A New Chlorine Logging Tool: Application In The Oilfield Development With High Salinity Formation Water

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SUMMARY: Chlorine spectrum well logging tool has been regarded as the important tool in determination of waterflooding intensity of formation intervals, especially in the oilfield development stages with high salinity formation water. However, the accuracy needs to be improved. A new chlorine spectrum logging tool with two detectors has been developed. The short (near) detector uses a He-3 counter tube to measure formation epithermal neutron intensity, the long (far) detector uses a BGO crystal detector to replace traditional NaI detector for measuring the captured gamma ray spectrum produced by the thermal neutron capture process in the formation. Energy resolution of BGO detector to gamma rays is less effective than that of NaI detector, but the efficiency of BGO detector to high energy gamma rays is much better. This advantage helps to detect captured chlorine gamma rays, which increases the ability of chlorine element detection. The effect of statistical errors is also reduced by the spectrum auto-stabilization in downhole tool. Three output curves are available simultaneously. When formation porosity is larger than 10p.u., formation water salinity is greater than 40000 PPM, the resolution to the oil/water- bearings is increased to about 10% compare with the old version tool. Field tests verify the results of waterflooding intensity evaluation.

1.INTRODUCTION

Water injection method in the production of oilfields is a common method widely used in many countries in order to improve recovery efficiently and increase the oil production rate from subsurface formations. China is one of the country that has biggest market of water injection development (under waterflooding) in oilfields. For a steady and high productivity of oil, an important work for Chinese log analysts to do is how to monitor the reservoir dynamic performance, to determine waterflooded intervals, to evaluate the remaining oil saturation (ROS) and its distribution in the subformations, this will contribute to the stable production of the oilfield.

During the development of the oilfield, ROS is determined with well logging method in cased borehloes. Because of the differences in formation water salinity, carbon/oxygen logging method (C/O log) or pulsed neutron capture logging (PNCL) are routinely used to evaluate formation ROS. But the oilfields with high salinity formation water, application of chlorine spectrum logging is more practical.

Different from the old chlorinilog developed in later sixty ,chlorine spectrum logging tool uses two detectors for the measurement of formation properties, measurements are also different form shale compensated chlorine logging routinely used in the Gulf of Mexico ,Texas, U.S.. New chlorine spectrum logging tool not only detects distribution of thermal neutron, but also analyze characteristics of captured gamma rays of chlorine element in the formations.

2.NEW CHLORINE SPECTRUM LOGGING TOOL

Basic Structure

The logging tool is composed of four parts, sensor assembly (source and detectors), electronic control section, telemetry cartridge, and surface computer software control and interpretation system. In the sensor assembly, there is a neutron source cell and two detectors, the structure schematic is shown in figure1. neutron source used is a sealed isotope Am-Be source. Short detector is a He-3 counter tube, source to detector spacing is 45 cm. long detector consists of a BGO crystal, size of $\Phi 50x100mm$, and a photomultiplier.

Principle of Measurement

Fast neutrons with average energy of 4.5 MeV emitted from a neutron source interact with the elements in the formation. These neutrons are slowdown by the elements contained in the formation matrix and fluids in the pores, and are slowly become to thermal neutrons . The thermal neutrons are finally captured by atomic nucleus of elements in the formation. During the capture process, specific energy gamma rays are emitted. When the fast neutron are slowdown , some thermal neutrons are scattered to the formation areas near the sensors and detected by thermal neutron detector. However, part of captured gamma rays are also scattered to the sensors and detected by scintillation detector. If there are two formations of same lithology and porosity, but different in the content of chlorine element in pore fluids. i.e. the salinity of formation water in the two formations are different. When two formation are logged, two significant different results are obtained. First, the thermal neutron counts in chlorine formation will less than that of formation with no chlorine element, this is because the chlorine element has a bigger thermal neutron capture cross-section. some of the thermal neutrons in the formation are captured , so the flux of thermal neutron decreases. Second, gamma rays counts detected in the chlorine energy window in the gamma ray spectrum are also different. Gamma rays counts in chlorine formation is greater than that of the formation with no chlorine element (figure.2). The reason is that when a thermal neutron is captured by a chlorine atom , it emits gamma rays with specific energy. The gamma rays almost fall into a higher energy window. In order to reduce the influences of casing ,cement, and other elements in the formation to the captured gamma rays ,only those gamma rays fallen into energy window of 3.5 to 6.5 MeV are recorded.

Suppose in formation i , $(N_{cl})_i$ represents the gamma rays counts of captured chlorine element, $(N_n)_i$ is the thermal neutron counts , $(A_{cl})_i$ is the chlorine element content , η is the tool's sensitivity to the detection of chlorine element in the formation. There are three ways to find out the value of η,

$$\eta_1 = \frac{(N_{cl})_i - (N_{cl})_0}{(A_{cl})_i - (A_{cl})_0} \quad (1)$$

$$\eta_2 = \frac{(N_n)_i - (N_n)_0}{(A_{cl})_i - (A_{cl})_0} \quad (2)$$

$$\eta_3 = \frac{(N_{cl})_i/(N_n)_i - (N_{cl})_0/(N_n)_0}{(A_{cl})_i - (A_{cl})_0} \quad (3)$$

Obviously, η_3 is the biggest value, this means with the use of ratio of captured chlorine gamma ray counts to thermal neutron counts, the best sensitivity of the detection for chlorine element is achieved. This is an unique advantage of new chlorine spectrum logging tool over other chlorine logging tools .

New Crystal detector

Because the main portion of captured chlorine gamma rays are in high energy window, if the detecting efficiency to the high energy gamma rays could be improved, the measuring accuracy of the tool can be increased. A new crystal detector ,BGO, is selected to replace traditional NaI crystal in the downhole tool.The detail specification and comparison of new and old detectors are listed in table 1.

From table 1, one can see that the density and effective atomic number of BGO crystal is greater than that of NaI crystal ,which means the detecting efficiency to the gamma rays, especially high energy gamma rays, is much improved. Although the energy discrimination of BGO crystal is less effective than that of NaI detector, this has a little effect for the detection of high energy chlorine captured gamma rays. Many experiments have shown that the chlorine captured gamma ray counts with BGO detector is 1.5 or 2 times compare to that of NaI detector. Using new detector improves the measuring accuracy of logging tool greatly.

However, there are some disadvantages with the use of BGO detector. Because the temperature feature of BGO crystal is not stable, the whole detector system must be kept in a dewar flask. Furthermore, an automatic spectrum stabilizer is used to improve the stabilization of the downhole tool. This is accomplished in measuring the reference peak of a standard gamma ray source in the downhole. The data representing standard gamma ray peak are transmitted upto the surface computer and processed, then the feedback control data are transmitted downto the downhole tool to adjust the high voltage of detector. By doing so, the shifting of gamma ray peaks detected is minimized. This makes tool high in detecting sensitivity, good in performance.

Main Specifications

The main specification of new chlorine spectrum logging tool is given as follows.

Downhole tool length : 3000 mm,

Tool diameter : 102 mm

Pressure rating : 80 Mpa.

Temperature rating : 150 C°

Logging speed : 200 m/h

Three logs are recorded simultaneously with a single logging run, they are porosity(Φ), intensity of captured Chlorine gamma rays (I_{cl}), and ratio of (I_{cl}/I_n).

3.GEOLOGICAL DATA RESPONSE OF NEW LOGGING TOOL

Theory and experiment have shown that new chlorine spectrum logging tool can be used for the determination of formation porosity, chlorine ion salinity in the formation fluid, and remaining oil saturation in the cased borehole.

Lithology response

Many experiments have been conducted in the model wells (test pits) filled with fresh water, table 2 shows one of the results.

From the data in table 2, a crossplot about correlation of I_n and I_{cl} is drawn in figure 3.

From figure 3, we find all experiment data of different lithologies shows a linear response. Using linear fitting algorithm, a linear response is derived :

$$N_{cl} = AN_n + B \qquad (4)$$

with correlation factor of 0.998.Coefficients A and B can be obtained by the calibrations in the model wells.

Downhole tool calibration

Downhole tool must be calibrated first before logging. For the calibration of downhole tool, there are three steps to follow:

(1).Response coefficiency to lithology:

Three model wells, namely *M1,M2* and *M3* as indicated in table 2, are used for calibration. There is a borehole of diameter of 206 mm in each well. Inside each borehole, there is a steel casing with inner diameter 13.97 mm(5.5 inches) and thickness of 9.17mm. There is a cement between the casing and borehole. Downhole tool is put inside the casing for calibration.

We can get three responses in these wells,

$$N_{cl}(M_1) = aN_n(M_1) + b \tag{5}$$

$$N_{cl}(M_2) = aN_n(M_2) + b \tag{6}$$

$$N_{cl}(M_3) = aN_n(M_3) + b \tag{7}$$

This is a set of over-estimated equations, with least square regression, coefficients a, b can be computed.

(2). Calibration factor

The chlorine counts measured in model well *M2* is defined as 100 units of the intensity of chlorine gamma rays (*CI*), intensity of chlorine gamma ray with this unit is labeled as I_{cl}. i.e.,

$$I = 100(CI) = CN_{cl}(M_2) \tag{8}$$

so, coefficient *C* can be written as:

$$C = 100(CI) / N_{cl}(M_2) \tag{9}$$

$$I_{cl} = CN_{cl} \tag{10}$$

dimension of above calibration unit is still the counts per second (CPS), it does not matter whether gamma ray or neutron is measured. For the convenience of log interpretation, we use the intensity of thermal neutron (I_n) as above calibration unit. We have

$$I_n = C(aN_n + b) \tag{11}$$

(3).After transformation of unit for the counts

of chlorine captured gamma rays and thermal neutron, a correlation in fresh water or oil-bearing zone (no chlorine content) can be expressed as

$$I_{cl} = I_n \tag{12}$$

3. Tool response to formation porosity

It has been proven from both theory and experiment that "neutron-neutron" logging or "neutron-gamma ray " logging has an exponent response relations to porosity in formation with fresh water.

$$\ln\Phi = AI_{cl} + B \tag{13}$$

$$\ln\Phi = A'I_{cl} + B' \tag{14}$$

In the formation with high salinity water, because of the effect of chlorine element ,porosity computed with equation (13) will give a lower value, but equation (14) will give a higher value.

Add equation(13) with equation (14), we get

$$\ln\Phi = \frac{A}{2}\left(I_{cl} + \frac{A'}{A}I_N\right) + (B + B') \tag{15}$$

equation (14) can be rewritten to

$$\ln\Phi = \frac{A}{2}(I_{cl} + \varepsilon I_n) + k \tag{16}$$

many experiments show that value of ε is near to 1 when calculating porosity with equation (16) in formation with high salinity formation water. Porosity calculated is less effected by formation salinity.

Tool response to chlorine ions in formation fluids

A lot of experiments have been done and data

are plotted in figure 4.
The best fitting response is as follows

$$P = W(1-\Phi)(\frac{I_c}{I_n}-1)/\Phi \qquad (17)$$

So, the formation water saturation Sw is given by

$$S_w = P / P_w \qquad (18)$$

where Pw is formation water salinity . Pw can be obtained form the water analysis data in particular oilfield.

In log interpretation, the coefficients of A, k in equation (16) and W in equation (17) can be statistically determined from the tool measurement in cored wells.

4.APPLICATIONS

Water injection development in one of the oilfield with high formation salinity water has more than twenty years in south of China. Now the oilfield has come to the second stage of development, many formations have been waterflooded with different water intensity. Determination of remain oil saturation is a critical problem to be solved. More than thirty wells have been logged with new chlorine spectrum logging tool. Good geological results have shown that the tool has a high successful operation rate. The tool is less effect by formation lithology and shale content when determining formation remaining oil saturation in the waterflooded intervals. Evaluation of remaining oil saturation has a high accuracy. For the formations with porosity of 20% , when formation water salinity is greater than 110,000 ppm, the error of water saturation estimation is less than 10%. The identification of the tool to the oil and water-bearing zones with the use of BGO detector is increased by 10% compared with the use of NaI detector .

Determination of waterflooded formations

Example 1: Well no. GXX 5-12 in JH oilfield, as shown in figure 5.The depth of this well is 3300 meter, chlorine spectrum log interpretation shows that there are two oil zones at depth of 3266-3267.5m and 3272-3274m, and one medium waterflooded zone at depth of 3287.5-3290m. First , above two oil zones are perforated and tested, with oil production of 1 ton/day. The interpretation agrees with the well testing. Several month later the two oil zones are hydraulic factured, many water produced come out from these two zones. After running a isotope trace log, it is founded that there is channeling between oil zones and waterflooded zone .

Example 2: Well no. WXX-5, as shown in figure 6. There are four interest zones at depth of 1422.2-1423.6m,1424.0-1426.4m,1427.8-1429.0m,1429.8-1430.8m. Routine log and neutron lifetime log interpretation show these four zones are pay zones, but chlorine spectrum log shows that the first two are pay zones, the third and last zones have been highly waterflooded. After perforation to these four zones, two days later, they produce oil and water 5.7, 0.5 tons a day respectively , watercut is 8%, six days later, with oil 12.9 tons, water 2.8 tons, watercut 18%. One month later, it becomes oil 5.3 tons, water 6.2 tons, watercut 54%. Chlorine log interpretation agrees with well production data.

Determination of remain oil saturation

Example 3: Well no. 36 MXX 4-61, as shown in figure 7. This is an infill well, the depth is 1480 meter, there are 11 thin oil-bearing interbeded zones. Log interpretation is difficult. Chlorine spectrum log interpretation in these zones shows good agreement with integrated log evaluation. ROS and porosity data calculated are reliable as compare with core data.

5.SUMMARY

It is a good tool for the evaluation of remaining oil saturation in the formation , new chlorine spectrum logging tool must be used in the oilfields with high salinity formation water. It give good indications in the cased borehole with formation porosity greater 10% and water salinity greater 40000 PPM. The favorable condition for the tool's application is the formation porosity of 15%, formation water salinity of 80000 (or more), good geological results can be obtained as expected.

6.ACKNOWLEDGEMENTS

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7.REFERENCES

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Table1: specification and comparison of new and old detectors

Detector Crystal Material	Size diameter,length (mm)	Density (g/cm3)	Effective atomic number.	Energy resolution*
BGO	50 x 100	7.13	75	9.3%
NaI	50 x 100	3.67	51	6.5%

*resolution of 1g/cm3 crystal to gamma ray of 622 MeV.

Table2: one of the results of lithology response in the calibration wells

lithology	limestone					dolomite					sandstone				
well nubmer	M1	M2	M6	M26	M31	M15	M8	M5	M10	M34	M12	M11	M4	M7	M30
porosity(%)	35.7	16.5	1.0	6.8	25.2	15.2	25.4	8.8	1.6	32.8	18.0	39	10.8	25.0	7.7
N_n	236	458	112	701	346	446	329	570	991	268	465	239	712	385	780
N_{cl}	68	138	318	200	102	122	88	157	267	73	135	69	207	108	231

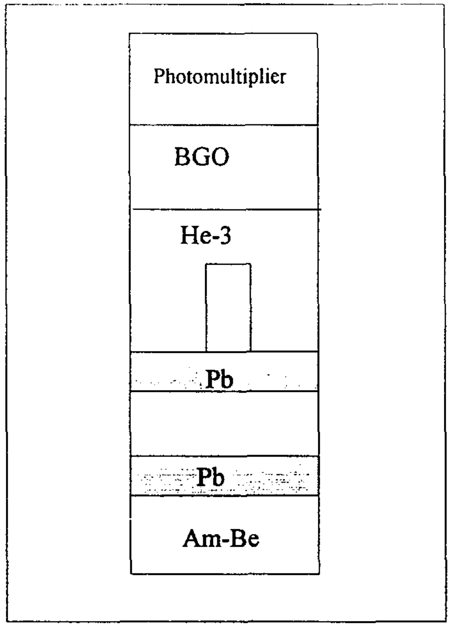

Figure 1, Schematic diagram of detctor.

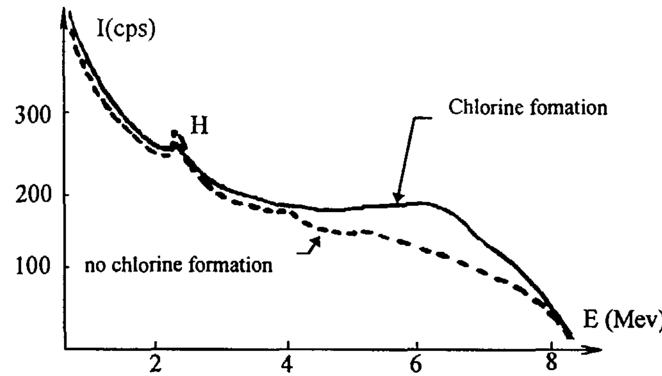

Figure 2, Gamma ray spectrum in formations with and without chlorine elements.

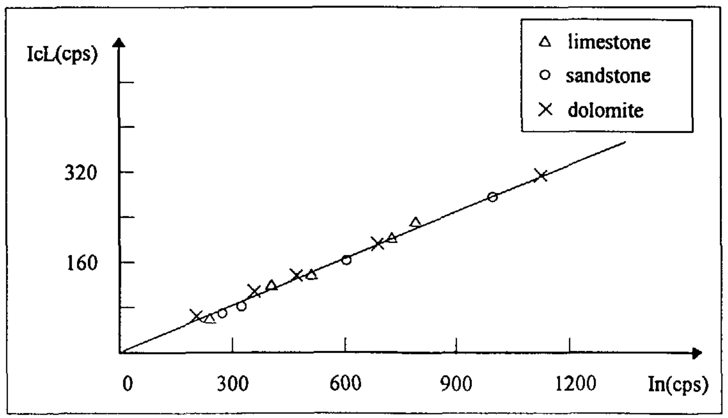

Figure 3, Correlation of In and Icl in different lithologies.

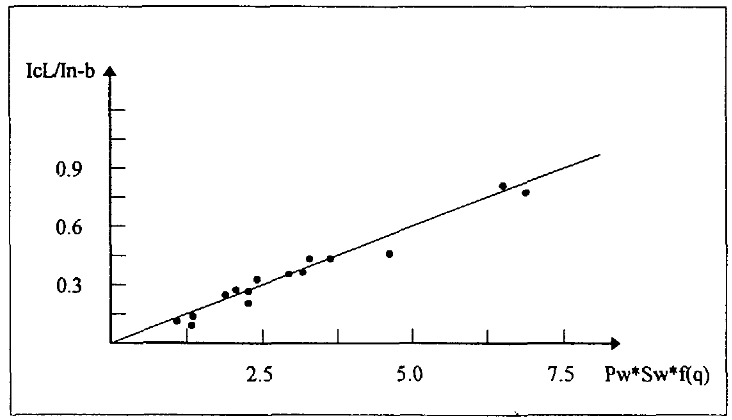

Figure 4, Tool response to chlorine ions in formation fluids.

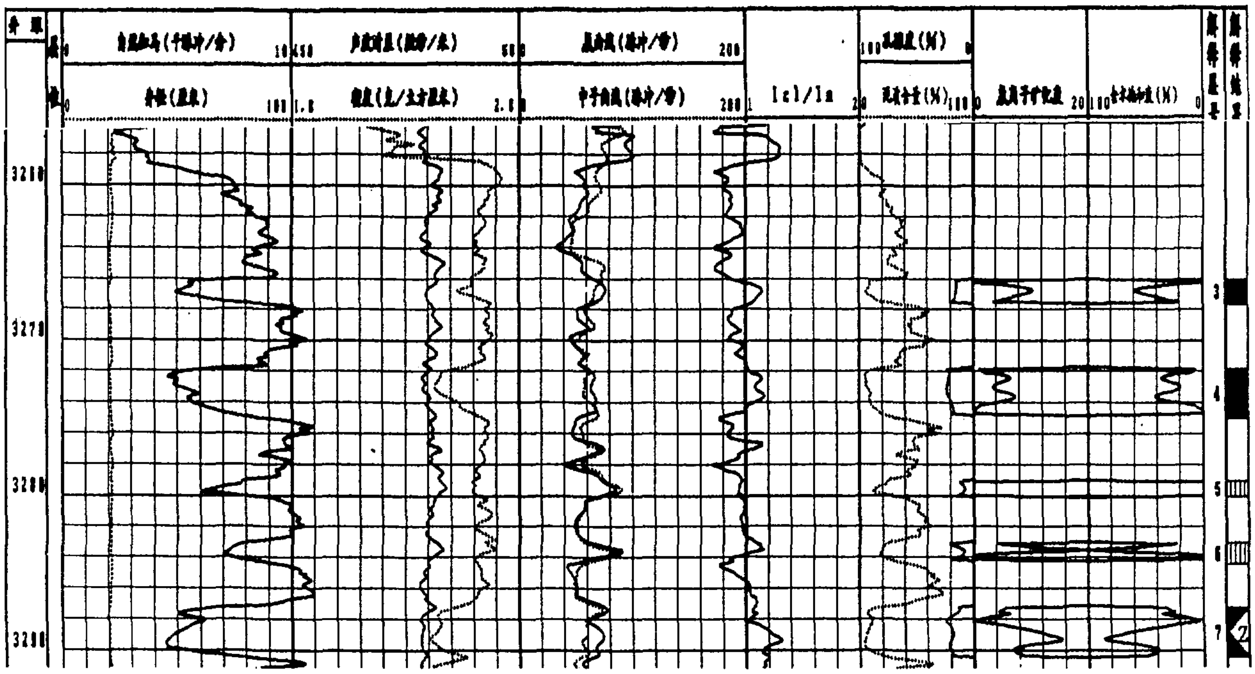

Figure 5, determination of waterflooded formations. zone3, 4 are oil zones, zone 5,6 medium waterflooded.

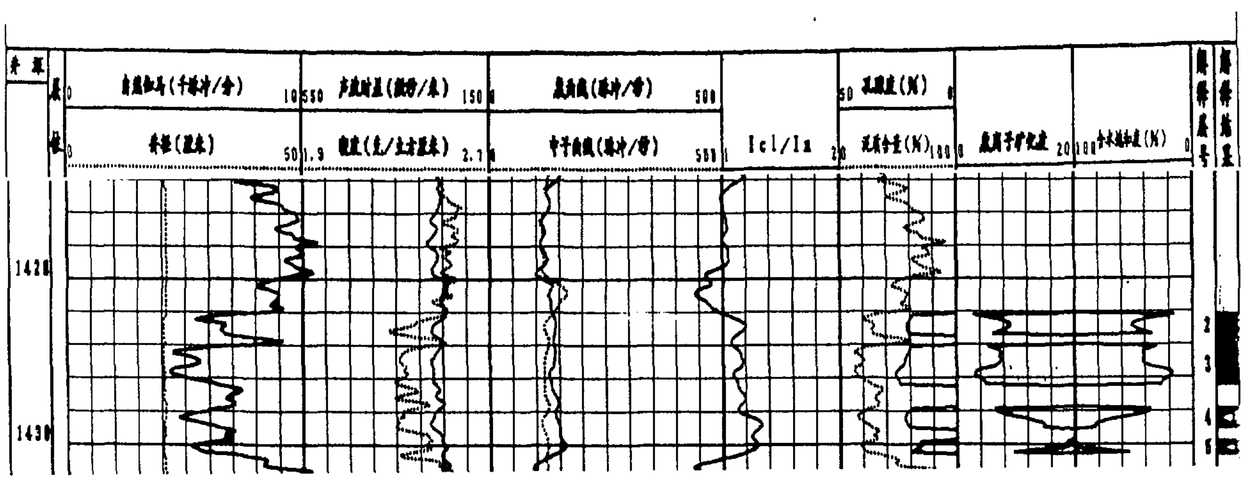

Figure 6, Routine log and NLL log show four zones are pay zones, but Chlorine spectrum log shows that third and last zones have been highly waterflooded.

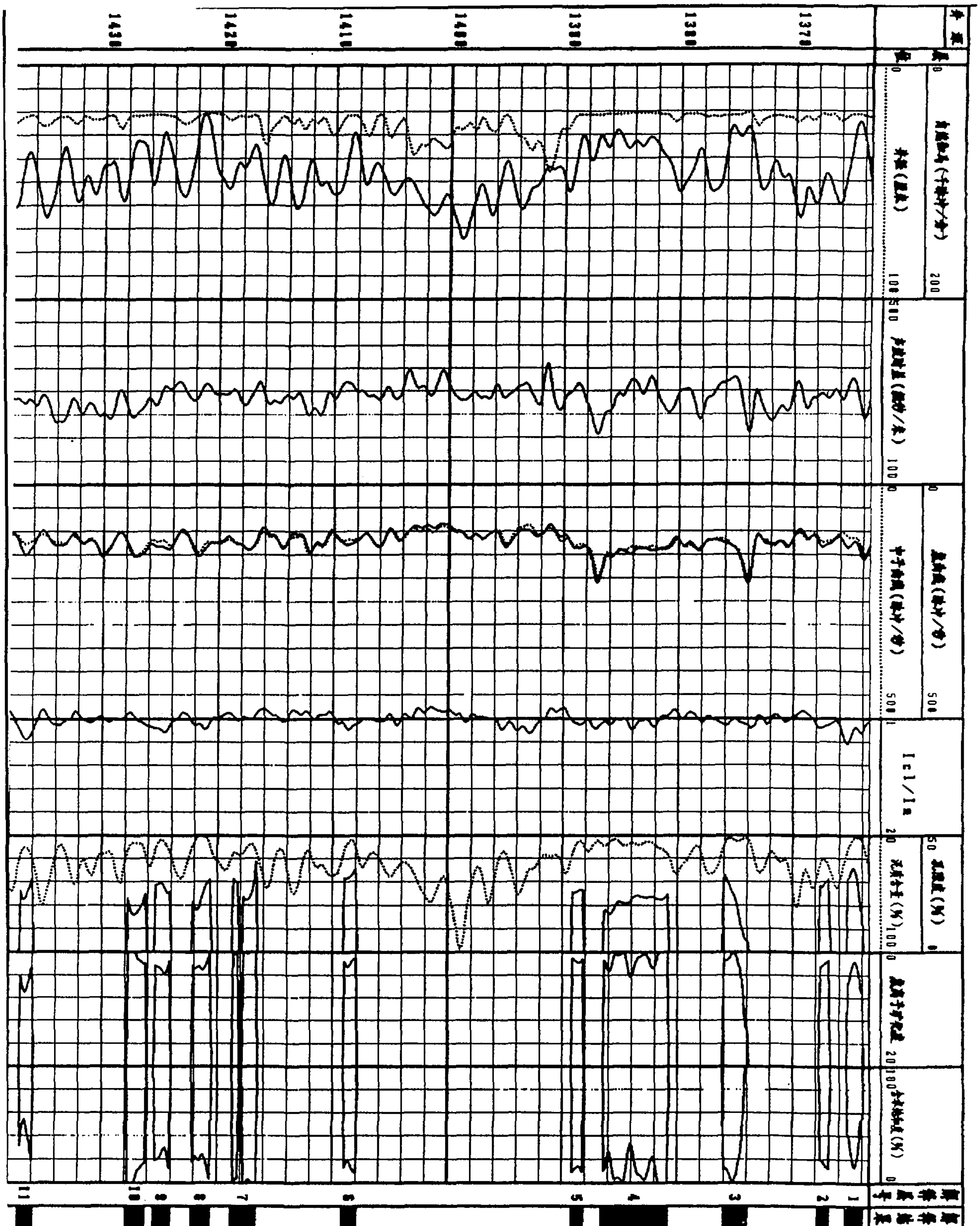

Figure 7, Determination of remaining oil saturation. Eleven thin oil-bearing interbeded zones, chlorine spectrum log interpretation shows good agreement with integrated log evaluation.