Shale Fluid Inclusion Stratigraphy: Insights into Thermal Maturation and Reservoir Fluid Composition

Mark H. Tobey[1], David E. Schmude[1], Thomas M. Smagala[1], and Donald L. Hall[2]
[1]*Encana Oil & Gas (USA) Inc., 370 17th Street, Suite 1700, Denver, CO 80202*
[2]*Fluid Inclusion Technologies, Inc., 2217 N. Yellowood Avenue, Broken Arrow, OK 74012*

Validating gas shale thermal maturity assessments based on optical and pyrolytic data is prudent, particularly if the composition of the hydrocarbon fluids within the reservoir is being modeled, and the regional thermal maturity is believed to straddle the oil, wet-gas / condensate, and dry gas windows. In a frontier basin where data are sparse, we added mass spectroscopic evaluation of hydrocarbon fluid inclusions and fluid inclusion thermometry to glean additional information from the few well samples available, with the goal of understanding how potential fluid compositions may vary across the basin with maturity. A major question was: are there enough inclusions within the very fine-grained shale to render useful data? Our results suggest that there are for the shale studied, and the data are useful for validating maturation and hydrocarbon fluid models of the basin.

Mass spectrometry of hydrocarbon fluid inclusions yields a spectrum of mass-to-charge (m/z) fragments which are surrogates for specific hydrocarbon species. We found systematic changes in the fluid inclusion hydrocarbon gas compositions from well cuttings and core in a frontier basin that co-varied with the modeled maturity (*e.g.*, Figure 1). Moreover, those changes in fluid inclusion hydrocarbon gas composition were consistent with produced gas hydrocarbon compositions observed from Ft. Worth Basin wells whose maturities were similar to those modeled for the frontier basin (*e.g.*, Figure 2).

Assessment of the fluid inclusion fluorescence and thermometry data supported, in general, the maturation trends indicated by the mass spectrometry data, though there were some differences, probably related to the timing of inclusion formation. Hydrocarbon inclusions from rocks believed to be in the 1.5 – 1.7 %Ro range exhibited little to no fluorescence, as these were mainly gas-filled and not liquid-filled. Aqueous inclusion measurements from a core believed to be 1.7 %Ro yielded a maximum burial temperature of 180ºC, suggesting an Ro equivalent of 1.8 %Ro. However, cuttings believed to be 1.5 %Ro yielded a maximum aqueous T_h of 135ºC, suggesting a much lower maturation: 0.95 %Ro. Given their location in the basin, the more likely explanation is that these aqueous inclusions formed after maximum burial during uplift.

Core believed to be 1.3 %Ro exhibited a blue fluorescence suggesting an upper-moderate API gravity fluid. Hydrocarbon and co-existing aqueous inclusions suggest trapping temperatures up to 150ºC. The core and cuttings believed to be 1.2 %Ro yielded yellow- and white-fluorescing inclusions as the dominant population (earlier inclusions), with a second population of blue-fluorescing inclusions (later inclusions, Table 1). In one of these wells, the low HC T_h (mainly 65-80ºC) suggests that most inclusions pre-date maximum burial. The presence of inclusion populations that differ in timing is consistent with the mass spectra compositional overlaps observed for the rocks believed to be of lower maturity. In the other well modeled at 1.20 %Ro, the maximum measured T_h of 145ºC suggests a maturity of 1.1 %Ro.

Oil extracts from the rocks were less informative, probably due to alteration of the retained oil, though the maturation trend based on pristane / n-C_{17} and phytane / n-C_{18} ratios mirrors – in general -- that indicated by other maturation parameters. Likewise, the lowest maturity rocks had the highest relative levels of C_{30+} n-alkanes.

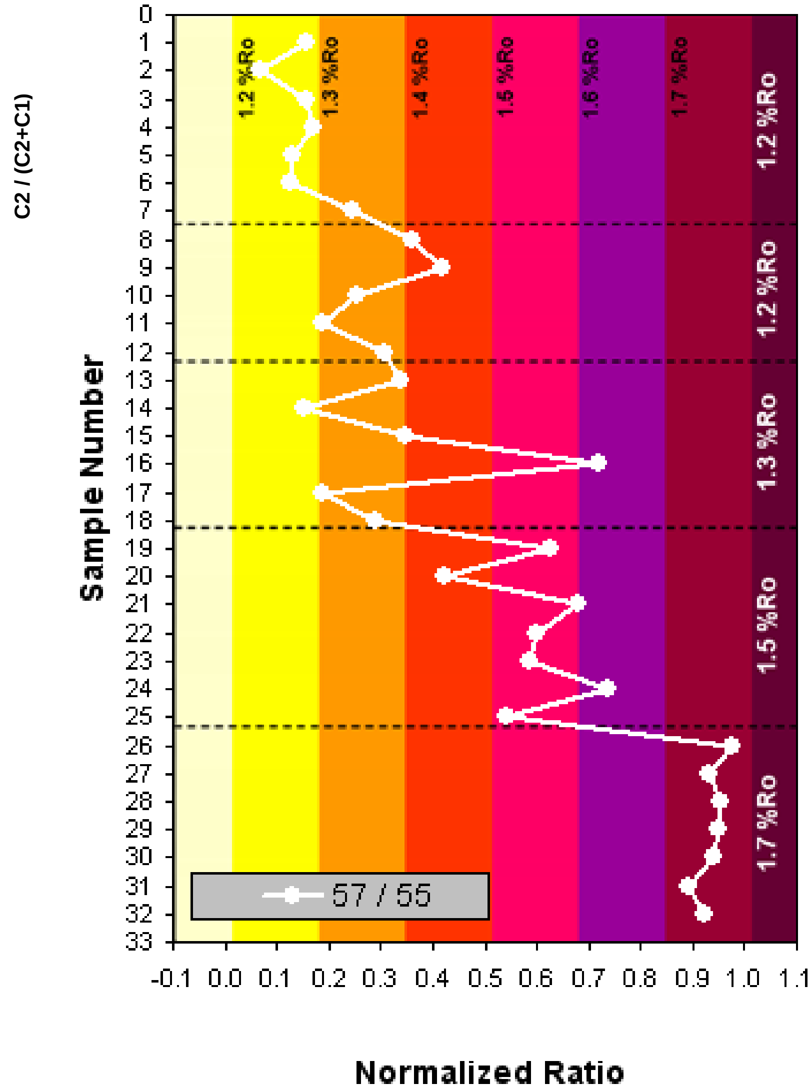

Figure 1: The ratio of the m/z 57 (paraffin surrogate) and m/z 55 (naphthene surrogate) for fluid inclusion gas increases with increasing thermal maturity.

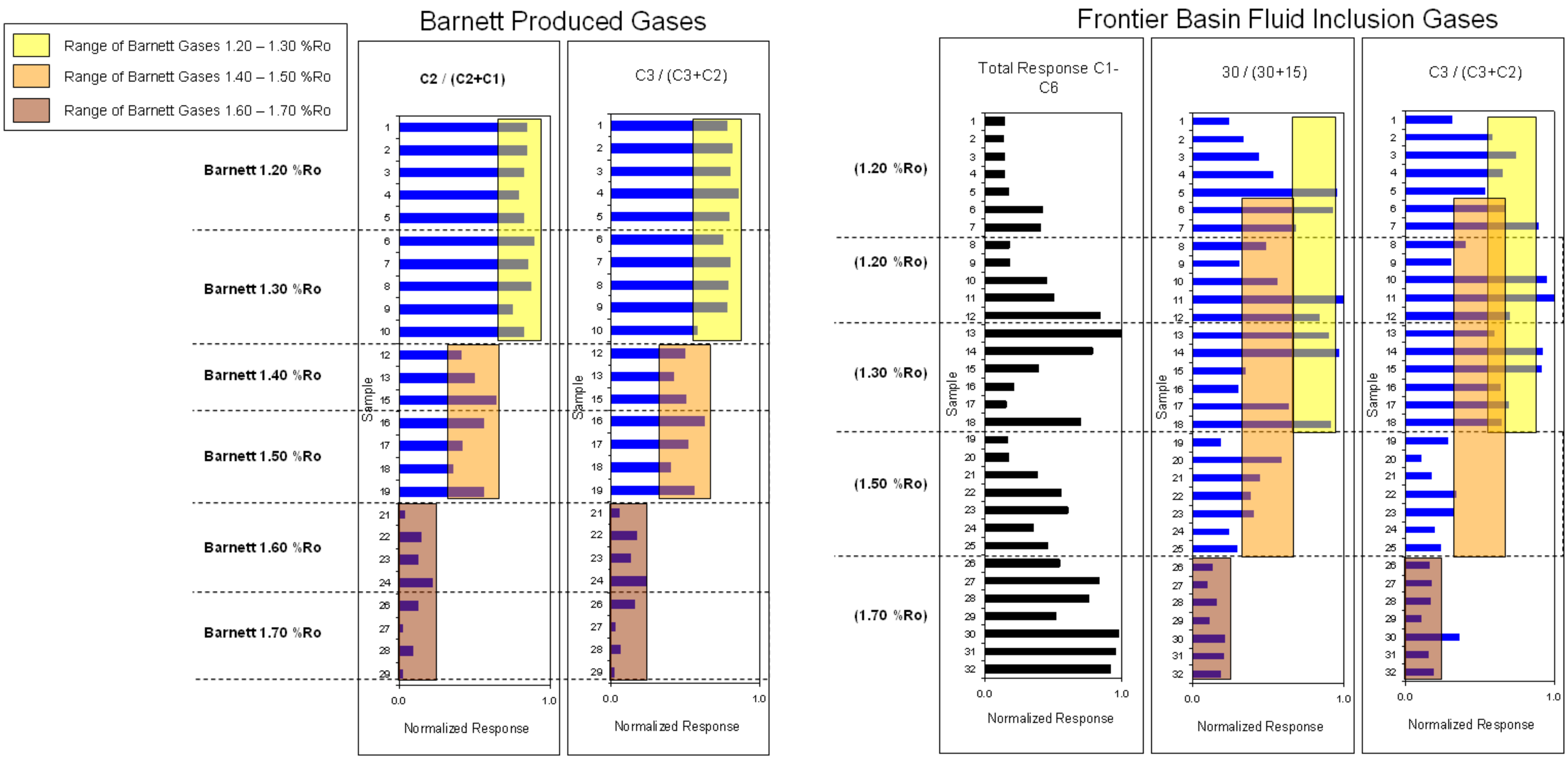

Figure 2: Ft. Worth Basin Barnett produced gas ratios vary with thermal maturity. The same ratios for fluid inclusions via mass spectrometry also vary in a similar manner with modeled thermal maturity.

Well Name:	Shale Samples (note that well name is abbreviated here)																			
Sample Depth	**Rock Type**	**Petroleum Fluid Inclusion Populations**												**Kerogen (possible source rk)**					**Bitu-men**	
		Population 1				**Population 2**				**Population 3**										
Units: (Feet)	*Dominant* / *Subordinate*	*Fluorescence Color*	*API Gravity (estimated)*	*Host Mineral & occurrence*	*Abundance*	*Fluorescence Color*	*API Gravity (estimated)*	*Host Mineral & occurrence*	*Abundance*	*Fluorescence Color*	*API Gravity (estimated)*	*Host Mineral & occurrence*	*Abundance*	*Host Rock*	*Type*	*OP Fluor Color*	*GP Abundance*	*OP Abundance*	*Type*	*Abundance*
(1.20 %Ro)	sh													sh	go	or	a	sv		
	shly dol	yl		cc	r	no	h	cm	sv					cb	go	or	a	sv	ds	a
	cb,shlydol	wt	um	cm	c	bl	um	cm	sv					cb	gp		c		ds	a
	dol	wt	um	cm	c	bl	um	cm	c										ds	c
(1.20 %Ro) CORE	dolomiticsh	wt		cm	r									sh	gp		c			
	shly cb	no	h	cm	sv									sh	gp		c			
	fossilif sh	yl		cm	c	bl	um	cm	sv	no	h	cm	sv	sh	gp		a		ds	c
	tight cb	bl	um	cc	sv														ds	sv
(1.30 %Ro) CORE	cb rich sh	bl	um	cm	c									sh	gp		c		ds	c
	shly cb	bl	um	cm	a	no	h	cm	sv					sh	gp		a		ds	c
	dol	bl	um	cm	c														ds	c
	fossilif cb	bl	um	cm	c									cb	gp		sv		ds	c
(1.50 %Ro)	shlydol,sh	bl	um	cm	r									cb	go	or	sv	r	ds	a
	dol	no	h	cm	sv														ds	c
	shlysndycb																		ds	sv
	cb																		ds	r
(1.70 %Ro) CORE	shly cb																			
	fossilif cb	no	h	cm	sv															
	fossilif cb	no	h	cm	sv															
	fossilif cb													cb	gp		sv		ds	sv

ss: sandstone	mt: metamorphic rock	m: moderate	r: rare	ds: dead petroleum stain
si: siltstone	no: none	um: upper-moderate	sv: several	po: pore-occluding bitmn
sh: shale	br: brown	h: high	c: common	pb: pyrobitumen
cb: carbonate	or: orange	dq: frac in detrital quartz	a: abundant	
sa: salt	yl: yellow	dr: quartz dust rim	xa: very abundant	Notes: no = non-fluorescent dry gas inclusions
an: anhydrite	wt: white	qc: quartz cement	go: oil and gas prone	
ch: chert	bl: blue	df: frac detrital feldspar	op: oil prone	
co: coal	l: low	cm: matrix carbonate	gp: gas prone	
ig: igneous rock	ul: upper-low	cc: carbonate cement	ls: live petroleum stain	

Table 1: Fluid inclusion florescence shows that at least two populations of inclusions exist in some rocks, highlighting differences in timing of inclusion formation. In general, the higher maturity rocks carry gas-filled inclusions which do not fluoresce, while the lowest maturity rocks contain populations of yellow- and white-fluorescing inclusions. There fluids are presumably not as light as those contained in the more mature, blue-fluorescing inclusions.