SCA2003-03: CARBONATE ROCK WETTABILITY INTERPRETED FROM CAPILLARY PRESSURE AND IMBIBITION RESISTIVITY INDEX ANALYSES

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Pau, France, 21-24 September 2003

ABSTRACT

The wettability of rock samples from 5 carbonate reservoirs in Western Canada varies from weakly water wet to mixed wet to mildly oil wet. Wettability was determined by USBM and Amott analyses on 17 aged rock samples. Evidence supporting these interpretations was provided in one case by a contact angle measurement of the live oil, and in other instances by relations between un-restored primary drainage and restored secondary drainage capillary pressure curves. Imbibition resistivity index (IRI) measurements were performed on 9 aged sister-plug samples to determine a restored Archie saturation exponent "n". The saturation exponent measured at the onset of the IRI test provides the most reliable "n" value as it is determined on a restored sample prior to any hysteresis that occurs during increasing Sw. Values for the restored "n" vary from 1.2 to 3.1. Although the imbibition RI tests provide a reliable measure of the saturation exponent, this number cannot be used alone as a valid indicator of wettability. Wettability and pore geometry principally control the shape of the RI profile during imbibition. Comparisons of imbibition RI profiles and water relative permeability curves were made between an oil wet and water wet reservoir with similar pore geometry. The water wet samples generally exhibit suppressed electrical and hydraulic behaviour during imbibition consistent with a more water wet pore system. In contrast, the oil wet samples exhibit an instantaneous flow of water and electric current with increasing Sw that is consistent with a more oil wet pore system. The wettability interpretations and saturation exponent measurements made for these 5 carbonate reservoirs were used to refine expectations of reservoir performance and enhance petrophysical interpretations.

INTRODUCTION

Wettability is one of the most important reservoir properties affecting oil recovery. Differences in relative permeability, capillary pressure and electrical properties between water wet and non water wet reservoirs may cause significant differences in reservoir appraisal and oil recovery. Although published studies indicate that most carbonate reservoirs are non water wet, wettability is rarely measured during many routine exploration programs for carbonate reservoirs in western Canada. To better understand reservoir character, this study primarily used USMB/Amott and imbibition resistivity index analyses to determine the wettability and electrical properties of five carbonate reservoirs from Western Canada, treated by some as being simply water wet and evaluated using a standard resistivity index of 2.

SAMPLING AND ANALYSIS

Twenty six small core plugs (1 ½" diameter and around 2" long) were obtained from the five studied pools (Table 1). After cleaning, samples for wettability and electrical property analyses were centrifuged to Swi and aged for 40 days in dead uncontaminated reservoir oil. Brine solutions for each pool were composed in the laboratory to mimic the reservoir brine. Wettability was determined using an ultracentrifuge to perform a combined USBM/Amott test. Details regarding the technique can be found in the literature [1]. Relative permeability curves for each sample were constructed using a simulation package which history matches the fractional flow curves from the centrifuge experiments [2]. Wettability was also determined for one oil sample by the dual drop/dual crystal contact angle technique using live oil and a dolomite crystal. Electrical properties were measured on samples taken immediately adjacent to some of those used in the wettability analyses. Continuous imbibition resistivity index (i.e. water displacing oil), performed using wettability-restored samples, provided the Archie saturation exponent "n". In this paper, "imbibition" will refer to tests in which water displaces oil whereas "drainage" will refer to oil displacing water, regardless of wettability.

USBM/AMOTT WETTABILITY ANALYSES

The United States Bureau of Mines (USBM) technique determines wettability by measuring the work expended in a sequence of forced displacement tests in a capillary pressure apparatus. The work required by one fluid to displace the other is indicated by the area under the forced drainage and imbibition capillary pressure curves. The USBM wettability index is defined as:

$$USBM = \log\left(\frac{A_{drainage}}{A_{imbibition}}\right) \qquad (1)$$

The Amott technique relies on measuring fluids volumes displaced by force and fluid volumes spontaneously imbibed into a rock. A porous medium with a uniform wettability will spontaneously imbibe only one phase, water if the rock is water wet and oil if the system is oil wet. Rocks that imbibe both oil and water have connected regions of both oil wet and water wet pores and possess an intermediate wettability (i.e. mixed, fractional or neutral). In the Amott method two volume ratios are used to give wettability; the Amott Index to water, and the Amott Index to oil. The Amott Index is defined as:

$$I_{Amott} = \frac{V_{spon\tan eous}}{V_{spontan\,eous} + V_{forced}} \qquad (2)$$

The relative displacement index (*RDI*) is the difference between the Amott index to water (*Iw*) and the Amott Index to oil (*Io*). As the Amott method relies on spontaneous imbibition of the wetting fluid displacing the non-wetting fluid it is most suitable for strongly water-wet and strongly oil-wet rock, but not for neutral wet rock.

$$RDI = I_w - I_o \tag{3}$$

It must be noted that differences in S_{wirr} between primary and secondary capillary pressure drainage are expected owing to wettability restoration that occurs during the ageing process. Samples becoming oil wet during restoration may exhibit reduced S_{wirr}. In samples becoming mixed wet the secondary drainage curve may cross the primary drainage curve to higher Swirr at increased capillary pressures. Such changes have been demonstrated in the literature [8,9]. In this study, such relations between primary and secondary drainage curves, consistent with interpreted USBM/Amott wettability, were observed in some of the samples (see "Pc relations" column in Table 2, Figs. 1a, b). However, interpretations regarding wettability cannot be made using relations between primary and secondary drainage curves alone owing to heterogeneity effects and mass balance errors.

Results and Discussion

Examination of the Relative Displacement Indices (RDI) and USBM indices in tandem (Table 2, Figure 2) suggests that Keg River, Sulphur Point and Midale Marly samples are generally oil wetted, whereas Nisku samples are generally water wet. RDI and USBM indices provide ambiguous results regarding wettability interpretation for Leduc, Midale Vuggy, and one each of the Wayne and Keg River samples, that is, they exhibit both water wet and oil wet indices (Table 2).

Examination of the Amott indices alone (Table 2) shows that Leduc, Midale Marly and 2 of 4 Keg River samples spontaneously imbibed both water and oil to some degree indicating a system of intermediate wettability (i.e. mixed or fractional). Spontaneous water imbibition is critical for counter-current production of oil during a waterflood. Four samples exhibited spontaneous oil imbibition *without* spontaneous water imbibition (i.e. 2 of 4 Keg River samples, both Sulphur Point samples). The lack of water imbibition combined with oil imbibition in these particular Keg River and Sulphur Point samples indicates a more uniformly oil wet condition. All six Nisku samples and the two Midale Vuggy samples exhibited spontaneous water imbibition *without* spontaneous oil imbibition. The lack of oil imbibition in the Nisku samples combined with water imbibition and consistently water wet RDI and USBM indices indicate a consistently and uniformly weakly water wet condition. The absence of oil imbibition in the two Midale Vuggy samples, combined with a small degree of water imbibition and weakly oil wet USBM indices may indicate a neutral to mixed wet system with a greater preference for water over oil. The two Midale Marly samples may also be mixed wet but as they exhibit a greater preference for oil over water may be weakly oil wet.

ELECTRICAL PROPERTIES AND WETTABILITY

The standard method of relating oil saturation to resistivity in a clay free reservoir is based on Archie's 1942 methodology known as the "Archie Equation" (4).

$$S_w = \left(\frac{a}{f^m} \bullet \frac{R_w}{R_t} \right)^{1/n} \qquad (4)$$

The Archie Equation is made up of two equations; the "Resistivity Index" (***RI***) and the "Formation Resistivity Factor". The Formation Resistivity Factor is controlled principally by pore fabric and rock consolidation and is apparently not impacted by wettability. The Resistivity Index, which can be impacted by changes in wettability, is defined as.

$$RI = \frac{R_t}{R_o} = \frac{1}{S_w^n} \qquad (5)$$

Drainage Resistivity Index

The Archie saturation exponent "n" in equation 5 is determined by injecting gas or oil into a cleaned, water-saturated rock and measuring R_t at decreasing water saturations. A log-log plot of RI versus S_w typically yields a straight line with the slope being "-n". The Archie equation assumes that all the brine in a sample contributes to the flow of electric current and that "n" is constant for a porous medium. This is generally true in a water wet rock where brine lines the pores and electrical continuity is maintained down to low S_w values. However, in a perfectly oil wet rock the brine resides in the pore centres where it may become disconnected at low water saturation causing R_t (and "n") to increase. In some cases oil wet rocks may have high resistivities at all water saturations. Clean, consolidated water wet rock is believed to have an "n" value near 2. However, oil wet rocks have reported "n" values in the 2 to 6 range [3,4,5,6]. Experimental data shows that a linear relation may exist between USBM wettability index and saturation exponent for samples from the same rock type [4].

The electrical properties of mixed wet pore systems are less well documented and understood. Mixed wet systems are anticipated to behave electrically like water wet rocks as smaller pores remain water wet and conductive at all water saturations. The main impact regarding wettability and the Archie saturation exponent "n' is that the use of a standard "n" of 2, when the actual "n" of the reservoir is higher, may produce a significant underestimation of water saturation and an overestimation of oil volumes.

Imbibition Resistivity Index

In contrast to the standard "drainage" RI test, tests performed for this study used an "imbibition" process in which water was injected into oil saturated samples at Swirr that had been aged for 40 days. This procedure was performed so that "n" could initially be measured at S_{wirr} under restored wettability conditions. Imbibition resistivity index (IRI) measurements on restored samples are infrequently performed and poorly understood.

IRI analyses have been performed to determine the electrical properties of rocks flushed by water during drilling or through waterflooding [6]. Moss and Jing, [6] present examples that show similar "n" values measured by drainage and imbibition RI in oil wet rock. However, in other cases [5,6] IRI profiles (and "n" values) are notably different from drainage RI in non-water wet rock. The non-linearity is attributed to hysteresis effects controlled by pore structure and wettability. Man and Jing [7] specifically attribute the maintenance of high resistivities during increasing S_w to the dominance of the electrical response by a mixed wet pore system.

Results and Discussion

Initial saturation exponent at S_{wirr}

Imbibition RI versus water saturation profiles for most samples in this study are non log-linear and exhibit a hysteresis that is likely controlled by differences in both wettability and pore fabric (Figure 3). The saturation exponent measured at the onset of the test is at S_{wirr} (initial "n" @ S_{wirr} in Table 3). This values provides the most reliable saturation exponent as it is determined on the restored sample prior to any hysteresis that occurs during increasing S_w. Values for initial "n" @ S_{wirr} vary from 1.15 to 3.1, notably different than the standard "n" of 2 employed for routine petrophysical evaluation. Strong relations between wettability and saturation exponent are not anticipated and do not exist (Figure 4) since the data set represents different rock and reservoir systems. It is interesting to note, however, that the most water wet Nisku rocks possess among the lowest initial saturation exponents whereas samples from the most oil wet Keg River rocks have among the highest initial saturation exponents. Nevertheless, the poor relation illustrated in Figure 4 indicates that, when "n" values are in the range of ~1 to 3, it is dangerous to infer wettability from the Archie saturation exponent alone.

Final saturation exponent

The slope of the linear portion of the IRI composite plot at higher S_w values is termed the 'final "n"' (Table 3, Figure 3). The slope of this line is not required to pass through $S_w = 1$ as dictated by the Archie model. The Archie equation assumes that all brine in a sample contributes to electric current and this is not necessarily the case in non-water wet rock. The value of 'final "n"' has been influenced by hysteresis and may be somewhat higher than would be measured in a drainage cycle [5] and, hence, is considered unreliable.

Shape of the IRI vs. S_w plot

The shape of the RI profile during imbibition will principally be controlled by wettability and pore geometry. As the rocks analysed in this study exhibit both differing wettability and variable pore fabric, it is difficult to determine the impact of either control on the IRI profile. Nevertheless, the two reservoirs exhibiting the most oil wet (Keg River) and most water wet character (Nisku) have similar pore fabric (Table 1) and certain observations can be made regarding the role of wettability and hydraulic/electric continuity on the IRI profile.

Water wet Nisku samples maintain high RI values as Sw initially increases (ie. a flat profile, Figure 3). In contrast, oil wet Keg River samples manifest a near immediate decrease in RI with increasing S_w. The maintenance of high RI values with increasing S_w for the Nisku samples indicates that water added to the oil-saturated rocks is initially not in *electrical* continuity. Relative permeability to water curves for Nisku samples (measured during forced imbibition in USBM analysis) reveal that water permeability is initially suppressed signifying that water added to these rocks is initially in poor *hydraulic* continuity (Figure 5a). Water initially introduced into these samples resides either in poorly connected water wet micropores or along the walls of larger vugs. Water saturation must increase to a certain critical value before significant electrical and hydraulic continuity is established. The suppressed electrical and hydraulic behaviour during imbibition is consistent with a more water wet pore system. The immediate decrease in IRI for Keg River samples signifies rapid establishment of electrical continuity. Water imbibition relative permeability curves for Keg River samples show a rapid increase in hydraulic continuity (Figure 5b). Water introduced into oil wet samples is more likely to rapidly form continuous paths through pore centres rather than along pore walls as in a water wet rock. The instantaneous flow of water and electric current with increasing S_w is consistent with a more oil wet pore system

Upscaling issues

Upscaling of analytical data in heterogeneous carbonate reservoirs is problematic, and the preceding discussion, which focused on “n”, should be buffered with an understanding of all parameters influencing log analysis. In this study, too few samples were taken to statistically assess the variation that may exist in pore fabric for rocks from the various pools. Given the variability in “m” which exists one must be careful not to over-emphasise the role that “n” has in controlling S_w in heterogeneous pools. The saturation exponent, although an important parameter, may play a second order role in petrophysical reserves assessment in heterogeneous pools.

WETTABILITY DISCUSSION

The wettability interpretations performed for this study were based on quantitative USMB and Amott indices, and in one case, an oil contact angle. Relations between primary/secondary capillary pressure curves provided evidence supporting these interpretations in some instances. Resistivity Indices measured at S_{wirr} at the outset of an imbibition RI test on a restored sample may provide a reliable measure of the Archie saturation exponent but this number cannot be used alone as a valid indicator of wettability. The preceding interpretations are based on laboratory analyses valid only at the scale and measurement conditions of the samples. The common occurrence of easily formed oil and water emulsions during production testing from the Sulphur Point formation in Beatty Lake provides empirical evidence that supports the interpretation of a more oil wetted system.

CONCLUSIONS

- The wettability of five carbonate reservoirs, assumed by some during routine appraisal to be water wet, is notably *not* water wet but ranges from weakly water wet to mixed wet to mildly oil wet.
- The use of a standard Archie saturation exponent (“n” = 2) will underestimate water saturation and overestimate hydrocarbon volumes due to increased oil wettability in two of five reservoirs.
- When “n” values are in the range of ~1 to 3, it is dangerous to infer wettability from the Archie saturation exponent alone.

RECOMMENDATION

- Saturation exponents measured on wettability restored samples should subsequently be re-measured on cleaned, water wetted samples in order to assist in determining the relative impact of wettability on “n”.

ACKNOWLEDGEMENT

The authors wish to acknowledge EnCana Corporation for permitting the publication of the presented data. The valuable contributions of Chris Pan (Core Laboratories), Don Bryan (EnCana) and helpful reviews by Jake Rathmell and Ole Torsaeter are also appreciated.

NOMENCLATURE

$A_{drainage}$	Area under drainage capillary pressure curve	R_o	Resistivity of rock at 100% S_w
$A_{imbibition}$	Area under imbibition capillary pressure curve	R_t	Resistivity of rock when partially saturated with brine
a	Constant	R_w	Resistivity of brine
FRF	Formation Resistivity Factor	RDI	Relative Displacement Index
I_{Amott}	Amott Index	RI	Resistivity Index
I_o	Amott Index to oil	S_w	Water saturation
I_w	Amott Index to water	S_{wirr}	Irreducible water saturation
IRI	Imbibition Resistivity Index	USBM	USBM Index
m	Archie's cementation factor	V_{forced}	Produced volume of water or oil during forced imbibition
n	Archie's saturation exponent	ϕ	Porosity

REFERENCES

1. Nikakhtar, B., Kantzas, A., de Wit, P., Pow, M. and George, A., "On the Characterization of Rock/Fluid and Fluid/Fluid Interactions in Carbonate Rocks Using the Ultracentrifuge", *J. Can. Pet. Tech.*, **35**(1), 47-56, 1996.
2. Kantzas, A., Nikakhtar, B., Ruth, D. and Pow, M., "Two Phase Relative Permeabilities Using the Ultracentrifuge", *J. Can. Pet. Tech.*, **34**(7), 58-63, 1995.
3. Anderson, W.G. “Wettability Literature Survey – Part 3: The Effects of Wettability on the Electrical Properties of Porous Media”, *JPT*, **38**(13), 1371-1378, Dec. 1986.
4. Donaldson, E.C. and T.K. Siddiqui, 1989. “Relationship Between the Archie Saturation Exponent and Wettability”, SPE paper 16790.
5. Elashahab, B.M., Jing, X.D, Archer, J.S., “Resistivity Index and Capillary Pressure Hysteresis for Rock Samples of Different Wettability Characteristics”, SPE 29888, 11-14 March, 1995.
6. Moss A.K. and X.D. Jing, 1999, “Resistivity Index and Capillary Pressure Characteristics of Reservoir Sandstones in Different Wettability Conditions”. SCA Paper No 9945, presented at the 1994 International Symposium of the Society of Core Analysts, Stavanger, Norway, Sept. 12-14, 1994.
7. Man, H.N. and X.D. Jing, “Network Modelling of Wettability and Pore Geometry Effects on Electrical Resistivity and Capillary Pressure”. *J. Petr. Sci. Eng.* **24**, pp. 255-267, 1999.
8. Anderson, W.G. “Wettability Literature Survey – Part 4: Effects of Wettability on Capillary pressure”, *JPT*, **39**(10) pp.1283-1299, 1987.
9. Nikakhtar, B., Kantzas, A., Wong, F. and Pow, M., "Some Observations on the Capillary Pressure Hysteresis Using the Ultracentrifuge", SCA Paper No 9424, presented at the 1994 International Symposium of the Society of Core Analysts, Stavanger, Norway, Sept. 12-14, 1994.

Table 1 Summary of Sample Data

Pool	Formation	Petrology	Number of samples		
			USBM/ Amott	Electric props	contact angle
Wayne	Nisku	Dolomite pin-point vugs to vuggy, microcrystalline, local fractures and solid hydrocarbon	6	3	
Weyburn	MidaleVuggy	Limestone, small to med vugs to microcrystalline porosity	2	1	
	Midale Marly	Dolomite, pin-point vugs to sucrosic porosity	2	1	
Garrington	Leduc	Limestone, microcrystalline to intercrystalline porosity, local solid hydrocarbon	1	1	
Beatty Lake	Sulphur Point	Limestone, pin-point vugs to small vugs, microcrystalline	2	1	
Yates	Keg River	Dolomite pin-point vugs to vuggy, microcrystalline, local fractures	4	2	1

Table 2. Summary of Wettability Analyses

Samples	#	Wettability Indices and Indicators						Interpreted Wettability
		Amott water	Amott oil	RDI* index	USBM* index	Pc relations	Contact Angle	
Nisku, Wayne	101a	.056	0	**0.06**	**0.24**	-		consistently and uniformly weakly water wet
	101b	.040	0	**0.04**	-0.06	-		
	105	.037	0	**0.04**	**0.59**	-		
	202a	.040	0	**0.04**	**0.05**	-		
	205a	.059	0	**0.06**	**0.51**	mixed?		
	302	.030	0	**0.03**	**0.04**	oil wet		
Midale, Weyburn	vuggy 22	.012	0	**0.01**	-0.20	mixed?		Mixed wet (vuggy) Mixed to weakly oil wet (marly)
	vuggy 37	.009	0	**0.01**	-0.29	mixed?		
	marly 8	.009	.119	-0.11	-0.12	mixed?		
	marly 9	.005	.154	-0.15	-0.03	mixed		
Leduc, Garrington	2	.053	.23	-0.18	**0.04**	oil wet		neutral to weakly oil wet
Sulphur Point, Beatty Lake	5B	0	.186	-0.19	-0.25			consistently and uniformly weakly oil wet
	6B	0	.167	-0.17	-0.25			
Keg River, Yates	1a	.13	.091	**0.03**	-0.02	oil wet	mod oil wet (wtr adv ang 129^{o})	mixed to consistently and uniformly mildly oil wet
	1b	.01	.074	-0.07	-0.2	mixed?		
	3a	0	.231	-0.23	-0.46	mixed		
	4b	0	.11	-0.11	-0.19	oil wet		

* RDI and USBM Indices indicating a more water wet condition in **bold font**

Table 3. Summary of Electrical Property Analyses

Samples	#			Electrical Properties			
		Φ	Air K	Initial “n” @ Swirr	Final “n”	“m”	FRF
Nisku, Wayne	203b	.07	9.9	1.15	2.1	2.66	1237
	205b	.04	2.2	2.75		2.15	844
	305a	.09	21.5	1.66		2.28	279
Midale, Weyburn	vuggy 38	.2	274	1.83	2.4	2.25	36.6
	marly 11	.29	6	1.51		1.97	11.8
Leduc, Garrington	53	.02	2.36	3.1	4.1	1.88	1.59
Sulphur Point, Beatty Lake	5a	.17	93	1.84	2.4	2.32	58.1
Keg River, Yates	2b	.16	383	3.04	3.05	2.21	54.9
	3b	.16	10.4	2.62		1.93	41.1

The initial “n” of Nisku sample 205b may be too high due to incomplete dew atering during aging.

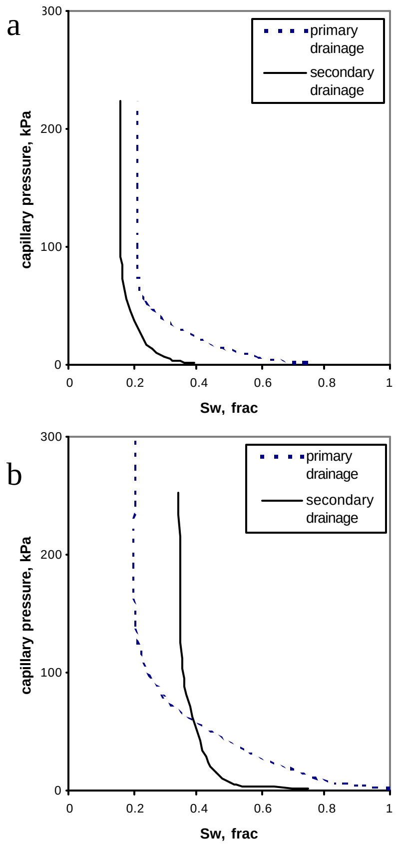


Figure 1. Pc profiles showing changes in primary and secondary drainage curves in oil wet (a, Keg River, smpl.4b) and mixed wet (b, Midale Marly smpl.8) rock.

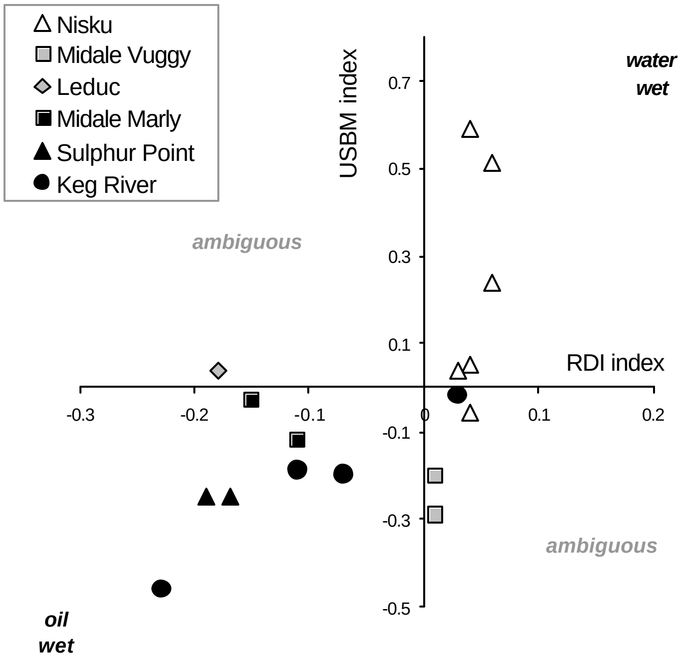
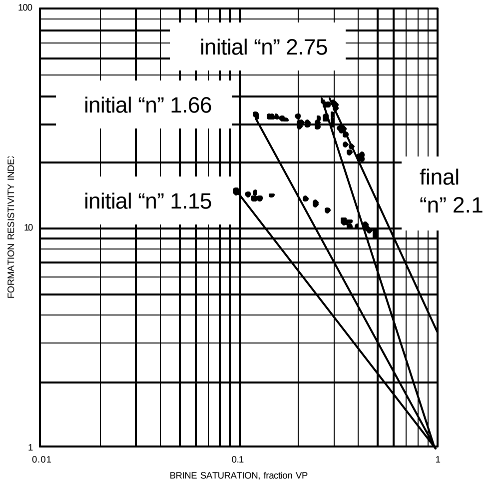
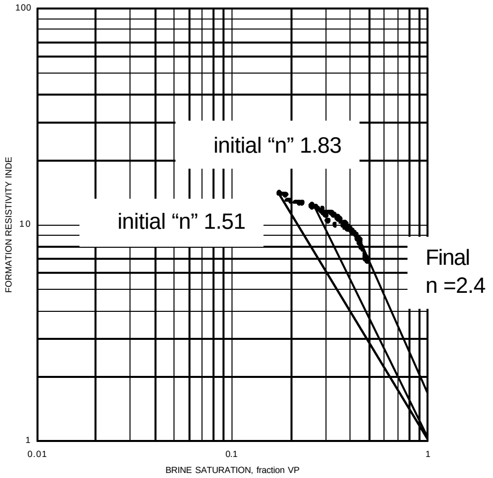


Figure 2. wettability defined in crossplot of Amott RDI and USBM index.

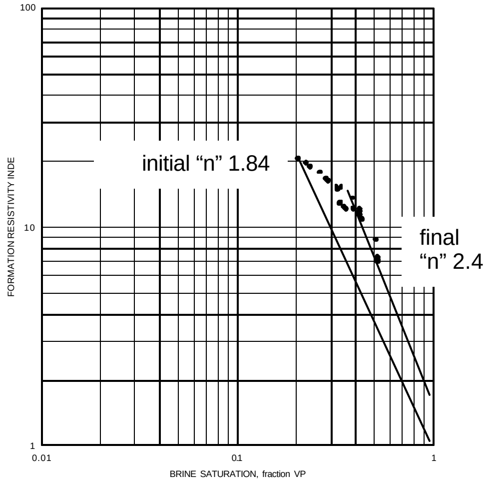
Nisku Fm, Wayne composite of 3 samples



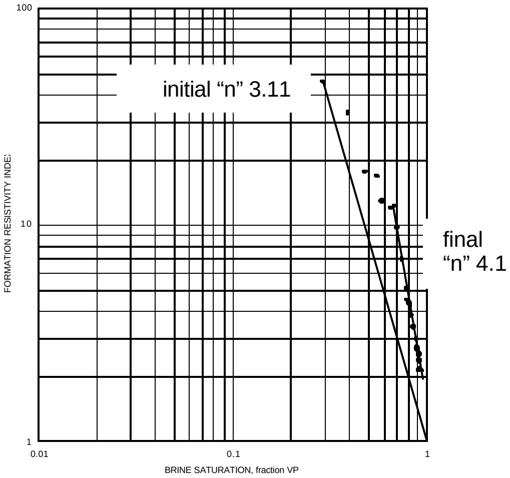
Midale Fm, Weyburn composite of 2 samples



Sulphur Point, Beatty Lake Pool



Leduc, Garrington Pool



Keg River, Yates P ool composite of 2 samples

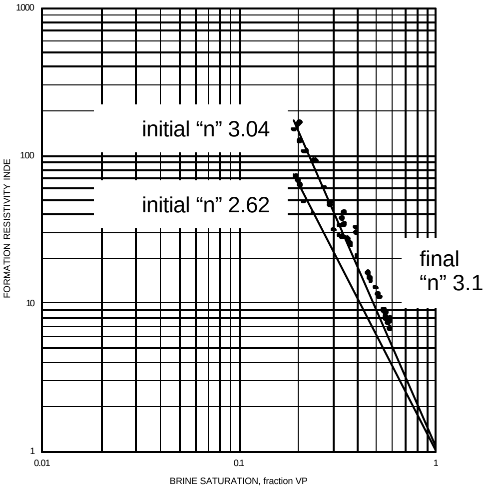


Figure 3. Composite imbibition RI plots

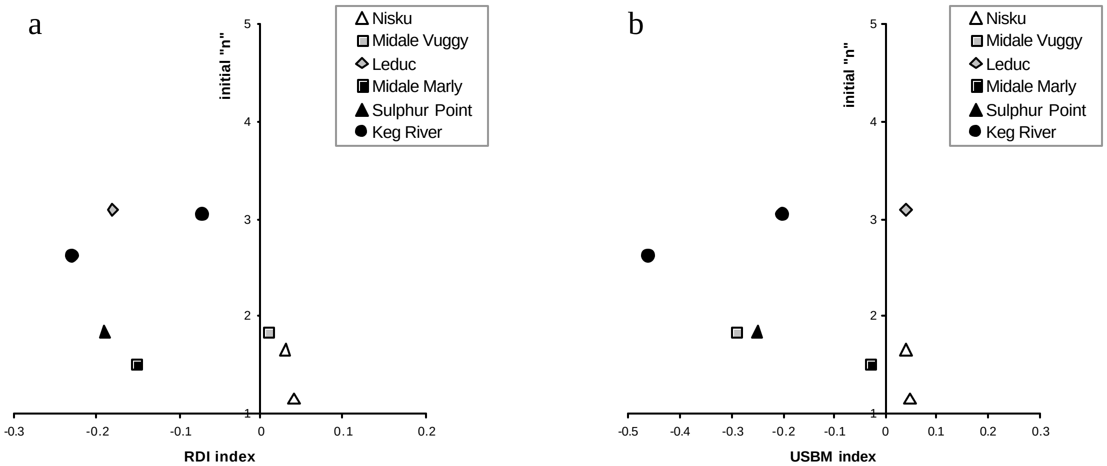


Figure 4. (a) Amott RDI versus initial “n” at S_{wirr}, (b) USBM index versus initial “n” at S_{wirr}

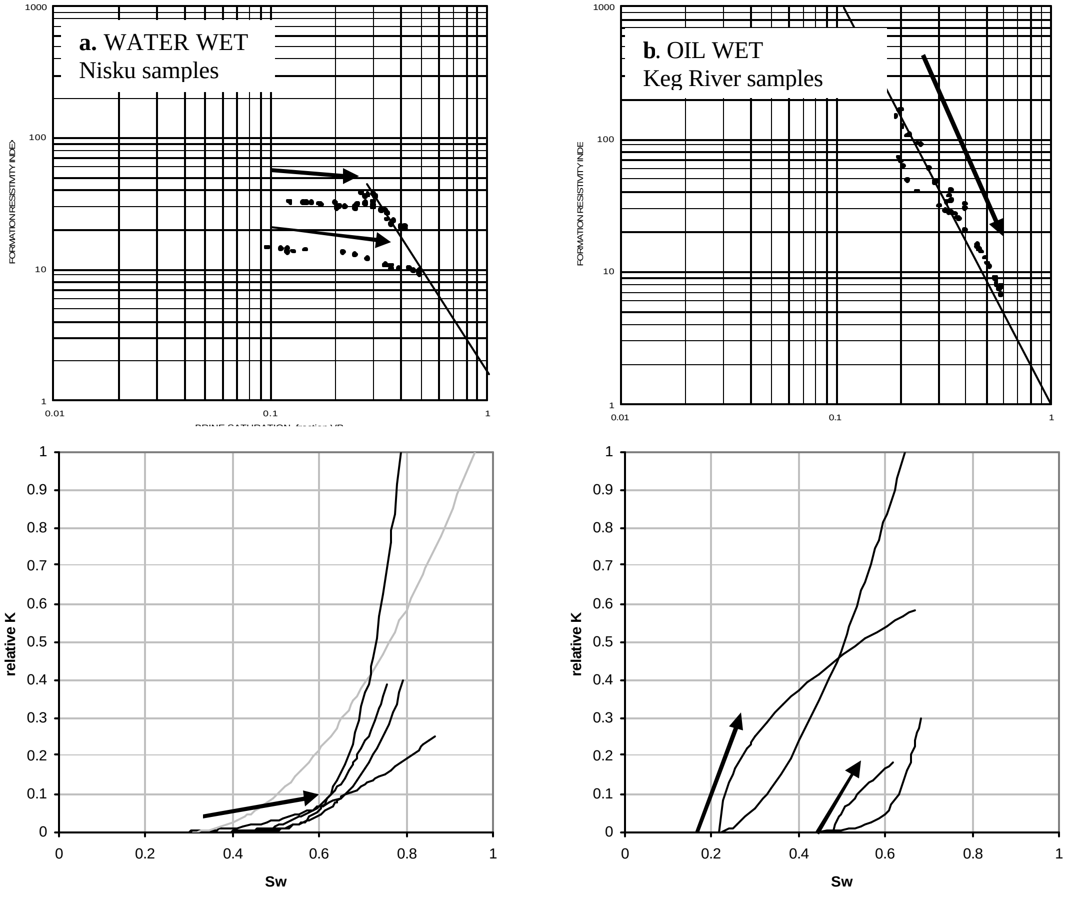


Figure 5. IRI plot (top) and water relative permeability plot (bottom) showing suppressed electrical and hydraulic continuity as Sw initially increases in water wet Nisku (a) and immediate electrical and hydraulic continuity as Sw initially increases in oil wet Keg River samples (b).