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Depositional Environment analysis within reservoir sections of Mesozoic Jhuran formation by integrating Image log interpretation and Hi-resolution well logs in Kutch Offshore basin

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Abstract

The Kutch Basin is a late Triassic to Cretaceous rift basin that evolved into a passive margin basin during the Cenozoic age. The Mesozoic sediments are heterogeneous in nature and often exhibit low porosity in reservoir sections of wells in the study area. The main objective of the present study is to understand depositional environment for Mesozoic Jhuran formation and deduce paleo-micro environment of reservoir sections. An integrated approach, using high resolution image logs, litho-facies analysis, and macro-depositional components from conventional log were used. Extensive cross plotting & ternary plots of Potassium, Thorium & Uranium concentrations from geochemical logs, inferences from NMR porosities and micro sedimentary features from image logs were used for analysis.

Introduction

The Kutch Basin is a late Triassic to Cretaceous rift basin that evolved into a passive margin basin during the Cenozoic. The evolution of the western continental-margin basins of India is related to the breakup of eastern Gondwanaland from western Gondwanaland in the Late Triassic / Early Jurassic and the subsequent spreading history of the Eastern Indian Ocean. Subsequent development and geometry of the basin has been influenced by the underlying regional and stratigraphic succession and structural framework dating back to the Archean. The western margin evolved through early rift and post-rift phases of divergent margin development. A series of regional and local horsts and grabens resulted in response to rifting along the dominant basement tectonic trends (NNW-SSE, NE-SW and ENE-WSW). The initial block was modified by intra-basinal tilted fault blocks and half grabens, caused by the development of major faults parallel to the basin margin faults. These major faults influenced sediment deposition and facies distribution during later rift phases. The northernmost part of the western continental margin was the first to be subjected to continental rifting and crustal subsidence in the Late Triassic. The process of rifting gradually In Western Margin, Kutch basin (Fig.1) occurred in three distinct phases: (Biswas 1982; Kutch Basin).

(1) Pre-Rift, (2) Syn-Rift & (3) Post-Rift.

The postrift stage in the pericratonic Kutch Rift Basin of western India is represented by a thick sequence of a diachronous megadelta system. The deposition of this deltaic sequence was initiated during the mid-Kimmeridgian and ended in the Albian. (Desai and Biswas 2018). The sedimentation was interrupted by two transgressive events demarcating three subcycles within the megadelta system. Jhuran Delta is represented by the Jhuran Formation in the lower part of the megadelta Jhuran Delta is characterized by prodelta, subaqueous gravity flow, delta front, distributary channel, distributary mouth bar, transgression, and shoreface environments. Jhuran Delta

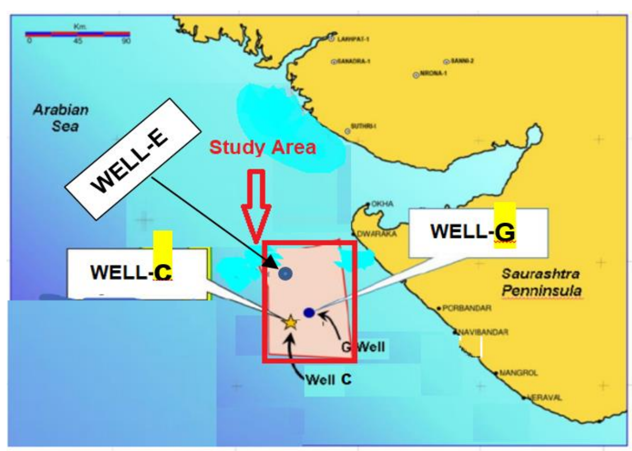


Figure 1: Kutch Offshore basin with the location of wells under study.

represents a mixed-influenced, river-dominated, wave-influenced delta.

The Jhuran delta was evolved in mainly four stages, Stage I comprises the prodelta environment during the Middle Kimmeridgian. Stage II shows a marked increase in the influence of rivers. Associated sedimentary structures and low ichnodiversity indicate a higher rate of sedimentation resulting in wide-scale gravity failures. Stage III developed during the Late Kimmeridgian to Early Tithonian and is characterized by a prograding system. (Biswas 1982; Kutch Basin). This stage is also associated with periods of reduced salinity in a delta front environment. This study also envisages a distributary mouth bar environment have stacked, prograding thickening and coarsening-upward cycles. Stage IV, a high-energy, marine transgression with erosion and reworking of delta sands, which marks the end of the Jhuran Delta sedimentation. To understand the geological and depositional processes comprehensively by assemblage of hi-tech well log data vis-à-vis resistivity image analysis was carried out and the inferences are discussed (Desai and Biswas 2018; Desai 2016; Kutch Basin).

Generalized stratigraphy

The generalized stratigraphy of the Kutch basin is given in the Fig.2. The Mesozoic sequence consists of the following stratigraphic units 1) Jhurio (Middle Jurassic) 2) Jhumara (Middle to Late Jurassic) 3) Jhuran (Late Jurassic) 4) Bhuj (Early Cretaceous) 5) Naliya / Mundra (Late Cretaceous)

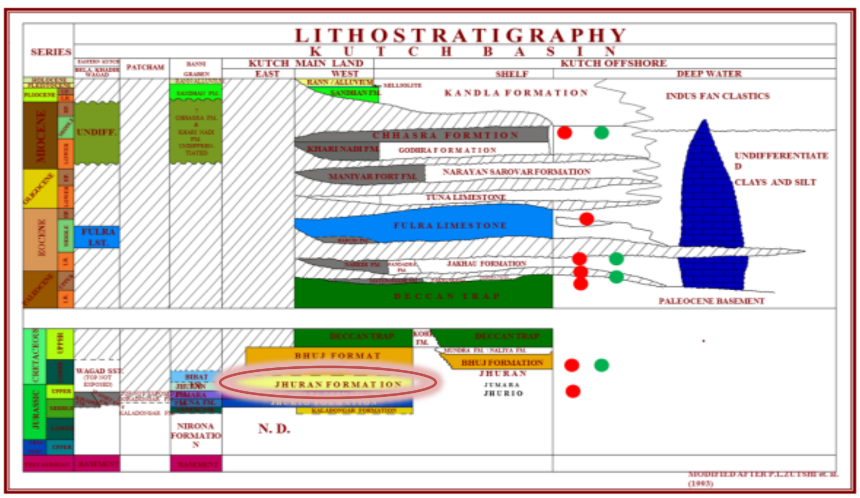


Figure 2: Generalized stratigraphy of Kutch offshore
(Unpublished ONGC report modified referring PL Zutshi, etal 1993)

Study Approach & Methodology:

In present study integration of conventional logs, Spectral logs, Resistivity Image interpretation data have been integrated for deducing depositional environment

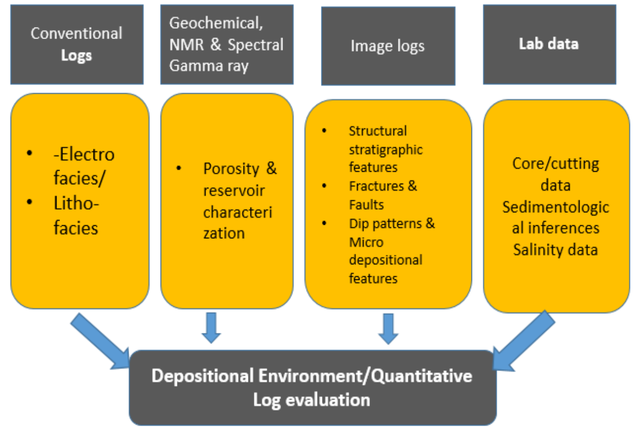
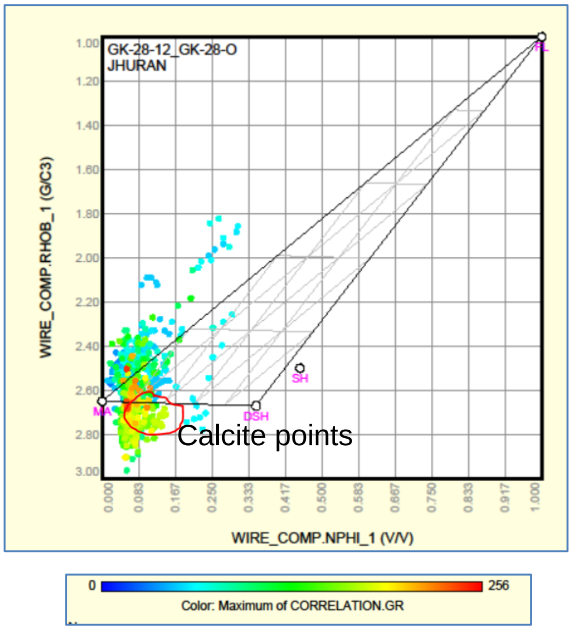


Figure 3: Study Approach

- On processed resistivity image data, various Dips are picked to identify structural and stratigraphic dips
- Prepared rose plots, stereonet plots from the dips and generated dip distribution histograms.
- Fractures are marked, whose orientation, magnitude and conductive/resistive nature are described.
- Geochemical logs analysis including cross-plots of Thorium-Uranium, Thorium-Potassium are made. Ternary plots of elemental capture spectroscopy (ECS) estimated Quartz-Feldspar, Mica (WQFM), carbonates (WCAR) and clay volume (WCLA) are prepared. Cross-plots of WCAR, WQFM, WCLA and elemental weights of calcium, silicon and aluminium are generated. All the plots are prepared for each formation of the Mesozoic section to infer the mineralogy and depositional environment.
- Porosity characterization in reservoir sections and basaltic intrusions wherever image logs and CMR data is available.

Analysis of Mesozoic section: In the present study area three wells viz. Well-E, Well-G and Well-C were taken for analyzing petrophysical characteristics against Jhuran formation. Conventional logs illustrates that in general sand layers developed within Jhuran formation are characterized by low porosity and high resistivity in water bearing sand packs. Shale beds consists presence of minor calcareous streaks which are indicated by high resistivity (up to 20 ohm-m) and high density (upto 2.7 g/cc). The salinity values of production testing are in good agreement with the conventional log estimates. The salinity values are in brackish range, thus indicating a mixing of marine and fluvial waters and transitional deposition environment. The salinities are in the range of 15-30gpl for Jhuran formation which are also estimated from Pickett plot. Resistivity index plotted from petrophysical analysis of Side wall core sample for Well-E also suggests salinity around 17.5gpl. Estimated petrophysical parameters and Resistivity index plot are given in Fig.5.



Calcitic points are plotted in RHOB-NPHI cross-plot.

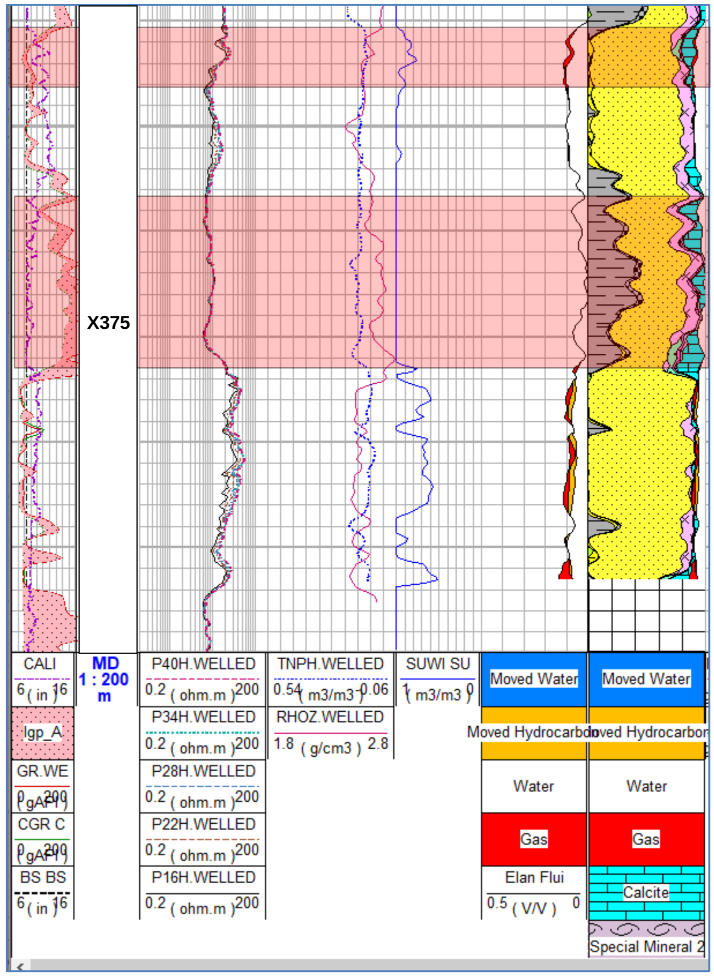
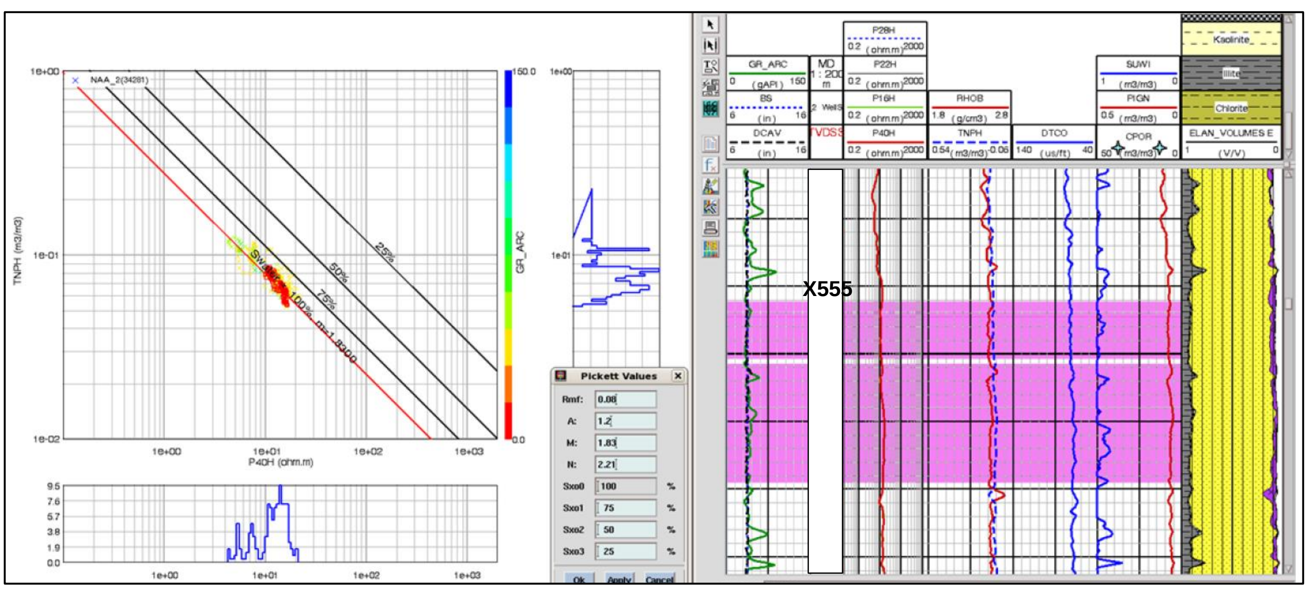


Fig.4 RHOB-NPHI Crossplot for Jhuran section indicating calcareous points



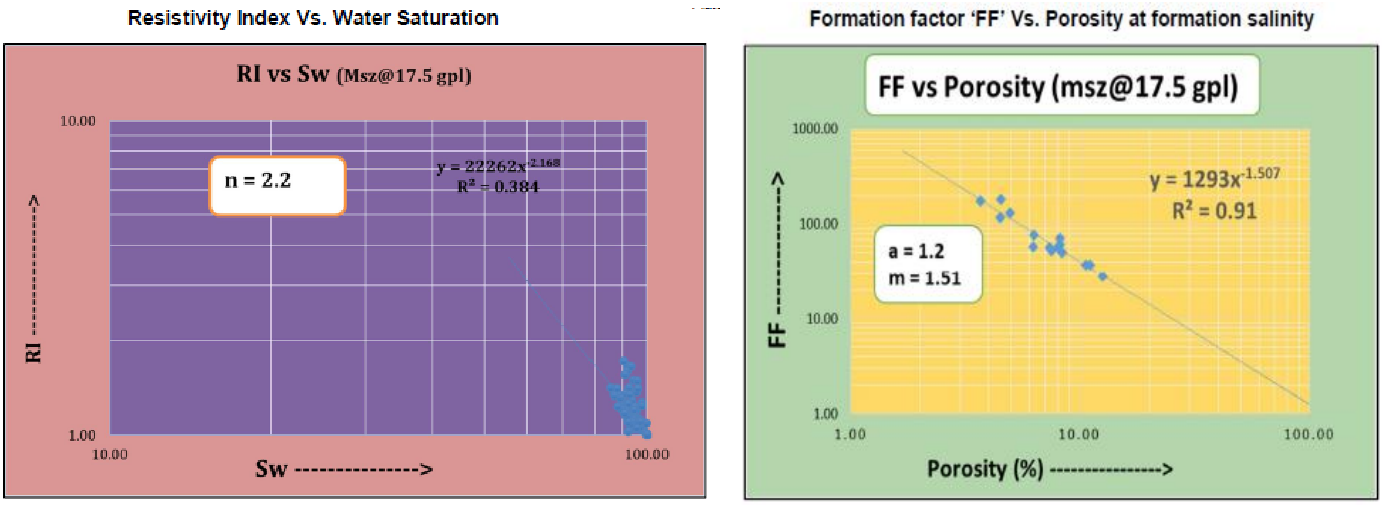


Fig.5 Pickett plot for Rw estimation against Jhuran sand layer and Computed Resistivity index vs Water saturation & Formation factor vs Porosity plots generated from Lab measurements.

From petrophysical laboratory study, the estimated value of tortuosity constant (a), cementing factor (m), and saturation exponent (n) at formation salinity (17.5 g/lt) are 1.2, 1.51 and 2.20.The range of Porosity by He porosity meter (KEYPHI) is from 4.8 to 12.1%, permeability range is 0.02 to 4.59mD and the value of matrix density, determined from porosity and bulk density plot is 2.66 gm/cc. The range of porosity estimated using saturated method is from 3.62-12.47%. Petrophysical studies on Mesozoic section cores also suggests the salinity values are in brackish range, indicating a mixing of marine and fluvial waters and transitional deposition environment.

Spectral gamma ray cross plots:

In all the three wells the Th-U crossplot against Jhuran shows a distinct character among different facies. The data of the lower interval dominantly indicates the transitional nature of the deposition, which gradually becomes shallow marine towards the top. The points in Thorium and Uranium cross plots are falling around the TH/U=7 line (Fig 6). Following the criteria mentioned in (Klaja and Dudek 2016), the Jhuran formation deposited in a transitional environment. The points in Thorium and Potassium crossplot indicates that Illite, smectite and mixed clay are main clay minerals.

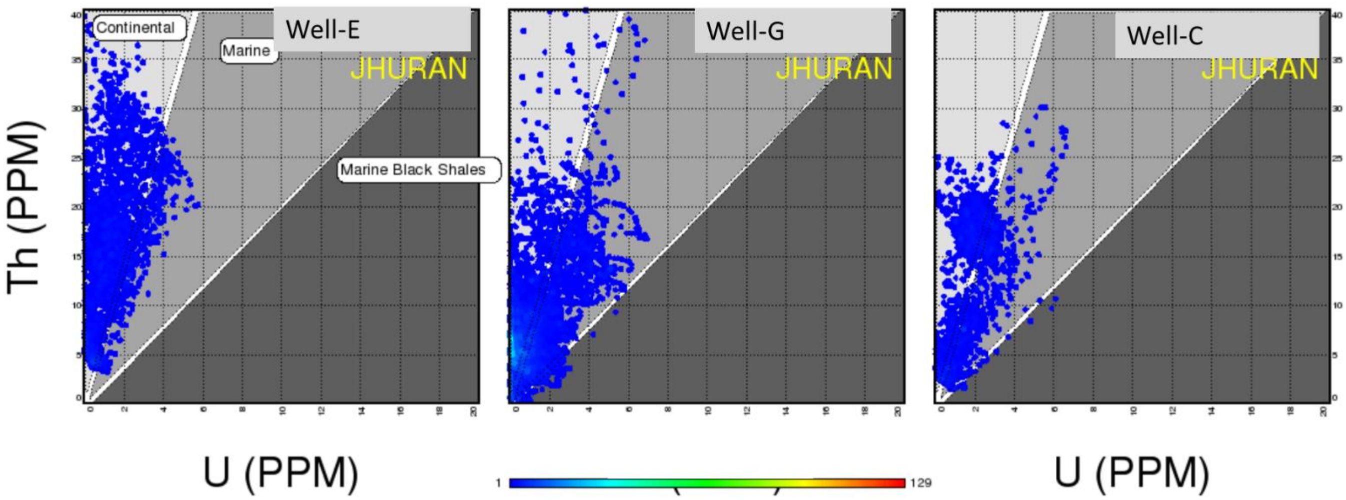


Figure 6: Thorium and Uranium crossplot of Jhuran formation

Discussion & Results:

1) Well-E:

Conventional Log analysis: In this well, the inferences from the conventional logs (GR, Rt, NPHI and RHOB) such as clay presence, mineralogical constituents, conductive/resistive nature, presence of fractures, compactness of different layers are in good agreement with the image log and ECS. The lower clastic section of this well is characterized by resistivity of 10-100 Ohm-m, low effective porosity 0.08-0.12 (v/v) and bulk density 2.4-2.7 g/cc, for cleaner sandstone intervals suggesting compact nature of these packs (Fig.7). The shales display resistivity of 2-5 ohm-m, and higher resistivity peaks corresponds to calcareous rich shale.

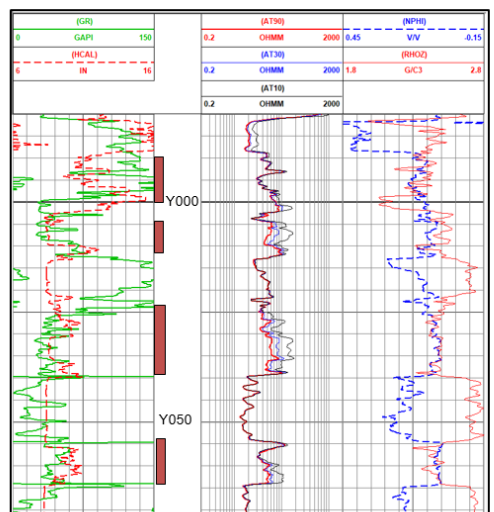


Figure 7. Log Motif of Well E

Formation water of salinity from testing is in corroboration with estimated Rw from conventional logs ~0.03-0.05 ohm-m, these value suggests that the depositional area was influenced by marine processes. In general, the clean limestone sections are compact and described by high resistivities up to 2000 ohm-m, low neutron porosity and high bulk density values. The ECS ternary crossplot displays the gradual increase of carbonates towards top (Figure 6 A B), which suggest that the changing depositional setting from transitional environment at the lower section to shallow marine at the upper section which is also supported by image log data .

ECS Cross plots

The ECS ternary crossplot (Figure 8A) is showing presence of clastic & carbonate mixed lithology, dominated by silica rich carbonate mudstone, carbonate rich argillaceous mudstone and mixed mudstone. The ECS ternary crossplot of Jhuran formation comprises mainly silica dominated lithotype, silica rich argillaceous mudstone and mixed mudstone. It can be also noted that the some points are falling towards carbonate, these data points lie at the bottom of the Jhuran section which may indicate the prodelta environment prior to delta progradation. Crossplot of carbonate volume fraction and clay volume (Figure 8B) indicates that Jhuran formation consists minor marl deposition suggesting clastic & carbonate mixed transitional environment.

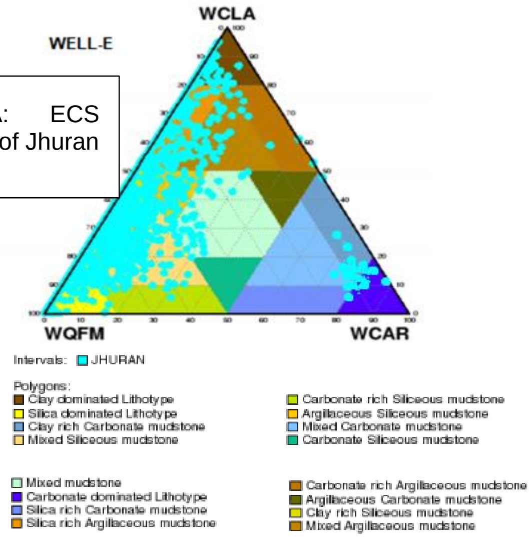


Figure 8A: ECS Ternary plot of Jhuran formation

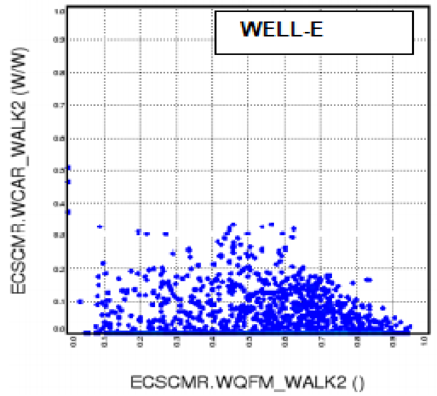


Figure 8B : (ECS) Elemental Capture Spectroscopy log measured dry weight carbonate (W/W) and dry weight Quartz Feldspar Mica(W/W) cross-plot of Jhuran formation

Resistivity image log analysis:

In this well OBMI data quality is good. This interval is represented by alternations of sandstone and shale. Image log is characterized by thin laminations of mean dip 10 degrees with predominant azimuth towards SE (Figure 9A). Filled fractures cutting across the borehole are observed in the interval Y102-Y105m, with angles are in the range of 20-40 degrees predominantly oriented towards NE (Figure 9B). Sub vertical fractures are present at places, which are either healed or filled with resistive minerals. The interval displays a highly cross cutting bedding features. Minute conductive features are distributed in this section, suggestive of pyritic nodules or grains coated with conductive clays or ferruginous matter. High resistive disseminated carbonaceous matter is evident in these intervals.

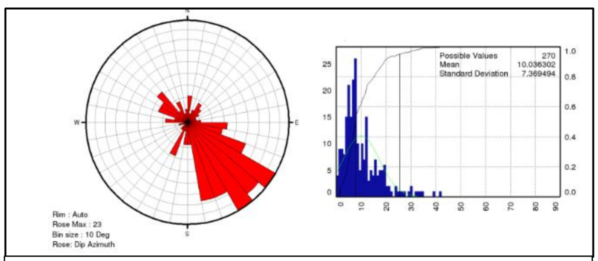


Figure 9A: Rose plot and dip distribution in the, Jhuran formation

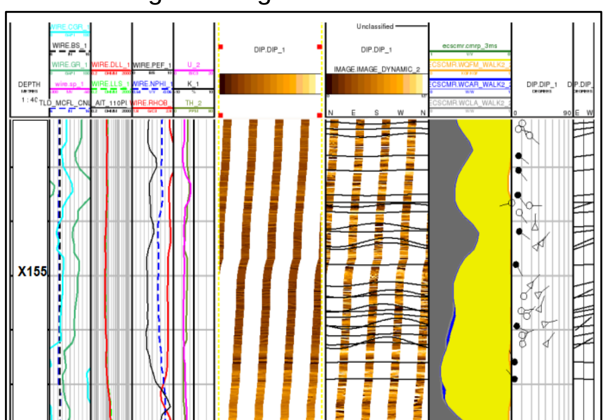


Figure 9B: Filled fractures cutting across the borehole, OBMI,

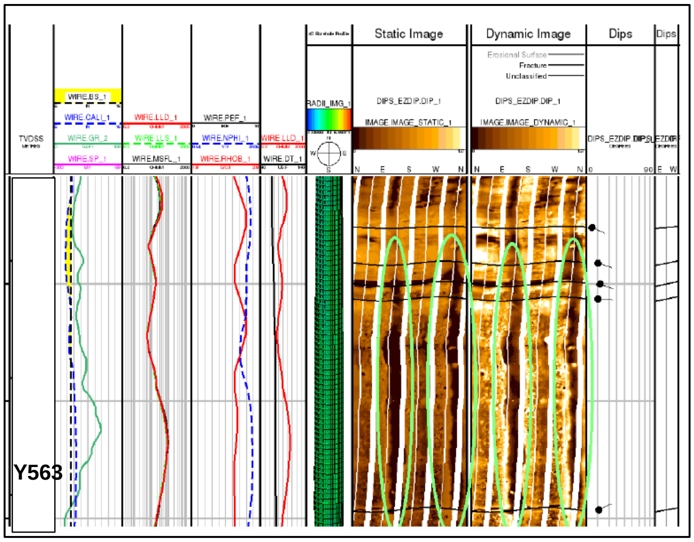


Figure-9c Drilling induced fractures are observed in NW and SE directions, indicating the maximum horizontal direction, Well E, Jhuran Formation

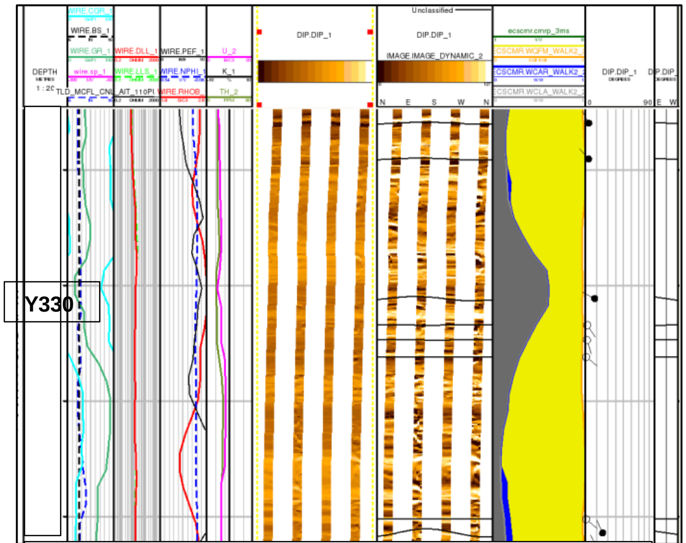


Figure-9D Channel fill Convolution beddings or localized deformation, OBMI, Well E, Jhuran

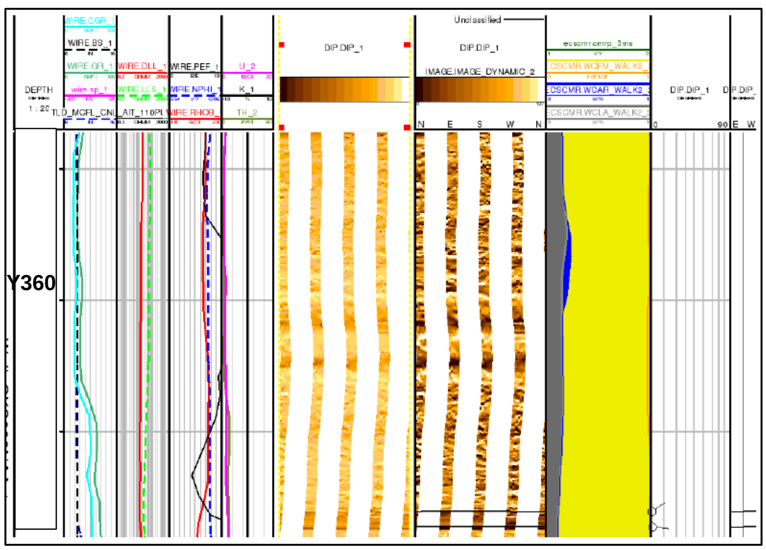


Figure-9E Bioturbated faint beddings, OBMI, Well E, Jhuran Formation

Inferences from Resistivity Image logs:

- At the end of Late Jurassic followed by a hiatus Bhuj succession was deposited during early Cretaceous. Bhuj represents the upper part of the diachronous mega-delta system (Lower succession being the Jhuran formation), which deposited during the regression of the sea level with minor short lived transgressions in between. Deposition of Bhuj succession started during the transgression phase at the end of Jhuran formation marked by thick shale deposition.
- During the regression phase delta started prograding, which resulted in deposition of mouth bars and distributary channels. Image log dips are characterized by magnitudes of range 0-40 degrees with a mean value of 9.7 degrees and wide range of azimuths mostly towards east, north and in between. Structural dips are less than 5 degrees (Fig.9A, 9B 9C).
- High angle fractures are noticed in the image log, which have angles ranging up to 70 degrees

and does not display any preferred orientation.

- The sand facies are identified as deposited during sea level regression mainly as distributary mouth bars, distributary channels influenced by marine processes. Shale and finer clastics are deposited in the inter distributary channel regimes and during short lived sea level transgressions (Fig.9D & Fig.9E).

2) Well-C

Conventional Log analysis: In general, conventional logs of Jhuran formation are characterized by low porosity and corresponding relatively high resistivity in clean water sandstones. Most of the clean sand intervals are marginally saturated. The sandstones are in genial not feldspathic. Shale beds are sometimes calcareous indicated by high resistivity (up to 10 ohm-m) and high density (upto 2.7 g/cc). The shales are characterized by resistivities of around 1-10 ohm-m (Fig.10).

The salinity values of production testing are in good agreement with the conventional log estimates. The salinity values are in brackish range, thus indicating a mixing of marine and fluvial waters and transitional deposition environment.

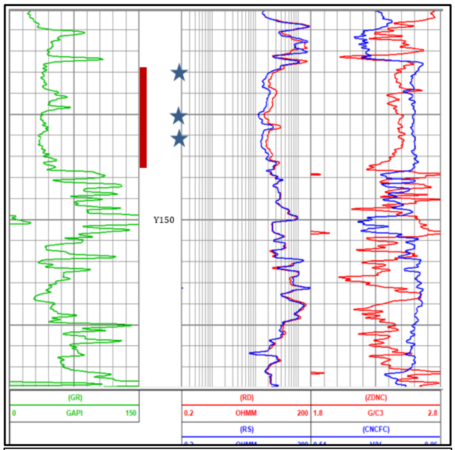


Figure 10. Log Motif of Well C
★MRF STATION DEPTH

Observation from NMR log:

CMR effective porosity (using 3ms clay cut off) is observed to be around 4-8% in the entire interval. But the "CMR Free Fluid porosity" computed is around 0-6% in this interval using 33ms (Default) T2 cutoff. CMR in sandstone intervals characterized by bi-model nature of T2 distribution indicating a intermixing of fine and coarse grained sediments resulted from episodic deposition. The effective porosity in sand intervals is poor to moderate (0.02 (v/v) to 0.15 (v/v)).

Advanced CMR Magnetic resonance fluid characterization was carried out at two stations (MRF) (Fig.12) @ Y129.5m, Y125.5m & Y115m were carried out to know type of the fluids at the respective depths of the reservoir. Water–Gas model have been used for MRF interpretations for these three stations. MRF station reading @ Y115m shows computed Sxo=86% and total porosity=9.6%. In DT2 plot, signal is coming on gas line. This indicates presence of gas. MRF @ Y125.5m shows computed Sxo=89.2% and total porosity=6.5%. Overall D-T2 map at these depths are indicative of poor permeability and tight formation.

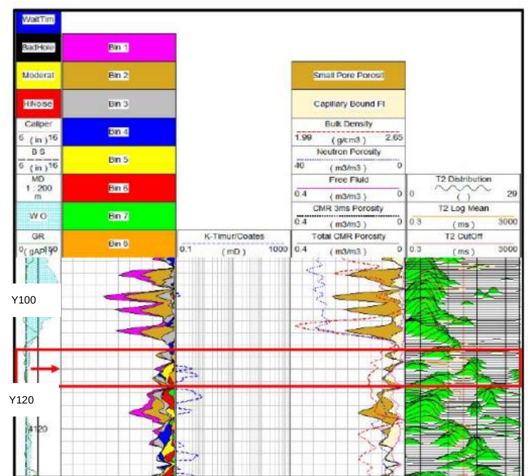
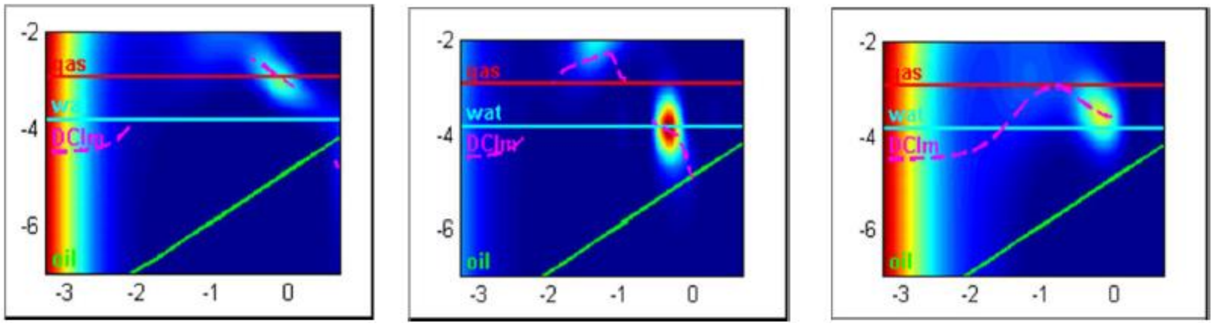


Figure 11: CMR log motif



MRF@Y115m: Sxo = 86% *MRF @Y125.5m: Sxo = 89.2%* *MRF @Y129.5m: Sxo = 89.0%*

Figure 12 D-T2 Map (Two dimensional T2 distribution map)

3) Well-G:

Conventional Log analysis: In this well, sand layers are characterized by resistivity 10-100 ohm-m, and porosity around 0.08-0.13 (v/v). Quantitative interpretation indicates the clean sandstone intervals are marginally gas bearing. Thick shale above sand layer is characterized by a resistivity 8-10 ohm-m and is compact in nature (Figure.13). Sedimentological and Biostratigraphy studies in this section indicate that the section is dominated by coarse to medium grained, at places very coarse to granular, hard, compact with closely packed/occasionally poorly consolidated, non-calcareous quartz arenite; associated with non- calcareous siltstone, minor claystone and shale represents active delta domain. Moreover, the facies relationship and nature of granularity indicates an active delta front setup.

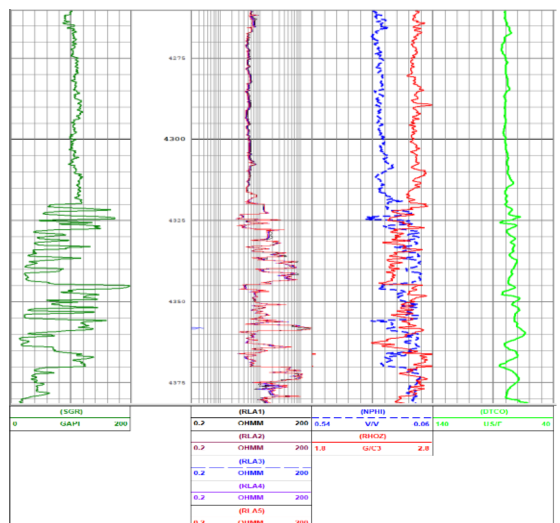


Figure 13: Log Motif of Well-G

Resistivity image log analysis: In the Well-G, image log analysis, together with conventional logs and core data, sedimentological inferences are made interval wise (Fig.14). The sand facies are identified as mainly distributary channel fills, estuarine fills, distributary mouth bars and sand flats. Faint cross beddings marked by shale layers is visible. In this interval, soft sedimentary deformation or sedimentary folding features are observed. Disseminated mica and pyrite are also noticed at places and embedded in carbonaceous matter (Figure 15). The faint beddings in the interval have dips in the range of 5 to 20 degrees trending predominantly towards East and SE. Fractures are noticed at places. The image log characteristics along with the core study results indicates the deposition took place in a backshore to foreshore set-up, specifically the vertical and horizontal bioturbation is also noticed in the entire interval

.

The shale and finer clastics are deposited in the inter distributary channel regimes and during sea level rise. The dip patterns indicate the channel features (Fig.14 15 & 16) and some of the blue patterns indicate the sediment direction from NW to SE. The difference in the sediment direction between structure contour map and the image dip log data could be due to the anti-clock wise rotation of Indian plate during drifting.

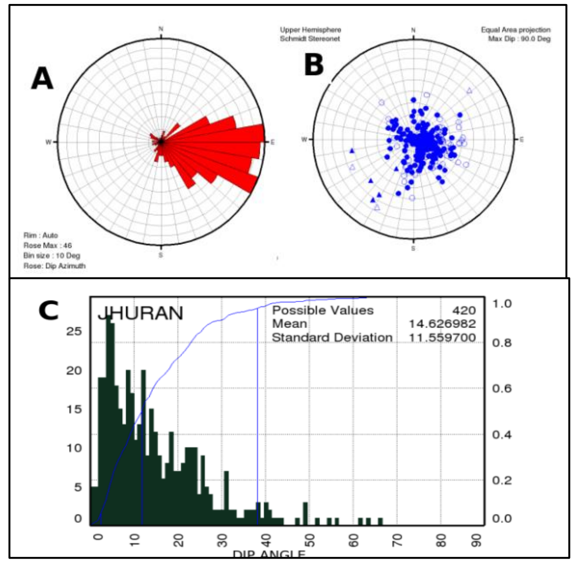


Figure 14: Dip statistsics of Jhuran Formation. A. Rose plot, B. Stereonet plot C. Dips distribution

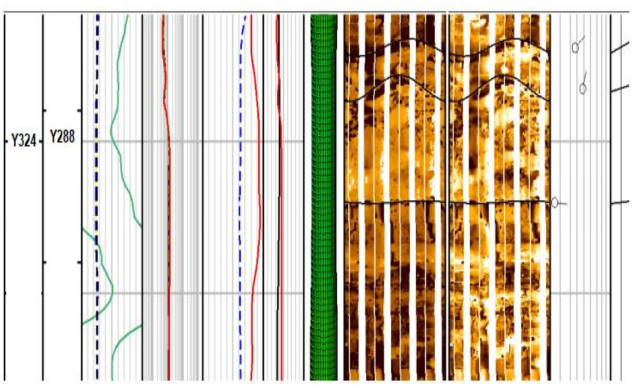


Figure-15: Image log display disseminated mica, pyrite and carbonaceous matter,

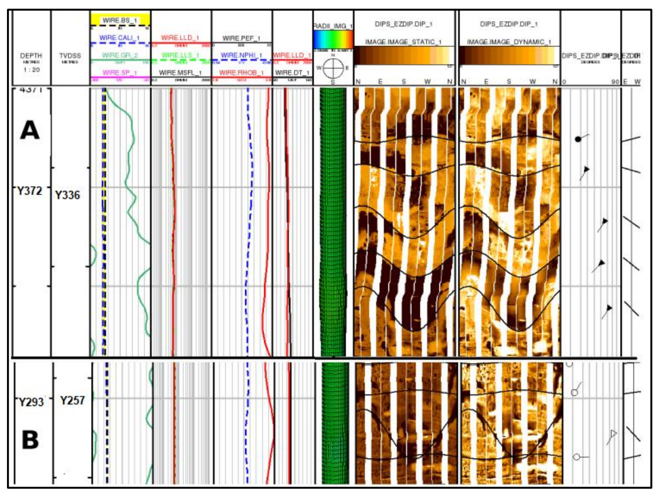


Figure 16: Image log display faults with dip direction of SW, which is similar to the regional dip direction of the faults, Well, Jhuran Formation

Summary:

* The log data in the sand intervals of Jhuran formation display mainly three features (Fig.17) viz:
    a) Erosional base followed by cylindrical GR, indicating distributary channel fills or tidal channels
    b) Funnel shape of GR, coarsening grain size upwards sequence, indicating distributary mouth bars.
    c) A funnel shape of GR followed by cylindrical shape, a distributary mouth- bar deposition followed by deposition of distributary channel fill

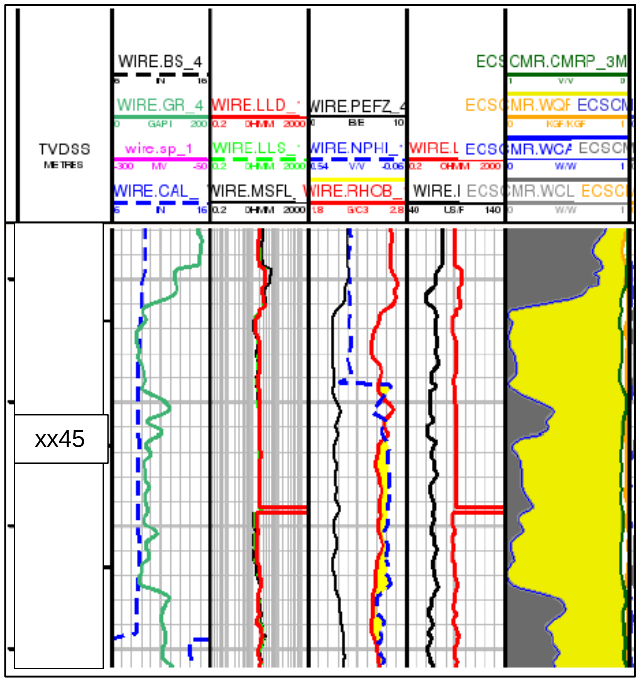
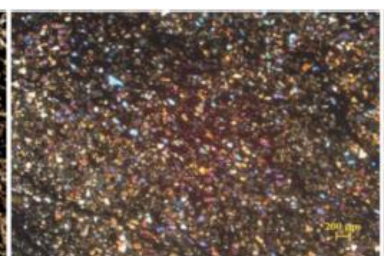


Figure 17: Conventional Log analysis, Well-E, Jhuran Formation

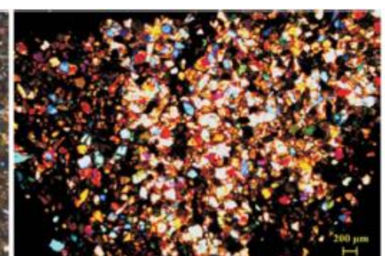
Sedimentological studies:

Mineralogy: Microfacies analysis of cutting samples (Fig.18) of Well-E shows the main lithological components as: Quartz arenite, weathered basalt, trap wash, minor siltstone, claystone, plagioclase, feldspar, minor pyrite etc. (Source: ONGC report WOB/RGL/GEOL/REP/16/2011-12 "Sedimentological, Biostratigraphy and Source Rock analysis Saurashtra -Dahanu Block, Mumbai Offshore")

(Mainly **Trap**, **Trap wash**) – **Basalt**. **Augite** enclosed by laths of **Plagioclase**. **Iron oxides** form the main ground mass. Appears to be **Tholeiitic Basalt** (Pyroxene and Plagioclase).

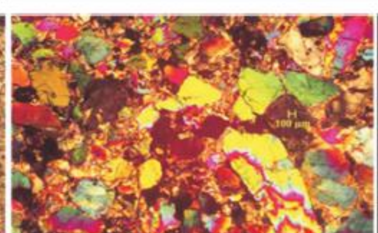


(Mainly **Trap**, **Trap wash** with traces of **sandstone**) – **Quartz arenite**. Occasionally showing **quartz wacke** characters



Weathered Basalt: 40%; **Sandstone** : 40% and **Claystone:** 20%: **Quartz arenite**

Fine grained Basalt; **Plagioclase** laths and **pyroxene** grains with **ferromagnesian** minerals.



Quartz Arenite, Plenty of **feldspar** grains. Black **ferruginous** matter sometimes acting as cement at places.

There is some variation in grain size of **plagioclase**: fine and coarse plagioclase laths

Figure-18 Microfacies analysis of cutting samples of the well E

Mineralogy: Well G is situated near by Well-E. Microfacies analysis of cutting samples (Fig.19) of Well-G shows the main lithological components as: Quartz arenite, fine grained sandstone/siltstone, oolitic limestone, basalt, claystone, plagioclase, orthoclase etc. (Source: ONGC report WOB/RGL/GEOL/REP/16/2011-12 "Sedimentological, Biostratigraphy and Source Rock analysis Saurashtra -Dahanu Block, Mumbai Offshore")

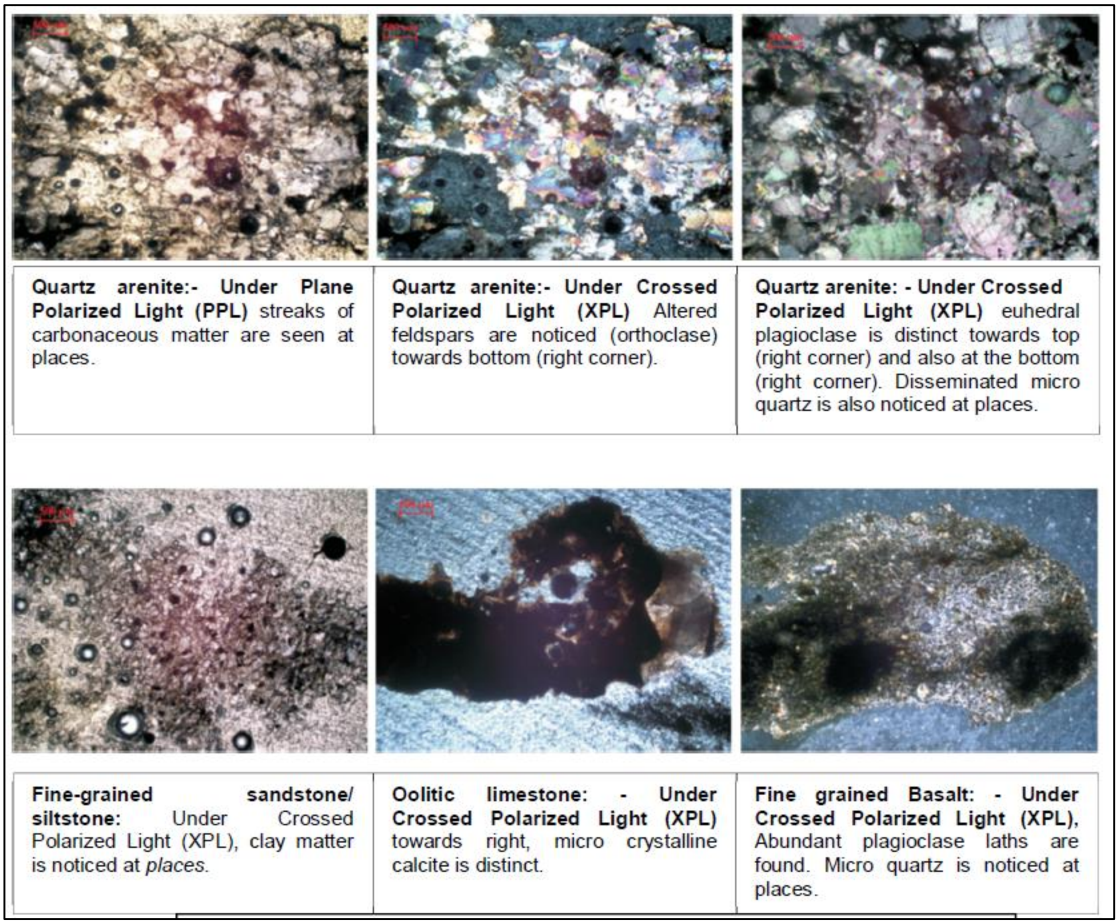


Figure-19 Microfacies analysis of cutting samples of the well G

Conclusions

- In the present study three wells of Kutch offshore basin, were analyzed for deducing depositional environment in geological successions of Mesozoic sediments using advanced log data. Image log processing is carried out and Dips, fractures, faults and erosional surfaces are identified in the image log.
- Within Jhuran formation, deduced paleo micro depositional environment is interpreted by integrating image logs, lab results, geochemical, NMR logs, conventional logs and production testing results.
- Mostly resistivity image log suggests gentle shale laminations (less than 5 deg, structural dip) and moderated dipping sandstone beds (10-30 deg) against reservoir sections in these wells. The dips are dominantly oriented in NW direction.

- Available Free fluid porosity from NMR logs suggests tight nature of sand layers, Pyrite presence in few layers as depicted by ECS & Image logs is in the form of nodules. CMR T2 display bi-model distribution in clean sandstones, which is due to the high energy coarse grain sands are intercalated with low energy finer clastics. The mixing of high and low energy sediments indicate episodic deposition.

- The integrated work flow developed is helpful in bringing out possible micro-depositional features within the sands. Sand depositions are represented by mouth bars and distributary channel fills, further influenced by marine processes. Shale and finer clastics are deposited in the inter distributary channel regimes and during sea level rise.
- Maximum horizontal stress directions inferred from natural fractures, drilling induced fractions and micro faults observed in the image log is towards NW-SE. This local stress orientation is in agreement with that of regional NW-SE striking faults.
- Different formations in Mesozoic sequences are the typical example of complex lithology. High order of heterogeneity and compositional complexity is observed in wells of the study area. Also no apparent correlativity could be established among the sand units. Presence of varying fraction of volcano-clastics make the formation compositionally complex. Plausible variation in depositional sub-environment as well as compositional changes are responsible for noticeable facies variation.

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