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Modeling of Compositional Variation with Depth for Five North Sea Reservoirs

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Abstract

Compositional data for reservoir fluids sampled in various depths in five different North Sea reservoirs is presented and analyzed. All five reservoirs have a gas-oil contact and for each reservoir one composition exists from above and two or more from below the gas-oil contact. For all reservoirs the compositional gradient is higher than can be explained by gravity segregation alone. The highest compositional gradient is seen for a reservoir, which is rich in asphaltenes. The compositional variation with depth is modeled using the Haase model, which expresses the influence of a temperature gradient in terms of the specific enthalpies of each fluid component. The high compositional variation seen for the asphaltenic reservoir fluid suggests that the condensed aromatic compounds, which are the main constituents of asphaltenes, have a significantly higher absolute specific ideal gas enthalpy than paraffinic and naphthenic compounds.

Introduction

Reservoir fluids show compositional variations with depth. The concentration of high molecular weight compounds increases with depth. If the reservoir pressure and the saturation pressure become equal the reservoir will have as gas-oil contact with a gas cap above and an oil zone below. Only part of the compositional variation can be explained by gravity segregation. A temperature increase with depth also contributes to the compositional gradient.

While the theory behind gravity segregation is well established, there is more uncertainty about the influence of a thermal gradient. A non-isothermal reservoir is not in an equilibrium state. There will be a heat flux from the (deeper) warmer layers to the colder (upper) layers. The impact of the temperature gradient on the compositional gradient can be modeled using irreversible thermodynamics. The model of [Haase \(1969\)](#) used in this work assumes stationarity and that all heat transport is tied to molecular movement. Ignoring gravity effects the Haase model will simulate that a component with a high absolute partial molar enthalpy per mass unit will have a preference for a warmer zone as compared with components with a lower absolute enthalpy per mass unit. The absolute enthalpy is difficult to quantify, for which reason it is custom in heat exchange calculations to use the enthalpy difference relative to some reference state. That is justified in simulations with a constant composition, while the absolute enthalpy is required in a simulation of the compositional variation with depth.

Field Data

Tables 1–5 show data for the variation in composition with depth in five different North Sea petroleum reservoirs. The depth is relative to the depth in which the upper fluid sample was taken. For Reservoir 5 in Table 5 the asphaltene content in the oil from a flash to standard conditions is also given. The remaining four fluids do not contain asphaltenes in significant amounts. The gas-oil contact in Reservoir 1 was found in a depth 140 m below the depth in which the gas sample was taken.

Table 1—Compositional data and pressure and temperature information for Reservoir 1. The depth is relative to the depth of the upper fluid sample. The fluid composition marked with * is used as reference in the simulations. The temperatures in the others depths are assuming a vertical temperature gradient of 0.025 °C/m. Gas-oil contact was found in a depth of 140 m.

	Depths (m)				
	0 m	*175 m	204 m	228 m	327 m
	Mol%				
N2	1.06	0.42	0.42	0.39	0.43
CO2	0.70	0.69	0.71	0.70	0.77
C1	75.66	50.04	49.88	48.89	45.66
C2	7.62	7.85	7.77	7.74	7.60
C3	5.33	6.77	6.74	6.76	7.13
iC4	0.73	1.04	1.03	1.04	1.13
nC4	2.02	3.20	3.21	3.24	3.52
iC5	0.67	1.16	1.16	1.18	1.31
nC5	0.84	1.55	1.55	1.58	1.75
C6	0.91	1.88	1.88	1.93	2.17
C7	1.29	3.50	3.49	3.62	4.01
C8	1.06	3.75	3.73	3.85	4.28
C9	0.54	2.28	2.31	2.36	2.58
C10+	1.57	15.88	16.11	16.70	17.66
C7+ Mol Wgt	126	196	197	197	200
C7+ Density (g/cm3)	0.785	.846	.848	0.848	0.850
Pressure (bar)	279	284	286	287	293
Temperature (°C)	89	93	94	94	97
Saturation Pressure (bar)	270	272	267	265	242
Single Stage GOR (m ³ /m ³)	3739	281.5	280.9	264.5	227.8

Table 2—Compositional data and pressure and temperature information for Reservoir 2. The depth is relative to the depth of the upper fluid sample. The fluid composition marked with * is used as reference in the simulations. The temperatures in the others depths are assuming a vertical temperature gradient of 0.025 °C/m.

		Depth (m)			
		0 m	*6.5 m	11.5 m	57.5 m
		Mol%			
	N2	3.37	1.22	1.05	0.98
	CO2	1.12	0.82	0.87	0.76
	C1	81.13	46.97	44.54	43.51
	C2	7.34	7.52	7.75	7.42
	C3	3.01	4.39	4.61	4.50
	iC4	0.46	0.84	0.89	0.88
	nC4	0.99	2.13	2.26	2.26
	iC5	0.33	0.92	0.97	0.99
	nC5	0.36	1.12	1.19	1.22
	C6	0.38	1.58	1.65	1.71
	C7	0.47	2.54	2.67	2.78
	C8	0.37	3.07	3.25	3.40
	C9	0.18	2.20	2.34	2.43
	C10+	0.49	24.70	25.95	27.16
	C7+ Mol Wgt	123	237	237	236
	C7+ Density (g/cm3)	0.776	0.849	0.850	0.851
	Pressure (bar)	243.0	243.0	243.3	246.4
	Temperature (°C)	89.8	90.0	90.1	91.3
	Saturation Pressure (bar)	243	243	-	-
	Single Stage GOR (m ³ /m ³)	15007	164.4	149.3	142.1

Table 3—Compositional data and pressure and temperature data for Reservoir 3. The depth is relative to the depth of the upper fluid sample. The fluid composition marked with * is used as reference in the simulations. The temperatures in the others depths are assuming a vertical temperature gradient of 0.025 °C/m.

		Depth (m)			
		0 m	*11 m	18 m	39 m
		Mol%			
	N2	6.86	1.57	1.52	1.47
	CO2	0.58	0.32	0.38	0.33
	C1	81.28	39.37	38.86	38.18
	C2	5.21	5.69	5.66	5.65
	C3	2.69	4.82	4.83	4.85
	iC4	0.44	1.11	1.12	1.12
	nC4	1.00	3.09	3.13	3.15
	iC5	0.32	1.40	1.43	1.44
	nC5	0.35	1.81	1.84	1.86
	C6	0.33	2.48	2.53	2.55
	C7	0.37	3.95	4.03	4.07
	C8	0.28	4.66	4.74	4.81
	C9	0.12	3.40	3.48	3.52
	C10+	0.15	26.34	26.45	27.00
	C7+ Mol Wgt	109	214	214	215
	C7+ Density (g/cm3)	0.757	0.844	0.845	0.845
	Pressure (bar)	195.4	195.6	196.1	197.5
	Temperature (°C)	73.7	74	74.2	74.7
	Saturation Pressure (bar)	-	192	-	186
	Single Stage GOR (m ³ /m ³)	53673	130.8	127.8	123.7

Table 4—Compositional data and pressure and temperature data for Reservoir 4. The depth is relative to the depth of the upper fluid sample. The fluid composition marked with * is used as reference in the simulations. The temperatures in the others depths are assuming a vertical temperature gradient of 0.025 °C/m.

		Depth (m)		
		0 m	*14 m	26 m
		Mol%		
	N2	2.00	0.64	0.62
	CO2	0.09	0.06	0.06
	C1	66.66	37.64	36.88
	C2	11.39	10.53	10.54
	C3	9.37	11.66	11.64
	iC4	1.66	2.46	2.43
	nC4	2.72	4.58	4.50
	iC5	0.96	1.98	1.89
	nC5	0.92	2.06	1.94
	C6	0.94	2.62	2.43
	C7	0.96	3.40	3.25
	C8	0.89	4.04	4.06
	C9	0.39	2.34	2.46
	C10+	1.04	16.00	17.29
	C7+ Mol Wgt	131	211	215
	C7+ Density (g/cm3)	0.788	0.875	0.885
	Pressure (bar)	-	191	-
	Temperature (°C)	79.2	79.5	79.8
	Saturation Pressure (bar)	190	187.5	-
	Single Stage GOR (m ³ /m ³)	4736	250.1	231.8

Table 5—Compositional data and pressure and temperature data for Reservoir 5. The depth is relative to the depth of the upper fluid sample. The fluid composition marked with * is used as reference in the simulations. The temperatures in the others depths are assuming a vertical temperature gradient of 0.025 °C/m.

		Depth (m)			
		0 m	*8 m	21 m	28 m
		Mol%			
	N2	2.80	0.77	0.66	0.63
	CO2	0.16	0.09	0.09	0.05
	C1	67.89	34.41	32.58	29.47
	C2	11.06	10.11	9.92	9.89
	C3	8.71	11.78	11.66	11.57
	iC4	1.78	2.51	2.49	2.36
	nC4	3.05	4.53	4.53	4.18
	iC5	1.12	1.95	1.99	1.70
	nC5	0.99	1.98	2.04	1.64
	C6	0.87	2.52	2.54	1.95
	C7	0.67	3.17	3.19	2.60
	C8	0.48	3.78	3.80	2.98
	C9	0.14	2.23	2.27	1.66
	C10+	0.29	20.16	22.22	29.33
	C7+ Mol Wgt	112	260	280	340
	C7+ Density (g/cm3)	0.764	0.909	0.930	0.980
	Pressure (bar)	-	194.0	194.1	195.1
	Temperature (°C)	79.6	79.8	80.1	80.3
	Saturation Pressure (bar)		185.7	175.4	152
	Single Stage GOR (m ³ /m ³)	2947	174.3	149.3	114.7
	Weight% Asphaltene of STO Oil		7.3	13.7	33.6

Theory of Compositional Grading

At equilibrium in a closed system with negligible height differences, the chemical potential of a component *i* is the same at all positions in the system. The criterion of equal chemical potentials is, however, not valid for a system with considerable height differences. For such system, the height potential must also be considered. For an isothermal system, the equilibrium relation for component *i* becomes

$$\mu_i(h) - \mu_i(h^o) = M_i g(h - h^o) \quad (1)$$

where μ is the chemical potential, *h* stands for depth, *M* for molecular weight, *g* for gravitational acceleration and *h*^o is a reference depth. The chemical potential is related to the fugacity through the following relation

$$d\mu_i = RT d\ln f_i = RT d\ln(\varphi_i z_i P) \quad (2)$$

T is temperature, *P* pressure, *R* gas constant, *f* fugacity, φ fugacity coefficient, *z* component mole fraction, and *i* a component index. For an isothermal reservoir, Equation (1) may, using Equation (2), be rewritten to

$$\ln f_i^h - \ln f_i^{h^o} = \frac{M_i g(h - h^o)}{RT} \quad (3)$$

For an *N* component system Equation (3) may be written

$$\ln(\varphi_i^h z_i^h P^h) - \ln(\varphi_i^{h^o} z_i^{h^o} P^{h^o}) = \frac{M_i g(h - h^o)}{RT} \quad i = 1, 2, \dots, N \quad (4)$$

The mole fractions of the components must sum to 1.0 giving one additional equation

$$\sum_{i=1}^N z_i = 1 \quad (5)$$

If the pressure P^{h° and the composition ($Z_i^{h^\circ}$, $i = 1, 2, \dots, N$) are known in the reference depth h° , there are $N + 1$ variables for a given depth, h , namely (Z_i^h , $i = 1, 2, \dots, N$) and P^h .

A set of $N + 1$ equations with $N + 1$ variables may be solved to give the molar composition and pressure as a function of height. [Schulte \(1980\)](#) has outlined how to solve these equations and has also given examples of compositional gradients calculated using [Equations \(4\) and \(5\)](#) with fugacity coefficients derived from an equation of state.

In most petroleum reservoirs, the temperature increases with depth. A temperature gradient introduces a flow of heat between locations at different temperatures, and the reservoir fluid is not at thermodynamic equilibrium.

The equations needed to solve for the molar compositions in a reservoir with a thermal gradient can be set up using the terminology of irreversible thermodynamics. To simplify the problem, one may assume that the system is at a stationary state. That is, all component fluxes are zero, and the compositional gradient is assumed to be constant in time. The [Haase \(1969\)](#) model used in this work further assumes that all heat transfer originates from molecular transport. With those assumptions the equivalent of [Equation \(4\)](#) for a system a thermal gradient in addition to a significant height difference becomes:

$$RT \ln(\phi_i^h z_i^h P^h) - RT \ln(\phi_i^{h^\circ} z_i^{h^\circ} P^{h^\circ}) = M_i g(h - h^\circ) - M_i \left(\frac{H^{abs}}{M} - \frac{\tilde{H}_i^{abs}}{M_i} \right) \frac{\Delta T}{T} \quad i = 1, 2, \dots, N \quad (6)$$

H is the molar enthalpy of the mixture, M the average molecular weight, ($z_i^{h^\circ}$, $i = 1, 2, \dots, N$) the partial molar enthalpy of component i , which is the sum of a residual and an ideal gas term

$$\tilde{H}_i = \tilde{H}_i^{res} + H_i^{ig} \quad (7)$$

Enthalpy per mass unit is also called specific enthalpy. ΔT in [Equation \(6\)](#) is the temperature difference between height h and height h° . The compositional gradient in a reservoir with a thermal gradient may be determined by solving the N equations expressed through [Equation \(6\)](#) together with [Equation \(5\)](#).

To make use of [Equation \(6\)](#), the absolute enthalpies are required

$$H^{abs} = \sum_{i=1}^N z_i \tilde{H}_i^{abs} = H^{res} + H^{ig} = \sum_{i=1}^N z_i \tilde{H}_i^{res} + \sum_{i=1}^N z_i H_i^{ig} \quad (8)$$

The residual term can be evaluated from an equation of state using

$$H^{res} = -RT^2 \sum_{i=1}^N z_i \frac{\partial \ln \phi_i}{\partial T} \quad (9)$$

The ideal gas enthalpy of component i at temperature T can be expressed as

$$H_i^{ig}(T) = \sum_{i=1}^N z_i H_i^{ig}(T_{ref}) + \sum_{i=1}^N z_i \int_{T_{ref}}^T C_{p_i}^{id} dT \quad (10)$$

$C_{p_i}^{id}$ may be calculated from a 3rd degree polynomial in temperature

$$C_{p_i}^{id} = C_{1,i} + C_{2,i}T + C_{3,i}T^2 + C_{4,i}T^3 \quad (11)$$

Poling et al. (2000) have tabulated C_1 - C_4 for defined components. For C_7+ components C_1 - C_4 may be calculated as outlined by [Kesler and Lee \(1976\)](#).

The last term in [Equation \(10\)](#) expresses the change in ideal gas enthalpy from a reference temperature, T_{ref} , to the actual temperature T . In heat balance calculations on a fluid mixture of constant composition the term (z_i^h , $i = 1, 2, \dots, N$) can be neglected as it will be the same independent of pressure and temperature. In a depth gradient calculation it is not justified to neglect the term \tilde{H}_i because the composition changes

with depth and each component will have different ideal gas specific enthalpies at the reference temperature.

Rutherford and Roof (1959) investigated a C1–nC4 mixture and Haase et al. (1971) a C1–C3 mixture in experimental set-ups with a temperature gradient. In these experiments, C1 segregated at the warmer side. Analyzing Equation (6) and neglecting the height term, it can be seen that in a system with negligible height differences, a component whose partial molar specific enthalpy is above average will segregate at the warmer side and a component whose partial specific molar enthalpy is below average at the colder side. In this work T_{ref} is chosen to 273.15 K and Table 6 shows the values of $H_i^{\text{ig}}(T_{\text{ref}})/M$ used for the defined components. It has been verified that those ideal gas enthalpies will comply with the above mentioned observations that C1 in a mixture with either nC4 or C3 will have a preference for the warmer side.

Table 6—Ideal gas specific enthalpies at 273.15 K.

Component	$H^{\text{ig}}/(M \cdot R)$ (K/g)
N2	-20
CO2	20
C1	0
C2	7.5
C3	15
iC4	17
nC4	17
iC5	25
nC5	25
C6	33

Depth gradient data for reservoir fluids have been presented by Creek et al. (1985), Montel and Gouel (1985), Whitson and Belery (1994), Hoier and Whitson (2000), Pedersen and Lindeloff (2003) and Pedersen and Hjermstad (2006). Most data suggests that a positive vertical temperature gradient will enhance the compositional variation with depth as compared to isothermal gravity segregation. That means a positive temperature gradient will strengthen C1's preference for the (cooler) top region and make it more preferable for the heaviest components to settle in the (warmer) bottom region. These observations are not necessarily contradictory to observations saying that the lighter C1 component in a binary mixture with a slightly heavier component (C3 or nC4) will segregate at the warmer side, but it requires that the C7+ fraction has a considerable content of components with a partial molar specific enthalpy that is higher than that of C1.

Equation of State Model

The fluids were characterized using the procedure of Pedersen et al. (2004) and the phase behavior modeled using the volume corrected Peng-Robinson equation of state (Peng and Robinson (1976) and Jhaveri and Youngren (1988)). Table 7 shows the EoS model used for Reservoir 1. The mol%'s are for the fluid composition sampled 175 m below the sample taken in the gas zone. That fluid composition is used as reference sample in the depth gradient calculations for Reservoir 1. The fluid has been tuned up to give a good match of the saturation point in Table 1.

Table 7—EoS model used for fluids sampled from Reservoir 1. The mol%'s are for the fluid sampled in a relative depth of 175 m.

Component	Mol%	Mol Wgt	Critical Temperature °C	Critical Pressure bar	Acentric factor	Volume correction cm ³ /mol	Non-zero Binary Interaction Coefficients		
N2	0.42	28.0	-147.0	33.94	0.040	-4.23	N2	N2	CO2
CO2	0.69	44.0	31.1	73.76	0.225	-1.91	CO2	-0.0170	
C1	50.04	16.0	-82.5	46.00	0.008	-5.20	C1	0.0311	0.1200
C2	7.85	30.1	32.2	48.84	0.098	-5.79	C2	0.0515	0.1200
C3	6.77	44.1	96.6	42.46	0.152	-6.35	C3	0.0852	0.1200
iC4	1.04	58.1	134.9	36.48	0.176	-7.18	iC4	0.1033	0.1200
nC4	3.20	58.1	152.1	38.00	0.193	-6.49	nC4	0.0800	0.1200
iC5	1.16	72.2	187.2	33.84	0.227	-6.20	iC5	0.0922	0.1200
nC5	1.55	72.2	196.4	33.74	0.251	-5.12	nC5	0.1000	0.1200
C6	1.88	86.2	234.2	29.69	0.296	1.42	C6	0.0800	0.1200
C7	3.50	96.0	269.9	29.60	0.338	8.45	C7	0.0800	
C8	3.75	107.0	290.9	27.86	0.374	9.20	C8	0.0800	
C9	2.28	121.0	315.3	25.83	0.420	10.32	C9	0.0800	
C10-C11	3.26	140.1	345.9	23.76	0.483	11.12	C10-C11	0.0800	
C12-C13	2.59	167.6	385.0	21.58	0.570	10.48	C12-C13	0.0800	
C14-C16	2.93	204.7	432.7	19.59	0.685	6.57	C14-C16	0.0800	
C17-C18	1.46	243.6	476.8	18.24	0.795	-1.30	C17-C18	0.0800	
C19-C21	1.65	275.3	511.1	17.54	0.881	-9.89	C19-C21	0.0800	
C22-C24	1.17	317.0	553.3	16.84	0.984	-23.43	C22-C24	0.0800	
C25-C29	1.24	370.4	604.9	16.23	1.098	-43.30	C25-C29	0.0800	
C30-C37	0.96	456.8	683.3	15.62	1.229	-79.96	C30-C37	0.0800	
C38-C80	0.63	640.9	847.8	14.72	1.159	-151.44	C38-C80	0.0800	

The fluids compositions from Reservoirs 1-4 were characterized in a similar manner and for each reservoir the oil composition taken nearest to the gas-oil contact was used as reference fluid in the depth gradient simulations.

Isothermal Depth Gradient Modeling

The compositional variation with depth is initially simulated assuming isothermal reservoirs. The variation in fluid composition with depth is calculated from [Equations \(4\) and \(5\)](#). [Figure 1](#) shows the simulated variation in pressure and saturation pressure with depth for each of the five reservoirs. All five reservoirs have a gas-oil contact, but the simulations only predict a gas-oil contact for the Reservoirs 1 and 2. For Reservoirs 1, 3 and 5 it is further seen that the saturation pressure simulated for the deepest sample is much too low. The gas-oil contact in Reservoir 1 is simulated to be in a (relative) depth of 100 m, while the experimental observations said 140 m.

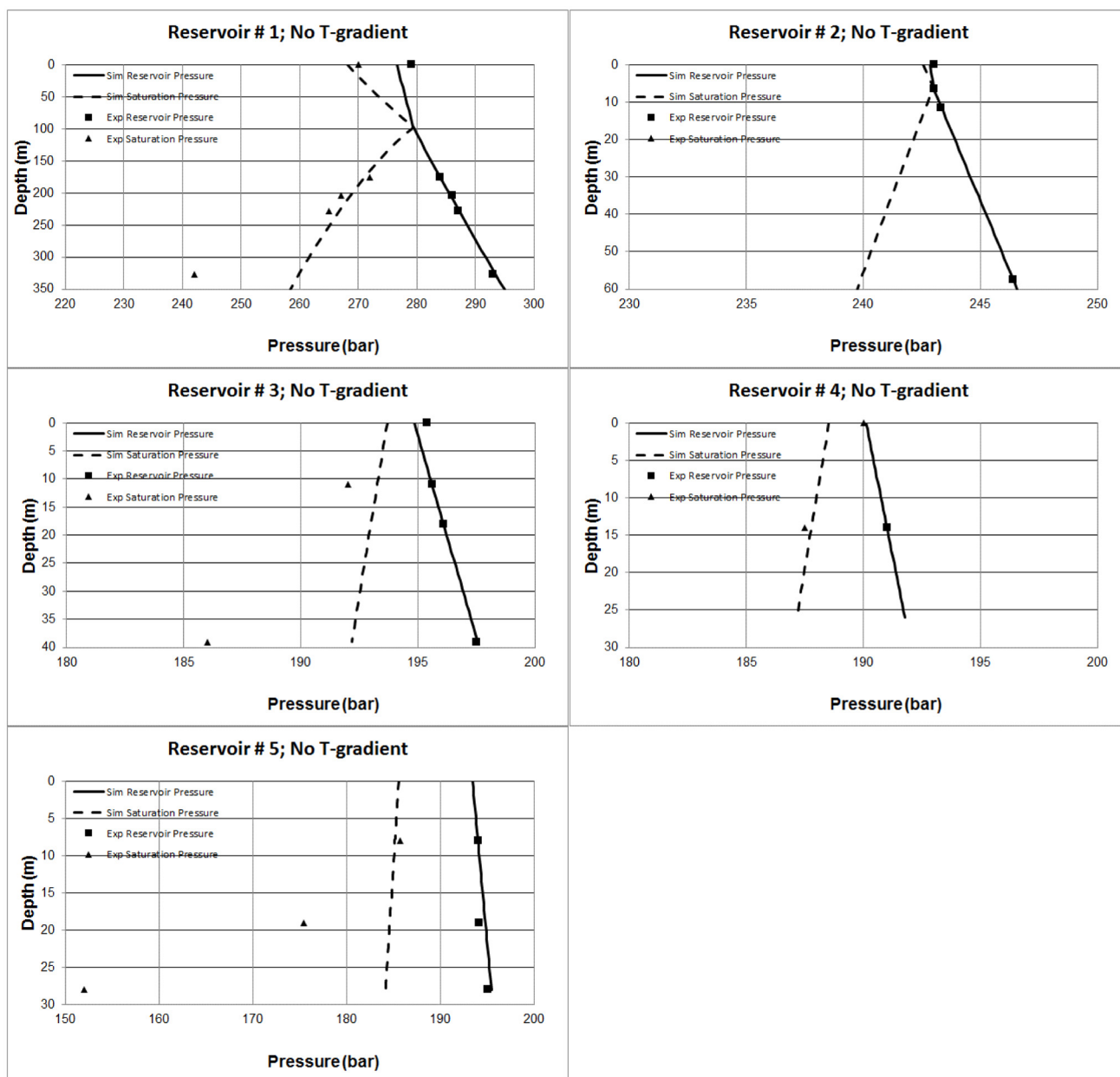


Figure 1—Measured and simulated variation in pressure and saturation pressure with depth for each of the five reservoirs. The simulation results are for isothermal reservoirs.

Non-Isothermal Depth Gradient Modeling

Equations (5) and (6) were used to simulate the compositional variation with depth in each of the five reservoirs taking into consideration a vertical temperature gradient. The ideal gas specific enthalpies in Table 6 were used for the defined components and the values in Table 8 for the C7+ components. The latter values are found to give a good match of the field data in Tables 1–5. Tables 9–13 show the match of the compositions in various depths for each of the five reservoirs. Figure 2 shows the match of the development in reservoir pressure and saturation pressure with depth and Figure 3 the match of the development in GOR with depth in Reservoirs 1 and 2. As can be seen from Figure 2 the gas-oil contact in Reservoir 1 is simulated to be in a depth of 140 m consistent with the field data.

Table 8—Ideal gas specific enthalpies at 273.15 K for C7+ pseudo-components.

Molecular weight M	$H^ig/(M \cdot R)$ (K/g)				
	Reservoir 1	Reservoir 2	Reservoir 3	Reservoir 4	Reservoir 5
M < 150	2	2	2	2	2
150 < M < 250	93	93	36	163	877
250 < M < 400	31	31	434	147	880
M > 400	8	8	29	7	639

Table 9—Measured and simulated composition for Reservoir 1 assuming a vertical temperature gradient of 0.025 °C/m.

Components	Depth = 0 m			Depth = 175 m (Reference Depth)		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	1.76	1.71	-3.0	1.11	1.11	0.0
C1	75.66	75.73	0.1	50.04	50.04	0.0
C2-C6	18.12	18.74	3.4	23.44	23.44	0.0
C7+	4.45	3.83	-14.1	25.41	25.41	0.0
Components	Depth = 204 m			Depth = 228 m		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	1.12	1.10	-1.9	1.09	1.09	0.0
C1	49.88	49.47	-0.8	48.89	49.04	0.3
C2-C6	23.35	23.24	-0.5	23.49	23.05	-1.8
C7+	25.64	26.19	2.1	26.53	26.81	1.1
Components	Depth = 327 m					
	Exp mol%	Sim mol%	% Deviation			
Inorganics	1.20	1.05	-12.1			
C1	45.66	47.33	3.6			
C2-C6	24.61	22.14	-10.0			
C7+	28.53	29.48	3.3			

Table 10—Measured and simulated composition for Reservoir 2 assuming a vertical temperature gradient of 0.025 °C/m.

Components	Depth = 0 m			Depth = 6.5 m (Reference Depth)		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	4.49	4.44	-1.0	2.04	2.04	0.0
C1	81.13	80.69	-0.6	46.97	46.97	0.0
C2-C6	12.87	12.99	0.9	18.49	18.49	0.0
C7+	1.51	1.88	24.5	32.50	32.50	0.0
Components	Depth = 11.5 m			Depth = 57.5 m		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	1.92	2.04	6.0	1.75	2.02	15.8
C1	44.54	46.91	5.3	43.51	46.50	6.9
C2-C6	19.32	18.47	-4.4	18.97	18.26	-3.8
C7+	34.21	32.58	-4.7	35.77	33.23	-7.1

Table 11—Measured and simulated composition for Reservoir 3 assuming a vertical temperature gradient of 0.025 °C/m.

Components	Depth = 0 m			Depth = 11 m (Reference Depth)		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	7.44	6.56	-11.8	1.88	1.88	0.0
C1	81.28	80.94	-0.4	39.37	39.37	0.0
C2-C6	10.36	11.40	10.0	20.40	20.40	0.0
C7+	0.92	1.10	19.7	38.34	38.34	0.0
Components	Depth = 18 m			Depth = 39 m		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	1.91	1.85	-2.9	1.81	1.74	-4.1
C1	38.86	38.78	-0.2	38.18	37.09	-2.8
C2-C6	20.54	20.18	-1.7	20.63	19.44	-5.8
C7+	38.70	39.19	1.3	39.39	41.74	6.0

Table 12—Measured and simulated composition for Reservoir 4 assuming a vertical temperature gradient of 0.025 °C/m.

Components	Depth = 0 m			Depth = 14 m (Reference Depth)		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	2.08	1.96	-5.9	0.70	0.70	0.0
C1	66.66	68.98	3.5	37.64	37.64	0.0
C2-C6	27.98	26.96	-3.6	35.89	35.89	0.0
C7+	3.28	2.09	-36.2	25.77	25.77	0.0
Components	Depth = 26 m					
	Exp mol%	Sim mol%	% Deviation			
Inorganics	0.68	0.68	0.0			
C1	36.88	37.01	0.3			
C2-C6	35.37	35.53	0.5			
C7+	27.06	26.78	-1.1			

Table 13—Measured and simulated composition for Reservoir 5 assuming a vertical temperature gradient of 0.025 °C/m.

Components	Depth = 0 m			Depth = 8 m (Reference Depth)		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	3.40	2.56	-24.6	0.86	0.86	0.00
C1	67.89	65.27	-2.4	34.41	34.41	0.00
C2-C6	27.58	29.59	3.7	35.40	35.40	0.00
C7+	1.13	2.58	128.0	29.33	29.33	0.00
Components	Depth = 21 m			Depth = 28m		
	Exp mol%	Sim mol%	% Deviation	Exp mol%	Sim mol%	% Deviation
Inorganics	0.75	0.75	0.0	0.68	0.70	3.5
C1	32.58	31.62	-2.9	29.47	30.49	3.5
C2-C6	35.17	31.83	-9.5	33.29	29.92	-10.1
C7+	31.50	35.80	13.7	36.56	38.89	6.4

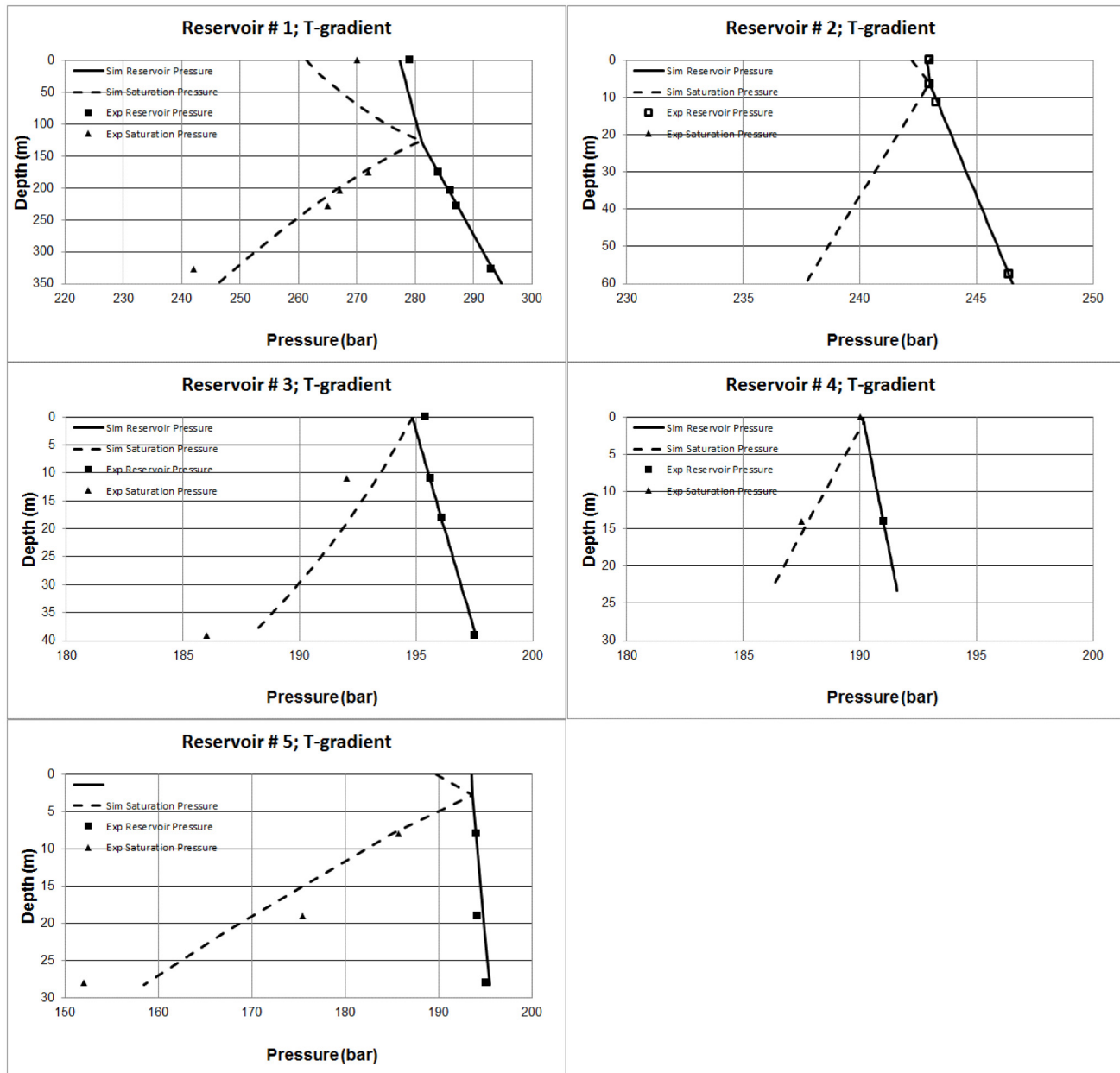


Figure 2—Measured and simulated variation in pressure and saturation with depth for each of the five reservoirs. The simulation results are for non-isothermal reservoirs with a vertical temperature gradient of 0.025 °C/m.

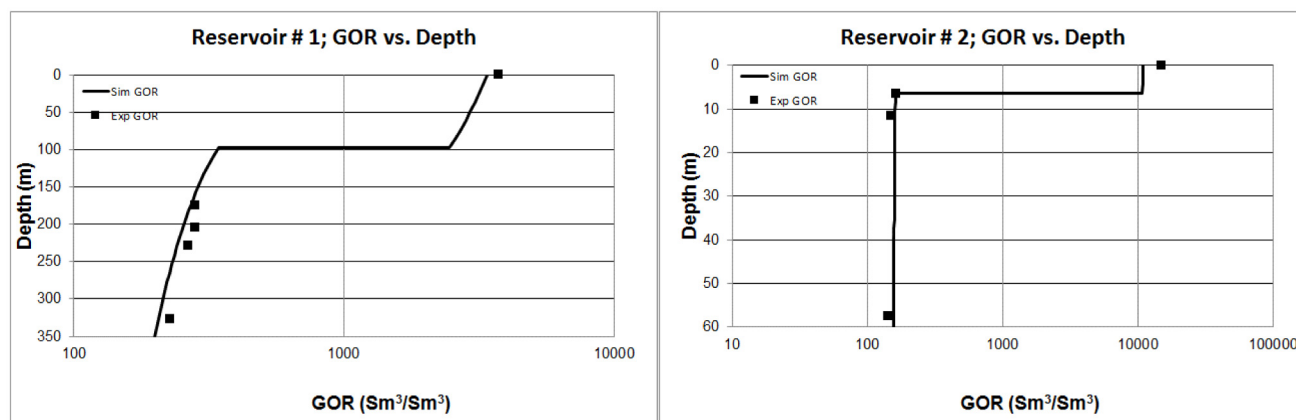


Figure 3—Measured and simulated variation in GOR with depth Reservoirs 1 and 2. The simulation results are for non-isothermal reservoirs with a vertical temperature gradient of 0.025 °C/m.

Discussion of Results

The simulation results show that the Haase model is capable of correlating the observed compositional variations with depth in the five considered North Sea reservoirs. The absolute ideal gas enthalpy at a selected reference temperature (273.15 K in this work) is a key parameter. The authors are not aware of any published procedure for evaluating the absolute ideal gas enthalpies and these are instead evaluated from the field data. The most valuable information are from the Reservoirs 1 and 5. Reservoir 1 has compositional data for a depth interval of 327 m. Reservoir 5 is interesting because its saturation point gradient is much higher than in the four other reservoirs. Reservoir 1 can, as is seen from Figure 1, be reasonably well be described using gravity segregation alone, while that would give a totally misleading picture for Reservoir 5. The C7+ densities of the fluids in the oil zone in Reservoir 1 are of the order of 0.85 g/cm³, which suggests a fluid dominated by paraffinic components. The C7+ densities of the fluids in the oil zone in Reservoir 5 are all above 0.9 g/cm³ and increase with depth signaling a high concentration of aromatic components increasing with depth. This is confirmed by a high content of asphaltenes (see Table 5), which component class is dominated by condensed aromatic rings (having two or more rings in the same aromatic molecular structure).

Table 8 consistently shows a high ideal gas enthalpy of some of the components with a molecular weight above 150. The number of condensed aromatics with a molecular weight below 150 is close to zero, while condensed aromatics may occur for higher molecular weights. The high ideal gas enthalpy seen for molecular weights above 400 for Reservoir 5 suggests a high concentration of high molecular weight condensed aromatics in that fluid. This is consistent with the high asphaltene content. For the other four fluids the ideal gas enthalpy of the highest molecular weight components is lower than for the molecular weight interval 150-400. Figure 4 shows the specific enthalpies of the hydrocarbon components versus molecular weight for Reservoirs 1 and 5. The difference is quite dramatic.

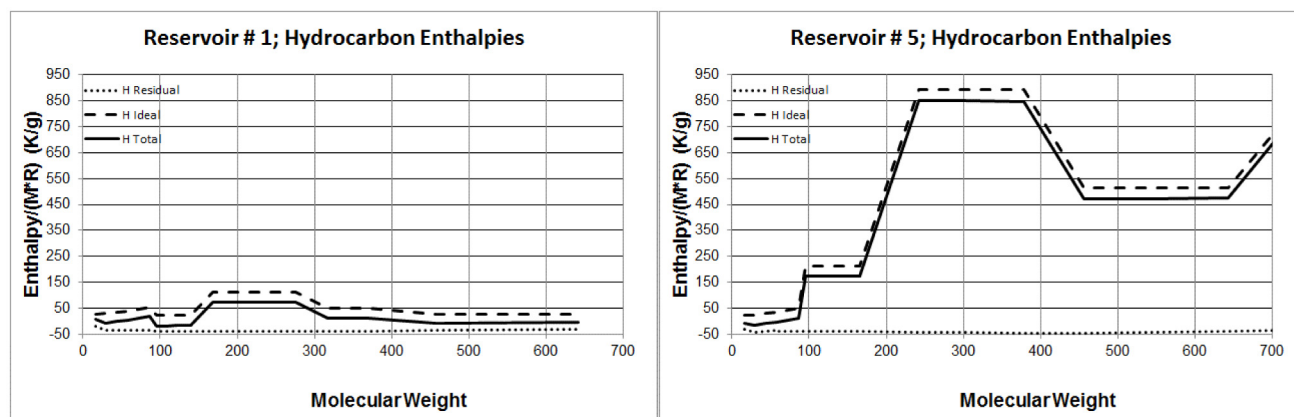


Figure 4—Specific component enthalpies versus molecular weight for Reservoir 1 and Reservoir 2.

This work suggests that the compositional grading in a reservoir is much dependent of the chemical composition of the fluid. The C7+ fraction consists of paraffinic (P), naphthenic (N) and aromatic (A) components and these component classes are seen to have absolute ideal gas enthalpies deviating by orders of magnitude. The deviation is comparable to the deviation seen between the heats of formation for the same component classes ([Journal of Physical and Chemical Reference Data, 1982](#)). A more refined simulation of the compositional grading would require a PNA analysis to high carbon number enabling each component class to have its own relation between ideal gas specific enthalpy and molecular weight.

Conclusions

Compositional data has been presented for fluids sampled in various depths in five different North Sea reservoirs. In all five reservoirs a higher compositional variation with depth is seen than can be explained by gravity segregation alone. One reservoir (#5) is rich in asphaltenes and shows a much higher compositional grading than is seen for the other four reservoirs.

The compositional variation with depth has been simulated using the Haase model. Neglecting gravity effects a component with a specific enthalpy above average will have a preference for a warmer region, while a component with a specific enthalpy below average will prefer a colder region. Key parameters in the Haase model are the absolute ideal gas specific enthalpy and the partial molar residual enthalpy of each fluid component. The latter has been simulated using the volume corrected PR equation while the absolute ideal gas enthalpies have been estimated from the field data. The data consistently suggests that some of the C7+ components with a molecular weight between 150 and 450 have specific enthalpies considerably above average. This has the effect that a positive vertical temperature gradient will make the compositional variation increase with depth as compared to the variation originating from gravity segregation alone. The more aromatic the fluid, the higher the ideal gas specific enthalpies of the C7+ components resulting in an increased impact of a temperature gradient. The highest compositional variation with depth is seen for a fluid with a considerable content of asphaltenes.

NOMENCLATURE

C_p	Heat capacity
C_1 - C_4	Constants in polynomial for ideal gas heat capacity
EoS	Equation of state
f	Fugacity
g	Gravitational acceleration
H	Enthalpy
$C_{p_i}^{id}$	Partial molar enthalpy
h	Height
M	Molecular weight
P	Pressure
PNA	Paraffinic, naphthenic and aromatic.
R	Gas constant
Specific enthalpy	Enthalpy per mass unit
T	Temperature
z	Component mole fraction

Greek letters

μ	Chemical potential
φ	Fugacity coefficient

Sub and superscripts

i	Component index
ig	Ideal gas
o	Reference
Ref	Reference

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