THE DISCOVERY AND DEVELOPMENT OF OIL RIM FIELDS IN THE BEIBU GULF, CHINA

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SUMMARY

The Beibu Gulf is a prolific hydrocarbon province on the western coastline of China. The Miocene Jiaowei Formation contains thick sandstone sequences with excellent reservoir quality, a low degree of internal heterogeneity and excellent aquifer support. Structures are low relief causing many discoveries to be classified as thin oil rim fields (<15m oil columns with bottom-water drive). These discoveries have moderate to heavy oils with low gas-oil ratios and moderate to high oil viscosities. The combination of these rock and fluid properties are ideal conditions for rapid water coning, hence early well water breakthrough and low oil recovery factors. However, multiple fields in the Beibu Gulf significantly exceed pre-development production expectations. Closer inspection of core and log data indicates there is often a dolomitic alteration zone at the oil-water contacts with permeabilities typically 2 to 3 order of magnitudes lower than the hydrocarbon-bearing reservoir which act as effective aquitards to slow the onset of water breakthrough. The diagenesis is theorized to be due to microbial decomposition of hydrocarbons at the oil-water interface which accrete dolomitic cements as a by-product. Seismic inversion and amplitude mapping reinforce the view that the alteration zones are pervasive and flat-lying. Case studies are presented covering the discovery, development and production performance of three oil rim fields in the Beibu Gulf.

Key words: Beibu Gulf, Jiaowei Formation, oil rim fields, oil-water interface diagenesis

INTRODUCTION

Oil rim reservoirs are characterised by oil columns of limited thickness (less than 25m), underlain by an aquifer and often overlain by significant a gas cap (Masoudi, 2012; Kolbikov, 2012). Typical recovery factors from these reservoirs are low, rarely exceeding 18%, due to rapid coning and early breakthroughs from gas and/or water, and oil smearing upwards into depleted gas caps. Each one of these reservoirs poses its own unique challenges for planning, development and reservoir management (Lawal et al., 2010). Key reservoir considerations include reservoir and oil column thickness, horizontal and vertical permeability, oil viscosity, size of gas cap, degree of heterogeneity and bed dip uncertainty, and strength of aquifer (Masoudi, 2012). Many issues of these issues can be offset by a suitable development strategy which often includes multiple horizontal wells and laterals with considerable reservoir contact and appropriate placements between gas-oil and oil-water contacts.

The Jiaowei Formation in the Beibuwan Basin is a prolific hydrocarbon bearing formation typically characterised by extensive, high quality massive sandstone reservoirs with low relief structures and minor faulting. Virtually all fields discovered within this formation are characterised as oil rim fields with minor gas caps and strong bottom-water aquifer drive. However, production performance of many these fields significantly exceeds the maximum expectation of 18% recovery for oil rim fields. In 2002 Hongyin and Pengxiao reported recovery factors of 32% from the Weizhou 11-4 Field with an expected total recovery factor of 43% despite relatively thin oil columns and moderately high oil viscosities of 14cP. These recovery factor expectations are mirrored by the authors' own findings. The unusually high recovery factors can only partially be explained by favourable reservoir conditions and appropriate development strategies.

Closer inspection of core and log data indicate there is often a dolomitic alteration zone at the oil-water interface that occlude porosity and permeability, and act as aquitards to prevent the onset of water breakthrough. Further studies of well and seismic data show that these zones are laterally pervasive and flat-lying. Developing methods for recognising, characterising and understanding these zones is critical for future exploration and development of fields in the Beibuwan Basin.

This study will present the learnings from three case studies of adjoining oil rim fields.

REGIONAL GEOLOGICAL BACKGROUND

The Beibuwan Basin is a Cenozoic rift basin in the Beibu Gulf of the South China Sea (**Figure 2**). The basin comprises of several kilometres of Palaeogene syn-rift sediments, and relatively thin Neogene post-rift sediments. There are two distinct phases of extension in the basin: the first in the Palaeocene to late Eocene, and the second in the Oligocene. Major NE to ENE trending basin-bounding fault systems evolved in the first phase resulting in simple half grabens which were reactivated during the second extensional phase along with numerous secondary faults. The relatively muted post-rift period was disrupted by two significant events: a short pulse of renewed subsidence in the middle Miocene and basin inversion since the late Pliocene. All post-rift sedimentary units are characterised by low relief structures and relatively low degree of faulting. Six sub-basins are recognised within the Beibuwan Basin and the area of study is on the southern margin of the Weixinan sub-basin (Li, 2009).

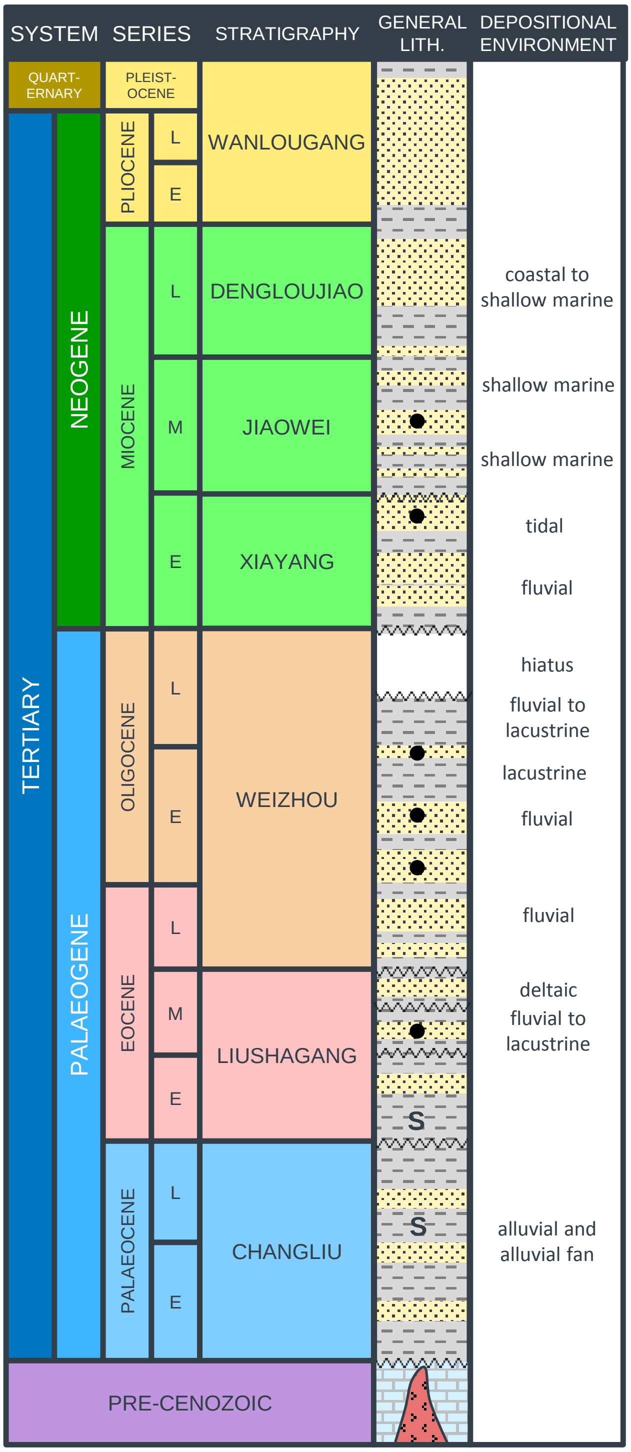

Figure 1: Generalised lithostratigraphy of the Beibuwan Basin, South China Sea (modified from Li, 2009)

The stratigraphy (**Figure 1**) comprises of 500m of Late Miocene to Pleistocene coastal to shallow marine sediments overlying the middle Miocene Jiaowei Formation and early Miocene Xiayang Formation. These formations comprise of deltaic to shallow marine to near-shore marine depositional facies. Numerous fields throughout the sub-basin, including the Weizhou 11-4 (Hongyin and Pengxiao, 2002), produce from these formations from multiple reservoir units, and oil and gas shows are regularly observed while drilling. Common volcanic events through this period deposited extensive ash fall layers that act as marker beds. An angular unconformity signifying the end of the second phase of rifting underlies the Miocene sediments marking the top of the Oligocene Weizhou Formation, another prolific oil-bearing formation within the basin. The Eocene Liushagang Formation, a lacustrine depositional environment, and Palaeocene Changliu Formation, an alluvial depositional environment, are the main sources.

MAIN RESERVOIR DESCRIPTION

There are several prolific reservoirs within the basin however the focus of this study is the Jiaowei Formation. The formation consists of shallow marine to near-shore marine depositional facies with occasional high-rainfall storm deposits. There are two main reservoir units, denoted here as the Upper and Lower Jiaowei units, which comprise of a number of extensive, thick, high quality sandstones intercalated with silty shale packages that act locally as sealing units. Sandstones units typically have low clay content (less than 5%), high porosity (greater than 30%), multi-Darcy permeability and strong aquifer support. The units are shallow, less than 1km burial depth, and low temperature, under 80°C. Evaluation of the units is complicated by radioactive sands, due to the presence of high gamma ray monazite, analogously low salinity formation water compared with surrounding reservoir units, and the presence of pelletal glauconite/verdine facies. High sandstone content, a general lack of trapping mechanisms due to low structural relief and minimal faulting mean virtually all discovered fields within the formation are categorised as oil rim fields.

A common observation is the existence of diagenetic alteration zones at the oil-water interface (Hongyin and Pengxiao, 2002). These zones are dolomitic cements with variable thickness (20cm to 8m), are 2 to 3 orders of magnitude lower permeability than the host reservoir, and act as aquitards to the underlying aquifers. Alteration zones observed in wells away from oil accumulations are frequently accompanied by oil and gas shows in overlying reservoir sediment. It is theorised that the dolomitic cements are accreted by interactions with sulfate-reducing bacteria and hydrocarbon at the oil-water interface. The thesis derives from frequent observations of the coexistence of shows with terminating with zones of cementation, combined with idyllic conditions such as shallow burial depths, low formation temperatures, high availability of organic-rich material, and anoxic environments (Machel, 2001; Lith 2001):. Sulfate-reducing bacteria use a form of anaerobic respiration to reduce sulfate (SO_4^{2-}) to hydrogen sulphide (H_2S) while producing energy from oxidising organic compounds. There are many permutations of distinct reactions however a reaction can generally be described by the following schematic net mass balance formula (Machel, 2001):

$$\boldsymbol{hydrocarbon} + \boldsymbol{SO_4^{2-}} = \boldsymbol{altered\ hydrocarbon} + \boldsymbol{solid\ bitumen} + \boldsymbol{H_2S(HS\_)} + \boldsymbol{HCO_3^-(CO_2)} + \boldsymbol{H_2O} + \boldsymbol{heat}?$$

Products and by-products of the reaction, including oil with low light components, H_2S, CO^2 and bitumen, are all observed in fluid and core samples throughout the Jiaowei Formation.

GEOPHYSICS

An evaluation of 3D seismic inversion and amplitude mapping was integrated with drilling results across the three contiguous oil fields with the aim of discriminating between residual and commercial hydrocarbons. Seismic reflection data shows the existence of an elongated, laterally extensive amplitude anomaly at the base of the Upper Jiaowei unit commonly referred to as 'The Snake' due to its meandering geometry. 'The Snake' anomaly is located along a structural ridge joining two mapped closures, 10 km apart. Several wells intersect this anomaly and indicate that the bright amplitudes are a function of the contrast between lower impedance hydrocarbon-filled reservoir sands and an underlying caliche aquitard. Amplitude extraction from seismic reveals the extent of this anomaly.

An integration of 1D amplitude and fluid replacement modelling (FRM) of well data with seismic inversion datasets has provided a better understanding of the oil accumulations away from well control.

A reasonable correlation between seismic amplitude and well-log acoustic impedance (AI) can be made across six out seven wells at the top of the reservoir. One of the wells sits off the trend significantly due to anomalously high seismic amplitude implying that tuning effects could be expected.

One-dimensional FRM was performed using a measured oil-on-altered zone scenario at one of the wells as a base case and variable velocity and density parameters from other wells, which simulated a range of scenarios intersected in other parts of the study area. This initial modelling concluded that acoustic impedance and by inference, seismic reflection data, was capable of identifying reservoir where alteration had occurred but was not capable of discriminating oil-saturated reservoir from residual oil reservoir (**Figure 3**).

Lambda Mu Rho (LMR) was modelled from one of the wells. Crossplots of MR versus LR, and VpVs versus Zp through the reservoir allowed good fluid discrimination (**Figure 3**). Cut-offs determined from LR crossplots were scaled before being applied to the LR seismic inversion volume. This work proved instructive in separating oil accumulations by discriminating between oil and residual oil (**Figure 4**).

FIELD 1 CASE STUDY

Field 1 was discovered in 2014 after drilling a high amplitude, flat-lying seismic event in the Lower Jiaowei reservoir unit 110m below 'The Snake' anomaly. The well identified a 12m oil column in high quality Jiaowei reservoir with a 3m thick dolomitic alteration zone at the base of the column and a bottom-water aquifer.

The reservoir is high net-to-gross with sidewall core porosities greater than 35%, Darcy-scale permeabilities and high vertical permeability. Sidewall core acquired in the altered layer indicate permeabilities of 0.1mD. The fluid is dead oil with low gas-oil ratio, low bubble point pressure and moderate oil viscosity of 9cP. The reservoir is normally pressured with strong bottom-water aquifer support.

An appraisal well in 2015 to test the eastern tested the eastern extent of the amplitude event identified verified oil and the existence of the 3m thick alteration zone 1km away confirming the layer extends across the base of the oil column.

In 2015 a single horizontal well was drilled at the crest of the structure with 500m of reservoir length and dual electrical submersible pumps (ESP). After 2 years the field is still producing at initial oil rates, has recovered 12% oil and is expected to recover over 45% with an additional infill well.

High vertical permeability, a strong aquifer and moderately viscous oil in this field are idyllic conditions for rapid water coning and early water breakthrough, the consequence of which should be low recovery factors. The alteration zone at the base of the reservoir is acting as an efficient baffle to delay the onset of water breakthrough.

All wells in Field 1 intersected an area towards the middle of 'The Snake' anomaly and discovered a 2.5m thick dolomitic alteration zone underlying a residual oil column. The anomaly in this location appears as strong seismic amplitude response but has minor Lambda-Rho response.

FIELD 2 CASE STUDY

Field 2 was discovered in 1994 after intersecting a 12m thick oil column with a 2m thick gas cap in the Upper Jiaowei reservoir unit.

The reservoir is high net-to-gross with mean core porosity of 30%, Darcy-scale permeabilities and high vertical permeability. The oil is a dead oil with low gas-oil ratio and moderate oil viscosity of 23cP. The gas cap is small and contains minor CO^2 and up to 140,000ppm H_2S. The reservoir is normally pressured with strong bottom-water aquifer support. Two dolomitic alteration zones are identified from core and logs: a relatively thin 17cm thick layer at the current oil-water contact with core permeability of 1.4mD; and a 2.5m thick layer 15m below the contact with core permeability between 10mD and 100mD.

The well intersects 'The Snake' anomaly at its western extent, 2km to the west of Field 1. The anomaly in this location is characterised by very strong amplitude response. Closer inspection of the seismic amplitudes show there are two events: a flat-lying, relatively low amplitude upper event; and a tilted higher amplitude lower event. There is also a strong LR response.

In 2013 five horizontal wells were drilled 8m to 10m above the oil-water contact and below the gas-oil contact. Each well has a reservoir length of 500m and dual ESPs. After 4 years the field has recovered more than estimated in development planning with 24% recovered to date. Production rates remain high and the field is ultimately expected to recover 45% of oil reserves.

Again high vertical permeability, strong aquifer, even more viscous oil and a gas cap in this field should have resulted in low recovery factors. Gas breakthrough occurred almost immediately however the size of the gas cap was small enough that it was produced early in the field life and did not affect recovery in a meaningful way. Water breakthrough was expected to occur within 1 month of first production but actually occurred almost a year later. The alteration layers in Field 2 are less thick, less extensive and more permeable than in Field 1, however the late onset of water breakthrough indicate that they are still acting as effective aquitards.

FIELD 3 CASE STUDY

Field 3 was discovered in 1994 after intersecting an 8m column of oil in the Upper Jiaowei reservoir unit.

The reservoir is high net-to-gross with mean core porosity of 34%, multi-Darcy scale permeabilities and high vertical permeability. The oil is a dead oil with very low gas-oil ratio and moderate to high oil viscosity of 69cP. The reservoir is normally pressured with strong bottom-water aquifer support. A single 8m thick alteration zone is identifies from core and logs with relatively high permeabilities between 100mD and 1000mD.

The well intersected ‘The Snake’ anomaly at its eastern extent, 10km east of Field 2. The two fields are connected by ‘The Snake’ with Field 3 being in an updip location. The anomaly at this location is characterised by moderate seismic amplitude response in the west that fades towards the east and terminates prior to eastern structural closure. Similarly the LR response is strong to the west and non-existent to the east.

Field 3 is the largest of the three fields but also has the thinnest oil column, highest vertical permeability and the most viscous oil of the three. The alteration zone at the base of the column is the thickest of the three but is also the most permeable. There is also uncertainty with regards to the seismic amplitude response as to whether a dolomitic layer is present. Hence, one of the key risks to development is the time to onset of water breakthrough.

The field is currently in development planning.

CONCLUSIONS

- Low permeability dolomitic alteration zones are deposited at oil-water interfaces through sulfate reducing bacterial processes and act to slow the onset of water breakthrough and increase oil recoveries in oil rim fields.
- These zones have been characterized using a combination of well data and seismic techniques and can be reliably predicted on seismic.
- Two of the fields in this study display the characteristics of dolomitic alteration at the OWC and demonstrate that the retardation of water breakthrough is beneficial to production rates and ultimate reserves.
- The third field does not display the same seismic response and this is considered to introduce a higher degree of risk in predicting the oil recovery factor.
- In general, aquifer retardation clearly enhances oil recovery in thin oil columns and the presence of such a mechanism would be a key element to investigate.
- Seismic amplitude and fluid properties can be useful in this regard.

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Figure 2: Map of Beibu Gulf showing the location of the Beinbuwan Basin and the study area.

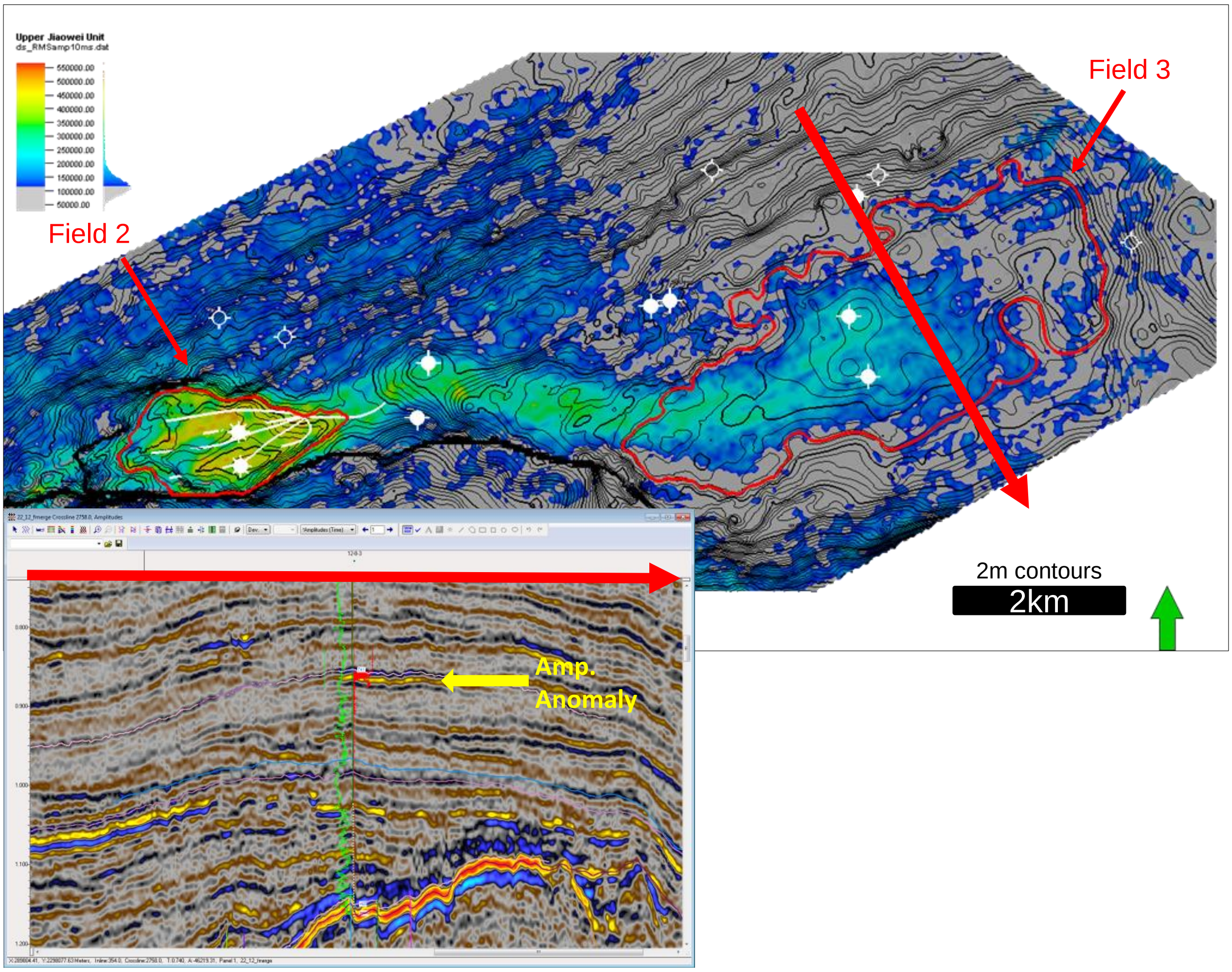

Figure 3: Amplitude extraction revealing the extent of the "Snake" anomaly at the base of the main producing reservoir.

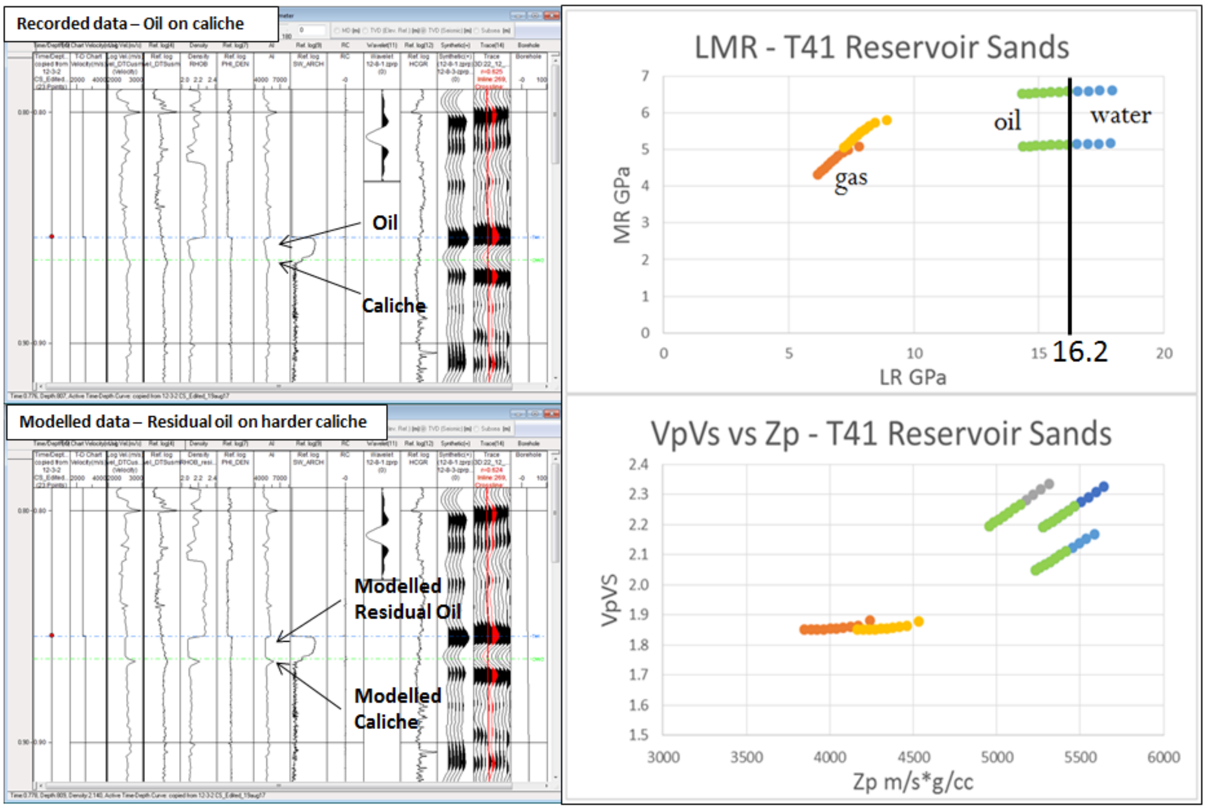

Figure 4: Figure 2: 1D modelling showing the limitations in discriminating oil from residual with respect to seismic amplitude (Left) and LMR plot from well data allowing clear cut off between oil and water.

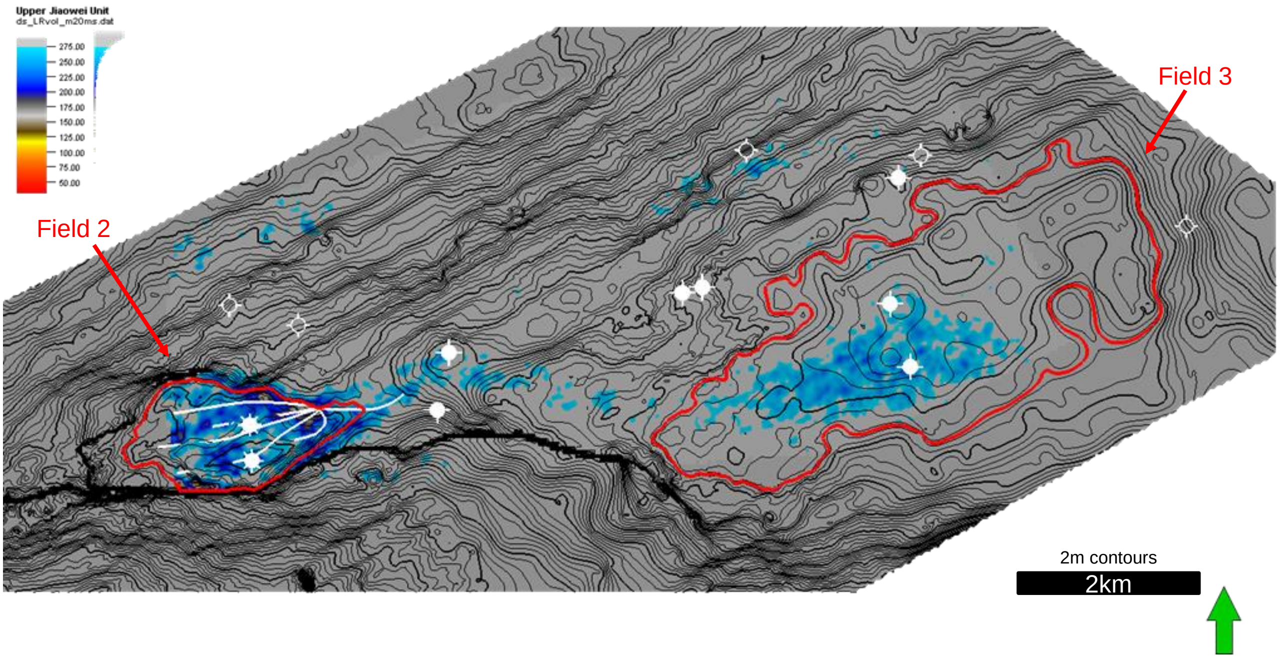

Figure 5: Figure 3:Lamda-Rho amplitude extraction over structural contours. Cut-off derived from well LMR crossplot and scaled.