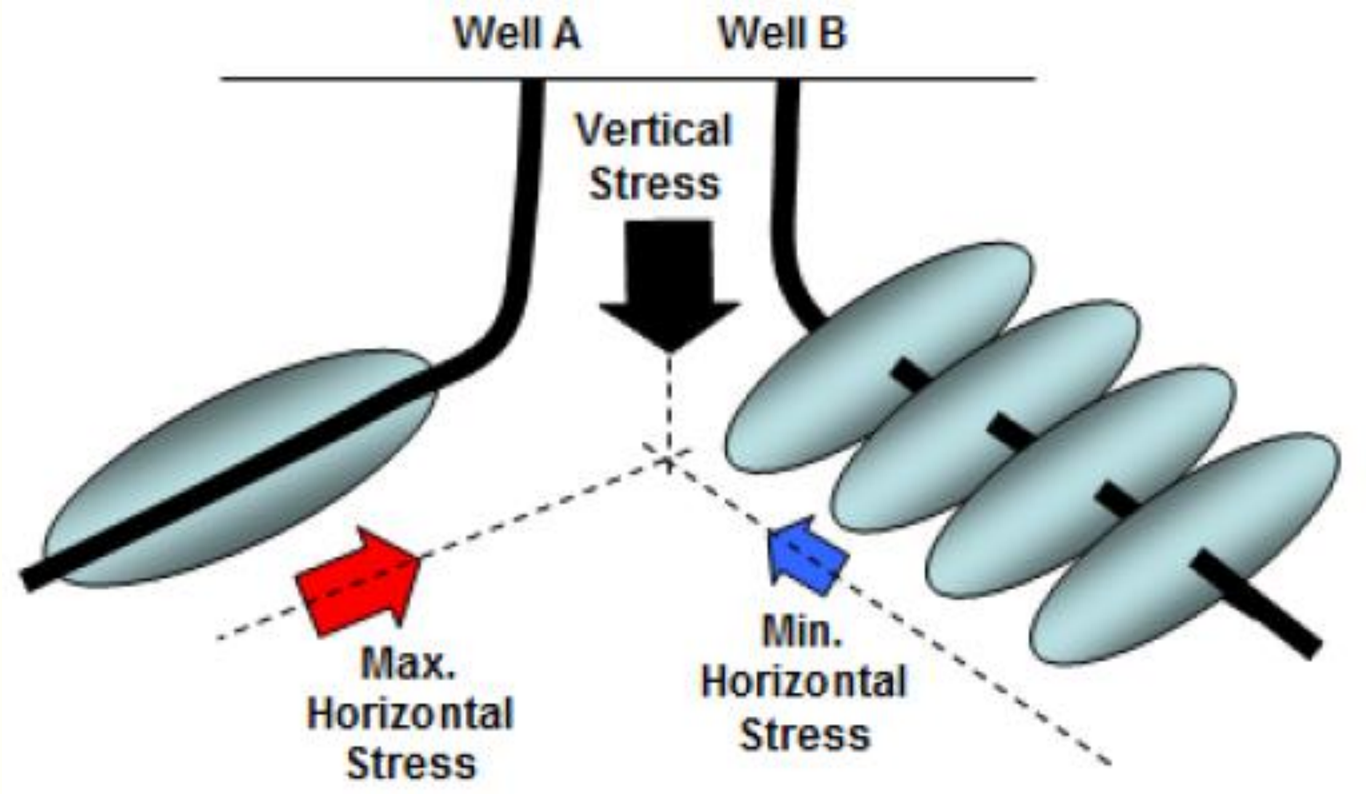


Figure 22: Longitudinal and transverse hydraulic fractures in unconventional reservoirs (Bahrami 2013)

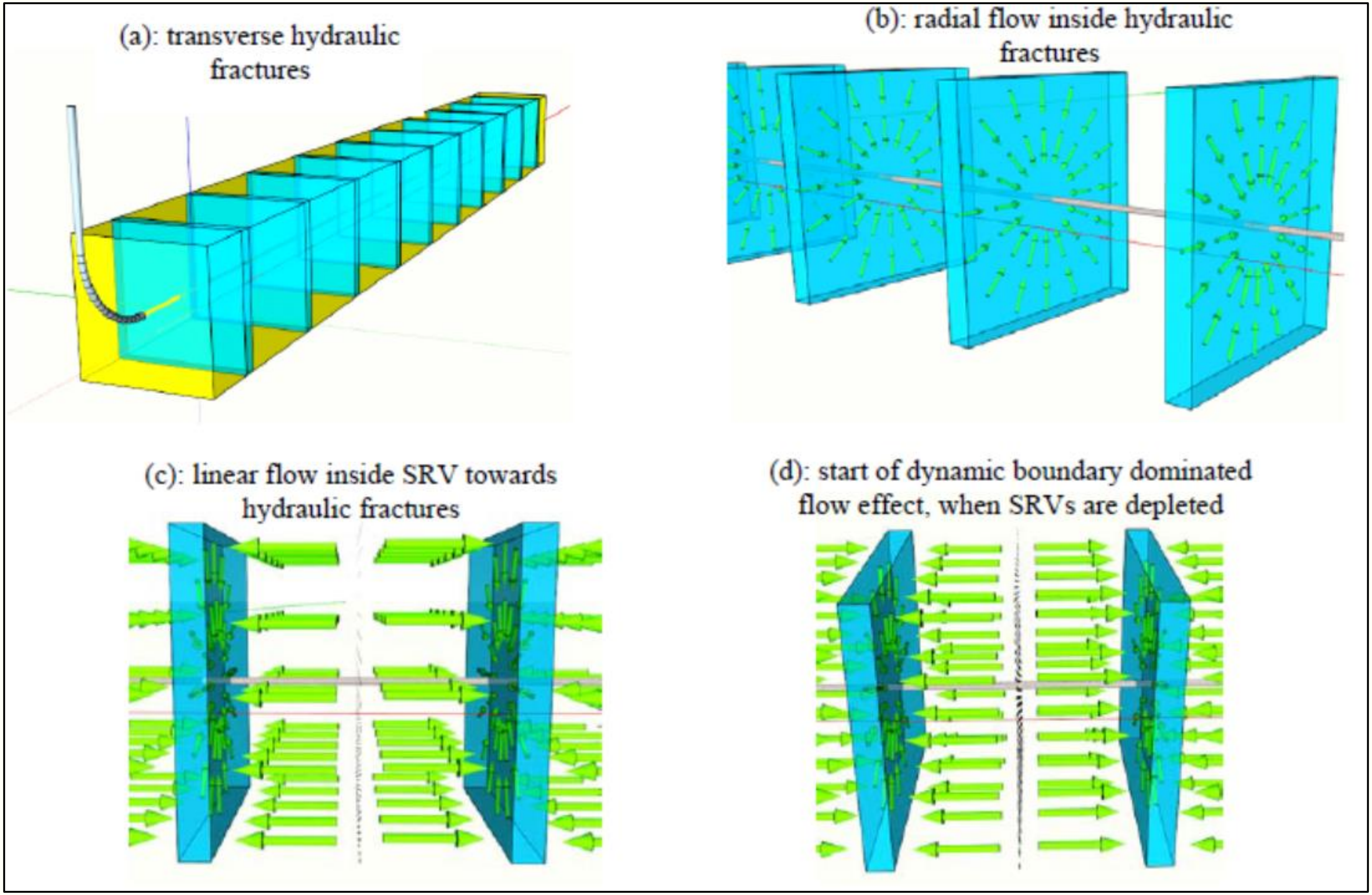


Figure 23: Flow regimes in MHFW:
(a) , (b) , (c) , (d) …. (Bahrami 2013)

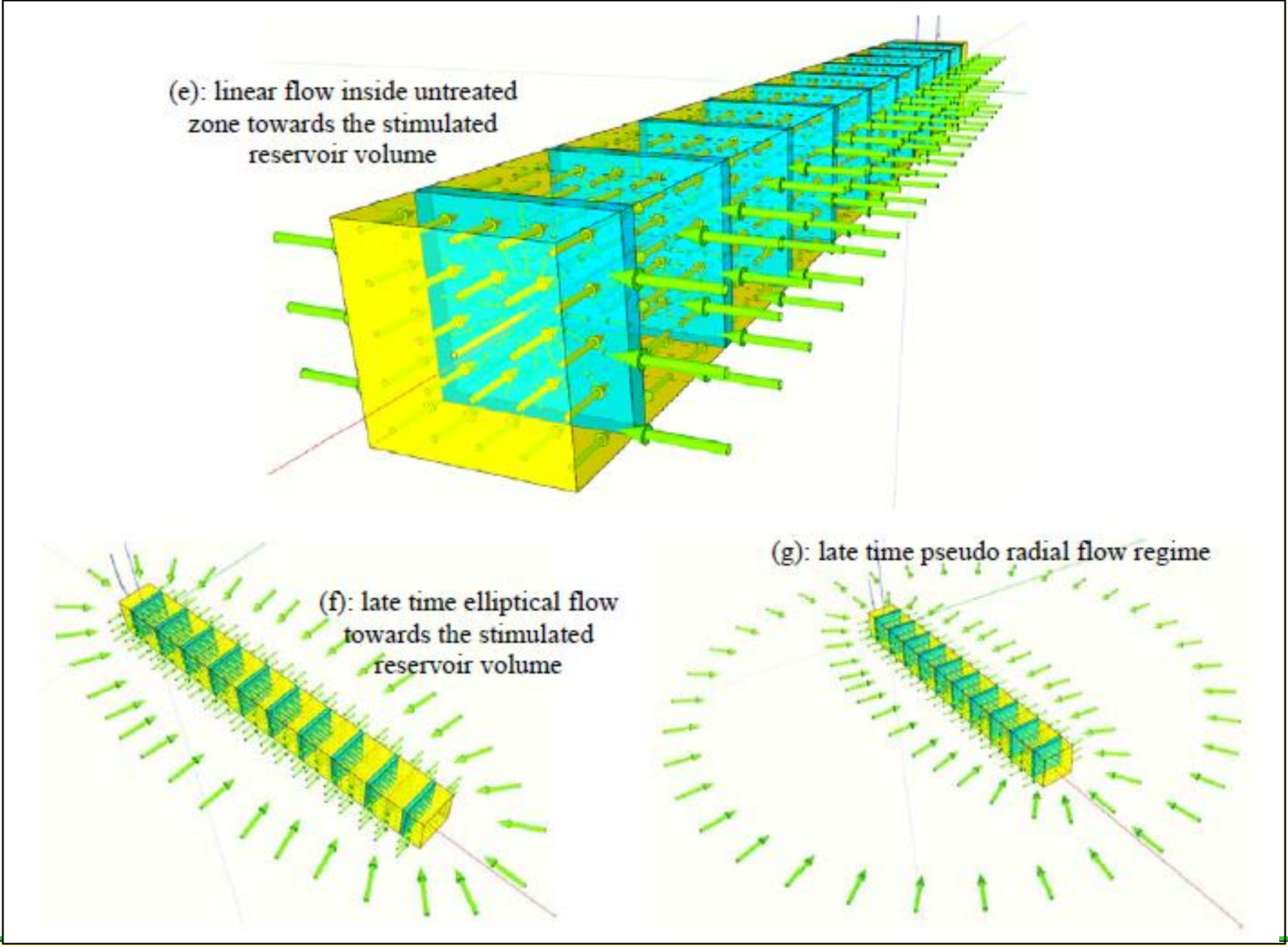


Figure 23 (continued): Flow regimes in MHFW : (e) , (f) , (g) …. (Bahrami 2013)

4. Novel approach for the unconventional reservoirs

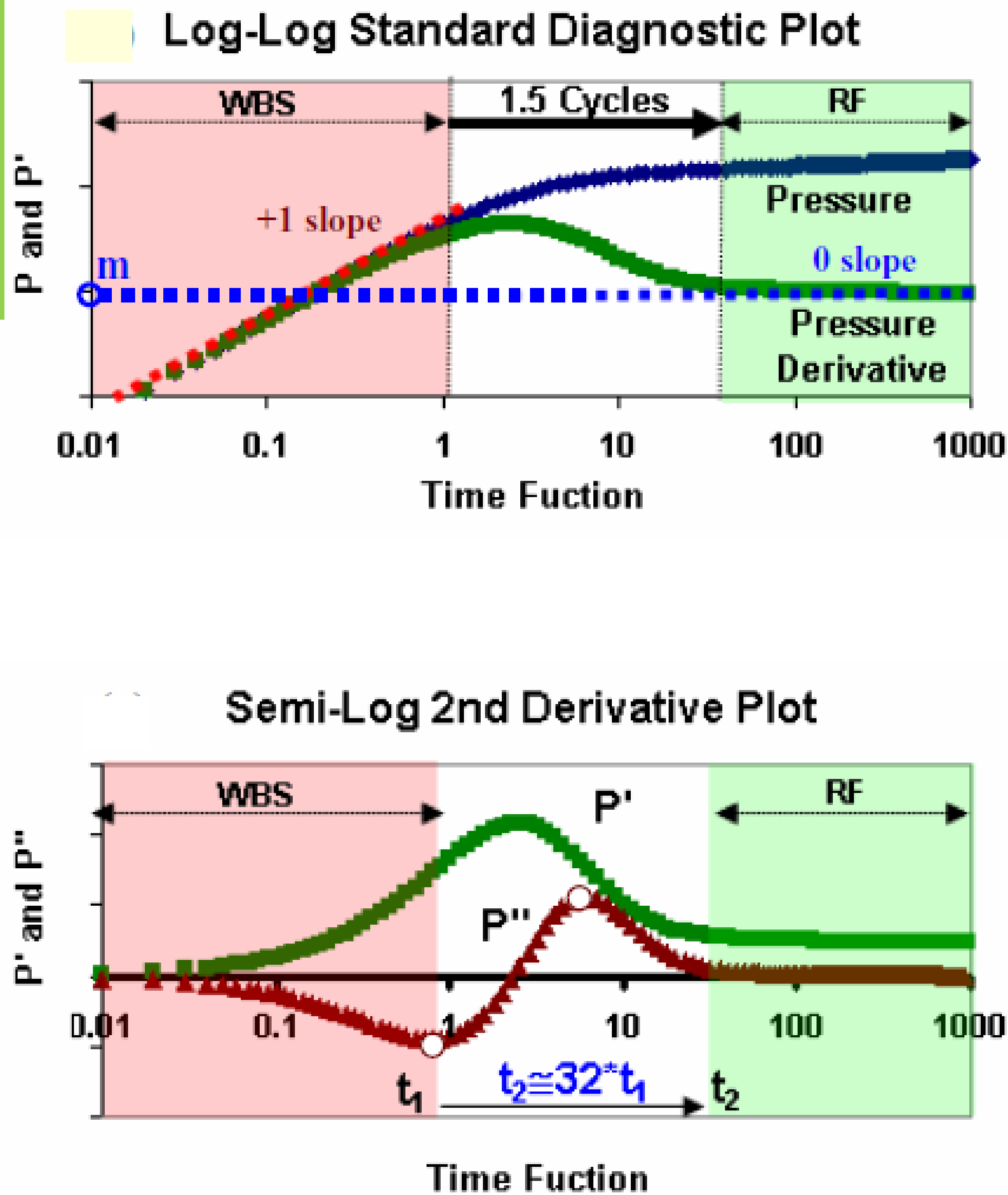
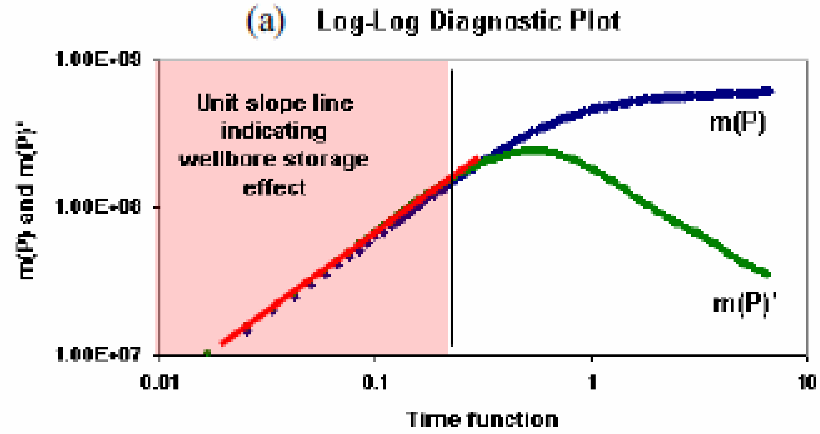


Figure 24 a & b: Pressure transient analysis diagnostic plots (Bahrami 2013)

4. Novel approach for the unconventional reservoirs



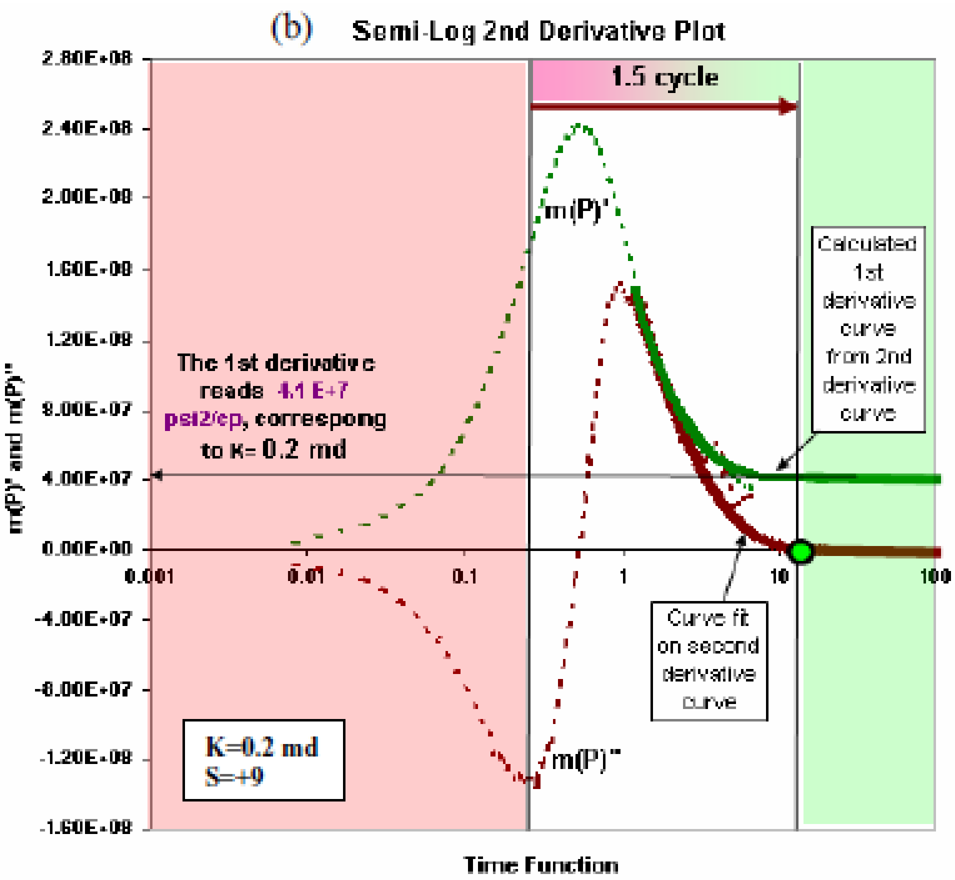
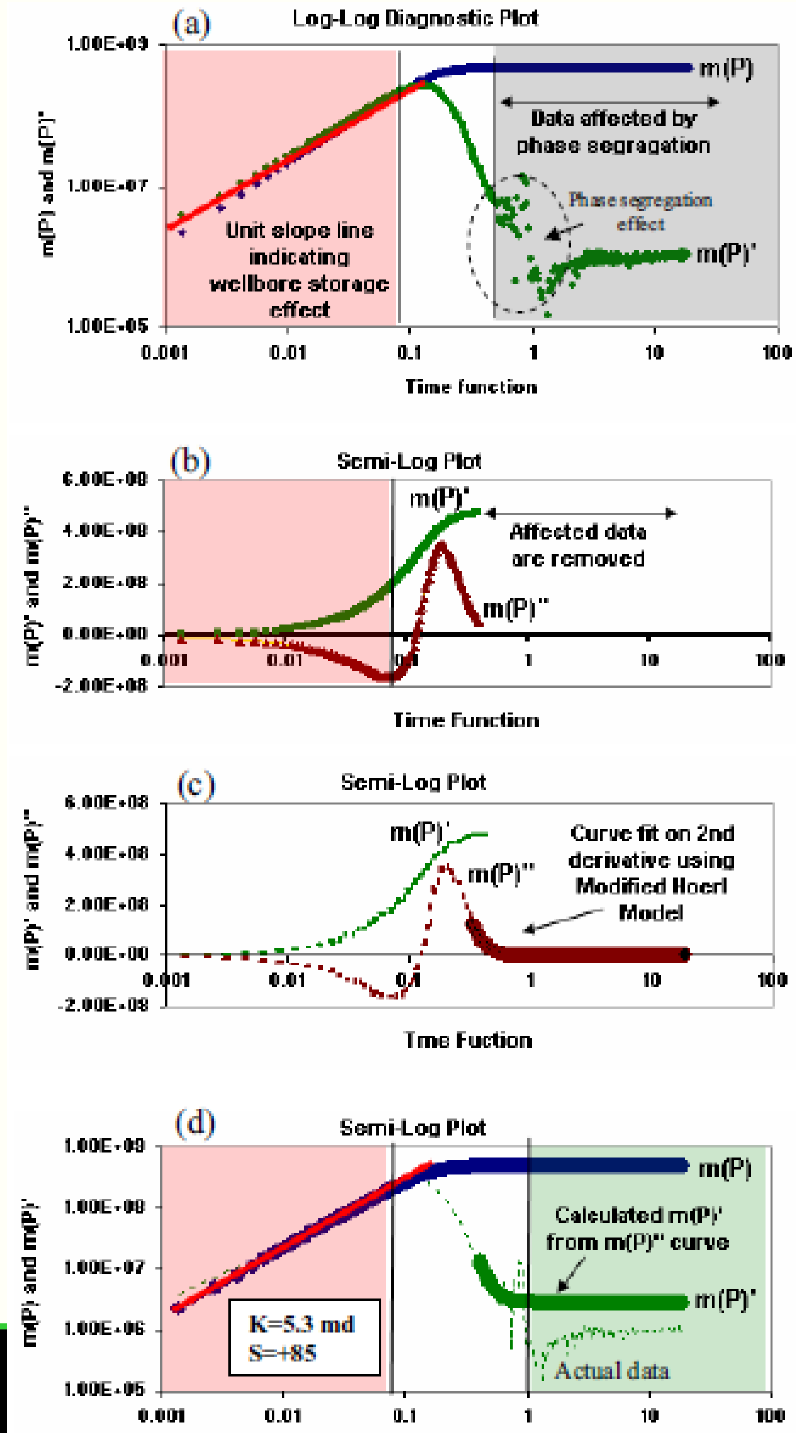


Figure 25 a & b: Pressure build up test analysis for an incomplete test in a low permeability gas reservoir (Bahrami 2013)

4. Novel approach for the unconventional reservoirs

Figure 26 a, b, c & d: Pressure build up analysis for a well in a medium permeability gas reservoir; a: Log-Log standard diagnostic plot, b: Semi-Log 2nd Derivative plot for reliable data, c: Semi-Log 2nd Derivative plot showing curve for on 2nd derivative curve, d: Log-Log standard diagnostic plot with predicted pressure 1st derivative [Time function: (tp+Dt)/Dt] (Bahrami 2013)



5. Conclusions

- Unconventional gas resources from tight sand and shale reservoirs have received a great attention around the world, because of their large reserves as well as technical advances in developing these resources.
- Compared with conventional reservoirs, gas flow in ultra-low permeability unconventional reservoirs is subject to non-Darcy flow and to rock deformation within nano-pores or micro-fractures, coexisting with complex flow geometry and multi-scaled heterogeneity. Therefore, quantifying flow in unconventional gas reservoirs has been a significant challenge, depending upon the proper well production model usage.
- The main challenge with well test analysis of the tight gas wells is that the testing time cannot be long enough to reach radial flow regime. Therefore, new methods of well test analysis for more reliable estimation of the average reservoir permeability are being developed.