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Hybrid gas condensates and the evolution of their volatile light hydrocarbons

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ABSTRACT

In a large database of broad provenance, the majority of oil reservoir fluids exhibit maturity levels in the C_3-n-C_5 complements which are discordant with, and greater than, those of the liquid components. The phenomenon is attributed to gas enrichment which can lead to in situ gasification accompanied by oil displacement. Thus, many gas condensates are evidently generated by enhanced gas advection from source regions. Such gas condensate mixtures, comprising gases of elevated maturity and residues of oils of various maturities, are termed here "hybrid" gas condensates, a subset of which are gas condensates due to evaporative fractionation. Thermal gas condensates are defined as those exhibiting equal, elevated, maturity levels in both the volatile light hydrocarbon (VLH) and liquid fractions. An indication of the thermal history of the VLH suite based on the propane, n-butane and n-pentane complements of oils and gas condensates is provided by the Slope Factor, $SF(C_3-n-C_5)$. The latter is a linear variable derived from the slope of the exponential equation fitted to molar concentration versus carbon number data in reservoir fluid PVT analyses. $SF(C_3-n-C_5)$ is justified as a maturity index by its relationship to elevated reservoir temperatures, carbon isotopic data, and by pyrolysis. All gas fractions in the evaluated gas condensates are over-mature, products of cracking at temperatures > 150 °C. Gas condensates are classified on the basis of values of mole percent methane and $SF(C_3-n-C_5)$ which characterize modifications accompanying increasing (catagenetic) or decreasing (migrational) dew point pressures. Relationships between gas/liquid ratio and dew point are presented, differing greatly between gas-condensates reflecting pressurization (maturation in a source region) and those reflecting depressurization (migration-depletion).

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1. Introduction

Processes leading to the vaporization of oil range from thermal transformation, to the distal effects of gas escape at elevated pressure from a source, to the addition of microbial methane. A classification scheme for gas condensates is developed, based upon compositional characteristics of intact or recombined reservoir fluids, specifically the concentration of methane and a function of inter-compound ratios in the range propane to n-pentane, the volatile light hydrocarbon (VLH) fraction, as measured in intact reservoir fluids. The volatile light hydrocarbons, thus analyzed, are demonstrated to yield indices of maturity which show that the gas fractions of all gas condensates examined here are post-mature, generated in cracking regimes at temperatures > 150 °C and as high as 217 °C. In numerous demonstrable instances the VLH fraction is allochthonous in relation to accompanying C_{6+} components which reflect substantially lower maturities. Large

numbers of gas condensates reflect complete vaporization and displacement of oil, processes described for Nisku Formation gas reservoirs in central Alberta, Canada, by Anderson and Machel (1989) and alluded to by Gussow (1954) for Leduc Formation gas-capped oils in Alberta.

In evaporative gas condensates (Thompson 1987, 1988) partial vaporization of an oil accumulation in migrant gas occurs. Members of both groups are named "hybrid" gas condensates. The difference relates to the propensity of reservoirs to leak gas, either through the cap or along fractures, or to retain gas. Gas condensates should be deemed thermal in nature if it can be shown that both VLH and liquid fractions are of equal, highly elevated, maturity. Conventional PVT data alone, as employed in the present study, seldom yield reliable evidence of the maturity of the liquid fraction of gas condensates because of alteration by liquid drop-out during subsurface migration.

Certain suites of gas condensates which reflect complete vaporization of oil exhibit a series of increasing dew point pressures attributable to the progressive, advective addition of methane and VLH fractions. Dew point at a given temperature represents

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not only the pressure at which liquid loss commences upon depressurization, but the confining pressure required to retain sufficient migrating gas to solvate a specific liquid. As long as reservoir pressure remains greater than the increasing dew point, progressive dissolution of liquid in gas continues. This may be partial or complete. Such suites exhibit a characteristic series of compositional changes accompanying pressurization.

It is also shown that confining pressure, if lower than original dew point, strongly influences gas condensate composition. Groups of gas condensates representing certain distinguishable geographic and stratigraphic entities exhibit a series of decreasing dew point pressures due to upward migration and depressurization. The two groups, pressurizing and depressurizing suites, differ radically in their systematic gas/liquid ratio versus dew point characteristics. The first group is, in part, parent to the second.

2. Databases

The study draws upon databases comprising 698 oil and gas condensate PVT analyses of reservoir fluids carried out through P7+ (a pseudo-component comprising all compounds beyond n-C_7) representing 527 oils and 171 gas condensates. Geographically, the data principally include the Western Canada Sedimentary Basin, with lesser contributions from Indonesia, Columbia, the Norwegian North Sea, the U.S. Gulf Coast shelf and deep water regions, the Jurassic Smackover Formation of southern Alabama and the gases of the Norphlet Formation, offshore Alabama (data of Mankiewicz et al., 2009). Both Type II and IIS kerogen sources are represented. Table 1 provides analytical and engineering PVT data representative of the groups and singular occurrences of the gas condensates evaluated here, and a number of closely associated oils. Analyses represent bottom hole or recombined fluids. Gas/liquid ratios represent production or separator test values.

Detailed analyses of C_1 through P30+ were available for 195 oils and 47 gas condensates in the above suites facilitating the determination of Slope Factors (SFs) in the volatile light hydrocarbon range, SF(C_3–n-C_5), and in the liquid range, SF(P10+). A Slope Factor expresses rate of concentration change with carbon number, i.e., the inter-component ratio in an exponential series. Three such series are illustrated in Fig. 1, evident in all petroleums barring significant alteration or the presence of waxes. Thompson (2006) described the occurrence of two exponential series of concentrations among the VLH of oils and gas condensates. One involves the compounds propane, n-butane and n-pentane, whence SF(C_3–n-C_5), employed here as a maturity index. An additional, covariant series comprises ethane, propane, pseudo-butane and pseudo-pentane where the pseudo-components comprise the sums of normal and branched alkanes. Minor compositional irregularities, departures from the pure exponential, occur in sequences of the latter type, employed here to reveal gas condensate evolutionary histories.

A major exponential series was discovered by Lohrenz and Bray (1963) representing the liquid pseudo-components commencing at P6, each comprising, to a satisfactory approximation, the suite of all compounds of a given carbon number. In unaltered oils P6 presents a secondary concentration maximum after methane due to a discontinuity such that P6 exceeds P5, as shown in Fig. 1. The configuration can be reproduced exactly by the pyrolysis of petroleum asphaltenes (Thompson, 2002). Fig. 1 represents a near-perfect oil having constant inter-component concentration ratios, lighter divided by heavier adjacent component, plotting as straight lines on log-linear axes. The slopes of all three series are covariant and provide indices of maturity. Three Slope Factors, SF(C_3–n-C_5), the related SF(C_2P5) and SF(P10+) as well as values of P5/P6 and C_1/C_2, suffice to define in detail the composition of an unaltered

oil. The ratio C_1/C_2 varies independently, being highly susceptible to modification. Values of C_1/C_2 in oils, in relation to gas–oil ratio and saturation pressure, were systematized in Thompson (2010).

Eq. (1) below is of the type fitted to a series of concentrations by carbon number to determine a Slope Factor. In a given reservoir fluid, concentrations of ethane, propane and the pseudo-components, y, in both VLH and liquid series, are expressed by such equations, where x is the carbon number of y, A is an intercept and e^{-a} is a number representing the slope of the series:

$$y = A(e^{-ax}) \tag{1}$$

Such equations define a series between chosen carbon number limits. The values of e^{-a} are decimal fractions, representing slope, that is, the value of a series of equal concentration ratios between adjacent pseudo-components in a decreasing series. The Slope Factor as derived here is given by the anti-natural-logarithm of e^a ("a" positive), a value greater than unity, the reciprocal of e^{-a}, perceived as representing a series of increasing concentrations from C_{30+} to C_1 in view of their mode of origin, the conversion of heavier to lighter molecules.

3. Slope Factors as indices of maturity

3.1. Liquid fraction of oils and gas condensates

The relative maturity of the liquid fraction of oils is indicated with high precision by the value of SF(P10+). This is illustrated by the data of Weissenburger and Borbas (2004) for Magnolia field, Garden Banks Block 783, deep water Gulf of Mexico, where the following relationship obtains:

$$\text{API Gravity} = 183.08 \times \text{SF(P10+)} - 170.87 \quad r = 0.99 \tag{2}$$

In other suites this relationship is broadened by oil alteration but remains relevant at lower levels of precision. The slope of the liquid fraction of gas condensates has limited applicability to maturity except at high pressures. SF(P10+) increases rapidly at dew point pressures < 27.6 MPa (Thompson, 2004) due to the precipitation of heavier liquid components upon depressurization (migration-depletion, England et al., 1987), as reviewed quantitatively in Section 8.

3.1.1. Maturity of VLH fraction of oils

In the pyrolysis of asphaltenes to increasing maturity levels, modeling oil evolution, increase in SF(C_3–n-C_5) is covariant with increase in slope in the liquid fraction, SF(P10+) (Thompson, 2002). Quantifying this dependence, Thompson (2010) developed the following relationship, Eq. (3), applicable to unaltered oils (inapplicable to gas condensates):

$$\text{SF}(C_3-n\text{-}C_5) = 2.786 \times \text{SF(P10+)} - 1.615 \tag{3}$$

Validation of Eq. (3) is provided in Fig. 2 which tests the equation against data representing all of the oils with a secondary maximum at P6 (n = 48 of 195), an assurance of the absence of, or only minor, alteration in the liquid fraction, but accommodating alteration in the VLH fraction. Fig. 2 illustrates the fact that the path of the line defined by Eq. (3) passes through the maximum density of plotted points, those with the lowest values of SF(C_3–n-C_5), observations considered to confirm the validity of the equation. Numerous P6 oils for which Eq. (3) is invalid are shown to exhibit elevated values of SF(C_3–n-C_5) compatible with enrichment by migratory lean gases. This is the usual condition among all oils (Thompson, 2004).

Additional evidence of the commonplace addition of VLH to oils is provided by the comparison of two histograms, Fig. 3a and b, frequency distributions of Slope Factors among liquid components, SF (P10+), and VLH components, SF(C_3–n-C_5) in western Canadian