CHAPTER TWO

Identification and Evaluation of Low Resistivity Pay Zones

2.1 Distribution of low-resistivity pay zones (China as an example):

With more and more oil exploration aiming at the stratigraphic traps and complicated reservoirs, as well as the re-exploration of the mature oil fields, and with the deepening understanding of the petrophysical characteristics of various complicated reservoirs, more and more low resistivity pay zones have been discovered in China in the last few years. Based on the statistics compiled by Petro China, 30-60% of the hydrocarbon reservoirs newly discovered in seven new exploration blocks of four mature oil fields, located in Bohai Bay Basin, could be classified as LRP zones.

2.2 Genetic types of low-resistivity pays:

The low resistivity pays, discovered by Petro China in the Bohai Bay Basin Junggar Basin, and Tarim Basin in the last few years, are classified into three types based on their genesis (Mao, 1999).

2.2.1 Conductivity of clay:

The LRP zone caused by clay conductivity is most common, especially in the Neogene formations in the Bohai Bay Basin, the Triassic formation in northern Tarim Basin, and in the Cretaceous formation in the Junggar Basin. These formations all possess mixed layer smectites and illites, characterized by the highcatiol1 exchange capacity (CEC). Their electrical resistivities are relatively low, some even close to that of the adjacent water formation. Fig. (2.1) shows the composite well log curves of low resistivity pay in a well located in Jidong Oilfield, Bohai Bay Basin. Zone No.l8 (x828-x841 m) in the upper part of the section is a low resistivity pay with deep resistivity log readings from 4 to 6.8 ohm.m exhibiting a resistivity index of 1 to 1.6 compared with that of water zone No.20 (x854-x862 m) in the lower part of the section. The resistivity of layer x828-x831m of the low resistivity pay equals that of water zone in the lower part. An oil production of 20 t/day was obtained by Dril1 Stem Test (DST) in the interval from x828 to x836 m. This type of low resistivity and low-contrast pay was also found in other fields in the Bohai Bay Basin. It is mainly distributed in the Neogene formation, which is characterized by low water salinity, with smectite c1ay and a high CEC. Fig. (2.2) is the histogram of relative clay content in sandstones of the Neogene formation in Jidong Oilfield. Obviously, smectite is the predominant clay in the formation.

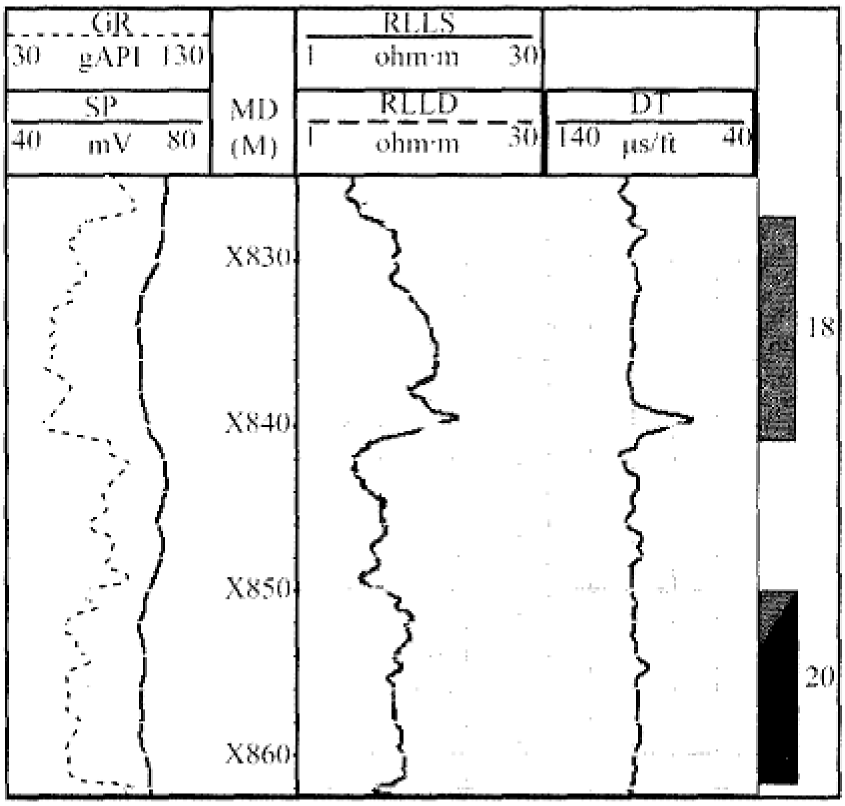

Fig (2.l) Log response of LRP in Neogene sandstone, (Mao Zhiqian, 2007).

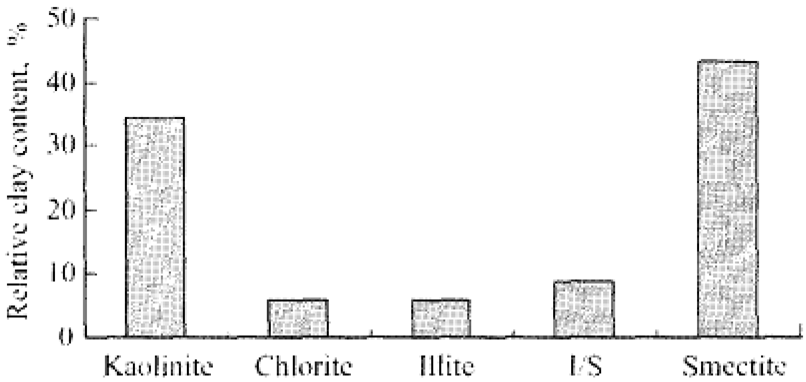

Fig (2.2) Relative content of clay in Neogene sandstone from (Mao Zhiqian, 2007).

This type of low resistivity pay caused mainly by clay conductivity was also found in the Triassic sandstone formation with high salinity of water in northern Tarim Basin. The log response is shown in Fig (2.3).

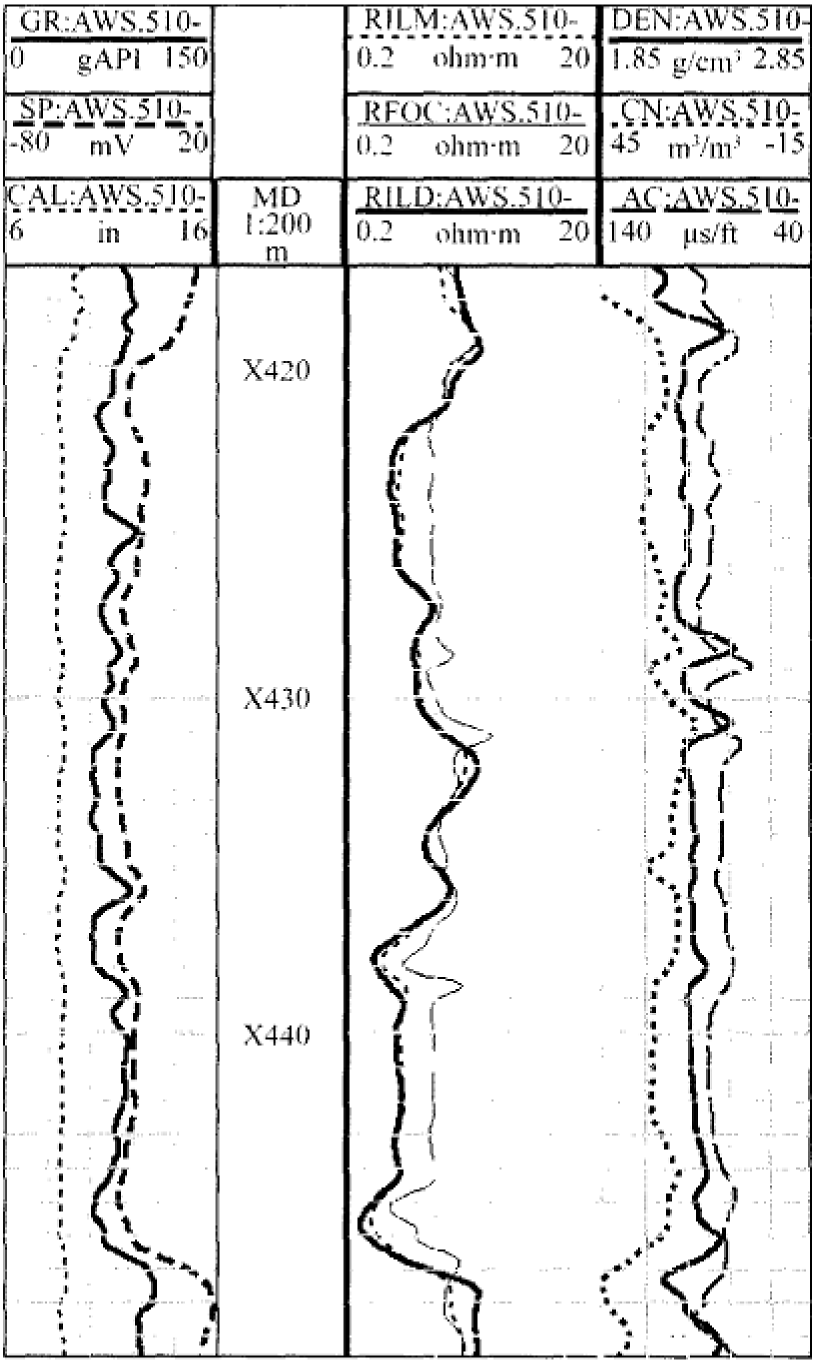

Fig (2.3) Composite log curves of LRP in Triassic Sandstone (Mao Zhiqian, 2007).

The deep induction reading is about 0.3 ohm.m in water zone below x446 m, while the resistivity of the pay zone at x422-x426 m is only 0.4 ohm.m Recognition of this type of low resistivity pays, occurring in high salinity of formation, took a long time since the clay conductivity had been ignored.

2.2.2 Micro porosity and high irreducible water saturation:

This type of low-resistivity pay is often developed in silt sandstones or sandstone with medium to high shale content. The main features of these low-resistivity pays are the abundant micro-porosity and high irreducible brine saturation resulted from cementation, clay coating or clay bridging within pores. It usual1y has an irreducible water saturation exceeding 50%. This type of LRP is mainly distributed in the Paleogene sandstone formation in the Bohai Bay Basin. The main difference of this type of LRPs from the ones caused by clay conductivity is that the formation contains clay minerals with low cation exchange capacity (CEC).

2.2.3 Deep invasion of high salinity filtrate:

Water salinity is generally low (less than 10,000 mg/l) in the Neogene formation in the Bohai Bay Basins. In some exploration areas, high salinity seawater-based dri11ing fluids were used. The deep invasion and long immersion in high salinity filtrate resulted in deep resistivity log readings much lower than the actual ones of pay zone. Meanwhile, the low salinity water zone was immersed in high salinity dri11ing mud for a long time, resulting in increasing salinity of water zone through diffusion, and hence decreasing the resistivity of water zone. This kind of low-resistivity pay was mainly discovered in offshore regions in the Bohai Bay Basin, where seawater-based mud was used as dri1ling fluids. This by-passed pay zone has become the re-exploration targets in many mature oil fields.

2.3 Distribution of low-resistivity pay zones (Sudan an example):

Block- 6 is located at NW part of Muglad Basin of Sudan. It lies approximately 750KM southwest of Khartoum and 1500KM from Port Sudan. Seven oil fields were discovered in the Block. The main oil fields are Great Fula and Great Moga from which 40000 BOPD of crude oil are producing.

Low resistivity is defined as the deep resistivity (RD) reading is 8-10 (ohm-m) for pay zones in Aradeiba reservoir. Low contrast pay occurs mainly when formation water are fresh or low salinity in Abu Gabra reservoir. Clay contributes to low -resistivity reading depend on the type, volume and distribution of clay in the formation.

2.3.1 Low resistivity in Aradeiba reservoir:

Aradeiba reservoir with thick shale intervals , sand in between, characterized by shallow burial depth, loose consolidation, good porosity and permeability, high sand production and low formation pressure, and the crude oils are characterized by high density and high viscosity.

Main petrophysical problem is low resistivity pay zones Fig. (2.4) and Fig. (2.5) show Well log and the Master log of low resistivity oil zone in Aredeiba, respectively.

Reservoir Normal oil zone in Aredeiba Reservoir in Fula north oil field, RD>30(ohm-m). Where:

RD=80ohm-m Rmsfl=2ohm-m

Normal water zone in Aredeiba Reservoir in Fula north oil field, RD 10-20(ohm-m). Where

RD=10ohm-m

Low resistivity oil zone in Aredeiba Reservoir in Fula north oil field, RD 8-10 ohm-m. Where:

RD=10ohm-m Rmsfl=1ohm-m

Test interval (1193.5-1211.0m) Test result: oil

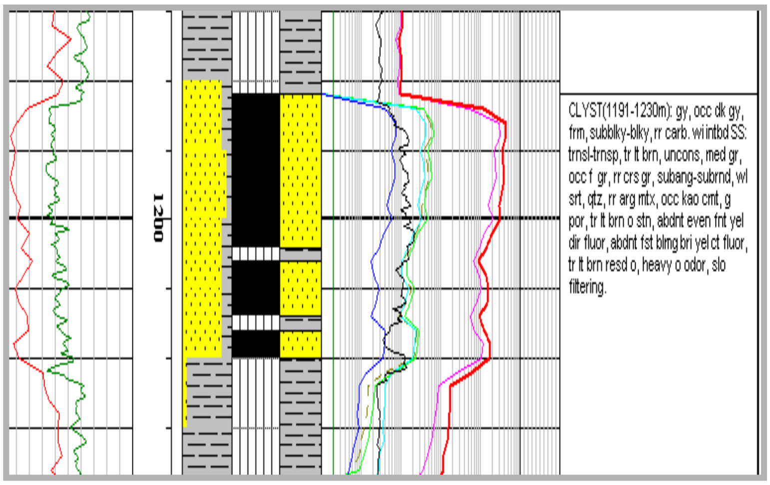

Fig. (2.4) Master log of low resistivity oil zone in Aredeiba Reservoir, (Eltayeb Adam, 2007)

Test interval (1193.5-1211.0m) Test result: oil

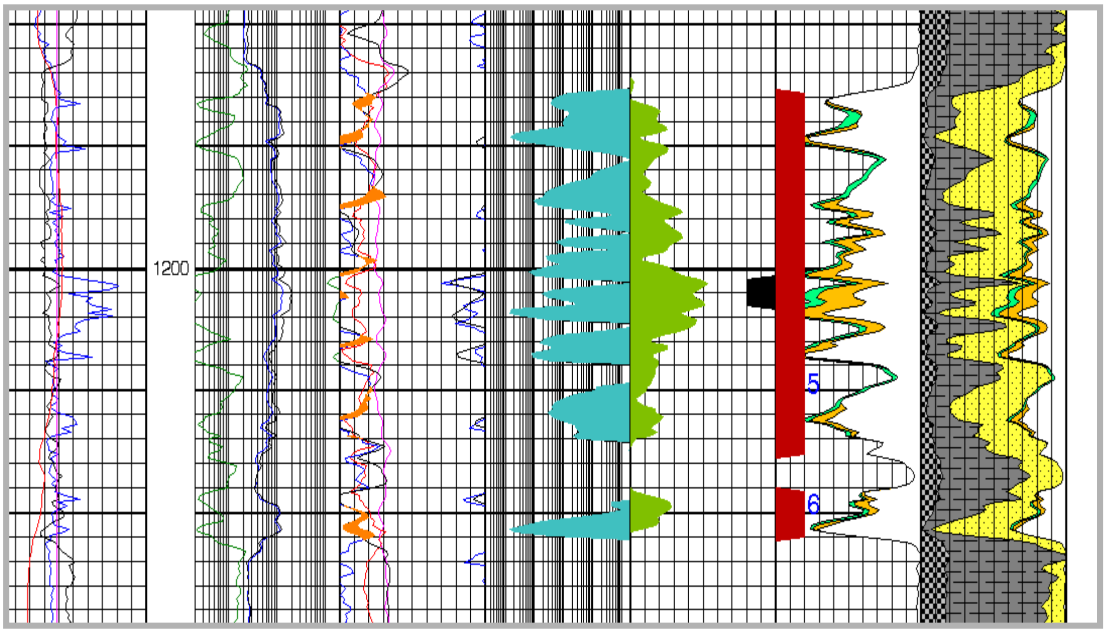

Fig. (2.5)Well log of low resistivity oil zone in Aredeiba Reservoir, (Eltayeb Adam, 2007)

2.3.2 Main reasons for the low resistivity in Aradeiba reservoir:

(i) Geological reasons:

- Clay minerals.
- Irreducible water.
- Conductive minerals.

(ii) Engineering reasons:

- Hole collapse.

Low Resistivity reading in Aredeiba reservoir not for Irreducible water (Swi).Analysis results show medium grain sizes and moderate to well sorting in Aradeiba reservoir, no conductive minerals result (it is not reason for low resistivity).Major clay kaolinite (main reason for low resistivity). Clay minerals distribution are the primary cause of the low resistivity in Aradeiba pay sand and it can form during and after deposition.

2.3.3 Low contrast resistivity in Abu Gabra reservoir:

Abu Gabra reservoir shaly sand with deep burial depth, consolidated sand, good porosity, lower part tight sand, the crude oils are low viscosity. The main petrophysical problem low contrast pay zones. Fig. (2.6) and Fig. (2.7) show Well log and the Master log of low resistivity oil zone in Abu Gabra, respectively.

Normal oil zone in Abu Gabra Reservoir in Fula north oil field, RD>30 (ohm-m). Where Test interval (1874.0-1880.1m

RD=80 ohm-m

Rmsfl=3 ohm-m

And also we have in interval (1963.0-1970.8m)

RD=90 ohm-m

Rmsfl=2 ohm-m

The water resistivity in zone in Abu Gabra Reservoir in Fula north oil field.

Where:

Test interval (1901.0-1904.5m)

Test result: water

Water Salinity=849.77 ppm

RD=30 ohm-m Rmsfl=1 ohm-m

Low contrast oil zone in Abu Gabra Reservoir in Fula north oil field. Where

Test interval (2084-2092.0m

RD=30ohmm-m Rmsfl=2ohmm-m

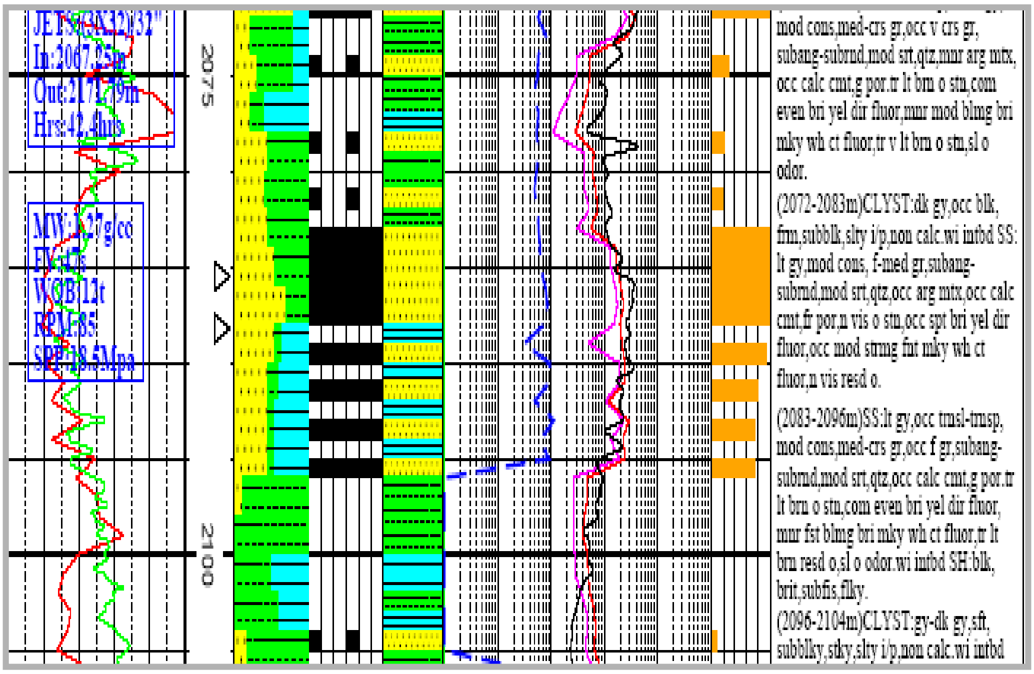

Fig. (2.6) Master log Low contrast resistivity in Abu Gabra, (Eltayeb Adam, 2007)

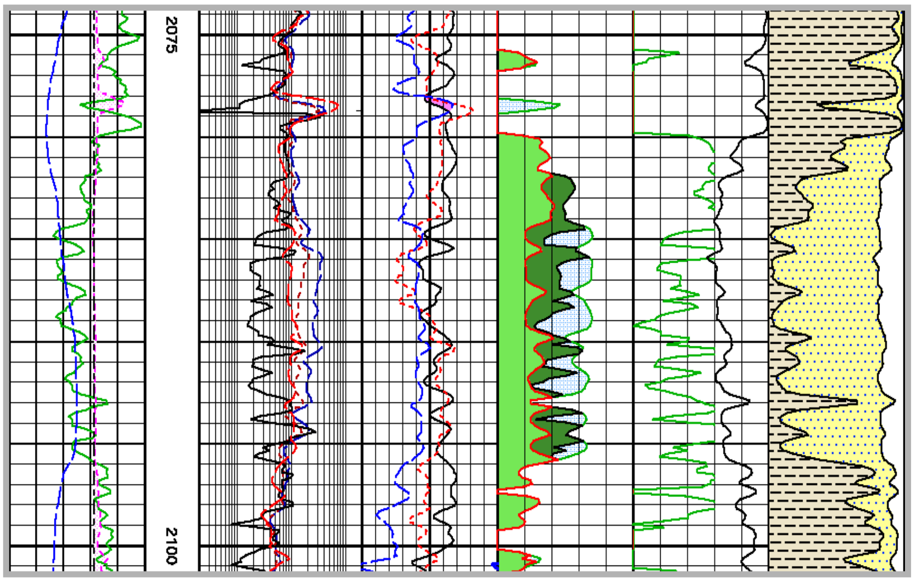

Fig. (2.7)Well logLow contrast resistivity in Abu Gabra, (Eltayeb Adam, 2007)

2.3.4 Main reasons for the low contrast resistivity in Abu Gabra reservoir:

- Shale volume.
- Fine grain.
- High invasion.

Low Resistivity Pay:

$$\mathbf{I} = \frac{\boldsymbol{RT}}{\mathbf{Ro}} \leq \mathbf{2} \qquad (\mathbf{2.1})$$

Zone Normal Pay:

$$\mathrm{I} = \frac{\mathrm{RT}}{\mathrm{Ro}} \geq 3 \qquad (2.2)$$

By definition, Ro is the resistivity of a rock with its pore space 100% saturated with water having a resistivity equal to R_w.

The value of I for a given rock sample, remains essentially constant for a wide range of R_w values encountered in reservoir rocks. This means that for a formation factor of a core may be determined from a clean water-bearing formation by measuring the resistance and physical dimensions of the core to determine its resistivity, Ro, and measuring the resistivity of the water in the rock.

2.4 Forming Mechanism of Low Resistivity Oil Zone:

2.4.1 High salinity formation water:

The relationship among formation water resistivity and salinity, Formation temperature.

$$\mathrm{Rwo} = 0.0123 + \frac{3674.5}{\mathrm{PPM}^{0.995}} \qquad (2.3)$$

$$\mathrm{Rw} = \mathrm{Rwo} * \frac{(1.8 * 24 + 39)}{(1.8 * \mathrm{T} + 39)} \qquad (2.4)$$

The following Fig (2.8) showing the relationship among formation water resistivity and salinity.

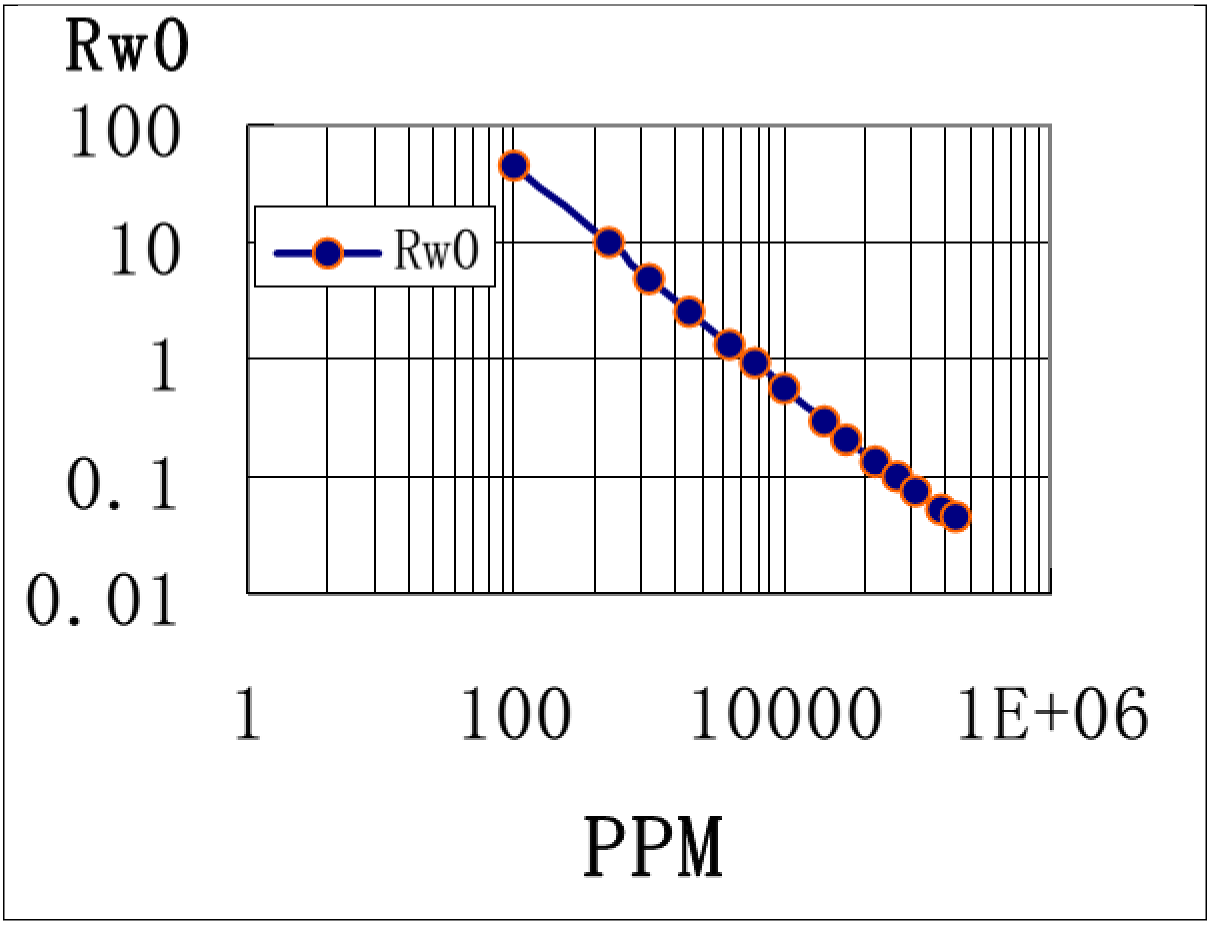

Fig (2.8) The relationship among formation water resistivity and salinity

2.4.2 High Irreducible Water Saturation:

The reason of LRLC in high irreducible water saturation are fine lithology and clay mineral.

Fine lithology makes pore diameter smaller, but micro system is developed and clay minerals such as the smectites which make great inner surface area and strongly water absorption (dilatability).

2.4.2.1 Property of low resistivity oil zone:

Lithology of LR pay is silt sand or fine sand, sediment property of such zone lie in upper part of fining upward cycles and lower part of coarsening upward cycles and Electrical property low resistivity and little difference from adjacent shale ;similar GR value with adjacent shale. Oil stored in tiny pore, water stored in micro pore which make a good production.

2.4.3 High excess conductivity of clay:

Depend on volume of the shale and its conductivity.

- **High conductivity clay**

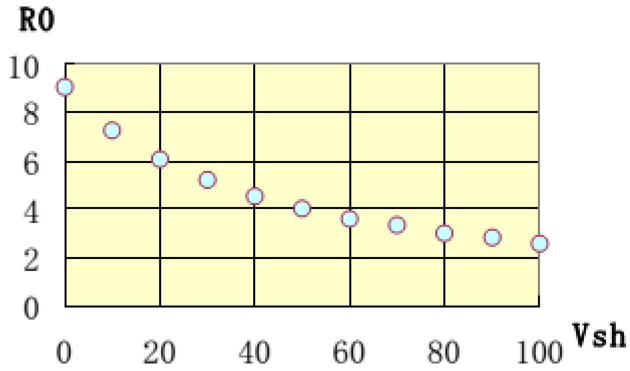

Fig (2.9) shows high conductive shale component

$$\frac{Rw}{Rwsh} = \frac{0.5}{0.2} \qquad (2.5)$$

- **Low conductivity clay**

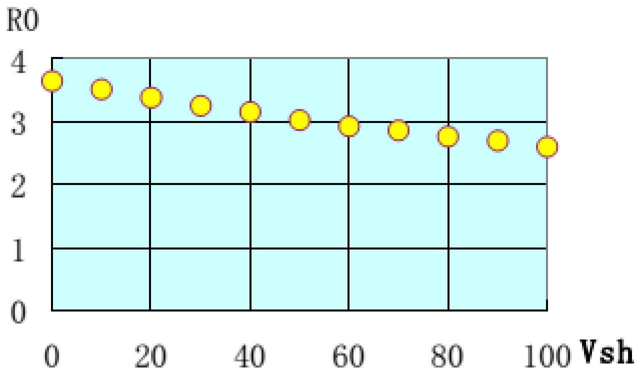

Fig (2.10) shows low conductive shale component

$$\frac{Rw}{Rwsh} = \frac{0.2}{0.5} \qquad (2.6)$$

2.4.4 Clay mineral component and content:

The presence of conductive minerals is the least cited cause of low-resistivity pay. The root of the problem is electronic conduction due to iron-bearing minerals that occur in clusters and whose concentration exceeds a critical level. Conductive minerals such as illite,

illite and smectite mixed layer and High conductivity minerals such as pyrite. For the case of pyrite as 7% by volume of the total solids. Another mineral that has been grouped in this category is glueconite, which can in many respects be regarded as a clay mineral. However, here it is seen as iron-bearing mica with a potential excess conductivity over and above any conductivity enhancement due solely to textural effects, volcanic tuffs have been cited as showing an excess conductivity beyond that predicted from electrochemical phenomena .Conductive minerals can co-exist with other causes of low resistivity pay.

In the context of conductive minerals, the low-resistivity pay problem reduces to correctly evaluating the water saturation. There is no generally accepted way of handling data from electronically conducting reservoirs. A first step towards recognizing the problem is to measure the conductivity of oven-dried core plugs. If the dry conductivity is finite, there will be a problem to investigate. If the dry conductivity is infinite, there could still be a problem, because the conductivity enhancement by clusters of iron-rich minerals might only become significant in the wet state. In this case, the concentration of metallic minerals should be investigated it is supercritical.

2.4.5 Fine-grained sands:

In context of fine-grained sands, the low-resistivity pay problem has two faces. First, the fines can act as a separate mineral even if they are comprised principally of quartz. This fact takes the form of non-trivial .surface conductance arising from a large pore surface area and giving arising to significant excess conductivity that has to be accommodated in the water-saturation algorithms . Second, the fines are associated with a high irreducible water saturation, which is present as a continuous phase and therefore raises the reservoir conductivity. The first stage is validate the proposed water saturation algorithms. The second stage is to evaluate the free fluid fraction of the pore space. This has usually done by referring interpreted water saturation to the irreducible water saturation for that particular group of sands, or more directly, by evaluating movable hydrocarbon on a level-by-level basis. The most common method for the evaluation of movable hydrocarbon entails a comparison of the characteristics of the flushed and undisturbed zones, possibly drawing on the self-potential (SP) log . Figure (2.11) shows how log run in Yabus Formation described as fairly clean, fine-grained sand.

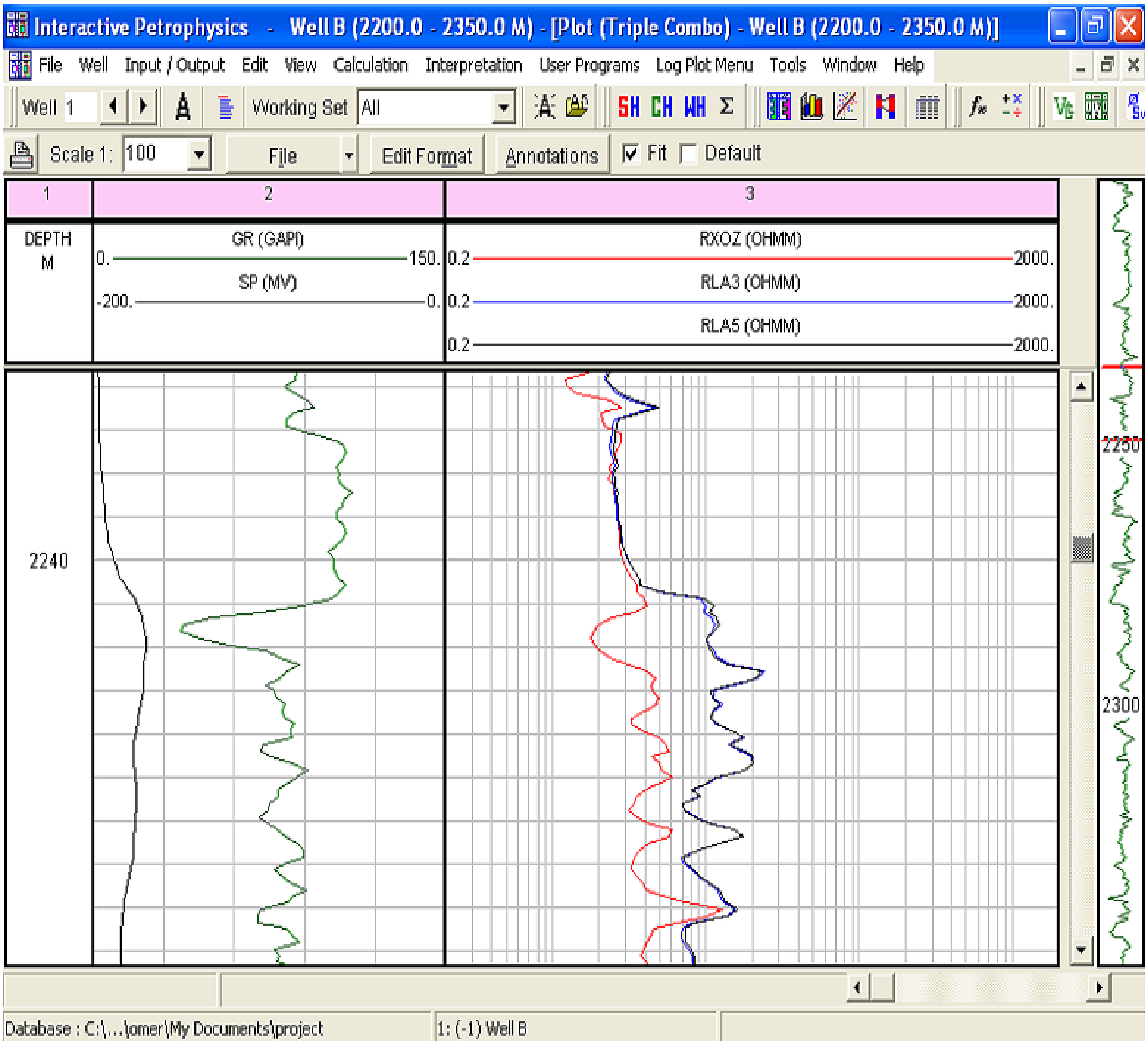

Fig. (2.11) wireline logs from a fairly clean, fined grained reservoir. The LRC between water and oil legs is due to the high capillarity.