

Analysis of GS-11 Low-Resistivity Pay in Main Gandhar Field, Cambay Basin, India – A Case Study

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ABSTRACT : Gandhar – a major onshore field situated in Cambay basin on the western margin of India – consists of multiple deltaic pay sand units GS-1 to GS-12, from bottom to top, of the Hazad member of Middle Eocene age. The present study deals with identification and evaluation of low-resistivity pay of GS-11 sand unit in the main Gandhar field. The low resistivity is caused by large irreducible water of high salinity. The identification and analysis of low-resistivity pay have been facilitated by special logs like EPT and NMR. From salinity analysis, the formation water resistivity for low-resistivity pays has been estimated in the range of 0.05 to 0.1 Ω m at formation temperature. The quantitative analysis by multiminer model using optimization technique has given porosities 18 to 25% which match with lab measured porosities, and water saturations 35 to 60% which, at first, seemed to be higher in view of clean oil production from the low resistivity pay in most of the wells. However, NMR log response against low-resistivity pay has shown high irreducible water saturation ($\approx 57\%$), which explains the high computed water saturations as well as negligible water production from the low-resistivity pay.

INTRODUCTION

Gandhar is a major oil and gas field spreading over 800 sq. km. in the Jambusar-Broach block of Cambay Basin (Figure-1). The field has developed in the western flank of Broach depression, which lies between Dadhar river in the north and Narmada river in the south. The hydrocarbons are mostly accumulated in the multiple sand units GS-1 to GS-12, from bottom to top, belonging to Hazad member of

Ankleshwar formation of Middle Eocene age. The sediments have been deposited in a deltaic setting. The hydrocarbon entrapment is mainly in the traps formed due to shaling of these sands on the western rising flank of Broach depression. The low resistivity pays are present in GS-4, GS-6, GS-11 and GS-12 sand units. The present study analyses low resistivity pay of GS-11 sand unit in the main Gandhar area where it is oil bearing.

GEOLOGICAL AND LOG CHARACTERISTICS OF GS-11 SAND UNIT

Figure-2 is a map of GS-11 sand unit in the study area showing depth, log character, distribution of low resistivity pays and locations of different wells, including those of wells A, B and C to be referred in the text later. The depth to the top of GS-11 varies from about 2750 m in the centre of the field to about 3050 m towards southeast, and the oil-water contact (OWC) is inferred at about 2825m. The map shows various log motifs (Gamma ray, Neutron porosity, Density porosity and Resistivity) against GS-11 at the selected respective well locations. The log motifs provide an overview of lateral and vertical variation in lithology, sand distribution, sand thickness, sand grain size and resistivity for GS-11 sand unit. Log shapes characteristic of channel sands and distributary mouth bars are seen at a number of well locations. As per core and log analysis, GS-11 represents a combination of channel fill, mouth bar and sometimes tidal sand along with intervening shale layers. The presence of abundant carbonaceous matter and pyrite encrustations suggests tidal influence during its deposition (Pandey et al., 1989).

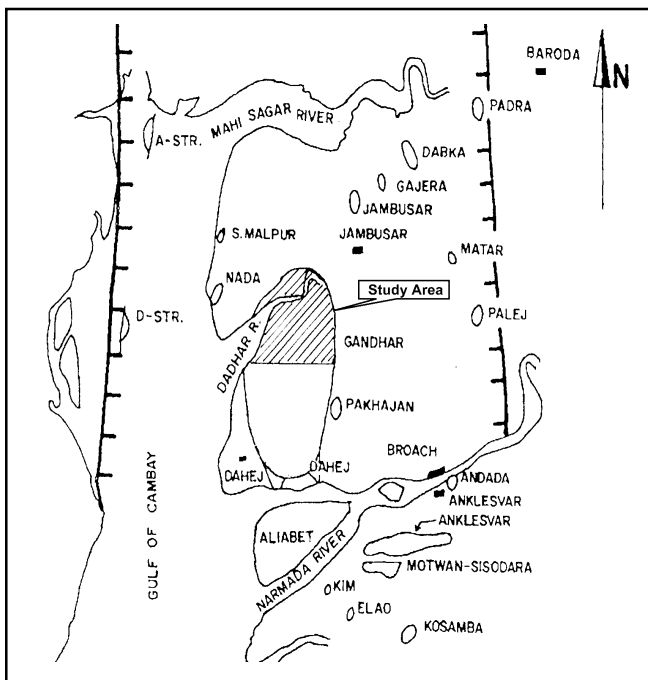


Figure 1: Map showing study area in Gandhar Field, Cambay Basin

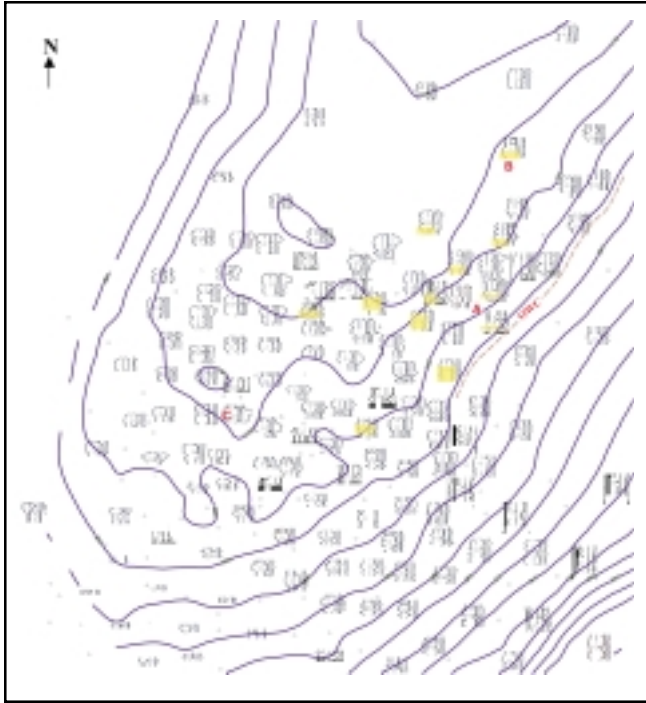


Figure 2: Map of GS-11 sand unit in the study area showing (1) locations of different wells including those of wells A, B and C referred in the text (2) depth to the top of GS-11 sand shown by contours (3) position of oil-water contact (OWC) (4) different log motifs (GR-NPHI-DEN-RES) at the selected respective well locations (5) low resistivity pay zone in yellow colour in wells where it has been tested and produced oil.

The resistivity of GS-11 sand unit shows a wide variation from 2.3 Ωm to 250 Ωm in the main Gandhar field but it is of the order of 5 Ωm or less in most of the wells situated in the eastern and northeastern parts of the main field where the low resistivity (5 Ωm or less) pays are also developed. Figure-3 shows the composite log alongwith core description of an oil bearing GS-11 sand unit in one of the wells 'A' (Figure-2) situated in the northeastern part of the main Gandhar field. The interval 2824-2829 m represents a low resistivity pay as it has a resistivity of about 4.5 Ωm and is oil bearing since the conventional core against the top part of this interval has shown total GYF and strong cut, and the same zone has produced oil in the nearby wells. As per core description, it is sandstone with light grey colour, fine to coarse grain size, silty and argillaceous matrix and is highly bioturbated and burrowed, the burrows filled with secondary sandstone fillings. From gamma ray shape, it seems to be a channel sand cut into a distributory mouth bar. This low-resistivity pay has developed in a number of wells situated in the northeastern part of the main Gandhar field.

Various core and log studies have been carried out to know the reasons for low resistivity of GS-11 pay zones (Guru et al., Kumar et al., 2003). These studies have shown that presence of micropores due to silt sized quartz grains and clay coated grains capable of holding large bound water, high formation water salinity and bioturbation are the main factors responsible for GS-11 low-resistivity pays. This observation is supported by NMR log analysis to be discussed later. Though some conducting minerals, mostly pyrite, are present, their contribution to low resistivity is not significant in view of their overall volume less than 4% (Guru et al.).

IDENTIFICATION AND EVALUATION OF LOW-RESISTIVITY PAYS

Identification of low resistivity pays has been difficult with conventional logs. However, the conventional sidewall coring and formation testing wireline tools have provided useful information about low resistivity pay zones. Special logs like EPT and NMR have also been helpful in delineating and analyzing the low resistivity pay zones as discussed below.

The Electromagnetic Propagation Tool (EPT) can distinguish between oil and water because the two have very different values of dielectric constant – about 2 and 80 respectively. An overlay of EPT porosity (EPHI) with either density or neutron porosity normalized in a clean water bearing zone can indicate oil bearing zones since EPT sees mainly water filled porosity, which is less than total porosity seen by density and neutron tools against oil bearing zones. However, due to very shallow depth of investigation (\approx 2-3 inches), EPT responds to the residual hydrocarbons present in the flushed zone and is borehole sensitive. The EPT log has been recorded in a number of wells in the study area. Figure -3 shows an overlay of EPT and density porosities normalized against clean water bearing interval 2912-2913m of GS-6 sand unit in well A. The EPT is showing less porosity than density against GS-11 and GS-8 sand units indicating them to be oil bearing. However, the separation between the two porosities is less against low resistivity GS-11 than high resistivity GS-8 implying that EPT is less effective against low resistivity pays than against high resistivity ones.

For quantitative analysis, the formation water resistivity (R_w) has been estimated by salinity analysis. Salinity data from testing and logs has been analyzed for GS-11 and for nearby GS-10 and GS-12 sand units (Kumar et al., 2003). Salinity has been estimated from logs by R_{wa} method against clean and water bearing zones. Salinity has been observed to

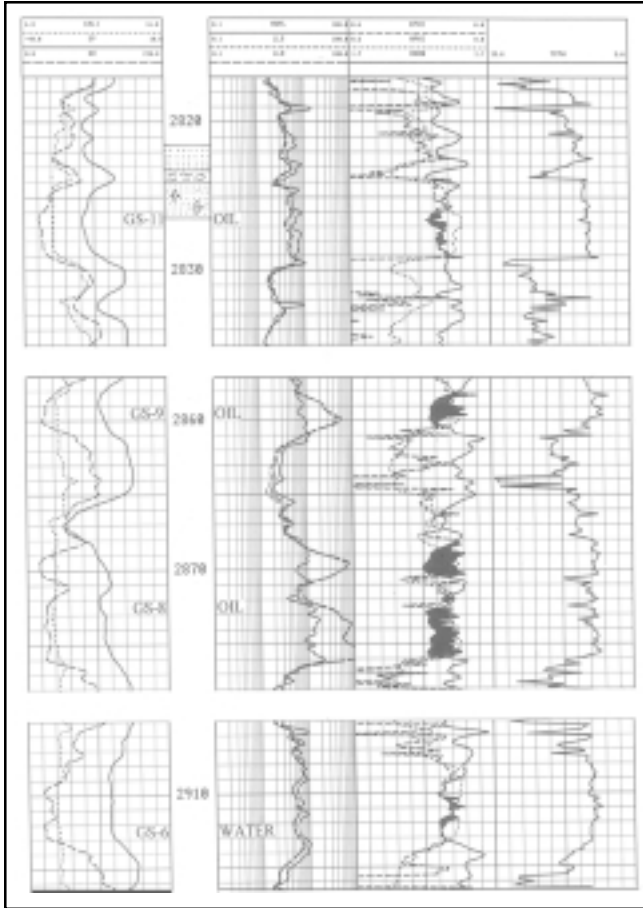


Figure 3: The core lithology and open-hole logs against GS-11 low-resistivity pay in well A. The core is highly borrowed and bioturbated and has shown total GYF and strong cut against the low resistivity pay. The EPT and Density porosities overlay normalized against clean water-bearing GS-6 layer indicates GS-8, GS-9 and GS-11 units to be oil bearing.

vary laterally in a similar trend for each sand. For GS-11, salinity is varying from about 6 gm/lit in the western side to about 40 gm/lit, in the eastern side, which corroborates variation in resistivity, since the resistivity of the pay zones is generally higher in the western side and lower in the eastern side. On the basis of salinity analysis, formation water resistivity for low resistivity pays has been estimated in the range of 0.05 to 0.1 Ω m.

The quantitative analysis has been attempted by inverse multi-mineral approach which is based on the mathematical solution of a set of response equations by least square optimization. Based on core analysis, three minerals, viz., sand, silt and clay have been selected for processing.

The a , m and n parameters have been estimated to be 1, 1.9 and 2.3 respectively by laboratory measurements on the core plugs (Lal et al., 2003). Indonesian equation was used for water saturation computation. The processed results of one of the wells B, which is located in the northeastern part of the main Gandhar field (Figure-2), are presented in the form of a paralog in Figure-4. In different wells, the estimated porosity ranged from 18 % to 25 % and the water saturation (S_w) values varied from 35 % to 60 % for low resistivity pay zones. The estimated porosities matched with those measured in the laboratory on core plugs. But the values of water saturation seemed to be higher as the low resistivity pays have generally produced clean oil with negligible water. One of the possible reasons for high S_w might be the large bound water present in the low resistivity

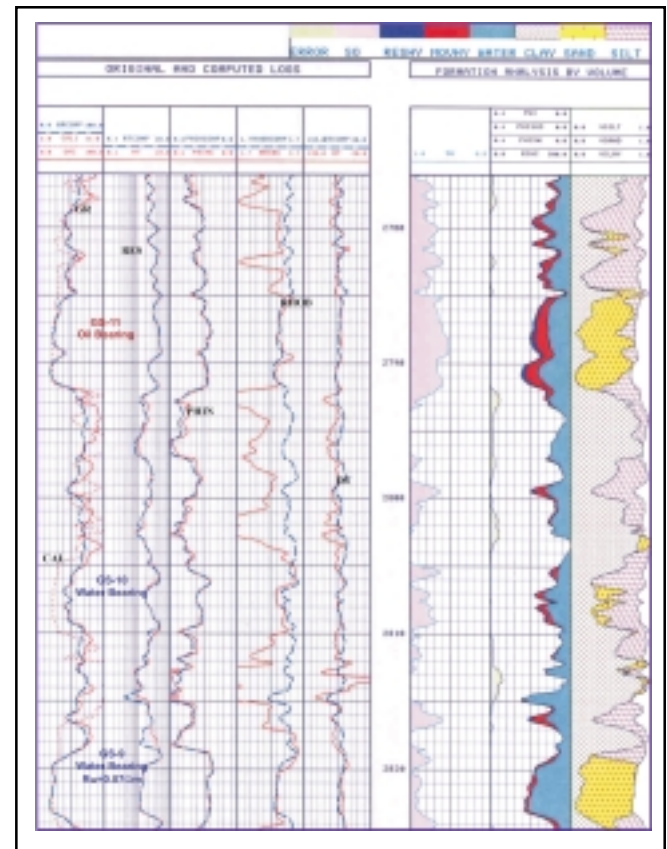


Figure 4: Formation evaluation by least square optimization against GS-9, GS-10 and GS-11 sand units in well B. Tracks 1 to 5 are showing original and reconstructed curves of gamma ray, resistivity, neutron, density and sonic travel time respectively. Tracks 6 to 8 are showing various estimated reservoir parameters, i.e., water saturation, porosity, mineral volumes, etc., along with the incoherence error RINC (left in Track-7) which is a measure of the departure of the reconstructed logs from the original ones due to bad hole.

zones. The NMR log analysis has shown that this indeed is the case.

The nuclear magnetic resonance (NMR) tool provides free fluid, irreducible water and effective porosities by certain manipulation of the hydrogen protons in the fluid of a rock's pore spaces. From the data provided by NMR, the permeability can also be derived. The NMR and the conventional logs against GS-9, GS-10 and GS-11 sand units in well B are shown in Figure-5. Here the GS-11 is a distributary channel fill with maximum 5 Ωm resistivity, and it has produced from the interval 2786-2789 m oil @ 35 m³/d, gas @ 6000 m³/d and water @ 0.1 m³/d through 4 mm bean on testing. The GS-9 and GS-10 sands are water bearing. The clean and water bearing GS-9 sand (2820-2823m) gives $R_w = 0.07 \Omega\text{m}$ at the formation temperature that corresponds to a

salinity of 28 gm/lit. Against the perforated zone of GS-11, NMR log shows about 21 % total porosity, 17 % effective porosity, 38 % capillary bound water, 19 % clay bound water and 43 % free fluid. The irreducible water saturation is 38+19=57 % and permeability is 5-40 md. The high irreducible water saturation explains anomalously low resistivity. The quantitative analysis has given $S_w \approx 60\%$ (Figure-4), which is only slightly higher than irreducible water saturation shown by NMR. This shows that most of the water present in the zone is irreducible (immobile) water that is not able to flow in spite of its large volume. It explains why there is negligible water-cut during production in spite of high water saturation. It also validates the water saturation obtained by quantitative analysis. The high capillary bound water and low permeability both indicate smaller pore and grain size.

For comparison, the NMR and other open hole logs of another well C (Figure-2) situated in the interior of the main Gandhar field are shown in Figure-6. Here, GS-11 is a

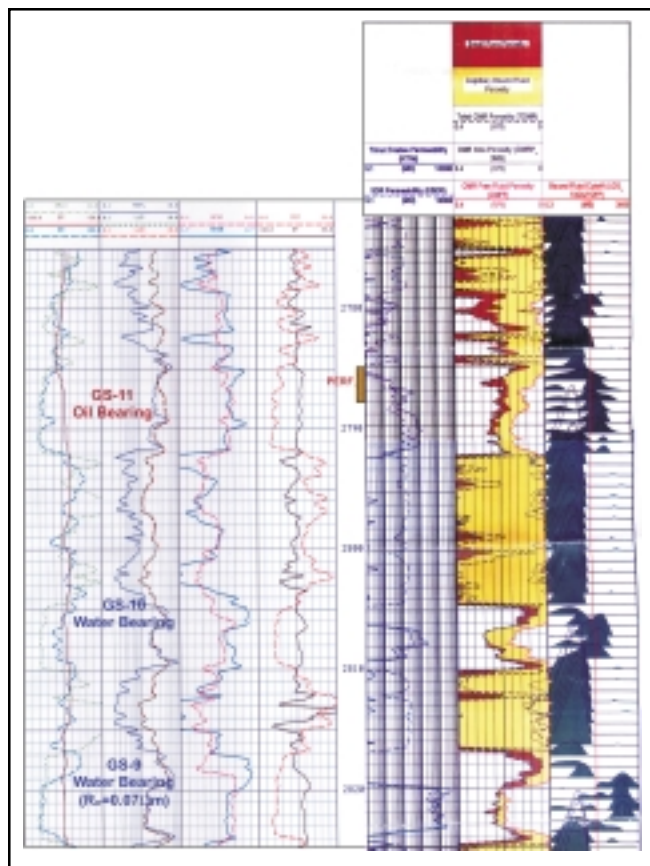


Figure 5: The conventional and NMR open-hole logs against GS-9, GS-10 and GS-11 sand units in well B. The NMR shows high irreducible water saturation ($\approx 57\%$) against the perforated part of GS-11 low resistivity pay which produced oil @ 35m³/d and associated gas @ 6000m³/d with negligible water-cut through 4mm bean on testing.

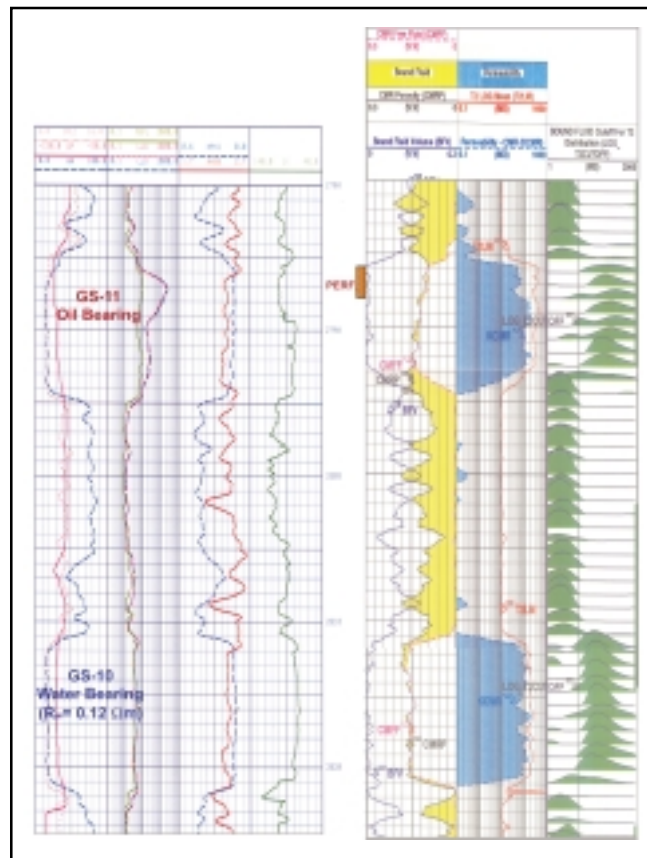


Figure 6: The conventional and NMR open-hole logs against GS-10 and GS-11 sand units in well C. The NMR shows very low irreducible water saturation ($\approx 9\%$) against oil bearing GS-11 sand unit whose resistivity is as high as 250 Ωm .

tidal channel sand with maximum 250 Ωm resistivity. The lower sand GS-10 is clean and water bearing (interval 2812-2820m) and it gives $R_w=0.12\ \Omega\text{m}$ at the formation temperature that corresponds to a salinity of 16.5 gm/lt. The top part of GS-11 (2786-2788m) produced oil @ 59.3 m³/d with negligible water through 14.3 mm bean initially. Against the perforated zone, NMR shows only about 9 %, irreducible water saturation and 30- 70 md permeability, both indicating bigger pore and grain size as compared to the earlier case.

CONCLUSION

The main low resistivity pay of GS-11 sand unit is developed in the northeastern part of the main Gandhar field. The low resistivity is mainly because of large irreducible water of high salinity ($\approx 25\text{-}40$ gm/lt). The special logs like EPT and NMR are helpful in the identification and analysis of the low resistivity pay. The NMR log response against low-resistivity pay in one well has shown 57 % irreducible water saturation mostly due to high capillarity indicating fine pore sizes. It also explains negligible water production from low resistivity pay and validates its high water saturation (≈ 60 %) obtained by quantitative analysis.

ACKNOWLEDGEMENTS

The authors express their sincere thanks to ONGC management for permission to publish this paper.

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