SPE 28000

Compostional Gradients in Petroleum Reservoirs

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Compositional Gradients

When & Why Are They Important?

- ☞ **Determining Original Hydrocarbons (IOIP/IGIP)**
  Needs to be done a component basis
- ☞ **Sampling Procedures and Test Interval Selection**
- ☞ **Reservoir Development Strategy**
  Producer/Injector Well Placement

Compositional Gradients

When & Why Are They Important?

☞ **Design of Miscibility Criteria for Gas Injection**

☞ **Design of Process Facilities**

☞ **Choice of Reservoir Simulation Model**

Literature Review

1800s	☞ **Gibbs**	***Fundamental Theory***
1930	☞ **Muskat**	***Theory/Simple Examples***
1938	☞ **Sage and Lacey**	***Theory/Simple Examples***
1980s	☞ **Schulte**	***Theory/Case History***
	☞ **Holt et al.**	***Thermal/Gravity Theory***
	☞ **Hirschberg**	***Asphaltenes/Tar Mat***
	☞ **Riemens et al.**	***Oman Case History***
	☞ **Montel and Gouel**	***Algorithm/Analysis***
	☞ **Metcalfe et al.**	***Anschutz Case History***
	☞ **Creek and Schrader**	***Overthrust Case History***
	... others	***Case Histories***
1990s	☞ **Belery and da Silva**	***Thermal/Gravity Theory & Application***
	☞ **Wheaton**	***Gravity/Capillary***
	☞ **Montel**	***Theory/Examples***
	☞ **Bedrikovetsky (Pavel)**	***Theory/Simple Examples***
	☞ **Faissat et al.**	***Thermal/Gravity Theory***

Compositional Gradients

Where Are They Found?

- ☞ **Thick Oil/Gas Reservoirs**
- ☞ **Oil/Gas Reservoirs with Significant Structual Relief**
- ☞ **Volatile and Near-Critial Oil/Gas Reservoirs**
- ☞ **Saturated or Slightly Undersaturated Reservoirs**
- ☞ ***All Over The Place!***

Isothermal
Gravity/Chemical Equilibrium (GCE)

$$\mu_i(p^o,z^o,T) = \mu_i(p,z,T) + M_i\, g\, (h-h_o)$$

μ_i = chemical potential of i
g = acceleration due to gravity
M_i = molecular weight of i

☞ T = temperature (constant)
☞ h^o = reference depth
☞ p^o = pressure at reference depth h^o
☞ z^o = composition at reference depth h^o

☞ h = *any* depth
z = composition at depth h
p = pressure at depth h

GCE Solution Algorithm

Equilibrium/Constraint Conditions

$(\mu_i = RT\,ln f_i + \lambda_i)$

$$f_i(h) = f_i(h^o)\ \exp[-\frac{M_i g(h - h^o)}{RT}],\ i = 1,2 \ldots N$$

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

GCE Solution Algorithm

Solution Function

$$Q(p,z) = 1 - \sum_{i=1}^{N} Y_i$$

$$Y_i = z_i \left[\frac{f_i(p^o, z^o)}{f_i(p,z)}\right] \exp\left[-\frac{M_i g(h - h^o)}{RT}\right]$$

☞ **Accelerated Successive Substitution for *z(h)***

☞ **Newton-Raphson for *p(h)***

Example Applications

☞ ***BO***	**Black Oil / Very Lean Gas**
☞ ***SVO***	**Slightly Volatile Oil / Lean Gas Condensate**
☞ ***VO***	**Volatile Oil / Rich Gas Condensate**
☞ ***NCO***	**Near Critical Oil / Near Critical Gas**

Phenomena Studied

- ☞ Degree of Undersaturation
- ☞ Heptanes-Plus Split
- ☞ Volume Translation
- ☞ "Passive" Thermal Gradient
- ☞ Thermal Diffusion
- ☞ EOS Fluid Characterization

Developing an EOS Fluid Characterization

- ☞ Use *ALL* Reservoir-Representative Samples & PVT Data
- ☞ Develop a *Single* EOS Fluid Characterization with Consistent Treatment of C_{7+}
- ☞ Tune EOS to Match *ALL* Reliable/Quality PVT Data *Simultaneously* (particularly compositional data)

Thermal Diffusion Effects

- ☞ Formal Thermodynamic Treatment of Thermal Diffusion is Lacking

  Several Zero Net-Mass-Flux Solutions are Available - Which to Use?

- ☞ Thermal Diffusion Can Enhance, Reverse, or Balance (Methane) Compositional Gradients Caused by Gravity/Chemical Equilibrium

Thermal Diffusion Effects

(continued)

- ☞ **Convection may Result from Thermally-Induced *Downward* Movement of Methane (**$k_{T\,C_1} < 0$**)**

$$\boxed{\frac{dz_i}{dh} = -\,k_{Ti}\,\frac{d\ln T}{dh}}$$

- ☞ **Convection Problem Can No Longer be Solved in One Dimension; *Very Complicated***

Key Conclusions

1. Expected Saturation Pressure Gradients Range from 0.025 bar/m to 1.0 bar/m (0.1 to 4.5 psi/ft)

2. Dewpoint and Bubblepoint Gradients are Approximately Symmetric in Saturated Systems

3. Compositional Gradients Decrease at Increasing Degrees of Undersaturation

4. An Efficient Algorithm is Given for Solving the Gravity/Chemical Equilibrium Problem.

Key Conclusions

(continued)

5. Special EOS Characterization Techniques are Required to Properly Characterize Reservoirs with Significant Compositional Gradients

6. Thermal Gradients May Enhance, Reduce, or Balance Gravity-Induced Compositional Gradients (particularly for Methane)

7. A Formal Thermodynamic Treatment of Thermal/Gravity/Chemical "Equilibrium" Does Not Presently Exist

MOLAR COMPOSITIONS & PHYSICAL PROPERTIES

Component/ Property	**Black Oil**	**Slightly Volatile Oil**	**Volatile Oil**	**Near Critical Oil**
N_2	0.262	0.270	0.930	0.550
CO_2	0.367	0.790	0.210	1.250
C_1	35.193	46.340	58.770	66.450
C_2	3.751	6.150	7.570	7.850
C_3	0.755	4.460	4.090	4.250
iC_4	0.978	0.870	0.910	0.900
C_4	0.313	2.270	2.090	2.150
iC_5	0.657	0.960	0.770	0.900
C_5	0.152	1.410	1.150	1.150
C_6	1.346	2.100	1.750	1.450
C_{7+}	56.226	34.380	21.760	13.100
M_{7+}	243	225	228	220
γ_{7+}	0.8910	0.8700	0.8559	0.8400

Reference Conditions

h^o (m)	1550	2635	3160	3049
T (^{o}C)	68	95	130	132
p^o (bara)	160	263	492	483/469
p_b (bara)	160	246	383	462
GOR (Sm^3/Sm^3)	62	156	299	560
γ_o (water=1)	0.887	0.860	0.825	0.827

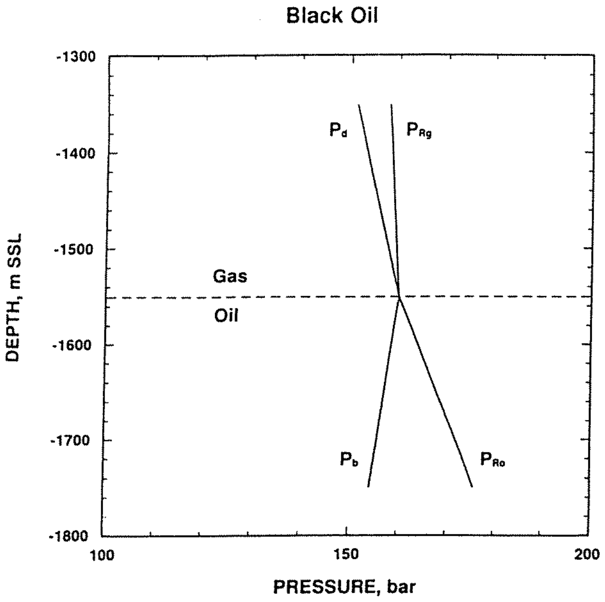

Fig. 1 Saturation pressure variation for Black Oil system using isothermal GCE.

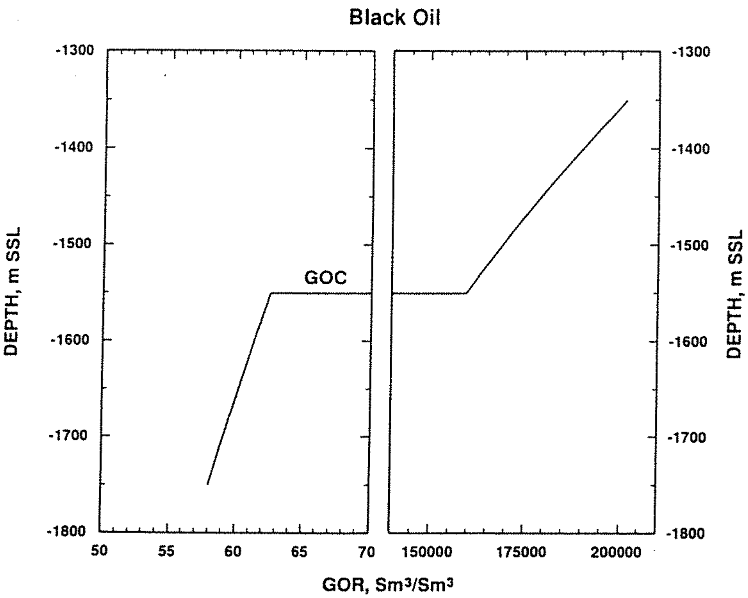

Fig. 2 Gas-oil ratio variation for Black Oil system using isothermal GCE.

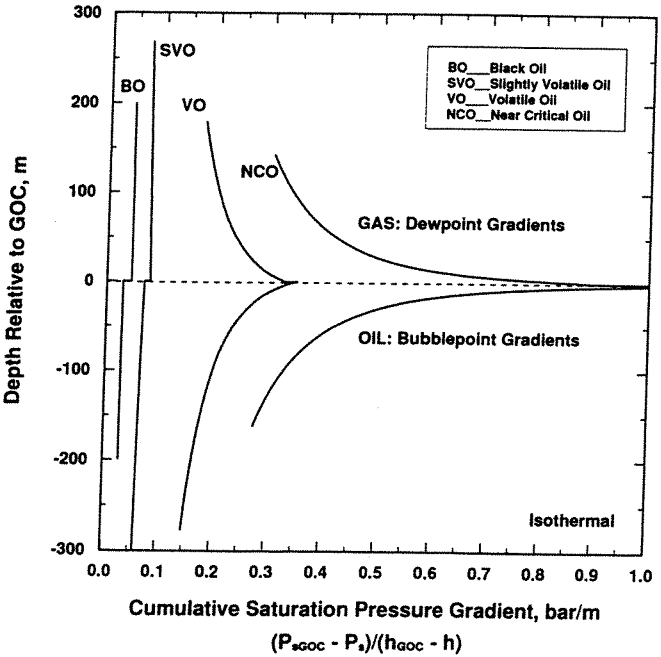

Fig. 3 Cumulative saturation pressure gradient versus depth relative to saturated GOC.

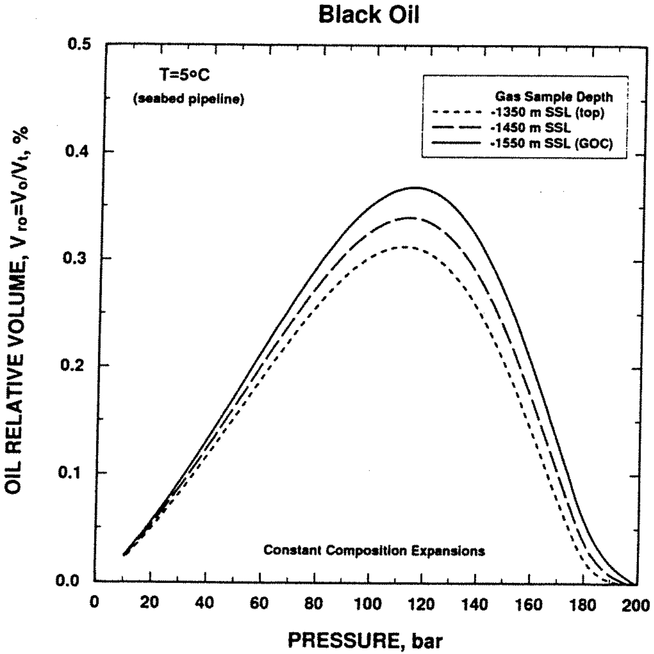

Fig. 4 Liquid dropout curves for reservoir gases at various depths for Black Oil system.

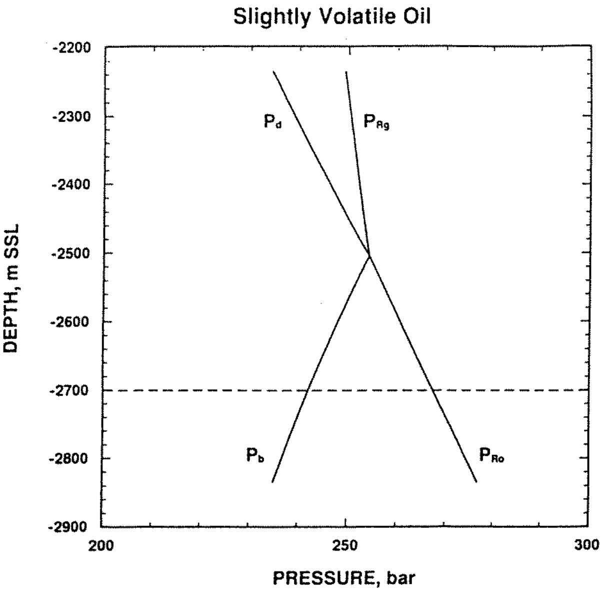

Fig. 5 Saturation pressure variation for Slightly Volatile Oil system using isothermal GCE.

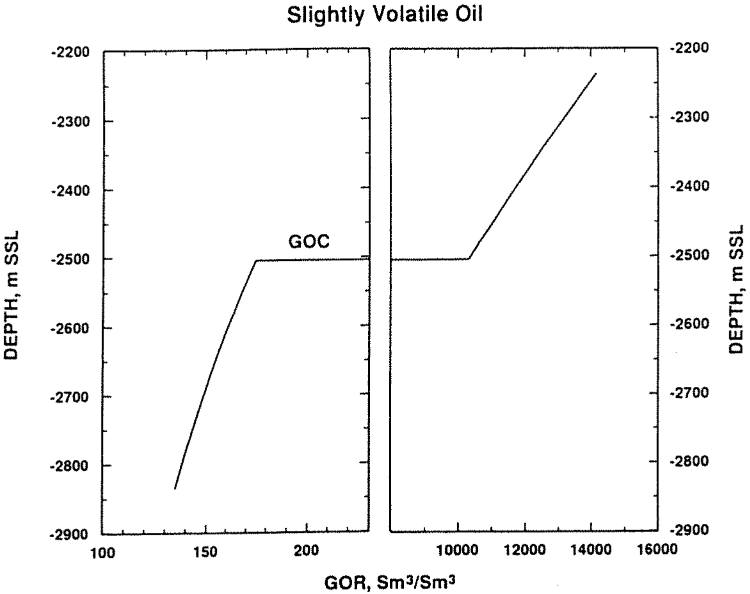

Fig. 6 Gas-oil ratio variation for Slightly Volatile Oil system using isothermal GCE.

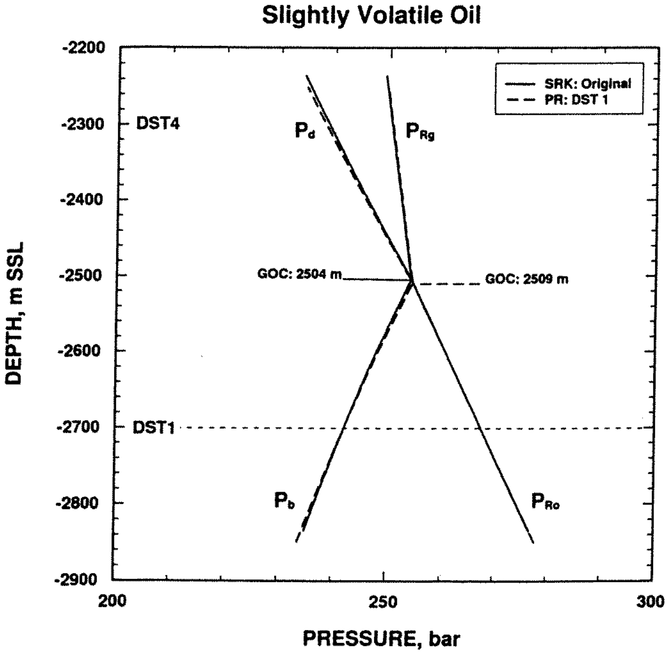

Fig. 7 Comparison of saturation pressure variation for original SVO fluid and the DST 1 sample.

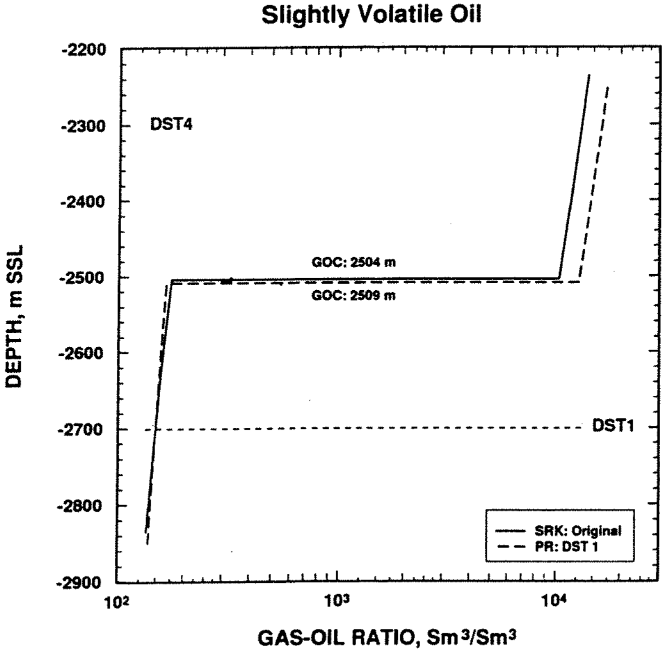

Fig. 8 Comparison of gas-oil ratio variation for original SVO fluid and the DST 1 sample.

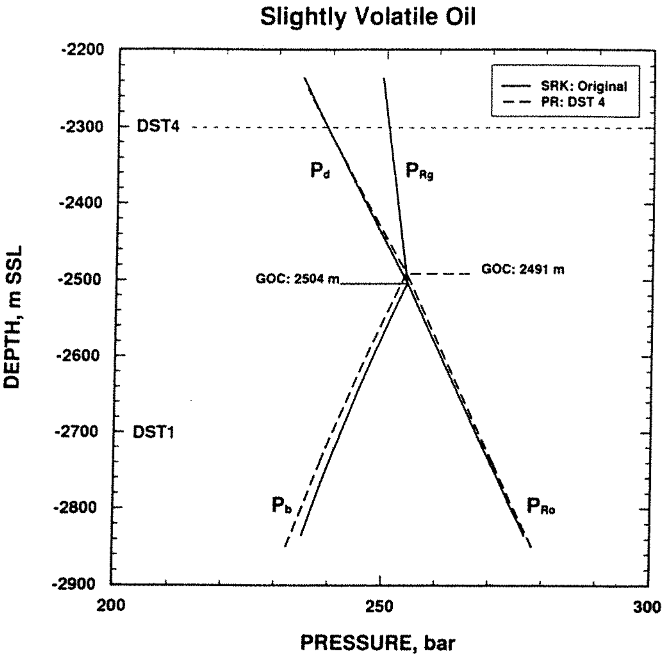

Fig. 9 Comparison of saturation pressure variation for original SVO fluid and the DST 4 sample.

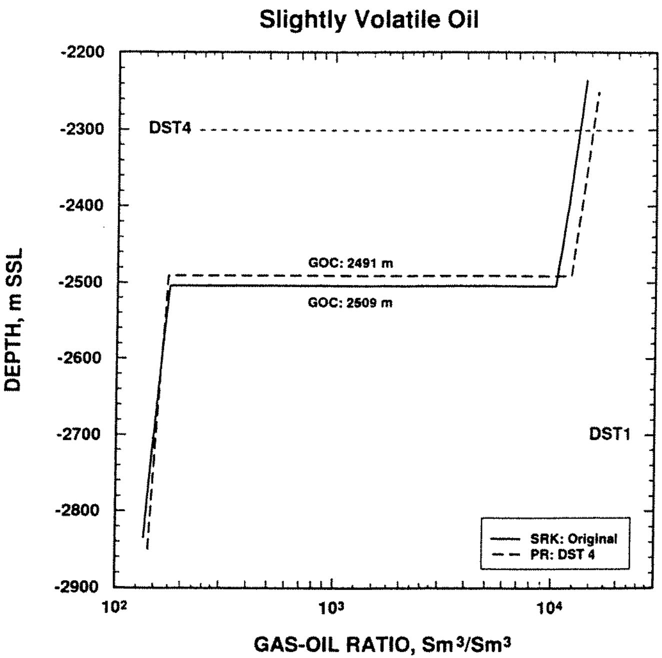

Fig. 10 Comparison of saturation pressure variation for original SVO fluid and the DST 4 sample.

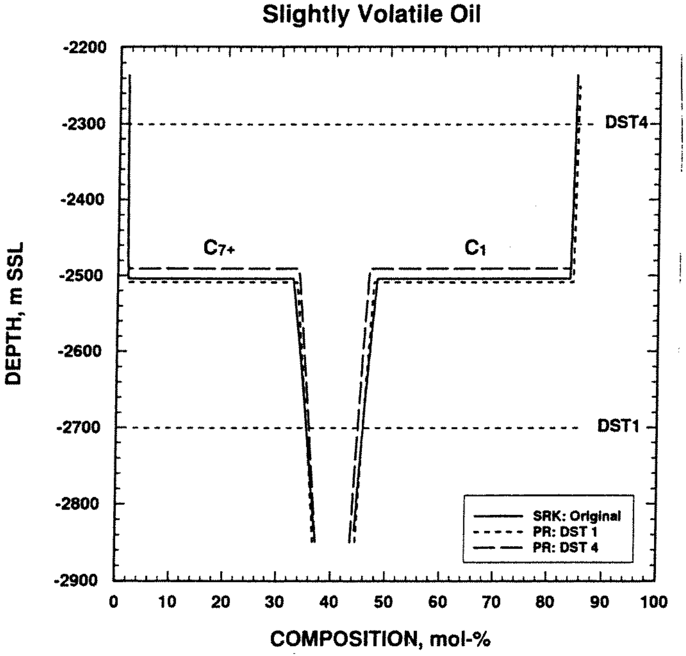

Fig. 11 Comparison of methane and C_{7+} compositional variation for original SVO fluid and the DST 1 & 4 samples.

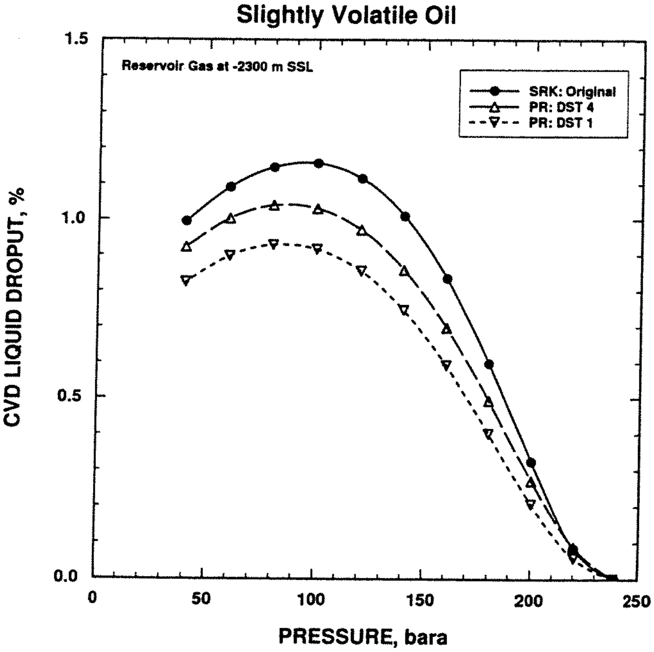

Fig. 12 Comparison of liquid dropout curves of reservoir gas at -2300 m for original SVO fluid and the DST 1 & 4 samples.

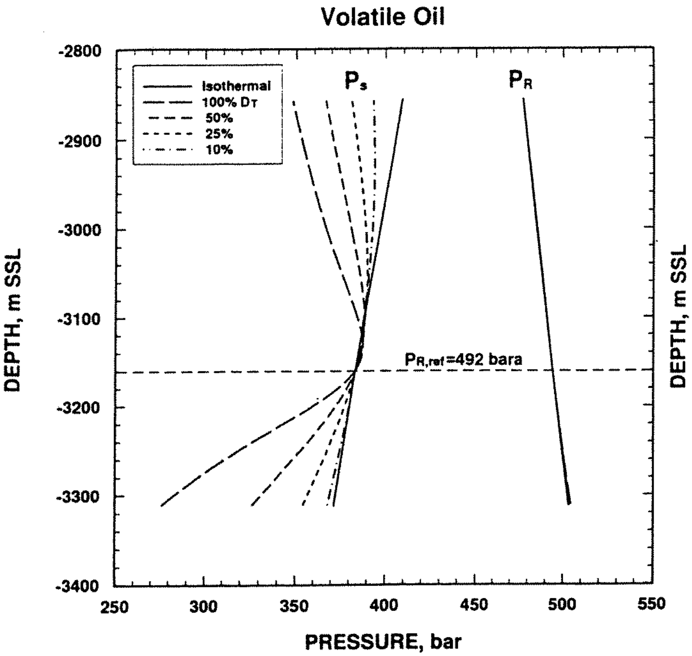

Fig. 13 Effect of thermal diffusion on saturation pressure variation for Volatile Oil system.

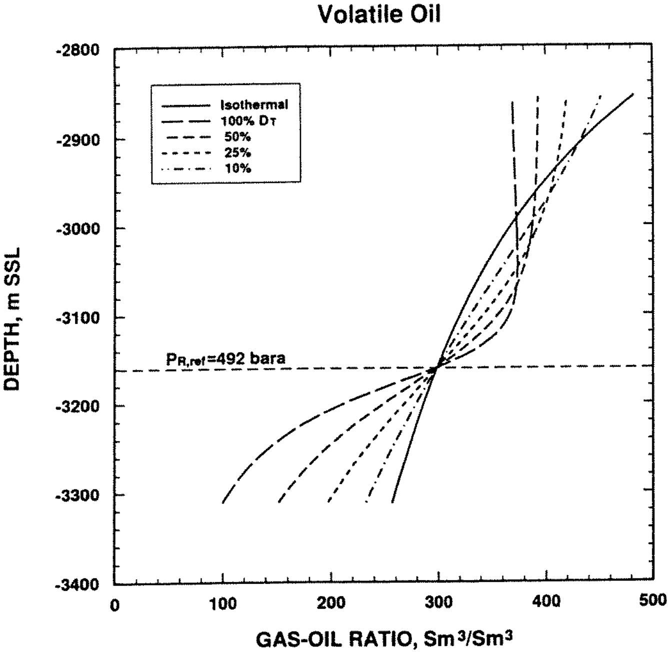

Fig. 14 Effect of thermal diffusion on gas-oil ratio variation for Volatile Oil system.

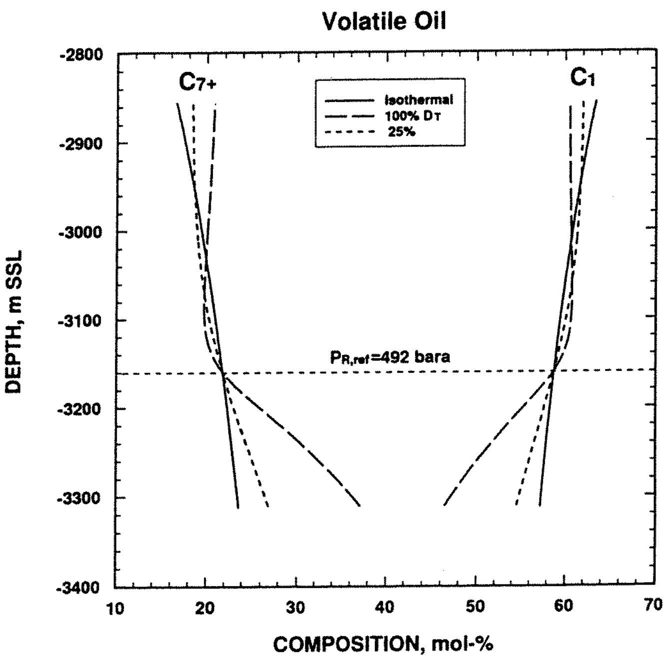

Fig. 15 Effect of thermal diffusion on methane and C_{7+} compositions for Volatile Oil system.

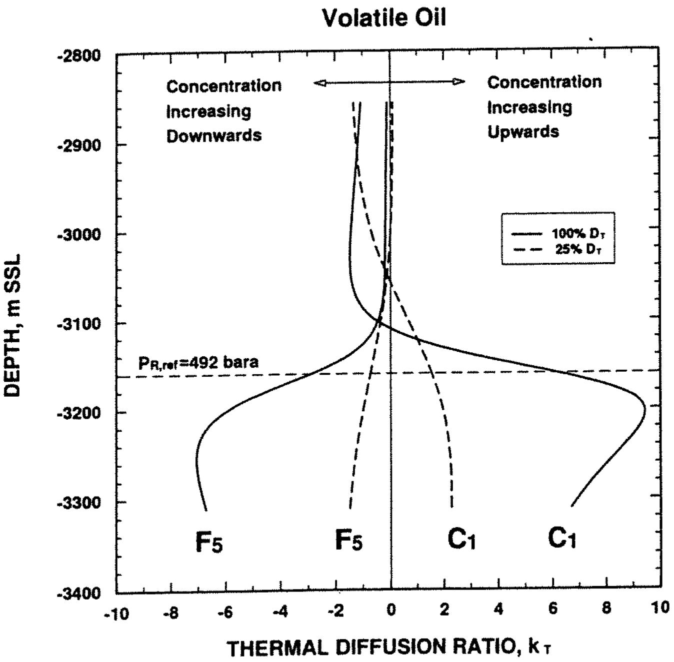

Fig. 16 Variation in thermal diffusion ratio for methane and heaviest C_{7+} fraction (F_5) for Volatile Oil system.

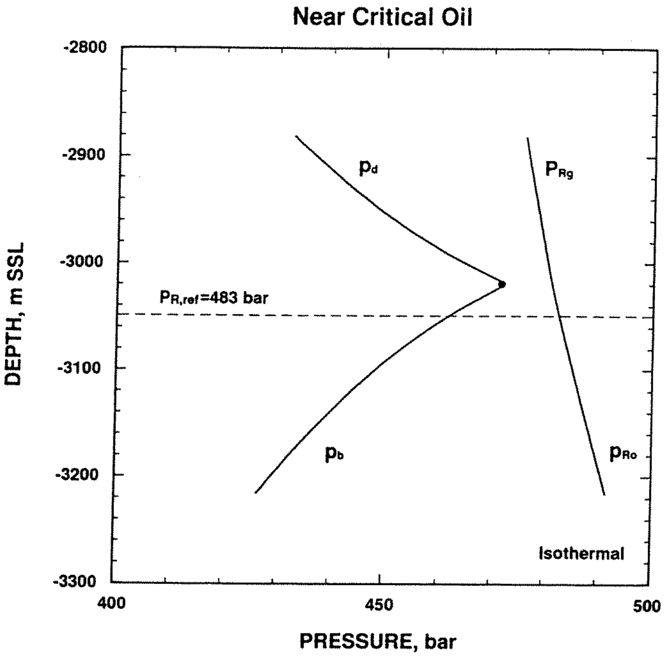

Fig. 17 Saturation pressure variation for Near Critical Oil system using isothermal GCE; slightly undersaturated GOC.

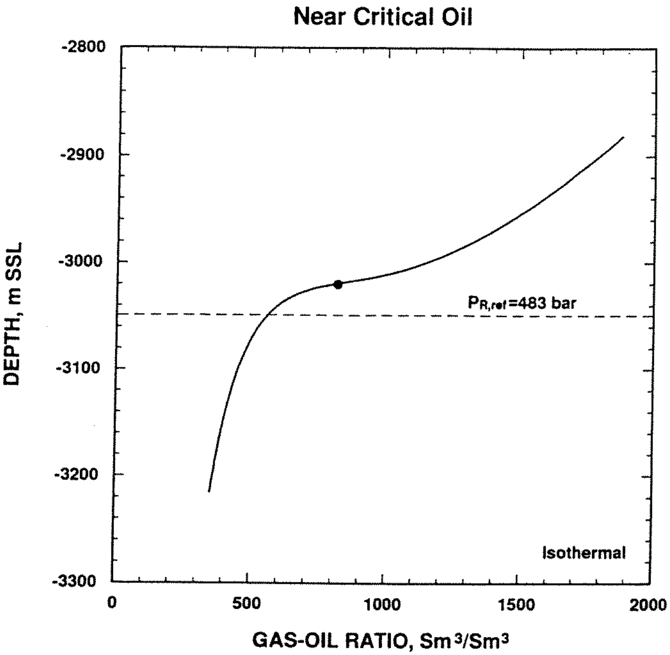

Fig. 18 Gas-oil ratio variation for Near Critical Oil system using isothermal GCE; slightly undersaturated GOC.

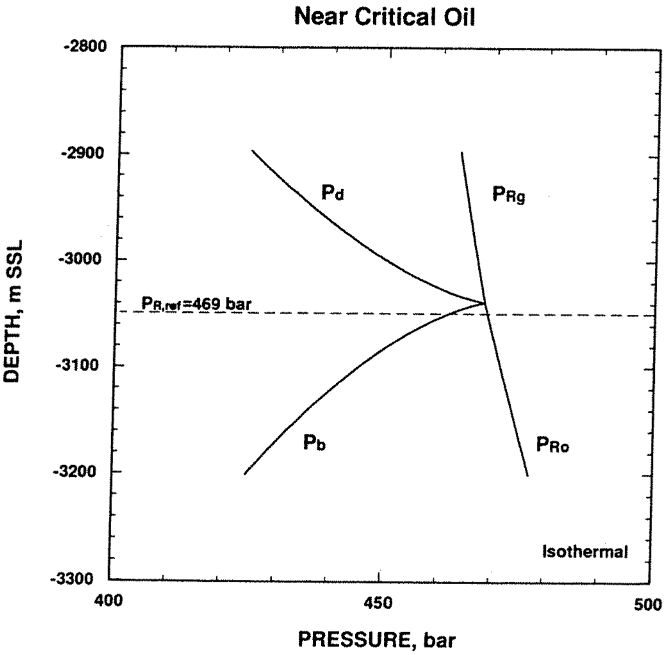

Fig. 19 Saturation pressure variation for Near Critical Oil system using isothermal GCE; saturated GOC.

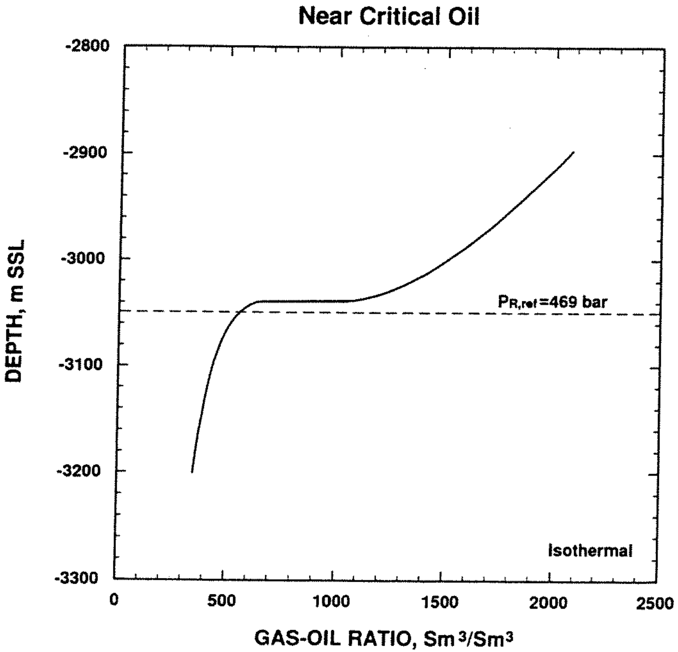

Fig. 20 Gas-oil ratio variation for Near Critical Oil system using isothermal GCE; saturated GOC.

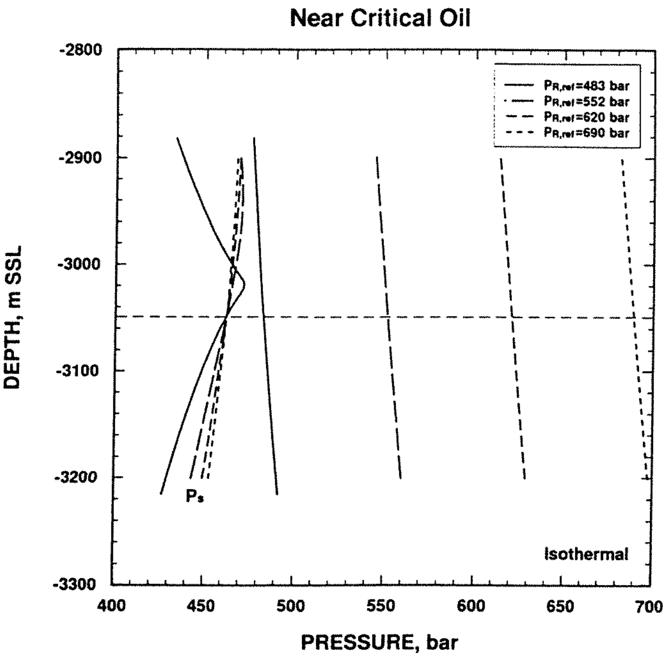

Fig. 21 Effect of degree of undersaturation on saturation pressure gradient for Near Critical Oil system using isothermal GCE.

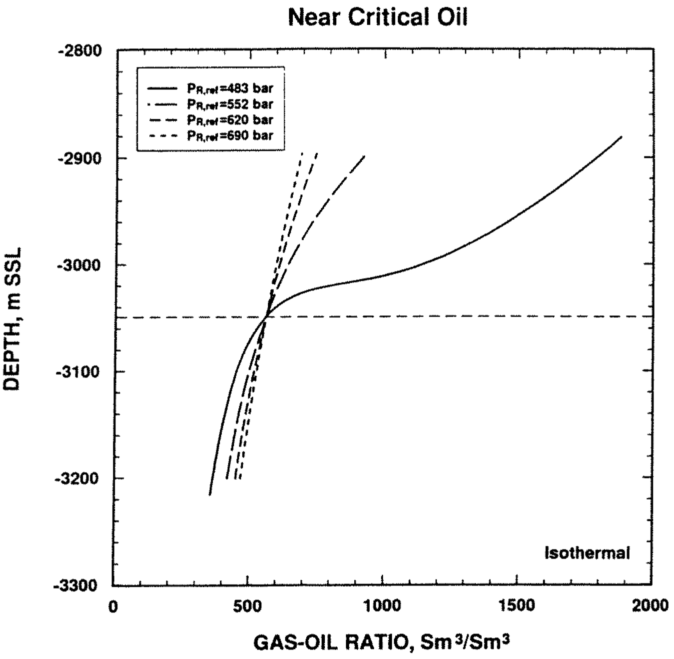

Fig. 22 Effect of degree of undersaturation on gas-oil ratio gradient for Near Critical Oil system using isothermal GCE.

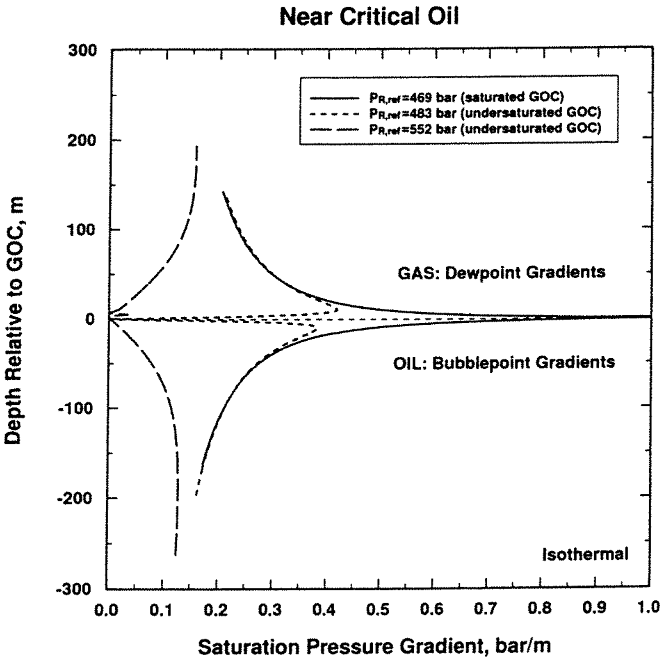

Fig. 23 Saturation pressure gradient versus depth relative to GOC for Near Critical Oil system at varying degrees of undersaturation.

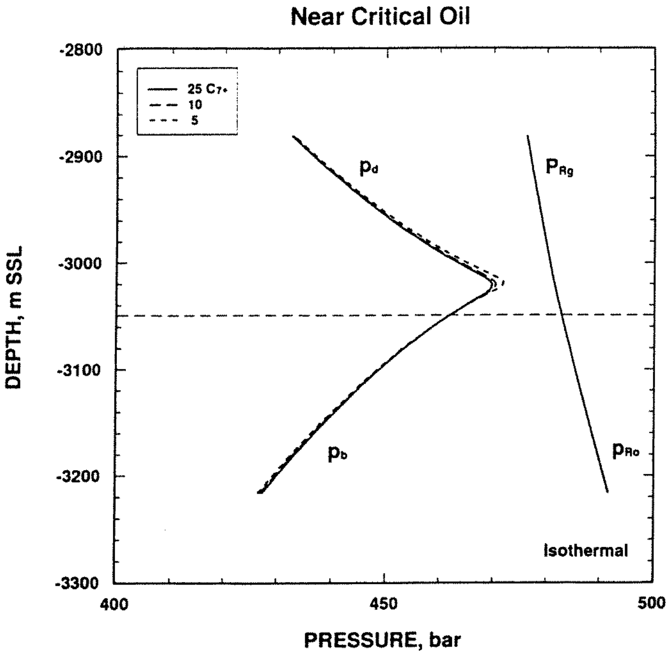

Fig. 24 Effect of number of C_{7+} fractions on the saturation pressure variation for NCO system using isothermal GCE; slightly undersaturated GOC.

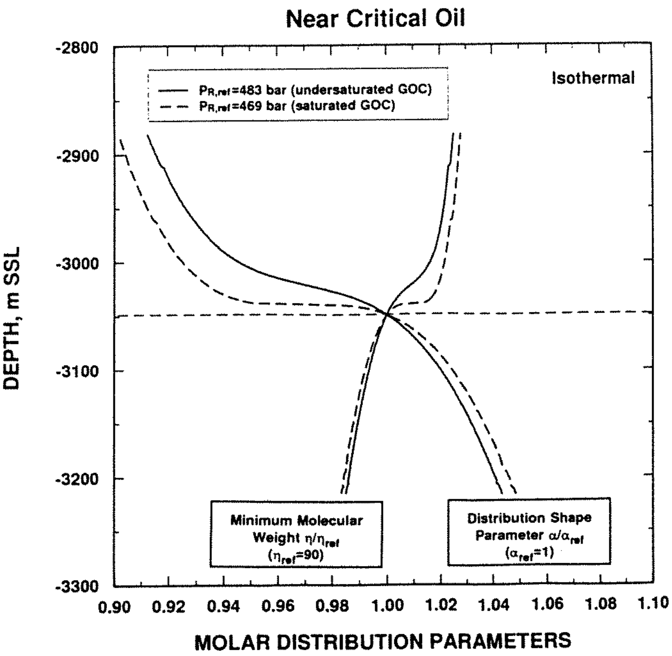

Fig. 25 Variation of molar distribution parameters for NCO system using isothermal GCE; slightly undersaturated GOC.

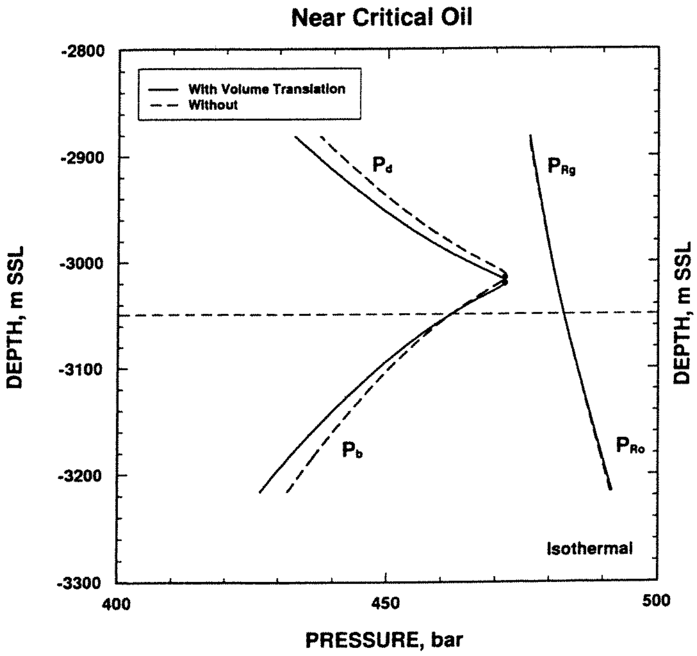

Fig. 26 Effect of volume translation on the saturation pressure variation for NCO system using isothermal GCE; slightly undersaturated GOC.

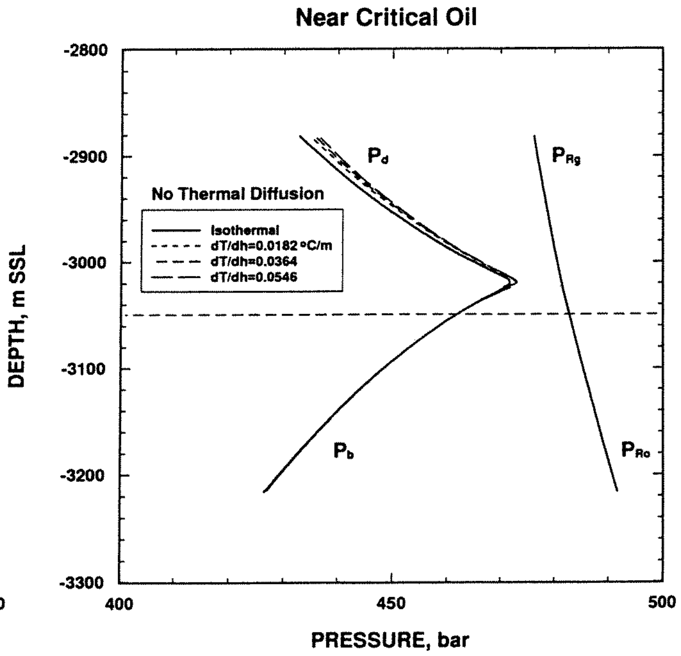

Fig. 27 Effect of passive thermal gradient on the saturation pressure variation for NCO system using isothermal GCE; slightly undersaturated GOC.

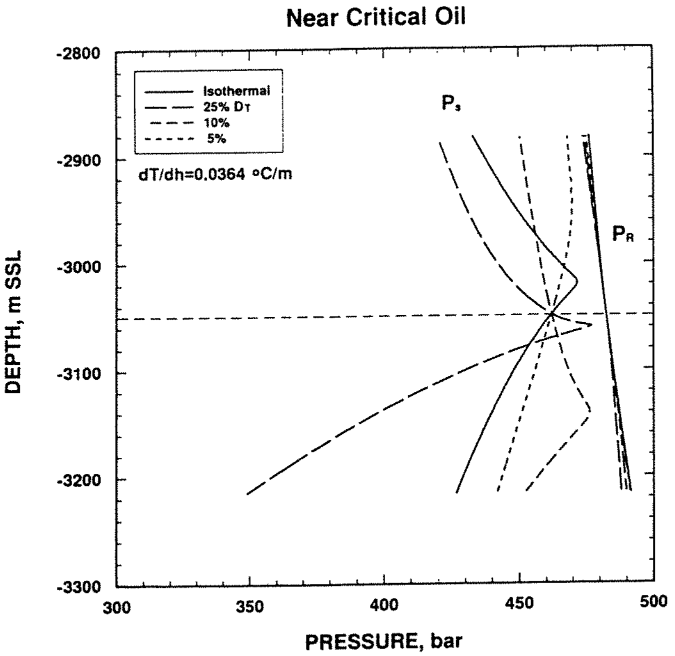

Fig. 28 Effect of thermal diffusion on saturation pressure variation for NCO system; slightly undersaturated GOC.

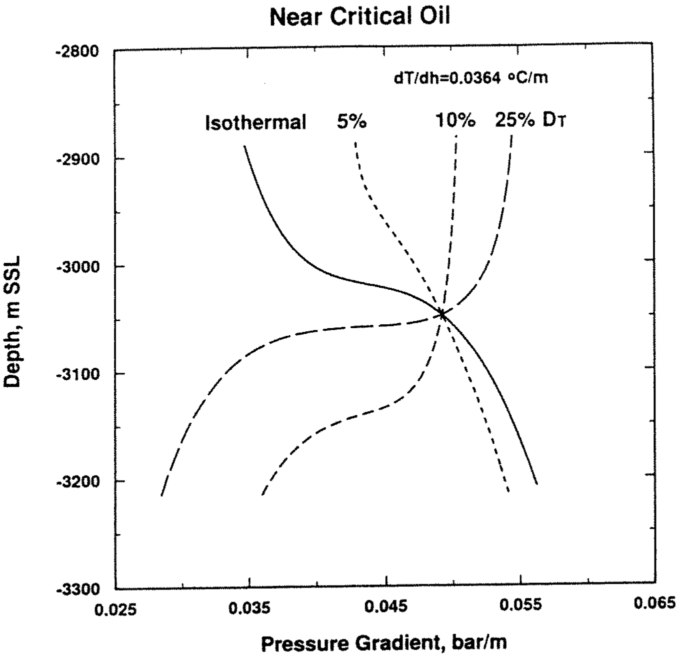

Fig. 29 Variation in pressure gradient (density) for different degrees of thermal diffusion for NCO system.

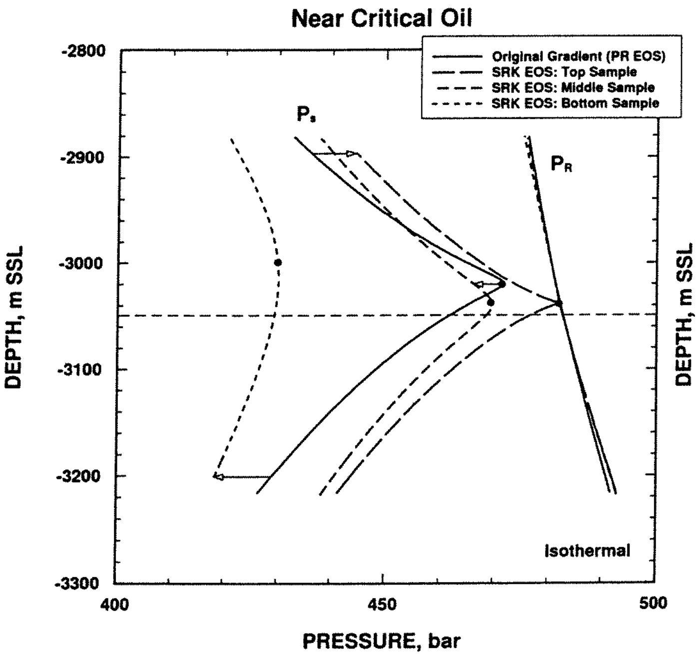

Fig. 30 Saturation pressure variation for original NCO system and for samples taken at different depths.

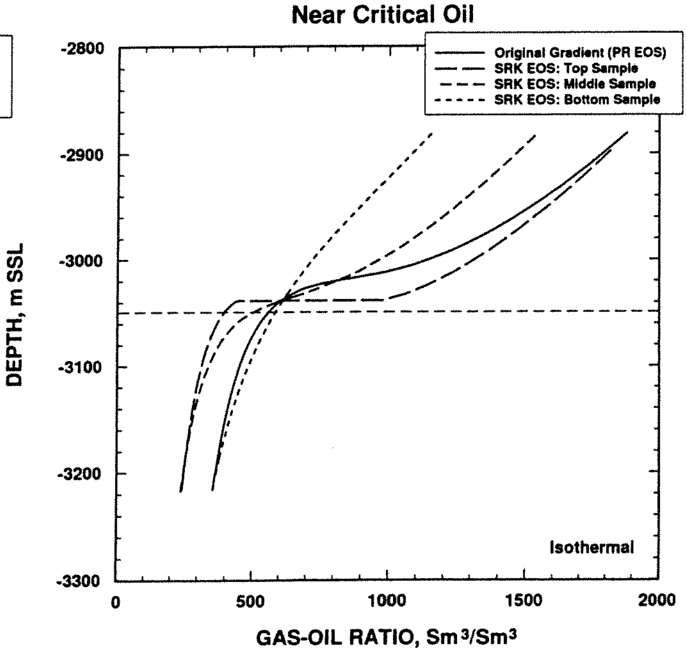

Fig. 31 Gas-oil ratio variation for original NCO system and for samples taken at different depths.