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Aquifer Detection and Characterisation Using Material Balance: A Case Study of Reservoirs A, B, C and D

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Abstract: Oil and gas production needs energy, sufficient enough to drive the produced hydrocarbon to the surface of the well. Usually some of this required energy is supplied by nature. The hydrocarbon fluids are under pressure because of their depth. The gas and water in petroleum reservoirs under pressure are the two main sources that help move oil to the well bore and sometimes up to the surface. Depending on the original characteristics of hydrocarbon reservoirs, the type of drive energy is different. The material balance equation has been a very useful tool in analyzing these mechanisms. If none of the terms in the material balance equation can be neglected, then the reservoir can be described as having a combination drive in which all possible sources of energy contribute a significant part in producing the reservoir fluids, and determining the primary recovery factor. For this to happen, the water must be produced from an aquifer. The aquifer water expands slightly, displacing the oil or gas from the reservoir towards the borehole as pressure drops around the borehole. Most literatures have been able to call attention to the analysis of strong and partial water drive. This study was able to bring to light the aquifer characteristics based on weak water drives. Knowledge of the cumulative water influx is also important to the reservoir engineer. This study also goes ahead to add to aquifer detection and characterization, the cumulative water influx of each reservoir. The whole process entailed analyzing reservoirs A,B,C and D using the method proposed by Cole and Campbell. The plots showed a weak water drive for all reservoirs. The water influx for all the reservoirs were calculated and results obtained. The Cole and Campbell plots were proven to be more accurate method of detecting and characterizing aquifer and water drive strength.

Keywords: Aquifer, Hydrocarbon, Material Balance Equation, Water Drive, Water Influx, Reservoir

1. Introduction

Successful reservoir management relies on the ability to generate reliable reservoir performance behavior. The primary questions that reservoir engineers are expected to answer are given in the following, in order of priority:

1. What are the expected quantities of original oil and gas in place (OOIP and OGIP)?
2. How much oil and gas can be economically recovered given the associated probabilities and risks?
3. How can a newly discovered field be developed, followed by implementation of the reservoir management plan and monitoring and evaluation of reservoir performance?

1.1. Natural Producing Mechanisms

There are natural sources of energy in oil reservoirs that control reservoir performance. These include the following:

- Liquid and rock compressibility drive
- Solution gas or depletion drive
- Gascap drive
- Aquifer water drive
- Gravity segregation drive
- Combinations of above'
- Drive mechanisms in gas reservoirs are as follows:
- Gas expansion or depletion drive
- Aquifer water drive
- Combinations of above

1.2. Aquifer Water Drive

When an oil or gas reservoir is in communication with a surrounding (bottom or edge) active aquifer, production from the reservoir results in a pressure drop between the reservoir and the aquifer. This allows influx of water into the reservoir. A producing reservoir is referred to as bottom water drive or edge water drive reservoir, depending on the location of the adjacent aquifer providing energy for production.

Reservoir pressures in water drive reservoirs remain high. Pressure is influenced by the rate of water influx, and by the rate of oil, gas, and water productions. Gas/oil ratios remain low if pressure remains high. Downdip wells produce water earlier, and water production continues to increase. Water drive is usually the most efficient reservoir driving force in oil reservoirs. Recovery efficiencies may vary from 30% to 80%, depending upon the size and strength of the aquifer. Recovery efficiencies for the depletion drive gas reservoirs can be 80% to 90%. However, in the case of water drive gas reservoirs, recovery efficiencies could be in the 50% to 60% range because of the bypassed gas and high reservoir pressures. Recovery from bottom water drive would be substantially affected by a water coning problem. The global average of recovery factor is found to be in the range of 35% or slightly less.

1.3. Reserve Estimation

Many petroleum engineers spend a major part of their professional lives developing estimates of reserves and production capabilities, along with new methods and techniques for improving these estimates. To understand the confidence levels and risks of the estimates, a clear and consistent set of reserve classifications must be used. The confidence level and the techniques implemented by the petroleum engineer depend on the quantity and the maturity of the data available. The data quality, therefore, establishes the classification assigned to the reserve estimates and indicates the confidence one should have in the reserve estimates.

Reserves are classified as proved, proved developed, proved underdeveloped, probable and possible reserves.

Reserve estimation is simply evaluating or assessing a particular reservoir.

One major reason for the estimates of reserves is for management decisions which are seen in the formation of policies for;

1. Exploration and development of oil and gas properties.
2. Design and construction of plants, gathering systems and other surface facilities.
3. Determining and construction of ownership in unitized projects.
4. Establishing sales contracts.

Reserves are frequently estimated before drilling or any subsurface development, during the development drilling of the field, after some performance data are available, and after performance trends are well established.

1.3.1. Reserve Estimation Techniques

Commonly used reservoir performance analysis and reserve estimation techniques are;

- Volumetric
- Decline curves
- Material balance
- Mathematical simulation

For the purpose of this project, attention will be restricted to reservoir estimation based on the material balance method.

1.3.2. Material Balance Method

The material balance equation (MBE) has been used by reservoir engineers for a long time as the basic tool for interpreting and predicting performance. When properly applied, the MBE can be used to;

Estimate initial hydrocarbon volumes in place.

Predict future reservoir performance.

Predict ultimate hydrocarbon recovery under various types of primary driving mechanisms.[2]

Schilthuis in 1941 was the first to present the general form of the material balance equation. The equation is derived as a volume balance which equates the cumulative observed production, expressed as an underground withdrawal to the expansion of the fluids in the reservoir resulting from a finite pressure drop.[6]

Evaluating the volume balance in reservoir barrels, he obtained;

Underground withdrawal (rb) = Expansion of oil + originally dissolved gas (rb) + Expansion of gascap gas (rb) + Reduction in HCPV due to connate water expansion and decrease in the pore volume (rb)

Mathematically,

$$N_p\left(B_o+\left(R_s-R_{si}\right)B_g\right)=NB_{oi}\left[\frac{\left(B_o-B_{oi}\right)+\left(R_{si}-R_s\right)B_g}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)+\left(1+m\right)\left(\frac{c_wS_{wc}+c_f}{1-S_{wc}}\right)\Delta P\right]+\left(W_e-W_p\right)B_w \quad (1)$$

Approximately two decades after the work of Schilthuis, Havlena and Odeh (1963-4) presented two papers describing MBE as a technique of interpreting the MBE as an equation of a straight line, the first paper describes the technique, and the second illustrates the application to reservoir case histories of various fields.[6, 7, 8]

One measure of the relative importance of the various drive mechanisms is the intrinsic energy of the different substances, more specifically the compressibility-volume product, which compensates for reservoir voidage (production) in maintaining reservoir pressure.

Aquifer strength has to be sufficient (size and connectivity) to sweep the oil at elevated pressure (ideally close to initial, bubble point pressure). It is the relative aquifer size, by comparison to the oil leg (and gas cap) that is of importance. Unfortunately, aquifer strength is usually not proven before development takes place but the chance for a strong or sufficient aquifer is accessed based on regional geology. This aspect is particularly important in offshore situations where pre-investment into a water injection plant has to be considered if the chance of a sufficient aquifer is relatively low.

The above material balance equation will be used to detect aquifers as well as to characterise them. The Cole and Campbell plot will be used as important tools for this project. We will see how these plots help us to carry out this project successfully.

1.4. Problem Statement

For proper estimation of reserves, an adequate approach is required so as to be able to gain adequate information about production and production histories. Drive mechanisms are important to the reservoir engineers as well as their strength and drive indices.

This leads us to detecting aquifers that produce through water drives and accurately characterizing them to be able to know the strength under which the reservoir is producing. These include:

Strong, moderate and weak water drives. Reservoir engineers have tried to do this but most works have been less accurate, accounting for mostly strong and moderate water drives. This work presents a more accurate way through which it is done.

1.5. Aim and Objectives of the Study

The aim of this study is to detect and characterize aquifers using four reservoir case histories around the world.

The objectives are to determine:

- Presence of water drive
- Strength of the water drive
- Cumulative water influx, and
- Drive indices

1.6. Significance of the Study

This study will help the reservoir engineer to understand the nature of the aquifer contributing to the production of the hydrocarbon. Failure to account for a weak water drive can result in significant material-balance errors. So the study will show an acceptable method of identifying strong, moderate and weak water drives.

1.7. Limitations

This study is limited to conventional oil and gas reservoirs around the world. Some parameters were assumed to aid full analysis.

2. Methodology

This study will be carried out with respect to gas and oil reservoirs. The two types of reservoirs therefore will involve two different methods of approach to detect and characterize the aquifer.

2.1. Gas Reservoir

2.1.1. The Cole Plot

The Cole plot is a useful tool for distinguishing between water drive and depletion drive gas reservoirs. We can derive the plot from the general gas reservoir material balance.

$$F = G\left(E_g + E_{f,w}\right) + W_e \tag{2}$$

Where F= cumulative reservoir voidage and

$$F = G_p B_W + W_p B_w \tag{3}$$

$$E_g = B_g - B_{gi} \tag{4}$$

Eg = Cumulative gas expansion and

Ef,w = cumulative formation and water expansion

$$E_{f,w} = B_{gi}\frac{S_w C_w + C_f}{1 - S_w}(P_i - P) \tag{5}$$

G = OGIP

Often in gas reservoirs, Efw is negligible compared to Eg and can therefore be ignored.

$$G_p B_g + W_p B_w = G\left(B_g - B_{gi}\right) + W_e \tag{6}$$

$$\frac{G_p B_g}{B_g - B_{gi}} + \frac{W_p B_w}{B_g - B_{gi}} = G + \frac{W_e}{B_g - B_{gi}} \tag{7}$$

$$\frac{G_p B_g}{B_g - B_{gi}} = G + \frac{W_e}{B_g - B_{gi}} - \frac{W_p B_w}{B_g - B_{gi}} \tag{8}$$

$$\frac{G_p B_g}{B_g - B_{gi}} = G + \frac{W_e - W_p B_w}{B_g - B_{gi}} \tag{9}$$

Cole proposed plotting $\frac{G_p B_g}{B_g - B_{gi}}$ on the Y-axis versus Gp, cumulative gas production, if the reservoir is depletion drive, right-handed term goes to zero and the points plot in a horizontal line with the Y intercept equal to G, the OGIP. If a water drive exists, the right-handed term is not zero and the points will plot above the depletion drive line with a type of slope. So we can say that when a sloping line exists with respect to the horizontal line, it can be used as a diagnostic tool for distinguishing between depletion drive and water drive.

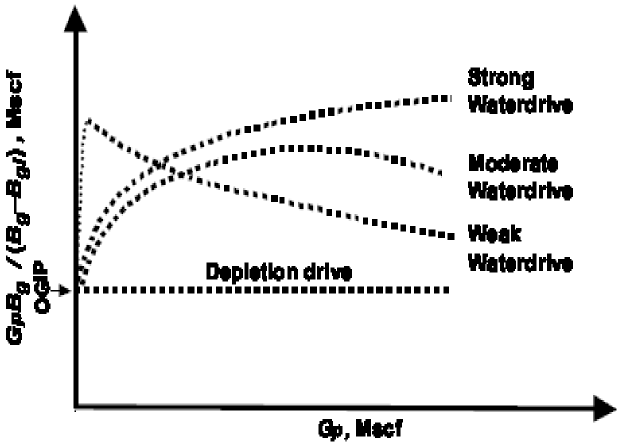

Fig. 1. *Cole plot of GpBg/Bg-Bgi vs Gp*

2.2. Oil Reservoirs

Campbell extended Cole's theory to oil reservoirs in order to characterize them. He developed a plot called the Campbell plot, used to identify the relative strength of aquifers.

2.2.1. Campbell Plot

For oil reservoirs, the Campbell plot is the counterpart to the modified Cole plot for gas. From the generalized material balance equation;

$$F = N_p\left[B_o + \left(R_p - R_s\right)B_g\right] + W_pB_w \tag{10}$$

$$E_o = B_{oi}\left(\left(\frac{B_g}{B_{gi}}\right) - 1\right) \tag{11}$$

$$E_g = B_{oi}(1+m)\frac{S_wC_w + C_f}{1-S_w}\Delta P \tag{12}$$

Introducing the terms into the MBE, it can be written as

$$F = N\left(E_O + mE_g + E_{f,w}\right) + W_e \tag{13}$$

If we let;

$$E_t = E_O + mE_g + E_{f,w} \tag{14}$$

We can further simplify equation (13) to

$$F = N(E_t) + W_e \tag{15}$$

Dividing through by E_t, we have

$$\frac{F}{E_t} = N + \frac{W_e}{E_t} \tag{16}$$

Where N = OOIP in STB
F = cumulative reservoir voidage

$$F = N_p\left[B_t + (R_s - R_{si})B_g\right] + W_pB_w \tag{17}$$

$$E_o = B_t - B_{ti} \tag{18}$$

$$E_o = \left(\frac{B_{ti}}{B_{gi}}\right)\left(B_g - B_{gi}\right) \tag{19}$$

$$E_{f,w} = B_{ti}(1+m)\frac{S_wC_w + C_f}{1-S_w}(Pi - P) \tag{20}$$

Et = cumulative total expansion
Eg = cumulative gas expansion
Ef,w = cumulative formation and water expansion
Eo = cumulative oil expansion
m = ratio of initial gas cap volume to initial oil zone volume at reservoir conditions.
Bt = total formation volume factor

$$B_t = B_o + B_g(R_{si} - R_{si}) \tag{21}$$

Plotting F/Et on the Y axis versus F on the X-axis will yield a plot with one of the characteristic curve shapes as shown below.

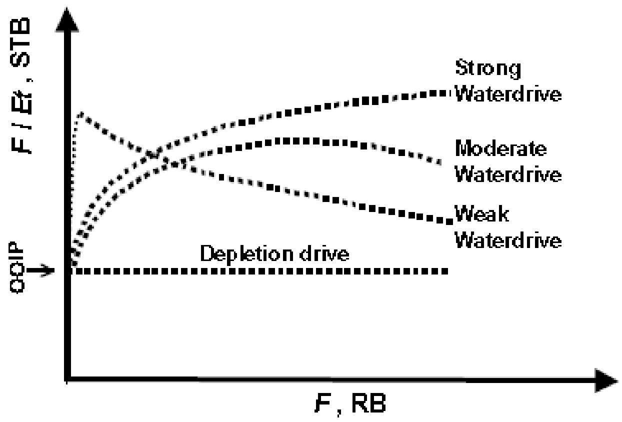

Fig. 2. Campbell plot of F/Et vs F

It should be noted that we assume the reservoir to be a volumetric reservoir, which is not producing under water drive so as to detect whether we have a producing aquifer with water drive or a depletion drive. Therefore we let We=0.

3. Result

Table 1. *Reservoir A (Gas Reservoir)*

Pressure	Gdf, z	Bg	Bw	Cum gas production	Cum water pproduction	Cum water influx
6411	1.1192	0.6279	1.0452	0	0	0
5947	1.089	0.6587	1.0467	5.475	378	273294
5509	1.0618	0.6933	1.048	10.95	1434	552946
5093	1.0374	0.7327	1.0493	16.425	3056	817481
4697	1.0156	0.7778	1.0506	21.9	5284	1068632
4319	0.9966	0.83	1.0517	27.375	8183	1307702
3957	0.9801	0.891	1.0529	32.85	11864	1535212
3610	0.9663	0.9628	1.054	38.325	16425	1752942
3276	0.9551	1.0487	1.0551	43.8	22019	1962268
2953	0.9467	1.1532	1.056	49.275	28860	2163712
2638	0.9409	1.2829	1.0571	54.75	37256	2359460

Table 2. *Data for the Cole plot for Reservoir A*

GpBg	Bg-Bgi	Gp	GpBg/Bg-Bgi
0	0	0	0
3.606383	0.0308	5.475	117.0903
7.591635	0.0654	10.95	116.08
12.0346	0.1048	16.425	114.8339
17.03382	0.1499	21.9	113.6346
22.72125	0.2021	27.375	112.4258
29.26935	0.2631	32.85	111.248
36.89931	0.3349	38.325	110.1801
45.93306	0.4208	43.8	109.1565
56.82393	0.5253	49.275	108.1742
70.23878	0.655	54.75	107.2348

From the above calculation the above data gave the following plot

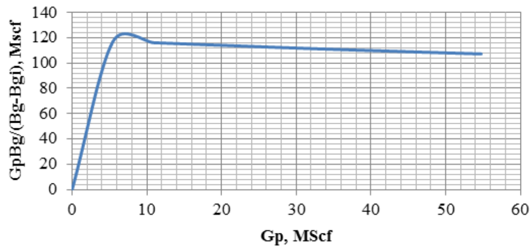

Fig. 3. *Cole plot for Reservoir A*

Table 3. *Reservoir B (oil reservoir)*

Days	Pressure (psia)	Cum oil production.	Cum water production	Cum gas production	Bo(rb/stb)
0	2855	0	0	0	1.2665
305	2779	192821	0	94513	1.2677
700	2627	633942	0	312064	1.2681
1285	2457	1314880	4	710870	1.2554
1456	2402	1524400	7	850934	1.2512
2005	2223	2152960	26	1355720	1.2383
2365	2080	2572000	60	1823250	1.2278
2905	1833	3200560	822	2732860	1.2074
3236	1665	3564680	11135	3397740	1.1949
3595	1460	4003720	97443	4216120	1.1802

Rs	Bg	Bt	Bw
0.501	0.9201	1.2665	1.0222
0.501	0.9637	1.2677	1.0224
0.4973	1.0502	1.272	1.0228
0.4671	1.0977	1.2926	1.0232
0.4574	1.1146	1.2998	1.0233
0.4289	1.201	1.3273	1.0237
0.4024	1.2825	1.3543	1.024
0.3579	1.4584	1.4161	1.0246
0.3277	1.6112	1.4741	1.025
0.2908	1.8526	1.5696	1.0254

EO	Eg	Ef,w	Et	F	F/Et
0	0	0	0	0	0
-0.0012	0.057299	0.482699	0.538799	530447.1	984499.8
-0.0055	0.156895	1.448098	1.599493	1825295	1141171
-0.0261	0.204911	2.52782	2.70663	3646223	1347145
-0.0333	0.221007	2.877141	3.064848	4174010	1361898
-0.0608	0.29622	4.014025	4.249445	5668458	1333929
-0.0878	0.357879	4.922262	5.192341	6483942	1248751
-0.1496	0.467469	6.491034	6.808903	7661163	1125168
-0.2076	0.543246	7.558054	7.8937	8414260	1065946
-0.3031	0.637489	8.860071	9.19446	9711717	1056257

The above calculation gave the following plot:

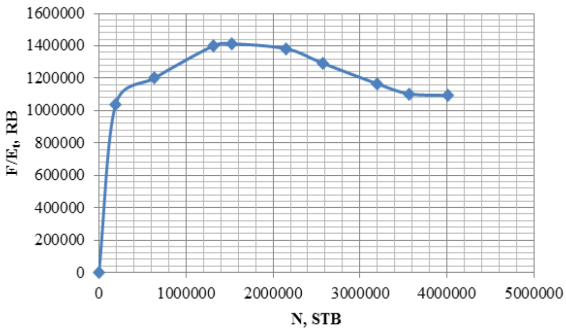

Fig. 4. *Campbell plot for Reservoir B*

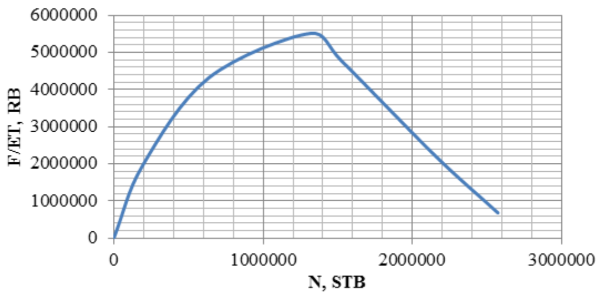

Fig. 5. *Campbell plot for Reservoir C*

Table 4. *Reservoir C (oil reservoir)*

N	p	Wp	Bo	Bw	Bg	Rs	Bt
0	2000	0	1.467	1.0222	0	838.5	1.467
192821	1800	0	1.472	1.0224	0	838.5	1.472
633942	1700	0	1.475	1.0228	0	838.5	1.475
1314880	1640	4	1.463	1.0232	1.92	816.1	44.471
1524400	1600	7	1.453	1.0233	1.977	798.4	80.7307
2152960	1400	26	1.408	1.0237	2.308	713.4	290.1388
2572000	1200	60	1.359	1.024	2.73	621	595.134
3200560	1000	822	1.322	1.0246	3.328	548	968.106
3564680	800	11135	1.278	1.025	4.163	464	1560.322
4003720	600	97443	1.237	1.0254	5.471	383	2493.278
4200350	400	120500	1.194	1.024	7.786	297.4	4214.199
5002340	200	150220	1.141	1.0245	13.331	190.9	8634.297

The method of calculation for F/Et in the oil reservoir above applies to this oil reservoir to get F/Et

Table 5. *Data for the Campbell plot for Reservoir C*

EO	Eg	F	Ef,w	Et	F/Et
0	-1.467	0	0	-1.467	0
-0.005	-1.467	-1.6E+08	-81.1251	-82.5971	1954022
-0.008	-1.467	-5.3E+08	-121.688	-123.163	4308330
-43.004	0	-1E+09	-146.025	-189.029	5509881
-79.2637	0.043552	-1.2E+09	-162.25	-241.47	4771310
-288.672	0.296456	-1.2E+09	-243.375	-531.751	2210868
-593.667	0.618891	-6.2E+08	-324.5	-917.549	674531.9
-966.639	1.0758	4.25E+08	-405.626	-1371.19	-310289
-1558.85	1.713792	2.59E+09	-486.751	-2043.89	-1266170
-2491.81	2.713186	6.65E+09	-567.876	-3056.97	-2174461
-4212.73	4.481991	1.42E+10	-649.001	-4857.25	-2925923
-8632.83	8.718717	3.91E+10	-730.126	-9354.24	-4176083

The above calculation gave the following plot:

Table 6. *Reservoir D (Gas)*

Time	Average pressure	(Gp)	Bo	Rs	Bg 10E-3
(Days)	(psia)	MMscf	(Rb/stb)	(scf/stb)	(rb/scf)
0	4487	0	1.308	811	0.639
365	4444	1.5	1.301	799	0.644
730	4416	3.1	1.298	793	0.647
1095	4370	5.2	1.297	788	0.65
1460	4332	8.5	1.293	785	0.654
1825	4298	11.8	1.29	779	0.659
2190	4260	16.7	1.287	774	0.653
2555	4228	23	1.285	769	0.666
2920	4230	24.7	1.286	772	0.667
3285	4259	25.4	1.289	778	0.665
3650	4282	25.9	1.299	780	0.665

The method of calculation for GpBg/Bg-Bgi in the oil reservoir above applies to this oil reservoir to get GpBg/Bg-Bgi

Table 7. *Data for the Cole plot for Reservoir D*

GpBg	Bg-Bgi	GpBg / Bg-Bgi
0	0	0
0.000966	0.000005	193.2
0.002006	8E-06	250.7125
0.00338	0.000011	307.2727
0.005559	0.000015	370.6
0.007776	0.00002	388.81
0.010905	0.000014	778.9357
0.015318	0.000027	567.3333
0.016475	0.000028	588.3893
0.016891	0.000026	649.6538
0.017224	0.000026	662.4423

The above calculations and equation gave the following plot:

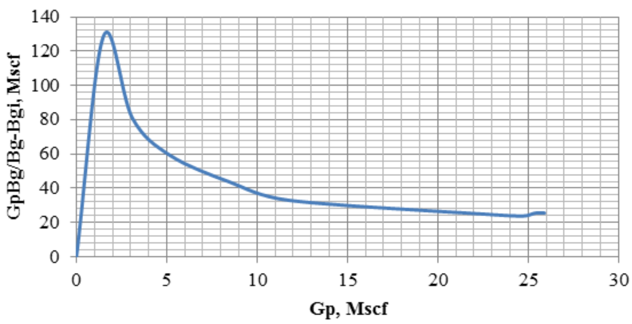

Fig. 6. *Cole plot for Reservoir D*

3.1. Calculation for Water Influx

Assumptions made:

Aquifers are radial aquifers

All reservoirs are characterized with the following properties:

h = 45ft μ = 0.2cp

Φ = 0.15 Cw = 6×10-6

K = 100md Cf = 3×10-6

Subtending angle = 75^0

$$t_D = \frac{2.309 \times 100 \times t}{0.15 \times 0.2 \times 0.000009 \times 5000^2}$$

$$= \frac{230.9t}{6.75}$$

$$= 34.2t$$

$$U = 1.119 f \Phi h c r_o^2$$

$$U = 1.119 \times 0.2083 \times 0.15 \times 45 \times 0.000009 \times 5000^2$$

$$U = 354 \text{bbls/psi}$$

Table 8. *Reservoir A*

T(years)	Pressure(psi)	Plateau pressure Level	ΔP(psi)	t_D	WD(tD) reD = 5
0	6411		451	0	
1	59947	5960	440	34.2	11.80
2	5509	5520	417	68.4	12.02
3	5093	5103	397	102.6	12.10
4	4697	4706	379	136.8	12.20
5	4319	4327	362	171	12.40
6	3957	3965	348	205.2	12.50
7	3610	3617	335	239	12.56
8	3276	3282	325	274	12.60
9	2953	2957	161	308	12.73
10	2638	2796		342	12.8

Table 9. *Calculation of the Water Influx for Reservoir A*

T(years)	$W_e = U \sum_{j=0}^{n-1} \Delta P_j W_D (T_D - t_{Dj})$	We(bbls)
1	354(451×11.8)	1883917.2
2	354(451×12.02+440×11.8)	3757009.1
3	354(451×12.10+440×12.02+417×11.8)	3833720.9
4	354(451×12.2+440×12.10+417×12.02+397×11.8)	7265191.6
5	354(451×12.4+440×12.2+417×12.10+397×12.02+379×11.8)	8938585
6	354(451×12.5+440×12.4+417×12.2+397×12.10+379×12.02+362×11.8)	9121390.6
7	354(451×12.56+440×12.5+417×12.4+397×12.2+379×12.10+362×12.02+348×11.8)	10477231.8
8	354(451×12.6+440×12.56+417×12.5+397×12.4+379×12.2+362×12.10+348×12.02+335×11.8)	13623428
9	354(451×12.73+440×12.6+417×12.56+397×12.5+379×12.4+362×12.2+348×12.10+335×12.02+325×11.8)	15106507.5
10	354(451×12.8+440×12.73+417×12.6+397×12.56+379×12.5+362×12.4+348×12.2+335×12.10+325×12.02+161×1 1.8)	14647366

Table 10. *Reservoir B*

T(years)	Pressure(psi)	Plateau pressure Level	ΔP(psi)	tD	WD(tD) reD = 5
0	2855		38		
0.8	2779	2817	168	33.6	11.4
1.9	2627	2703	161	65.7	11.9
3.5	2457	2542	112	119.7	12.03
4	2402	2430	117	136.8	12.13
5.5	2223	2313	161	188.1	12.3
6.5	2080	2152	195	222.3	12.5
8	1833	1957	208	273.6	12.52
8.9	1665	1749	186	304.4	12.6
10	1460	1563		342	12.8

Table 11. *Calculation of the Water Influx for Reservoir B*

T(years)	$W_e = U\sum_{j=0}^{n-1}\Delta P_j W_D(T_D - t_{Dj})$	We(bbls)
0.8	354(38×11.4)	153352.8
1.9	354(38×11.9+168×11.4)	838059.6
3.5	354(38×12.03+168×11.8+161×11.4)	1513328.8
4	354(38×12.13+168×12.03+161×11.8+112×11.4)	2003137.3
5.5	354(38×12.3+168×12.13+161×12.03+112×11.9+117×11.4)	2516469.18
6.5	354(38×12.5+168×12.3+161×12.13+112×12.03+117×11.9+161×11.4)	3210564.1
8	354(38×12.52+168×12.5+161×12.3+112×12.13+117×12.03+161×11.9+195×11.4)	4057204.6
8.9	354(38×12.6+168×12.52+161×12.5+112×12.3+117×12.13+161×12.03+195×11.9+208×11.4)	4905797.4
10	354(38×12.8+168×12.6+161×12.52+112×12.5+117×12.3+161×12.13+195×12.03+208×11.9+186×11.4)	5788749.6

Table 12. *Reservoir C*

T(years)	Pressure(psi)	Plateau pressure Level	ΔP(psi)	tD	WD(tD) reD = 5
0	2000		150	0	
1	1800	1850	130	34.2	11.80
1.5	1700	1720	70	51.3	11.92
2	1640	1650	130	64.4	12.02
3	1600	1520	120	102.6	12.10
4	1400	1400	200	136.8	12.20
4.5	1200	1200	200	154	12.35
5	1000	1000	200	171	12.40
6	800	800	200	205.2	12.50
7	600	600	200	239.4	12.57
8.5	400	400	200	290.7	12.7
9	200	200		307.8	12.75

Table 13. *Calculation of the Water Influx for Reservoir c*

T(years)	$W_e = U\sum_{j=0}^{n-1}\Delta P_j W_D(T_D - t_{Dj})$	We(bbls)
1	354(150×11.8)	626580
1.5	354(150×11.92+130×11.92+70×11.8)	925356
2	354(150×12.02+130×11.92+130×11.8)	1729856.4
3	354(150×12.10+130×12.02+70×11.92+130×11.8)	2034084
4	354(150×12.20+130×12.1+70×12.02+130×11.92+120×11.8)	2101202.4
4.5	354(150×12.35+130×12.20+70×12.1+130×12.02+120×11.92+200×11.8)	3412029
5	354(150×12.4+130×12.35+70×12.20+130×12.1+120×12.02+200×11.92+200×11.8)	4275930.6
6	354(150×12.5+130×12.4+70×12.35+130×12.20+120×12.1+200×12.02+200×11.92+200×11.8)	5146275
7	354(150×12.57+130×12.5+70×12.4+130×12.35+120×12.20+200×12.1+200×12.02+200×11.92+200×11.8)	6023664
8.5	354(150×12.7+130×12.57+70×12.5+130×12.4+120×12.35+200×12.20+200×12.1+200×12.02+200×11.92+200×11.8	6908699.4
9	354(150×12.75+130×12.7+70×12.57+130×12.5+120×12.4+200×12.35+200×12.20+200×12.1+200×12.02+200×11.92+200 ×11.8)	7800177.6

Table 14. *Reservoir D*

Time, t (Days)	Td	Wd(td)	Pressure (psia)	Pressure drop ΔP (psi)
0	0	0	4487	21.5
365	205.9	74	4444	35.5
730	411.7	140	4416	37.0
1095	617.6	190	4370	42.0
1460	823.4	240	4332	36.0
1825	1029.3	280	4298	36.0
2190	1235.3	328	4260	35.0
2555	1441.0	370	4228	15.0
2920	1646.9	400	4230	-15.0
3285	1852.7	430	4259	-25.0
3650	2058.6	465	4280	

Table 15. *Calculation of the Water Influx for Reservoir D*

TD	$We = U\sum_{i=0}^{n-1} \Delta PiWd\left(td - Tdi\right)$ **Mrb**	We (Mrb)
	21.5 x 0	0
205.9	21.5 x 74	1.59
411.7	(21.5 x 140) + (35.5 x 74)	5.46
617.6	(21.5 x 190) + (35.5 x 140) + (37.0 x 74)	11.79
823.4	(21.5 x 240) + (35.5 x 190) + (37.0 x 140) + (42.0 x 74)	20.19
1029.3	(21.5 x 280) + (35.5 x 240) + (37.0 x 190) + (42.0 x 140) + (36.0 x 74)	30.114
1235.3	(21.5 x 328) + (35.5 x 280) + (37.0 x 240) + (42.0 x 190) + (36 x 140) + (36.0 x 74)	41.56
1441.0	(21.5 x 370) + (35.5 x 328) + (37.0 x 280) + (42.0 x 240) + (36 x 190) + (36 x 140) + (35.0 x 74)	54.51
1646.9	(21.5 x 400) + (35.5 x 370) + (37.0 x 328) + (42.0 x 280) + (36 x 240) + (36 x 190) + (35.0 x 140) + (15 x 74)	67.12
1852.7	(21.5 x 430) + (35.5 x 400) + (37.0 x 370) + (42.0 x 328) + (36 x 280) + (36 x 240) + (35 x 190) + (15 x 140) + (-15.5 x 74)	77.27
2058.6	(21.5 x 465) + (35.5 x 430) + (37 x 400) + (42 x 370) + (36 x 328) + (360 x 328) + (36 x 280) + (35 x 240) + (15 x 190) + (-15.5 x 140) + (-25.0 x 74)	84.72

4. Discussion of Result

4.1. Reservoir A

In the first reservoir, the material balance method was applied to the reservoir history as described by Cole. The process produced a curve similar to one of the curves in the plot presented by Cole. This plot indicates the presence of an aquifer characterized by a weak water drive. From the plot we see an abrupt fall in the Y axis which is GpBg/Bg-Bgi with increasing X axis which is Gp. The abrupt fall can be noticed from around 5.5MScf of cumulative gas production.

In the case of the water influx calculation, the dimensionless time was calculated to be 34.2t with t being the number of years. The aquifer constant for radial geometry was calculated to be 354bbls/psi which was used to calculate the cumulative water influx.

From the cumulative water influx calculated, we see a trend in which the values are gradually increasing within the range of 1.5 to 14MMbbl

4.2. Reservoir B

In the second case, we see a similar trend which was in seen in the Cole plot of the first reservoir. The Campbell plot indicates a weak water drive though with some discrepancies which could be as a result of the nature of the reservoir and aquifer properties. The decrease of the X axis is noticed around 14MMRb of cumulative oil production.

For the cumulative water influx, we also see a trend that increases with large values ranging from 0.1 to 5.8MMbbl.

4.3. Reservoir C

For the third case, we observed a similar but deviated trend in the Campbell plot. The plot also shows the presence of an aquifer characterized by a weak water drive into the reservoir.

A gradual decline was about to be noticed before an abrupt decline on the X axis was noticed around 13MMrb of cumulative oil production.

Regarding the cumulative water influx, the calculated values show an increasing trend with large increment towards the end of the production period ranging from 0.6 to 7.8MMbbls.

4.4. Reservoir D

The last case scenario gave a perfect description of the Cole plot showing a weak water drive. The curve shows an abrupt decline at about 2.7Mscf.

Regarding the water influx calculation, it also shows similar trend to the previously treated cases with We ranging from 1.59 to 84MMbbls

Comparing the results of the three cases, we can summarize:

Table 16. *Range of Water Influx values*

	Range of We values	Point of decline
Reservoir A	1.5 – 14MMbbls	5.5Mscf
Reservoir B	0.1 – 5.8MMbbls	14Mrb
Reservoir C	0.6 – 7.8MMbbls	13Mrb
Reservoir D	1.59 – 84MMbbls	2.7Mscf

From table 16 above we can infer that reservoir D has the highest range of values for We and the smallest value for the point of decline of the curve.

The steps taken were successful because the Cole and Campbell plot were able to account for the weak water drive.

5. Conclusion and Recommendation

5.1. Conclusion

In this study, the material balance method has proven to be a very useful tool to the reservoir engineer with regards to aquifer detection and characterization. The general material balance equation was re-arranged to come up with an equation which an equation that plots a graph known as Cole and Campbell plot used to characterise the strength of the water drive.

Applying this method to the reservoir data, we were able to come up with plots similar to the modal proposed by Cole using Microsoft excel to aid accurate calculation.

These plots show the presence of a water drive and from the nature of the curves, the plots show weak water drives.

The Cole plot (gas) and Campbell plot (oil) diagnose the presence of a weak waterdrive unambiguously. Depletion-drive plots, such as the p/z, are ambiguous in the presence of a weak water drive and can give OHIP values that are erroneously high by a significant amount. As suggested by previous authors, the weak waterdrive signature on the Cole and Campbell plots is shown to be a negative slope. The study was successful and desirable results gotten.

Generally, the Cole and Campbell method was successful in determining weak water drives in aquifer.

5.2. Recommendation

Production data to be used for material balance analysis should be carefully obtained.

Reasonable assumptions can be made where necessary.

Microsoft excel can be used for calculations regarding material balance to be able to avoid human error and inaccurate result.

The Cole and Campbell plot should be used as a more accurate method for diagnosing aquifer strength.

During diagnoses of water drives, We should be assumed to be neglected in order to ascertain its presence.

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