DETERMINATION OF SOURCE AND BREAKTHROUGH MECHANISM OF WATER PRODUCTION IN A NATURALLY FRACTURED BASEMENT RESERVOIR BY ANALYSING WATER PRODUCTION DATA

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Summary

Excessive production of water in the naturally fractured basement reservoir has been one of the most intriguing problems in production engineering. Water may appear immediately at early production stage or break through after months on stream. Available methods to determine the source of produced water are entirely based on chloride content. Stiff diagram is one of the well-known graphical methods in place to confirm whether it is formation water by various chemical components. With the Stiff diagram, the operators are able to detect formation water at the early days which apparently assists in quantifying the potential of scale deposit, erosion and so on.

Apart from the water sources, it is crucial to understand the water-out mechanism also via graphical approach. The characteristic trend of water-oil-ratio and its derivative with time in log-log plot indicate a variety of slopes reflecting different flowing mechanisms and a vast majority of them are attributed to the coning and channelling dependent on the level of pressure depletion and rock fluid interaction. A thorough understanding of the water source and its break-through mechanism is indispensable to production monitoring and optimising well production performance in the long run.

Key words: *Water analysis, water breakthrough mechanism, excessive water production, production management, fractured basement, graphical methods.*

1. Introduction

Water production is among the problematic issues of the oil and gas industry nowadays. Formation water may appear at the beginning or after a period of production. In the early days, chloride and salinity assists in identifying the origin of water - whether it is drilling mud loss or formation water. In addition, the evaluation of formation water composition provides pertinent information to deal with potential scaling and corrosion from the exposure of formation water to well completion jewelries. During production phase, the produced water has been analysed constantly to monitor well performance and water encroachment so as to come up with a mitigation plan to sustain high production rates.

As mentioned, the determination of formation water from the sample analysis is fundamental along with other theoretical approaches which diagnose production data in the period with and without water production. In this paper, graphical methods are employed to get a close look at the Stiff diagram plotting produced water composition and the water-cut behaviour by a hypothesis developed by K.S.Chan [1]. Those methods have the advantages of being simple, handy and cost effective. However, the downside is the sampling frequency, which apparently increases the sampling cost and lab experiment. The Stiff diagram and Chan's hypothesis have been widely applied in Thang Long and Dong Do fields, Cuu Long basin offshore Vietnam as water production was observed from the early production phase. By diagnostic plots of the chemical indicators and water-cut with time, formation water and coning demeanour were confirmed in few wells which, indeed, supports a revision of production regime to cope with reservoir management policy.

2. Graphical methods for produced water analysis

Most of existing graphical methods are based on comparison of the chemical indicators. These indicators consist of the amount of anionic or cationic necessary to add to or removed from the compound 1 mole.

$$C\ (meq/L) = [g.m^{-3}]\ x\ Change/Mass = [g.m^{-3}]/equal\ wt$$

Where: Change: Chemotherapy;

Mass: Mass mole;

Equivalent wt: Volume equivalent conversion.

The equivalent conversion factor for some common ions is depicted in Table 1.

***Table 1.** The equivalent conversion factors [2]*

Ion	Charge	Mass	Equivalent wt	Multiply by (to convert g.m^{-3} to meq/L)
H^+	1	1.0	1	1.0
Na^+	1	23.0	23.0	0.0435
K^+	1	39.0	39.1	0.0256
Ca^{2+}	2	40.1	20.15	0.0499
Mg^{2+}	2	24.3	12.15	0.0823
Fe^{2+}	2	55.9	28.0	0.0347
Zn^{2+}	2	65.4	32.7	0.0306
$(NH_4)^+$(as N)	1	14.0	14.0	0.0714
HCO_3^-	1	61.0	61.0	0.0164
CO_3^{2-}	2	60.0	30.0	0.0333
Cl^-	1	35.5	35.5	0.0282
F^-	1	19.0	19.0	0.0526
SO_4^{2-}	2	96.0	48.0	0.0208
NO_3^- (as N)	1	14.0	14.0	0.0714
H_2PO_4	1	97.0	97.0	0.0103

Stiff diagram

Among the available textbook methodologies in produced water analysis, Stiff diagram is the most popular one in which some key chemical indicators represented for seawater and formation water are plotted altogether as illustrated in Figure 1. In a Stiff diagram, data is plotted as a polygon, with cations to the left and anions to the right. Stiff diagrams are useful for looking at spatial relationships because they can be readily plotted on a map. In this respect, it is also a robust tool to compare between different water sources.

This method is easy to construct graphs of chemical indicators of multiple samples from different sources. When the water is determined, this diagram may point out a change of the chemical indicators from different sources in space and time. However, this method has the disadvantage that there is only one analysis performed on a single diagram.

Similarly, other methodologies being widely used in ground water analysis include Piper, Durov and Schoeller diagram, ion balance diagram, radial plot and chemical properties vs. time plot [2]. Nevertheless, they are simple graphics to track changes of each ion and do not analyse the combination of ions at the same time. Zaporozec summarised the methods for presentation of water analyses which were divided into four major sections: classification, correlation, analytical and illustrative [3].

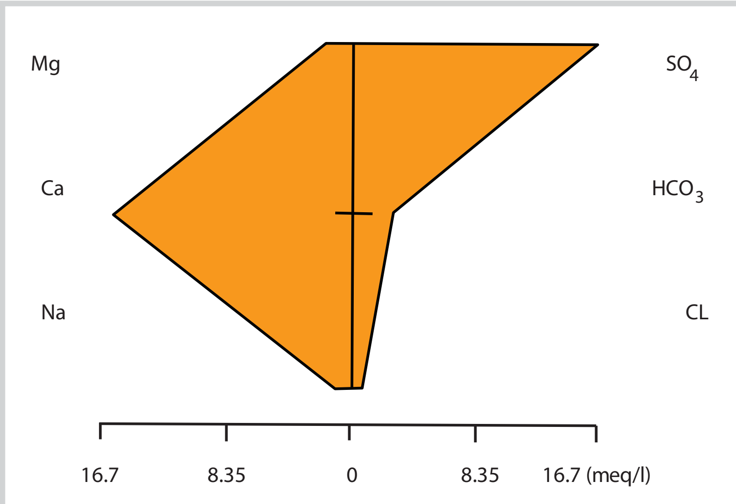


***Figure 1.** A typical Stiff diagram [2]*

All the above methods depend primarily on the purpose and the specific field applied. The change in the ion index of formation is complicated because water may penetrate from various sources. In the narrow scope of this research, Stiff diagram is the basis for analysing the water sources and its change with time.

3. Diagnostic plots to determine water breakthrough mechanism

Tracking water movement in the reservoir is a top priority in reservoir management when the wells commence water-out. There are numerous strategies for monitoring water encroachment, such as material balance, graphical analysis of production water and simulation model. An intuitive method introduced by K.S.Chan in

1995 where the WOR (water-oil ratio) and its derivative are drawn on the log-log plot with time. The disparity between the WOR and WOR' suggests potential issues: water channelling or coning. The formula for computing the WOR and its derivative are as follows:

$$WOR = \frac{q_w}{q_o}$$

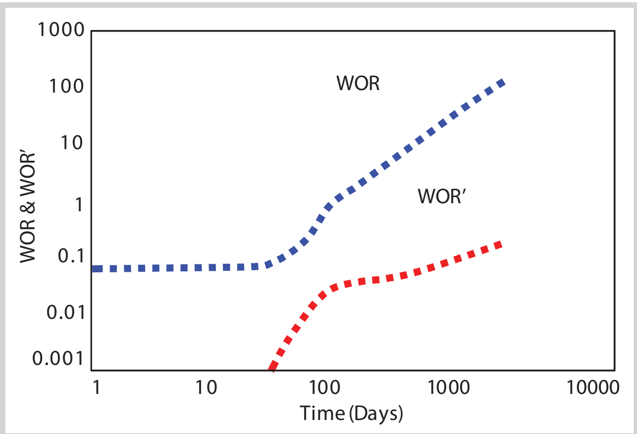
$$WOR' = \frac{dWOR}{dt} = \frac{WOR_2 - WOR_1}{t_2 - t_1}$$

Chan's hypothesis was based on the examination of actual production data to forecast the water-cut behaviour with time. As mentioned, two typical issues at the excessive water production wells were attributed to the coning and penetration by channel (fractures, and aquifer zones). Figure 2 plots the ideal expression of the WOR-WOR' relationship.

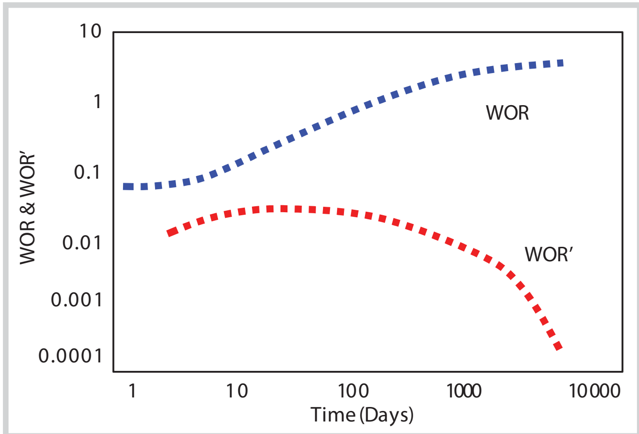
According to Chan, a log-log plot of WOR behaviour for both coning and channelling is divided into three periods. The first period extends from the start of production to water breakthrough where the WOR is constant for both mechanisms. When water production begins, during the second period, WOR behaviour becomes disparate for coning and channelling. In the transition period, the rate of WOR increase after water breakthrough is relatively slow and gradually reached a constant value for the coning mechanism. For channelling, the water production from the breakthrough layers or fracture increases very quickly. The end of this period shows the WOR resumes at about the same rate. After the transition time, Chan's plot describes the WOR increase to be quite rapid for both mechanisms, which begins in the third period.

Figure 2 illustrated WOR time derivatives (WOR') versus time for the different excessive water production mechanisms. Chan mentioned that the WOR' can distinguish between coning and channelling. Coning shows a changing negative slope, as channelling WOR' curves show an almost constant positive slope.

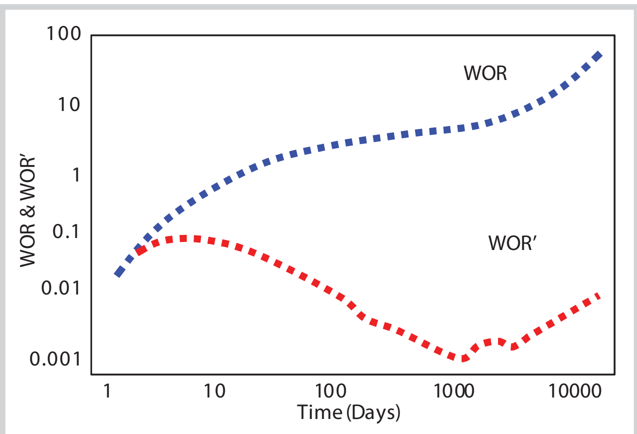
The excessive water production is controlled by the reservoir management or well workover depending on



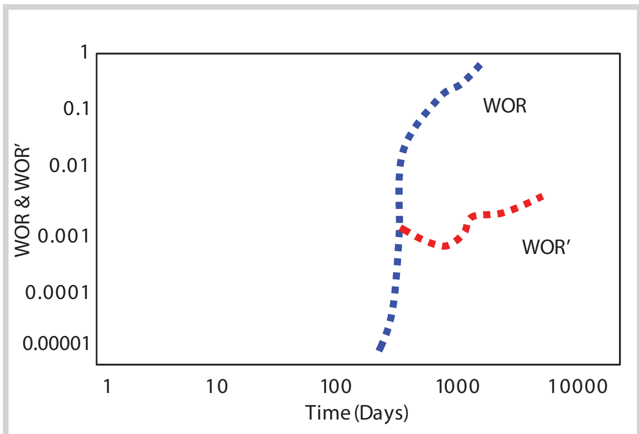
WOR and WOR' multilayer channelling



Bottomwater conning WOR and WOR'



Bottomwater conning with late time channelling behaviour



WOR and WOR' thief layer water recycling

***Figure 2.** The K.S.Chan ideal plots [1]*

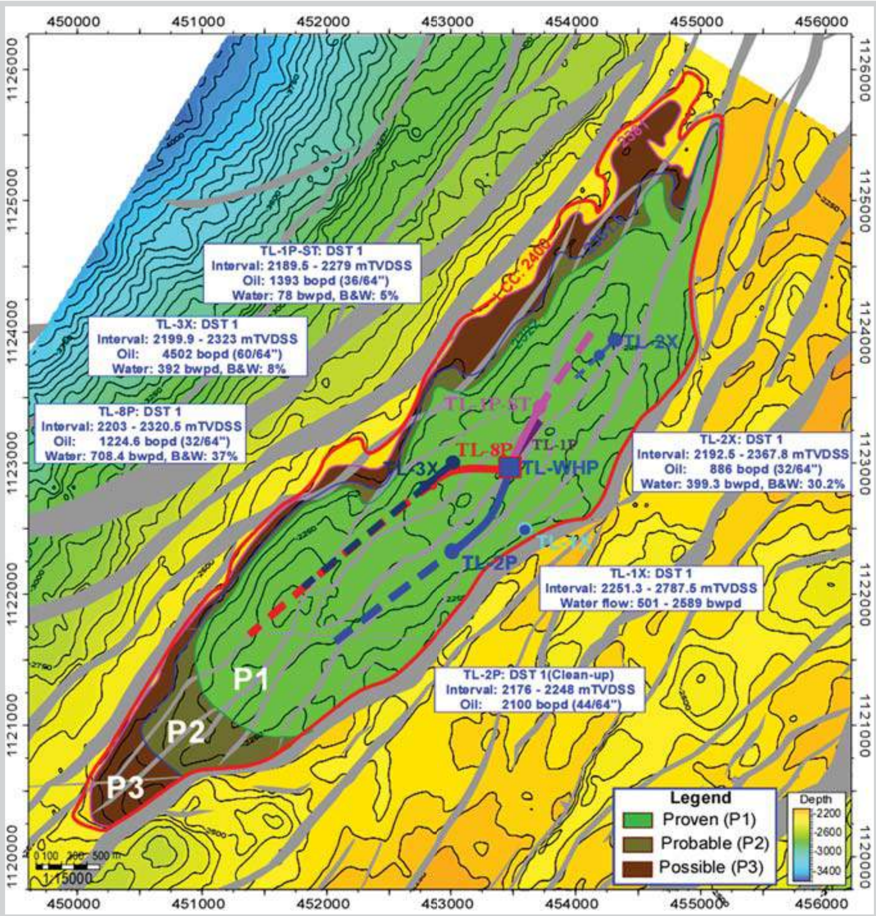


Figure 3. *Top Thang Long fractured basement depth map*

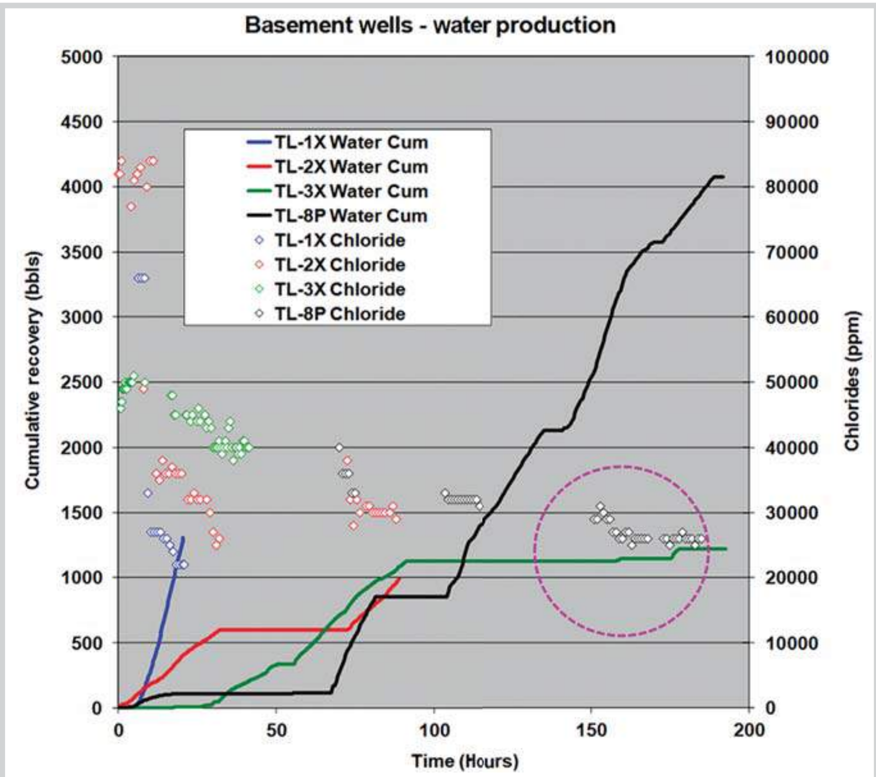


Figure 4. *Water production and chloride content with time in Thang Long fractured basement reservoir producers*

the type of the problem occurring at the well. The prediction of the water-cut tendency is vital to the remedial treatment like water shut-off and changing production conditions. Classification of well problems and water shut-off suggestion are mentioned in [4].

4. Water production behaviour in naturally fractured basement reservoir in Thang Long field

The naturally fractured basement reservoir in Thang Long field was first discovered in 2008 by three wildcat wells. To date, six wells have been drilled into this reservoir in the exploration and development phases as shown in Figure 3. Well testing data from the exploration wells demonstrated the recovered water was identical to the drilling mud loss and there were no signs of formation water. Chloride levels are diminishing steadily but remained above 30000ppm (Figure 4). However, only well TL-8P produced water immediately from the inception. The chloride content was decreasing slowly to around 22000ppm after three months on stream as shown in Figure 4. The question is whether well TL-8P has been producing formation water or drilling mud. After more than a year of production and having no water injection, the chloride content and other chemical components behave consistently and there is no doubt on its origin.

The results of produced water analysis are shown in Table 2. The sample of LS1.01.41, 01.53, 01.56 and 01.58 are analysed for TL-8P from the beginning. Based on Saline Water Classification, this produced water is a kind of saline water type [5].

Table 2. Water sample analysis of Thang Long fractured basement reservoir producers

Ion	LS1.01. 12	LS1.01. 58	RD-N-3P (Formation water)	Seawater	TL-8P (13/6/ 2014)	TL-1P (13/6/ 2014)	TL-1P (1/7/ 2014)	TL-8P (18/12/ 2014)	TL-8P (18/12/ 2014)	TL-1P (09/5/ 2015)	TL-8P (09/5/ 2015)
Sodium Na^+	16052	11226	5649	10180	10352	22101	9020	8314	8408	5732	5643
Potassium K^+	281	128	453	394	173	263	102	154	161	280	179
Calcium Ca^{2+}	4912	4198	2909	495	3690	3814	2534	3422	3512	5320	5200
Magnesium Mg^{2+}	1335	1136	10	3301	168	154	91	142	154	72	96
Chloride Cl-	35678	27944	14914	20411	22609	38697	19986	19216	19382	19525	19170
Bicarbonate $(HCO_3)^-$	439	398	68	264	267	435	267	272	274	250	275
Sulphate $(SO_4)^{2-}$	1478	1342	47	2599	358	974	366	101	104	58	49

Stiff diagram to determine water sources

As soon as water appeared in TL-8P, consistent analysing of samples was indispensable to provide adequate information for plotting the Stiff diagram. The water sample analysis result, then, is double check with the ones of nearby fields for reference.

In Figure 5, the first water samples lay far from the formation curve of nearby fields (in orange - LS.01). Visually, the shape of the envelope of cations and anions has been changing with time. The envelopes gradually shrink and move towards the formation water (the blue and red lines). Water sample analysis dated 18/12/2014 (in orange) was almost approaching the formation water one.

In principle, it is possible to distinguish three fundamental stages in the above Stiff diagram. In the early stage, water production was mostly concluded as drilling mud loss. The shape of the envelope tends to gradually shrink in the second stage depending on the level of water production and the distance to water sources. During the second stage, the envelopes of water production were proximate to formation water and the well may produce entirely formation water. The third stage appeared only when the reservoir had influx from other water sources. The speed of

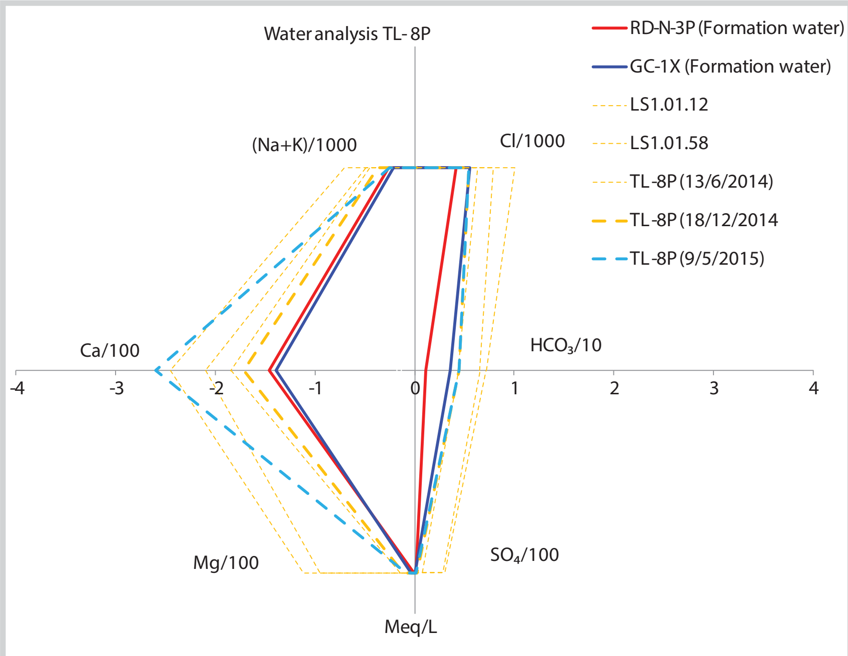


***Figure 5.** Stiff diagram compares water sample analysis of TL-8P well with time*

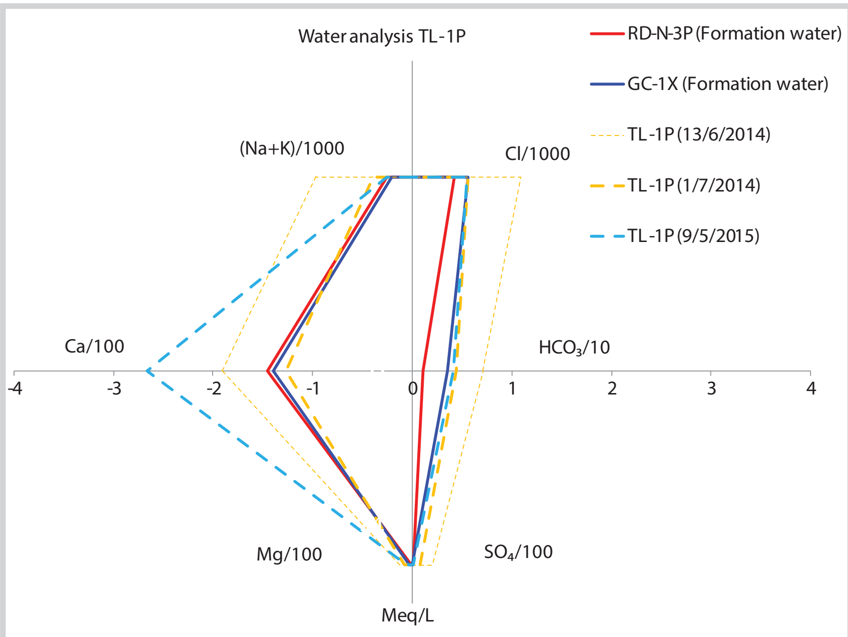


***Figure 6.** Stiff diagram compares water sample analysis of TL-1P well with time*

moving from the second to the third stage depends on the capacity of the external water source. Usually, the indicators change in the third phase is Ca or/and HCO_3.

This technique is similarly applied to the second well TL-1P. The envelope expressed the changes identical to TL-8P well. The envelope of this well, as described in Figure 6, in July 2014 was pretty close to the formation water curve.

By statistical methods, a baseline of the formation water for this kind of reservoir is developed and serves as a pragmatic source for analog down the road. The amplitude change in each ion indicator is depicted in Figure 7 and Table 3.

Through the Stiff diagram, water production from this fractured basement reservoir was pinpointed as kinds of formation water. As a result, the well placement of the third production well, TL-2P, was fine-tuned with well trajectory kept in close proximity to the top structure and shunned potential fracture areas which deemed connecting to the water zone. Consequently, the wells produced free water from the beginning and the Stiff diagram proved a good practice in production monitoring and well placement.

5. Determination of water breakthrough mechanism

After confirming the sources of produced water, understanding the breakthrough mechanism is crucial with regard to optimum production regime to level off the water cut. It is the point to bring up Chan's diagnostic plots to analyse production data. The plots in Figures 8 and 9 are designated for wells TL-8P and TL-1P respectively.

The water production in TL-8P and TL-1P appeared from the first days and was presumed to originate from the bottom aquifer. Moreover, the rapid raise

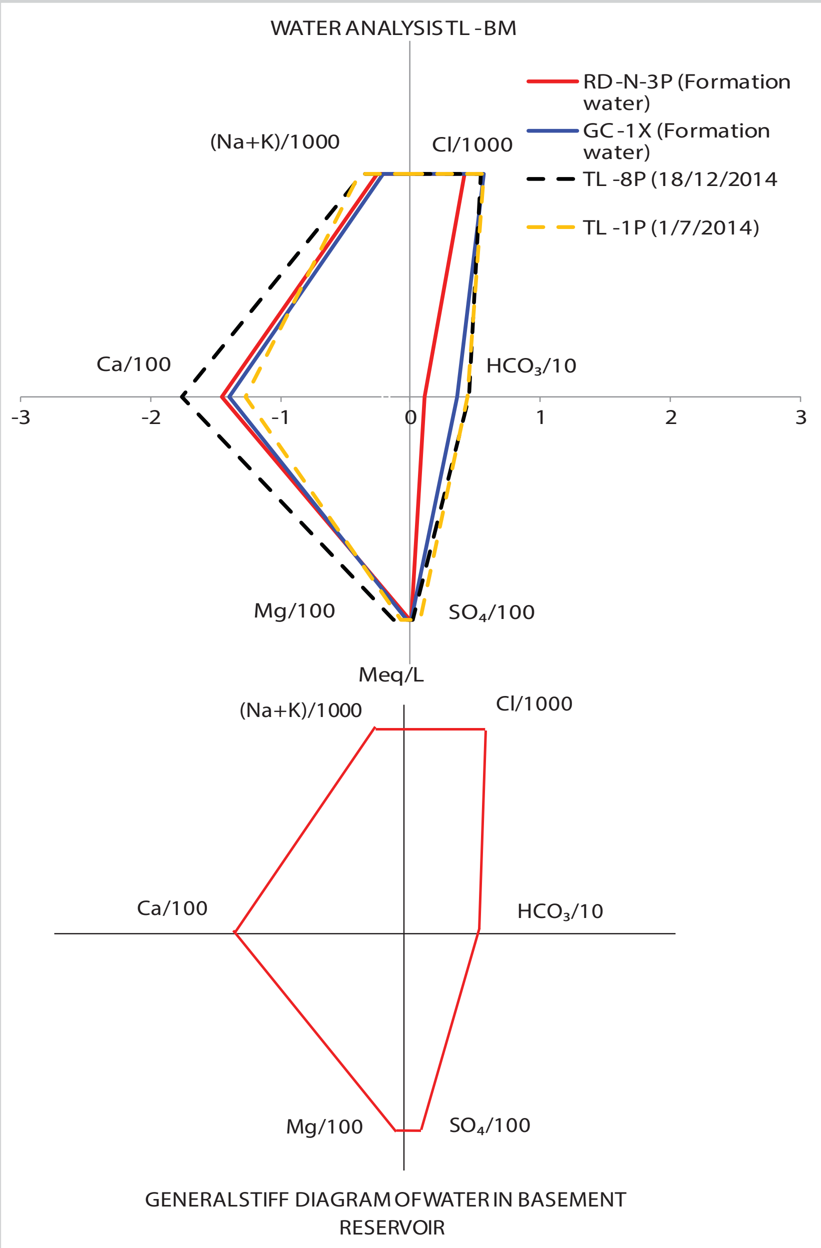
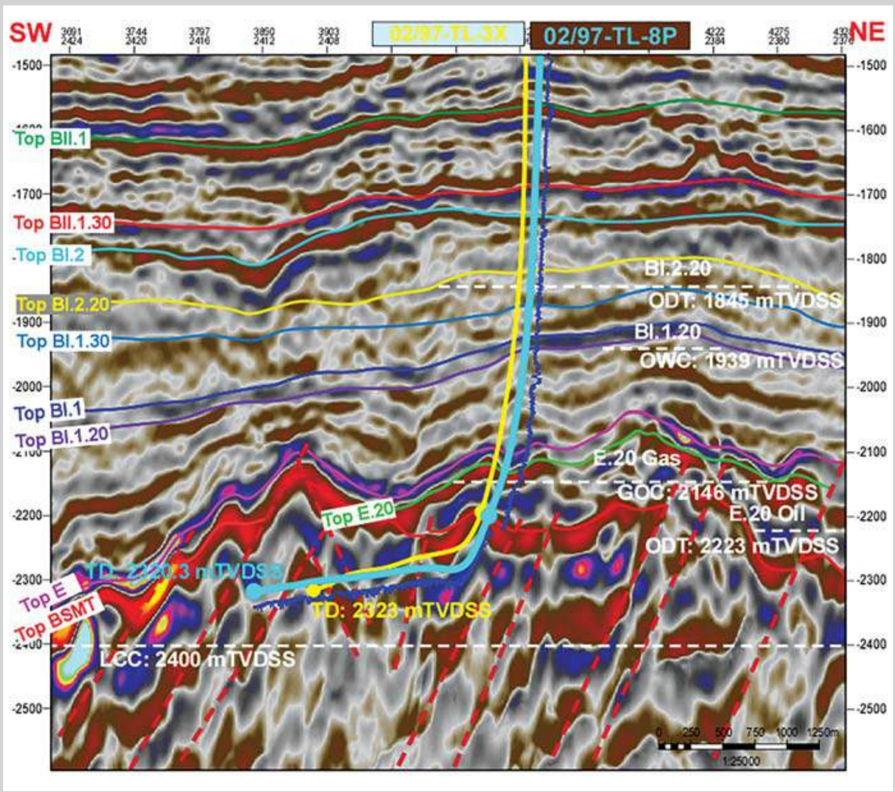


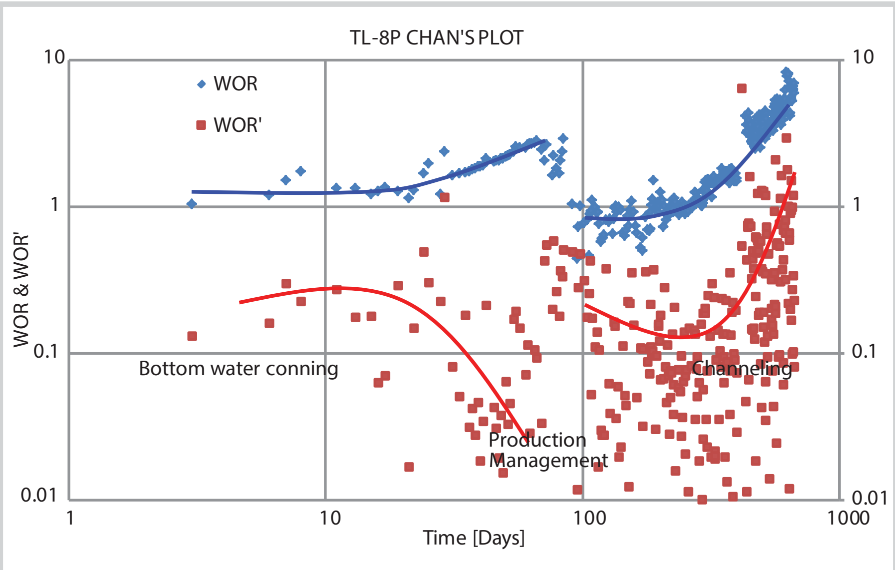
Figure 7. *Baseline of formation water of naturally fractured basement reservoir in Thang Long field*

Table 3. *The amplitude changes of ions in the formation water*

Ion	(Na + K)/1000	Ca/100	Mg/100	SO_4/100	HCO_3/10	Cl/1000
Tolerance (meq/L)	-(0.21 - 0.39) / - 0.28	-(1.27 - 4.36) / - 2.68	-(0.01 - 0.12) / - 0.05	(0.004 - 0.076) / 0.002	(0.11 - 1.18) / 0.64	(0.42 - 0.63) / 0.55



(a)



(b)

Figure 8. *Seismic cross section through (a) TL-8P and Chan's diagnostic plot (b)*

of water production could be from high permeability channels (large fractures connected directly to the bottom water zone) as illustrated in the seismic cross section. Oil production was maintained for a while until the coning influence. It can be seen that separate mechanism occurred in both cases where the coning appeared shortly in few months then abruptly switched to channelling.

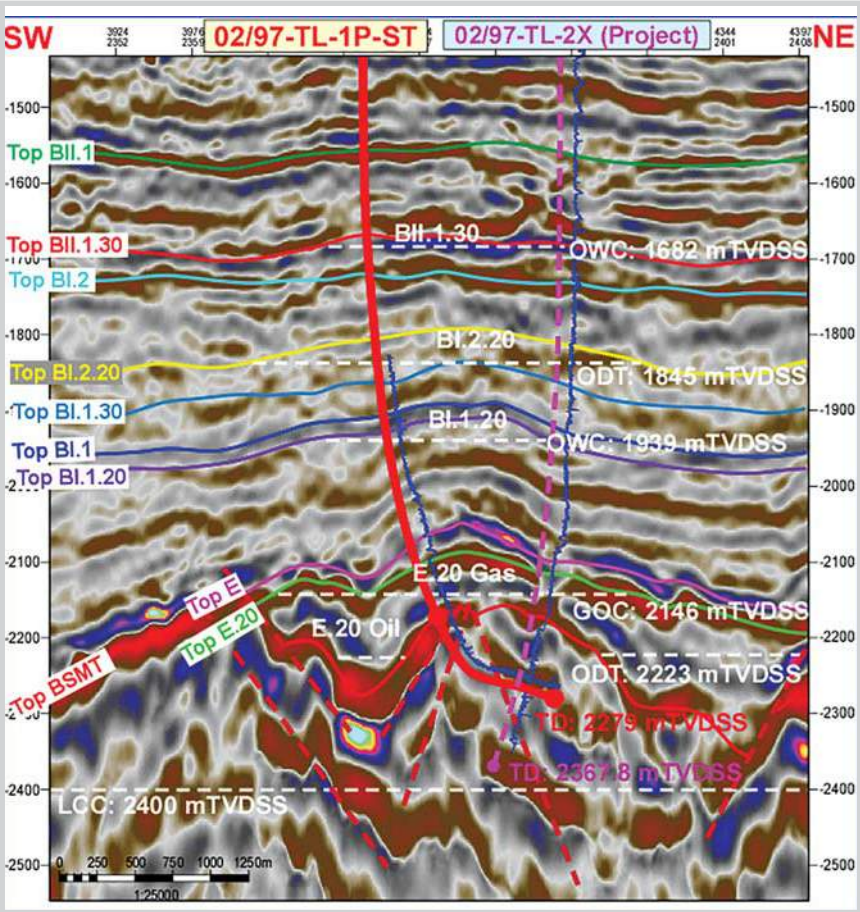
In the TL-8P case, a step change of data was recorded over 100 days which coincided with the effort to boost production by drastically applying pressure drawdown to productive fractures at the oil zone close to well heel. After a period with severe depletion, water started channelling massively to the well and production curtailment is expected. In contrast, well TL-1P water encroachment was smoothly transitioning from coning to channelling due to low permeability in oil zone and drastic depletion of reservoir energy. Drastic depletion has not made any difference to the well because of low average permeability from the well testing (k ~ 1.7md).

Depending on the mechanism of water production and reservoir properties, an adaptive strategy shall be made to slow down the water-cut development. In the naturally fractured basement reservoir, transition time between coning and channelling are fairly short if producing at excessive rates. Therefore, it is essential to constantly update the Chan's plots to stay tuned with the reservoir performance, thus optimising production.

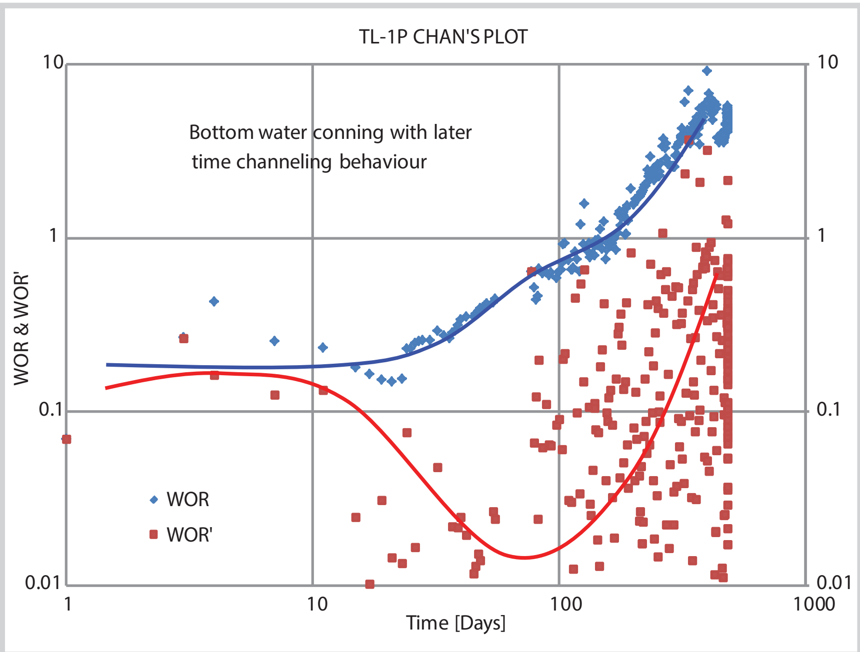
In a broader view, the more application to the fractured basement wells with longer production history and production rates is paramount to improve the accuracy of the assessment. By far, they are a much simple approach for daily operation monitoring.

6. Conclusions and recommendations

The graphical methods in analysing produced water help determine sources of water production in the naturally fractured basement reservoir in Cuu Long basin. The shift of the envelope in Stiff diagram was exhibited in three main phases:



(a)



(b)

Figure 9. *Seismic cross section through TL-1P and Chan's diagnostic plot*

phase (1) drilling mud loss, phase (2) formation water and phase (3) additional water influx;

When determining the water-out mechanism, K.S.Chan's diagnostic plots indicate whether it is coning or channelling and the transition time if applicable;

A general trend of water from the naturally fractured basement reservoir in Thang Long field has been developed in a hope to be a source for reference in dynamic Cuu Long basin analysis;

The more applications the better accuracy level of the reservoir performance monitoring by these approach.

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